

# Paleomagnetism of Miocene volcanic rocks from southwestern Arizona: Tectonic implications

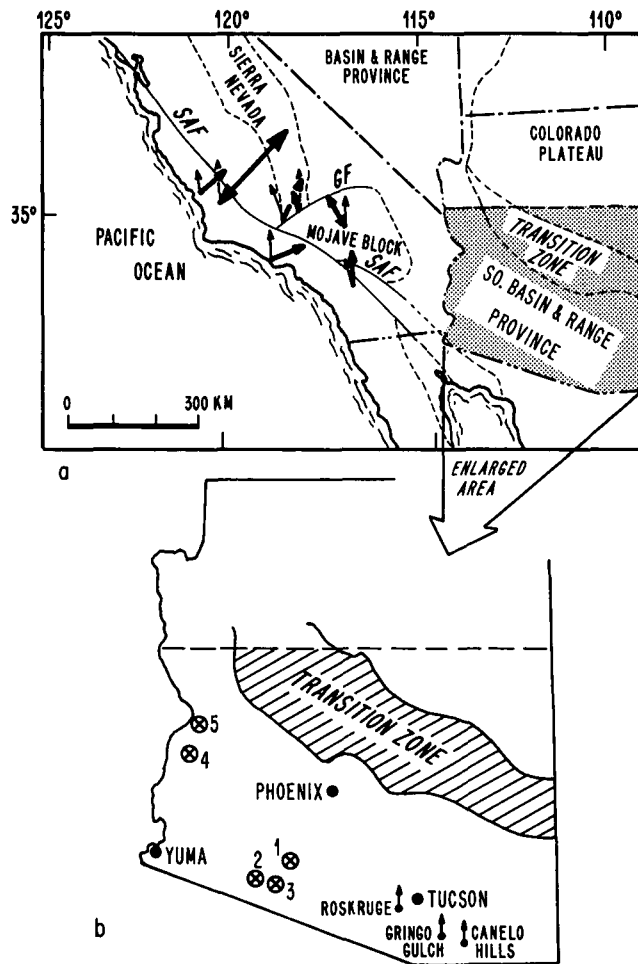
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## ABSTRACT

Paleomagnetic data were acquired from 58 Miocene volcanic units exposed in five mountain ranges in southwestern Arizona. Unlike results of similar paleomagnetic studies west of the San Andreas fault, no clockwise rotations of the paleomagnetic vectors are observed. In fact, the data indicate a statistically significant counterclockwise rotation of  $13.7^\circ \pm 12.2^\circ$ . This counterclockwise rotation is consistent with Garfunkel's tectonic model for the Mojave block. The paleomagnetic data from southwestern Arizona could indicate that a similar counterclockwise rotation during Basin and Range crustal extension has also occurred in southwestern Arizona.

Figure 1. a: Regional location map showing major tectonic provinces, after May et al. (1983). Discordant paleomagnetic vectors in southern California are depicted as follows: Thin arrow of each pair is expected direction. Thick arrow is observed direction. Length of observed-direction arrow is proportional to paleomagnetic inclination given arbitrarily by length of expected-direction arrow (longer observed arrow indicates shallower inclination than expected). Azimuths of arrows represent paleomagnetic declinations. See text for references of paleomagnetic data. Mojave block boundaries are from Garfunkel (1974). b: Location map of volcanic sequences studied in southwestern Arizona. 1 = Saucedo Mountains; 2 = Growler Mountains; 3 = Little Ajo Mountains; 4 = Plomosa Mountains; 5 = Buckskin Mountains. Ages of volcanics in Ma: Saucedo Mountains =  $20.1 \pm 0.3$ ; Growler Mountains =  $14.4 \pm 1.0$  (R. J. Miller, 1983, personal commun.); Little Ajo Mountains =  $25.0 \pm 2.7$  (Eberly and Stanley, 1978); Plomosa Mountains =  $17.2 \pm 0.4$ ; Buckskin Mountains =  $16.1 \pm 0.7$  (Shafiqullah et al., 1980). Single arrows at Roskrue (Vugteveen et al., 1981), Gringo Gulch (Barnes and Butler, 1980), and Canelo Hills (Kluth et al., 1982) localities represent concordant paleomagnetic vectors.



## INTRODUCTION

Beck (1976, 1980) and Irving (1979) have reviewed the paleomagnetic evidence for clockwise rotations and northward translations of crustal fragments along the western margin of the North American Cordillera. Significant northward translation is evident in many cases (e.g., Hillhouse, 1977; Alvarez et al., 1980), whereas in other cases clockwise rotation seems to have occurred unaccompanied by large northward translations (e.g., Oregon-Washington Coast Range from studies of Simpson and Cox, 1977; Bates et al., 1981; Magill and Cox, 1981; Magill et al., 1981; and Beck and Plumley, 1980; and western California from studies of Kammerling and Luyendyk, 1979; and Greenhaus and Cox, 1979). Although the basic conclusion of clockwise rotation along the western margin of the Cordillera is well established, more data are required to distinguish between competing models of rotation (Bates et al., 1981; Magill and Cox, 1981). Additionally, more data are needed to determine the boundary between rotated and unrotated terranes on the western margin of the North American Cordillera, particularly the southern Basin and Range province (Fig. 1).

Paleomagnetic studies of mid-Tertiary rocks west of the San Andreas fault (Fig. 1) clearly indicate that large clockwise rotations have occurred since Miocene time. Post-Miocene clockwise rotations also are indicated a short distance east of the San Andreas fault (Luyendyk et al., 1982). Counterclockwise rotation of Miocene paleomagnetic directions has been reported by Burke et al. (1982) from the Mojave block, although because of the small number of

flows sampled, this apparent rotation may also be explained by an incomplete averaging of secular variation. Paleomagnetic studies from southeastern Arizona (Fig. 1) indicate no rotations since Jurassic time (Kluth et al., 1982). The Colorado Plateau is considered to be part of "stable" North America, within the limits of paleomagnetic resolution (e.g., Elston and Grommé, 1974; Elston and Bressler, 1977). Little attention has been given in paleomagnetic studies to the intervening southern Basin and Range province, yet the boundary between rotated and unrotated terranes in the southwestern Cordillera must lie somewhere within this province. Paleomagnetic directions from Miocene rocks of the Colorado River region (Veseth et al., 1982) are statistically concordant with the Miocene direction expected for North America. Although it is not statistically required, Veseth et al. (1982) speculated on the possibility that shallow magnetic inclinations in their data may suggest northward translation of the region. Clearly, more paleomagnetic data are needed in the southern Basin and Range.

We have undertaken a paleomagnetic study of Miocene volcanic sequences in southwestern Arizona in an attempt to determine the magnitude, sense, and spatial distribution of block displacements that may have accompanied or followed crustal extension on the southern Basin and Range.

#### MIOCENE VOLCANIC SEQUENCES, WESTERN ARIZONA

Southwestern Arizona is characterized physiographically by northwest-trending mountain ranges separated by alluvium-filled basins. Geology in the mountain ranges is variable and complex but commonly includes Miocene basaltic volcanic sequences unconformably overlying older silicic volcanic rocks and/or older sedimentary and metamorphic rocks. We chose volcanic sequences in western Arizona that met the following four criteria. (1) Structural simplicity: We would like to know that the paleomagnetic direction obtained from each mountain range is applicable to a structural

domain at least the size of that particular range. For this reason, we have sampled flat-lying (dipping less than 5°) volcanic sequences that are essentially unfaulted, although faults may bound the range itself. (2) Numerous flows in stratigraphic succession: Sampling multiple flows has the advantage of allowing secular variation to be averaged, or at least evaluated. (3) Good exposures and fresh rock. (4) Age control from isotopic dating. Figure 1 shows the location of volcanic sequences in five ranges that met these criteria.

#### Field and Laboratory Methods

Six to eight oriented core samples from each of 62 flows in five ranges were collected using a portable drilling apparatus similar to that described by Doell and Cox (1965). Cores were oriented by both sun compass and Brunton compass. Sun-compass readings were converted to true azimuths in the field using a hand calculator. Direct comparisons of sun-compass and Brunton-compass azimuths in the field provided means of detecting possible lightning strikes and local magnetic anomalies. The 1.5-cm-diameter cores were trimmed into specimens 2.4 cm long, and the natural remanent magnetism (NRM) was measured on a fluxgate spinner magnetometer. The Curie temperatures of specimens from each mountain range were measured, revealing that nearly pure magnetite is the dominant ferromagnetic mineral.

Stepwise progressive alternating-field (AF) demagnetization treatments were performed on single specimens from 6 to 10 different sites within each range. Many specimens contain two components of magnetization. A low to moderate coercivity component with erratic direction and high intensity is usually erased by AF demagnetization to a peak field of 20 milliteslas (mT). This component is most likely an isothermal remanent magnetism (IRM) induced by nearby lightning strikes. The second component is a stable high-coercivity remanence that usually was isolated by AF demagnetization to peak fields of  $\geq 20$  mT. This high coercivity component is almost certainly a

high-temperature thermal remanent magnetization acquired at the time of extrusion of the volcanic flows. On the basis of the progressive demagnetization behavior, all samples were then AF demagnetized in peak fields ranging from 20 to 50 mT. In most cases, the cleaning successfully removed the secondary IRM. Aberrant samples, in which IRM could not be removed, were deleted from the data set. Directions from four flows were discarded from the data set because a stable NRM could not be isolated. Specimens from these flows contain a high coercivity component of magnetization of erratic direction and high intensity which could not be completely removed by AF demagnetization in peak fields of up to 90 mT. This component is most likely a high-coercivity IRM induced by very close or direct lightning strikes. After magnetic cleaning and the rejection of aberrant specimens, a mean direction was calculated for each flow. Using each flow mean as a unit vector, a mean direction and its attendant statistics were calculated for each mountain range.

Within each range we have observed groups of flows within which the paleomagnetic directions are statistically indistinguishable from one another. Such groups are almost certainly the result of episodic volcanism in which several flows were extruded in rapid succession. Such groups of flows provide only a single time recording of the geomagnetic field. The mean directions calculated from the five volcanic sequences are thus biased in the direction of the rapidly extruded groups of flows. To eliminate this bias, we have calculated mean directions for such groups of flows. Treating each group as a single cooling unit, we then recalculated the mean directions for each mountain range. Table 1 summarizes the paleomagnetic data for cooling units in each volcanic sequence.

#### Analysis

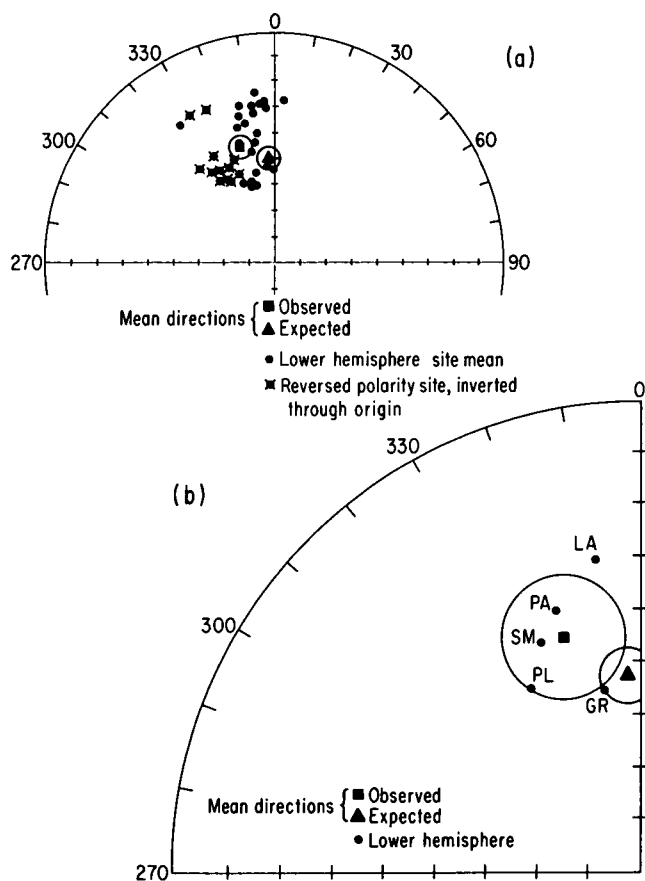
Within each mountain range, sampling has probably not afforded an adequate averaging of the secular variation of the Miocene geomagnetic field. We cannot use the results from any of these individual mountain ranges to draw conclusions regarding tectonic rotations or translations. Consistency of results between these mountain ranges is required before such conclusions can be drawn. Consequently, all the data from the five mountain ranges must be merged into a single data set and the region analyzed as if it were a single block. Unfortunately, possible differences in tectonic rotation or translation between mountain ranges will not be decipherable in this analysis. If the consistency of directions from other ranges supports a general tectonic rotation, it will not be possible to distinguish between multiple block rotations and the rotation of the region as a

TABLE 1. 'COOLING UNIT' PALEOMAGNETIC RESULTS (AFTER MAGNETIC CLEANING)

Range	N*	Mean incl. (°)	Mean decl. (°)	Alpha 95† (°)	k†
Sauceda	7	42.7	335.9	9.5	40.9
Growler	9	55.1	348.7	3.7	189.5
Little Ajo	12	30.6	351.6	3.0	203.5
Plomosa	7	49.3	328.4	3.6	282.3
Buckskin	4	38.2	341.5	15.2	37.6

\*Number of cooling units.

†Statistical parameters of Fisher (1953).



**Figure 2. a:** Equal-area stereographic projection of mean cleaned NRM vectors from cooling units in five ranges studied. Square = mean direction of this set with its 95% confidence circle; triangle = expected direction calculated from Harrison and Lindh (1982) Miocene reference pole. **b:** Equal-area stereographic projection of mean paleomagnetic directions observed from each range. Square = mean and its 95% confidence circle; triangle = Miocene expected direction calculated from Harrison and Lindh (1982) reference pole.

single unit. This fundamental limit of resolution is a function of the geologic record in this region.

The merged set of cooling-unit directions from all the mountain ranges is plotted in Figure 2a. The mean direction calculated from this data set, the 95% confidence limit, and the expected direction with the 95% confidence limit are also shown in Figure 2a and listed in Table 2. The expected direction was computed using the 20 mA average pole for North America of Harrison and Lindh (1982). The expected direction according to the Harrison and Lindh (1982) compilation is within 1.2° of that predicted by Irving's (1979) 20 mA pole. Thus, conclusions regarding concordance or discordance of the observed mean pole are not affected by any reasonable choice of reference pole.

Two features of the "cooling-unit" data set indicate that averaging of secular variation is incomplete. (1) Normal and reversed polarities are not equally represented. The small number of reversed-polarity cooling units has undoubtedly led to an inadequate averaging of secular variations while the field was in reversed polarity. Indeed, the mean direction of the reversed-polarity cooling units is not antiparallel to the mean direction for the normal-polarity units. Because these flows are very fresh and we are

confident of the magnetic cleaning techniques, it seems clear that the lack of antiparallel normal- and reversed-polarity groups indicates incomplete sampling of secular variation rather than uncleaned secondary components. (2) The directions are not evenly distributed about the mean direction. Computing the mean observed direction and concordance/discordance parameters based on the cooling-unit direction may thus overestimate the precision with which that direction has been determined.

With these cautions in mind, we believe that an even more conservative approach with respect to interpretation is in order. Because the volcanic sequences sampled are remnants of different volcanic episodes that yield different K/Ar ages, we do not anticipate a time correlation of volcanism between sequences. An average direction calculated from each sequence (range average) should provide an independent sample of the Miocene geomagnetic field.

These range average directions are plotted in Figure 2b, along with the mean calculated from these five directions and the attendant 95% confidence limit. The results are also listed in Table 2. This analysis is certainly a conservative (perhaps overly conservative) approach in that it underestimates the precision with which the observed mean direction has been determined. This analysis does have the advantage, however, that the resulting discordance/concordance analysis will be rigorous. The discordance/concordance results using this approach (Table 2) indicate no statistically significant translation but a significant counterclockwise rotation ( $13.7^\circ \pm 12.2^\circ$ ).

## DISCUSSION AND CONCLUSIONS

The most important feature of the data set is that we do not observe the large clockwise tectonic rotations that are observed in paleomagnetic studies west of the San Andreas fault (e.g., Kammerling and Luyendyk, 1979). This conclusion is evident using any approach to analyze the data, and it is not likely to be altered by acquisition of additional data. The lack of significant clockwise rotation in southwestern Arizona indicates that the tectonic mechanism responsible for the clockwise rotations near the San Andreas has not affected areas as far inboard as southwestern Arizona.

Two other aspects of the data set are less firmly established and will require additional

TABLE 2. MEAN DIRECTION AND ROTATION STATISTICS

N	Mean incl. (°)	Mean decl. (°)	Alpha 95 <sup>†</sup> (°)	k <sup>†</sup>	Paleomagnetic Pole		R±ΔR <sup>§</sup> (°)	F±ΔF <sup>§</sup> (°)
					lat	long		
<u>Cooling unit analysis</u>								
39 <sup>*</sup>	43.5	343.6	4.3	33.3	72.8°N	127.9°E	-11.6± 5.8	7.8±4.6
<u>Range mean analysis</u>								
5 <sup>**</sup>	43.5	341.5	11.1	48.2	72.2°N	136.4°E	-13.7±12.2	7.8±9.0

\*Number of cooling units.

\*\*Number of ranges.

†Statistical parameters of Fisher (1953).

§Rotation (R) and flattening (F) parameters of Beck (1980), corrected using factors of Demarest (1983).

data before tectonic significance can be attached to them. The first aspect is the suggestion of a barely significant flattening of inclination in the cooling-unit analysis and the lack thereof in the range mean analysis. Using the data set of cooling-unit directions from all the ranges, we calculated the rotation and flattening (along with the 95% confidence limits) as described by Beck (1980) and made corrections using the factors of Demarest (1983). Results are listed in Table 2. A barely significant flattening of  $7.8^\circ \pm 4.6^\circ$  is indicated. We are skeptical of this result because the shallow inclination observed in the Little Ajo Range is primarily responsible for this discordance. Additionally, the range mean analysis indicates no statistically significant flattening at the 95% confidence level. Tectonically, the region has probably not been translated in a north-south sense.

The second aspect is the indication of a counterclockwise rotation of declination in both the cooling-unit analysis and the range mean analysis. The cooling-unit analysis indicates a significant counterclockwise rotation of  $11.6^\circ \pm 5.8^\circ$ , whereas the range mean analysis indicates a barely significant counterclockwise rotation of  $13.7^\circ \pm 12.2^\circ$ . The cooling-unit analysis overestimates the precision by which the mean direction has been determined, but the range mean analysis certainly underestimates that precision. Thus, even the more conservative range mean analysis indicates that the probability of a counterclockwise rotation less than  $13.7^\circ - 12.2^\circ = 1.5^\circ$  is only 0.025, whereas the most probable amount of counterclockwise rotation is  $13.7^\circ$ . Tectonically, the region has probably undergone rotation in a counterclockwise sense of magnitude  $\sim 14^\circ$ . It is interesting to note that similar results were reported by Burke et al. (1982) from the Mojave block and that Garfunkel (1974) predicted counterclockwise tectonic rotations for the Mojave. It is also worth noting that the region from which our results have been obtained lies within the Sonoran tectonophysical subprovince of the Basin and Range (Aldrich and Laughlin, 1983). The northern boundary of the Sonoran subprovince, when projected into California, includes the Mojave block. As the paleomagnetic data from the southwestern Arizona and Mojave region are increased, it will be interesting to determine the degree to which the boundaries of rotated regions correspond to the boundaries of the Sonoran subprovince.

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#### ACKNOWLEDGMENTS

We thank Gayle Weiss, Andy Sandberg, Kathy Flanagan, Lucy Harding, Steve May, and Wayne Haulk for their assistance in the field and laboratory. Discussions with Myrl Beck, Floyd Gray, Gordon Haxel, Richard Tosdal, and Monte Marshall proved very valuable. We thank Adison Smith for access to the Papago Reservation and Frank Hancock for access to military property. Jim Abbott drafted the figures. Funding for this project was provided by National Science Foundation Grant EAR 80-24274.

Manuscript received March 16, 1984

Revised manuscript received May 31, 1984

Manuscript accepted June 13, 1984