Geomagnetic Paleosecular Variation and K–Ar Ages in Hiva-Oa Island, Marquesas, French Polynesia

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Paleomagnetic analysis was made on 36 lava flows and dykes of different ages distributed in Hiva-Oa Island, the Marquesas Islands (9.7°S and 139.0°W) in an attempt to study the geomagnetic paleosecular variation. K–Ar ages of samples range from 2.74 m.y. to 1.63 m.y. The present rotation axis is contained within the 95% confidence limit of the mean VGP (88.1°N and 117.9°W). The angular dispersion of 32 poles is 13.8° with respect to the rotation axis, and its upper and lower confidence limits are 16.6° and 11.8°, respectively. These values are consistent with the values of the global trend and the values predicted by secular variation models. Low secular variation as reported in the Hawaiian Islands is not observed in the Marquesas Islands.

1. Introduction

The angular dispersion of the ancient geomagnetic field at given locality and/or their corresponding virtual geomagnetic poles (VGPs) are useful to provide valuable information on paleosecular variation (PSV) of the geomagnetic field. PSV data of the world indicate a strong latitude dependence; angular dispersion of VGP increases with latitude (MCELHINNY and MERRILL, 1975). Various models are proposed to describe secular variation and its latitude dependence.

Geomagnetic secular variation observed in the Pacific region is lower than those observed in other regions (FISK, 1931; FLEMING, 1939; VESTINE *et al.*, 1947; VESTINE and KAHLE, 1966). The non-dipole field intensity in the Pacific region is very low at present. This notable feature has been recognized since 1829, when the oldest reliable spherical harmonic analysis was performed. DOELL and COX (1971, 1972) showed anomalously low secular variation based on both observatory data and paleomagnetic data during the Brunhes polarity chron in Hawaii, and explained that this phenomenon is caused by a lateral inhomogeneity of the lower mantle which is coupled to the core in such way as to partially prevent the generation of non-dipole field beneath the central Pacific Ocean. This phenomenon is named the Pacific non-dipole low or the Pacific dipole window. It is profoundly interesting to see how far this non-dipole low region extends. Unfortunately, there is little information on

the dimension of the Pacific dipole window, except for the Hawaiian Islands.

Hiva-Oa Island (9.7°S and 139.0°W) is one of volcanoes composing the Marquesas Islands. Marquesas chain exhibits volcanic migration from northwest to southeast, and is explained to have been formed through the volcanic activity generated at a hotspot which is situated at 112 km southeast of Fatu-Hiva Island (10.5°S and 138.3°W) in the same way as the Hawaii-Emperor chain (DUNCAN and MCDUGALL, 1974; JARRARD and CLAGUE, 1977). In this paper, we present a data set of the geomagnetic secular variations in Hiva-Oa Island, and examine the extent of the Pacific non-dipole low.

2. Paleomagnetism

In 1979, we collected 211 oriented rock samples from 36 sites of lava flows and dykes in Hiva-Oa Island (Fig. 1). Samples were oriented by a magnetic compass. One to five core subsamples, 25 mm long and 25 mm in diameter, were prepared from each sample in the laboratory.

Remanent magnetization of subsamples was measured using a spinner magnetometer. Stepwise demagnetization in alternating-field (AF) up to 50 mT was performed on three or more pilot subsamples from each site. Median destructive field (MDF) ranged from 5 mT to over 50 mT; generally between 20 mT and 30 mT. Vector component diagram was used to identify the primary component. Most of pilot subsamples did not significantly change their remanent direction during stepwise AF demagnetization up to 50 mT (Fig. 2). Other pilot subsamples lost their secondary components at the AF levels up to 30 mT and revealed their characteristic (single) components. The AF level to completely lose the secondary component was chosen as the optimum demagnetization level (ODF) of each site. All the remaining subsamples were demagnetized by ODF determined every site.

Stepwise thermal demagnetization was also performed on pilot subsamples from four sites, which were chosen at random to justify the AF demagnetization results. Directions of magnetization did not significantly change under thermal demagnetizing process. Consequently no behavior, different from that during AF demagnetization treatment, was observed during thermal demagnetization.

Paleomagnetic results are summarized in Table 1. Both normal and reversed polarities are present; polarities of 13 sites are normal and polarities of 23 sites are reversed. Mean field directions for every site are shown using equal-area projection (Fig. 3). VGP positions for each site are plotted in Fig. 4. VGPs having reversed polarity are inverted to give a distribution confined to the northern hemisphere. Mean pole for all VGPs is located on 88.0°N and 126.3°W. These VGP positions were calculated using the present location of Hiva-Oa Island. No correction of VGP positions for plate motion is needed. Because, when Hiva-Oa is brought back to the position of 2 m.y. ago using the rotation pole of Pacific plate, the angular distance corresponding to the distance is a few degrees.

Fig. 1. Locations of the Marquesas Islands and sampling sites in Hiva-Oa Island.

3. Geochronology

Eleven basalt lava flow (E3, G5, M2, R7, R28, BB1, BF5, and BF8) or dyke (N1, O3, and BH4) samples from 5 sites of reversed polarity and from 6 normal sites were dated by the K-Ar method. Argon was extracted by fusing a 0.5–0.9 g of whole-rock sample at about 1600°C in a high vacuum line. The amount of radiogenic ^{40}Ar was determined by the isotope dilution method using an ^{38}Ar tracer. All samples for argon analysis were baked out at 150°C for a whole day in vacuum prior to fusion to reduce the atmospheric Ar component on the surface. Potassium content was determined in duplicated atomic absorption spectrometry using the addition of strontium solution (TERASHIMA, 1970) and KCl standard solution. The K-Ar age and its error were calculated in accordance with COX and DALRYMPLE (1967) using the refined

Fig. 2. Vector component diagrams of stepwise AF and thermal (right) demagnetizations. Solid (open) symbols refer to the horizontal (vertical) plane.

constants: $\lambda_e = 0.581 \times 10^{-10}$ yr., $\lambda_\beta = 4.962 \times 10^{-10}$ yr., $^{40}\text{K}/\text{K}_{\text{total}} = 1.167 \times 10^{-2}$ at percent (STEIGER and JAGER, 1977).

The results of K-Ar dating are tabulated in Table 2. The ages for Hiva-Oa by DUNCAN and MCDOUGALL (1974) are also listed, which are recalculated using the refined constants. Our ages lie in a range 2.74–1.77 m.y., which are in good agreement with the ages reported by DUNCAN and MCDOUGALL (1974). Two pairs of samples; N1 and M2, BH4 and BH8, show the ages consistent with stratigraphic sequence. For example, the age of the dyke sample N1 which intruded into the lava sample M2 is younger than that of sample M2.

The obtained K-Ar ages and the paleomagnetic polarity data are in good accordance with the geomagnetic reversal time scale constructed by MANKINEN and DALRYMPLE (1979) except for the samples BF5 and BH4 (Fig. 5). The ages show that the volcanic activity of Hiva-Oa continued on about 1 m.y. On closer investigation, however, it may be found that the volcanic activity was relatively gentle over a span of about 2.36–2.08 m.y. for samples from lava flows. Five samples (E3, M2, O3, BH8, and 73-32) show ages of 2.81–2.36 m.y. with their age error, and twelve samples (G5, R7, R28, BB1, BH4, BF5, 73-29, 73-28, 73-29, 73-31, 73-33, and 73-34) show 2.08–1.60 m.y. with their age error. No samples which lie in a range of 2.36–2.08 m.y. were found; the sample N1, which shows an age of about 2.27 m.y., was collected from a dyke. In the case of the above description, it might be stated that the former lava flows were erupted in the early vigorous volcanism, and that the latter accumulated in the declining stage of shield building phase. MCDOUGALL and DUNCAN (1980) concluded from K-Ar dating studies on oceanic islands that the shield building is

Table 1. Paleomagnetic results.

Site	<i>N</i>	<i>J</i> (A/m)	Demag. level (mT)	Direction's				VGP's		
				Dec. (deg.)	Inc. (deg.)	κ	α_{95} (deg.)	Lat. (°N)	Long. (°E)	<i>S_w</i> (deg.)
B	10	1.22	10	186.8	5.2	330.3	2.6	-80.2	84.8	3.5
C	5	0.55	15	183.1	10.0	19.2	17.9	-84.4	74.3	14.8
D	8	1.52	10	180.0	39.9	102.8	5.4	-77.1	221.0	7.9
E	9	0.72	10	205.0	28.6	118.8	4.7	-65.0	146.2	6.6
F	7	5.31	5	349.9	13.2	230.1	3.9	70.7	189.2	4.3
G	8	1.06	10	349.9	3.9	136.2	4.7	74.6	179.8	5.5
H	9	2.06	20	177.2	25.3	113.5	4.8	-85.5	258.4	6.6
J	4	6.49	10	185.1	19.2	35.9	15.5	-85.0	132.9	11.3
K	5	5.65	20	175.4	9.1	26.5	15.1	-83.1	359.3	12.6
L	9	1.76	5	181.0	17.4	203.0	3.0	-88.7	90.6	4.7
M	4	2.59	5	2.4	-6.0	695.7	3.4	32.8	240.6	2.4
N	10	2.66	5	169.5	24.6	102.3	4.7	-79.2	293.0	6.9
O	13	7.79	5	8.3	-3.7	96.4	4.2	78.6	267.8	6.5
P	5	3.80	5	6.1	-13.6	75.7	8.8	83.3	286.2	7.6
R1	31	6.41	15	346.1	-14.9	131.1	2.2	76.1	138.9	5.8
R2	12		30	10.1	-16.8	55.5	5.8	80.0	305.2	8.9
R3	5		15	352.1	-19.5	121.3	6.9	82.2	128.2	6.1
T	5	4.78	20	185.4	39.6	358.6	4.0	-76.3	199.5	4.2
U	9	1.48	5	172.6	28.5	84.9	5.6	-81.0	273.3	7.8
V	9	6.35	5	351.4	13.0	818.3	1.8	71.6	193.0	2.3
W	10	4.76	10	348.9	17.1	213.0	3.3	68.5	189.8	4.6
X	8	1.98	30	193.6	27.1	205.3	3.8	-75.9	151.4	5.0
Y	5	2.05	20	190.3	15.4	79.9	8.6	-79.6	121.1	7.4
Z1	5	4.64	30	180.5	2.3	82.8	8.4	-81.4	44.3	7.0
Z2	7	2.67	30	174.4	18.6	28.1	11.5	-84.5	312.6	12.7
BA	12	5.16	5	167.5	27.7	622.2	1.8	-76.8	287.7	2.9
BB	7	9.00	5	176.9	6.4	336.7	3.2	-82.8	15.6	3.5
BC	6	6.07	5	173.6	14.8	73.3	7.8	-83.3	329.9	7.7
BD	6	3.67	5	175.1	16.7	352.7	3.6	-85.0	324.7	3.5
BE	7	2.25	20	354.4	-30.6	352.2	3.2	82.3	79.5	3.9
BF	6	1.16	30	17.0	35.1	361.9	3.5	56.4	250.9	4.0
BG	6	3.95	5	3.5	-16.1	264.2	4.1	86.2	287.3	4.1
BH1	6	7.55	20	199.3	34.7	190.9	4.8	-69.1	159.8	5.5
BH2	9	3.51	20	179.1	16.9	35.2	8.7	-88.6	2.3	11.2
BJ	8	3.22	10	183.9	11.6	287.7	3.2	-84.5	86.1	3.8
BK	8	1.10	10	188.6	44.3	72.7	6.5	-71.8	195.5	10.0

N, number of subsamples; *J*, intensity of NRM; Demag. Level, optimum demagnetizing field intensity; Dec., declination; Inc., inclination; κ , precision parameter of FISHER (1953); α_{95} , 95% confidence semiangle about mean direction; *S_w*, within-site angular dispersion.

Fig. 3. Mean directions of remanent magnetization after AF demagnetization for 36 sites.

Fig. 4. Virtual geomagnetic pole (VGP) positions. Equal-area projection to a portion of the northern hemisphere. Solid (open) symbols refer to normal (reversed) polarity.

Table 2. K-Ar ages of volcanic rocks from Hiva-Oa.

Sample	K		Rad ^{40}Ar ($\times 10^{-8}$ cm 3 STP/g)	Rad ^{40}Ar Total ^{40}Ar (%)		Age (m.y.)
	(%)					
E3	1.627	1.585	15.22	16.0		2.44 ± 0.08
G5	2.814	2.690	18.93	87.7		1.77 ± 0.05
M2	1.062	1.059	11.30	31.7		2.74 ± 0.07
N1	1.478	1.486	13.05	38.2		2.27 ± 0.06
O3	0.863	0.872	8.473	30.0		2.51 ± 0.07
R7	1.951	1.950	13.45	82.9		1.77 ± 0.05
R28	1.685	1.610	11.36	76.9		1.77 ± 0.05
BB1	1.195	1.179	8.627	46.8		1.87 ± 0.05
BF5	4.178	4.174	31.32	85.7		1.93 ± 0.05
BH4	1.123	1.123	8.037	59.5		1.84 ± 0.05
BH8	1.320	1.336	12.70	43.2		2.46 ± 0.06
73-27*	1.979	1.996	14.63	14.0		1.89 ± 0.15
73-27*	1.979	1.996	14.99	10.5		1.94 ± 0.11
73-28*	1.960	1.943	12.35	69.4		1.63 ± 0.03
73-29*	1.640	1.630	12.01	75.1		1.89 ± 0.03
73-31*	2.133	2.131	13.46	68.0		1.63 ± 0.03
73-32*	1.030	1.045	10.29	63.2		2.55 ± 0.06
73-32*	1.030	1.045	10.24	62.3		2.54 ± 0.06
73-33*	2.366	2.341	18.71	78.4		2.04 ± 0.04
73-34*	1.102	1.099	7.569	38.3		1.77 ± 0.04

*DUNCAN and McDOUGALL (1974): K-Ar ages were recalculated with refined constants; $\lambda_e = 0.581 \times 10^{-10}$ yr $^{-1}$. $\lambda_\beta = 4.962 \times 10^{-10}$ yr $^{-1}$. $^{40}\text{K}/\text{K} = 1.167 \times 10^{-2}$ at % (STEIGER and JAGER, 1977).

short lived, commonly less than 1 m.y. in duration. Actually, the shield building stage of volcanism at Nuku-Hiva in the same Marquesas Islands was reported to be as relatively short as 0.4 m.y. (DUNCAN and McDOUGALL, 1974). Our obtained period of the shield building at Hiva-Oa is also short at 0.3 m.y. (2.74–2.44 m.y.). In Table 2, it seems that the K contents of the samples having ages in the range of 2.04–1.63 m.y. are comparatively higher than those in the shield building stage of 2.74–2.44 m.y. This implies the fact that the volcanism become more alkaline in the declining stage of shield building.

4. Discussion and Conclusions

Reliability of paleomagnetic data of Hiva-Oa is ascertained through both AF and thermal demagnetizations, presence of normal and reversed polarity and their consistency with geomagnetic time scale. These data are suitable to investigate PSV in Pacific region.

It is difficult to determine a minimum age range of paleomagnetic data which is needed to obtain meaningful PSV value. Since most of the paleomagnetic studies that have been made for the investigation of PSV generally cover only a part of the

Fig. 5. Diagram of the geomagnetic polarity vs. K-Ar ages for volcanic rock samples. Solid (open) circles indicate samples of normal (reversed) polarity. Shaded pattern represents periods of normal polarity (MANKINEN and DALRYMPLE, 1979).

Brunhes polarity chron, it is likely that no more than one tranquil or noisy period which are 0.2–0.6 m.y. long should be represented. In order to estimate PSV value fully and effectively, it appears to be necessary to use paleomagnetic data distributed over a very long period, such as several millions of years (MCELHINNY and MERRILL, 1975). Recently HEKI (1983), however, pointed out that meaningful estimates of PSV can be obtained at least over the time interval of more than a few times 10^4 years. Since the interval of paleomagnetic data from Hiva-Oa is longer by two orders than 10^4 years (7×10^5 years), our estimate of PSV is obviously meaningful.

Paleomagnetic data used to estimate PSV value are required to be random in time. If lava flows were produced during a short period, angular dispersion should not represent a value of complete secular variation, and should be biased toward the lower value. It appears, based on geochronological data, that lava eruption and dyke intrusion did not occur during some short periods.

Angular dispersion was calculated from paleomagnetic results for 32 out of the 36 sites. In order to maintain statistical uniformity, four sites with a greater α_{95} than 9.0° were excluded from dispersion analysis (ISAACSON and HEINRICHS, 1976). Mean VGP position was 88.1° N and 117.9° W with an α_{95} of about 4.2° for 32 poles. The geographic pole is contained within the 95% confidence limit circle. Total angular

dispersion S_t is defined with respect to VGP as

$$S_t^2 = \frac{1}{N-1} \sum_{i=1}^N \Delta_i^2,$$

where N is number of poles, Δ_i is angle between i -th pole and the mean pole. S_t and the dispersion due to secular variation (S_f) are related as

$$S_t^2 = S_f^2 + \frac{S_w^2}{n},$$

where S_w is the average within-site dispersion due to experimental errors and n is the average number of subsamples per site. Dispersion due to effects of local anomalies was not considered. The 95% confidence limits of S_f are calculated after COX (1969). The S_f of Hiva-Oa was estimated to be 13.6° with respect to mean VGP, and its upper and lower limits were 16.4° and 11.6° , respectively. Since it is generally recognized that the averaged geomagnetic field can be represented by a geocentric axial dipole field, dispersion analysis was also made with respect to the geographic pole on the assumption that true mean VGP is located on the geographic pole. The S_f was 13.8° with respect to geographic pole, and its upper and lower limits were 16.6° and 11.8° , respectively. These results are summarized in Table 3.

The angular dispersion value of Hiva-Oa (13.8°) is consistent with the values predicted by secular variation models (Fig. 6); e.g., Model C (COX, 1962), Model D (COX, 1970) and Model F for the past 5 m.y. (MCFADDEN and MCELHINNY, 1984). It is concluded that low secular variation as reported on the Hawaiian Islands did not exist in the Marquesas Islands region at least during the period from 2.74 to 1.63 m.y.

In Hawaii, DOELL and COX (1971, 1972) reported angular dispersion of 10.8° . MCWILLIAMS *et al.* (1982) showed that the VGP angular dispersion of Hawaiian

Table 3. Dispersion statistics.

Data set	with respect to mean VGP								with respect to geographic pole				
	N	Lat.	Long.	α_{95}	S_t	S_f	S_u	S_l	S_t	S_f	S_u	S_l	S_w
Combined	32	88.1°N	117.9°W	4.3	13.7	13.6	16.4	11.6	13.9	13.8	16.6	11.8	5.7
Normal	13	81.6°N	150.1°W	7.2	13.8	13.7	18.5	10.9	16.4	16.3	22.0	12.9	5.1
Reverse	19	86.6°S	179.2°E	5.0	11.9	11.7	15.0	11.1	12.4	12.2	15.6	10.0	6.1

N , number of sites; Lat., Long., latitude and longitude of mean VGP; α_{95} , 95% confidence semiangle about mean; S_t , total angular dispersion; S_f , dispersion due to the paleosecular variation; S_u , S_l , upper and lower confidence limits of S_f at 95% level; S_w , average of within-site angular dispersion.

Combined; data set which contains all sites with α_{95} less than 9° .

Normal; data set which contains only sites of normal polarity.

Reverse; data set which contains only sites of reverse polarity with α_{95} less than 9° .

Fig. 6. Virtual geomagnetic pole angular dispersions covering the past 5 m.y. in the Pacific Ocean: Galapagos (DOELL and COX, 1972), Society (DUNCAN, 1975), Easter (ISAACSON and HEINRICHS, 1976), Pagan (U.S.-JAPAN P. C. P. M., 1975), Hawaii (MCWILLIAMS *et al.*, 1982), Model C (COX, 1962), Model D (COX, 1970), and Model F (MCFADDEN and MCELHINNY, 1984).

Brunhes age lava is 11.2° , which is also significantly lower than that expected in areas of a similar latitude.

Low PSV values on Kauai Island and Oahu Island suggest that the Pacific non-dipole low persisted during the past 5 m.y. (DOELL, 1972a, 1972b). ISAACSON and HEINRICHS (1976) pointed out that angular dispersion of Easter Island is lower than the predicted value, and the Pacific non-dipole low extends to the southeast Pacific. However, the PSV values on Galapagos (DOELL and COX, 1972) and the Society Islands (DUNCAN, 1975) are in accordance with values predicted by secular variation models, suggesting that the Pacific non-dipole low has not extended to these region.

MCELHINNY and MERRILL (1975) described that low angular dispersion on Hawaii may have been due to unrepresentatively dense sampling of lavas which erupted during a short time interval and the Pacific non-dipole low should be a

relatively recent phenomenon which is probably limited to the Holocene. COE *et al.* (1978) pointed out that sizable non-dipole fields have existed in the region of Hawaii at various times during the Holocene epoch and perhaps earlier. The angular dispersion of Easter Island was obtained from Brunhes polarity chron basalts with age younger than 0.24 m.y. It may be rather questionable that time interval of 0.24 m.y. was sufficient to obtain a complete secular variation value.

It is likely that the Pacific non-dipole low does not exist at all, or should be restricted regionally to the Hawaiian Islands and chronologically to the recent period.

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REFERENCES

- COE, R. S., S. GROMME, and E. A. MANKINEN, Geomagnetic paleointensities from radiocarbon-dated lava flows on Hawaii and the question of Pacific non-dipole low, *J. Geophys. Res.*, **83**, 1740-1756, 1978.
- COX, A., Analysis of the present geomagnetic field for comparison with paleomagnetic results, *J. Geomag. Geoelectr.*, **13**, 101-112, 1962.
- COX, A., Confidence limits for the precision parameter k , *Geophys. J. R. Astr. Soc.*, **18**, 545-549, 1969.
- COX, A., The latitude dependence of the angular dispersion of the geomagnetic field, *Geophys. J. R. Astr. Soc.*, **20**, 253-269, 1970.
- COX, A. and G. B. DALRYMPLE, Statistical analysis of geomagnetic reversal data and the precision of potassium-argon dating, *J. Geophys. Res.*, **72**, 2603-2614, 1967.
- DOELL, R. R., Paleomagnetism of lava flows from Kauai, Hawaii, *J. Geophys. Res.*, **77**, 862-876, 1972a.
- DOELL, R. R., Paleosecular variation of the Honolulu volcanic series, Oahu, Hawaii, *J. Geophys. Res.*, **77**, 2129-2138, 1972b.
- DOELL, R. R. and A. COX, Pacific geomagnetic secular variation, *Science*, **171**, 248-254, 1971.
- DOELL, R. R. and A. COX, The Pacific geomagnetic secular variation anomaly and the question of lateral uniformity in the lower mantle, in *The Nature of the Solid Earth*, edited by E. C. Robertson, pp. 245-284, McGraw-Hill, New York, 1972.
- DUNCAN, R. A., Paleosecular variation at the Society Islands, French Polynesia, *Geophys. J. R. Astr. Soc.*, **41**, 245-254, 1975.
- DUNCAN, R. A. and I. MCDUGALL, Migration of volcanism with time in the Marquesas Islands, French Polynesia, *Earth Planet. Sci. Lett.*, **21**, 414-420, 1974.
- FISHER, R. A., Dispersion on a sphere, *Proc. R. Soc., Ser. A.*, **217**, 295-305, 1953.
- FISK, H. W., Isopors and isoporic movements, *Bull. Int. Geod. Geophys. Union*, No. 8, 280-292, 1931.
- FLEMING, J. A., (Ed.), *Physics of the Earth, 8, Terrestrial Magnetism and Electricity*, McGraw-Hill, New York, 1939.
- HEKI, K., Paleomagnetic study of the Higashi-Izu Monogenic Volcano Group and pyroclastic flow deposits in Kagoshima Prefecture: Paleosecular variation during the last 40,000 years in Japan, *J. Geomag. Geoelectr.*, **35**, 383-390, 1983.

- ISAACSON, L. B. and D. F. HEINRICH, Paleomagnetism and secular variation of Easter Island basalts, *J. Geophys. Res.*, **81**, 1476–1482, 1976.
- JARRARD, R. D. and D. A. CLAGUE, Implications of Pacific island and sea-mount ages for the origin of volcanic chains, *Rev. Geophys. Space Phys.*, **15**, 57–75, 1977.
- MANKINEN, E. A. and G. B. DALRYMPLE, Revised geomagnetic polarity time scale for the interval 0–5 m.y. B.P., *J. Geophys. Res.*, **84**, 615–626, 1979.
- MCDUGALL, I. and R. A. DUNCAN, Linear volcanic chains recording plate motion?, *Tectonophysics*, **63**, 275–295, 1980.
- MCELHINNY, M. W. and R. T. MERRILL, Geomagnetic secular variation over the past 5 m.y., *Rev. Geophys. Space Phys.*, **13**, 687–708, 1975.
- McFADDEN, P. L. and M. W. MCELHINNY, A physical model for paleosecular variation, *Geophys. J. R. Astr. Soc.*, **78**, 809–830, 1984.
- McWILLIAMS, M. O., R. T. HOLCOMB, and D. E. CHAMPION, Geomagnetic secular variation from ¹⁴C-dated lava flows on Hawaii and the question of the Pacific non-dipole low, *Phill. Trans. R. Soc. Lond. A*, **306**, 211–222, 1982.
- STEIGER, R. H. and E. JAGER, Subcommittee on geochronology: Convention on the use of decay constants in geo- and cosmo-chronology, *Earth Planet. Sci. Lett.*, **36**, 259–362, 1977.
- TERASHIMA, S., Determination of sodium, potassium, magnesium, calcium, manganese and iron in the silicate rocks and terrestrial water by atomic absorption spectrophotometry, *Bull. Geol. Surv. Jpn.*, **21**, 693–707, 1970 (in Japanese).
- U.S.-JAPAN PALEOMAGNETIC COOPERATION PROGRAM IN MICRONESIA, Paleosecular variation of lavas from the Marianas in the western Pacific Ocean, *J. Geomag. Geoelectr.*, **27**, 57–66, 1975.
- VESTINE, E. H. and A. B. KAHLE, The small amplitude of magnetic secular change in the Pacific area, *J. Geophys. Res.*, **71**, 527–530, 1966.
- VESTINE, E. H., L. LAPORTE, C. COOPER, I. LANGE, and W. C. HENDRIX, *Description of the Earth's Main Magnetic Field and Its Secular Change, 1905–1945*, Carnegie Inst. Wash. Publ., 578 pp., 1947.