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Paleomagnetic volcanic data and geometric regularity of reversals and excursions

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Abstract. Mostly on the basis of paleomagnetic sedimentary data, it has been suggested that maps of virtual geomagnetic poles (VGPs), corresponding to directions of the magnetic field at each site, tend to fall along American and Asian longitudes during reversals and excursions. Such geometric regularity in transitional fields may indicate that the core and mantle are dynamically coupled. However, studies of paleomagnetic lava data have thus far failed to show any pattern in transitional fields. In this paper we examine a paleomagnetic lava database covering reversals and excursions which have occurred over the last 20 Myr. Volcanic eruptions occur sporadically, thus we normalize the data to account for the fact that reversal and excursional events at the various sites are recorded by different numbers of intermediate directions, but we prefer not to use averaging methods of previous investigators, who discarded or combined directions when they appeared to be similar. We find that volcanic data give intermediate VGPs which tend to fall along American and Asian longitudes, roughly consistent with the sedimentary data. This result is not an apparent artifact arising from the nonuniform geographic distribution of volcanic sites. Provided the appropriate polarity is assigned to intermediate VGPs, we find that Icelandic VGPs tend to fall along Asian longitudes. Other patterns in the data, for example, latitudinal clustering of VGPs or distinguishing longitudinal preferences of excursions from reversals, are not resolved. However, it appears that in general, transitional fields are nondipolar.

1. Introduction

Paleomagnetic studies show that the Earth's magnetic field is far from static. It is well known, initially deduced from a study of lava baked clay [*Brunhes*, 1906], that the geomagnetic field occasionally reverses its polarity, moreover, inter-reversal periods can also exhibit significant secular variation with occasional extreme departures from an axial dipole [*Bonhommet and Babkine*, 1967], such excursions might themselves be considered aborted reversals [*Doell and Cox*, 1972]. These phenomena are the most dramatic parts of the secular variation of the magnetic field and are the product of convective fluid motion in the Earth's core, the source of the geodynamo. Although theoretical progress is being made [*Glatzmaier and Roberts*, 1995; *Hollerbach and Jones*, 1993], a complete understanding of the geodynamo, and of geomagnetic transitions, remains elusive. What is clear is that further improvement in our understanding of the reversal process will depend, in large part, on data analysis.

Recently, several compilations of sedimentary paleomagnetic data have appeared to show that reversals and excursions exhibit geometric regularity; maps of virtual geomagnetic poles (VGPs), the south magnetic pole of a dipole corresponding to field directions from each paleomagnetic site, tend to fall along two separate paths: one along American longitudes and the other along Asian longitudes [*Clement*, 1991; *Laj et al.*, 1991]. These observations have been greeted with scepticism, with doubt expressed about the adequacy of the geographic distribution of sites [*Egbert*, 1992; *Valet et al.*, 1992] and the reliability of sedimentary records [*Barton and McFadden*, 1996; *Langereis et al.*, 1992]; and arguments over statistics have, thus far, failed to provide convincing resolution [*Laj et al.*, 1992; *McFadden et al.*, 1993]. But the assertion that intermediate VGPs fall along so-called preferred longitudes was perhaps most seriously damaged when *Prévot and Camps* [1993] published a study of paleomagnetic lava records. Lava data, in addition to being independent from sedimentary data, are not subject to the same controversies over reliability which make interpretation of sedimentary data so difficult [*Hoffman and Slade*, 1986]. Prévot and Camps found an absence of preferred VGP longitudes for geo-

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magnetic transitions over the last 16 Myr, concluding that transitional fields are statistically axisymmetric.

The issue of preferred transitional VGP longitudes is important for geodynamo theory; preferred paths may indicate that the core and mantle are dynamically coupled. Since the mantle changes very slowly compared to the frequency of reversals and excursions, the relatively steady nature of conditions established by the mantle at the core-mantle boundary (CMB) could be responsible for regularity in transitional fields [*Laj et al.*, 1991]. Core flow may lock onto mantle heterogeneities, possibly via topographic [*Hide*, 1969], electromagnetic [*Runcorn*, 1992] or thermal [*Bloxham and Gubbins*, 1987] mechanisms, and persistence in core flow might produce persistent patterns in the magnetic field, even during reversals and excursions. Of course, theories such as these are only viable so long as they are motivated and supported by observations; for a review see *Gubbins* [1994].

In this paper we report on our examination of paleomagnetic lava data covering reversals and excursions for the last 20 Myr. Although our database is somewhat different from that of Prévot and Camps, we consider, for example, only data from stratigraphic sections, the main difference between our analysis and theirs is in the treatment of the data: we prefer not to average or discard similar paleomagnetic directions, a practice which, by itself, can obliterate preferred VGP longitudes. However, because volcanic eruptions occur with extreme variability we normalize the data to account for the fact that the various reversal and excursional events are recorded at the different sites by widely varying numbers of intermediate directions. We suggest that our treatment of paleomagnetic lava data is appropriate for examining the possibility that intermediate VGPs tend to fall along either American or Asian longitudes or, alternatively, for testing the hypothesis that the Earth's transitional magnetic field is statistically axisymmetric.

2. Method

2.1. Data Selection

Our database relies on published records of reversals and excursions which occurred during the last 20 Myr, a period of time over which most plate tectonic movement can be neglected relative to the 180° directional change of reversals, and a period of time over which the conditions at the CMB have probably not changed appreciably [*McFadden and Merrill*, 1995]. The literature survey of *Prévot and Camps* [1993] was very thorough, and we considered data from each of the published sources that they used; we included data from a few papers published since Prévot and Camps conducted their analysis, and we included data from a few other papers which they did not include. Obviously, we considered only data sets with intermediate directions (defined below). Our selection criteria for each individual datum were similar to those of *Camps* [1994] and *Quidelleur et al.* [1994] and slightly stricter than those of *Johnson and Constable* [1996]. We accepted only average directions, inclinations (I) and declinations (D), taken 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, less than 20°. We accepted only absolute intensity measurements (F), when they were available, obtained by the Thellier method.

We have taken care to avoid possible data overlap by requiring that the data be temporally ordered, coming from nonoverlapping stratigraphic sections of extruded lava piles. Unfortunately, in practice, it is often difficult to work out the relative stratigraphy; in which case, overlap cannot be excluded as a possibility; see, for example *Aziz ur Rahman* [1971, p. 275]. In lieu of stratigraphy some investigators estimate the temporal order of paleomagnetic data using radiometric dating of the flows [*Abdel-Monem et al.*, 1972; *Mankinen et al.*, 1978; *Mankinen et al.*, 1981], but because of uncertainties in the dates, this is often insufficient to insure that unintentional multiple sampling of the same flow has not occurred and is usually only adequate to allow approximate temporal ordering. In some cases, investigators, having only partial stratigraphic information, attempt to place paleomagnetic vectors into temporal order by finding the smoothest variation in directions and intensities; see, for example, *Roperch and Duncan* [1990]. This is subjective, and we find it unacceptable. We note that paleomagnetic vectors taken from intrusive igneous bodies (dykes) are of unknown temporal order, thus we excluded any data from intrusive bodies. Finally, if the same site has been visited by more than one group of investigators, we kept data from the most detailed study, which was usually the most modern.

We follow Prévot and Camps and *Valet et al.* [1992] by defining an intermediate direction (I) as an inclination-declination pair with a corresponding VGP between latitudes ±60°N. Other investigators have adopted slightly different definitions, ±55°N is common, but clearly, because VGP latitude is a function of site location and field morphology, defining an intermediate direction is somewhat arbitrary; VGP latitudes of the modern field range from about 55°N to 85°N because the field is not a perfect dipole [*Love and Mazaud*, 1997]; moreover, the field during reversals and excursions is almost certainly not a perfect dipole either. Continuing, a direction is normal (N) if it has a VGP latitude above 60°N and reverse (R) if it has a VGP latitude below −60°N. The polarity of a transition is defined by the relative order of N and R directions; so, for example, a reversal from normal (reverse) to reverse (normal) is denoted N-R (R-N); whilst a normal (reverse) excursion is denoted N-N (R-R). Sometimes, because of incomplete recording of a transition in the lava flows, the polarity is undetermined or only partially determined, so for example, N-I (I-N) denotes a transition from normal (undetermined) to undetermined (normal) final polarity.

In some cases we know the polarity of the transitional event because it is sufficiently well dated, for example, the excursional data from Amsterdam Island [*Watkins and Nougier*, 1973] or Vulcano [*Laj et al.*, 1997] are from the Brunhes epoch and therefore represent N-N events; but in most cases we deduce the polarity of the transitional event from the stratigraphy. In a few cases, multiple transitions recorded at a particular site are actually just parts of a single complex transition; in which case the transition is counted more than once; this is true of the Steens Mountain sequence, for example, which is often considered to be a single reversal transition [*Prévot et al.*, 1985a] but which may also be a reversal followed by an excursion [*Valet et al.*, 1985]. The problem here is that it is often difficult (some might say "arbitrary"), simply on the basis of an examination of a sequence of paleomagnetic lava data, to determine when one transition begins and another ends; radiometric dating is inadequate for assigning most intermediate data to specific known events. Therefore we have opted for simplicity and avoided a great deal of subjectivity by counting each sequence of intermediate directions, bounded by reverse or normal directions, as separate transitional events. We have found by experiment that relaxing this strict assignment has virtually no effect on our conclusions; there are few complex transitions recorded in lava with multiple sequences of low latitude VGPs. For a minimal amount of resolution, in part of the analysis below we restrict ourselves to transitional events recorded (locally at each site) by three or more consecutive intermediate directions (*Valet et al.*, [1988] recommend four). This also has the advantage of providing some additional quality control: single intermediate directions are sometimes artifacts due to laboratory error or overprint.

The database is summarized in Table 1 and in Figure 1, where we show the geographic distribution of sites as well as the geographic distribution of VGPs per transitional event. Note that the distribution of sites is not uniform; our database is dominated by data from Iceland, and few transitions are recorded in the southern hemisphere. Furthermore, some sites have many intermediate directions per transitional event, whilst others have few intermediate directions per event. Among the various sites, there are 3275 directions, 1318 of which are intermediate, and 131 absolute Thellier intensities; 507 (local) transitions are recorded; 141 of these (local) transitions are of known initial polarity and are recorded by three or more consecutive intermediate directions for a total of 790 intermediate directions. (The total number of reversal and excursional events is smaller than the number of local transitions because some events are recorded at more than one site.) In the appendix we discuss our reasons for excluding parts of some data sets because they come from (possibly) overlapping neighboring stratigraphic sections, and we discuss the polarity assignments to each intermediate direction in our database (when they are not clearly determined by the stratigraphy alone).

2.2. Data Analysis

Because volcanoes erupt sporadically, paleomagnetic lava data represent a temporally discontinuous record of geomagnetic secular variation. It is possible for multiple lava flows to be deposited over a duration of time, short compared to the rate of secular variation of the magnetic field; in which case the flows will preserve more or less similar records of the magnetic field. In an attempt to account for such nearly identical data, in most of their analysis, *Prévot and Camps* [1993] combined consecutive directions from stratigraphic sections when they appeared to be similar (to within estimates of the directional errors), and they discarded apparently redundant directions when they were taken from different neighboring but stratigraphically unconstrained sites. Such treatments of lava data are fairly common, *McElhinny et al.*, [1996] advocate a similar procedure which they call "rationalizing" the data, and *Quidelleur et al.* [1994], in their dismissal of preferred VGP longitudes for inter-transitional data, discarded data on the basis of directional similarity.

However, the practice of combining, discarding, and rationalizing data on the basis of directional similarity is demonstrably dangerous. In Figure 2 we compare, where both directional (I, D) and Thellier intensity measurements (F) were available, the change in field direction between successive flows δ versus the change in the field intensity between successive flows ΔF. Since our database incorporates reversals and excursions both change in direction and change in intensity can be very large. But notice that sometimes the direction changes by only a few of degrees, an amount comparable to directional errors, while the intensity changes by tens of microteslas, an amount comparable to the present surface intensity of the Earth's magnetic field. Given (say) the present rate of westward drift, $\sim 0.2°/\text{yr}$, it might (mistakenly) be thought that such relatively small differences in magnetic direction represent only a few years between successive depositions; on the other hand, given the rate of decay of the dipole, $\sim 15\mu\text{T/kyr}$, the intervening times between successive depositions may be centuries. Most likely, what is represented here is a broad range of times, and thus we conclude that clusters of VGPs are not necessarily due exclusively to successions of rapidly deposited lava flows; they may actually be part of the secular variation. This possibility is supported by measurements from shallow marine clay [*Valet et al.*, 1986] and high-deposition-rate ocean cores [*Channell and Lehman*, 1997], which show significant clustering of intermediate VGPs despite the fact that the vertical accumulation of sediments is much more temporally uniform than the vertical accumulation of lavas. Of course, we are not implying that consecutive paleomagnetic vectors should be combined on

Table 1. Summary of Database (Stratigraphic Sections)

Locality	Name	Lat °N	Long °E	Age Myr	Data	Demag Method	Demag Steps	I VGPs	Weighted Events	Source
Alaska	Wait	62.3	217.0	3.4	*I,D*	AF	8?	13	0.7	*Bingham and Stone* [1976]
Alaska	Castles	62.3	217.0	3.4	*I,D*	AF	8?	8	0.6	*Bingham and Stone* [1976]
Aleutian	Kanaga	51.9	182.9	0.2	*I,D*	AF	7?	1	0.0	*Bingham and Stone* [1972]
Aleutian	Ashishik	53.3	192.0	1.7-2.1	*I,D*	AF	7?	7	0.7	*Bingham and Stone* [1972]
Amsterdam	17,18,19	-39.8	77.5	Brunhes	*I,D*	AF	2	3	0.9	*Watkins and Nougier* [1973]
Arizona	Hackberry (lavas)	34.4	248.2	7.9-11.5	*I,D*	AF	3+	11	0.8	*McKee and Elston* [1980]
British Columbia	Level	58.5	228.7	1.0-6.6	*I,D*	AF	6	15	1.4	*Hamilton and Evans* [1983]
British Columbia	Edziza (B)	57.5	229.2	0.0-6.0	*I,D*	AF	8	9	0.6	*Souther and Symons* [1974]
Canary	La Palma (LL)	28.6	342.2	0.8	*I,D,F*	AF,T	10+?	17	0.9	*Quidelleur and Valet* [1996]
Chile	Tatara-San Pedro	-36.0	289.0	0.3-1.0	*I,D*	AF,T	3+?	10	1.0	*Brown et al.* [1994]
China	Tongjing	37.8	120.8	0.8	*I,D,F*	T	14	1	0.0	*Zhu et al.* [1991]
Easter	32,33	-27.1	250.8	0.2	*I,D*	AF	6	2	0.0	*Isaacson and Heinrichs* [1976]
France	Laschamp	45.7	3.0	0.4-0.5	*I,D,F*	AF,T	6?	1	0.0	*Roperch et al.* [1988]
France	Olby	45.7	3.0	0.4-0.5	*I,D,F*	AF,T	6?	1	0.0	*Roperch et al.* [1988]
France	Louchadière	45.7	3.0	0.4-0.5	*I,D,F*	AF,T	6?	1	0.0	*Chauvin et al.* [1989]
Georgia	Akhalkalaki (W)	41.5	43.3	3.6	*I,D,F*	T	7?	14	0.8	*Camps et al.* [1996]
Hawaii	Necker	23.6	195.3	10.0	*I,D*	AF	4+?	7	0.0	*Doell* [1972]
Hawaii	Oahu (F69-72)	21.4	201.9	1.9	*I,D,F*	AF,T	5+?	1	0.0	*Doell and Dalrymple* [1973], *Coe et al.* [1984]
Hawaii	Oahu (O15-42)	21.4	201.9	3.0	*I,D,F*	AF,T	5+?	5	0.8	*Doell and Dalrymple* [1973], *Coe et al.* [1984]
Hawaii	Oahu (N1-13)	21.4	201.9	3.6	*I,D,F*	AF,T	5+?	1	0.0	*Doell and Dalrymple* [1973], *Coe et al.* [1984)]
Hawaii	Kauai (A)	22.0	199.5	3.8-5.1	*I,D,F*	AF,T	5+?	8	0.6	*Bogue and Coe* [1984]
Hawaii	Kauai (DG-OK)	22.0	199.5	3.8-5.1	*I,D,F*	AF,T	5+?	14	1.1	*Bogue and Coe* [1984]
Iceland	A,B,C,L,M	65.2	346.3	12.1-16.3	*I,D*	AF	3	25	4.2	*Dagley et al.* [1967], *Dagley and Lawley* [1974]
Iceland	Jökuldalur (GH1-GL5)	65.2	344.8	1.6	*I,D*	AF	2	5	0.6	*Watkins et al.* [1975]
Iceland	Bessastadaa (EQ)	65.0	345.0	4.8-6.5	*I,D*	AF	3	19	2.8	*McDougall et al.* [1976]
Iceland	Borgarfjördur (NP1-NT112)	64.5	337.5	1.6-6.7	*I,D*	AF	2	98	2.8	*Watkins et al.* [1977]
Iceland	Esja (FA02-SC11)	64.2	338.0	1.8-4.2	*I,D*	AF	2	71	5.8	*Kristjánsson et al.* [1980]
Iceland	Tröllaskagi (PA02-PG60)	66.0	341.0	8.2-11.2	*I,D*	AF	2	130	11.0	*Saemundsson et al.* [1980]
Iceland	SK1-JF159	65.7	337.0	11.0-14.0	*I,D*	AF	2	174	17.0	*McDougall et al.* [1984]
Iceland	SR0-BX08	65.7	338.5	8.0-14.0	*I,D*	AF	2	115	7.4	*McDougall et al.* [1984]
Iceland	BT1-BV55	65.7	338.5	14.0	*I,D*	AF	2	51	5.3	*McDougall et al.* [1984]
Iceland	Tjörnes (GS)	66.0	342.8	0.7	*I,D*	AF	3+?	5	0.8	*Kristjánsson et al.* [1988]
Iceland	Langidalur (TL1-TN85)	65.6	339.7	7.3-8.2	*I,D*	AF	2-4	47	6.1	*Kristjánsson et al.* [1992]

Table 1. (continued)

Locality	Name	Lat °N	Long °E	Age Myr	Data	Demag Method	Demag Steps	I VGPs	Weighted Events	Source
Iceland	R3-N3 (HU)	64.2	338.0	2.1	I,D	AF	3+	12	0.9	*Kristjánsson and Sigurgeirsson* [1993]
Iceland	R5-N5 (SH)	64.2	338.0	3.4	I,D	AF	3+	12	0.8	*Kristjánsson and Sigurgeirsson* [1993]
Iceland	Mjóifjör∂ur (DA1-MC56)	65.3	346.5	10.0-13.0	I,D	AF	3+	71	4.0	*Kristjánsson et al.* [1995]
Iceland	RK	64.4	338.5	2.5	I,D,F	AF,T	11	3	1.0	*Tanaka et al.* [1995]
Iceland	N4-R3 (FI)	64.5	338.8	2.5	I,D	AF	3-4	16	1.7	*Kristjánsson* [1995]
Iceland	Ísafja∂ardjúp (DO1-DM14)	65.4	337.5	12.0-13.7	I,D	AF	4	86	6.2	*Kristjánsson and Jóhannesson* [1996]
Idaho	Rocky (RC1-17)	46.0	243.0	14.5-16.0	I,D	AF	2	2	0.0	*Hooper et al.* [1979]
Japan	Usami (UV)	35.0	139.0	0.8	I,D,F	AF,T	5	4	0.6	*Kono* [1968]
Japan	Nagao-toge (HN)	35.0	139.0	Brunhes	I,D,F	AF,T	3+?	1	0.0	*Kono* [1971]
Kenya	Lengitoto (GT)	-1.5	37.4	6.9	I,D	AF	12+	4	0.9	*Patel and Raja* [1979]
Nevada	Santa Rosa	41.8	242.5	15.0	I,D	AF	20	6	0.9	*Roberts and Fuller* [1990]
Nevada	Lousetown (F2-34)	39.4	240.4	1.1-6.8	I,D	AF	8?	31	0.0	*Heinrichs* [1967]
New Mexico	Valles Caldera	36.0	253.5	0.1-0.9	I,D	AF	8	2	0.0	*Doell et al.* [1969]
New Zealand	Swampy (Fig3)	-46.0	170.0	12.4	I,D	AF	10	3	0.0	*Sherwood* [1988]
New Zealand	Akaroa	-44.0	173.0	8.2-9.4	I,D	AF	10	9	0.0	*Sherwood* [1988]
Oregon	Coast (DB2-CF1)	46.0	236.0	14.0-16.0	I,D	AF	3+	9	0.0	*Choiniere and Swanson* [1979]
Oregon	Fall Creek (FL3-1)	46.0	243.0	16.0	I,D	AF	2	1	0.0	*Hooper et al.* [1979]
Oregon	Joseph Creek (GRJ7-1)	46.0	243.0	16.0	I,D	AF	2	3	0.0	*Hooper et al.* [1979]
Oregon	Steens (A)	42.6	241.4	15.5	I,D,F	AF,T	8+?	36	2.1	*Mankinen et al.* [1985], *Prévot et al.* [1985a]
Polynesia	Huahine (H21-D40)	-16.0	209.0	2.9-3.1	I,D	AF,T	5+?	29	0.9	*Roperch and Duncan* [1990]
Polynesia	Huahine (F66-68)	-16.0	209.0	2.9-3.1	I,D	AF,T	5+?	8	1.0	*Roperch and Duncan* [1990]
Réunion	RN29-GC1	-20.9	55.4	2.0	I,D	AF	1	2	0.0	*McDougall and Watkins* [1973]
Sicily	Vulcano	38.0	15.0	0.0-0.1	I,D,F	T	10+	12	0.6	*Laj et al.* [1997]
Syria	Levant (S14-S19)	33.3	36.3	19.5	I,D	AF,T	5?	2	0.0	*Roperch and Bonhommet* [1986]
Tahiti	Punaruu Valley	-17.7	210.3	0.6-1.2	I,D,F	AF,T	4+?	42	3.0	*Chauvin et al.* [1990]
Tanzania	Ngorongora	-3.3	35.6	2.5	I,D	AF	4+?	7	0.7	*Grommé et al.* [1970]
Turkey	Gürün (G)	38.7	37.4	Quaternary	I,D	AF	6	3	0.0	*Sanver* [1968]
Washington	Saddle (OI1-LM1)	46.3	242.8	6.0-13.7	I,D	AF	3+	6	0.0	*Choiniere and Swanson* [1979]
Washington	Wanapum (RM1-RZ1)	46.3	242.8	13.7-14.5	I,D	AF	3+	1	0.0	*Choiniere and Swanson* [1979]
Washington	Grande Ronde (24-2)	46.3	242.8	14.5-16.0	I,D	AF	3+	5	0.8	*Choiniere and Swanson* [1979]

Data (I, D, F) is inclination, declination, (Thellier) intensity; Demag Method is either AF (alternating field) or T (thermal) demagnetization; Demag Steps is the number of steps in step-wise demagnetization (not counting uncleaned remanent magnetization); I VGPs is the total number of intermediate VGPs in each sequence; Weighted Events is the relative contribution of VGPs weighted by $(\cos\lambda)/N_I$, where λ is VGP latitude and N_I is the number of intermediate directions for each transition ($N_I \geq 3$).

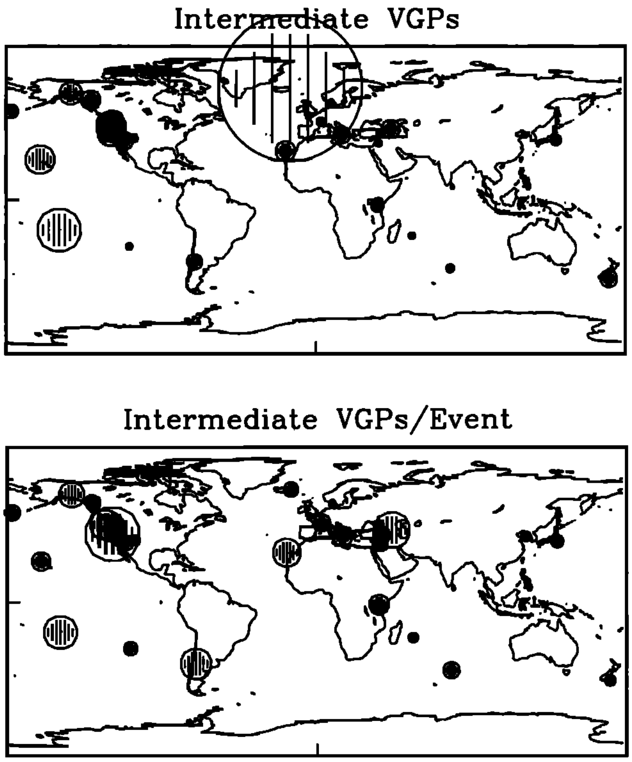

Figure 1. Geographic distribution of sites, the size of the symbol is proportional to the (top) number of intermediate VGPs and (bottom) number of intermediate VGPs per transitional event. Note that our database is dominated by intermediate directions from Iceland, but a few events; for example, Steens Mountain and Lousetown in the United States, give many intermediate directions per transition.

the basis of similarity in both direction and intensity; we present Figure 2 simply to illustrate the fact that field directions may change more slowly at some times than at other times. In other words, directional similarity does not necessarily mean near coincidence in time.

We do not a priori know the time dependence of transitional magnetic fields. It is possible that preferred VPG longitudes, if they are real, may be a property of the secular variation whereby field directions change more slowly (or are less scattered) when VGPs lie along a preferred longitude and that field directions change more rapidly (or are more scattered) when the VGPs do not lie on a preferred longitude. Volcanic data would preserve such variations as clusters of VGPs, perhaps (but not necessarily) in both latitude and longitude. In this scenario, if we averaged similar directions, then longitudinal preferences would be obliterated since VGP clusters would be combined into a few or even one VGP. We should emphasize one additional, but obvious, point: preferred VGP longitudes may not necessarily be accompanied by latitudinal clustering; intermediate VGPs might be distributed over many latitudes. If this is the case, then tampering with the field directions simply on the basis of their similarity, whilst perhaps not completely removing, can at least obscure preferred longitudes. In the next section we shall demonstrate this fact using the data themselves.

Clearly, any discarding or combining of field directions should be made independently of one's knowledge of the field directions themselves; to do anything else introduces bias. Therefore, to test for preferred longitudes, we contend that it is not advisable to combine and exclude data on the basis of directional similarity. We recognize that volcanic eruptions are very sporadic and some VGP clusters may not be representative of the secular variation. Unfortunately, we have no means of distinguishing geomagnetic secular variation from irregularity of volcanic eruptions (if we did, we would). Having said that, in the long run any accidental unevenness in the distribution of VGPs caused by a few unusually prolific volcanoes should be diluted by a preponderance of data; there is, of course, no reason to expect that preferred transitional longitudes are the result of volcanoes preferentially erupting while VGPs happen to lie on one of the preferred longitudes! Relying on the expectation that volcanic eruptions and geomagnetic variations are temporally uncorrelated, we choose to leave the directions as they are, uncombined and unrationalized.

Although we do not discard or combine similar directions in an attempt to account for eruptive variability during each transitional event, we weight the data to account for the fact that the total duration of some transitions is recorded at the various sites by widely differing

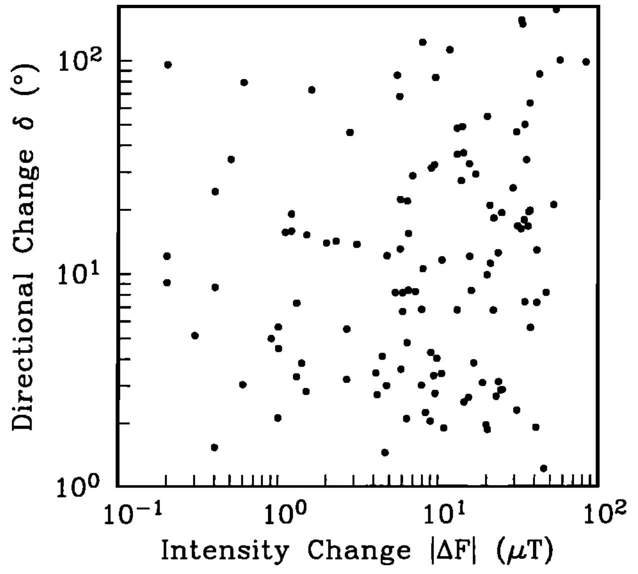

Figure 2. Directional change δ versus intensity change ΔF between successive lava flows where both directions and intensity are available. Note that ΔF denotes a simple difference between absolute Thellier measurements, not simple magnetization intensities. Sometimes, in the intervening time between successive depositions, 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. This demonstrates that the field direction sometimes changes very little over long periods of time.

numbers of intermediate directions. There is precedence for such normalization: *Valet et al.* [1992] calculated the mean VGP longitude (MVL) for each transition at each site and studied the geographic distribution of the MVLs (instead of the VGPs themselves), thus, in effect, counting each transition at each site equally. We find this treatment attractive because of the wide range of frequencies with which volcanoes erupt at different sites; at some sites (for example, Iceland) each transition is recorded by relatively few intermediate VGPs, whilst at other sites (like Steens Mountain) a few transitions are recorded by many intermediate VGPs; see Figure 1. Since we seek to test the hypothesis that VGPs from many transitions tend to fall along preferred longitudes it is inappropriate to count all VGPs equally; to do so would bias our study toward just a few transitions recorded at just a few sites thereby defeating our goal of finding patterns which might only be evident from a consideration of many transitions.

In detail the weighting scheme we adopt is a modification of that used by Valet et al.: we weight each VGP for a particular transition at a particular site by $(\cos\lambda)/N_I$. The $\cos\lambda$ term, where λ is the latitude of the VGP, gives more weight to low-latitude VGPs, which is fine, and removes some of the sensitivity of this analysis to other definitions of intermediate VGP cutoff. N_I is the total number of intermediate VGPs for that transition at that site, thus dividing by N_I insures that each transition at each site is weighted appropriately. By retaining the weighted VGPs, instead of the corresponding MVLs, we get a sense of the geographic distribution of VGPs, which is mostly lost when considering only mean VGP longitudes. But for this weighting to be meaningful we need some minimum number of intermediate VGPs for each transition. Certainly an average only begins to have meaning with (say) three samples; therefore, when weighting VGPs by $(\cos\lambda)/N_I$, we consider only transitional events with a minimum of three intermediate directions. We note that this criterion eliminates from consideration data from China, Easter Island, France, New Mexico, New Zealand, Réunion, and Syria, as well small parts of sections from other sites (where events are recorded by only one or two intermediate directions).

2.3. Paleomagnetic and Geomagnetic Conventions

We conclude this section with a note on VGP plotting conventions. Many studies of transitional field morphology have displayed VGPs with what *Prévot and Camps* [1993] call the paleomagnetic convention, south magnetic poles corresponding to field directions from each paleomagnetic site plotted on maps. But the equations of magnetohydrodynamics (MHD) are invariant under change in sign of the magnetic field [*Stevenson*, 1983], and therefore, if a reversal involves the entire magnetic field, the sense of the reversal (N-R or R-N) is irrelevant [*Gubbins and Coe*, 1993]. This led *Hoffman* [1984] to suggest that in the search for patterns from one transitional event to another the data are more readily interpreted if the magnetic pole lying initially near the (say) north geographic pole is plotted regardless of magnetic sign; this is what Prévot and Camps call the geomagnetic convention.

One of the advantages of using the geomagnetic convention is that if transitional fields display geometrical regularity, perhaps as the result of core-mantle coupling, and if transitional fields are dominantly dipolar, then VGPs may tend to fall along a single longitude (regardless of the sign of the field); on the other hand, for the same transitional fields, using the paleomagnetic convention will yield two preferred antipodal longitudes (depending on the sign of the field). Furthermore, assuming geometric regularity of transitional fields, then under the geomagnetic convention VGPs falling along (say) two longitudes would be evidence for a nondipolar transitional field, with the particular longitude being a function of site location (under this convention a particular site should give VGPs falling along one longitude). Thus, because it is perhaps more physically relevant and because it might allow for some discrimination between dipolar and nondipolar transitional fields, we prefer the geomagnetic convention, and in most of the discussion which follows we are restricted to data of known initial polarity. We note that this criterion eliminates from consideration data from Lousetown Nevada, Necker Island Hawaii, the Oregon Coast and Turkey, as well as small parts of sections from other sites (where events of unknown initial polarity are recorded).

3. Discussion

3.1. Geographic Distribution of VGPs

In Figure 3 we plot the (unweighted) intermediate VGPs for reversals and excursions for our database; histograms showing their longitudinal distribution using both the paleomagnetic and geomagnetic conven-

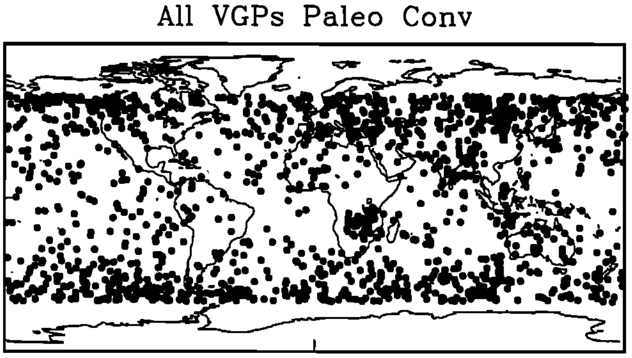

Figure 3. Map of intermediate VGPs (latitudes between ±60°N) from our database plotted with the paleomagnetic convention (south magnetic poles). Note that there is much scatter, as well as many clusters of VGPs; the cluster of VGPs in Africa is from a single sequence of lava flows for a single transition.

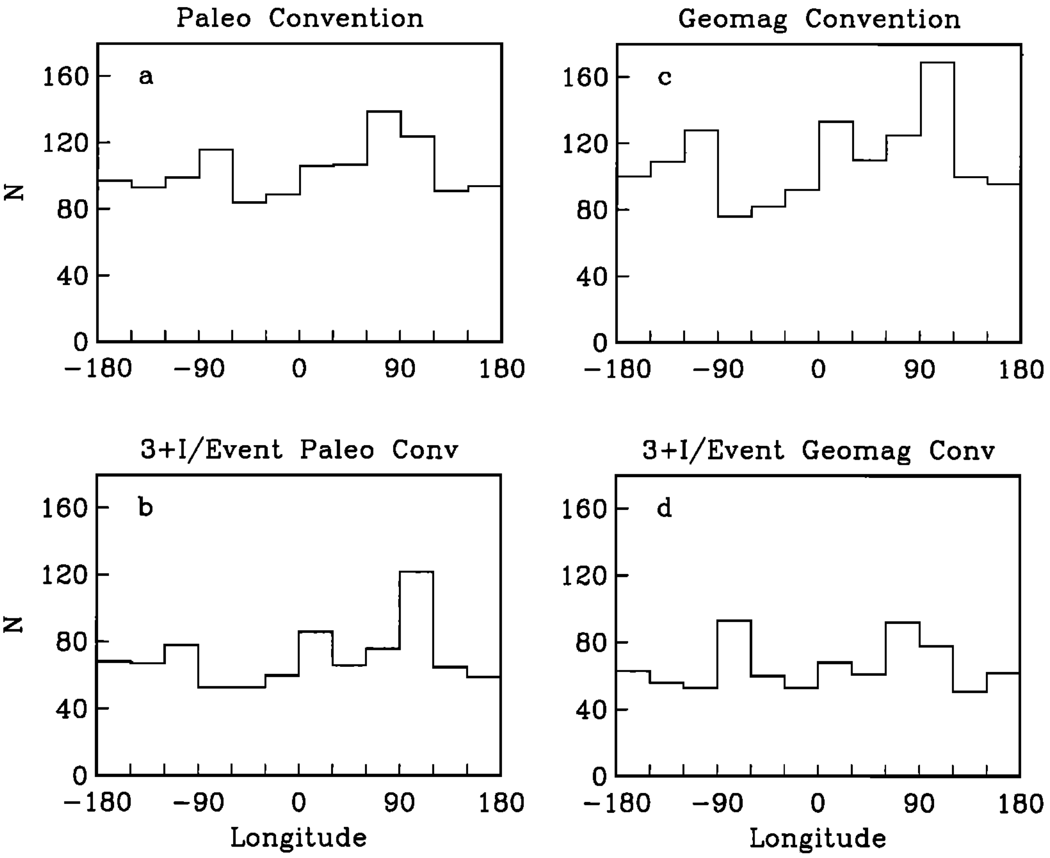

Figure 4. Histograms of intermediate (unweighted) VGP longitudes using both (a,b) the paleomagnetic and (c,d) geomagnetic conventions. In Figures 4b and 4d we have only included data which comes from sequences of three or more consecutive intermediate directions per transitional event. Both χ^2 and Kolmogorov-Smirnov (Kuiper) tests confirm that these longitudinal distributions of VGPs are not uniform, with significance levels well below 1%. Note that in Figure 4d there is a hint of a preference for VGPs to fall along American and Asian longitudes.

tions are shown in Figure 4. The VGPs are not uniformly distributed; there are many clusters of VGPs, and both χ^2 and Kolmogorov-Smirnov (Kuiper) tests confirm the obvious observation that the longitudinal distribution of VGPs is not uniform, with significance levels well below 1%. The situation is only slightly different when we consider transitional events recorded by three or more consecutive intermediate directions. *Constable* [1992], upon analysis of nontransitional volcanic data, also found a nonuniform distribution of VGP longitudes. And in the one instance when they did not combine similar directions into single directions, *Prévot and Camps* [1993] found a nonuniform distribution of VGP longitudes, at least for certain tests of nonuniformity (Watson's); see their Figure 2b. Prévot and Camps found that intermediate VGPs, when they are counted equally, do not tend to fall along American and Asian longitudes. In Figure 4d we see a hint of confinement along those longitudes, but there are numerous exceptions; for example, the concentration of VGPs in southern Africa (Figure 3) is due to a single sequence of lava flows from Lousetown Nevada; this highlights one of the problems of not accounting for the differing number of intermediate directions per transitional event.

When we weight VGPs by $(\cos\lambda)/N_I$ so that our results are not biased by a few transitional events from a few sites where the volcanoes just happen to have erupted profusely, then preferred longitudes become clearer. In Figure 5 we binned the weighted VGPs in latitude and longitude and plotted them as a gray-scale histogram on a map; since we have adopted the geomagnetic convention, VGPs tend to be concentrated in the northern hemisphere, the result of excursions which do not always yield southern hemisphere VGPs. In the same figure we also show a histogram of the longitudinal distribution of intermediate weighted VGPs. Note the tendency for VGPs to fall along American and Asian longitudes (±75°E); this result stands in stark contrast to that of Prévot and Camps, who reported no preferred longitudes.

An interesting comparison can be made now by plotting VGPs under the paleomagnetic convention; the histogram is shown in Figure 6. Notice that although the histogram shows two preferred longitudes, they are neither as distinct nor are they exactly the same as those in Figure 5. The preferred longitudes under the geomagnetic convention are not exactly antipodal; indeed, we have no reason to expect that they should be. What

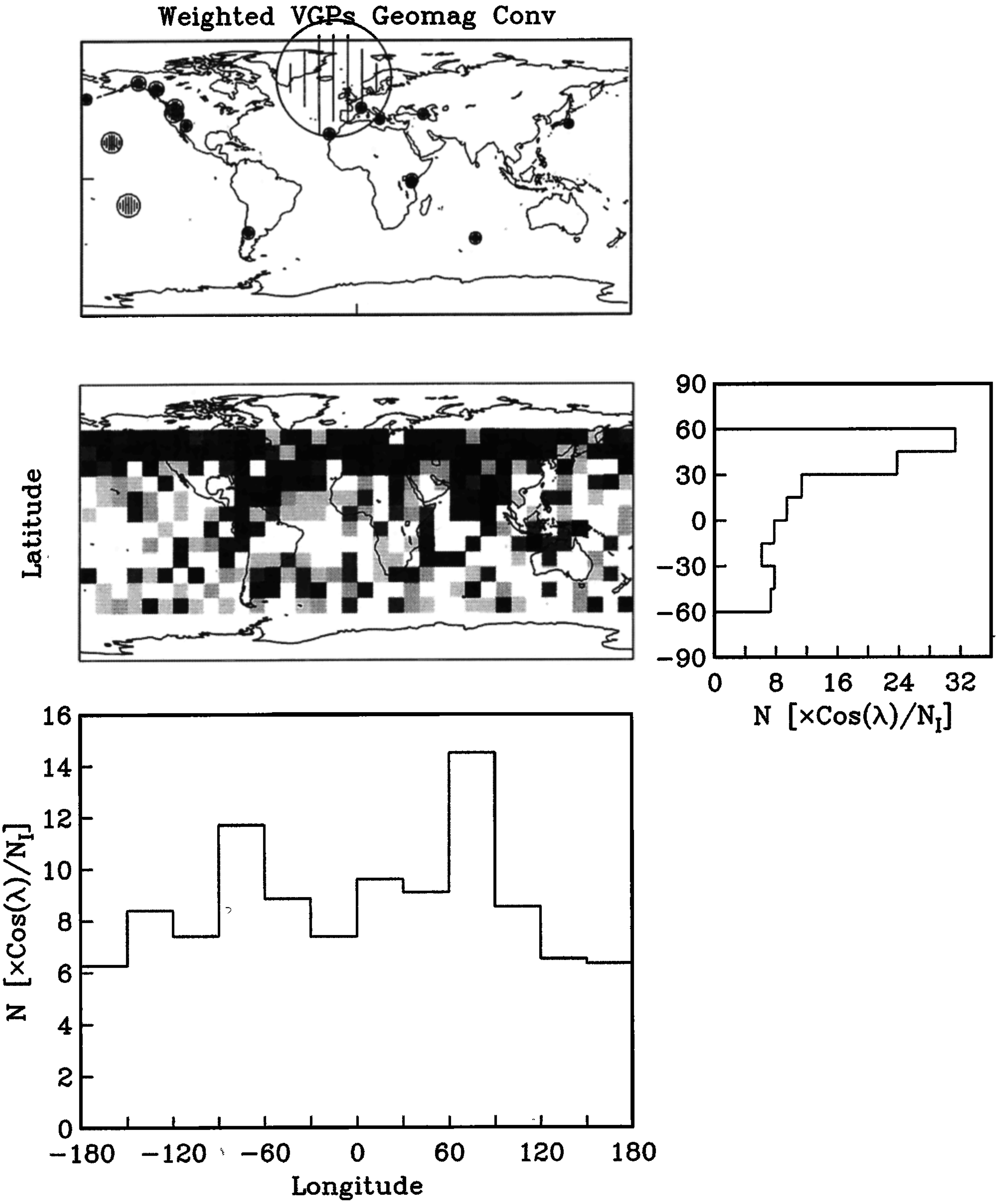

Figure 5. Map of gray-scale histogram of intermediate (weighted, geomagnetic) VGPs and histograms showing longitudinal and latitudinal distributions. Dark (light) shading indicates a high (low) average concentration of VGPs. All data are weighted by $(\cos\lambda)/N_I$, where λ is VGP latitude and N_I is the number of intermediate directions for each transition ($N_I \geq 3$). Note a preference for VGPs to fall along American and Asian longitudes; there is significant latitudinal scatter, but the histogram does not show any obvious tendency for intermediate VGPs to cluster at midlatitudes. In the top map the size of the symbol is proportional to the contribution of weighted VGPs from each site.

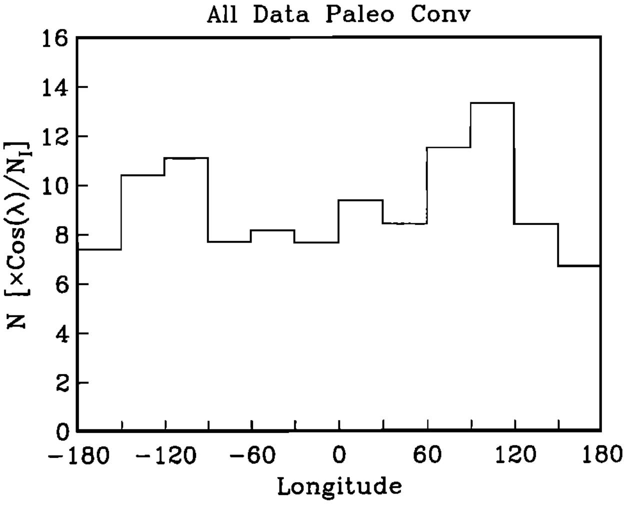

Figure 6. Histogram of intermediate (weighted) VGP longitudes using the paleomagnetic convention. Whilst we see American and Asian preferred longitudes, we note that the paleomagnetic convention (here) does not show them as clearly, nor even in exactly the same place, as when VGPs are plotted under the geomagnetic convention (Figure 5).

happens, then, when VGPs are plotted under the paleomagnetic convention is that some (but not all) of the VGPs which would fall along (say) +75°E (−75°E) under the geomagnetic convention are, instead, plotted along the antipodal longitude of −105°E (+105°E); this has the effect of shifting and broadening the preferred longitudes. Thus one of the advantages of the geomagnetic convention is that it allows for more accurate location of nonantipodal preferred VGP longitudes.

From their study of sedimentary records, *Laj et al.* [1992] found somewhat different preferred longitudes, near −60°E and +120°E. The discrepancy between our result and that of Laj et al. is probably due to a combination of scatter in the data (of which there is much), their consideration of fewer (local) transitions (41) than we considered (141), their use of the paleomagnetic convention (we prefer the geomagnetic convention), and of course, there are many technical problems with sedimentary records (most of which are irrelevant for lava data). Other comparisons can be made with, for example, *Clement* [1991], who restricted his study to the Matuyama-Brunhes reversal, he found preferred VGP longitudes near −80°E and +100°E; and *Constable* [1992], who restricted herself to nontransitional lava data, found preferred VGP longitudes near −90°E and +70°E. Finally, we remark, as others already have, that preferred transitional VGP longitudes are near longitudes where magnetic flux is concentrated at the CMB for both paleomagnetic time-averaged models [*Gubbins and Kelly*, 1993] and historical models [*Bloxham and Gubbins*, 1985], although Constable has noted that modern field VGPs are really only clustered over the American flux patch.

Hoffman [1992] has suggested that transitional fields may, at times, assume an inclined dipole configuration, with VGPs tending to cluster at particular midlatitudes along Asian and American longitudes. In Figure 5 the gray-scale histogram shows a good deal of scatter in the latitudinal distribution of weighted VGPs, which is almost certainly due to a combination of secular variation and uneven temporal recording of the magnetic field due to irregularities in volcanic eruptions (recall that we have no objective way of separating these two effects). However, the histogram of weighted VGPs does not show any obvious tendency for VGPs to cluster at midlatitudes; thus we are unable to confirm the hypothesis of Hoffman; our observation on this matter is consistent with that of Prévot and Camps.

3.2. Icelandic and Non-Icelandic Data

Since ~75% of the transitional events in our database come from Iceland it is worthwhile examining the lava data from this site in some detail. A measure of the quality of the Icelandic data can be made by examining its antipodal symmetry, something which is now recognized as an important test of the fidelity of sedimentary records as well [*Clement*, 1994; *Langereis et al.*, 1992]: at a particular site, reverse data should have an average direction which is opposite that of normal data, an expectation which is consistent with the invariance of the equations of MHD under change of sign of the magnetic field. For Icelandic data we find that the mean normal direction (I, D, α_{95}) to be $(75.5°, 5.4°, 0.7°)$, whilst the mean reverse direction is $(-75.8°, -177.8°, 0.7°)$. The angle between the mean normal direction and the direction antipodal to the mean reverse direction is 0.8°, which is less than the sum of the α_{95}s; therefore we conclude that the Icelandic data are statistically antipodally symmetric.

If transitional fields do display geometric regularity with preferred VGP longitudes, then we might expect multiple transitions from a single site to give VGPs falling along a single longitude (so long as the geomagnetic convention is adopted for plotting VGPs). In Figure 7 we plot histograms of the Icelandic intermediate weighted VGPs using both the paleomagnetic and geomagnetic conventions; under the former convention the histogram of intermediate VGPs shows two longitudinal peaks, whilst under the later convention the histogram shows a single longitudinal peak; there is a tendency for Icelandic (geomagnetic) VGPs to fall along Asian longitudes. This observation, of course, does not by itself indicate that transitional fields are dipolar; it simply reflects a pattern in the direction of the transitional field at Iceland.

If transitional fields are nondipolar, then geomagnetic VGPs from other sites may follow different paths; this point is illustrated in Figure 7 where we see that non-Icelandic geomagnetic VGPs fall along both American and Asian longitudes. Oddly enough, if the paleomagnetic convention is adopted, non-Icelandic VGPs tend to fall mostly along Asian longitudes; this asymmetry is almost certainly due to the small number of available

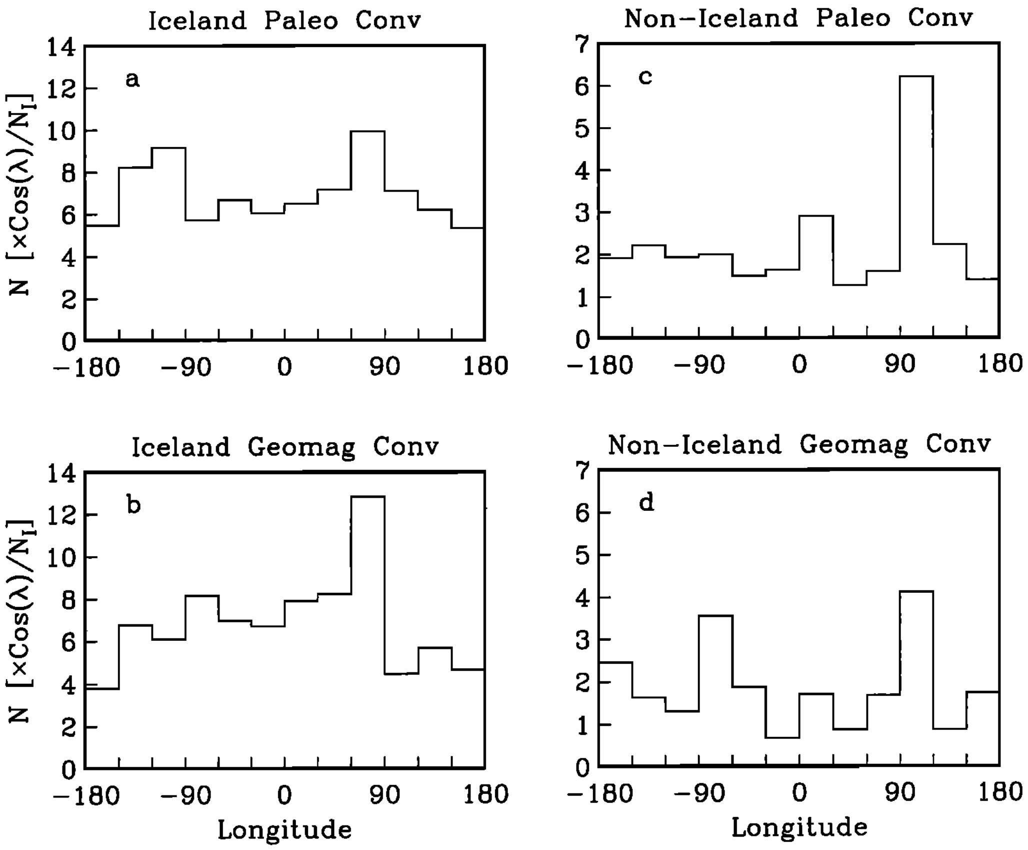

Figure 7. Histograms of intermediate (weighted) VGP longitudes for Icelandic and non-Icelandic data. For Icelandic data, under the paleomagnetic convention, VGPs fall (roughly) on two antipodal longitudes, whilst under the geomagnetic convention they preferentially fall along one (Asian) longitude. For non-Icelandic data the single peak seen under the paleomagnetic convention is split into two (American and Asian) longitudinal peaks, an oddity which we believe is related to the relatively small number of non-Icelandic data.

non-Icelandic data with attendant uneven sampling of both normal and reverse transitions at the different volcanic sites. It should, however, be emphasized that under neither convention are the distributions of non-Icelandic weighted VGPs uniform.

3.3. Subsets of the Database

In Figure 8 we show histograms of various subsets of our database, and in Figure 9 we show the corresponding relative contribution to these histograms from each site. Notice that the reversal VGPs by themselves tend to fall along American and Asian longitudes, whilst excursional VGPs tend to fall along only Asian longitudes; however, both of these histograms show significant scatter, being based on many fewer data than the histogram shown in Figure 5; thus we are hesitant to conclude that reversals and excursions are somehow fundamentally different from each other. We do not know the reason for the apparent asymmetry between normal and reverse transitions; inspection of the corresponding site distributions in Figure 9 shows that normal intermediate data actually come from a slightly better distribution of sites, although in both cases the geographic sampling is sparse. Apparent differences between data which are younger and data which are older than 10 Myr are certainly due to differences in site distribution: the data from 10-20 Myr come from only two regions, the western United States and Iceland, and since Icelandic data give geomagnetic VGPs which tend to fall along Asian longitudes the histogram of data from 10-20 Myr also shows an Asian preference.

Next, in Figure 10 we examine the importance of some of the data selection criteria. Up to now we have considered weighted VGPs coming from transitional events with three or more intermediate directions, but notice that we obtain the same preferred American and Asian longitudes if we consider instead events with four or more intermediate directions; a similar consistency is found if we consider a stricter criterion on each individual direction, namely four or more magnetically cleaned samples per flow with $\alpha_{95} < 15°$. Concerning measurement methods, many of the data considered in this analysis were obtained by alternating field (AF) demagnetization of rock samples; however, many researchers prefer thermal (T) measurements. Unfortunately, of the source papers considered here many authors using thermal demagnetization also used some AF demagne-

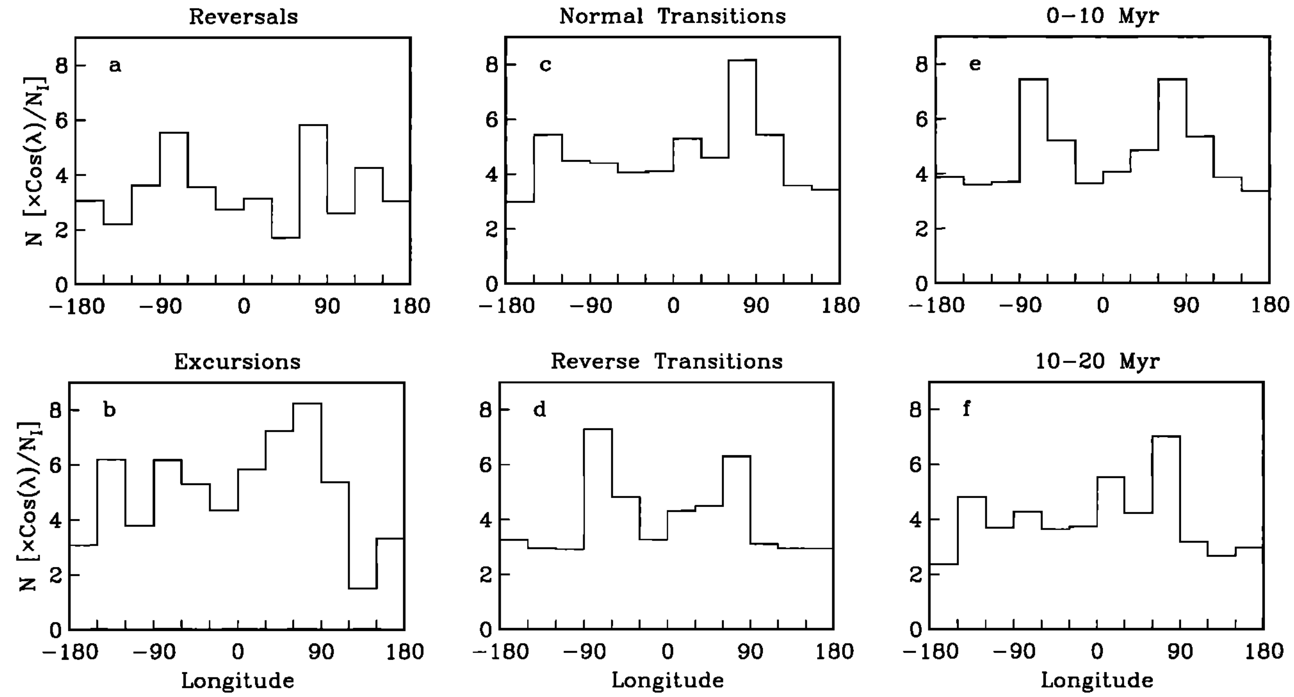

Figure 8. Histograms of intermediate (weighted, geomagnetic) VGP longitudes for various subsets of our database. (a) and (b) We compare data for reversals and excursions separately (note that this requires that we know both the initial and final polarities of each transition, a criterion somewhat more strict than that used in Figure 5, where we only needed the initial polarity). The reversal data show some hint of American and Asian preferred longitudes, but both Figures 8a and 8b also show significant scatter. (c) Normal and (d) reverse transitions both show preferred Asian longitudes, but only reverse transitional data show a preferred American longitude. Data from flows (e) younger than 10 Myr and (f) older than 10 Myr show Asian longitudes, but only the younger flows show a preferred American longitude. We believe that the asymmetry between Figures 8e and 8f is the result of a poor geographic distribution of sites and uneven temporal sampling.

tization but do not clearly state which directions were obtained with which demagnetization method. When authors mention both demagnetization methods, we assume that AF results are consistent with thermal results; the subset of our database which comes from these papers is very small, and yet, it shows some American and Asian longitudinal confinement of intermediate VGPs. Finally, some of the data in our database were obtained by either blanket demagnetization (usually at 15 mT) or simple two-step demagnetization (usually at 10 and 20 mT); many Icelandic data fall into this category. Although blanket demagnetization may at times be acceptable, often only 10 or 15 mT are sufficient to remove overprint from Icelandic lavas [*Kristjánsson and Jóhannesson*, 1996]; if we consider only data which has been demagnetized with three or more steps, we find that this too yields preferred American and Asian longitudes for intermediate VGPs. Taken as a whole, Figure 10 indicates that our conclusions are relatively insensitive to more stringent data selection criteria.

3.4. On Grouping Similar Directions

Toward examining the effect of combining directions on the basis of their similarity, we follow *Prévot and Camps* [1993] by making the simple definition: for data from stratigraphic sections, if the angle between successive directions δ is less than the sum of the corresponding α_{95}s, then these two directions are considered to belong to the same directional group; this grouping is applied along the stratigraphic section until δ exceeds the α_{95} cutoff. With this definition, single directions can be separate directional groups, but often, multiple directions fall into a single group; examination of specific sequences of data shows that this simple definition gives directional groups like those of Prévot and Camps.

Repeating our analysis on these directional groups, we obtain the histograms in Figure 11. Note that applying directional grouping reduces significantly the number of directions; for the unweighted intermediate (grouped) VGPs (Figure 11a) a χ^2 test indicates that the longitudinal distribution of VGPs has a 60% chance of being drawn from a uniform population; the reader will recall that without grouping this probability was less than 1%. Furthermore, when we compare the distribution of weighted grouped VGPs (Figure 11b) with the weighted but ungrouped VGPs in Figure 5, we see that grouping data by directional similarity all but erases the preferred American and Asian longitudes, which in hindsight is hardly surprising.

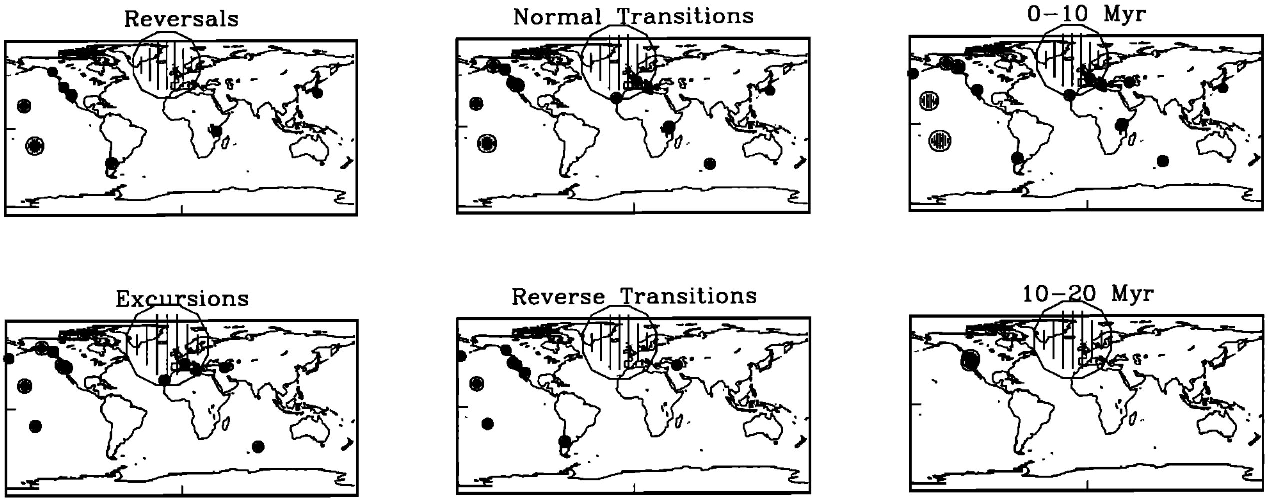

Figure 9. Maps, corresponding to the histograms shown in Figure 8, where the size of symbol is proportional to the contribution of VGPs from each site weighted by $(\cos\lambda)/N_I$, where λ is VGP latitude and N_I is the number of intermediate directions for each transition ($N_I \geq 3$).

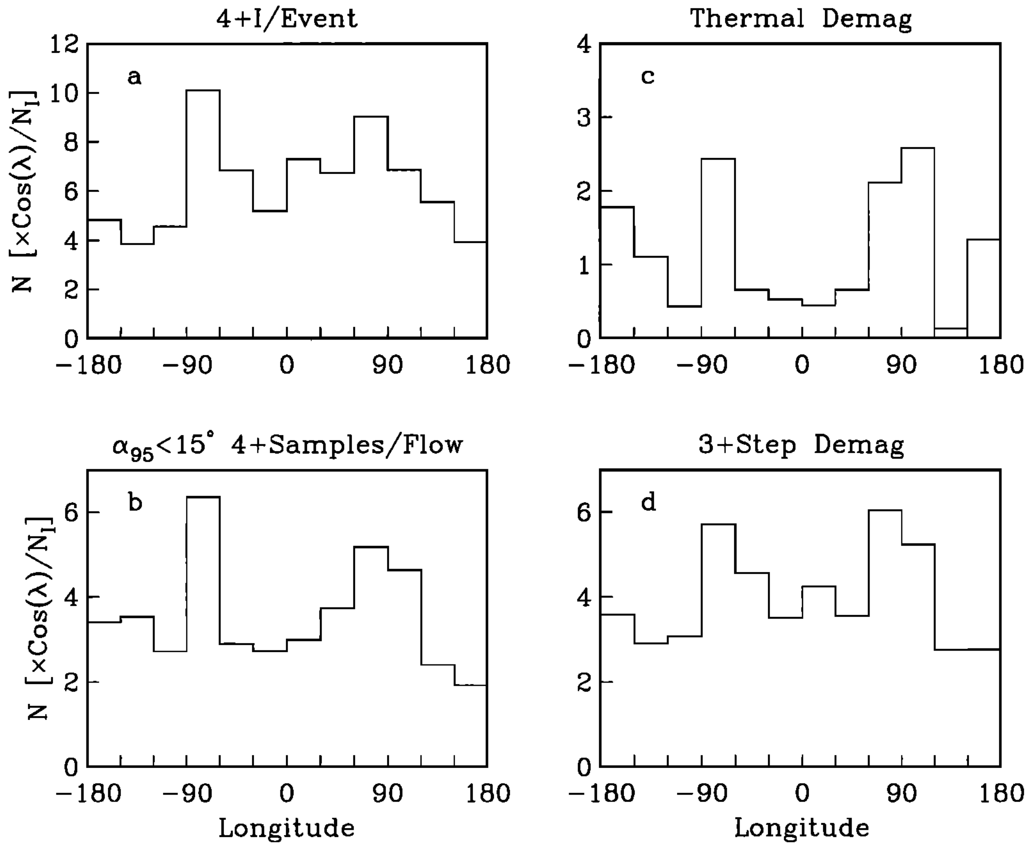

Figure 10. Histograms of intermediate (weighted, geomagnetic) VGP longitudes for different (stricter) data selection criteria. (a) We plot VGP longitudes from events with $N_I \geq 4$; (b) data with four or more magnetically cleaned samples per flow and with $\alpha_{95} < 15°$; (c) the (few) data from sites where samples were subjected to at least some thermal demagnetization; (d) measurements made with at least three steps in step-wise demagnetization. Taken as a whole, these histograms indicate that the apparent preference for transitional VGPs to fall along American and Asian longitudes is relatively insensitive to the data selection criteria.

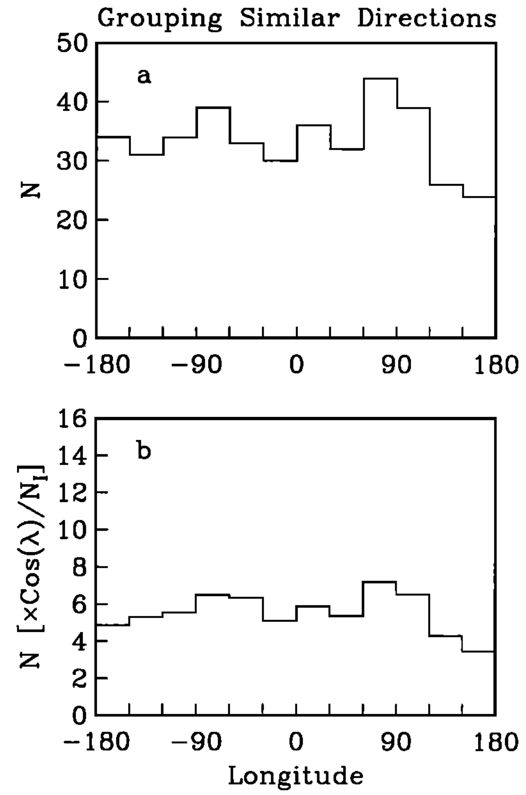

Figure 11. Histograms of intermediate (geomagnetic) VGP longitudes for directional groups: (a) unweighted VGPs and (b) weighted VGPs, in both cases for events with $N_I \geq 3$. Combining data into directional groups reduces the number of transitional events to 86 and the number of intermediate directions to 403, compared to 141 and 790, respectively, for ungrouped data. For Figure 11a a χ^2 test indicates that the distribution has a 60% chance of being drawn from a uniform population. Clearly, combining data on the basis of directional similarity effectively homogenizes the longitudinal distribution: compare Figure 11b with Figure 5.

3.5. On Site Bias

Despite the relative reliability of paleomagnetic lava data, preferred paths may be an artifact of a poor geographic distribution of sites combined with a bias inherent to VGP mapping whereby random noise causes VGPs to fall along longitudes ±90°E from site longitudes [*Egbert*, 1992]. To check for site distribution bias, we consider VGP longitude minus site longitude, or common site longitude; see Figure 12. Since we do not see peaks at both −90°E and +90°E we conclude that the bias suggested by Egbert is not an important factor in the apparent longitudinal preference of intermediate VGPs found here. The tendency for the weighted VGPs to fall +90°E of the site longitude is due to Icelandic data (Iceland happens to sit on a longitude about −90°E of the Asian longitude, where most of the Icelandic VGPs fall).

4. Conclusions

In this analysis we used a weighting method which accounts for the different number of intermediate VGPs recording each transitional event at the different volcanic sites, but we did not combine directions simply on the basis of their similarity. We appreciate the motivation that others have had when combining or discarding similar paleomagnetic directions. Sporadic volcanic eruptions can give VGP clustering; however, changes in the secular variation itself can also give VGP clustering. Unfortunately, there is no objective means of untangling these two effects. With enough data it should not be necessary; obviously, the frequency of volcanic eruptions are unrelated to, and therefore uncorrelated with, variations in the magnetic field. Barring a remarkable coincidence, there is no reason to expect that preferred VGP paths are the result of volcanic variability. Thus, in the search for preferred VGP paths it is difficult to justify combining or discarding similar directions; more importantly, the practice itself introduces bias. Since VGP paths are (at each site) equivalent to the magnetic field pointing preferentially within a range of certain directions, tampering with similar directions will change the geographic distribution of VGPs. More specifically, combining or discarding similar directions will, inevitably, homogenize the geographic distribution of VGPs.

In no case, from our analysis of paleomagnetic lava data, have we found uniform longitudinal distributions of intermediate VGPs; therefore we conclude that tran-

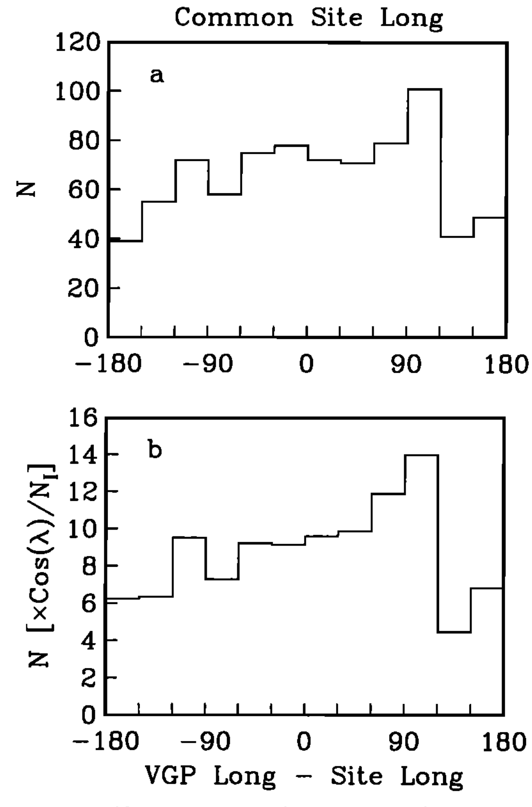

Figure 12. Histograms of (geomagnetic) VGP common site longitude (VGP longitude minus site longitude): (a) unweighted VGPs and (b) weighted VGPs, in both cases for events with $N_I \geq 3$. In neither case do the VGPs tend to fall along longitudes ±90° from site longitude; therefore the preferred longitudes seen in Figure 5 are not an artifact of site bias like that suggested by *Egbert* [1992].

sitional fields are not statistically axisymmetric. More specifically, we have found evidence, as others have from sedimentary data, that the geometry of the geomagnetic field during transitions appears to repeat sufficiently often over millions of years to give preferred American and Asian VGP longitudes. Interestingly, for Iceland alone, under the geomagnetic convention, VGPs tend to fall along Asian longitudes; thus the transitional field displays regularity at a single site. Since the VGP depends on site position and field morphology the presence of two preferred VGP longitudes (geomagnetic convention) from data from different sites indicates that transitional fields are nondipolar. These observations are contradictory to those of *Prévot and Camps* [1993]. Finally, latitudinal clustering of transitional VGPs [*Hoffman*, 1992] is simply not supported by our (large) database. Because of the limited quality and number of data, additional conclusions remain elusive; we were unable, for example, to come to any conclusion regarding differences (or similarities) in VGP distribution between reversals and excursions. Clearly continued progress will benefit from the ongoing collection of paleomagnetic lava data.

Appendix: 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 possible overlap of neighboring stratigraphic sections, some issues related to dating and demagnetization, and assignment of transitional polarity. Usually, the polarity of the intermediate data are determined by the stratigraphy, but in some cases, where the stratigraphy by itself does not fix the polarity, the polarity is determined either by the age of the data or by other geological information taken from the source papers.

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 stratigraphic section. Amsterdam Island intermediate data are Brunhes age and therefore are N-N.

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

Canary, La Palma, *Quidelleur and Valet* [1996]: Possible overlap with LS; keep LL.

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

France, Laschamp, *Roperch et al.* [1988], *Chauvin et al.* [1989]: Samples taken from three separate flows. Laschamp intermediate data are Brunhes age and therefore are N-N.

Georgia, Akhalkalaki, *Camps et al.* [1996]: Possible overlap with X,Y,Z, keep W. Initial polarity of data was not measured, but age of flows corresponds to a reverse Gilbert epoch; therefore intermediate data are R-R.

Iceland, Jökuldalur, *Watkins et al.* [1975]: Possible overlap with GK, GJ; keep GH1-GL5.

Iceland, Bessastadaa, *McDougall et al.* [1976]: Possible overlap with EW; keep EQ.

Iceland, Borgarfjördur, *Watkins et al.* [1977]: Keep nonoverlapping composite section NP1-NT 112 specified in Figure 2 of *McDougall et al.* [1977].

Iceland, Esja, *Kristjánsson et al.* [1980]: Keep nonoverlapping composite section FA02-SC1 specified on page 38.

Iceland, Tröllaskagi, *Saemundsson et al.* [1980]: Keep nonoverlapping composite section PA02-PG60 specified on page 12. PA02-PC39 (PC40-PG60) are older (younger) than 10 Myr; see Figure 4.

Iceland, SK1-JF159, SR0-BX08, BT1-BV55, *McDougall et al.* [1984]: Keep nonoverlapping composite sections specified in Figure 2. SR0-BD10 (BD12-BX08) are older (younger) than 10 Myr; see Figure 7.

Iceland, Tjörnes, *Kristjánsson et al.* [1988]: Possible overlap with GF, BA, GM; keep only GS.

Iceland, Langidalur, *Kristjánsson et al.* [1992]: Keep nonoverlapping composite section TL1-IN85 specified on page 39. TL1-33 were demagnetized with two steps; the remaining flows were demagnetized with three or more steps; see page 38.

Iceland, R3-N3, *Kristjánsson and Sigurgeirsson* [1993]: Possible overlap with MO, KY, SE, FL, BO, MU; keep only HU, which is R-N.

Iceland, Mjóifjörður, *Kristjánsson et al.* [1995]: Keep nonoverlapping composite section DA1-MC56 specified on page 824.

Iceland, Ísafjaðardjúp, *Kristjánsson and Jóhannesson* [1996]: Keep nonoverlapping composite section DO1-DM14 specified on page 12.

Nevada, Lousetown, *Heinrichs* [1967]: Possible overlap with Clark section and other nonstratigraphic data; keep F1-F34. Originally thought to be R-N, but recently *Roberts and Shaw* [1990] have concluded that flow F1 is not R; therefore Lousetown sequence is I-N.

Oregon, Steens Mountain, *Mankinen et al.* [1985], *Prévot et al.* [1985b]: Possible overlap with sections B and C; keep section A. 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). On page 2722 authors offer a grand composite section of the data in Table 2, and Table 5 summarizes this section in terms of directional groups. To avoid subjective interpretation of the paleomagnetic record, as well as potential overlaps in stratigraphic sections; keep only 83H21-D40 and F66-68. Intermediate data are N-I.

Sicily, Vulcano, *Laj et al.* [1997]: Initial polarity of Vulcano intermediate data was not measured, but intermediate data are Brunhes age and are N-N.

Syria, Levant, *Roperch and Bonhommet* [1986]: Possible overlap among different small sections; keep S14-S19.

Tahiti, Punaruu Valley, *Chauvin et al.* [1990]: On the basis of radiometric dating, BKH-BKL taken as lower Cobb Mountain (R-N) transition, whilst BKN-BKT2 are taken as upper Cobb Mountain (N-R) transition. Remaining polarities of Punaruu data determined by stratigraphic section.

Washington, Grande Ronde, *Choiniere and Swanson* [1979]: Possible overlap with GR of *Hooper et al.* [1979].

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].

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