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Comment on "Tectonic Rotations in Extensional Regimes and Their Paleomagnetic Consequences for Ocean Basalts" by Kenneth L. Verosub and Eldridge M. Moores

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INTRODUCTION

One of the more intriguing results from paleomagnetic studies of Deep Sea Drilling Project (DSDP) basalts is that a surprisingly large number of samples have inclinations that deviate significantly from expected values. *Verosub and Moores* [1981] sought to account for what appear to be systematic departures of mean inclination at several DSDP basement sites in terms of tectonic rotations along listric normal faults. Such rotations, about horizontal axes perpendicular to the extension direction and typically amounting to 30°–50° but as large as 70° to 90°, were suggested to be characteristic of an extensional tectonic regime such as near an ocean spreading ridge system. There is a clear implication that large tectonic rotations are a characteristic process associated with ocean crust formation.

Although remanent inclination has been measured on basalt recovered from many DSDP drill sites [e.g., *Lowrie*, 1977], most of these holes have shallow penetration. Only a few deep penetration sites are thought to provide an adequate sampling of the earth's magnetic field during formation of the oceanic crust and thus data relevant to tectonic rotations [*Harrison and Watkins*, 1977; *Hall and Robinson*, 1979; *Verosub and Moores*, 1981]. Consequently, it is not entirely clear from such few determinations how pervasive and systematic are the directional deviations. A major piece of evidence pertaining to this question not fully addressed by *Verosub and Moores* [1981] is the shape or skewness of seafloor spreading anomalies. A marine magnetic anomaly represents the aggregate effect of the magnetization of the entire oceanic crust over an area of several tens of square kilometers. Moreover, magnetic anomalies not only record reversals of the magnetic field but are also extremely sensitive to processes occurring at the ridge crest [e.g., *Schouten and McCamy*, 1972; *Blakely*, 1976]. In particular, magnetic anomalies record in an easily measurable and understandable way the average amount of tilting of the magnetized layer(s) of the oceanic crust. Analysis of marine magnetic anomaly data available from the world ocean can therefore be used to test the suggestion of *Verosub and Moores* [1981] for widespread and systematic tectonic rotation of the oceanic crust which presumably includes the magnetic source layer(s).

Tectonic rotations of the magnetic source layer should be recorded as a phase shift in the magnetic anomaly pattern. This follows from the mathematical expression for a thin layer source model developed by *Schouten and McCamy* [1972]. In their model the phase parameter θ is given by the expression

$$\theta = I_0' + I_r' - 180°$$

where I_0' and I_r' are the effective present and remanent inclinations, respectively. The effective inclination, as shown in Figure 1, is the inclination in the plane perpendicular to the lineation direction [*Gay*, 1963]. Consequently, a tectonic rotation about an axis parallel to the lineation direction has the effect of changing I_r' and therefore θ by the amount of the rotation. This change in θ is equivalent to phase shifting the magnetic anomaly pattern. Such phase shifts in the magnetic anomaly pattern that are not predicted by the standard, thin layer block model are referred to as "anomalous skewness" [*Cande*, 1976]. For example, a 10° tectonic rotation of this idealized source layer would cause 10° of anomalous skewness.

THREE TESTS FOR ANOMALOUS SKEWNESS

Verosub and Moores [1981] considered the inclinations at four DSDP sites: 319, 332, 410, and 417. At three of these sites the magnetic anomalies are not suitable for a detailed skewness analysis. Sites 332 and 410 are near the Mid-Atlantic Ridge axis. It is difficult to determine accurately the skewness of anomalies formed at slow spreading centers during a time of frequent polarity reversals, as was the case for these two sites. Hole 319 was drilled on the flanks of the extinct Galapagos Rise in an area with poorly defined magnetic anomalies.

The magnetic anomaly sequence that crosses DSDP site 417 on anomaly M0 in the central Atlantic, however, is exceptionally clear. *Verosub and Moores* [1981] argue that the anomalous inclination in the basalts recovered at site 417 are due to an outward rotation of 58°. If this tectonic rotation is representative of the entire magnetic source layer in the region around the site, we would expect 58° of anomalous skewness in the overlying anomaly pattern. A straightforward way to check for anomalous skewness is to compare the skewness of the observed profile to the skewness predicted by an independently determined paleomagnetic pole position. An accurate way to do the comparison is to reduce the observed anomaly to the pole [*Blakely and Cox*, 1972] and compare the reduced profile to a model constructed for $\theta = 0°$ [*Schouten and Cande*, 1976].

In Figure 2 the observed profile at site 417 is compared to models constructed for $\theta = 0°$, corresponding to no rotation, and models for $\theta = 20°$, 40°. and 60° corresponding to 20°, 40°, and 60° of outward tilting. It is apparent from Figure 2 that the observed profile most closely resembles the model for $\theta = 0°$. For $\theta = 60°$ the model profile bears little resemblance to the observed profile. We therefore conclude that the average amount of tectonic rotation of the entire magnetic source layer in the general vicinity of site 417 must be near 0°.

The same conclusion can be reached by comparing the skewness of anomalies that formed at the same time and place but on opposite sides of the spreading center. Regardless of paleomagnetic pole position, such conjugate anomalies theoretically have the same effective remanent inclination I_r'. If there is no tilting, the difference in their observed skewness will equal the difference in I_0' at the present locations of the

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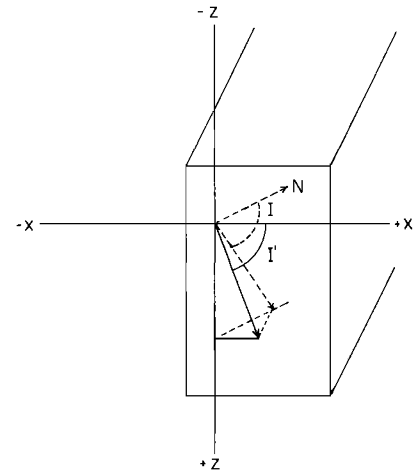

Fig. 1. The effective inclination I' is the inclination of the vector component in the plane normal to the strike of the lineations [from *Schouten and Cande*, 1976].

anomalies. In Figure 3 we compare the skewness of anomalies M0 to M4 from conjugate locations in the central Atlantic: the western Atlantic profile is located 150 km south of the New England Seamounts and the eastern Atlantic profile is from 120 km south of the Canary Islands. (We did not use the profile at site 417 because there was no profile available from the conjugate location on the African plate.) Both profiles have been phase shifted through a range of θ values. It is apparent from Figure 3 that both profiles appear deskewed for the same value of I_r' (indicated by an asterisk). This value also corresponds to the Lower Cretaceous pole position for North America of *Van der Voo and French* [1974]. Indeed, anomalous skewness is not observed in anomalies M0 to M4 anywhere in the North and South Atlantic [*Cande*, 1978].

Verosub and Moores [1981] advocate a rather obscure method of combining magnetic anomaly and magnetic inclination data to determine paleolatitude and tectonic tilting for areas, such as the northwestern Pacific plate, which are not tied to any continental land masses. The theta method of *Schouten and Cande* [1976] can be combined with magnetic inclination data to deal more simply with the same problem. *Larson and Lowrie* [1975] showed how magnetic inclination data and anomaly skewness data can be combined in a straightforward way to determine paleopoles, in this case for the Late Jurassic and Early Cretaceous of the Pacific plate. Tectonic rotations were not considered by *Larson and Lowrie* [1975]. However, the geometry of the magnetic lineations in the northwestern Pacific are sufficient not only to determine a paleopole [*Larson and Chase*, 1972] but also to estimate the amount of tectonic rotation.

In the theta method the skewness of a set of magnetic lineations is used to determine a lune of confidence, i.e., the locus of paleomagnetic poles that satisfy the observed skewness. Two or more lunes of confidence determined from the skewness of anomalies of the same age from different areas of the same rigid plate should intersect at the position of the paleopole. The size of the zone of confidence varies depending on how well the skewness is known and on the geometry of the lineations.

Larson and Chase [1972] used the "theta" method to calculate a paleomagnetic pole from the skewness of anomalies M0 to M10 in the Japanese, Hawaiian, and Phoenix lineations. The intersection of the lunes of confidence for these lineations is very sensitive to the presence of anomalous skewness and therefore to systematic tectonic rotations. We have reexamined the data used by *Larson and Chase* [1972] to see what further limits can be placed on anomalous skewness. First, we recalculated the skewness of the lineations using the method of phase shifting the anomalies until they appeared to be deskewed. This method has been shown by *Schouten and Cande* [1976] to be more precise than the method of comparing the observed anomalies to models constructed for a range of theta values used by *Larson and Chase* [1972]. The result is that we have reduced the width of the 95% confidence interval from 10° to about 5° (Table 1). Consequently, the intersection of the revised lunes of confidence, shown in Figure 4*a*, defines a much smaller zone of confidence than that given by *Larson and Chase* [1972]. We can now test for anomalous skewness, corresponding to systematic tectonic rotations, by determining the effect of changing the theta values on the intersection of the lunes. In Figure 4*b* it is shown that if there is as little as 10° of systematic anomalous skewness, corresponding to an average of 10° of outward tilting on each set of lineations, then the lunes no longer intersect. The most plausible interpretation is that there is less than 10° of outward tilting, although we have made the critical assumption that the amount of tilting is the same for each set of lineations. The best intersection of the lunes is for about 3° of anomalous skewness which is not considered significantly different than 0°.

Discussion

Tectonic rotation and magnetic anomaly skewness data are not necessarily irreconcilable. Basement holes are generally shallow, and even the deepest, site 504B, has not penetrated all of layer 2 [*Scientific Party*, 1982]. Several researchers [*Blakely*, 1976; *Kidd*, 1977; *Harrison*, 1976] including ourselves

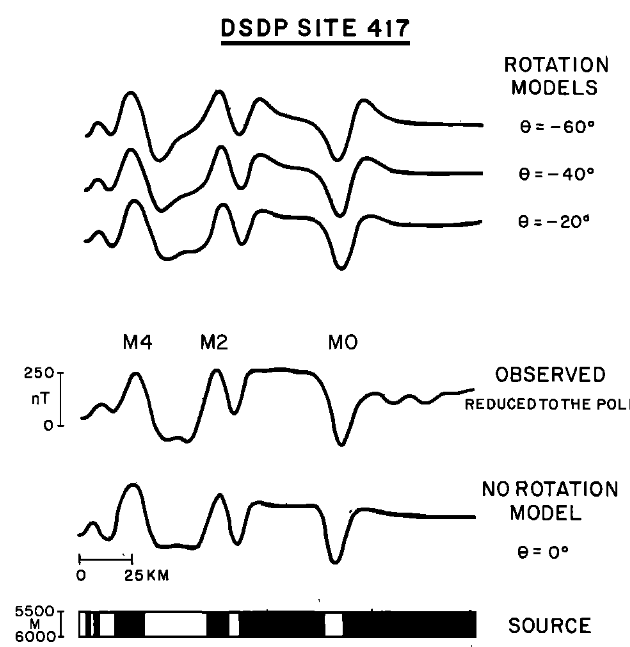

Fig. 2. Magnetic anomaly profile across DSDP site 417 reduced to the pole and compared to models for no rotation (bottom) and 20°, 40°, and 60° of the rotation (top). Note that the observed profile most closely resembles the model with no rotation ($\theta = 0°$). There appears to be no anomalous skewness. Profile from USNS *Lynch*. Parameters for reduction to the pole: $I_0 = 57°$, $D_0 = -9°$, $I_r = 31°$, $D_r = 18°$, azimuth = 30°, $\theta = 74°$, The Lower Cretaceous pole for North America (72.2°N, 185.5°E) of *Van der Voo and French* [1974] was used to determine the remanent magnetization directions.

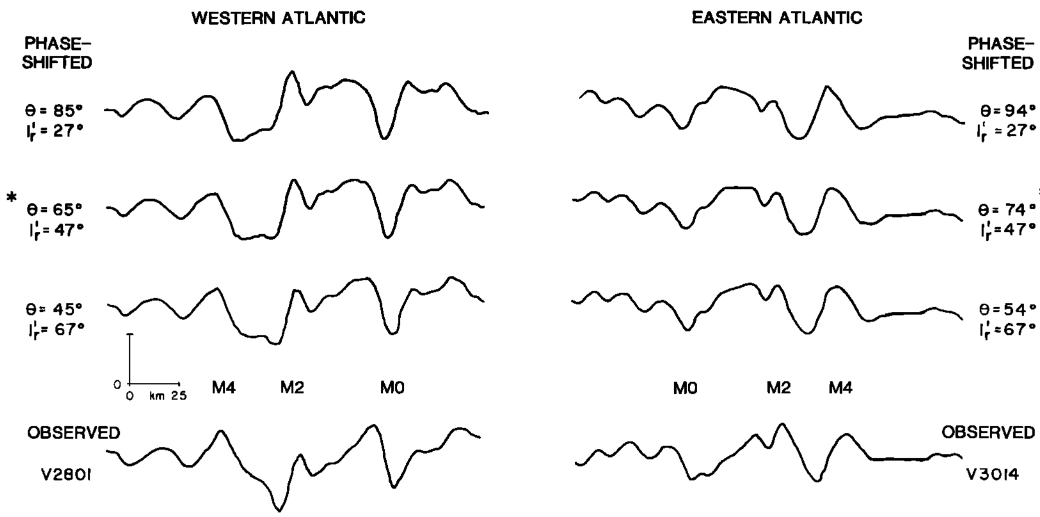

Fig. 3. Profiles from conjugate locations in the central Atlantic phase-shifted through a range of θ values. Since the two profiles appear deskewed for the same value of I_r' (47°), we conclude that there is no measurable anomalous skewness. Western Atlantic parameters: latitude = 36°N, longitude = 61°W, $I_0 = 65°$, $D_0 = 18°$, azimuth = 40°, $I_0' = 68°$; eastern Atlantic parameters: latitude = 28°N, longitude 22°W, $I_0 = 42°$, $D_0 = 13°$, azimuth = 20°, $I_0' = 59°$. A no-rotation model corresponding to the western Atlantic profiles is given in Figure 2.

[*Cande and Kent*, 1976; *Kent et al.*, 1978] have suggested that a significant portion of the magnetic source lies below layer 2. The entire oceanic crust, both upper and lower source layers, may be tilted. The acquisition of magnetization of a lower layer may be delayed until after the tilting has occurred, for example, not until it cools conductively below the Curie point; alternatively, the tilting is confined to the upper layer. In either case, the net magnetization of the rotated upper layer must be assumed to decay and to not make an appreciable (skewed) contribution to the total anomaly. It should be pointed out that this assumption is implicit in the method for combining basalt inclination and anomaly skewness data proposed by *Verosub and Moores* [1981]. In their method the curves representing the inclination data are adjusted for varying amounts of tectonic rotation, while the curves representing anomaly skewness data are not adjusted. This is only valid if the source region of the magnetic anomaly has either not been systematically rotated or else acquired its magnetization after the rotation.

We do not believe that such models are generally warranted. It seems highly improbable that the upper layer does not remain the dominant source even though deeper sources may well contribute to the generation of marine magnetic anomalies. The upper layer in young oceanic crust has been shown to be strongly magnetized on the basis of detailed magnetic surveys [*Talwani et al.*, 1971; *Atwater and Mudie*, 1973] and from dredge and DSDP sampling [*Irving*, 1970; *Lowrie*, 1977]. Decay of the upper layer contribution has been interpreted from the decrease in anomaly amplitude near the ridge crest [*Klitgord et al.*, 1975] and from the apparent increase with time in transition zone widths [*Blakely*, 1976]. However, the older Mesozoic (M sequence) anomalies appear sharply defined with narrow transition zones, observations that are most plausibly explained by the continued dominance of a strongly magnetized upper source layer [*Larson et al.*, 1975].

We have demonstrated that there is strong evidence from analysis of marine magnetic anomalies against anomalous skewness in the vicinity of site 417 and in oceanic crust of similar age in the North and South Atlantic and the northwestern Pacific. If indeed the upper layer is the dominant source of the anomalies, then this absence of anomalous skewness in anomalies M0 to M4 strongly suggests that tilting is not systematic over at least these wide areas and in particular over site 417 where anomalous inclinations are observed. Consequently, we believe that the anomalous basalt inclinations obtained from the small number of deep drill holes are only of local significance and are not representative of the upper oceanic crust.

Anomalous skewness is observed in other areas, at different times. For example, 14° of anomalous skewness is observed in anomalies 27–32 in the North and South Pacific [*Cande*, 1976]. Unfortunately, there is not a unique interpretation to a small amount of anomalous skewness. Although it may be due to outward tilting (rotation of only 14°), it can also be explained by a two-layer (or more) model of the ocean crust in which the remanent magnetization within the deeper layer was acquired along a sloping Curie point isotherm [*Cande and Kent*, 1976; *Blakely*, 1976; *Kidd*, 1977]. A particular long-term variation of the dipole field may be a contributing factor.

A more puzzling and potentially more interesting observation is the 30°–40° of anomalous skewness that is seen in anomalies 33 and 34 throughout the North and South Atlan-

TABLE 1. Skewness of Anomalies M0 to M10

Area	Latitude	Longitude	Inclination	Declination	Azimuth	Number of Points	Mean θ	$\Delta\theta$
Japanese	39°N	153°E	51°	356°	250°	28	−231°	5.4°
Hawaiian	27°N	179°E	39°	9°	150°	21	−150°	5.4°
Phoenix	2°N	178°W	1°	10°	80°	35	−230°	5.3°

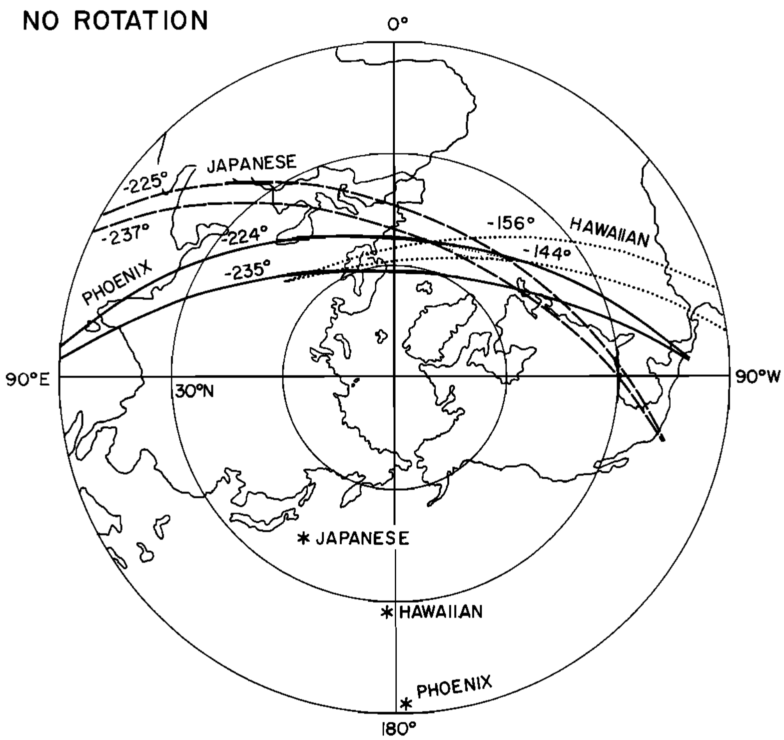

Fig. 4*a*. Lunes of confidence for anomalies M0 to M10 for the Japanese, Hawaiian, and Phoenix lineations assuming no anomalous skewness. The intersection of the lunes near 50°N, 30°W defines the zone of confidence for the early Cretaceous Pacific plate pole. See Table 1 for parameters.

tic [*Cande*, 1978]. It is difficult to model such a large phase shift with the two-layer model with no tilting; geomagnetic field behavior was thought to be responsible. If the anomalous skewness is instead due to tectonic rotation, it raises the problem of why tilting should be so large and widespread at anomaly 33–34 time and yet not be present at all in the oceans at M0 to M4 time.

We think that drilling additional deep basement holes on

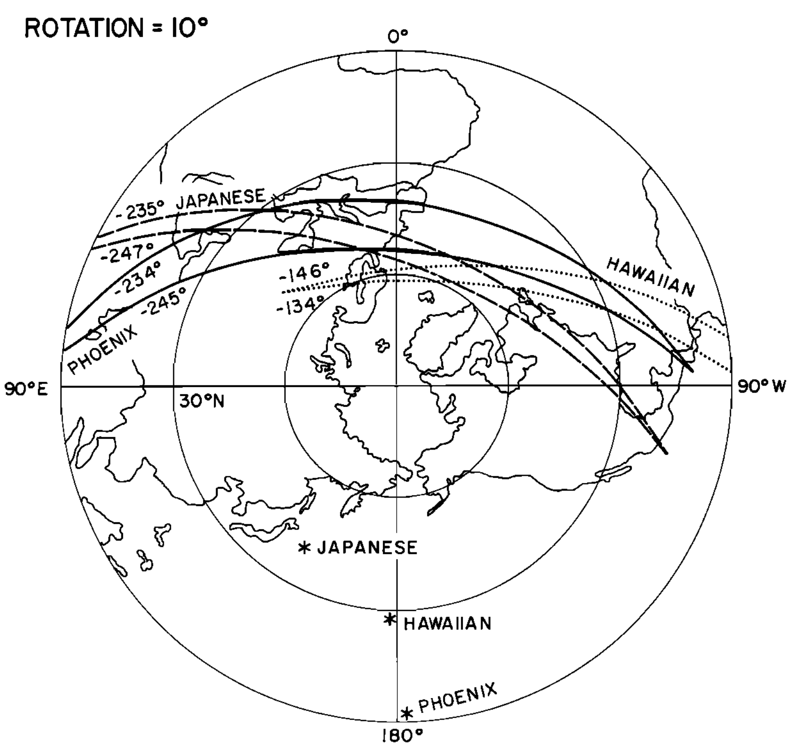

Fig. 4*b*. Same as figure 4*a* only the lunes have been correct for 10° of anomalous skewness corresponding to 10° of outward tilting. Since the lunes no longer intersect in a common area, we conclude that there must be less than 10° of anomalous skewness. The best intersection is for about 3° of anomalous skewness.

oceanic crust is necessary to resolve questions of systematic tectonic tilting, of the contributions of the magnetic source layers, and of the significance of anomalous skewness. For example, a comparison of oceanic crust in the North Atlantic underlying anomaly M0, where no anomalous skewness is observed but systematic tilting has been inferred, and anomalies 33–34, where large anomalous skewness might reflect systematic tilting, would make a good program for future crustal drilling.

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