Temporally constrained tectonic rotations derived from magnetostratigraphic data: Implications for the initiation of the Garlock fault, California

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ABSTRACT

Examination of declination anomalies within a well-controlled chronologic framework can permit precise delineation of the progression of a tectonic rotation. In the past, declination anomalies from numerous spatially separated and individually dated localities have been synthesized in order to define regional, progressive rotations. Rarely, however, have magnetostratigraphic data from a single locality been used successfully to chronicle a sequential rotation that resulted from movement along a nearby fault. Magnetostratigraphic studies from the El Paso basin in southern California reveal progressively smaller amounts of counterclockwise rotation for strata dated between 11 and 7 Ma. Two tests indicate that this is a temporally controlled, rather than a spatially controlled, rotation. This rotation is interpreted to have resulted from sinistral shear along the Garlock fault. As such, it appears to delimit the initiation of Miocene movement along the western segment of this major strike-slip fault.

INTRODUCTION

In numerous previous studies, the sequence of magnetic reversals recorded by a succession of volcanic or sedimentary rocks has been used to define a local magnetic polarity stratigraphy (MPS), which in turn has been correlated with the magnetic polarity time scale (MPTS) in order to generate a chronology for the rock succession. Frequently, directional magnetic data used to define the MPS are statistically grouped in order to demonstrate the presence or absence of postdepositional tectonic rotations for the studied strata (e.g., Opdyke et al., 1982). Such averaging of the data defines the mean amount of rotation but usually reveals little about the specific timing of the rotational events. When magnetic sampling sites are placed with sufficient density and when they yield high-quality data, however, it is possible to examine successive increments of a single magnetostratigraphy and to delineate the progression of a tectonic rotation through a brief interval of geologic time. The analytical technique involves clustering of the declination data within discrete chronologic intervals as defined by the magnetostratigraphy, calculation of the uncertainty associated with each declination mean (Demarest, 1983), and analysis of the resulting rotation-vs.-time data. The data must also be tested to examine the effects of both plunging structures and spatially, rather than temporally, modulated rotations. After making corrections for previously defined apparent polar wander paths, such plots illustrate changes in the amount and rate of local rotation through time and may be interpreted as representing deformation related to specific tectonic events.

A similar result (rotation vs. time) has been achieved in the past by examining data for chronologically restricted intervals from many localities and grouping these together to synthesize a regional rotational history (e.g., Hornafius et al., 1986; Van der Voo, 1969), but rarely have magnetostratigraphic data from a single section been successfully utilized for the same purpose (e.g., Wright and Walcott, 1986). In this paper, we present an example based on magnetostratigraphic studies in southern California that permits us to define discrete intervals of rotation related to movement along the Garlock fault and to illustrate some of the problems encountered in the interpretation of these data.

GARLOCK FAULT AND ROTATION OF THE RICARDO GROUP

The Ricardo Group (Loomis and Burbank, 1988; formerly termed the Ricardo Formation, Dibblee, 1952) comprises 1700 m of homoclinally dipping, fluviolacustrine strata situated in the El Paso basin between the southeastern edge of the Sierra Nevada and the Garlock fault (Fig. 1). Located along the northern margin of the Mojave Desert, the Garlock fault is a major tectonic boundary that delimits the southern extent of the Basin and Range province (Davis and Burchfiel, 1973). Because of its proximity to the Garlock fault, the Ricardo Group can potentially reveal information concerning the history of movement along the fault. Fission-track dates and a recently developed magnetostratigraphy, comprising 84 sites of 3 or more specimens/site (Burbank and Whistler, 1985; Loomis and Burbank, 1988), indicate that the Dove Spring Formation (formerly designated as the upper 1500 m of the Ricardo Formation) was deposited between 13.5 and 7 Ma. On the basis of the magnetic chronology and the declination data, a rotation-vs.-time plot (see Fig. 3) was constructed by separating the normally and reversely magnetized data, averaging 10–50 data points over each ~1- to 2-m.y. interval, and calculating the appropriate error (Demarest, 1983) for each declination anomaly (Table 1). There are no reversed data for the interval from 9 to 10.3 Ma (Fig. 2), and the relatively small number of reversed sites led us to group the 7–9 Ma reversed data together. The reversed data show greater scatter and larger uncertainties, perhaps due to incomplete removal of a postdepositional, normally magnetized overprint that persisted above the 450–500 °C demagnetization level used to determine the polarity of each specimen. Nonetheless, within the error limits of these data (Table 1 and Fig. 3), the trend and sense of rotation of the reversely magnetized points mimic that shown by the normally magnetized data. Because the declination of the North American paleopole position for the Miocene is within 1° to 3° of the modern axial dipole (Irving and Irving, 1982), no significant part of the observed declination anomalies in the Ricardo Group can be attributed to rotations of the North American plate.

The data indicate that the Dove Spring Formation has undergone an average of ~15° of counterclockwise rotation. Moreover, the timing of this rotation can be specified (Fig. 3). Dove Spring strata older than ~10 Ma are rotated about 15°–20°. Progressively younger strata appear to be rotated by diminishing amounts until 7 to 8 Ma, when the rotation appears to have been completed. Thus, over a 3-m.y. span, the Dove Spring Formation apparently underwent 15°–20° of counterclockwise rotation at a mean rate of ~5°–6°/m.y.

Although the homoclinal dips and nearly hor-

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izontal fold axes rule out plunging structures as a cause of the observed declination anomalies, this interpretation of the rotational data as a time-related phenomenon could be questioned because of the geometry of the exposures of the Ricardo Group. The oldest deposits were sampled to the southeast closer to the Garlock fault, whereas the younger deposits were sampled to the northwest nearer to the Sierra Nevada (Fig. 1). Consequently, the geographic distribution of the sampling sites permits an interpretation in which the observed differential rotation could reflect *spatial* control, similar to that observed along shear zones in southern Nevada (Nelson and Jones, 1987). In this scenario, the areas closest to the Garlock and El Paso faults would have rotated most freely, whereas the region to the northwest would have been restrained by the Sierra Nevada and would have undergone little or no rotation. Because the Ricardo strata strike obliquely southwest toward the El Paso and Garlock faults, there is considerable overlap (in terms of distance from the Sierra Nevada or from the Garlock fault) between parts of the section of different age (Fig. 1). This suggests that the observed rotation is a temporally, rather than a spatially, controlled phenomenon.

In order to test this hypothesis further, we used two additional approaches. First, we collected 24 specimens from the Cudahy Camp Formation (the basal 300 m of the Ricardo Group; Loomis and Burbank, 1987) that underlies the Dove Spring Formation in this area. The data from these ~18 Ma strata group together well (Table 1) and indicate that they have been rotated approximately the same amount as the overlying 13–10 Ma Dove Spring strata (Fig. 3). Thus, although the Cudahy Camp strata are both older and closer to the Garlock fault, their declination anomalies do not support the concept of increasing amounts of rotation as the Garlock fault is approached.

Second, we sampled a pair of ~12 Ma volcanic ash deposits along strike for 6 km (solid dots, Fig. 1). Along this traverse, the northern sampling sites are nearly as far from the Garlock and El Paso faults as the youngest sampled strata are in the upper part of the Dove Spring Formation to the west, whereas the southern sites are closer to the fault than any other magnetic sites used in this study of the Dove Spring. Furthermore, by sampling ash, we can be assured that virtually isochronous surfaces are being considered. The magnetic results from the 24 samples collected along the ash deposits (Table 1 and Fig. 4) show some scatter but indicate that the ash deposits have been generally rotated about 16°–20°. There is no significant trend as a function of distance from the faults ($r^2 = 0.01$, where r^2 equals the percentage of the variance explained by the correlation), and the amount of rotation seen in these ash deposits agrees with

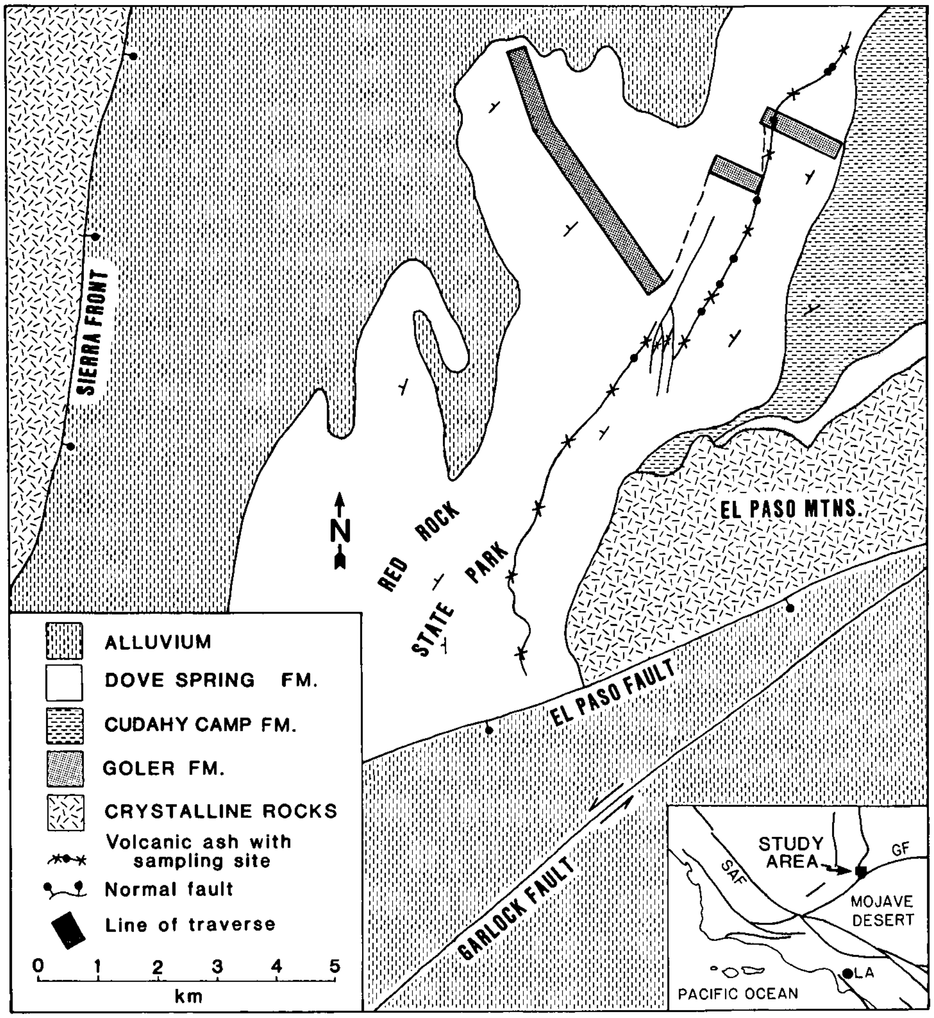

Figure 1. Simplified geologic map of northern Mojave Desert and southern Basin and Range province in vicinity of El Paso basin. Also depicted are position of magnetic sampling traverse in Dove Spring Formation of Ricardo Group and additional sampling sites (solid dots) in ~12 Ma volcanic ash deposits. Inset: LA = Los Angeles; SAF = San Andreas fault; GF = Garlock fault.

TABLE 1. ROTATIONAL DATA FROM THE RICARDO GROUP

Formation	Age (Ma)	Polarity*	N	k	α_{95}	I (°)	D (°)	δ (°)
Cudahy Camp	~18	N	18	33.4	6.1	36.3	-14.6	6.1
"	~18	R	5	26.0	15.3	-30.1	168.4(-11.6)	12.4
Dove Spring	12-13.5	N	21	31.2	5.8	50.8	-20.7	7.4
"	10-12	N	36	16.0	6.1	39.7	-20.8	6.3
"	9-10	N	45	18.3	5.1	52.2	-12.6	6.7
"	8-9	N	15	46.8	5.7	46.7	-7.1	6.7
"	7-8	N	12	71.3	5.1	54.9	2.0	7.1
Dove Spring	12-13.5	R	15	6.1	16.8	-41.0	165.5(-14.5)	18.1
"	10-12	R	15	27.0	7.5	-42.7	154.8(-25.2)	8.2
"	7-9	R	27	5.3	13.3	-57.8	183.9 (3.9)	20.5
"								
Dove Spring (ash sites)	~12	N	24	80.5	3.7	56.0	-17.9	5.3
Dove Spring (S. of El Paso Flt.)	~7-9	R	12	9.6	14.8	-46.2	142.0(-38.0)	16.1

Note: N = number of specimens; k = Fisher statistic; α_{95} = radius of 95% confidence cone around mean; I = inclination; D = declination; δ = 95% confidence limits on declination anomaly as corrected by Demarest (1983).
*N = normal; R = reversed.

the observed rotation in other Dove Spring strata of this age (Fig. 3). These results lend additional support to our interpretation that this rotation occurred between 10 and 7 Ma.

The precise cause of the syndepositional rotation of the upper Ricardo Group during this limited interval of time is not yet clear. Although it could possibly be related to counterclockwise rotations determined for several localities in the central and western Mojave block or in the San Gabriel Mountains to the south (Burke et al., 1982; Luyendyk et al., 1985; Hornafius et al., 1986; MacFadden et al., 1987), these other rotations are not very well constrained in either time or space; except for their similar magnitude and sense of movement, there is little to suggest any causal link with the Ricardo rotation. Instead, we interpret the rotation as resulting from shearing caused by major sinistral movement along the Garlock fault (Fig. 1).

No previous studies, however, have clearly defined the timing of initiation of movement along this fault. Total offset along the Garlock fault is at least 64 km (Smith, 1962; Davis and Burchfiel, 1973). Estimates of Quaternary rates of movement along the fault range from 2 to 12 mm/yr (Carter, 1980; Rodgers, 1979; LaViolette et al., 1980). If a mean long-term rate of ~7–8 mm/yr (Carter, 1980) is extrapolated back in time, movement along the Garlock fault would have commenced 8–9 Ma in order to accommodate the minimum of 64 km of offset. The initiation of basin and range extensional tectonics immediately north of the Garlock fault is also not well dated, but studies east of the Ricardo area in the Kingston Peak region indicate that 12.5 Ma plutonic rocks (Jones, 1983) are cut by younger, westward-propagating detachment faults (Burchfiel et al., 1985). This extension was probably accommodated by concurrent movement along the Garlock fault. These previous studies suggest that initial movement along the Garlock fault should be constrained to an interval between 8 and 12.5 Ma. Our magnetic rotation data (Fig. 3) suggest that the inception of motion and the resultant sinistral shearing in the Ricardo area occurred at ~10 Ma.

Because evidence for continuing Quaternary motion is strong (Clark and Lajoie, 1974; Carter, 1980), the apparent termination of differential rotation ~7 Ma would suggest either that movement has occurred in two widely separated pulses or that the initiation of the El Paso fault (Fig. 1) may have structurally isolated the El Paso basin from further rotation. This latter possibility is supported by the observed rotation of >35° (Table 1) of a block of upper Ricardo sediments trapped between the Garlock and El Paso faults.

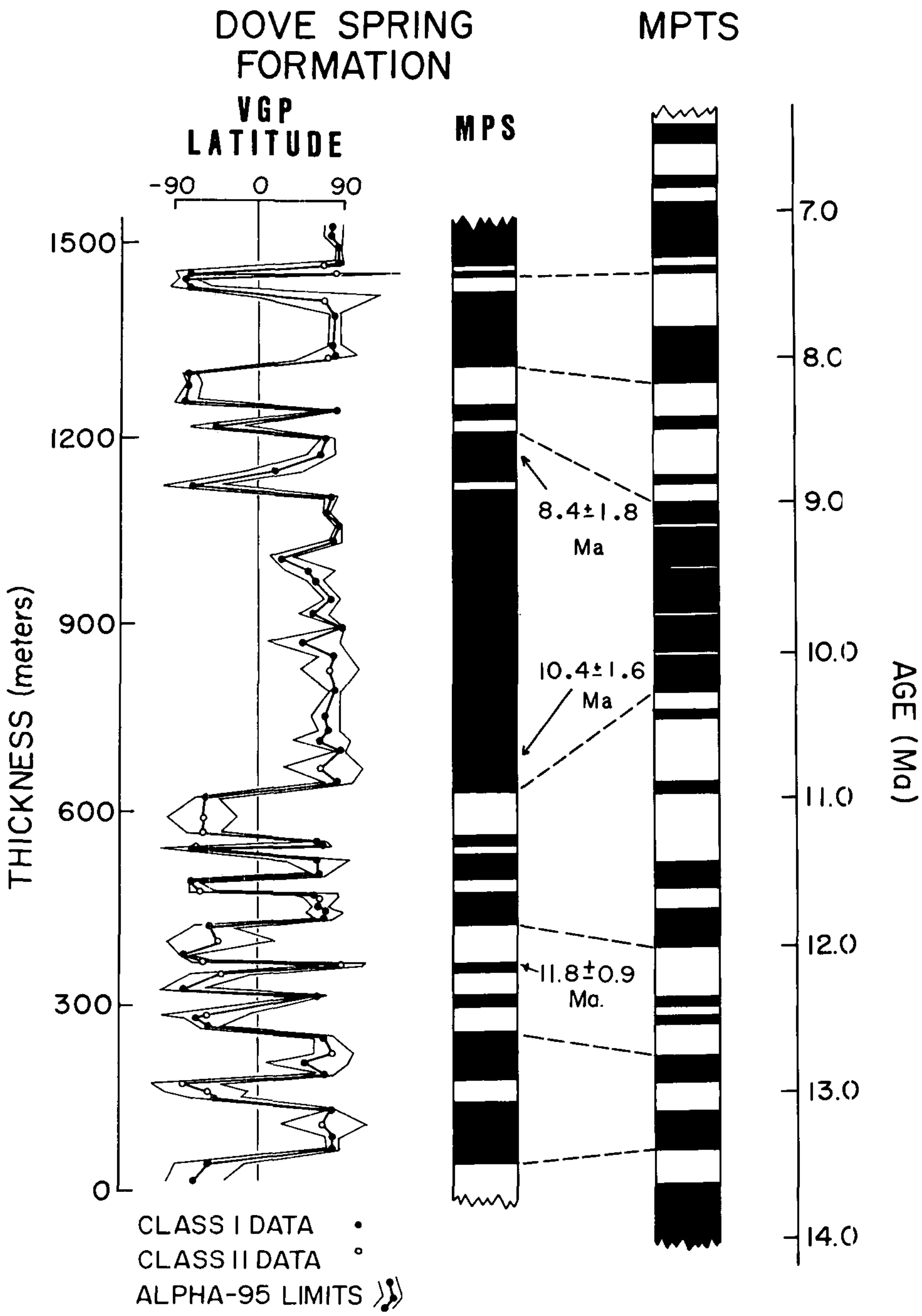

Figure 2. Dove Spring Formation magnetic polarity stratigraphy (MPS) and its correlation with magnetic polarity time scale (MPTS) (Berggren et al., 1985). Ricardo magnetic zonation is based on latitude of virtual geomagnetic pole (VGP). Three fission-track dates (Burbank and Whistler, 1985; Cox and Diggles, 1986) on zircons extracted from volcanic ash deposits are shown at ~370, 680, and 1180 m. Dates help to corroborate correlation depicted here.

SUMMARY

This example from southern California illustrates that, through the use of detailed magnetostratigraphic data, the timing of a tectonic rotation can be specified with improved precision. From these data, both the amount and rate of rotation can be calculated, and discrete intervals of rotational activity can be delineated. Although the techniques described here can provide a new level of insight into tectonic and kinematic phenomena, at least two criteria must be met before the data can be confidently interpreted. First, it must be demonstrated that the observed rotations are temporally, rather than spatially, controlled. This criterion is met by the described example. Second, in order to make a reliable tectonic interpretation, there must be a sufficient spread and density of magnetic data to remove most ambiguities. In the example presented here, the rotation itself is unambiguous, and it can be logically linked to the initiation of movement along the Garlock fault ~10 Ma. However, there are no time-controlled kinematic data for the actual faults bounding the

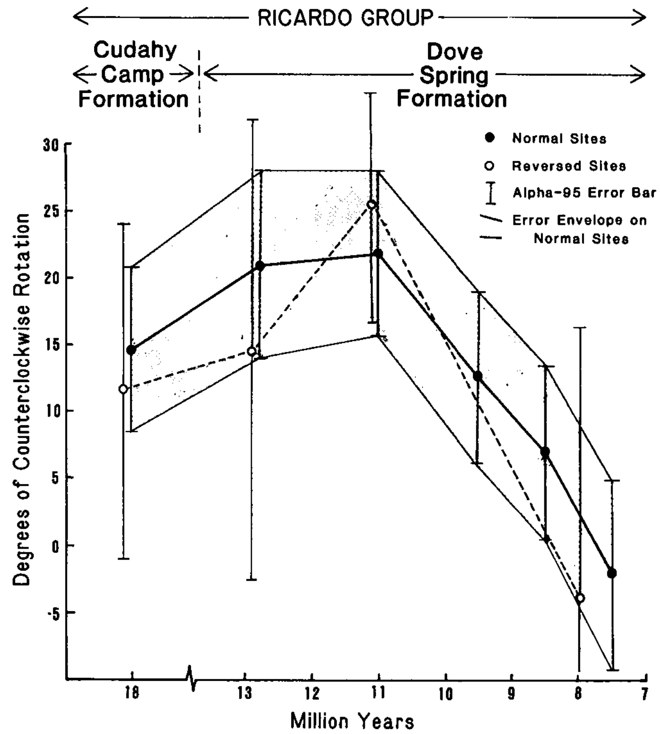

Figure 3. Counterclockwise rotational history of Ricardo Group. Normally and reversely magnetized data are plotted separately; path of rotation is defined by alpha-95 error envelopes on normally magnetized data and is referred to modern dipole field. Averaged data for 24 specimens from ~18 Ma Cudahy Camp Formation reveals amounts of rotation similar to that of overlying Dove Spring strata.

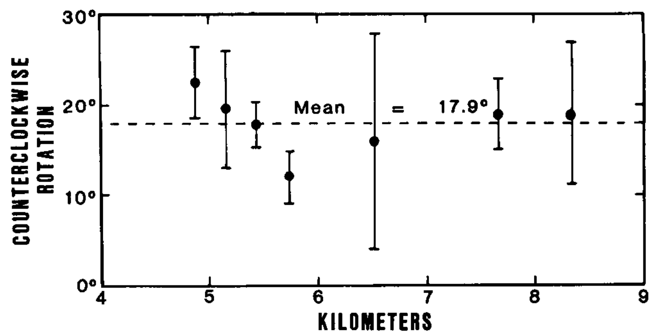

Figure 4. Counterclockwise rotations of isochronous volcanic ash deposits collected along strike at varying distances from Garlock fault. For site locations, see Figure 1. There is no statistically significant correlation (r^2 = 0.01) between degree of rotation and distance from fault.

Ricardo area that could definitively demonstrate the cause of the observed rotation. Despite these uncertainties, this study illustrates an unusual application of magnetostratigraphic data, and because it indicates the timing of initial sinistral movement along the Garlock fault, it provides a refinement on previous tectonic models for this area.

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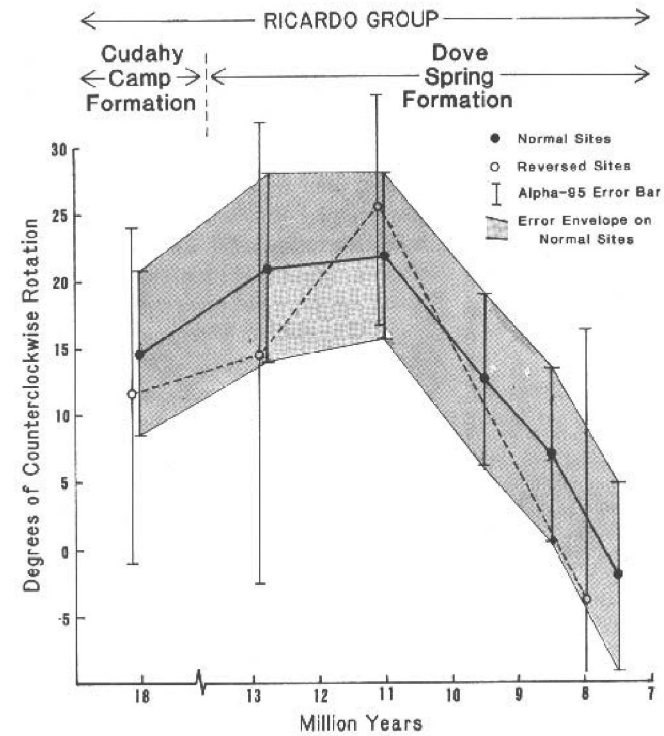

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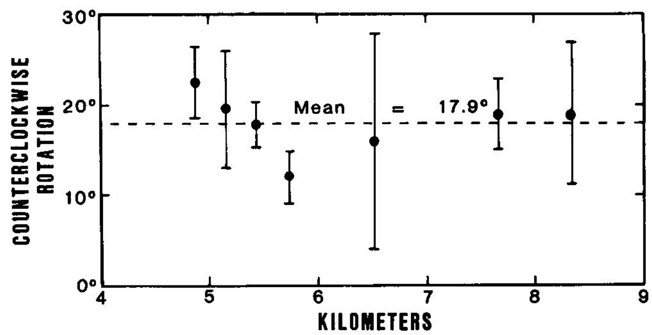

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