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Pacific Geomagnetic Secular Variation

A smooth field over the central Pacific for a million years indicates a nonuniform lower mantle of the earth.

Richard R. Doell and Allan Cox

Among the more important recent advances in geophysics has been the discovery that the earth's upper mantle is heterogeneous. There have been several attempts to determine whether the lower part of the mantle is also heterogeneous and to discover something about the shape of the interface between the earth's core and mantle. Geophysical information of two types has been used in this search: seismic signals from earthquakes that penetrate to the core-mantle boundary and changes in the earth's magnetic field (geomagnetic secular variation) as recorded at magnetic observatories and as recorded by remanent magnetism in rocks and archeological objects.

The main difficulty in the seismic approach is that seismic waves passing through the lower mantle must also pass through two different parts of the upper mantle—the first near the source of the signals and the second near the seismic observatory. Therefore, it is difficult to ascribe differences in the time of travel of these waves from source to receiver to heterogeneity along any particular part of the ray path. One may assume (*1*) that the upper mantle is homogeneous and that observed differences in travel time of waves reflected from the core are due to variations of about 100 kilometers in the radius of the boundary between the core and mantle. However, these seismic data fit equally well an earth model in which the core-mantle boundary is smooth and the mantle is laterally inhomogeneous.

In an attempt to reduce this inherent ambiguity of analyzing seismic travel times, Alexander and Phinney (*2*) studied waves that had been diffracted by the core (waves that travel along the core-mantle boundary during part of their propagation); they restricted their attention to a parameter that depends mainly on the diffraction process itself. This parameter is the seismic attenuation coefficient along paths of constant azimuth from an epicenter. Along ray paths diffracted by patches of the core beneath the Pacific Ocean, they found that the attenuation coefficient has certain properties that are missing for rays diffracted by the core beneath the Atlantic Ocean. Various theoretical reasons have been proposed for these differences. For present purposes, however, the importance of this line of research lies less in the details of the models than in the observational evidence that seismic parameters sensitive to physical properties in the lower 200 kilometers of the mantle are different beneath the Pacific and Atlantic regions.

The use of geomagnetic secular variation to determine mantle properties began with the classic determination of Lahiri and Price (*3*) of the electrical conductivity of the upper mantle by use of short-period magnetic waves that originate in the ionosphere. Because electrical induction in the mantle suppresses the propagation of these short-period waves into the mantle, information about the conductivity of the lower mantle has had to come from analyzing magnetic waves generated in the earth's core. In these studies, the electrical induction in the lower portion of the mantle suppresses the shorter-period waves originating in the core and allows the longer-period ones to propagate to the surface (*4*). From spectrum analysis of observatory records over the period range of 40 days to 22 years, Currie (*5*) determined that waves with periods less than about 4 years did not reach the surface, and he used this determination to place constraints on the conductivity structure of the lower mantle. He did not find a significant difference between the spectra of records from different parts of the world; however, he noted that models of lower-mantle conductivity are not unique, owing to uncertainty about the frequency characteristics of the geomagnetic waves originating in the core.

A different approach to interpreting the longer-period part of the geomagnetic spectrum is based on the concept that it is not attenuation in the mantle that might vary laterally but, rather, the frequency characteristics of the sources that produce the geomagnetic waves (*6, 7*). The nature of the magnetic waves originating in the core may be controlled by lateral variations in mantle properties or by undulations of the core-mantle boundary in the following way. An essential feature of theories of the geomagnetic dynamo is partial control by Coriolis forces of the fluid motion of the earth's core; this motion is therefore similar to the planetary movement of the earth's atmosphere, with both motions having approximate symmetry about the earth's rotation axis. Fluid motions in both the earth's core and atmosphere undergo transient departures from axial symmetry because of turbulence and other random processes. These short-term departures

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disappear when averages are taken over time intervals that are long compared with the time a given departure exists. In addition, permanent departures from axial symmetry can be expected if the fluid is influenced by some condition on the surface between the fluid and solid which is not itself symmetric about the rotation axis. For both the geomagnetic dynamo and the earth's atmosphere, the conditions that may influence the fluid motion are (i) the temperature of the solid-fluid surface and (ii) the topography of the surface. Both exert partial control on atmospheric motions, and either might also influence the flow of fluid in the earth's core (*7*, *8*) and, hence, the nature of the geomagnetic waves generated.

The type of asymmetry we are concerned with in this article is lateral variation in the amplitude of the geomagnetic secular variation, which is a result of lateral differences in the characteristics of the magnetic waves generated in the core. Secular variation in the geomagnetic field arises primarily from changes in the irregular, or nondipolar, part of the geomagnetic field. Thus, lateral differences in the strength of the nondipole field also indicate lateral lower-mantle differences. In view of the present rather sketchy state of the theory of the geomagnetic dynamo, information of this type cannot be used to define a precise model of the lower mantle. However, this approach is able to give a "yes" or "no" answer to the question of whether lateral differences in the lower mantle exist at all. As we shall show, it appears that the nondipole field has been essentially absent under the Pacific Ocean for an extended period of time, which implies that such differences do, in fact, exist.

Present Geomagnetic Field

At the present time the earth's field is far from axially symmetric, and it is likely that, at any instant in the past, asymmetrical irregularities have been present comparable to those that exist today. The potential of the magnetic field V may be expressed as a series of spherical harmonic functions:

$$V = a \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+1} P_n^m(\theta) \left(g_n^m \cos m\varphi + h_n^m \sin m\varphi\right)$$

where a is the radius of the earth, r is the radial distance of the point of observation, θ is the colatitude, φ is the longitude, $P_n^m(\theta)$ are associated Legendre functions, and g_n^m and h_n^m are the Gauss coefficients. For a field with axial symmetry, the only terms that appear are those for which $m = 0$. Values of the Gauss coefficients for the 1965 International Geomagnetic Reference Field (IGRF) (*9*) up to $n = 4$ are given in Table 1. Strong departure from axial symmetry may be seen in the relatively large value of coefficients with $m > 0$, which are comparable in magnitude to many of the zonal coefficients ($m = 0$). The largest departure from axial symmetry is produced by the equatorial dipole terms g_1^1 and h_1^1, which together with the g_1^0 term define the geomagnetic dipole. This dipole is inclined 11.4° from the rotation axis, is in the meridional plane with longitude 69.8°W, and is situated at the earth's center. The magnetic field that it produces is essentially the "best-fit" geocentric dipole field for the observed field over the entire earth. This *geomagnetic dipole* has not changed its orientation significantly during the time (about 140 years) that sufficient measurements have been available for spherical harmonic analyses; however, its strength has been decreasing at a rate of about 7 percent per century. Because of its geocentric location, changes in the geomagnetic dipole will not yield secular variation evidence for lateral inhomogeneities in the mantle.

The largest departures of the observed field from the field of the geomagnetic dipole, including those with which the present study is primarily concerned, are best seen on contour maps that show the nondipole field. The

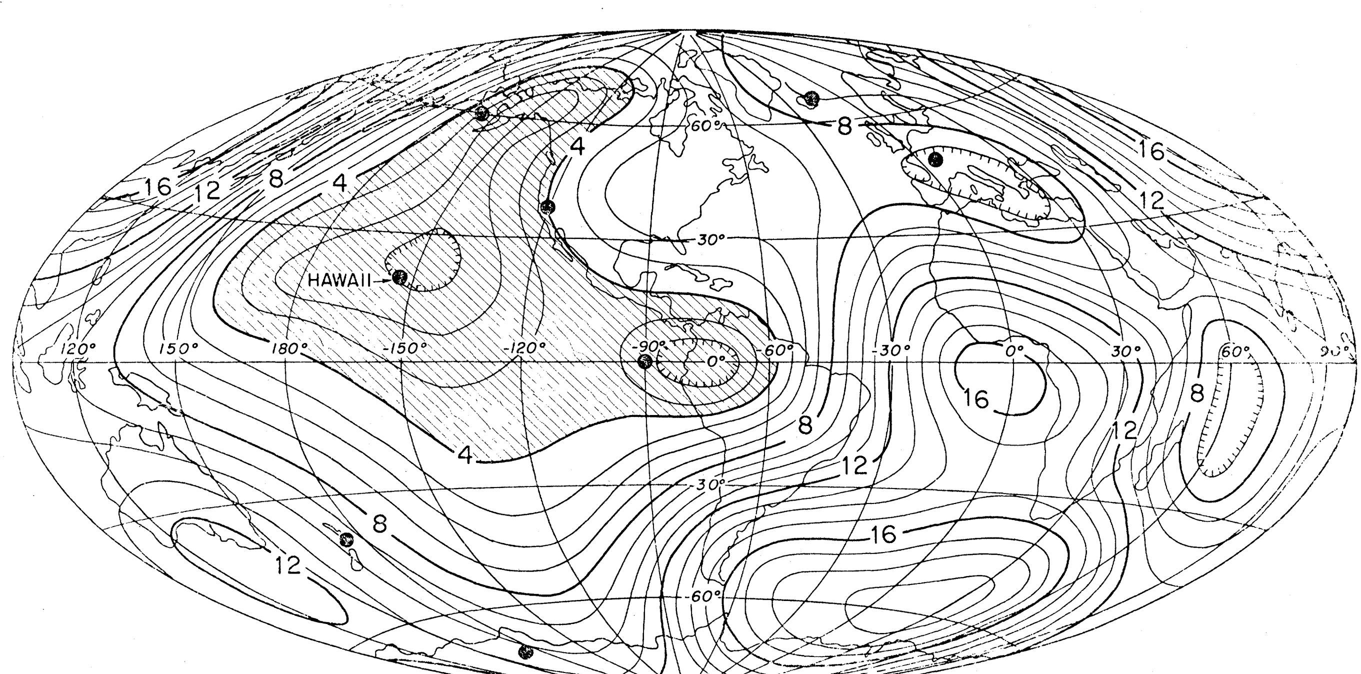


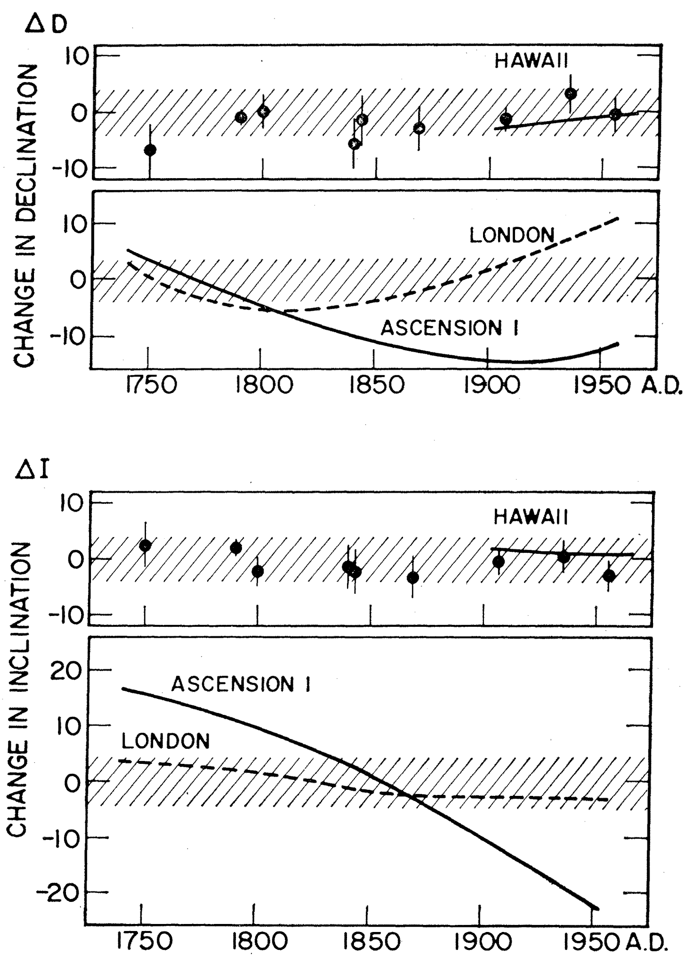
Fig. 1. Intensity of the nondipole portion of the 1965 International Geomagnetic Reference Field. Contour interval, 1000 gammas (= 0.01 oersted = 0.000126 ampere-turns per meter). Shaded area, intensity less than 4000 gammas. The map is the Aitioff (equal area) with the pole of projection on the equator at 80°W. The contours are based on values at grid intervals of 10°. Solid circles show the location of the paleomagnetic angular variance studies referred to in Fig. 5.

nondipole field intensity over the earth's surface (see Fig. 1) is determined by vectorially subtracting the field due to the geomagnetic dipole from the observed field at each locality. The major features, less than ten in number, are characterized by wavelengths of about 60° and amplitudes of 0.08 to 0.16 oersted. Of particular interest in the present study is the fact that the intensity of the nondipole field is unusually small over a region centered in the Pacific Ocean (*6, 7*). The question of whether this low in nondipole intensity is a persistent characteristic of the earth's field or is merely a transient feature resulting from the random distribution of such a small number of highs and lows over the entire earth is the main question that we shall attempt to answer.

Historically Observed Secular Variation

During the several centuries spanned by observatory measurements, the nondipole field has been observed to change slowly in shape and to drift westward at a rate of about 0.2° of longitude per year (*10*). A substantial part of the geomagnetic secular variation observed at a fixed locality is due to the westward drift of nondipole features past the locality. Hence, where the relief of the nondipole field is small, the secular variation should also be small.

The obvious way to determine whether the Pacific low is permanent or transient would be to make maps of the nondipole field for earlier times. Maps of the nondipole field for the years 1650, 1700, 1780, 1829, 1845, 1885, and 1922 have been constructed by Yukutake and Tachinaka (*11*) from spherical harmonic coefficients for these epochs. Their maps for 1650 and 1700 show large values for the nondipole field in the central Pacific, but it is difficult to ascertain whether these large values are the result of using spherical harmonic functions to extrapolate from distant observational sites or whether they are real. Even for the 1780 field, considerable uncertainty exists about the nondipole field; there are large inconsistencies between two sets of coefficients calculated independently for this time (*11*). By the 19th century, more measurements had been made, and the results of the analyses are more consistent. The earliest reliable analysis is for the year 1829. Since then, the nondipole field intensity has been about



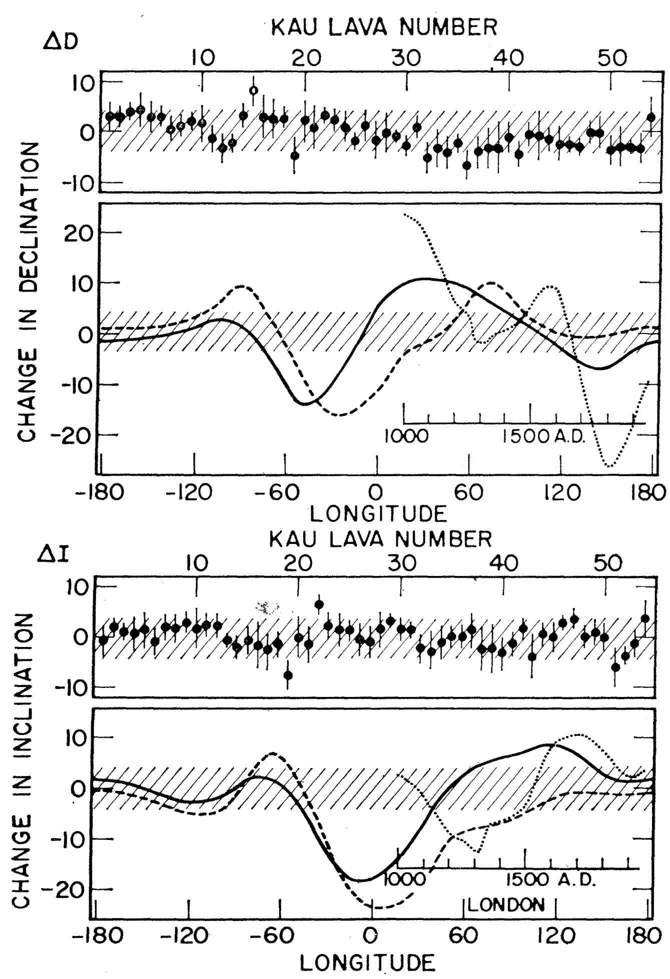


Fig. 2 (left). Changes in magnetic declination(ΔD) and inclination(ΔI) since 1750 at the Hawaii, London, and Ascension Island magnetic observatories (solid and dashed lines). Paleomagnetic results from Hawaiian lava flows are shown as solid circles; the vertical bars are the 95 percent confidence limits (*12*). The zero base line in all cases corresponds to the directions at the observatories of the 1965 International Geomagnetic Reference Field. The shaded area $\pm 4°$ about this base line approximates the precision of the paleomagnetic measurements. Fig. 3 (right). Changes in declination (ΔD) and inclination (ΔI) of the Kau Volcanic Series. The lava flows are numbered from the bottom of the exposure. Solid circles show the average direction (*26*) for each flow, the zero base lines being the average values of declination and inclination for the entire sequence. For comparison, changes in declination and inclination are shown along the 20°N circle (solid line) and 20°S (dashed line) for the nondipole part of the 1965 geomagnetic field. The dotted curve shows the changes in declination and inclination in England since A.D. 970 (*27*), the zero base line being the declination and inclination at London due to the dipole component of the 1965 geomagnetic field. Shaded zones, as in Fig. 2.

as low in the central Pacific as it is now.

Maps such as these point out the main obstacles to determining whether the Pacific low is a persistent or transient phenomenon. The first is that the rate of westward drift of the nondipole field, which is the principal contributor to secular variation, is only 0.2° of longitude per year. During the interval of 140 years for which adequate records are available, the total drift is only 28°. Therefore there has not been time for a major nondipole center to move into the central Pacific because, as may be seen in Fig. 1, about 90° of drift is required for this movement. The second problem is that the rate at which old features of the nondipole field decay and new ones form is so slow that there has not been time for the growth of a major new nondipole feature. The phenomena of greatest interest for determining the persistence of the Pacific anomaly thus appear to occur over periods of time just beyond the reach of direct observatory measurement.

Paleomagnetic Results from the Hawaiian Islands

The Hawaiian Islands, situated in the central Pacific Ocean and built up primarily of successive lava flows, provide a rather fortunate situation for paleomagnetic studies of the Pacific secular variation anomaly for two reasons. First, extrusive volcanic rocks of the Hawaiian types are ideal materials for paleomagnetic studies, as they acquire a relatively strong and stable remanent magnetization during cooling. Moreover, it has been established that this magnetization is very closely parallel to the magnetic field in which the Hawaiian lavas cooled (*12*) and, under certain conditions, the magnetization has an intensity that is proportional to the intensity of the ambient field during cooling (*13*). Thus, this magnetization is a "spot" measurement of the ancient magnetic field, because most Hawaiian lavas require less than a year in which to cool. Second, there has been more or less continuous volcanic activity in the Hawaiian Islands during the past several million years, extending to the present. There exists, therefore, a natural record of geomagnetic field changes in the central Pacific extending far beyond that of magnetic observatories.

The existence on Hawaii of lava flows with ages that are well determined from historical records provides an opportunity to extend the accurately dated magnetic record back beyond the beginning of observatory measurements in Hawaii to determine whether the nondipole field was small in earlier times. It is possible to determine an ancient field direction from a lava flow with an accuracy of about 4° at the 95 percent confidence level (*12*). This method is much less accurate than observatory measurements, yet accurate enough to detect changes in direction resulting from the presence of a large nondipole field. As an example of the amplitude of such fluctuations, between 1750 (the age of the earliest historically dated Hawaiian lava flow) and 1945, the direction of the earth's field changed by 45° on Ascension Island and by 22° at Cape Town, Africa. Both would have been easily detectable paleomagnetically.

Table 1. Gauss coefficients (in gammas) up to $n = 4$ for the International Geomagnetic Reference Field 1965.0.

n	m	g_n^m	h_n^m
1	0	−30339	
1	1	−2123	5758
2	0	−1654	
2	1	2994	−2006
2	2	1567	130
3	0	1297	
3	1	−2036	−403
3	2	1289	242
3	3	843	−176
4	0	958	
4	1	805	149
4	2	492	−280
4	3	−392	8
4	4	256	−265

On Hawaii, paleomagnetic measurements were made on nine flows with known ages back to 1750 (*12*). Most of the values of inclination and declination shown in Fig. 2 are within 4° (shaded bands) of the magnetic field direction in Hawaii corresponding to the terms g_1^0, g_1^1, and h_1^1 of the 1965 IGRF. The only exceptions are the values of declination for 1750 and 1840. The angular difference of 3.5° between the paleomagnetic directions for the years 1840 and 1843 also suggests that much of the observed scatter is due to experimental error. These results thus cannot preclude the possibility of angular changes up to some 4° at individual data points, but they are also quite consistent with an unchanging field having essentially the direction of the dipole component of the present field. As an estimate of an upper limit on the nondipole field present during this time, an angular change of 4° would correspond to a nondipole field component of 2400 gammas normal to the dipole field component or to a nondipole field component of 3400 gammas at an angle of 45° to the dipole field. Such values are within the 4000-gamma level that is shaded in Fig. 1 and are therefore consistent with the idea that the nondipole field in the central Pacific has been anomalously low for 200 years. However, because of the slow rate of westward drift (40° of longitude in 200 years), a still longer paleomagnetic record is needed to test conclusively the persistence of the nondipole low in the Pacific.

Thousands of prehistoric lava flows suitable for paleomagnetic measurements are exposed on the Hawaiian Islands. The main limitation on the geophysical usefulness of paleomagnetic data from these flows is the lack of accurate information about their ages. However, for some flows enough is known from geologic evidence to permit useful conclusions to be drawn about the ultra–low-frequency characteristics of the geomagnetic field.

The Kau Volcanic Series provides some particularly important information. It is exposed near the summit of Mauna Loa, Hawaii, in a caldera wall that is 140 meters high. Paleomagnetic measurements were made on 54 superimposed lava flows to produce the set of directions given in Fig. 3 (*14*). Each point shows the direction of the field at the time one of the flows cooled. The sequence of measurements in this "time series" is known from the superposition of the lava flows in the section, but the length of time between flows is unknown and can only be estimated indirectly.

The most useful piece of geologic information about the age of the Kau Volcanic Series is that flow number 1 at the bottom of the section can be no more than 10,000 years old. This follows from the observation that the section in the caldera is not deep enough to expose the locally ubiquitous Pahala Ash, the uppermost layer of which is 10,000 years old as determined by the ^{14}C method (*15*). The minimum age of the youngest flow in the series is determined by the date of collapse of the northwest wall of the caldera, which could have been as recent as several hundred years ago. The maximum duration of the entire series is thus no more than about 10,000 years (*16*). The average time between successive measurements of the geomagnetic field from these lavas is probably about 200 years, although the actual time between successive eruptions was undoubtedly irregular. At a rate of westward drift of 0.2° of longitude per year, 1800 years would be required to sample the entire nondipole field around a circle of latitude. Therefore, the paleomagnetic record of the Kau Volcanic Series appears to be long enough to provide a good sample of the nondipole field.

The changes in declination and inclination shown in Fig. 3 are compared with changes in declination and inclination due to the nondipole part of the 1965 field along the latitude circles 20°N and 20°S, 20° being the latitude of Hawaii. These are the angular changes in field direction to be expected at a sampling site if the present dipole field remained fixed and the present nondipole field drifted westward for 1800 years. Also shown are changes in the magnetic field direction in England for the past thousand years. Even if the Kau Volcanic Series has recorded changes in only the nondipole part of the field, the changes are surprisingly small.

The important question of whether this record is long enough to have also recorded changes in the orientation of the geocentric dipole is difficult to answer because little is known about the way in which the geomagnetic dipole changes orientation or about the rate at which this occurs. During the past few centuries, the change in geomagnetic dipole orientation has been too small to detect by means of spherical harmonic analysis. However, it is known from paleomagnetic research (*17*) that, during the past few million years, the average orientation of the dipole has been parallel to the earth's rotation axis. There can be no question, therefore, that the dipole's present 11½° displacement from the rotation axis is a transient phenomenon, but the nature of dipole movement about the geographic axis is uncertain. Thus, the changes in direction of the Kau Volcanic Series may or may not include contributions from changes in the orientation of the geomagnetic dipole. If they do, then the reduced intensity of the nondipole field in the Pacific region during the time of formation of the Kau Volcanic Series is even more pronounced.

The weakest point in the above interpretation lies in the estimate of the time required for extrusion of the Kau Volcanic Series. Imagine that, contrary

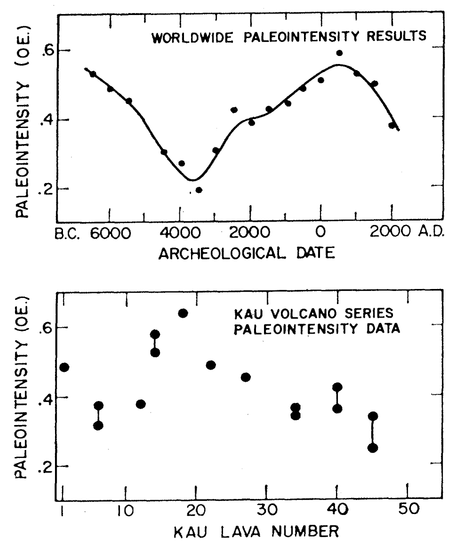


Fig. 4. (Top) Intensity of the earth's field in Hawaii calculated from changes in the earth's main geomagnetic dipole strength during the past 8000 years. Each point is an average of worldwide archeomagnetic data for an interval of 500 years (*18*). (Bottom) Paleointensity of the earth's magnetic field in Hawaii measured in ten lava flows from the Kau Volcanic Series. Determinations on different samples from the same flow are joined by bars.

to the geologic evidence, the entire sequence formed during a few centuries or less. It might then be argued that secular variation in the Pacific at that time happened to be unusually low, just as it is today. The Kau paleomagnetic data would then not imply that the nondipole field was low in the Pacific. The argument is a strong one. No matter how many individual lava flows were sampled, if they all formed during a short time, they could not supply very much information about the long-period characteristics of the field.

It has proven possible to obtain additional information about the length of this record by determining paleomagnetically the intensity of the magnetic field during the time the lavas of the Kau Volcanic Series formed. Worldwide archeomagnetic determinations of the ancient intensity of the earth's field during the past 8000 years have been averaged (*18*) to obtain an estimate of changes in the earth's dipole moment. In the upper diagram of Fig. 4, these have been converted to show the changes in the intensity of the earth's field at the latitude of Hawaii. The most recent fluctuation in the amplitude of the dipole field appears to have a period of about 8000 years and an amplitude about a mean value of 0.4 oersted of ± 0.2 oersted or ± 20,000 gammas. The connection between time and magnetic intensity in the Kau data can be appreciated by considering the field intensity variation to be expected under two different assumptions: (i) the lavas formed during a few centuries when the secular variation was small; (ii) the lavas formed over an interval of 10^4 years. In the first case, the intensity variation will be small for the following reasons: To produce the maximum observed changes of about 10° in the Kau field directions, nondipole field vectors with a maximum intensity of 5000 gammas oriented normal to the mean direction would be needed. Thus, ± 5000 gammas (± 0.05 oersted) is also the expected variation of field intensities in the Kau data under the first assumption. For the second case, when an interval of 10^4 years is assumed, the expected intensity variation is at least as large as that of the earth's main dipole field during the past 8000 years—that is, ± 0.2 oersted in Hawaii.

For ten of the flows from the Kau Volcanic Series, determinations were made [by Smith's method (*19*)] of the intensity of the earth's field at the time the lavas originally cooled. The data (lower diagram of Fig. 4) show a range of paleointensity values from a high of about 0.6 oersted (lava 18) to a low of about 0.3 oersted (lavas 5 and 45); this range is considerably larger than the average spread of 0.07 oersted in several duplicate determinations. The 0.61-oersted peak in the intensity of the earth's field at the time of lava 18 may correspond to the peak in the worldwide data at A.D. 500, or possibly to the peak at 7000 B.C. or an earlier peak. The importance of the intensity results from the Kau Volcanic Series does not lie in making a point-to-point correlation with the worldwide data but rather with the demonstration that the intensity of the earth's field varied by a factor of 2 during the time these lava flows were extruded. This variation is not consistent with formation of the flows during a few centuries. It requires, at the very least, a few thousand years.

In summary, despite the lack of precise absolute ages for the lavas of the Kau Volcanic Series, the measurements of ancient field intensity indicate that the lavas span at least several thousand years, which is adequate to sample variations in the nondipole field; and the measurements of ancient field directions indicate that during this time the nondipole field was remarkably small. Paleomagnetic studies have also been made on several other volcanic series exposed on Hawaii (*20*). Results of these studies also show unusually small changes in direction throughout thick sequences of superimposed lava flows.

Variation of Angular Dispersion with Latitude

In most paleomagnetic studies of past secular variation, there is very little information about the elapsed time between the eruption of successive lava flows and the total time spanned by a given sequence; thus interpretations like that made for the Kau Volcanic Series are not applicable. Generally, the paleomagnetic information about ancient secular variation may be described by a single parameter: the angular standard deviation of ancient field directions from their mean. Where the average value of the nondipole field has been small, this parameter will be small, and, conversely, where this value has been large, the parameter will be large. The critical test for the longer-term permanency of the Pacific low might thus appear to be a simple matter of comparing the angular deviation parameter from Hawaiian paleomagnetic data with the same parameter from other localities over the globe. In practice, however, several complications need to be considered.

The first is that the wobble of the geomagnetic dipole is so large that it tends to mask changes in direction due to changes in the nondipole field. To handle this, we have transformed ancient field directions to equivalent virtual geomagnetic poles (*21*). These provide a convenient method for comparing magnetic field directions at widely separated localities and also for assessing the relative intensities of the dipole and nondipole fields. For a pure central dipole field, the virtual geomagnetic poles calculated from magnetic field directions of points distributed over the surface of a sphere all coincide. When there is a nondipole field, then the virtual poles are dispersed. A measure of the nondipole field is provided by the variance

$$S^2 = \frac{1}{N} \sum_{i=1}^{N} \Delta_i^2$$

where N is the number of observations distributed over the sphere and Δ_i is the displacement of individual poles from the mean position of all poles. The advantage of analyzing paleomagnetic data in this way is that the angular dispersion due to dipole wobble is the same at all latitudes, whereas if field directions are analyzed directly, the angular dispersion is strongly latitude-dependent, even in the absence of a nondipole field. When virtual poles are used, the effect of the nondipole field is seen as an increase in angular dispersion, which rises above a base level common to all sampling sites regardless of their geographic location. If S_D is the angular standard deviation of the dipole wobble and S_N that of virtual poles produced by the nondipole field, then by simple analysis of variance arguments, the angular standard deviation S_T due to both the dipole and nondipole components of the field is

$$S_T = (S_D^2 + S_N^2)^{1/2}$$

The lowest level of S_T determined paleomagnetically at any site with adequate sampling can be taken as an upper bound for S_D, the dipole wobble. Our best estimate of the value of S_D is about 11° (*7, 14, 22*).

A second problem in interpreting angular dispersion data is that paleomagnetic sampling sites are not well distributed for testing the permanency of the Pacific low. For the interval from 0.7 million years to the present, which constitutes the Brunhes normal polarity epoch, the angular dispersion is well determined for the island of Hawaii (*14, 20*). However, there are no comparable paleomagnetic results from sites at the same latitude in other parts of the world where the nondipole field is large at present. On the other hand, suitable results are available from other latitudes. To tie together the available data, we need a model that describes the variation of angular dispersion with latitude.

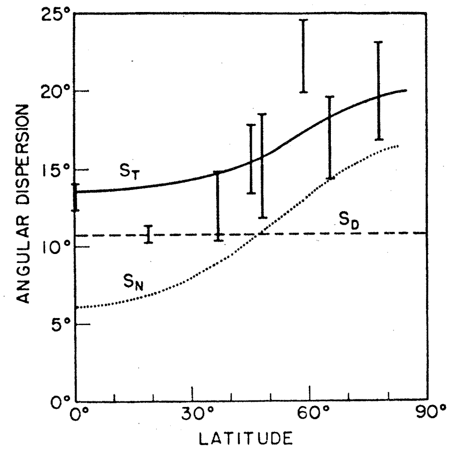


Fig. 5. Angular standard deviation of virtual geomagnetic poles calculated from paleomagnetic data of rocks less than 0.7 million years old collected at the following localities (listed in order of increasing latitude, with the number of lava flows at each site): Galapagos, 147; Hawaii, 219; western United States, 21; New Zealand, 21; France, 31; Alaska, 60; Iceland, 28; and Antarctica, 28. The localities are indicated on Fig. 1. The limits of the data bars are at the 90 percent confidence level (*25*). The dotted curve (S_N) indicates the angular dispersion of virtual geomagnetic poles expected from the nondipole component of the 1965 IGRF, with data averaged between hemispheres. The dashed curve (S_D) indicates the angular dispersion due to an 11° dipole wobble. The solid curve (S_T) indicates the total angular dispersion from both of the above; $S_T = (S_D^2 + S_N^2)^{1/2}$ (*28*).

The latitude variation of angular dispersion of virtual geomagnetic poles depends on several variables: the direction and intensity of the nondipole field, the relative strength of the nondipole and dipole fields, and the wobble of the geomagnetic dipole. Cox (*23*) has extended earlier model studies (*6, 24*) to show how these variables may be combined to produce various models of secular variation. The solid line in Fig. 5 shows the result of a model for which the dipole wobble is 11° and the angular dispersion of the nondipole field is the same as that of the present nondipole field along circles of latitude, when results for the Northern and Southern hemispheres are averaged. Other likely models do not differ greatly from this curve. If the angular standard deviation of virtual poles from any sampling site falls below this curve, then the average amplitude of the nondipole field at that site was anomalously low relative to the present worldwide field.

The final analytical problem is to establish confidence limits for the determinations of angular standard deviation. This procedure is straightforward from a formal statistical point of view (*25*). However, an important practical problem is to determine the relevant number of degrees of freedom in the sampling, which in turn depends on whether a set of ancient field determinations constitutes a truly random sample. A necessary condition for randomness is that the time between successive paleomagnetic data points must be at least as long as the longest periods present in the geomagnetic spectrum. Our experience has been that this condition is commonly not met (*14, 20*). Consequently, in many investigations, including some cited in this article, the indicated confidence limits on S_T are probably too low.

The results of our studies of the

angular variance of Brunhes age lavas (<700,000 years old) from different parts of the world are given in Fig. 5. All of the experimental results fit the expected model except for Hawaii, which has less angular dispersion than the model, and Alaska, which has more. We believe that the confidence limits on the Alaskan result may be too small for the reasons given above and that the indicated deviation from the curve may not be statistically significant. The sampling on Hawaii was much more extensive, and the angular dispersion indicated is therefore on a firmer experimental basis. Although the indicated confidence limits shown for the Hawaiian results are probably too small, the total number of degrees of freedom is great enough to indicate that the angular dispersion falls significantly below the curve.

When compared with similar Brunhes age paleomagnetic data from other localities, the angular variance of the Hawaiian results is anomalously low. The most straightforward conclusion is that the nondipole field in the central Pacific has been greatly subdued throughout the past 0.7 million years. These studies also imply that angular variance of virtual geomagnetic poles which is due to wobble of the geomagnetic dipole about the axis of the rotation is approximately 11°. The present 11½° angle between the rotation and dipole axis is apparently a typical value.

Summary and Conclusion

We have considered several different types of records of long-period geomagnetic secular variation: direct measurements made in geomagnetic observatories; paleomagnetic measurements on Hawaiian lava flows with accurately known ages in the interval 0 to 200 years; paleomagentic measurements on Hawaiian lava flows with loosely determined ages within the interval 200 to 10,000 years ago; and worldwide paleomagnetic measurements of the average geomagnetic angular dispersion recorded in lava flows that formed during the past 0.7 million years. All these magnetic records indicate that, during this time, the nondipole component of the earth's field was lower in the central Pacific than elsewhere, as it is today. This, in turn, indicates that there is some type of inhomogeneity in the lower mantle which is coupled to the earth's core in such a way as to suppress the generation of the nondipole field beneath the central Pacific. With the present incomplete state of knowledge about the processes that give rise to the earth's field, it is uncertain whether undulations in the core-mantle interface or lateral variations in the composition and physical state of the lower mantle are ultimately responsible for the pattern of secular variation seen at the earth's surface.

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29. Publication authorized by the director, U.S. Geological Survey. This article is adapted from an address delivered 16 April 1970 in Cambridge, Massachusetts, at a symposium in honor of Prof. Francis Birch. A complete account will appear in the proceedings volume [*The Nature of the Solid Earth*, E. C. Robertson, Ed. (McGraw-Hill, New York, in press)].