Geomagnetic Secular Variation from ^{14}C-Dated Lava Flows on Hawaii and the Question of the Pacific Non-Dipole Low [and Discussion]

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Geomagnetic secular variation from ^{14}C-dated lava flows on Hawaii and the question of the Pacific non-dipole low

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New palaeomagnetic data from 106 ^{14}C-dated lava flows ranging in age from 200 to 31000 years B.P. yield an estimated angular dispersion value of 9.5°. These data and other new geological information permit a more precise estimate of the time interval recorded by lava flow sequences previously used to measure palaeosecular variation in Hawaii. When weighted according to revised estimates of recording interval, the combined Brunhes lava sequences yield an angular dispersion of $11.2^{+0.9}_{-0.8}$ degrees, still lower than that predicted by global models of the secular variation. Several of the lava flow sequences previously thought to have recorded quiet intervals of geomagnetic behaviour actually record only very short time intervals.

INTRODUCTION

A considerable amount of research and debate has centred about the existence and duration of anomalously low geomagnetic secular variation in the north-central Pacific Ocean region. The primary evidence for low secular variation comes from analyses of geomagnetic and palaeomagnetic data from Hawaii. This paper integrates new palaeomagnetic data from ^{14}C-dated Hawaiian lava flows with previously available data, providing constraints on the amplitude and duration of geomagnetic secular variation.

As a prelude to the presentation and analysis of new palaeomagnetic data, a brief chronological summary of the previously available data and interpretations is presented. Doell & Cox (1963) studied historic lavas from Hawaii and concluded that the low geomagnetic secular variation observed in the Pacific from magnetic observatory data (Fisk 1931) had extended at least as far back as A.D. 1750. Doell & Cox (1965) conducted a detailed study of five sequences of prehistoric lava flows on the island of Hawaii and made the suggestion that low secular variation has been a relatively permanent feature in the Pacific, having lasted for at least the last several hundred thousand years.

Yukutake & Tachinaka (1968) constructed maps of the non-dipole field back to A.D. 1650 based upon spherical harmonic analyses of historical observatory records. These maps indicated large non-dipole fields in the central Pacific at A.D. 1700 and 1650, in conflict with the interpretation of Doell & Cox (1963, 1965). However, Doell & Cox (1972) considered the A.D. 1700 and 1650 analyses of Yukutake & Tachinaka to be unreliable, as the spherical harmonic coefficients were constrained by relatively few reliable observatory data. Doell & Cox (1972) consider the 1829 analysis (by Gauss) to be the oldest reliable spherical harmonic representation of the field; maps of the non-dipole field for that year and subsequent years show very low non-dipole fields in the Pacific region.

With the addition of new data from Hawaii (see, for example, Doell 1969, 1972*a*, *b*) and progressively more detailed analyses (Cox & Doell 1964; Doell & Cox 1971, 1972) an internally consistent picture of anomalously low geomagnetic secular variation emerged. This led to speculations on lateral variations in core–mantle interface temperature, topography and composition (see, for example, Cox & Doell 1964; Hide 1967; Doell & Cox 1971, 1922; Cox & Cain 1972).

As the body of evidence from Hawaii suggesting a sustained interval of low geomagnetic secular variation accumulated, analogous studies were conducted elsewhere in the Pacific (Galapagos (Doell & Cox 1972), Easter Island (Isaacson & Heinrichs 1976), Society Islands (Duncan 1975)). These studies revealed secular variation consistent with a 'standard' model of global variation based upon modern dipole and non-dipole fields (see, for example, Cox 1970) and hence constrained the region of anomalously low secular variation to correspondingly smaller regions of the Pacific. The tendency for angular dispersion, and hence secular variation estimates, to be lower in younger lava sequences had been noted by this time (Bingham & Stone 1972; Doell & Dalrymple 1973; Duncan 1975). This raised the fundamental issue of whether sequences of lava flows are fully representative samples of the ancient geomagnetic field (McElhinny & Merrill 1975). This problem and its constraints on interpretation of secular variation were recognized and clearly stated in the earlier studies of Cox & Doell (1964) and Doell & Cox (1965, 1971, 1972). They considered the data from young lava flow sequences on Hawaii to be representative of time intervals long enough to sample secular variation adequately; however, McElhinny & Merrill (1975), Duncan (1975) and Coe *et al.* (1978) adopted a different view, namely that at least some of the lava sequences do not represent a significant sampling of the geomagnetic field. In their interpretation, the interval of low secular variation in the Pacific would either be restricted to Holocene time, or may not exist at all.

At the focus of the debate is an estimate of the time interval recorded by a sequence of lava flows. In the absence of radiometric data, the original estimates of Doell & Cox were based upon geologically reasonable rates of magma supply and eruption frequency in Hawaii. However, understanding of volcanic processes on Hawaii has improved significantly since the time of these analyses, especially since many new ^{14}C age determinations of flows from Mauna Loa and Kilauea have become available.

NEW PALAEOMAGNETIC RESULTS FROM ^{14}C-DATED LAVAS

Palaeomagnetic data have been reported recently from 106 Kilauea and Mauna Loa flows spanning the interval 200–31000 years B.P. (Coe *et al.* 1978; Holcomb *et al.* 1982; McWilliams *et al.* 1982). The data distribution is markedly non-uniform in time, with a strong bias toward younger ages. Younger flows have concealed older flows to such an extent that more than 90 % of the surface area surrounding Kilauea is covered by flows less than 1000 years old (Holcomb 1980). Complete sampling and laboratory details are given in Holcomb *et al.* (1982) and McWilliams *et al.* (1982). At most sites a minimum of 12 individually oriented core samples were drilled and oriented by Sun and magnetic compass. Laboratory analysis consisted of alternating field (a.f.) treatment of one or two specimens from each site in peak fields of 5–80 mT in 5 or 10 mT steps. The a.f. demagnetization experiments invariably yielded vector path segments with excellent linearity in the 20–50 mT range. Initial flow mean directions were calculated by averaging magnetization directions from all samples after demagnetization in appropriate peak alternating fields. A one-step filtering procedure was applied to this initial average, whereby individual sample directions differing by more than two standard deviations from the initial mean were excluded, and a final mean direction was then calculated by averaging the remaining specimen directions. The resulting mean flow directions are extremely well grouped, having an average k (precision parameter) of 642, calculated from an average of 11.9 sample mean directions. This corresponds to an average α_{95} of about 1.6°. Details of the

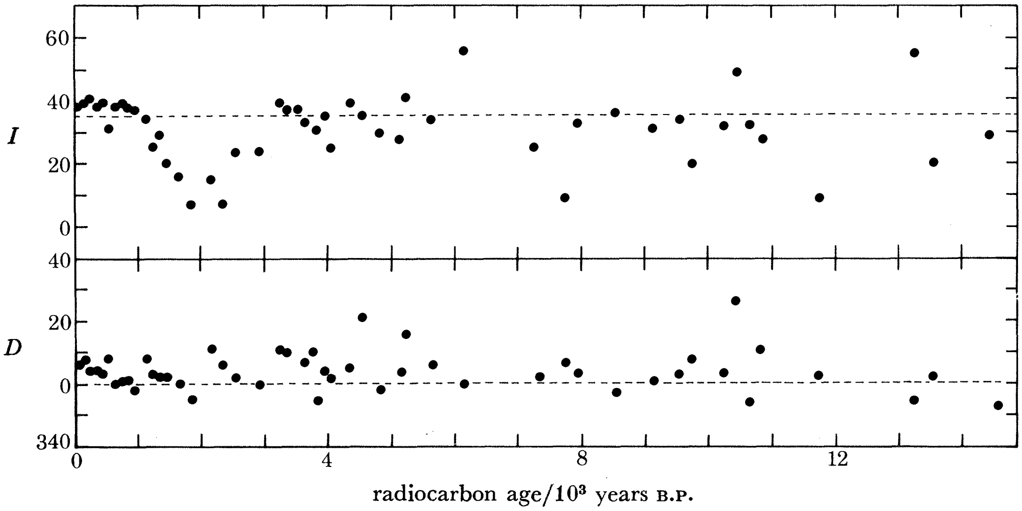

FIGURE 1. Inclination (I) and declination (D) plotted against ^{14}C age for Hawaii. The data of Coe *et al.* (1978), Holcomb *et al.* (1982) and McWilliams *et al.* (1982) have been thinned by using a 100 year non-overlapping window. Dashed lines represent expected axial geocentric dipole field directions.

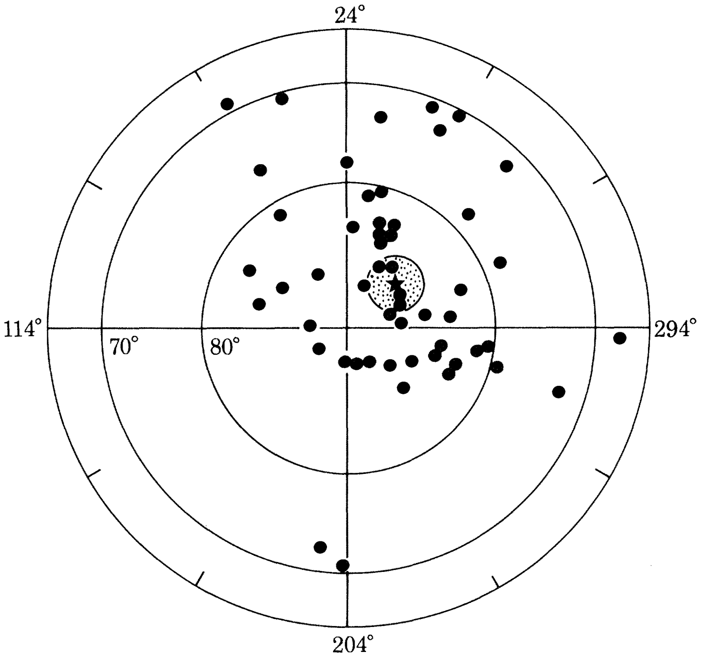

FIGURE 2. Virtual geomagnetic poles calculated from the directional data of figure 1. Only the uppermost 15° of the stereographic projection is shown. V.g.p. data have been rotated so that the sampling site lies towards the bottom of the diagram to illustrate the 'far-sided, right-handed' nature of the distribution. Star indicates mean v.g.p.; stippled region is α_{95} circle.

relative importance of the various sources of within-flow error are discussed by Holcomb *et al.* (1982).

The temporal distribution of these new data is biased toward younger (2000 years B.P. and less) ages. If unit weight were given to individual flows, calculating an angular dispersion from this data set would incorrectly bias an estimate of secular variation because of the domination of these younger flows. The data set must therefore be thinned to produce field directions representing equally spaced time windows. The choice of thinning window is potentially quite important, for too short a window might unduly bias the results toward the numerous flows in the range 0–1000 years B.P., whereas too long a window might tend to average secular variation within the interval and would therefore yield an underestimate of angular dispersion. Thinning the data with a 100, 250 or 500 year non-overlapping window produces 54, 43 or 28 mean directions, respectively. Significant gaps are present in the record before 10000 years B.P. in all cases.

TABLE 1. V.G.P. AVERAGES AND DISPERSIONS, INDIVIDUAL BRUNHES LAVA SERIES

series	λ	ϕ	N	R	K	S_l	S	S_u
(1) ^{14}C, 100 years	85.6	334.5	54	53.270	73	8.5	9.5	11.0
(2) ^{14}C, 250 years	85.3	344.2	42	41.447	74	8.2	9.4	11.0
(3) ^{14}C, 500 years	85.4	350.6	28	27.599	67	8.4	9.9	12.0
(4) Kahuku	79.6	336.2	29	28.250	37	11.3	13.3	16.2
(5) Ninole	84.6	21.7	25	24.580	57	9.0	10.7	13.3
(6) Pololu	82.6	313.5	29	28.690	90	7.2	8.5	10.3
(7) Kiekie	79.8	223.5	11	10.886	88	6.7	8.6	12.0
(8) Honolulu	86.4	20.9	25	24.679	75	7.9	9.4	11.7
(9) Kau†	81.5	61.3	54	53.914	617	2.8	3.2	3.7
(10) Kau‡	81.5	61.3	5	4.997	1334	1.6	2.2	3.6
(11) Hamakua†	72.4	243.8	11	10.970	313	3.6	4.6	6.4
(12) Hamakua‡	72.4	243.8	1	1.000	—	—	—	—
(13) Puna	86.9	226.9	44	43.811	227	6.2	5.3	4.6

Notes: λ, ϕ, latitude and longitude of mean v.g.p.; N, number of v.g.ps averaged; R, vector resultant; K, estimate of precision parameter, S, angular standard deviation; S_l, S_u, lower and upper limits on S at 95% level.

† As originally published.

‡ With reduced weighting (see text for details).

The windowed declination and inclination values are plotted in figure 1 and transformed to virtual geomagnetic poles (v.g.ps) in figure 2. The general style of directional and v.g.p. variation is reminiscent of within-section variation of the Kahuku, Ninole and Pololu volcanic series of Hawaii (Doell & Cox 1965). Figure 1 illustrates the tendency of inclination values to be less than the 35° predicted by the axial geocentric dipole model, while the declination values tend to be slightly greater (eastward) than the 0° predicted. These tendencies produce a significant bias in the v.g.p. locations, as shown in figure 2. The overall distribution of v.g.ps is not markedly skewed or distorted, but the mean of v.g.ps departs significantly from the geographic pole, and is displaced to the opposite side of the geographic pole from the sampling locality and rotated slightly clockwise about the sampling locality. This 'far-sided, right-handed' tendency has been noted in other lava flow sequences in Hawaii (see, for example, Doell & Cox 1965) and from elsewhere in the world when sampling localities are reduced to a common site longitude (Wilson 1972; McElhinny & Merrill 1975).

Estimates of the overall v.g.p. dispersion of the thinned data set range from 8.2° to 12.0°, less than the 15° predicted by model D of Cox (1970) assuming an 11° dipole wobble. This is true regardless of whether a 100, 250 or 500 year window is used to thin the data (table 1). The difference is significant at the 95% confidence level, using the criteria of Cox (1969). This observation, when coupled with the general style of directional variation and the far-sided, right-handed nature of v.g.p. distribution already noted, leads to the conclusion that the new data from Hawaii show group characteristics virtually identical to some of the previously sampled lava sequences (see, for example, Doell & Cox 1965). The fundamental difference is that detailed radiometric age control is available for the first time.

Comparison with other data from Hawaii

The next step in analysis is to compare the new data from ^{14}C-dated flows with the existing data from Brunhes-age lava flow sequences. The data used for comparison are the Puna, Kahuku, Ninole, Hamakua and Pololu volcanic series of Doell & Cox (1965), the Kau series of Doell (1969) and the Kiekie and Honolulu series of Doell (1972*a*, *b*). The reader will recall that it was an analysis of data from these lava flow sequences that led Doell & Cox to suggest that secular variation in the Pacific was anomalously low for as long as the past 700000 years. They believed that each of the sequences studied represented a sampling of the geomagnetic field long enough to adequately record secular variation. The reader will also recall that other workers (e.g. McElhinny & Merrill 1975; Duncan 1975; Coe *et al.* 1978) have suggested that some of these sequences (notably the Puna and Kau series) do not record anomalously low secular variation sampled for a long time, but rather record normal (?) secular variation sampled for a much shorter time.

In an attempt to resolve some of these questions, Cox (1975) subsequently produced a model of secular variation for Hawaii incorporating the data from these and other volcanic series. In this model, the lava flow sequences in question are still interpreted as having recorded time intervals long enough to sample secular variation, but the behaviour of the geomagnetic field was characterized by 'quiet' and 'noisy' times, represented by sequences exhibiting lower and higher angular dispersion values, respectively. Whether Cox (1975) or McElhinny & Merrill (1975) and Coe *et al.* (1978) are correct depends therefore on the time interval recorded by these 'quiet' sequences, as was clearly stated by Doell & Cox (1965) and Cox (1975). Fortunately, new palaeomagnetic data, ^{14}C ages, and geological mapping on Hawaii allow for the first time a relatively accurate estimation of the time intervals of interest.

The procedure that will be followed is: (1) to consider each of the Puna, Kau, Kahuku, Ninole, Hamakua, Pololu, Kiekie and Honolulu series in turn, attempting to estimate the time interval recorded by each, (2) to weight each lava flow sequence according to the estimated amount of time recorded, (3) to produce a more or less evenly distributed sample of geomagnetic variation (albeit a discontinuous one) by collecting together the properly weighted data sets and (4) to calculate overall dispersion data for this combined data set, and compare this value with previous secular variation models. Palaeomagnetic data from each of the lava flow sequences are compiled in table 1.

Puna series

Detailed geological mapping (Holcomb 1980) has shown that the Lua Pele and Hale O Ai-laau vents at Kilauea produced numerous young flows during a sustained eruption that built a distinct lava shield in the summit region of Kilauea. Holcomb *et al.* (1982) showed that the uppermost four flows in the Puna series sampled by Doell & Cox (1965) are probably products of the Lua Pele events. These four flows lie above a thin tuff layer in the Uwekahuna

Bluff area of Kilauea crater; the next 15 flows beneath this tuff layer are probably products of the Hale O Ai-laau vent. When combined with the available ^{14}C evidence, these new geological data indicate that most of the Puna series sampled by Doell & Cox (1965) record a 200 year interval from about 300 to 500 years B.P., in contrast to the 7000–30000 year interval previously estimated. If this interpretation is adopted, the data of Doell & Cox (1965) agree with the new ^{14}C data, when the Puna series are split into their respective upper and lower parts by the tuff layer. Obviously, if the Puna series record only 200 years of geomagnetic history, including these data in an estimate of angular dispersion might incorrectly bias the result, as had been suggested. One option would be to divide the section into the intervals proposed by Holcomb *et al.* (1982), average all flows in each interval, and use this average as a single datum in the final dispersion analysis. However, this same time interval (300–500 years B.P.) is adequately recorded by the ^{14}C-dated flows of figure 1, and therefore their inclusion would constitute repeated sampling of the time period. The Puna series data will therefore not be used in final dispersion analysis.

Kau series

The Kau volcanic series sampled by Doell (1969) lies above the widespread Pahala Ash, which is about 10000 years old (Rubin & Berthold 1961). As the Kau series must therefore be younger than about 10000 years B.P., the Kau data should be compared with the new ^{14}C data to judge the time interval recorded by this sequence of flows. Holcomb *et al.* (1982) conclude that, although the ages are not well constrained, best estimates for the Kau series are the 600 year interval from 2300 to 2900 years B.P. (preferred) or the 500 year interval from 1500 to 2000 years B.P. (possible). However, the Kau series may be older than 2300–2900 years B.P., and in this case an absolute determination of the age is made difficult by the sparse data before 2900 years B.P. However, if the Kau series is indeed older than 2900 years B.P., the time interval recorded is probably not longer than 1000 years and is probably less. This is evident by inspecting figure 1 and noting that the Kau series data can only fit (*a*) where the ^{14}C-dated flows have similar directions, or (*b*) where there are gaps in the record. Since the data from 2900–10000 years B.P. show considerable directional variation, it may be concluded that the Kau series data probably do not represent a time interval long enough to provide a representative sample of secular variation.

Again the problem is raised of whether to include the Kau series data in final dispersion analysis. If the age range is 2300–2900 or 1500–2000 years B.P., as suggested by Holcomb *et al.* (1982), then including these data would constitute repeated sampling of the same time interval and should be avoided. If, however, the Kau series are older, it might be safe to include these data, albeit with significantly reduced weighting. The choice is considered further in a later section.

Kahuku series

The 29 flows of the Kahuku volcanic series studied by Doell & Cox (1965) lie stratigraphically beneath the Pahala Ash, and the uppermost flow sampled is in contact with the ash. The Kahuku lavas must therefore be older than about 10000 years, and thus will not significantly duplicate the record of secular variation provided by the ^{14}C-dated lavas. Magnetization directions vary considerably within the sampled section and display marked serial correlation (figure 16 of Doell & Cox 1965). There can be little doubt that the directions of magnetization from the Kahuku series record geomagnetic secular variation over a significant time interval. By comparing the style of directional variations in the Kahuku series with the ^{14}C-dated record and making the assumption that rates of secular variation did not change drastically before and after deposition of the Pahala Ash at 10000 years B.P., it is estimated that the Kahuku series represent perhaps 5000–7500 years of geomagnetic recording. It would therefore appear to be correct to include the entire section in the final dispersion analysis of secular variation. Clearly, successive flows in some parts of the record (for example flows 122–125 of Doell & Cox (1965)) may not represent independent time samples of the geomagnetic field. However, in the absence of additional ^{14}C or stratigraphic control, conservative analysis suggests that unit weighting be given to individual flows, as was done originally by Doell & Cox (1965). The consequences of this approach are outlined in the concluding section.

Ninole series

As with the Kahuku series, it is unlikely that the Ninole series will seriously duplicate the ^{14}C-dated secular variation record, as these lavas are more than 10000 years old. For reasons identical to those outlined above, the entire section is considered a valid record and is weighted accordingly.

Hamakua series

As discussed earlier, the Puna and Kau series records display low angular dispersion because in all probability they represent very short (less than 1000 years and probably less than 500 years) time intervals. This conclusion was reached on objective grounds from newly available geological, isotopic and palaeomagnetic data. The Hamakua series data from before 10000 years B.P. present a more difficult problem, as there are no new data that can be used to estimate directly the length of time recorded by the 43 m section that was sampled. The judgements made here are therefore of a more subjective nature.

The angular dispersion of v.g.ps from the Hamakua series record is extremely low ($K = 313$ for the Hamakua series, compared with 57 and 37 for the Ninole and Kahuku series, respectively). Further, little serial correlation is apparent in the record, even by comparison with the Puna series. The observations of Holcomb (1980) and Holcomb *et al.* (1982) demonstrate that thick lava sequences in Hawaii can accumulate in times as short as 300–500 years. These observations, when coupled with the fact that the value of k for the Hamakua series is large and lies between that of the Puna series and the Kau series (both of which have been excluded on the grounds that little time was sampled), make a strong case for weighting the Hamakua series as if it represented only 100–200 years of geomagnetic recording.

Of the three volcanic series whose weightings will later be adjusted downwards (Puna, Kau and Hamakua), the time interval recorded by the Hamakua series is clearly the least well understood. The Hamakua data could indeed represent an extremely 'quiet' geomagnetic record, in the context of Cox (1975). However, this would be the only 'such quiet' record known, and its validity would be that much more questionable. It is at least equally probable that the Hamakua series data represent a short time interval. The consequences of including the Hamakua series as an instantaneous sample or as a much longer sample are considered in the conclusion of this paper.

Pololu series

As with the Kahuku and Ninole series, the Pololu series record displays considerable directional variation in direction and marked serial correlation (figure 19 of Doell & Cox 1965). For the same reasons outlined for the Kahuku and Ninole sections above, the intact Pololu series record is included in final dispersion analysis. Reliable K–Ar ages for the Pololu series lie between 200000 and 300000 years B.P. (McDougall & Swanson 1972) and it is therefore unlikely that the record will duplicate any of the other records from the island of Hawaii.

Kiekie series (*Niihau*) *and Honolulu series* (*Oahu*)

Data have been reported from two other Brunhes-age lava sequences in the Hawaiian chain. These are the Kiekie series on Niihau Island (Doell 1972*a*) and the Honolulu series on Oahu Island (Doell 1972*b*). The Kiekie lavas yield K–Ar ages that lie between 300000 and 700000 years B.P. (G. B. Dalrylmple, in Doell 1972*a*), and have normal polarity directions, except for two flows near the base of the sequence (flows 6 and 7 of Doell 1972*a*). The reversed flows have been excluded from this analysis. Magnetization directions vary by over 20° between some flows; in addition, the data do not appear to show significant serial correlation, although some flows may have been sampled more than once (Doell 1972*a*). By analogy with the lava sequences already discussed, the Kiekie series are included as if they recorded sufficient time to provide an adequate sample of secular variation.

Isotopic ages from the Honolulu series indicate that this sequence is probably much older than the young lava sequences on the island of Hawaii. Individual K–Ar ages range from 30000 to 850000 years B.P., but there is evidence to suggest that the upper part of the series is less than 70000 years in age, while the older part may be about 350000 years old. In any case, all the lavas are almost certainly of Brunhes age. As with the Kiekie lavas, considerable directional variation is apparent, with successive flows in the sequence differing by over 25° in several instances. The data are therefore included in the final dispersion analysis as valid recorders of secular variation.

DISPERSION ANALYSIS

In the preceding section, the ^{14}C, Kahuku, Ninole, Pololu, Kiekie and Honolulu series data were considered to have spanned time intervals long enough to record significant secular variation. The Puna, Kau and Hamakua series were considered to have spanned much shorter time intervals and therefore require modified weighting in the final dispersion analysis. The Puna series are completely represented by the younger parts of the ^{14}C sequence and are therefore excluded. As discussed previously, the best estimates of the age of the Kau series suggest that it may span only 500–600 years. In keeping with the choice of a 100 year thinning window for the ^{14}C-dated flows, the Kau series data are weighted as five successive groups (groups A–E of Holcomb *et al.* 1982), each sampling a 100 year interval. The Hamakua series data are interpreted as having recorded an extremely short time interval and are therefore given unit weighting in the analysis. A summary of the v.g.p. data for each of these data sets is given in table 1.

As an initial estimate of v.g.p. dispersion, we consider the average of all the 'most reliable' lava sequences, i.e. those for which there is less doubt about the recording interval. As mentioned above, these are the ^{14}C, Kahuku, Ninole, Pololu, Kiekie and Honolulu series. Entries 1, 2 and 3 in table 2 describe v.g.p. averages of these volcanic series, which include the ^{14}C series, windowed at 100, 250 and 500 years, respectively. Regardless of which form of the ^{14}C series data is used, the overall angular dispersion remains essentially the same, and ranges from 11.1° to 11.4°.

Since the correct weighting of the remaining data sets (Kau and Hamakua) is debatable, we consider two extreme end-member solutions. At one end the data are weighted according to the preferred scheme described above, i.e. the Kau series is weighted as five independent samples, and the Hamakua is given unit weight. At the opposite extreme the data are weighted as they were originally, i.e. with unit weight given to individual flows. Again, each of the 100, 250 and 500 year ^{14}C series data are considered separately. As entries 4, 5 and 6 of table 2 illustrate, incorporating the Kau and Hamakua series data in preferred form does not change the overall dispersion. Furthermore, incorporating the Kau and Hamakua series data in their original form changes the angular standard deviation values by only about 0.1° (entries 7, 8 and 9 of

TABLE 2. V.G.P. AVERAGES AND DISPERSIONS, COMBINED LAVA SEQUENCES

Combination†	λ	ϕ	N	R	K	S_{l}	S	S_{u}
(1) 1 and 4–8	85.1	333.9	173	169.793	54	10.3	11.1	12.0
(2) 2 and 4–8	84.9	336.2	161	157.968	53	10.4	11.2	12.1
(3) 3–8	84.9	336.6	147	144.117	51	10.6	11.4	12.4
(4) 1, 4–8, 10, 12	85.3	335.6	179	175.671	54	10.3	11.1	12.0
(5) 2, 4–8, 10, 12	85.1	338.0	167	163.846	53	10.4	11.2	12.1
(6) 3–8, 10, 12	85.1	338.5	153	149.995	51	10.6	11.4	12.4
(7) 1, 4–9, 11	86.2	351.3	238	233.470	52	10.6	11.2	11.9
(8) 2, 4–9, 11	86.0	353.8	226	221.650	52	10.6	11.3	12.1
(9) 3–9, 11	86.1	355.6	212	207.808	50	10.7	11.4	12.2

Column headings are explained in table 1.
† Entries in this column refer to table 1.

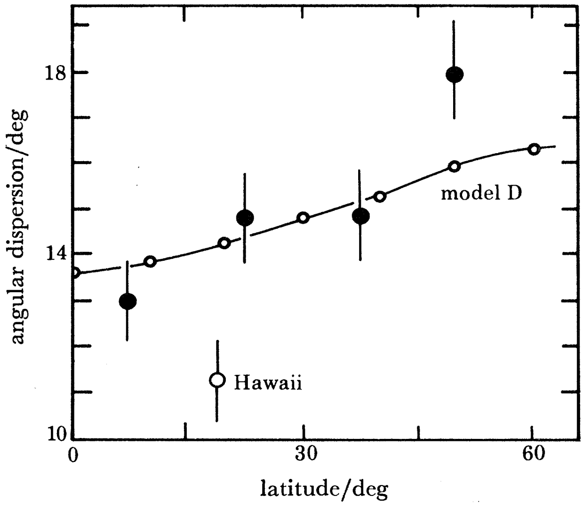

FIGURE 3. Angular dispersion for Hawaii from table 2 compared with global values for the Brunhes Epoch. Solid symbols: angular dispersion averaged over 15° latitude strips, after McElhinny & Merrill (1975). The 16–30° value has been modified to exclude Hawaiian data. Line indicates angular dispersion with latitude as predicted by model D of Cox (1970).

table 2). These observations lead to two important conclusions: (1) overall angular dispersion is essentially unaffected by the choice of either a 100, 250 or 500 year thinning window, and (2) regardless of whether the Kau and Hamakua series data are excluded, included with reduced weighting, or included with unit weight given to individual flows, the overall angular standard deviation remains in the range 10.3° to 12.4°.

In the simplest case, overall dispersion S and geomagnetic field dispersion S_{f} are related by

$$S^2 = S_{\mathrm{f}}^2 + (S_{\mathrm{w}}^2/N),$$

where S_w is the average within-flow dispersion and N the average number of samples per flow. Taking reasonable values for S_w and N to be approximately 4.0° and 12 respectively, the actual field dispersion is smaller than overall dispersion by approximately 0.1°. Therefore, for practical purposes we may consider S_f to lie within the upper and lower limits (S_u, S_l) of S table 2 and we choose for convenience a value of $11.2^{+0.9}_{-0.8}$ as a reasonable value for comparative purposes. This value is not significantly different from the original value of 10.8° inferred by Doell & Cox (1972) nor from the value of $11.8^{+0.9}_{-1.0}$ of McElhinny & Merrill (1975), but it probably does differ slightly from the value of $12.7^{+1.2}_{-1.0}$ found by Coe *et al.* (1978). The only real difference between the results of table 2 and those of Coe *et al.* (1978) is the inclusion of a different set of ^{14}C-dated flows; the other data are essentially the same. Therefore the difference between dispersion values probably results from the use of a more complete set of 54 ^{14}C-dated results than the 8 flows used by Coe *et al.* (1978).

As illustrated in figure 3 (adapted from McElhinny & Merrill 1975) these newest angular dispersion estimates for Hawaii are still low when compared with other Brunhes-age data sets from elsewhere in the world. Since the time interval spanned by the new combined data set includes a considerable fraction of the Brunhes Epoch, it seems reasonable to suggest that either secular variation is indeed anomalously low in this region of the Pacific as suggested by Doell & Cox, or that the Brunhes Epoch is too short a time interval to average adequately the secular variation produced by dipole and non-dipole sources (Ozima & Aoki 1972; Aziz-ur-Rahman & McDougall 1973; McElhinny & Merrill 1975). All of the time-averaged v.g.ps listed in table 2 are significantly different from the geographic (rotation) axis, yet they differ little from the present dipole or the mean v.g.p. of historic lavas calculated by Coe *et al.* (1978), suggesting that the latter explanation is probably the more correct.

SUMMARY

Recent analyses by Duncan (1975), McElhinny & Merrill (1975) and Coe *et al.* (1978) have suggested that geomagnetic secular variation reported previously from Hawaii by Doell & Cox (1965, 1971, 1972) and Doell (1972*a*, *b*) was unduly biased toward low values. This suggestion was made on the grounds that the Puna and Kau series data, which made up nearly half of the original data set used by Doell & Cox, record a very short time interval. With the addition of new ^{14}C and geological data, it is now clear that the grounds for this suggestion were well founded, as the best estimates now available indicate that the sequences in question accumulated over time intervals of 500 years or less. However, new data from ^{14}C-dated flows, when combined with the previously available data, yield dispersion values consistent with the original dispersion estimate of 10.8° by Doell & Cox (1972). This is true regardless of whether the 'suspect' Kau and Hamakua series data are included with their original weighting, or with a more reasonable attenuated weighting, as discussed above. The Puna series are not included in an overall estimate of dispersion, as they represent a very short time interval that is adequately covered by the ^{14}C series data set.

Having recognized that some lava sequences in Hawaii probably record only a very short time interval, it seems reasonable to reconsider the concept of 'quiet' and 'noisy' behaviour of the geomagnetic field, as proposed by Cox (1975). For Brunhes-age lavas, three sequences had suggested 'quiet' behaviour and two of these (Puna and Kau) can be shown to have artificially low angular dispersion values resulting from a sampling bias. The remaining Hamakua series data are more equivocal, since there is no direct evidence available to constrain the interval of their accumulation. However, it is equally likely that the Hamakua series also represents a short interval. If this is indeed correct, then the 'quiet' and 'noisy' subdivision would be an artificial one, at least on a 10^3 to 10^4 year timescale. However, as noted by Kawai *et al.* (1973), quiet and noisy behaviour on a timescale of 2–3×10^5 years may be possible. The apparently low overall dispersion from Brunhes-age lavas in the Hawaiian Islands may reflect such behaviour.

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Discussion

R. HIDE, F.R.S. (*Meteorological Office, Bracknell, U.K.*). Has anyone carried out a comparable study of the geomagnetic secular variation over Antarctica, which I understand has been systematically *more* intense than the worldwide average during the past few decades?

M. O. McWilliams. To the best of my knowledge a comparable study has not been done. Doell & Cox reported an angular dispersion of about 19° from Cox's unpublished study of 28 undated flows. Other studies by Blundell & Valencio were of a more limited scale; these too were derived from lava flow sequences whose ages are not as well known as the Hawaiian flows in our study. In fact, Hawaii may be the only place where such detailed ^{14}C age control on such a long sequence of flows is currently available. Comparable data may be forthcoming from studies of modern sediments from the Dry Valley of Antarctica which are now under way, but unfortunately the results are not yet available.