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A test of the geocentric axial dipole hypothesis from an analysis of the skewness of the central marine magnetic anomaly

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Abstract

A new, global set of palaeomagnetic observations was obtained from analysis of the symmetry of the shape of 203 crossings of the Central marine magnetic anomaly, the anomaly observed above seafloor, formed during the Brunhes normal polarity chron (0–0.78 Ma). The data indicate that the time-averaged field can be described best by a dominant geocentric axial dipole component, whose position differs insignificantly from the present spin axis, and by a small geocentric axial quadrupole component ($6.0\%^{+5.7\%}_{-6.7\%}$ the size of the dipole component). If we simply assume that the Brunhes palaeomagnetic axis has been aligned with the present spin axis, the quadrupole component is 6.2% $\pm$ 4.7%, which differs significantly from a purely dipolar field, and is in good agreement with estimates from other palaeomagnetic data. Besides expanding the spatial distribution of palaeomagnetic field observations, an important step in removing biases in prior field estimates caused by poor global coverage, these results illustrate that valuable geomagnetic information as well as accurate palaeomagnetic poles can be obtained from skewness data.

Keywords: magnetic field; magnetic anomalies; paleomagnetism; skewness

1. Introduction

The geocentric axial dipole (GAD) hypothesis supposes that the time-averaged palaeomagnetic field, presumably generated by convection in the outer core, is identical to that produced by a dipole located at Earth's center and aligned with Earth's spin axis. This hypothesis has proven valuable in relating palaeomagnetic data to a common reference frame, that of the spin axis. Working with this fundamental hypothesis, palaeomagnetists have studied the palaeogeographic positions of the continents, the absolute and relative motions of plates, motions of terranes and microplates, ages of seamounts and rock outcrops, and true polar wander.

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Within the uncertainties of other palaeogeographic indicators, such as palaeoequatorial sediment facies, organic reefs, and evaporites, the GAD hypothesis cannot be rejected. When detailed analyses of globally distributed palaeomagnetic data are carried out, however, a geocentric axial dipole field does not provide the best description of the observations.

Wilson and Ade-Hall [1] first noted that if palaeomagnetic poles from late Tertiary and Quaternary outcrops are calculated assuming a dipolar palaeomagnetic field, the poles tend to be far-sided, that is, the angular distances between the outcrop and the palaeomagnetic pole is greater than the distance from the outcrop to Earth's palaeo-spin axis. Wilson [2–4] confirmed this result through the analysis of global palaeomagnetic data and suggested that, rather than being geocentric, the dipole that best described the Earth's field was displaced northward along the spin axis by about 200 km, a distance that was subsequently refined [5–7].

Other studies have analyzed a variety of palaeomagnetic data sets in terms of a spherical harmonic representation [8–12], which provides a convenient means for describing the Earth's magnetic field in terms of a scalar potential [13,14]. For the palaeomagnetic field, the magnitude of the Gauss coefficients is not well resolved because palaeointensity data are currently of insufficient quality and quantity. The ratios of the coefficients, however, can be determined from directional data (palaeomagnetic inclinations and declinations) alone.

Early analyses found large contributions from several of the coefficients of degree and order less than four [15]. In general, these studies agree that a significant geocentric axial quadrupole (GAQ) component, represented by the g_2^0 coefficient, is needed to explain Quaternary and late Tertiary palaeomagnetic results. The magnetic field produced by a GAD plus a GAQ is roughly the same as that produced by Wilson's eccentric dipole; thus, these more recent results confirmed Wilson's observations, but provided a new perspective and illustrated the nonuniqueness in determining magnetic sources in the core from observations at Earth's surface.

Accurate description of the magnetic field at Earth's surface is, however, important in understanding the sources in the core because, ultimately, this description is the constraint against which physically meaningful models of the geomagnetic field must be tested. Improvements have come from the recognition that part of the apparent deviation of the palaeomagnetic field from a GAD field may be caused by plate motions. More recent investigations have either restricted their analyses to data from rocks less than 5 Ma and/or corrected the data for relative and absolute plate motions [14–24]. Even with these improvements and with the progressively larger data sets that have accumulated with time, the uneven spatial distribution and uncertainties in the data have prohibited the resolution of zonal harmonics with degree greater than four and all non-zonal and sectorial harmonics. These studies have documented, however, that over 90% of the time-averaged palaeomagnetic field can be described by a reversible GAD field (g_0^1) with a reversible GAQ field (g_2^0), which has the same sign (at least through the Cenozoic) as the axial dipole and is 2–10% as large, making up most of the remaining field. Furthermore, several of these prior studies have documented a polarity asymmetry in which the size of the quadrupole component is larger during reversed polarity intervals than during normal polarity intervals.

The persistent quadrupole field has been attributed, among many explanations, to: (1) variations in the temperature or topography at the core–mantle boundary, which presumably perturbs convection in the outer core or causes variations in the electrical conductivity of the lowermost mantle [18]; and (2) an inner core that is anisotropic in magnetic susceptibility and electrical conductivity [25,26]. The polarity asymmetry, in contrast, has been interpreted as an artifact of a sampling bias caused by the uneven geographic distribution of palaeomagnetic data sets [26,27], although a core-field origin is not excluded.

To constrain the geometry of the time-averaged geomagnetic field more narrowly, larger palaeomagnetic data sets with better spatial distribution are needed. Here we extend the catalog of observations by analyzing the shape of the Central marine magnetic anomaly, which occurs above very young seafloor that was magnetized during the Brunhes normal polarity chron (0–0.78 Ma). Because the asymmetry or skewness in the shape of a marine magnetic anomaly can be related to the palaeomagnetic inclination and because the Central anomaly has been recorded above seafloor spreading axes around the globe on many ship and airplane profiles, we in effect obtain a globally distributed set of palaeomagnetic inclinations. The new global data set is combined with results from a previous analysis of the geomagnetic field by Schneider [24], who examined the skewness of the Central anomaly along the Cocos–Nazca ridge. This global data set, with 189 new skewness estimates and the 14 prior estimates from Schneider [24], is used to find the best-fit palaeomagnetic field that can be described by the geocentric axial dipole and quadrupole terms.

2. The skewness method

Skewness data are obtained from an analysis of the shapes of marine magnetic anomalies. The skewness is defined as the phase shift — an angle that describes the relative proportions of antisymmetric and symmetric components of a signal in spectral analysis — that gives the anomaly a shape that would be expected if the anomaly had been produced by oceanic lithosphere that formed and remained at the North pole [28–30]. The anomaly's departure from this expected shape is related to the remanent magnetization of the seafloor, the orientation of the present geomagnetic field, and the strike of the mid-ocean ridge (i.e., the azimuth of the magnetic lineation) where the magnetic profile was collected. The latter two are obtained from the International Geomagnetic Reference Field (IGRF) and from global plate motion models [32,33], respectively, allowing us to extract palaeomagnetic field directions from the observed skewnesses.

We use a revised version of a maximum-likelihood method [31,34,35] to compute the palaeomagnetic field, where the inclination we use contains an additional quadrupole term:

$$\tan I_r = \frac{2\cos\theta + \left(g_2^0/g_1^0\right)\left(9/2\cos^2\theta - 3/2\right)}{\sin\theta + \left(g_2^0/g_1^0\right)\left(3\sin\theta\cos\theta\right)} \qquad (1)$$

where I_r is the remanent inclination; θ is the palaeomagnetic colatitude; and g_2^0/g_0^1 is the ratio of the GAQ term to the GAD term [20]. The present analysis implicitly assumes that higher order zonal harmonics are negligible. If they are not, then the resulting estimates of the quadrupole term and its uncertainties would need to be revised. In the analysis below, we give the GAQ component as a percentage of the GAD component. This value is positive when the GAD and GAQ components have the same sign.

The skewness method depends on magnetization contrasts between strips of oceanic lithosphere of different polarities. This has advantages and disadvantages: An advantage is that induced or viscous components of magnetization, that probably produce a fairly homogeneous magnetization (a vector component with the same direction and intensity) in the magnetized portion of the ocean lithosphere, do not contribute to the magnetic anomaly. Likewise, any non-dipole component that produces a homogeneous

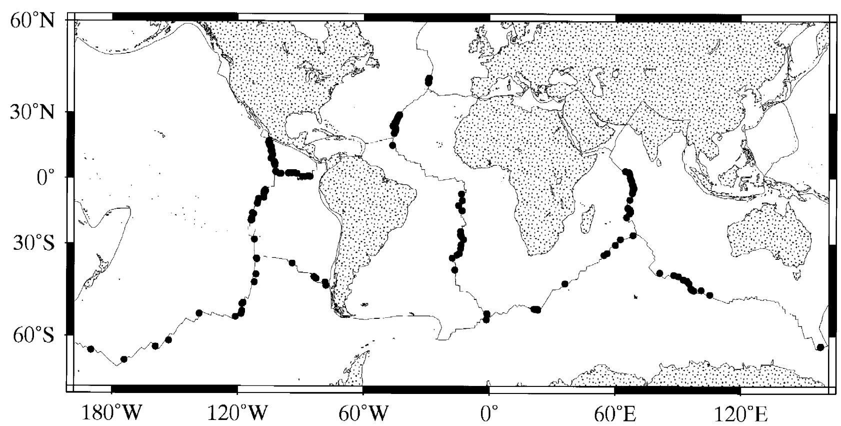

Fig. 1. Location of Central anomaly skewness data (Mercator projection).

magnetization across adjacent strips of oceanic lithosphere of different polarities would not produce an anomaly. Thus, such components would not be seen. Furthermore, non-dipole components that are reversible, but have different magnitudes during normal and reversed polarity intervals, will be averaged in the skewness analysis [24]. Our estimate of the GAQ component for the Brunhes field may thus be partially influenced by the geomagnetic field present during the Matuyama reversed polarity interval, which preceded the Brunhes Epoch.

3. Data and results

Our data set consists of skewnesses estimated for the Central anomaly on marine magnetic anomaly profiles collected over the global mid-ocean ridge system. In all, there are 189 new estimates of skewness from 13 different plate boundaries plus 14 prior estimates obtained by Schneider [24] from profiles over the Nazca–Cocos ridge (Figs. 1 and 2). The new estimates are from 165 ship profiles that were obtained from the United States National Geophysical Data Center and from S.P. Maschenkov [36] and 24 aeromagnetic profiles from a survey over the Central Indian Ridge [33].

We grouped the 203 skewness data into four categories based on their quality [37]. Each skewness datum was then converted into an effective remanent inclination (the inclination of the palaeomagnetic vector projected onto a vertical plane perpendicular to the ridge strike) [31,38]. We then assigned standard errors to each group of inclinations based on four preliminary geomagnetic field inversions, using data from a single group in each inversion. The standard error is estimated by requiring that the errors for each datum in a group are of equal size and that the resulting best-fit model has a reduced χ^2 statistic equal to one. The error budget is derived in this manner only because we do not know the true standard errors in the observations. We can estimate the skewness of an anomaly to better than $\pm 30°$ on all profiles, however, and so we suspect that this

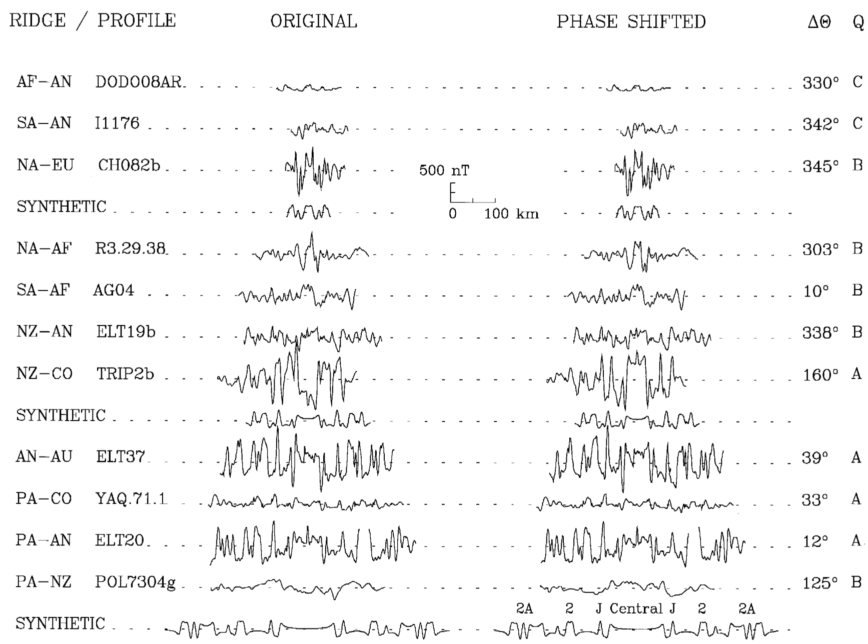

Fig. 2. Examples of de-skewed profiles from 11 different spreading centers. Plates bounding the spreading centers are abbreviated as follows: *AF* = Africa; *AN* = Antarctica; *AU* = Australia; *CO* = Cocos; *EU* = Eurasia; *NA* = North America; *NZ* = Nazca; *PA* = Pacific; *SA* = South America. The skewnesses or phase shifts are given by $\Delta\theta$. The synthetic profiles show the ideal anomalies from a standard block model. The letters A, B, C, and D are used to denote the quality of the profiles, where A is the highest quality (see text).

represents a rough upper bound for the standard error related to the deskewing an anomaly. Our error budget analyses from this and a prior study of the skewness of anomaly 25r on the Pacific plate [37] indicate that standard errors between 10° and 40° are typical, with the standard errors larger than 30° arising perhaps from other sources of noise (see below).

A preliminary model of the geomagnetic field, calculated from data from these four groups, gives a GAQ component of 3.6% ± 7.1% (95% confidence limits) and a pole located at 88.5°N, 147.8°E with a 95% confidence ellipse that has a 5.8° major semi-axis oriented 10° clockwise from north and a 3.5° minor semi-axis.

Examination of the residuals (observed effective inclinations minus model-predicted effective inclinations) revealed several data with unreasonably large misfits. To avoid excessive culling of the data, we discard only those data with residuals greater than 90°. This cutoff is considered conservative because it spans half of the total effective inclination space (half of ±180°). Furthermore, given that the upper bound for the standard error in deskewing an anomaly is about ±30°, we would suspect only about 0.3% of the data to have residuals outside $\pm 3\sigma$ (approximately ±90°). As with many real data sets, normal distributions are poorly realized [39]. Indeed, we expected only one datum out of 203 to lie outside ±90°, but found nine. Three outliers, which have consistent residuals of about ±140°, were obtained from profiles over a seafloor spreading segment between the Siqueros and Clipperton fracture zone along the East Pacific Rise. Another two outliers with consistent residuals of about −120° come from a ridge segment along the Pacific–Nazca plate boundary between 7.2°S and 7.6°S. Clearly, the outliers are not part of randomly distributed noise in a normal distribution. Instead, they appear to have some systematic origin, which could be related to anomalous tectonic or magmatic processes along a few seafloor spreading centers. Asymmetric spreading, ridge jumps, propagating ridges, off ridge-axis formation of volcanoes, variations in the degree of serpentinization of the lower crust and upper mantle [40], and other such phenomena are possible processes that could produce irregularities in magnetic anomalies. These large residuals may thus provide an important observation tool for identifying regions where such anomalous behaviour is occurring or has occurred in the past few hundred thousand years. For this study, the most important observation is that outliers are relatively rare, constituting only 4% of the data, and do not significantly affect our best-fitting geomagnetic field model.

After removal of the outliers, the errors of the individual groups were then reassessed as described above. The standard errors for the groups, from lowest to the highest quality, are 34.1°, 38.0°, 28.1° and 21.3°. The new best-fit model gives a quadrupole coefficient of 6.0% ± 5.8% and a pole located at 88.4°N, 140.7°E, with a 95% confidence ellipse that has a 4.6° major semi-axis oriented 359° clockwise from north and a 2.9° minor semi-axis (Fig. 3; the data set and calculations for this pole are available on the World Wide Web at http://www-odp.tamu.edu/~acton/max.5April96). In addition, we solve for a case in which the dipole axis is fixed at the north pole and the quadrupole component is the only adjustable parameter. In this case, the best estimate of GAQ component is 6.2% ± 4.7%.

4. Other sources of uncertainties

At this point, we might claim that a marginally significant GAQ component existed during the Brunhes chron. Such a claim, however, would neglect other sources of errors that should be propagated into the final confidence limits. In particular, we know that data with high importances will be sensitive to errors in the magnetic lineation azimuth [38]. In addition, Petronotis et al. [31] showed that the geometry of skewness observations and the nonlinearity of the inversion method may result in confidence limits that are more complex than those estimated by linear propagation of errors (LPE), which was used in the above estimates. To test the robustness of the data set further, we recalculated the confidence limits of the pole and g_2^0 using constant-chi-square (χ^2) boundaries and Monte Carlo simulations [31]. Both methods give similar results that are in very good agreement with the confidence limits estimated from (LPE) in the maximum-likelihood inversion (Fig. 3). The constant-χ^2 boundaries that define the 95%

confidence limit for g_2^0 are at -0.1% to $+12.0\%$; those found by LPE are $+0.2\%$ to $+11.8\%$.

To investigate the uncertainties caused by errors in lineation azimuths, we used Monte Carlo simulations in which not only are the skewness data perturbed to within their uncertainties but also the lineation azimuths are perturbed to within $\pm 4°$ (95% confidence region) of the values estimated from the NUVEL-1 plate motion model [32]. The mean of 10,000 simulations gives a pole located at 89.2°N, 144.6°E with a 95% confidence ellipse that has a 4.4° major semi-axis oriented 358.7° clockwise from north and a 2.6° minor semi-axis, as estimated from Bingham statistics [41] (Fig. 3). The quadrupole coefficient is $6.0\%^{+5.7\%}_{-6.7\%}$) (Fig. 4), which we consider as our best overall estimate. Overall, the constant-χ^2 and Monte Carlo methods indicate that the confidence limits should be elongated slightly toward Greenland in pole space (Fig. 3) and slightly toward more negative values in GAQ space (Fig. 4).

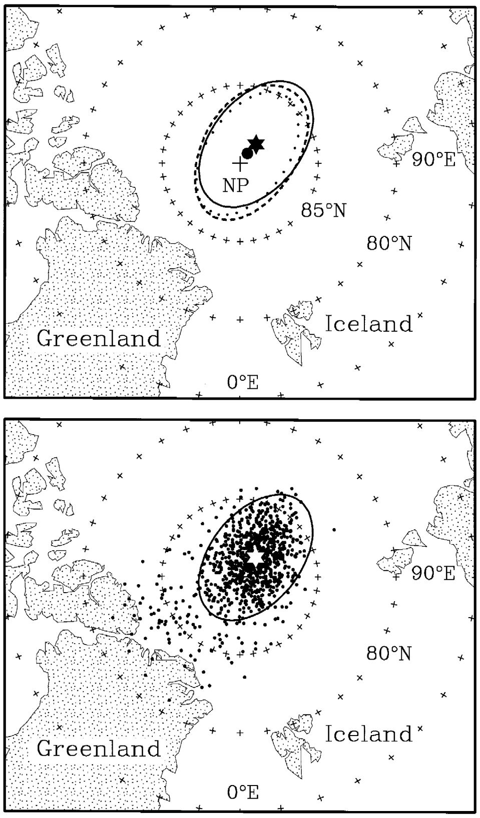

Fig. 3. Palaeomagnetic poles for the Brunhes epoch. Above: The solid curve represents the 95% confidence limits obtained from linear propagation of errors, the dashed curve gives the limits obtained by contouring the values of the χ^2 statistic corresponding to the 95% confidence level, and the dotted curve gives the limits obtained from Bingham statistics applied to the Monte Carlo simulated poles, which included simulating a 2° standard error in ridge strike. Below: The dots represent the poles obtained from 1000 Monte Carlo simulations. (Polar stereographic projections with latitude tick marks every 5° and longitude tick marks every 10°).

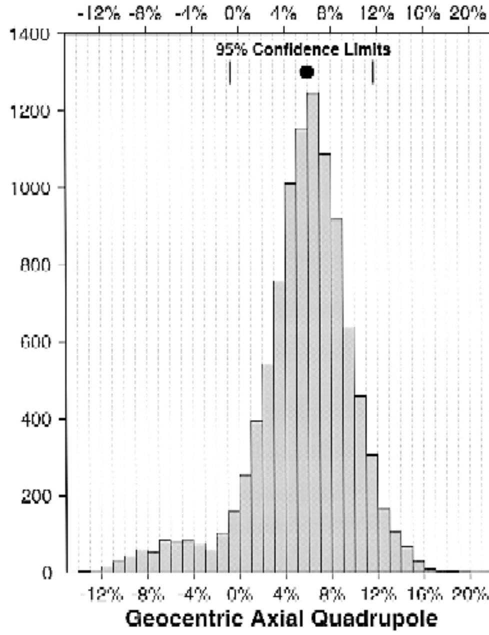

Fig. 4. Histogram of the GAQ component (given as a percentage of the GAD component) obtained from 10,000 Monte Carlo simulations assuming a 2° standard error in ridge strike.

In general our error analysis shows that, within the uncertainties, a pure GAD field is marginally acceptable and thus the GAD hypothesis cannot be rejected, unless we further assume that the Brunhes palaeomagnetic axis coincides with the present Spin axis. Larger data sets that combine skewness observations with continental palaeomagnetic data may narrow the uncertainty region and constrain the size of the quadrupole and other non-dipole components.

5. Data importances

Data importances determined by the maximum-likelihood inversion method [38] indicate that 11%

of the data (22 of 194 data with importances greater than 0.03) contain 49% of the information content that constrains the three adjustable parameters (latitude and longitude of the pole and the GAQ component). These data are from regions in which the ridge axis strikes within 60° of due north and is located within 15° of the palaeoequator. Data with these attributes are very sensitive to changes in the position of the palaeomagnetic pole and to the size of the GAQ component (Fig. 5). In contrast, 56% of the data (109 data with importances less than 0.01) contribute only 14% of the information content. In general, these relatively unimportant data come from regions with palaeolatitudes greater than 30°.

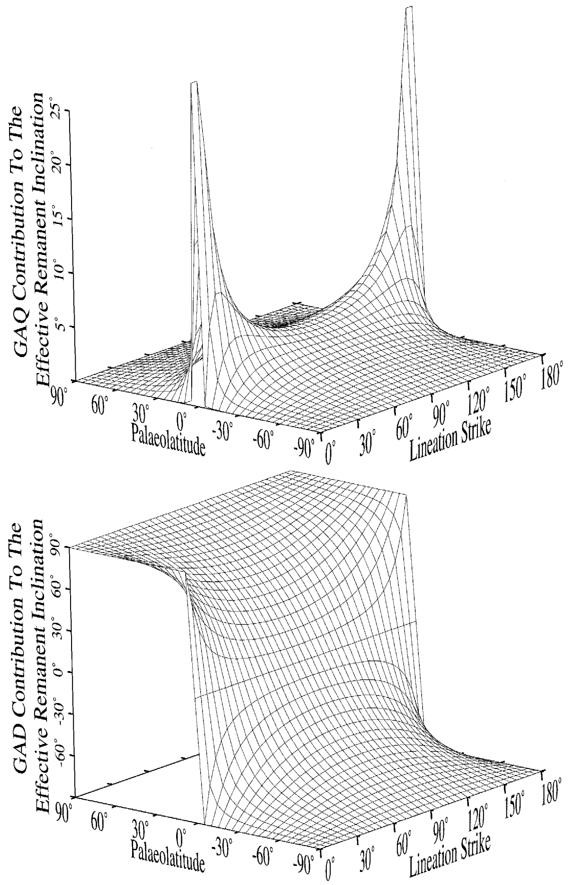

Fig. 5. The variation in the effective remanent inclination versus palaeolatitude and lineation strike is illustrated for a pure GAD field (bottom) and for the contribution of a GAQ component that is 5% of the GAD component (top). Both diagrams illustrate that the effective remanent inclination, and hence the skewness, varies most rapidly at low palaeolatitudes for lineations that have near north–south strikes. The amplitudes of magnetic anomalies with such properties are, however, smaller than those of other anomalies, which in general results in a smaller signal-to-noise ratio. Maximum values for the change in effective inclination caused by a GAQ field have been truncated at 25° for illustrative purposes.

The data importances could be distributed more evenly amongst the data, however, if more magnetic anomaly profiles were available from near-equatorial ridge axes, particularly those with northerly trends. Collection of such profiles will be an important step in providing much tighter constraints on the size of the non-dipole components of the geomagnetic field.

6. Anomalous skewness test

Past skewness studies observed that the apparent effective remanent inclination computed from the observed phase shift systematically differs from the true effective remanent inclination [31,40,42–49]. Most mechanisms invoked to explain anomalous skewness predict that it would be distributed symmetrically about the ridge axis. Because the Central anomaly spans both sides of a spreading axis, biases caused by anomalous skewness should be negligible; the effect of anomalous skewness from one side of the ridge axis should cancel that from the opposite side.

We test this assumption by performing an additional inversion where we include anomalous skewness as an adjustable parameter. Neither the best-fitting pole nor the GAQ change significantly and, as expected, the anomalous skewness differs insignificantly from zero ($3.0° \pm 4.4°$). If anomalous skewness is symmetrically distributed about the ridge axis, and therefore the true mean value of anomalous skewness is zero for the Central anomaly, then this test indicates that our inversion method [31] provides accurate estimates of anomalous skewness. Extension of this method to older magnetic anomalies has and should continue to provide important new constraints on the size and source of anomalous skewness.

7. Conclusions

New skewness data from the Central anomaly add nearly 200 palaeomagnetic observations of the Brunhes field. These observations indicate that the palaeomagnetic field averaged over the past 0.78 m.y. can best be described by a geocentric axial dipole term and a small geocentric axial quadrupole term that has the same sign as, and is $6.0\%^{+5.7\%}_{-6.7\%}$ the size of, the dipole term. The Geocentric Axial Dipole Hypothesis is marginally acceptable within the uncertainties and thus withstands the test provided by this new independent data set. If we further assume that the palaeomagnetic field is aligned with the present spin axis, however, the quadrupole term then differs significantly from zero.

The quadrupole component estimated from the skewness data is comparable to values found in prior studies, although the uncertainty in the estimate is about double that estimated from other palaeomagnetic data sets [19,23,24]. Our results, however, indicate several future directions for improvement: First, the uncertainty in GAQ component could be significantly reduced, perhaps to a few percent or less if more near-equatorial magnetic profiles existed. Currently, roughly 50% of the solution is constrained by 22 profiles within 15° of the equator. Thus, future high resolution magnetic surveys over the East Pacific Rise, the Mid-Atlantic Ridge, and the Central Indian Ridge between 15°N and 15°S latitude will offer important new geomagnetic constraints. Second, combining our skewness data with other types of palaeomagnetic data should reduce biases caused by the poor geographic distribution of data and improve the accuracy and precision of geomagnetic field estimates.

The skewness method shows great promise for future palaeomagnetic studies. Our results illustrate that skewness data can provide accurate palaeomagnetic poles that have precisions similar to typical palaeomagnetic poles estimated from rock exposures on continents. Thus, extension of the skewness method to older magnetic anomalies will provide not only a means for documenting geomagnetic field behaviour through time, but also a means for improving our knowledge of the palaeogeographic positions and kinematics of the major lithospheric plates.

The analysis of the shapes of magnetic anomalies extends the use of the large marine magnetic database in a manner similar to the way waveform analysis has opened new frontiers in seismology: Seismograms were originally interpreted in terms of the spacing or arrival times of different seismic phases, which gave information about the location of the quake and structure of Earth's interior. By analogy, marine magnetic anomaly profiles were interpreted in terms of the spacing or positions of different anomalies, which gave the relative positions and motions of the lithospheric plates. Waveform analysis in seismology has provided valuable new information on the earthquake source mechanism and rupture history. In this study, we have shown that shape analysis of marine magnetic anomalies may similarly provide valuable information on the geomagnetic field source and plate palaeogeographies.

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