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Statistical assessment of preferred transitional VGP longitudes based on palaeomagnetic lava data

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SUMMARY

We examine the statistical significance of a recent report indicating that palaeomagnetic lava data recording reversals and excursions over the past 20 Myr yield transitional virtual geomagnetic poles (VGPs) tending to fall along American and Asian longitudes. Using a bootstrap analysis of spherical densitygrams, we find that this result is neither a sensitive function of nor heavily dependent upon particular transitional records. Previous analyses used χ^2 and Kuiper tests of longitudinal uniformity of transitional VGPs. However, the bootstrap analysis presented here takes such statistical tests one step further, showing specifically that American and Asian longitudes are preferred, with significance at about the 95 per cent confidence level. Furthermore, provided the appropriate polarity convention is used, we confirm that Icelandic transitional VGPs tend to fall along Asian longitudes. These results are indicative of non-dipolar transitional fields whose structure is governed by some form of core–mantle coupling.

Key words: Earth's magnetic field, geomagnetic reversals, geomagnetism, palaeomagnetism.

INTRODUCTION

Of all the secular variation exhibited by the Earth's magnetic field, the occasional reversals of polarity and extreme excursional departures from an axial dipole are perhaps the most dramatic. Despite having been discovered almost a century ago (Brunhes 1906), a complete understanding of these phenomena remains elusive. We know that the Earth's magnetic field is sustained by convective fluid motion in the core, and that the dynamic processes operating there are also responsible for reversals and excursions. Important theoretical progress is being made towards solving the mathematical equations describing the workings of the core (Hollerbach & Jones 1993; Glatzmaier & Roberts 1995; Kuang & Bloxham 1997), and yet work on observational aspects of geomagnetic transitions is mired in controversy; palaeomagnetic data are not interpreted easily.

On the basis of sedimentary palaeomagnetic records (Laj *et al.* 1991, 1992; Weeks *et al.* 1992) it has been asserted that, from one transition to another, reversals and excursions exhibit geometric regularity. Maps of virtual geomagnetic poles (VGPs), the magnetic pole of a dipole corresponding to field directions from each palaeomagnetic site, tend to fall along two separate paths: one along American longitudes and the other along Asian longitudes. The issue of preferred transitional VGP longitudes is important for geodynamo theory; persistent preferred paths may indicate that the core and mantle are dynamically coupled (Hide 1967; Gubbins 1994), with the relatively slowly changing conditions at the base of the mantle providing the requisite memory from one transition to another. However, these observations have been greeted with scepticism, with doubt expressed about statistical significance (McFadden *et al.* 1993), adequacy of the geographical distribution of sites (Valet *et al.* 1992; Egbert 1992) and reliability of the sedimentary records (Langereis *et al.* 1992; Barton & McFadden 1996). Furthermore, in an important analysis of lava data, which individually are probably more reliable than sedimentary data, Prévot & Camps (1993) found an absence of preferred VGP longitudes for geomagnetic transitions over the past several million years, concluding that transitional fields are statistically axisymmetric. However, this work has recently been re-examined, with the conclusions called into question, by Love (1998).

Within the palaeomagnetic community it is common practice, and is not restricted to studies of reversals and excursions, to average or discard lava data on the basis of directional similarity (Mankinen *et al.* 1985; Quidelleur *et al.* 1994; McElhinny *et al.* 1996; Camps *et al.* 1999). The motivation for this is understandable. Because volcanoes erupt sporadically, palaeomagnetic 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 redundant records of the magnetic field. However, as Love has emphasized, the rate of secular variation is itself variable, and thus similar palaeomagnetic directions may be at least partially due to real stasis of secular variation. With just a few data and without any independent means of accurately dating lavas, it is impossible to untangle objectively these two effects. Fortunately, volcanic eruptions are unrelated to, and therefore uncorrelated with, geomagnetic secular variation. Thus, when analysing large data sets there really is no reason to average and discard data on the basis of directional similarity; after all, we do not expect volcanoes to erupt preferentially when VGPs fall along certain longitudes. Indeed, VGP paths, or for that matter any interesting structure in the magnetic field, are equivalent to the magnetic field (at each site) preferentially pointing within a certain range of directions. Tampering with the directions will, inevitably, bias the analysis and could tend, for example, to homogenize the geographical distribution of VGPs.

Considering a large lava database covering reversals and excursions for the past 20 Myr, Love neither averaged nor discarded similar palaeomagnetic directions, since he had no objective means of doing so. However, some transitions are recorded at some sites (such as Iceland) by relatively few intermediate directions per transition, whilst at other sites (such as Steens Mountain) they are recorded by many intermediate directions per transition, Love applied a normalization to account partially for such differences. Without some adjustment, if each intermediate direction were counted equally, then a statistical study of transitional field behaviour would be biased by a few transitions recorded at just a few sites. Love found that transitional data from lavas gave VGPs that tended to fall along American and Asian longitudes. He also found that the Icelandic data showed some repeat behaviour from one transition to another.

If these results are to be taken seriously and eventually considered by dynamo theorists, then their validity needs to be assessed statistically. In his study, Love utilized both χ^2 and Kolmogorov–Smirnov (Kuiper) tests of the longitudinal distribution of transitional VGPs, finding, with statistical certainty above 99 per cent, that the distribution was not uniform. However, the former test depends on both the longitudinal bin size and the location of bin boundaries, whilst the latter test is perhaps overly sensitive to the observed clustering of VGPs. Moreover, since both the χ^2 and Kuiper tests employed only address the issue of longitudinal uniformity, the more specific question of whether or not transitional VGPs tend to fall along American and Asian longitudes remains unquantified. Last but not least, some of the palaeomagnetic records used by Love might be erroneous for any one of myriad reasons (due to lightning strikes, differing amounts of overprint across stratigraphic sections, etc.), and despite his use of data selection criteria like those of his predecessors, critics may not be satisfied with Love's use of certain palaeomagnetic records. Therefore, the sensitivity and reliance of his analysis on the inclusion of different transitional records needs to be investigated. In this paper we examine these issues with a bootstrap analysis of spherical densitygrams.

METHOD

Data

The database considered is that of Love (1998); our summary here is brief. The data come from published records of reversals and excursions that occurred during the past 20 Myr, a transition being somewhat arbitrarily defined by VGP latitudes between $\pm 60°$N (Valet *et al.* 1992; Prévot & Camps 1993). Each palaeomagnetic direction, inclination and declination (I, D), is an average of measurements from at least three magnetically cleaned samples per flow, with the precision parameter α_{95}, the semi-angle of the cone of 95 per cent confidence centred on the mean direction, less than 20°; these selection criteria are similar to those of others (Camps 1994; Quidelleur *et al.* 1994). By considering only measurements coming from stratigraphic sections of extruded lava piles, we eliminate data overlap; we also know the temporal order and the number of intermediate directions per transition, $N_{\rm I}$, at each site. A direction is normal (reverse) N (R) if it has a VGP latitude above (below) 60°N (60°S). 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). Because of occasional incomplete recording of a transition, the polarity is sometimes 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 record because it is sufficiently well dated, but in most cases we deduce the polarity of the transitional record from the stratigraphy. Among the different sites there are 3275 directions from 67 stratigraphic sections recording 507 (local) transitions, 1318 of the directions being intermediate.

VGP polarity conventions

Two polarity conventions are used within the palaeomagnetic community for plotting VGPs (Prévot & Camps 1993). Under the (more common) so-called palaeomagnetic convention, south magnetic poles corresponding to field directions from each palaeomagnetic site are plotted on maps. However, since the equations of magnetohydrodynamics are invariant under change in sign of the magnetic field (Merrill *et al.* 1979), something which makes the polarity of a transition (N–I or R–I) irrelevant, Hoffman (1984) suggested that the data are more easily interpreted if the magnetic pole lying initially near the (say) north geographical pole is plotted regardless of magnetic sign; this is the geomagnetic convention. Under it, if transitional fields display geometrical regularity, and if transitional fields are dominantly dipolar, 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 palaeomagnetic convention will yield two preferred antipodal longitudes, depending on the sign of the field. Furthermore, under the geomagnetic convention, VGPs falling along (say) two longitudes would be evidence for a non-dipolar transitional field, with the particular longitude depending on site location; however, similar interpretations are problematic under the palaeomagnetic convention. Since it is more physically relevant, and because it allows for some discrimination between dipolar and non-dipolar transitional fields, we follow Love and adopt the geomagnetic convention. In the discussion that follows we are, therefore, restricted to data of known initial polarity.

Data weighting and densitygrams

Love used a modification of Valet *et al.*'s (1992) method to account for the fact that the total duration of some transitions is recorded at the various sites by widely differing numbers of intermediate directions. We follow their lead and weight each VGP for a particular transitional record by $(\cos\lambda)/N_I$. The $\cos\lambda$ term, where λ is the latitude of the VGP, gives more weight to low-latitude VGPs and removes some of the sensitivity of this analysis to other definitions of intermediate VGP cut-off; dividing by N_I ensures that each transition at each site is weighted appropriately. Since an average only begins to have meaning with (say) three samples, we consider only transitional records such that $N_I \geq 3$. In the database there are 141 (local) transitional records of known initial polarity that are recorded by three or more consecutive intermediate directions for a total of 790 intermediate directions. In Fig. 1 we show the geographical distribution of the palaeomagnetic sample sites.

In his analysis of the geographical distribution of VGPs, Love binned VGPs and plotted results as histograms. This has the advantage of being simple, yet the results depend, somewhat unsatisfactorily, on the choice of both bin size and bin boundary. These deficiencies can be partially remedied by the use of densitygrams (Fisher *et al.* 1987). We average the geographical distribution of VGPs with a continuous function such as the Fisherian distribution:

$$P_{dA}(\theta) = \frac{\kappa}{4\pi \sinh\kappa} \exp(\kappa\cos\theta)\,. \tag{1}$$

For each point on the globe, latitude and longitude (λ, φ), the geographically averaged density of VGPs, a probability density function (pdf), is

$$P_{d\lambda,d\varphi} = a \sum_{j,i} \frac{\cos\lambda_j}{N_{Ii}} P_{dA}(\theta)\,, \tag{2}$$

where a is a normalization factor, N_{Ii} is the number of intermediate directions for the ith transition, and $\theta(\lambda, \varphi, \lambda_j, \varphi_j)$ is the angle between the geographical point and the jth VGP at latitude and longitude (λ_j, φ_j). The Fisherian averaged longitudinal pdf is just

$$P_{d\varphi} = \int P_{d\lambda,d\varphi} \cos\lambda d\lambda\,. \tag{3}$$

With this averaging, or densitygram, analysis, we avoid the arbitrariness of selecting bin boundaries (which mars studies using histograms). There remains, however, an averaging width, analogous to bin size, which is fixed by the parameter κ; we take $\kappa = 66$, which gives us an averaging width of about 20°.

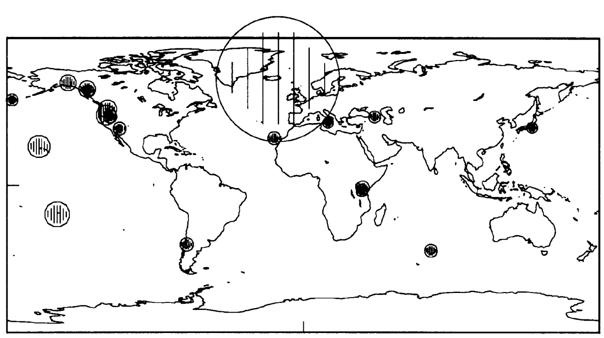


Figure 1. Geographical distribution of sites. The size of the symbol is proportional to the number of intermediate VGPs weighted by $(\cos\lambda)/N_I$, where λ is VGP latitude and N_I is the number of intermediate directions for each transition ($N_I \geq 3$).

Bootstrapping

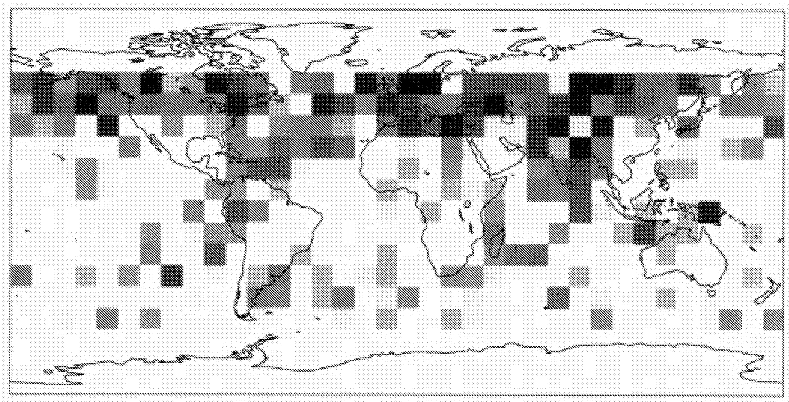
Confidence in the value of the pdf $P_{d\varphi}$ at a particular longitude is established by bootstrap analysis (Efron 1982). The population of transitional records $\mathscr{T}$ is assumed to be an approximation of the probability distribution of all possible (hypothetical) transitional records. If $\mathscr{N}$ is the number of records in $\mathscr{T}$, then $\mathscr{N}_B$ populations of test transitions, each of size $\mathscr{N}$, the kth being denoted $\mathscr{T}^k$, are generated by sampling randomly with replacement from the actual set transitional records. Because of the replacement the $\mathscr{T}^k$ typically have some duplication, and, of course, are also missing a corresponding number of records contained in $\mathscr{T}$. From the test $\mathscr{T}^k$ Fisherian, averaged longitudinal pdfs $P^k_{d\varphi}$ are calculated. The dispersion of the $P^k_{d\varphi}$ at a specific longitude, expressed in terms of confidence limits, gives an indication of the degree of faith with which we can regard the actual pdf $P_{d\varphi}$ at that same longitude.

Any interpretation of a bootstrap analysis must be made with consideration of the independence of the data. We note that each transitional record is a (locally) independent volcanic record, although not necessarily an independent record of a separate (global) transitional event; some transitions are recorded at more than one site. We have not attempted to treat as redundant the (few) stratigraphic sections that we know record the same global transitional events. To do so would be unsatisfactorily incomplete, and would itself open up an additional unpleasant set of complications: for example, exactly how accurate would radiometric dating need to be before we decide whether or not two records are of the same transitional event? A similar problem exists within each stratigraphic section: in some cases stratigraphically adjacent transitions may actually be parts of a single complex transition. Based simply on an examination of a sequence of lava data it is often a completely arbitrary designation as to when one transition begins and another ends. In an attempt to avoid subjectivity we count each sequence of intermediate directions, bounded by reverse or normal directions, as a separate transitional record. Obviously, our approach, which follows that of Love, has been motivated by a desire to keep things as simple as possible. Bearing these issues in mind, the bootstrap analysis that follows does not address the sensitivity and dependence of apparent preferred VGP paths on the inclusion of specific (global) transitional events, but rather addresses the sensitivity and dependence of apparent preferred paths on the inclusion of different transitional records, or equivalently, (possibly large) subsets of our palaeomagnetic database.

DISCUSSION

Geographical distribution of VGPs

In Fig. 2 we show, by greyscale histogram in latitude and longitude, the geographical distribution of weighted transitional VGPs from our database, from Love (1998). Since we have adopted the geomagnetic convention, VGPs tend to be concentrated in the Northern Hemisphere, the result of excursions that do not always yield Southern Hemisphere poles. In the same figure we also show a histogram of the longitudinal distribution of weighted VGPs. Note the tendency for VGPs to fall along American and Asian longitudes (±75°E). The



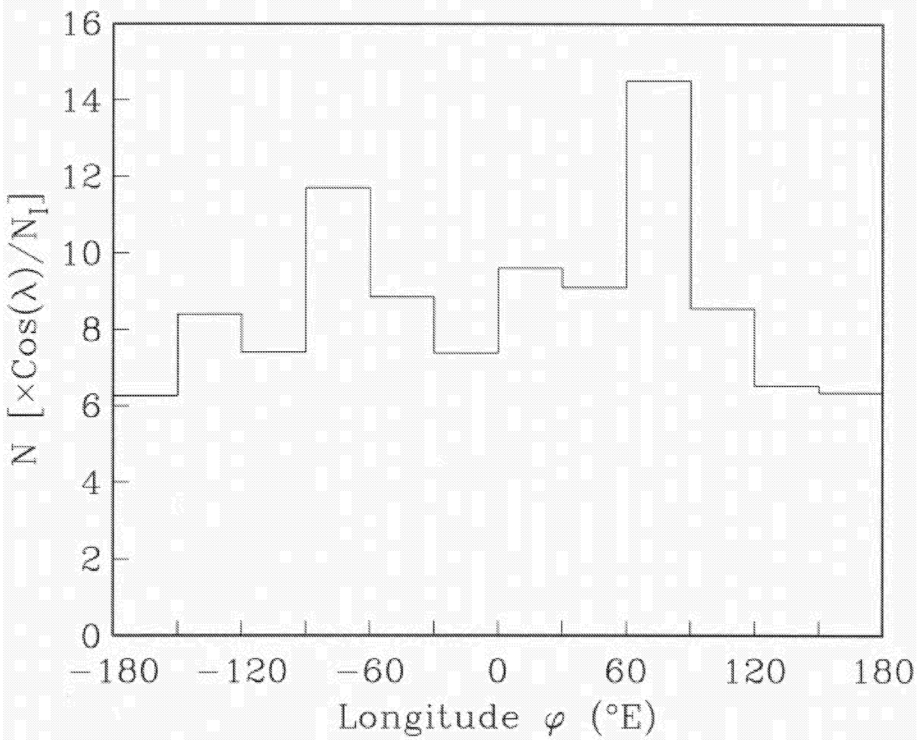
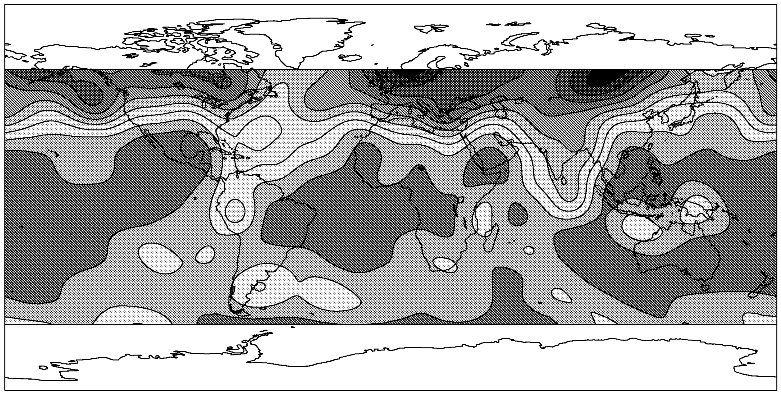
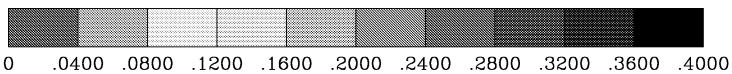


Figure 2. (Top) Map of greyscale histogram of intermediate [weighted by $(\cos\lambda)/N_{\mathrm{I}}$ with $N_{\mathrm{I}} \geq 3$] VGPs for 141 separate transitional events. Dark (light) indicates a high (low) average concentration of VGPs. The geomagnetic polarity convention (Prévot & Camps 1993) has been used; magnetic poles lying initially near the north geographic pole are plotted regardless of magnetic sign. The inclusion of excursional data means that the VGPs are concentrated in the north near the VGP cut-off of 60°N. (Bottom) Histogram showing the longitudinal distribution. Note the preference for VGPs to fall along American and Asian longitudes.

same results, however, are expressed somewhat more clearly in Fig. 3, where the geographical distribution of weighted VGPs is shown by contour of the Fisherian densitygram; the longitudinal distribution along with confidence limits determined by bootstrap analysis is also shown. Note that the peaks in the longitudinal distribution corresponding to American and Asian longitudes exceed the longitudinal average by an amount greater than or equal to the 95 per cent confidence limit; we say that these peaks have a statistical significance at that level. These results are broadly consistent with Laj *et al.*





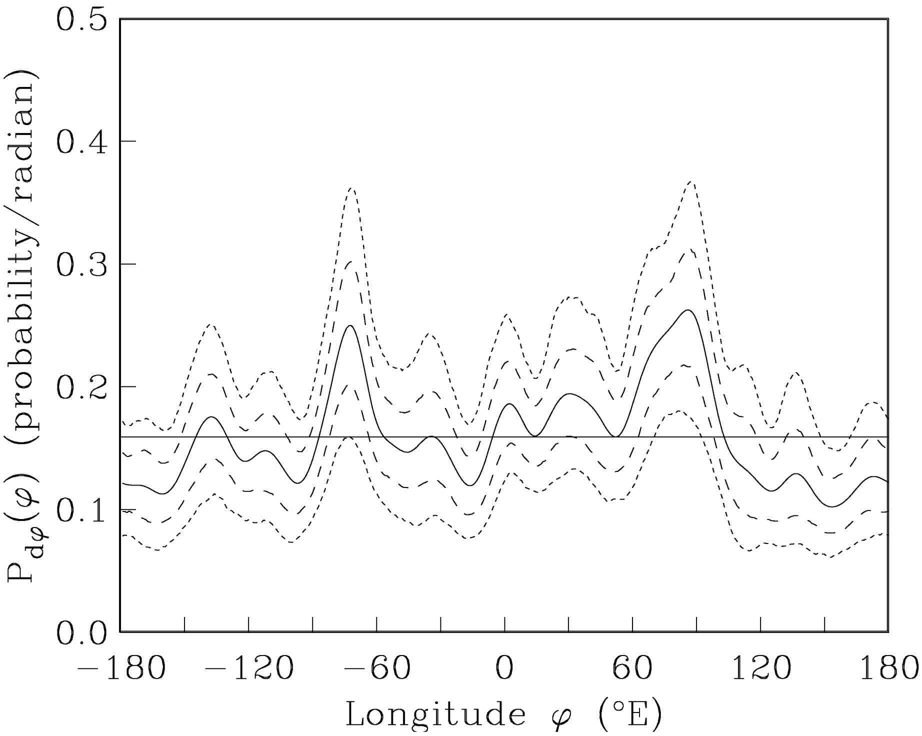


Figure 3. (Top) Contour map of Fisherian averaged VGP densitygram [weighted by $(\cos\lambda)/N_I$ with $N_I \geq 3$]; units are probability/steradian. The geomagnetic polarity convention (Prévot & Camps 1993) has been used; magnetic poles lying initially near the north geographic pole are plotted regardless of magnetic sign. The inclusion of excursional data means that the VGPs are concentrated in the north near the VGP cut-off of 60°N. (Bottom) The corresponding longitudinal VGP densitygram; dashed (dotted) line indicates 68 per cent (95 per cent) confidence limit. The solid horizontal line denotes the longitudinal average $(2\pi)^{-1}$. Note the tendency for VGPs to fall along American and Asian longitudes.

(1991); differences are probably due to their use of sedimentary data (which are prone to corruption), their consideration of fewer transitional events than are considered here, and their use of the palaeomagnetic convention.

To examine the importance of using the geomagnetic convention for plotting VGPs, in Fig. 4 we show the geographical densitygram of weighted VGPs by contour and the longitudinal densitygram with the palaeomagnetic convention. A bilongitudinal distribution is virtually indiscernible; only an Asian longitude can be considered statistically significant here. As Love has noted, since the preferred longitudes under the geomagnetic convention are not exactly antipodal, when the

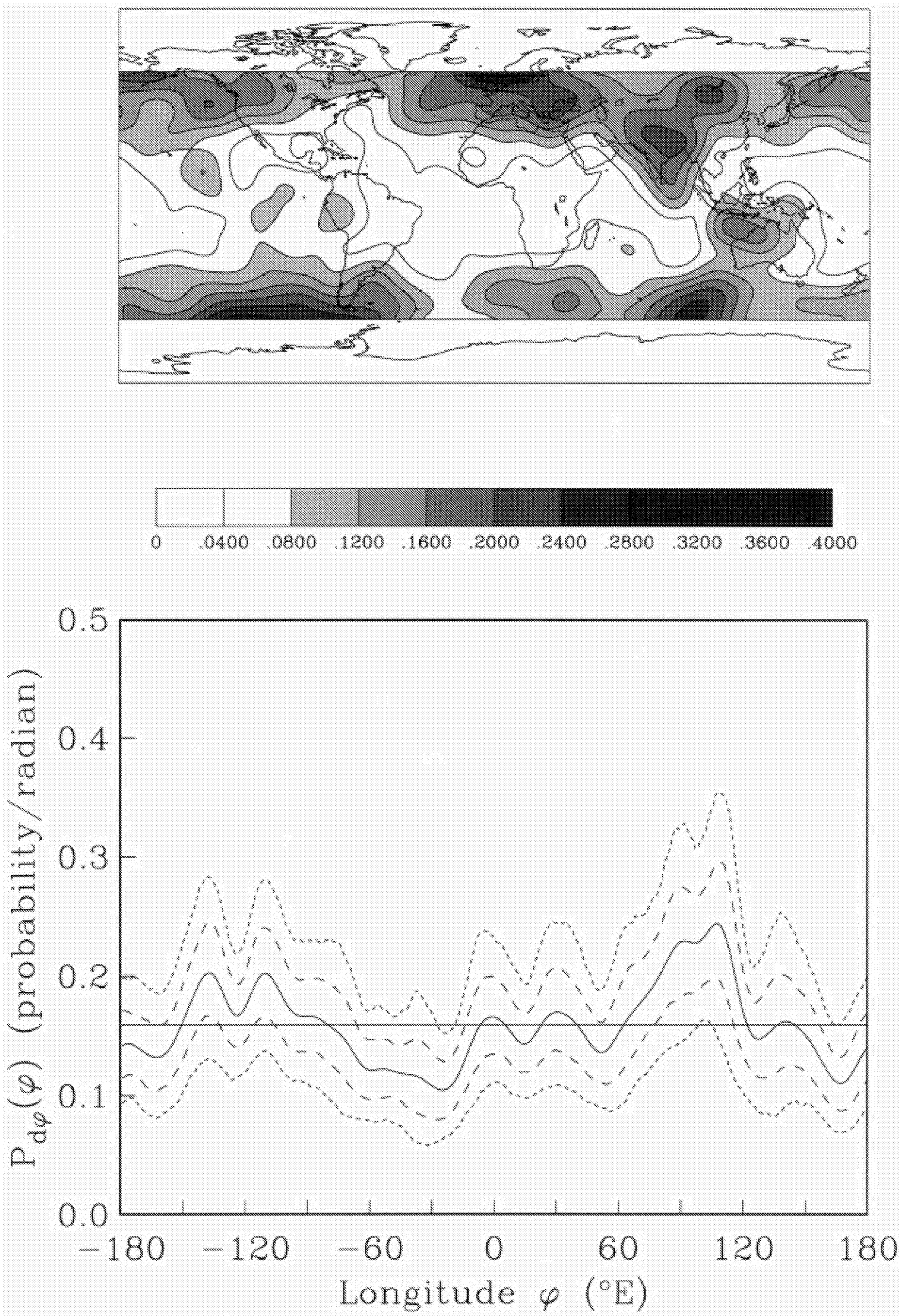


Figure 4. (Top) Contour map of Fisherian average VGP densitygram [palaeomagnetic, weighted by $(\cos\lambda)/N_{\mathrm{I}}$ with $N_{\mathrm{I}} \geq 3$]; units are probability/steradian. (Bottom) The corresponding longitudinal VGP densitygram; dashed (dotted) line indicates 68 (95) per cent confidence limit. The solid horizontal line denotes the longitudinal average $(2\pi)^{-1}$. Compare with Fig. 3, where the geomagnetic convention is used instead.

same data are plotted under the palaeomagnetic convention some of the VGPs that 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, broadening and even obscuring the preferred longitudes. There is, of course, no theoretical reason to expect VGP preferred longitudes plotted under the geomagnetic convention to be exactly antipodal, and thus, since the palaeomagnetic convention implicitly assumes such a symmetry, we prefer to use the geomagnetic convention.

In a similar vein, we examine the effect of weighting the transitional VGPs by $\cos\lambda$, where λ is the latitude of the VGP. In Fig. 5 we show the geographical distribution of VGPs without the cosine weighting, normalized only by N_{I}, the

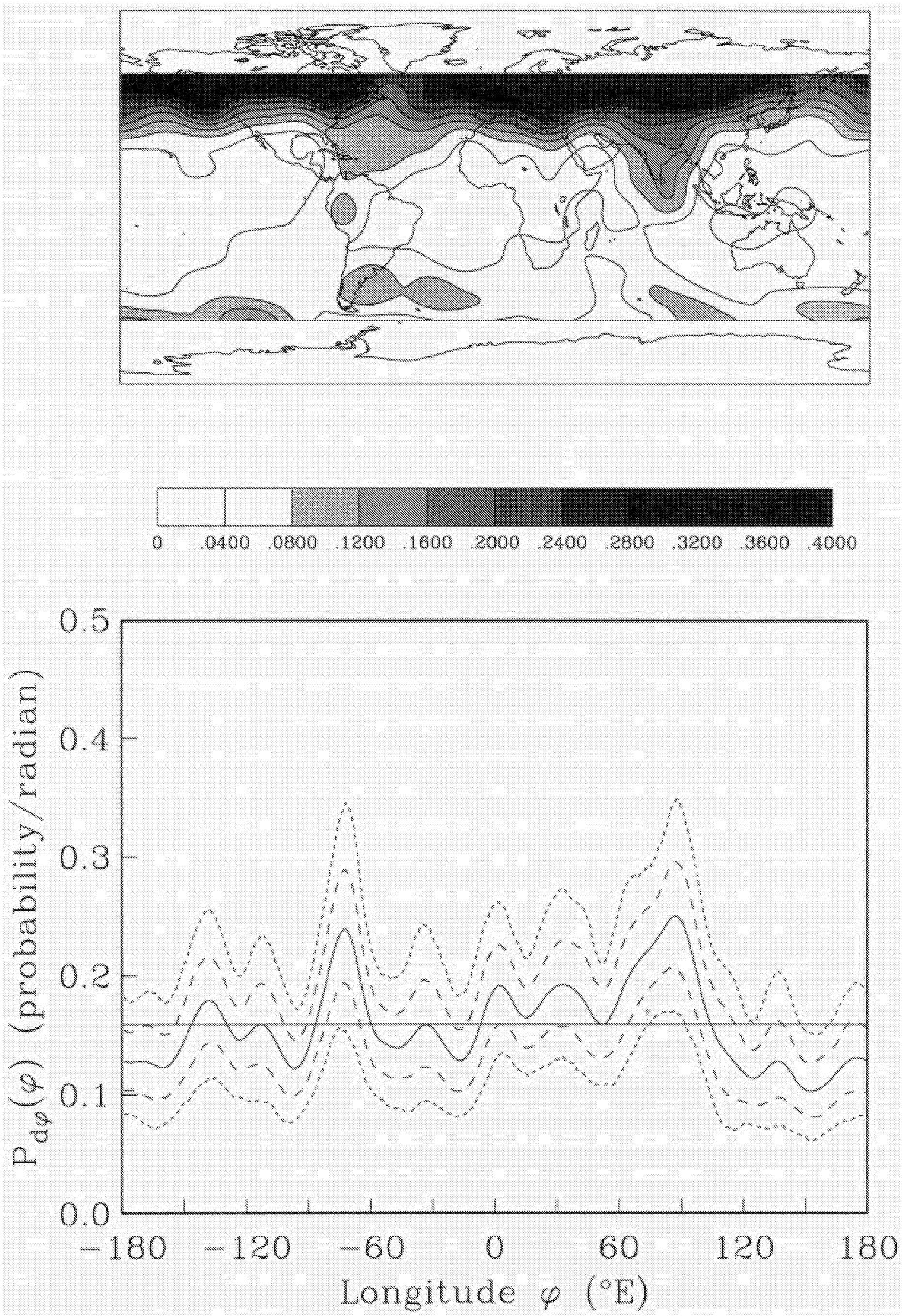


Figure 5. (Top) Contour map of Fisherian averaged VGP densitygram (geomagnetic, weighted by $1/N_I$ with $N_I \geq 3$); units are probability/steradian. (Bottom) The corresponding longitudinal VGP densitygram; dashed (dotted) line indicates 68 (95) per cent confidence limit. The solid horizontal line denotes the longitudinal average $(2\pi)^{-1}$. Compare with Fig. 3, where the VGPs are weighted by $\cos\lambda/N_I$.

number of intermediate VGPs per transitional event. The bilongitudinal distribution of VGPs is slightly less clear in this figure than it is in Fig. 3, although the peaks are still apparently significant at about the 95 per cent level. We present these slightly more equivocal results simply for the sake of those who might be curious about our weighting scheme. We continue to prefer, however, to weight transitional VGPs by $\cos\lambda_j/N_I$ since it helps to reduce artefacts associated with the use of arbitrary latitude cut-offs for defining transitional directions, which characterize not only our study but those of others as well. We note that there is absolutely no reason why weighting VGPs by latitude should give preferential longitudes (the two coordinates are orthogonal); therefore, our weighting scheme cannot be considered biased.

Subsets of the database

In Fig. 6 we compare records of reversals and excursions. Despite the fact that the number of data is less than that used in producing Fig. 3, reversal VGPs by themselves tend to fall along American and Asian longitudes, although the statistical significance of the American longitude is somewhat lower. Excursional records are more difficult to interpret; there is a broad peak along Asian longitudes, the statistical significance of which might be debated, together with multiple peaks in the Western Hemisphere. Love hesitated to draw any firm conclusion about differences (or similarities) between reversals and excursions; on the basis of the statistics presented here, we concur. In the same figure we compare normal transitions with reverse transitions, the former showing only a statistically significant preference for Asian longitudes and the latter for both American and Asian longitudes. As Love has noted, this difference is puzzling, especially since there is no theoretical reason to expect that transitional polarity should be relevant.

Comparisons of palaeomagnetic site locations and age are made in Fig. 7. Love found that VGPs from Icelandic data, under the geomagnetic polarity convention, tend to fall along Asian longitudes, in other words the field at this single site seems to show some repeat behaviour from one transition to another. It should be noted that the evident scatter in the longitudinal distribution of Icelandic VGPs, which undoubtedly represents real secular variation, has tended to disguise the pattern found by Love; the densitygram makes the preferred longitude more evident, with the bootstrap analysis showing that it is statistically significant to better than 99 per cent confidence. The many fewer non-Icelandic data show two fairly significant preferred longitudes, consistent with non-dipolar transitional fields being sampled at different geographical locations. Bisecting the data by age we find that the younger data show American and Asian longitudes, although the latter peak is not as well resolved as the former, whilst the older data only show a significant peak along Asian longitudes. Love suggested that these differences are due to the poorer site distribution of the older data (mostly from Iceland and Steens Mountain).

Finally, we examine the importance of some of the data selection criteria (Fig. 8). Until now we have considered

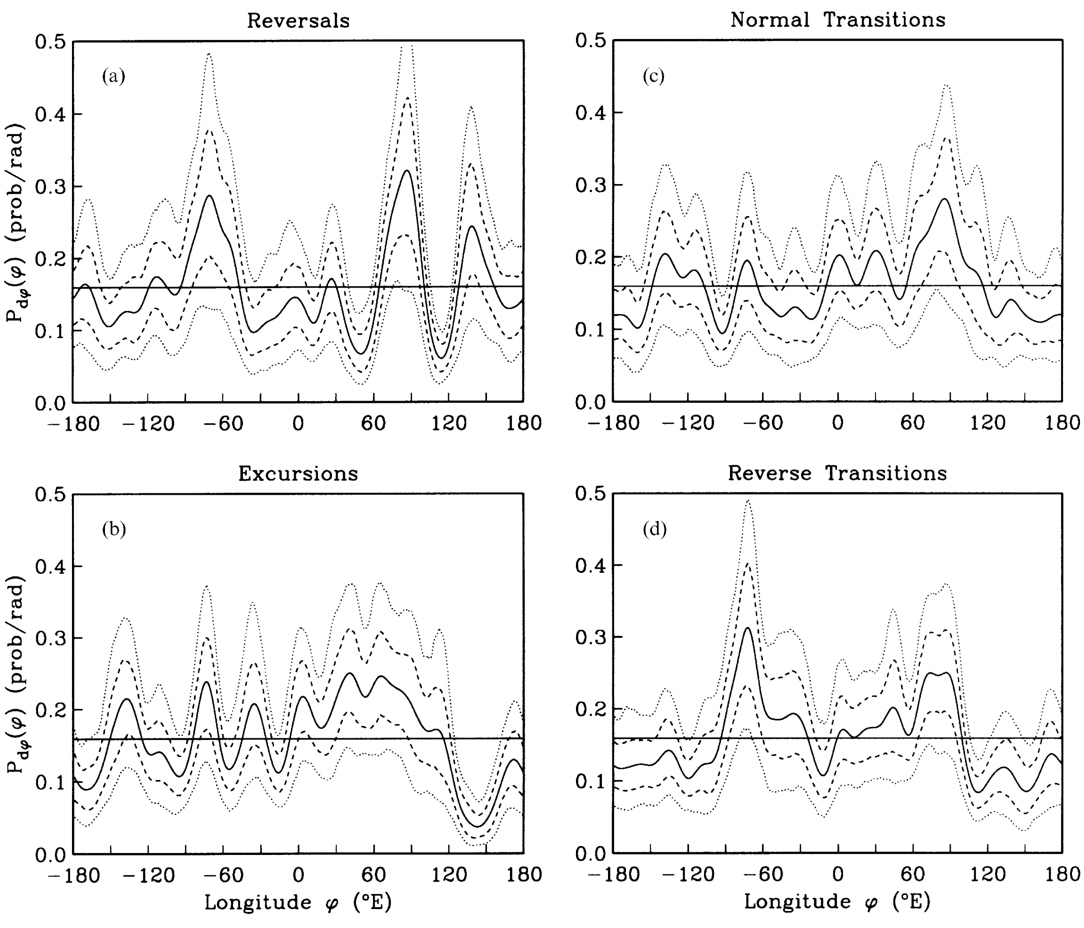


Figure 6. Densitygrams, together with confidence limits, of intermediate (geomagnetic, weighted) VGP longitudes for different types of transitions. In all cases the solid line is the densitygram itself and the dashed (dotted) line is the 68 (95) per cent confidence limit. In (a) and (b) we compare data for reversals (N–R, R–N) and excursions (N–N, R–R) separately (note that this requires that we know both the initial and final polarities of each transition, a criteria somewhat more strict than that used in for Fig. 3, where we only needed the initial polarity). The reversal data show fairly clear American and Asian preferred VGP longitudes, but the excursional data are not so easily interpreted. (c) Normal (N–R, N–N, N–I) and (d) Reverse (R–N, R–R, R–I) transitions show preferred Asian longitudes, but only reverse data show a clear preferred American longitude.

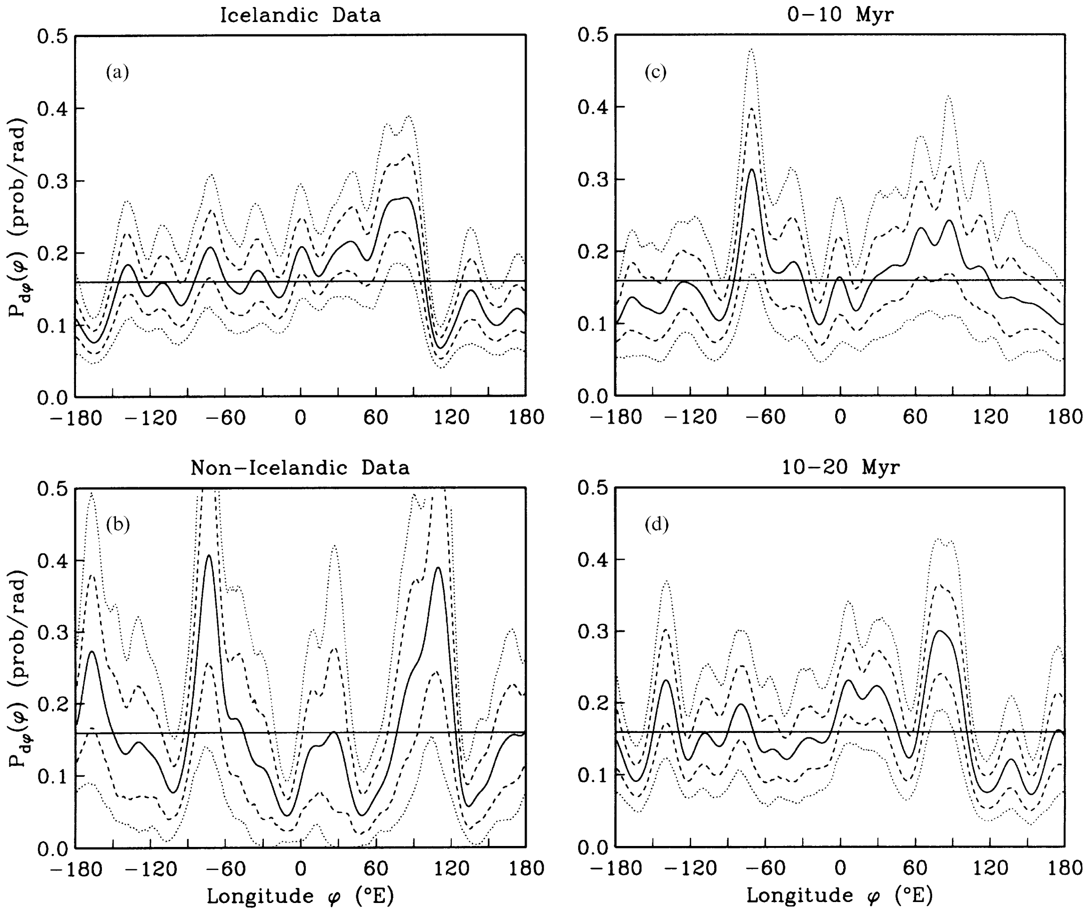


Figure 7. Densitygrams, together with confidence limits, of intermediate (geomagnetic, weighted) VGP longitudes for different sites and ages. In all cases the solid line is the densitygram itself and the dashed (dotted) line is the 68 (95) per cent confidence limit. In (a) and (b) we compare Icelandic data and non-Icelandic data separately; the Icelandic VGPs show a distinct tendency to fall along Asian longitudes, whilst VGPs from other sites tend to fall along American and Asian longitudes (observations that are consistent with non-dipolar transitional fields). (c) Data from flows younger than 10 Myr and (d) older than 10 Myr show Asian longitudes.

weighted VGPs coming from transitional records with three or more intermediate directions; if we consider instead records with four or more intermediate directions, as recommended by Valet *et al.* (1988), we find that this smaller, but presumably somewhat better, data set gives statically significant American and Asian preferred longitudes. Likewise, if we consider a database with somewhat more stringent criteria on each individual direction, $\alpha_{95} < 15^\circ$ and four or more samples per flow, we find significant American and Asian preferred longitudes. If we restrict ourselves to data collected with at least some thermal demagnetization, which is, unfortunately, a minority of the available data, we find fairly significant American and Asian preferred longitudes. Finally, considering data which has been collected using three or more steps during magnetic cleaning, which by modern standards is certainly a bare minimum, we find American and Asian preferred longitudes, although the latter peak is better resolved than the former. Taken as a whole, the results shown in Fig. 8 indicate that the bilongitudinal distribution of transitional VGPs is not a sensitive function of data selection criteria or laboratory method, although analyses such as ours will certainly benefit from their continued refinement.

CONCLUSIONS

From our bootstrap analysis we conclude with ~95 per cent statistical confidence that transitional fields are non-axisymmetric; this result is consistent with that of Love (1998), who employed both χ^2 and Kuiper tests of longitudinal uniformity. The work presented here takes such statistical tests one step further; our bootstrap analysis shows specifically that American and Asian preferred transitional longitudes are resolvable with a statistical confidence of about 95 per cent, and that the tendency for Icelandic (geomagnetic) VGPs to fall along Asian longitudes is statistically significant to a confidence level of 99 per cent. Having conducted our bootstrap analysis on the population of (local) transitional records, and having also conducted the analysis on numerous subsets thereof, we can conclude that these results are neither a sensitive function of nor heavily dependent upon particular transitional records. The beauty of a bootstrap analysis is that such a statement can be made objectively; we have not selected, discarded or in any way manipulated any data on a subjective basis. However, as provocative as these results may be, our search for additional patterns in the data such as distinguishing differences

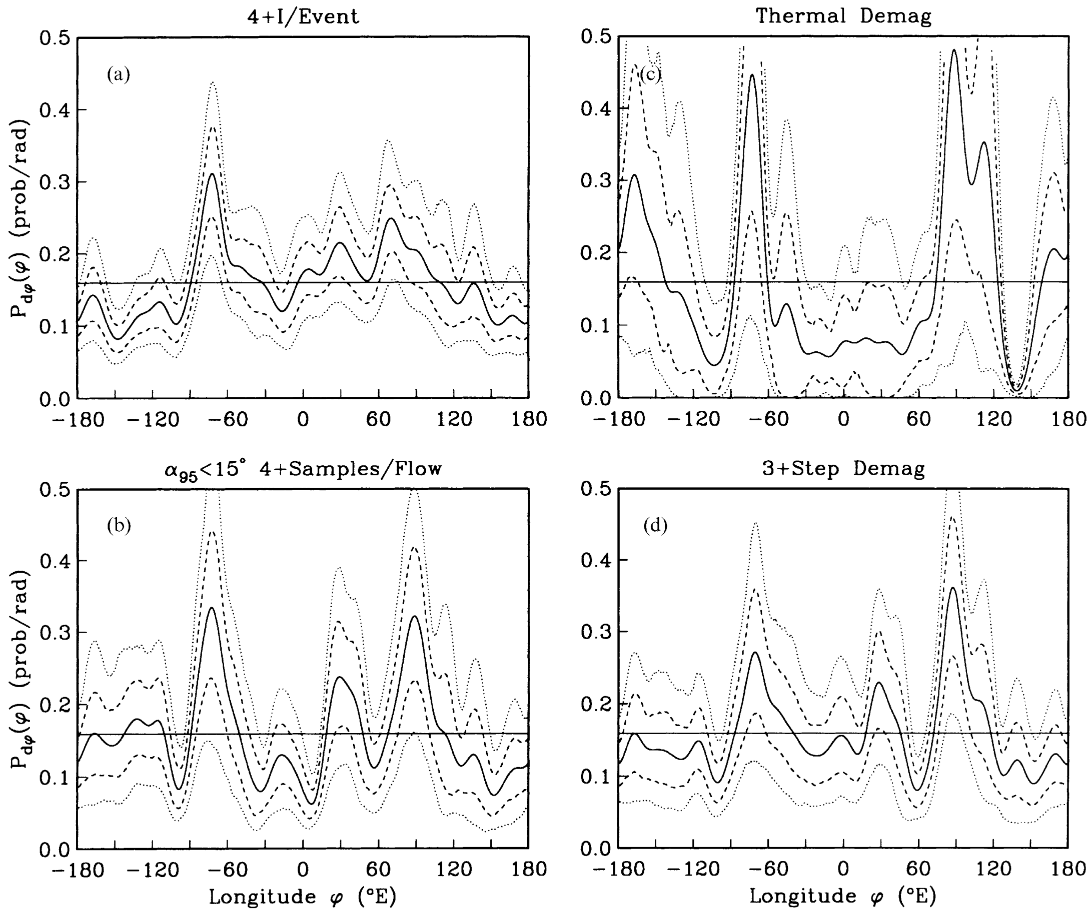


Figure 8. Densitygrams, together with confidence limits, of intermediate (geomagnetic, weighted) VGP longitudes for different (stricter) data selection criteria. In all cases the solid line is the densitygram itself and the dashed (dotted) line is the 68 (95) per cent confidence limit. (a) VGP longitudinal densities from events with $N_{\mathrm{I}} \geq 4$; (b) data with 4 or more magnetically cleaned samples per flow and with $\alpha_{95} < 15°$; (c) data from sites where samples were subjected to at least some thermal demagnetization; (d) measurements made with at least three steps in stepwise demagnetization. Taken as a whole these densitygrams indicate that the apparent preference for transitional VGPs to fall along American and Asian longitudes is relatively insensitive to data selection criteria.

or similarities between reversals and excursions has proved to be frustrating, whilst some other observations such as apparent differences between reverse and normal transitions are problematic. As has been repeatedly said by us and others, many of these issues will be better resolved with additional palaeomagnetic data. Such technicalities, however, should not obscure the fact that the lava data available today covering the past 20 Myr as a whole display a bilongitudinal distribution of (geomagnetic) VGPs, indicative of non-dipolar transitional fields whose structure is governed by some form of core–mantle coupling.

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