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Paleosecular Variation of Lavas from the Marianas in the Western Pacific Ocean

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A paleomagnetic study of 24 lava flows from Pagan Island (18.1°N, 145.7°E) in the Mariana Islands was conducted to determine the geomagnetic paleosecular variation in the Western Pacific. All flows are normally magnetized, and attempts to obtain radiometric ages for these flows were unsuccessful, and paleointensity determinations by the 'Thellier method' were unreliable. The mean virtual geomagnetic pole, (88°N, 110°W) is not significantly different from the rotation axis, suggesting that the lavas erupted over a period that spans at least several thousand years. The between-site angular dispersion S_B, is used as a measure of the secular variation. $S_B=6.0°$ with respect to the mean VGP, and $S_B=6.2°$ with respect to the axis of rotation with a 95 percent confidence interval for the latter of $5.2° < S_B < 7.8°$. Possible interpretations of the data include: (1) the sites studied represent an inadequate coverage in time; (2) the Marianas should be included in the Pacific dipole window; (3) there is a belt of average low angular dispersion encircling the earth between (roughly) 0° and 40°N.

1. Introduction

Studies of the secular variation of the earth's magnetic field are made to provide a better understanding of the history and origin of the earth's magnetic field and, possibly, to provide data concerning physical and/or chemical inhomogeneities near the core-mantle boundary (DOELL and COX, 1971, 1972). Although continuous monitoring of the earth's magnetic field began in the 16th century, only since 1829 have there been sufficient observatory data to obtain the dipole, quadrupole and octupole terms in a spherical harmonic analysis. However, YUKUTAKE (1971) did obtain these terms for the 16th and 17th century by interpolating values for the intensity between archeomagnetic and observatory data. Analyses dating from 1829 indicate that most of the magnetic field at the earth's surface can be represented by a geocentric dipole tilted roughly at *11.5 degrees* with respect to the earth's rotation axis. These analyses

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further indicate that this dipole has decreased about 7% in intensity and has either remained stationary with respect to the rotation axis or experienced a very small amount of drift since that time (BULLARD *et al.*, 1950; NAGATA, 1962). The nondipole field changes more rapidly in intensity and direction, but on the average appears to undergo about 0.2 degree/year westward drift (BULLARD *et al.*, 1950; YUKUTAKE, 1962). The accuracy of all analyses decreases back in time, due to nonuniform spacing of recording stations and a decrease in their number.

To obtain information on the secular variation thousands and millions of years before present, many scientists have turned to paleomagnetism. Although several paleomagnetic techniques are available, we follow the suggestion of COX and DOELL (1964) of using the dispersion of virtual geomagnetic poles (VGP). This approach does not record all the secular variation, since usually only the directions of remanence are used, owing to the difficulty in obtaining reliable intensities from rocks (COE, 1967). Therefore, any secular change affecting the intensity of the field at one location, but not its direction, will go unrecorded. Nevertheless, it is generally accepted that the relative dispersion of VGPs averaged over sufficient time will give an accurate indication of the relative magnitude of the differences in secular variation at different locations. Although it is difficult to resolve the question of what constitutes "sufficient time," the time spanned must be longer than 10^4 years, since fluctuations in dipole intensity of this size appear in the geomagnetic record (COX, 1969). An upper limit on the secular variaion that can be resolved is the minimum time span for which *significant* continental drift can occur (roughly 10^7 years).

The total magnetic field averaged over "sufficient time" can usually be closely approximated by a geocentric axial dipole field. The most recent demonstration is by WELLS (1973) who fits the spherical harmonic dipole, quadrupole and octupole terms to paleomagnetic data of rocks less than 3 million years of age. With the exception of very small components in the axial quadrupole and octupole terms, he shows that the average field can be represented by a simple geocentric axial dipole field. Therefore, the instantaneous dipole must also undergo significant changes in direction. COX and DOELL (1964) refer to these directional changes in the dipole field as "dipole wobble." DOELL and COX (1971) further suggest that the magnitude of the "dipole wobble" can be estimated from paleomagnetic studies in Hawaii, where the present nondipole field is essentially absent and where, according to their interpretation of the paleomagnetic data, it may have been absent for the last few million years (DOELL, 1972a, b). As they point out, if this is so, then the dispersion due to the dipole field can be separated from the nondipole field at any location on the earth by doing a proper statistical analysis of VGPs. However, there is not general agreement on the question of whether or not the Hawaiian Islands truly represents a "Dipole window." Indeed a different interpretation is required if YUKUTAKE's (1971) analysis, which indicates the presence of a large nondipole feature in the central Pacific, is correct. YUKUTAKE (personal communication, 1973) offers an alternate interpretation, which suggests a belt of low average angular dispersion of VGPs encircling the earth between latitudes 0° and 40°N. To help resolve some of these questions, paleomagnetic studies on Pagan Island (near 18°N, 145°E) in the western Pacific were undertaken. This area appeared ideally located in the Pacific to answer some of these questions as it lies nearly at the same latitude as Hawaii, but roughly 60° further to the west.

2. Samples and Methods

A total of twenty-four distinct flows were sampled from Pagan over an elevation difference of roughly 500 meters. With the exception of two flows from which 6 cores were taken, 7 one-inch diameter oriented cores were obtained by procedures similar to those used by Cox and Doell in Hawaii. With

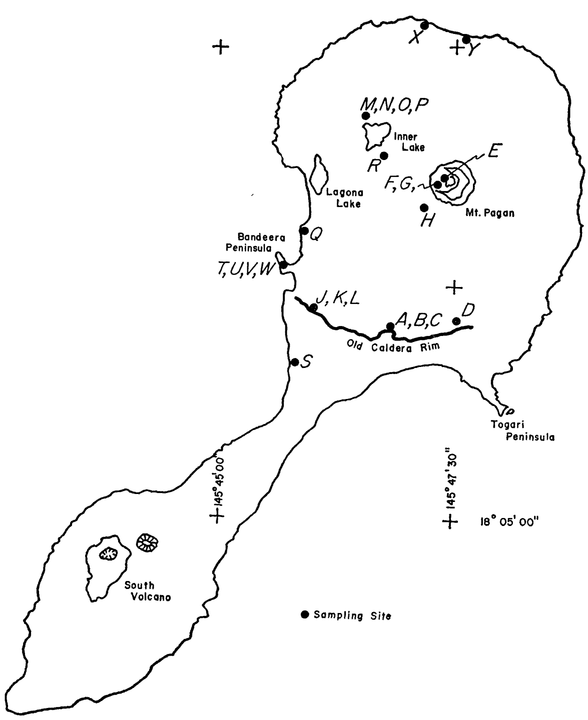

Fig. 1. Location of sampling sites on Pagan Island.

the use of a geologic map of Pagan provided by E. Corwin of the U.S. Geological Survey and some field work, the following stratigraphy for the Pagan flows was estimated: from youngest to oldest, E, H, F, G, X, Q, A, D, R, M, P, O, N, C, B, L, K, J, W, V, U, T, Y. According to CORWIN (personal communication), flows sampled extend back in time from the youngest two of historical age (1925 and 1873) on Mt. Pagan to mid or Late Quaternary flows in a wall of an older collapsed caldera that partially rims the younger Mt. Pagan. Flow "S" from the southern part of Pagan is the only flow not directly associated with Mt. Pagan (Fig. 1) and, therefore, is not included in the above stratigraphy. In addition to NRM, AF demagnetization of 100 oe and 200 oe using a 4-axis tumbler was done on one sample from every core. The direction reported for a given lava flow corresponds to that peak alternating field which produced the smallest dispersion.

3. Results

Table 1 summarizes the magnetic results. All the flows sampled exhibit normal polarity and probably are from the Brunhes polarity epoch. Flow "D" had a very large α_{95} after demagnetization and its direction deviated significantly from the other flows. Consistent with the procedures used on Hawaii (for example, DOELL, 1972a, b), the data from this flow have not been used in the subsequent statistical analyses.

The quantity of main interest in this study is the angular dispersion which can be given by either the total standard deviation, S_T, or Fisher's precision parameter, K_T. For smaller angular dispersion the two are related by the relation: $S_T^2 \approx 2/K_T$, a relationship which has not been directly used in this analysis because of its approximate nature. The total dispersion consists of two components: the between-site dispersion (K_B or S_B) and the within-site dispersion (K_W or S_W). As indicated by COX (1969) and followed by DOELL (1972a, b), it is preferable to use S_B, which should not be affected by within-site scatter, rather than S_T. We will follow this procedure in this paper. Table 3 gives the statistics obtained in this study. Alternate methods of analysis are available (for example, WATSON and IRVING, 1957), but differences between these methods make only minor differences in the resulting estimates of dispersion and make no differences in the interpretations (COX, 1969b). Figure 2 gives a summary of several secular variation studies completed on Brunhes-aged Lava Flows.

4. Interpretations: The Time Factor

The critical question as to the amount of time spanned by these flows has

Table 1. Flow-average data for Pagan Island volcanics.

Unit No.	No. of Samples*	af Demag. (Peak field), oe	RM Declination, °E	RM Inclination, deg. Down	Length of Resultant R	Precision Parameter k	$\alpha95\%$ Confidence, deg.	Angular s.d., deg.	VGP Long., °W	VGP Lat., °N
A	7	200	14.1	37.1	6.9741	232.0	3.97	5.32	137.7	76.4
B	7	200	−5.3	42.0	6.9893	560.0	2.55	3.42	−108.0	82.1
C	7	200	−2.6	38.3	6.9611	154.0	4.87	6.52	−111.4	85.8
D**	6	200	−102.1	37.7	5.3654	7.9	25.45	26.35	−79.7	−4.3
E	7	200	−2.6	22.2	6.9078	65.0	7.54	10.05	12.5	83.0
F	7	200	10.7	27.2	6.9745	235.0	3.94	5.28	106.1	79.1
G	7	200	4.4	29.9	6.9793	290.0	3.55	4.76	99.2	85.3
H	7	200	6.3	15.1	6.9711	207.0	4.20	5.63	65.4	77.9
J	6	200	2.2	45.4	5.9870	384.0	3.42	4.13	−158.3	81.0
K	7	200	0.2	34.3	6.9887	533.0	2.62	3.51	−159.5	89.3
L	7	200	−5.6	33.9	6.9816	326.0	3.35	4.49	−62.1	84.7
M	7	200	7.1	31.0	6.9966	1747.0	1.44	1.94	113.6	83.1
N	7	NRM	3.7	31.9	6.9924	789.0	2.15	2.88	111.8	86.4
O	7	200	−3.2	30.4	6.9832	357.0	3.20	4.29	−25.7	86.5
P	7	200	−0.1	31.4	6.9932	879.0	2.04	2.73	28.1	88.9
Q	7	200	5.5	30.7	6.9768	258.0	3.76	5.04	108.7	84.5
R	7	NRM	0.5	28.6	6.9722	216.0	4.12	5.51	44.5	87.1
S	7	100	4.7	23.4	6.9948	1156.0	1.78	2.38	72.1	82.6
T	7	100	2.1	34.0	6.9773	265.0	3.72	4.98	138.6	87.9
U	7	100	−4.3	32.5	6.9882	510.0	2.67	3.59	−50.3	85.9
V	7	100	−3.5	33.6	6.9614	156.0	4.85	6.50	−60.6	86.6
W	7	NRM	1.1	33.3	6.9850	401.0	3.02	4.05	129.2	89.0
X	7	200	6.7	32.5	6.9834	361.0	3.18	4.26	121.5	83.6
Y	7	100	1.6	38.5	6.9938	969.0	1.94	2.60	−168.0	86.1

* A mean N equal to 7 was used in the Flow-average analysis.

** Not included in analyses for paleosecular variation because its direction deviated significantly from the directions of other flows and its $\alpha95$ is very large.

Table 2. Relationships between the precision parameters and between angular standard deviations.

$k_T=(N-1)/(N-R)$	$s_T^2=\frac{1}{N-1}\sum_{i=1}^{N}\Delta_i^2\approx\frac{2}{k_T}$
$\frac{1}{k_W}=\left[\sum_{i=1}^{N}\left(\frac{1}{k_i}\right)\right]\Big/N$	$s_W=\left[\sum_{i=1}^{N}s_i\right]\Big/N$
$\frac{1}{k_T}=\frac{1}{k_B}+\frac{1}{\bar{N}k_W}$	$s_T^2=s_B^2+s_W^2/\bar{N}$
$\frac{1}{k_B}=\frac{1}{k_F}+\frac{1}{k_A}$	$s_B^2=s_F^2+s_A^2$

N=total number of lava flows used in the analyses.

Δ_i=the angular separation of the RM direction of the i^{th} lava from the mean about which the dispersion is desired (mean direction or direction of axial dipole).

s_A=angular standard deviation due to local paleomagnetic anomalies.

$$s_A\equiv 1.25°\rightarrow k_A=\frac{2}{s_A^2}=4202$$

meaning of other symbols as in Table 3.

Table 3. Dispersion statistics of flow-average data.

	Angular standard deviations				Precision parameters			
Pagan I. volcanics ($\bar{N}$=6.96)	s_T	s_W	s_B	s_F	k_T	k_W	k_B	k_F
Referred to mean direction	7.7°	4.5°	7.5°	7.4°	110	282	116	119
Referred to axial dipole direction	8.0°		7.9°	7.8°	101		106	109
	S_T	S_W	S_B	S_F	K_T	K_W	K_B	K_F
Referred to mean VGP	6.3°	5.8°	6.0°	5.8°	163.5	197	189	194
Referred to geographic pole	6.6°		6.2°	6.1°	148		173	178

s, S=angular standard deviations for RM directions and VGP's, respectively.
k, K=precision parameters for RM directions and VGP's, respectively.
Subscript T =total dispersion.
Subscript W=within flow dispersion.
Subscript B =between flow dispersion (experimental errors only removed).
Subscript F =dispersions of VGP's and directions (experimental errors and effects of local anomalies removed).
$\bar{N}$=mean number of samples per lava used in the analyses.

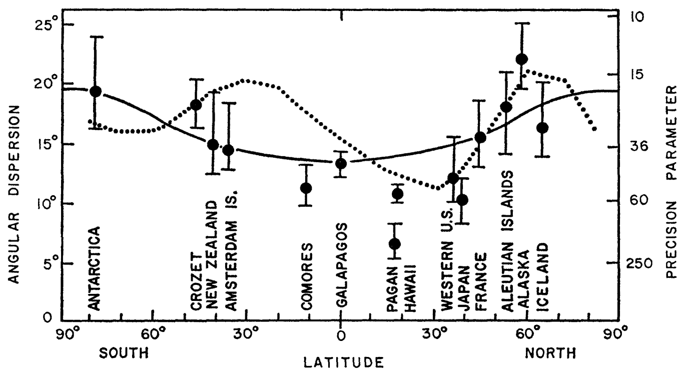

Fig. 2. Angular standard deviation for secular variation of Brunhes-aged Lavas versus latitude. Solid curve is Model C from Cox Dotted curve is a model presented by Yukutake on the basis of a standing and drifting field model for the geomagnetic secular variation. In addition to the data summarized in the review by Doell and Cox (1971), data from Ozima and Aoki (1972) and Watkins (1973) have been included along with our Pagan data.

not been answered. If very similar magnetic directions in a sequence of lava flows are the result of extrusion over a short time period, then the basic statistical assumption of random sampling is not satisfied. Such "serial correlation" results in estimations of dispersion that err in being too small (Watson and Beran, 1967). Potassium-argon and fission track dating were attempted to determine the age spanned by the Pagan Flows. These attempts were unsuccessful primarily because even the oldest rocks are apparently too young for these methods to work. Paleointensities were also attempted. A modified "Thellier technique" (the version used here is that described by Coe (1967)) produced linear NRM-TRM curves for many of the flows for temperatures below 400°C to 500°C. Above these temperatures, deviation from ideal Thellier behavior was observed. Figure 3 gives some examples of these data. Almost all the intensities (obtained from the slopes of the linear segments of the lower temperature data of the NRM-TRM plots) are substantially higher than the present field, including that of an historically dated flow which is unreasonably high. In addition, for most flows, where multiple samples were used, there is a large within-flow dispersion of the intensities. For these reasons the intensity data were not used for age estimates.

Whatever the actual time spanned by these flows is, it is of sufficient duration that the field averages to a geocentric axial dipole field. Although better times estimates are not presently available, most other studies, excepting the Hawaiian Islands, that have been used to argue for a dipole window have also encountered similar difficulties in estimations of time.

The angular dispersion, S_B, is 6.0 with respect to the mean VGP and 6.2° with respect to the geocentric axial dipole, with a 95 percent confidence interval for the latter of 5.2° $<S_B$ 7.8° $<$ (Cox, 1969a). These values for the angular dispersion are significantly smaller than the 11° figure found in Hawaii (Fig. 2) and previously interpreted as indicating the magnitude of the dipole wobble

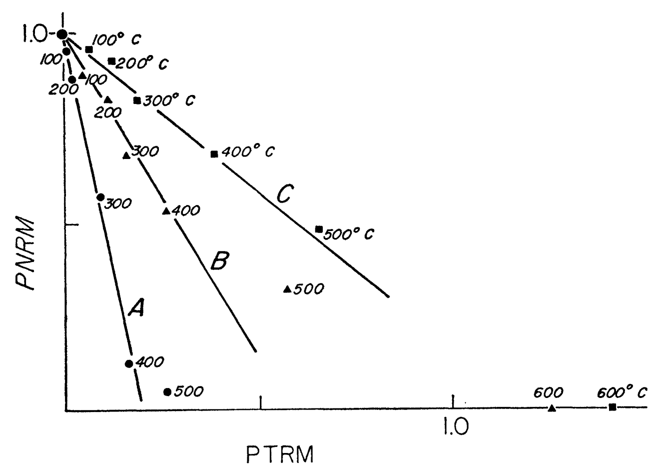

Fig. 3. Application of a modified "Thellier Technique" to samples from three lava flows from Pagan Island. A description of this technique is given in Coe, 1967. The PNRM-PTRM curves are straight lines out to 400° to 500°C and deviate to the right at higher temperatures. Sample A is from a historical lava flow and its data indicates an apparent intensity that is several times the actual intensity.

(DOELL and COX, 1971). Regardless of whether or not the Pagan flows have erupted over sufficient time to sample all the secular variation, it does appear from these data together with a large body of other paleomagnetic evidence (for example, DOELL, 1970) that the angle between the instantaneous dipole and the rotation axis has been much smaller than the present $11\frac{1}{2}°$.

Further unique interpretations are difficult. It is possible that there is a "dipole window" and that the Marianas are included in it, but the total dispersion associated with the dipole wobble was not recorded because of insufficient time (for example, see discussions by BINGHAM and STONE, 1972, and BROCK, 1971). Similar arguments may be applicable to data from Japan even though the data is believed to uniformly cover time back to 9,500 years ago (OZIMA and AOKI, 1972). However if such data are not judged acceptable for this reason, then to be consistent one must also judge unacceptable the data for rocks obtained from most other regions, with a few exceptions such as Hawaii, that have been used to define the dipole window. One could also argue for a belt of small angular dispersion of VGPs between latitudes 0° and 40°N that encircles the earth (YUKUTAKE, personal communication, 1973).

Still another interpretation is that made recently by AZIZ-UR-RAHMAN and MCDOUGALL (1973). They produced evidence that the VGPs for lava flows in Norfolk and Philip Islands in the southwest Pacific Ocean have a very low angular dispersion of 7.5° (with respect to the Mean VGP), even though they span a time from 2.8 up to 2.35 my before present. Their data further suggests that this period of time is insufficient for the field to average to a geocentric axial dipole field, provided that no significant rotation of the islands (around 14°) has occurred since 2.35 my ago. Because the mean dipole field in their study significantly deviated from the rotation axis, they interpreted their data as showing that secular variation could not be averaged out in the nearly one-half million years of the Gauss epoch spanned by their flows. Alternately, if one evokes tectonic rotation to explain the deviation of their mean VGP from the dipole axis, then one is left with the very low value for angular dispersion of 7.5° which can be contrasted with the 19.6° dispersion of VGPs from some Brunhes Lavas at a similar latitude in New Zealand (COX, 1969b). Therefore, regardless of how one interprets their data, one encounters difficulties in the acceptance of the "dipole window model" between two and three million years before present.

Figure 2 summarizes the data for Brunhes-aged lavas. Two models, Cox's Model C (COX, 1969b) and a new model by Yukutake, are shown for reference. Yukutake's model is obtained from his analysis of the geomagnetic field in terms of a standing and a drifting part. It is apparent that no simple curve can be fitted to these data. With the exception of data from Hawaii, the data for most sites shown reflect changes in the earth's magnetic field of probably only a few thousand years and it is not clear that this time span is sufficient to sample the whole spectrum of secular variation. These data taken together with those of AZIZ-UR-RAHMAN and MCDOUGALL (1973) suggest that secular variation may be highly variable in time and space. Analogous to the apparent lack of simple periodicity of field reversals, there may be no simple periodicity in the variation of directions of the dipole and nondipole fields. In any case, the paleomagnetic data now available appears insufficient to distinguish between competing theoretical models for secular variation.

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