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Paleomagnetism of Young New Zealand Basalts and Longitudinal Distribution of Paleosecular Variation

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A paleosecular variation (PSV) study was carried out on monogenic basalt volcanoes of the northern part of North Island, New Zealand. A new method of calculating angular standard deviation (ASD) by fitting a combination of two Fisher distributions to the cumulative histogram of VGP data is presented, which avoids the necessity of applying an arbitrary cut-off angle to exclude intermediate magnetic directions. The resultant ASD of 11.5° for northern New Zealand is smaller than that predicted by previous PSV models.

Using this new method, recalculation of published data from elsewhere spanning the last 10Ma suggests that the ASD commonly has been over-estimated and that the global distribution of ASD exhibits a significant longitudinal variation. This relatively long-term non-axisymmetric distribution of ASD implies that the core dynamo process may be strongly influenced by the thermal and/or mechanical regime of the solid mantle.

1. Introduction

New Zealand contributes an important dataset to studies of paleosecular variation (PSV) because there is little relevant paleomagnetic data from the southern hemisphere. The dataset published by Cox (1969b) is often referred to in tests of the symmetry of the PSV in two hemispheres, however the number of sites in this dataset (22) is insufficient for such an assessment. In order to extend the available dataset we began a paleomagnetic study of monogenic volcanoes in the northeastern part of the North Island, New Zealand.

The monogenic volcanoes are very suitable for a PSV study because (1) they have stable and strong magnetization, (2) their frequent small scale eruptions give paleomagnetic records of many different ages, and (3) they are restricted to a small area so that spatial variation is negligible. Further, virtually all the sites reported in this study were dated by K-Ar method so that their ages are well known.

2. Paleomagnetism of Monogenic Volcanoes in the Northeastern Part of the North Island, New Zealand

2.1 Experimental

The temporal and spatial distribution of sampled sites (which reflect the distribution of young basaltic rocks in North Island) are shown in Fig. 1. All but one of the volcanoes in the South Auckland and Northland volcanic fields were dated by K-Ar methods (Briggs *et al.*, 1994; Smith *et al.*, 1993). Some of the sites in the Auckland volcanic field have not been dated, but their age is known to lie between 0.14 Ma and 700 BP.

Paleomagnetic results from the South Auckland and Auckland volcanic fields have already been published (Briggs *et al.*, 1994; Shibuya *et al.*, 1992). Here we will report the paleomagnetic directions from the Northland volcanic field. The experimental procedures for the samples from

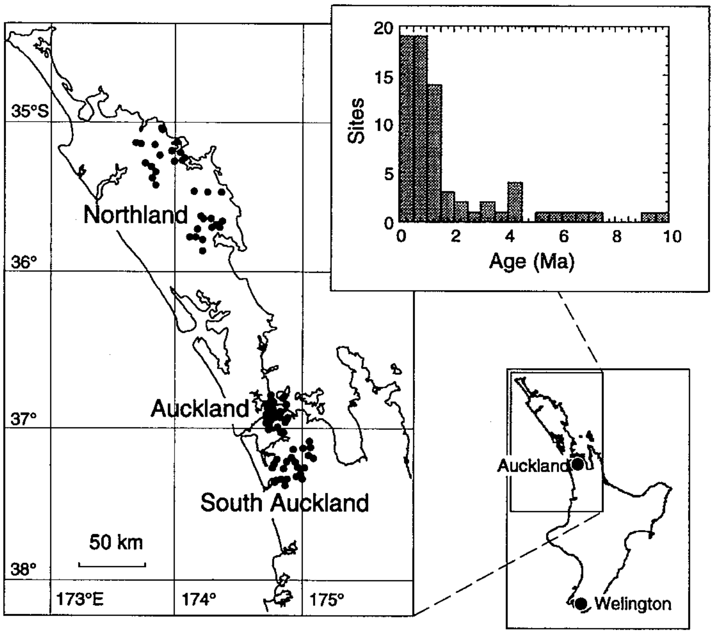

Fig. 1. Distribution of the monogenic volcanoes sampled. Inset shows the distribution of K-Ar ages for these volcanoes.

the Northland volcanic field are essentially the same as for the published studies. All the samples from the Northland volcanic field were hand samples, which were cut into cylinders with a diameter and length of about 25 mm for the magnetic measurements. Two to four specimens were usually obtained from each sample. The measurements were performed with Natsuhara Giken's SMM-85 spinner magnetometer at the University of Osaka Prefecture. An alternating field (af) demagnetizer DEM-8601M (also made by Natsuhara Giken Co.) capable of producing a peak field of 70 mT was used for magnetic cleaning. One pilot specimen from each site was first subjected to a progressive af demagnetization with 12 steps up to 70 mT. If the demagnetization diagram showed a simple nature, all other samples were demagnetized at an appropriate step. In other cases, they were also demagnetized progressively.

2.2 Results

Most of the samples from the Northland volcanic field were magnetically stable, and it was easy to establish the demagnetization level required to obtain the primary component. In this respect they were similar to specimens from the Auckland volcanic field (Shibuya *et al.*, 1992). Paleomagnetic results together with K-Ar ages for Northland volcanic field, are summarized in Table 1. The site mean directions for sites with more than 3 samples and with α_{95} less than 10°, as well as those from the Auckland and South Auckland volcanic fields (Briggs *et al.*, 1994; Shibuya *et al.*, 1992), are shown in Fig. 2A. Figure 2B is the equal area plot of VGPs corresponding to the paleomagnetic directions.

A recurring problem in PSV studies is the treatment of the intermediate directions. Since we are interested in periods of normal geomagnetic behavior, data from transition periods such as excursions or geomagnetic reversals should be excluded. Such intermediate directions are often simply discarded before the calculation of ASD. However, it is very difficult to determine an objective upper limit to the displacement of a VGP from the geographic pole for it to be

Table 1. Paleomagnetic direction and age data from sites within the Northland volcanic field.

								Site		VGP		
Site No.	Grid ref.	N	D.F. (mT)	Dec (°)	Inc (°)	α_{95} (°)	Int. (A/m)	Lat. (°')	Long. (°')	Lat. (°)	Long. (°)	Age (Ma)
Northland Volcanic Field												
51	N24 738787	8	30	7.1	-60.8	3.5	0.33	-35.52	174.13	81.9	-46.5	0.29±0.05
52	N19 600938	8	30	6.2	-59.9	4.1	0.27	-35.45	174.05	83.0	-48.1	0.54±0.1
53	N20 666943	8	30	3.8	-54.8	2.7	0.71	-35.45	174.09	86.9	-102.5	0.52±0.04
54	N20 742935	5	20	14.8	-68.2	5.8	0.31	-35.45	174.14	71.2	-35.4	0.50±0.05
55	N20 731941	8	20	4.2	-60.6	3.1	0.77	-35.45	174.13	83.3	-33.8	0.32±0.09
57	N20 698000	6	30	127.0	73.9	4.5	0.22	-35.42	174.11	-48.6	-148.7	6.00±0.97
58	N20 847016	8	20	60.8	-68.3	2.8	0.16	-35.41	174.20	44.7	-55.5	2.38±0.21
59	N20 886044	2	20	30.5	-57.6	16.4	2.8	-35.40	174.22	65.6	-80.5	0.30±0.12
62	N20 790080	4	20	21.7	-57.3	3.5	0.37	-35.38	174.17	72.5	-81.8	4.20±1.12
63	N20 728068	5	20	102.5	77.3	17.0	0.22	-35.38	174.13	-37.1	-155.6	2.34±0.17
64	N20 705948	8	20	12.7	-67.8	3.1	1.4	-35.44	174.11	72.4	-33.2	1.06±0.08
65	N20 794018	8	20	10.3	-52.5	2.7	3.6	-35.41	174.17	81.1	-109.7	0.31±0.15
68	N15 333308	8	20	167.0	58.2	2.8	2.0	-35.26	173.49	-79.1	-118.5	1.27±0.06
69	N15 315358	8	20	162.7	-46.2	2.8	0.089	-35.24	173.48	-25.0	-23.1	0.06±0.05
70	P05 893473	8	20	0.1	-55.6	2.6	1.7	-35.23	173.52	89.2	-12.2	0.36±0.06
71	P05 822539	8	20	16.4	-52.4	2.9	2.8	-35.19	173.47	76.2	-101.2	2.65±0.14
72	P05 717716	8	30	-2.4	-63.8	2.6	0.49	-35.09	173.40	79.5	3.0	9.35±0.49
73	P05 756684	7	30	165.0	59.9	6.4	2.0	-35.11	173.43	-76.9	-126.1	6.98±0.25
74	P05 907620	4	30	179.6	68.0	6.0	0.16	-35.15	173.53	-74.2	174.8	1.33±0.11
76	P05 863512	5	30	-6.5	-48.7	8.9	1.9	-35.21	173.50	82.1	128.2	0.28±0.02
77	P04 922818	8	30	178.6	58.8	1.5	0.22	-35.04	173.54	-85.4	-172.6	4.48±0.3
79	P04 927836	5	20	-0.9	-59.2	10.6	1.2	-35.03	173.54	85.0	1.9	5.04±0.2
82	P04 023720	8	20	-177.2	60.0	2.4	0.50	-35.09	174.00	-83.9	153.8	3.98±0.26
83	P05 983434	8	20	47.4	-12.4	4.8	0.51	-35.25	173.58	37.7	-118.4	0.19±0.07
84	N16 651287	7	20	29.2	17.1	3.8	0.13	-35.28	174.08	37.9	-148.2	5.70±0.42
85	N16 782269	7	20	-171.4	30.7	6.8	0.42	-35.29	174.16	-69.6	18.5	4.42±0.31
88	N16 884267	6	30	175.3	60.7	3.9	0.42	-35.29	174.23	-82.8	-156.5	9.66±1.84
89	N20 826024	6	20	3.0	-60.7	5.3	0.15	-35.41	174.21	83.5	-26.0	0.79±0.17
90	P05 986645	11	20	147.1	41.4	4.3	0.55	-35.13	173.58	-59.4	-83.2	3.46±0.29
91	P05 990659	8	20	-174.3	57.4	1.7	2.5	-35.13	173.58	-84.6	117.1	7.17±2.7
92	P05 985644	3	20	-164.9	59.8	2.2	0.51	-35.13	173.58	-76.9	113.1	4.02±0.43
93	P05 042643	4	20	50.2	-12.0	36.6	1.8	-35.13	174.02	35.5	-116.1	0.14±0.06
94	P05 042643	6	20	-10.7	-52.4	8.8	0.28	-35.13	174.02	80.9	95.1	—±—
95	P05 004551	2	20	54.8	-13.2	8.7	1.9	-35.18	173.59	32.3	-112.2	0.10±0.06
96	P05 065575	7	20	7.7	-57.4	2.6	2.9	-35.17	174.03	83.2	-69.8	1.85±0.09
97	P05 094585	8	20	7.7	-59.3	1.9	2.1	-35.17	173.55	82.2	-55.4	1.87±0.18

Grid references refer to NZMS 1 1:63,360 for N15–N24, and NZMS 260 1:50,000 for P04 and P05. N is the number of samples measured per site. D.F. is the peak alternating field for demagnetization. Int. is geometric mean after demagnetization; sample volumes are approximately 1.2×10^{-5} m^3. α_{95} is the radius of 95% confidence circle in degrees. Site latitude and longitude are in degrees and minute, while VGP latitude and longitude are in degrees. Negative latitude denotes southern hemisphere, negative longitude denotes westing. Ages are from Smith *et al.* (1993).

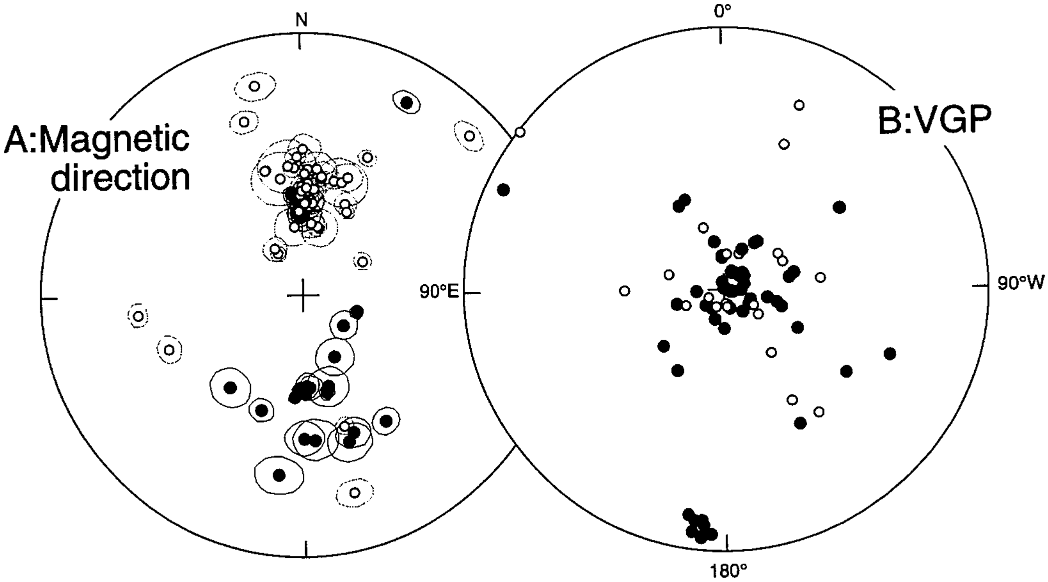

Fig. 2. Equal area projection of paleomagnetic directions (A) and VGPs (B) for the sites with more than three samples and with α_{95} less than 10°. Open and closed symbols indicate upper and lower hemisphere for (A) and northern and southern hemisphere for (B), respectively. Oval around data in (A) are its 95% confidence circles.

considered intermediate. The resulting value of ASD usually depends strongly on the cut off angle used. In the New Zealand dataset we found considerable number of intermediate directions, some of which are clearly records of an excursion (Shibuya *et al.*, 1992). Thus we can get almost any value of ASD by taking different cut off angles (Fig. 3). A more statistically sophisticated method for the determination of rejection angle has been developed (McFadden, 1982) but are also intrinsically arbitrary. The confidence level of rejection works just the same as the cut off angle.

In order to avoid this ambiguity, we assumed that the distribution of the VGP directions is the sum of those in the 'stable' period and unstable periods of geomagnetic variation, and further, that they follow different Fisher distributions (Fisher, 1953) around the axis of the geographic pole. The justification for this approach is that as well as avoiding the necessity of applying an arbitrary cut-off angle, it minimizes the number of degrees of freedom in the fitting procedure to the determination of just three parameters, namely the precision parameter for each distribution and the ratio of their intensity.

Another merit of using the ASD with respect to the geographic pole (S_p) is that it is robust to any bias in age distribution of the data. The ASD for the mean VGP (S_m) always tend to be biased to smaller values if the data are biased in age, since the mean VGP typically approaches any cluster in the age distribution which reflects that bias. On the other hand, the S_p is neutral to any bias in age distribution of the data, although the resulting error in S_p increases.

Even though S_m may be a better index for comparing PSV values, the penalty in using S_p would not be large, since S_p is approximately root sum square of S_m and the colatitude of the mean VGP. ASD is typically 12 to 15 degree, with a corresponding offset of the VGP about a few degree. If the latter is as large as a quarter of the former (e.g. 3° and 12°, respectively) S_p is only 3% larger than S_m.

The actual distribution of poles or directions during the time of unstable geomagnetism is not

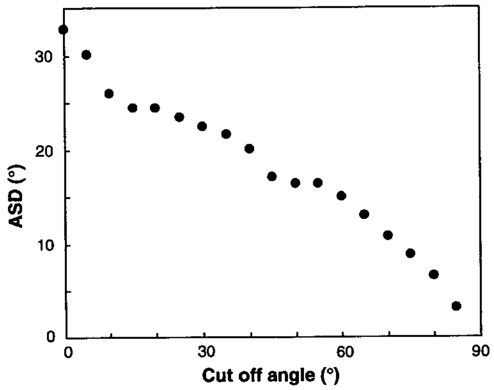

Fig. 3. Relationship between the cut off angle for the intermediate VGP and the resulting ASD for the present New Zealand dataset. Clearly an ASD of any value between 0° and 30° can be obtained from this dataset using different cut off angles.

well known, both uniform distribution and Fisher distribution have been suggested as possible. In fact, the dataset in this paper does not fit well with uniform distribution. This result does not seem to be a particular characteristic of the present dataset since similar poor fits are found with most of the other datasets discussed later in this paper. It may imply that the geomagnetic axial dipole plays relatively important roll compared with other components, even during the unstable periods.

The least square fitting calculation is performed for the cumulative histogram, because in the usual histogram the result of fitting to the distribution depends on the arrangement of sections, in other words, the information of the position of a data within a section is lost in the histogram. Since the marginal distribution to the absolute value of the VGP latitude (λ) of the Fisher distribution centered at the pole is

$$f_\kappa(\lambda) = \int_0^{2\pi} \left(\frac{\kappa e^{\kappa \sin\lambda}}{4\pi \sinh\kappa} \cos\lambda + \frac{\kappa e^{\kappa \sin(-\lambda)}}{4\pi \sinh\kappa} \cos(-\lambda)\right) d\phi = \frac{\kappa \cosh(\kappa \sin\lambda)}{\sinh\kappa} \cos\lambda$$

the cumulative form is

$$F_\kappa(\lambda) = \int_0^{\lambda} \frac{\kappa \cosh(\kappa \sin\alpha)}{\sinh\kappa} \cos\alpha d\alpha = \frac{\sinh(\kappa \sin\lambda)}{\sinh\kappa}$$

where κ is the precision parameter. Thus, the fitting function is

$$F(\lambda) = rF_{\kappa_1}(\lambda) + (1-r)F_{\kappa_2}(\lambda)$$

where κ_1, κ_2 and r are the precision parameters and relative weight of the two distributions.

Figure 4 shows a histogram of the VGP latitude for all of our data and data from Cox (1969b). The absolute value of the latitude was used in this analysis, with the assumption that the variation is independent of polarity. This assumption is adopted partly to minimize the parameters, but mainly because of the fact that polarity takes no effect in the MHD (magneto-hydrodynamics) equations governing the generation of the Earth's magnetic field. The composite Fisher distribution fits the histogram very well and therefore supports the validity of the method, giving values of κ_1, κ_2 and r as 49.2, 3.2 and 0.63, respectively.

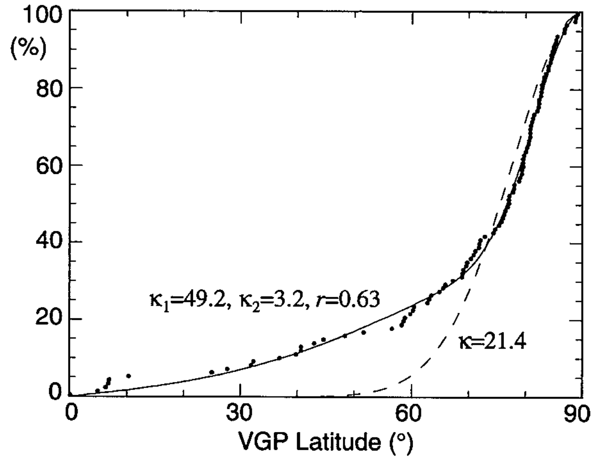

Fig. 4. Cumulative distribution for the VGP latitude in Fig. 2B. Data from Cox (1969b) are also added. Solid line and broken line are least squares fits of a composite and single Fisher distribution, respectively. The optimal parameters for each distribution are indicated in the figure.

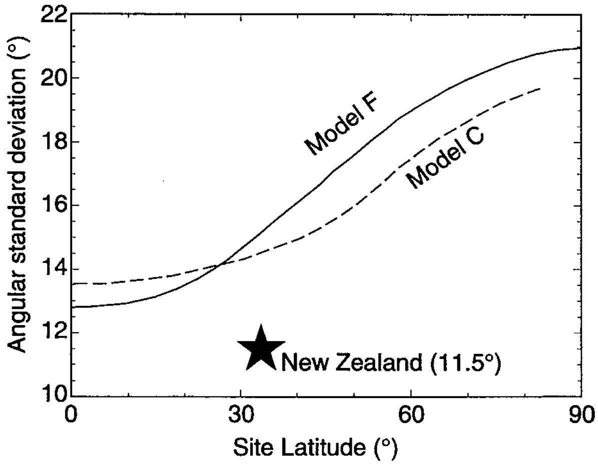

Fig. 5. Comparison of the ASD value calculated from the New Zealand data reported in this paper with the published PSV models C and F (Cox, 1962; McFadden and McElhinny, 1984, respectively).

The approximate relationship between the precision parameter and the ASD is given as (Tarling, 1983)

$$ASD = \frac{81}{\sqrt{\kappa}}$$

where ASD is measured in degrees. ASD values therefore can be calculated from both κ_1 and κ_2 values. The value of 49.2 for the precision parameter gives an ASD value of 11.5°. This value is significantly smaller than the value of 19.65° as given in Cox (1969b).

Figure 5 shows comparison of the new ASD values with the two representative models in the literature (Cox, 1962; McFadden and McElhinny, 1984), which are often referred as Model C and Model F, respectively. Applying the confidence limits given by Cox (1969a), the number of the sites in the narrower distribution ($N \times r = 104 \times 0.63 = 65.5$) gives about 1.5°. The ASD from New Zealand does not agree with either model.

3. Distribution of ASD

The discrepancy between the present results and the models may be caused partly by the fact that the models have been constructed based mainly on data from the northern hemisphere. However, more importantly, the method of calculating the ASD is also different. For the purpose of comparison, the ASDs are recalculated for various datasets for volcanic rocks younger than 5 Ma from other areas in the world. They are: Aleutian Is. (Bingham and Stone, 1972), Amsterdam I. (Watkins and Nougier, 1973), Canary Is. (Watkins *et al.*, 1972), Comores Is. (Watkins *et al.*, 1972), Crozet Is. (Watkins *et al.*, 1972), Easter Is. (Isaacson and Heinrichs, 1976), France (Doell, 1970), Gulf of Guinea, (Piper and Richardson, 1972) Hawaii Is. (Coe *et al.*, 1978; Doell, 1969; Doell, 1972a; Doell, 1972b; Doell and Cox, 1965; Doell and Dalrymple, 1973), Japan (Heki, 1983), Hiva-Oa I. (Katao *et al.*, 1988), Marion I. (Amerigian *et al.*, 1974), Mexico (Mooser *et al.*, 1974), Pagan I. (U.S.-Japan Paleomagnetic Cooperation Program in Micronesia, 1975), Réunion I. (Chamalaun, 1968), Society Is. (Duncan, 1975), Tahiti I. (Chauvin *et al.*, 1990), and Turkey (Sanver, 1968). To avoid biases due to data selection, no data were excluded from calculation, unless they were explicitly shown to be unreliable.

Figure 6 shows cumulative histograms of VGP latitudes. The resultant summary of statistics based on the present method is also tabulated in Table 2. Single Fisher distribution fits well in about half of the data sets. In most cases, it was clear from the histogram whether the single or composite Fisher distribution should be used. For a few areas where distinction was not clear, we set a criterion that if ASD corresponding to κ_2 was smaller than 30° (i.e. $\kappa_2 > 7.3$), a single Fisher distribution was preferred. No selection was made by the value of κ_1 itself.

The reliability of this method is demonstrated by the agreement of the precision parameters calculated using two datasets from the Society Islands. PSV studies in the Society Islands have been made by Duncan (1975) and, on Tahiti, by Roperch and Duncan (1990) who investigated the reversal sequence around Jaramillo event. These two completely different dataset gave very close values for κ_1. Values for κ_2 and r are different, however, since the former study avoided samples close to the reversals, while the latter preferred horizons around the reversals.

There have been different descriptions of the complexity of the PSV including the suggestion that the distribution of VGPs is anisotropic (Constable, 1992; Tsunakawa, 1988). We did not take account of this possible effect because of the importance of minimizing the number of parameters in the calculation.

The values of the ASD calculated using the present method have been plotted on the world map (Fig. 7). The data for Iceland was adopted from Kristjansson and McDougall (1982), since they used similar method of fitting to get precision parameters. The distribution they fitted was a Fisher distribution plus random distribution, instead of composite Fisher distribution as here. It corresponds to the case setting $\kappa_2 = 0$ in our method. They made calculation using a conventional histogram rather than a cumulative one, because the number of data in Iceland is so large (2163) that they draw histograms with small segments. These differences in method is insignificant for the value of the κ_1, as the number of data is large and the fitting is well, thus it is directly comparable with our results. It is clear from the figure that the ASD depends on longitude as much as, or more than, on latitude. The large ASDs occur around 0° of longitude and the small ASDs are on the opposite side of the earth.

Most of the models for PSV implied axisymmetric distribution of the ASD. For example, McFadden and McElhinny (1984) averaged out all the data from a latitude band to get the ASD value. Since the Earth is virtually axisymmetric, it may seem to be reasonable to assume that the dynamo process is also axisymmetric, provided that data are averaged over longer than the

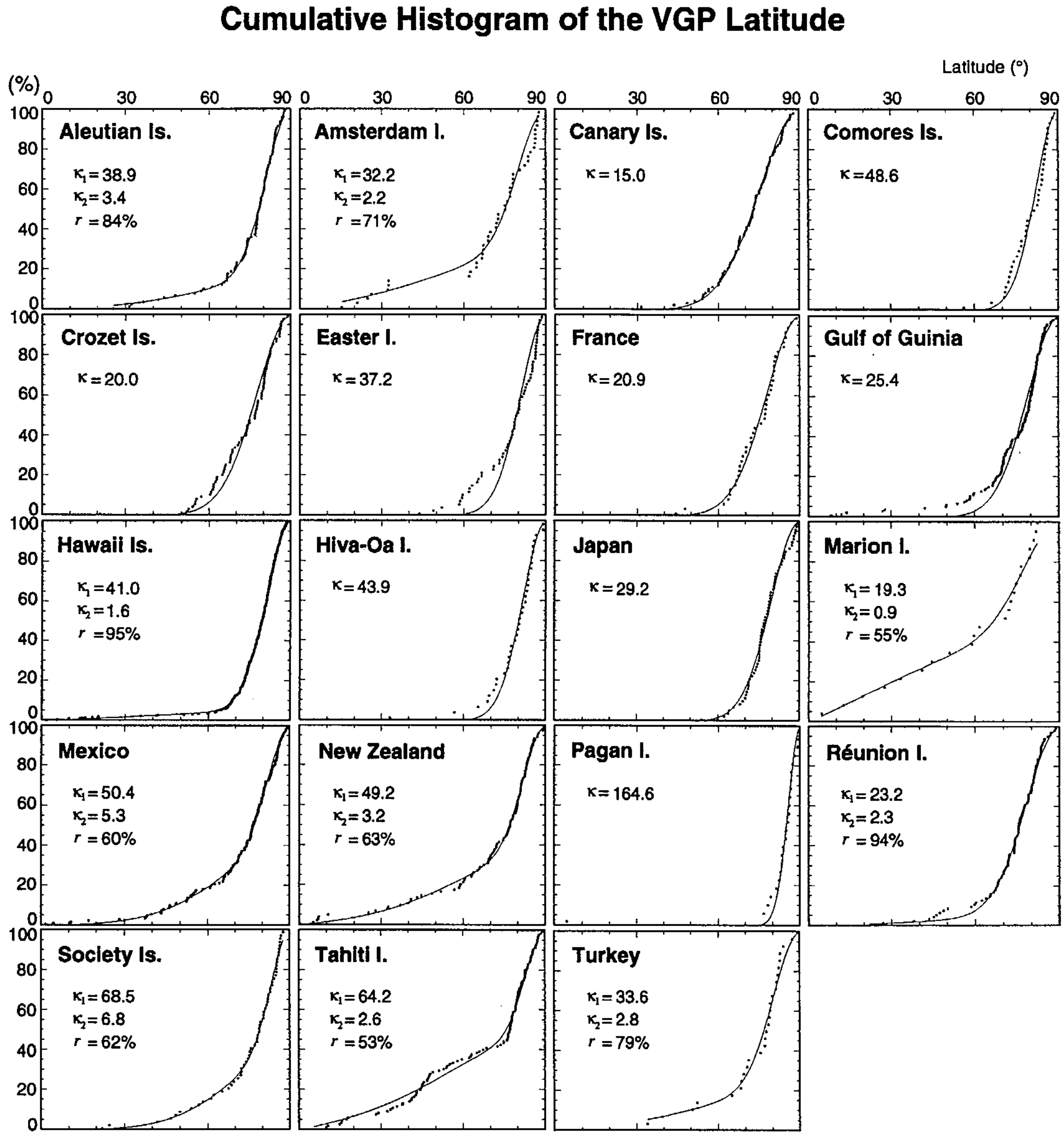

Fig. 6. Cumulative histograms for the VGP latitude elsewhere (reference cited in text). The optimal parameters are written on each graph. Two precision parameters indicate where a composite Fisher distribution has been used.

characteristic period of the motion of the liquid core. However, this assumes that the dynamo is driven by processes within the core.

One example of a deviation from the axisymmetric PSV is the repeatedly claimed Pacific non-dipole low (Doell and Cox, 1972). These authors collected a considerable number of paleomagnetic directions for the last few million years in Hawaii, and concluded that the PSV has been smaller in the Pacific region for the past 0.7 m.y. or more. This conclusion was criticized by Coe *et al.* (1978) because the small PSV seemed to be caused by a large number of Hawaiian data falling

Table 2. Statistics characterizing worldwide VGP data.

	Lat. (°)	Long. (°)	N	κ_1	ASD (°)	κ_2	r (%)
Aleutian Is.	53N	172W	92	38.9	13.0	3.4	84
Amsterdam I.	38S	78E	45	32.2	14.3	2.2	71
Canary Is.	29N	15W	99	15.0	20.9		
Comores Is.	12S	44E	39	48.6	11.6		
Crozet Is.	46S	52E	81	20.0	18.1		
Easter I.	27S	109W	63	37.2	13.3		
France	46N	3E	42	20.9	17.7		
Gulf of Guinea	3N	8E	132	25.4	16.1		
Hawaii Is.	21N	157W	484	41.0	12.7	1.6	95
Hiva-Oa I.	10S	139W	36	43.9	12.2		
Japan	35N	139E	63	29.2	15.0		
Marion I.	47N	38E	23	19.3	18.4	0.9	55
Mexico	20N	99W	40	50.4	11.4	5.3	60
New Zealand	37S	174E	104	49.2	11.5	3.2	63
Pagan I.	18N	146E	24	164.6	6.3		
Réunion I.	21S	55E	96	23.2	16.8	2.3	94
Society Is.	17S	152W	60	68.5	9.8	6.8	62
Tahiti I.	18S	149W	123	64.2	10.1	2.6	53
Turkey	39N	35E	28	33.6	14.0	2.8	79
Iceland	65N	19W	2163	8.5	27.8	0.0	10

N is number of sites. κ_1 and κ_2 are the precision parameters corresponding to the narrow and wider distributions, respectively, in the composite Fisher distribution (see text). r is the ratio of the intensity of those distributions. ASD is angular standard deviation corresponding to κ_1.

in a short time span. McWilliams *et al.* (1982) examined the weight of each data to correct the bias of the age distribution, and concluded that it does not significantly affect to the PSV value.

As shown in Fig. 6, the composite Fisher distribution model fits quite well the histogram for the data from Hawaii Is. (Coe *et al.*, 1978; Doell, 1969; Doell, 1970; Doell, 1972a; Doell, 1972b; Doell and Cox, 1965; Doell and Dalrymple, 1973), supporting the validity of our assumptions. The fitting method gave an ASD of 12.7°, which seems to support the conclusion of Coe *et al.* (1978). However, once we abandon the zonal PSV models, 12.7° is still small compared with the area outside the Pacific Region (see Fig. 7).

The extent of the Pacific non-dipole low was discussed in reference to paleomagnetic results from other islands in the Pacific Ocean (Duncan, 1975; Isaacson and Heinrichs, 1976; Katao *et al.*, 1988; U.S.-Japan Paleomagnetic Cooperation Program in Micronesia, 1975). Some of these authors accept its existence while others do not. Figure 7 indicates that the extent of the Pacific non-dipole low is as large as the Pacific Ocean, and it should be regarded as a global feature of non-axisymmetry rather than as a local feature in the axisymmetric PSV distribution. It could therefore be more correctly described as a sectorial distribution of the PSV rather than an anomalous area in the Pacific Region.

If there is non-axisymmetric behavior of the geomagnetism in the long term, it must be due to the influence of the solid part, hence the mantle. There are two possibilities: (1) The dynamo process is symmetric, but the non symmetric conductivity of the lower mantle attenuates the fluctuation. (2) The dynamo process itself is not axisymmetric even after averaged over considerably long period. These conclusions are essentially in agreement with Cox's (1962) explanation of the

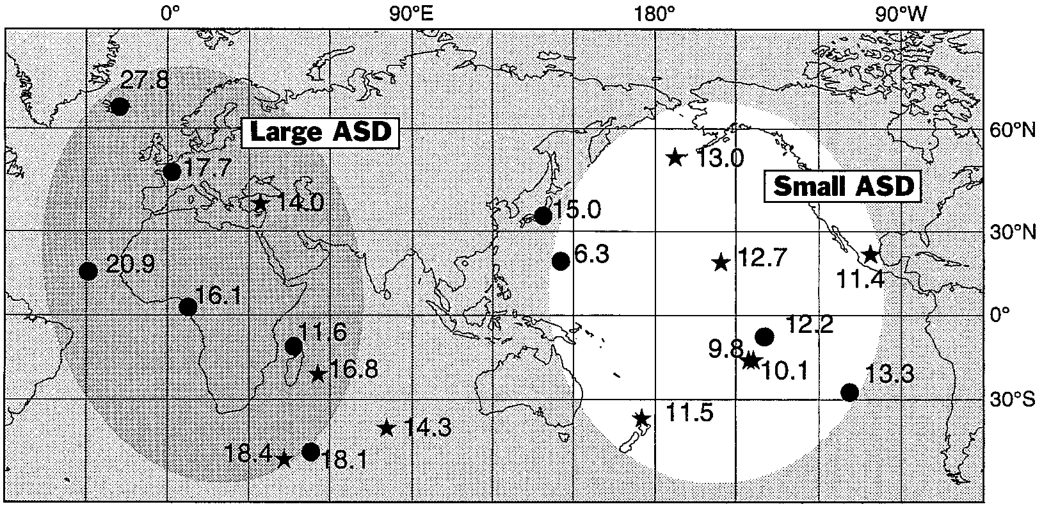

Fig. 7. Distribution of the ASD value (degrees) calculated by the least square fitting to the cumulative distributions. Stars and circles indicate that composite and single Fisher distribution were used for fitting, respectively.

persistence of the Pacific non-dipole low. The latter explanation was taken in their later papers (Doell and Cox, 1972), the former seems to be unlikely because the conductivity required is too large for the mantle material (Gubbins and Robberts, 1987). The analyses of recent geomagnetic data also accept the homogeneous conductivity of the mantle (Bloxham *et al.*, 1989).

The implication here is that the thermal or mechanical regime of mantle, especially at the core mantle boundary, strongly influences the dynamo process. This may relate to the controversial preferred VGP path for geomagnetic reversals (e.g. Laj *et al.*, 1991; McFadden and Merrill, 1995). If the dynamo process during stable periods is influenced by the mantle, there should be similar effects also during the unstable period of geomagnetism.

4. Conclusions

(1) A new method of analyzing PSV data which allows for the possibility of a composite Fisher distribution gives ASD values which do not depend on applying arbitrary cut-off criteria for intermediate magnetic directions.
(2) The ASD for northern New Zealand (11.5°) is smaller than that predicted from previous PSV models.
(3) Applying the composite Fisher method to data from elsewhere suggests that previous estimates of ASD often have been over-estimated and that the hypothesis that the ASD depends solely on latitude is invalid. Longitudinal variation of ASD is at least as large as that reported for latitudinal variation.
(4) The non-axisymmetric distribution of the ASD implies that the dynamo process is strongly influenced by the thermal and/or mechanical regime of solid mantle.

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