Paleomagnetic evidence for counterclockwise block rotation in the north Nevada rift region

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ABSTRACT

Paleomagnetic data from mid-Miocene dikes and flows at three localities within the north Nevada rift indicate that some crustal blocks have rotated approximately 19° (±7°) counterclockwise relative to stable North America. As one possible consequence, a revised mid-Miocene extension direction for the area is about N89°E-S89°W, indicating an approximately 25° difference between mid-Miocene and modern least principal stress directions. The rotation may be accommodated by a right-lateral component of slip on northwest-trending oblique slip faults. These, as well as data from other parts of the Basin and Range province, indicate that strike-slip faulting and associated block rotation contributed to Cenozoic extension.

INTRODUCTION

In north-central Nevada, a 250-km-long north-northwest–south-southeast–trending rift system, referred to as the north Nevada rift (Zoback and Thompson, 1978), is evidenced by a zone of mid-Miocene diabase dike intrusion and, locally, by graben-filling lavas and tuffs. The development of the rift was contemporaneous with early Columbia Plateau volcanism. Analysis of the orientations and offsets of dikes and of magnetic and gravity data along the rift led Zoback and Thompson (1978) to interpret the direction of late Cenozoic extension to have changed approximately 45° clockwise, from west-southwest–east-northeast to west-northwest–east-southeast. The possibility of rotation of fault-bounded blocks within the rift region, resulting in only an apparent change of stress orientation, was not evaluated. Our paleomagnetic data from igneous units show that at least parts of the rift have undergone approximately 19° of counterclockwise rotation since mid-Miocene time. Thus, an inferred Neogene change in extension direction may in part be a manifestation of counterclockwise rotation of individual crustal blocks in the rift.

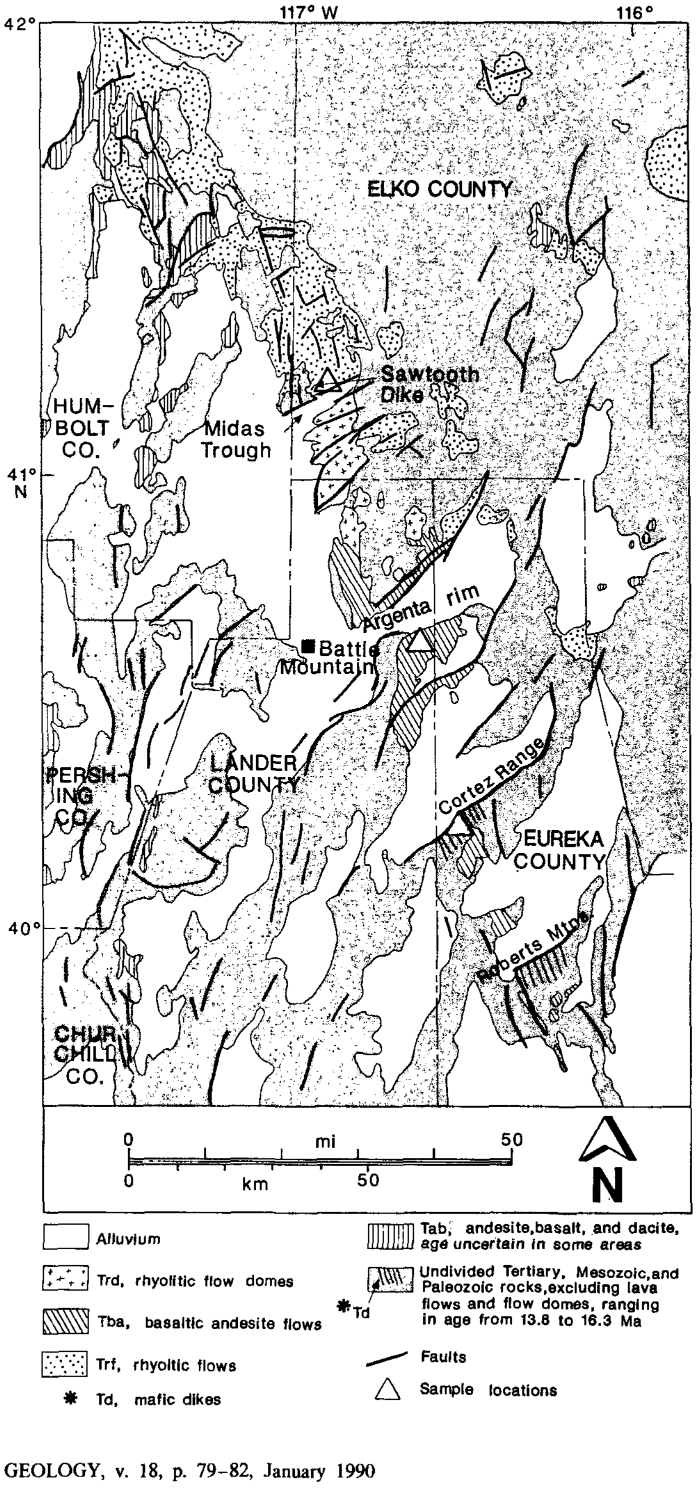

Figure 1. Generalized geologic map of north Nevada rift area, showing major Cenozoic faults in and adjacent to rift. Modified from Stewart et al. (1975). T = Tertiary.

GEOLOGIC SETTING

Early Tertiary (Eocene–early Oligocene) igneous units in the north Nevada rift area include intermediate composition intrusions and andesite and dacite flows and breccias. Widespread rhyolite to quartz latite ash-flow tuffs (22–34 Ma) reflect calc-alkalic arc-related volcanism. Rift-related bimodal basaltic and rhyolitic lavas, as well as swarms of mafic dikes, mark the inception of more recent phases of Cenozoic extension. Additional normal faulting, blocking out of local alluviated basins, and eruption of local basalt flows occurred during late Miocene and Pliocene time.

In the northern half of the rift, rhyolite flows and flow domes predominate, and there are minor amounts of interfingering basalt, andesite, dacite, and tuffaceous sediments. Large rhyolite feeder dikes (e.g., Sawtooth dike; Zoback and Thompson, 1978) are exposed in the Midas trough (Fig. 1). The southern half is characterized by small volumes of mid-Miocene basaltic andesite lavas deposited on Paleozoic strata. Numerous diabase dikes trend roughly parallel to the rift and are well exposed in the Cortez Mountains and Roberts Mountains (Fig. 1). The overall width of the swarm is about 6 km, although the main zone of intrusion, as indicated by field geophysical data (Zoback, 1978), is only about 3 km wide. Isotopic age determinations (K/Ar, whole rock) on dikes and lava flows related to the rift yield dates ranging from 14 to 17 Ma (McKee et al., 1971; Zoback, 1978).

PALEOMAGNETISM

Oriented paleomagnetic samples were collected at three localities (Fig. 1). At the Midas trough, 11 sites (42 to 52) were sampled from the Sawtooth dike and overlying rhyolitic flows. An additional 7 sites (53 to 59) were sampled from underlying basaltic andesite flows. A local tilt correction (dip direction: 282°; dip: 15°) was based on the average orientations of tuff layers at sites 46 (283°/13°, three observations) and 49 (282°/19°, one observation). At Argenta rim, samples from 22 sites (1 to 22) were collected in basaltic andesite flows, domes, and minor rhyolitic flows. In the Cortez Mountains, 19 sites, each representing a separate diabase dike, were sampled. Minor tilt corrections (dip direction: 145°; dip: 7°) at Argentarim and Cortez Mountains are based on measurements of Zoback (1978) and are in agreement with measurements we obtained on several tuff layers.

Each site consists of at least six and usually eight to ten independent field-drilled samples, oriented by a magnetic compass and, in most cases, a sun-shadow angle. Specimens from all samples were subjected to either alternating field or thermal demagnetization. Excluding samples from site 44, which gave poor results in demagnetization, all sites yielded readily defined, well-grouped magnetizations (Fig. 2). We believe these to be thermoremanent magnetizations. Alternating field demagnetization was most effective in removing occasional viscous components parallel to the present Earth field (PEF) direction.

At Midas trough, sites 43, 45, and 52 were not accepted for a locality mean because mixed polarities were indicated by samples from each of these sites; this suggests either incomplete removal of a positive-inclination overprint or the recording of the transitional part of a reversal. At Argenta rim, 13 sites were excluded because they probably record a transitional part of a reversal. These sites are stratigraphically between sites of normal and reversed polarities, and their directions differ considerably from in situ time-averaged mid-Miocene and PEF directions. In the Cortez Mountains, all 19 site means were used to calculate a locality mean.

Tilt-corrected locality mean data are summarized in Table 1. For each of three localities the mean direction is discordant (counterclockwise) from an expected mid-Miocene direction (D = 358°, I = 59°, calculated from Irving and Irving, 1982). Angular differences in declination between observed and expected directions for each locality are statistically significant (Table 1) (Demarest, 1983). However, mean inclinations are virtually concordant with expected values (Fig. 3).

At each of the three localities, secular variation of the geomagnetic field may not be averaged over a sufficient period of time because of the relatively short cooling history of individual flows and thin dikes. A more complete representation of the mean mid-Miocene paleomagnetic direction in the north Nevada rift area, and thus a more representative estimate of the rotation of each locality, may be represented by a grand mean direction calculated from all 42 accepted

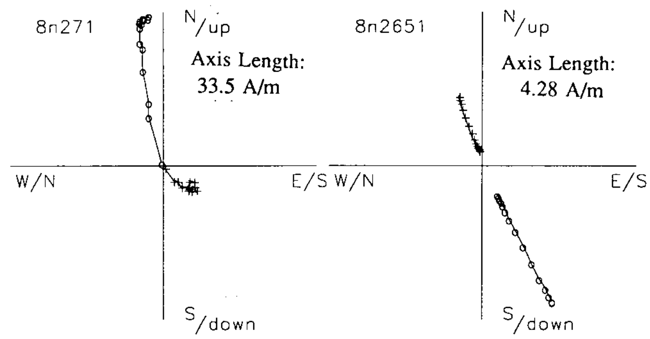

Figure 2. Orthogonal vector plots of thermal and alternating field demagnetizations of representative specimens, geographic coordinates. Plus symbols refer to projection on horizontal plane; circles refer to projection on vertical, north-south plane. Demagnetization steps plotted for specimen 8n2651 are natural remanent magnetization, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, and 70 mT; for specimen 8n271, natural remanent magnetization, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 575, and 600 °C.

TABLE 1. PALEOMAGNETIC DATA FROM THE NORTHERN NEVADA RIFT, NEVADA

Locality	N (n)	D (°)	I (°)	K	α_{95} (°)	R (°)	ΔR (°)	F (°)	ΔF (°)
Midas trough	14 (18)	338	59	46	5.9	−20	10	0	5
Argenta rim	9 (22)	331	64	127	4.6	−27	9	−5	4
Cortez Range	19 (19)	342	64	51	4.7	−16	9	−5	4
Locality mean (g)	3(3)	343	60	73	14.5				
Grand (site) mean(g)	42 (58)	344	60	39	3.0				
Grand (site) mean(s)	42 (58)	339	62	57	2.9	−19	7	−3	3

Note: N (n): number of sites or localities accepted (measured). D, I, K, and α_{95} are declination, inclination, precision parameter, and radius of 95% confidence. Values of rotation (R) and flattening (F) and their 95% confidence levels (ΔR and ΔF, respectively) calculated following Demarest (1983). Locality or site mean, g: in situ; s: corrected.

sites (Table 1). This determination includes statistically antiparallel site mean directions, indicating that secular variation of the geomagnetic field has been averaged.

Although different tilt corrections at three localities conceivably permit a fold test (Table 1), the positive results are limited in significance by the possibility of differential rotations. On the basis of the grand mean, the declination discordance ($R \pm \Delta R$) is −19° ±7°. Dikes, flows, and, presumably, underlying and host pre-Miocene rocks at the three localities were rotated in a counterclockwise fashion about vertical axes. The lack of an inclination error provides a first-order confirmation that the tilt corrections used are realistic. Small tilt corrections preclude the possibility of significant apparent tectonic rotation (Chan, 1988).

MID-MIOCENE EXTENSION DIRECTION

Zoback and Thompson's (1978) proposed 45° (±~25°) change in least principal stress direction between 15 and 6 Ma was based on an inferred mid-Miocene extension direction of N68°E–S68°W (±5°) and a modern extension direction of N65°W–S65°E (±20°), based on geologic data, earthquake focal mechanisms, and in situ stress measurements. Zoback (1989) suggested a modern extension direction of N45°–60°W. Paleomagnetic data imply that mafic dikes originally had a more northerly orientation. If approximately 19° of the difference in extension directions is caused by counterclockwise rotation of blocks within the rift, with dimensions approximating the width of the rift itself, then the actual clockwise change in least principal stress direction is only about 25°, again assuming that the dikes were originally perpendicular to the least principal stress. Thus, a revised mid-Miocene extension direction for the rift area would be approximately east-west. Uncertainties in the estimate of a mid-Miocene least principal stress direction, combined with observed rotation within the rift, do not preclude the possibility that a rotation in least principal stress direction never occurred. Some field measurements of Miocene extension directions in the Basin and Range province are approximately east-west or west-northwest, although numerous southwest-northeast extension directions have been documented (Anderson and Ekren, 1977; Zoback et al., 1981; Best, 1988). Alternatively, the original northerly trend of the dikes may reflect a condition where magmas penetrated along favorably oriented (within ±20° or more of the perpendicular to the true extension direction) preexisting fractures (Delaney et al., 1986). Regardless of the origin of this discrepancy, it is clear that crustal rotations may complicate assessment of principal stress directions (Hudson and Geissman, 1987).

DISCUSSION

Crustal rotations within extensional regions are in many places associated with strike-slip faulting (e.g., Freund, 1974; McKenzie and Jackson, 1986). A two-dimensional model for this association involves blocks bounded by parallel faults that have a significant component of strike-slip motion (Ron et al., 1984). Right-lateral slip would result in counterclockwise rotation (Fig. 4a). The pattern of Cenozoic faulting in the north Nevada rift, summarized in Figure 4b, has been discussed by Zoback (1978). Figure 4b shows two sets of oblique-slip faults in the rift. One fault set trends east-northeast–west-southwest and accommodates dip slip as well as left-lateral strike slip. Strike-slip displacements range from 1 to at most 4 km, on the basis of offsets of mafic dike trends between ranges (Zoback, 1978). Faults of the second set trend north-northwest–east-southeast, exhibit principally dip-slip motion, and are less continuous than east-northeast trending faults.

Counterclockwise rotation in the north Nevada rift may possibly have been accommodated largely along north-northwest–trending faults, with presumed right-lateral oblique-slip components, between the more extensive east-northeast–trending faults (Figs. 4c, 4d). Rotations of similar sense have been recognized elsewhere in the Basin and Range province. In the northern Dixie Valley, more than 30° of late Oligocene and younger counterclockwise rotation, as well as northwest-trending faults with right-lateral strike-slip components were recognized (Hudson and Geissman, 1987). At least locally, crustal block rotation and attending strike-slip faulting operated in addition to, but not necessarily concurrent with, well-documented normal faulting related to motion along gently dipping detachment structures during Cenozoic extension.

At present, we cannot assess the actual timing of rotation as well as the boundaries of the region partitioned by oblique-slip faults, which, at least locally, went through counterclockwise rotation in the rift area. In the northern Dixie Valley, rotation and a strike-slip component of faulting ceased prior to mid-Miocene time; data from mid-Miocene basalt flows do not reveal significant rotation (Hudson, 1988). The difference in timing of observed rotation in these parts of the central Basin and Range province possibly illustrates the importance of temporal and spatial variations in oblique-slip and/or strike-slip faulting during extension.

The paleomagnetic data from the north Nevada rift and northern Dixie Valley may be taken to indicate a possible mechanism of block rotation. If changes in principal stress directions occur where a preexisting fault pattern exists, attending rotation of crustal blocks and orientations of block boundaries may represent a re-

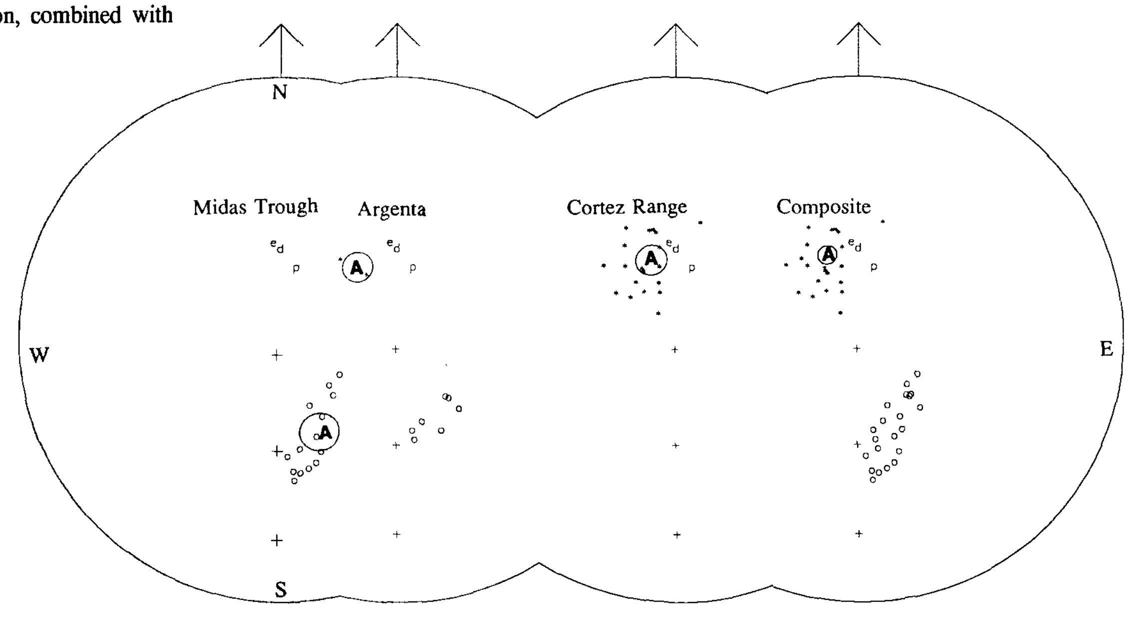

Figure 3. Equal-area projections of site mean directions from Midas trough, Argenta rim, and Cortez Range and composite data. Open symbols refer to site mean direction plotted on upper hemisphere; asterisk indicates direction on lower hemisphere. A is mean direction; d, p, and e are dipole field, present Earth field, and mid-Miocene expected (from North America craton) directions in sampling area.

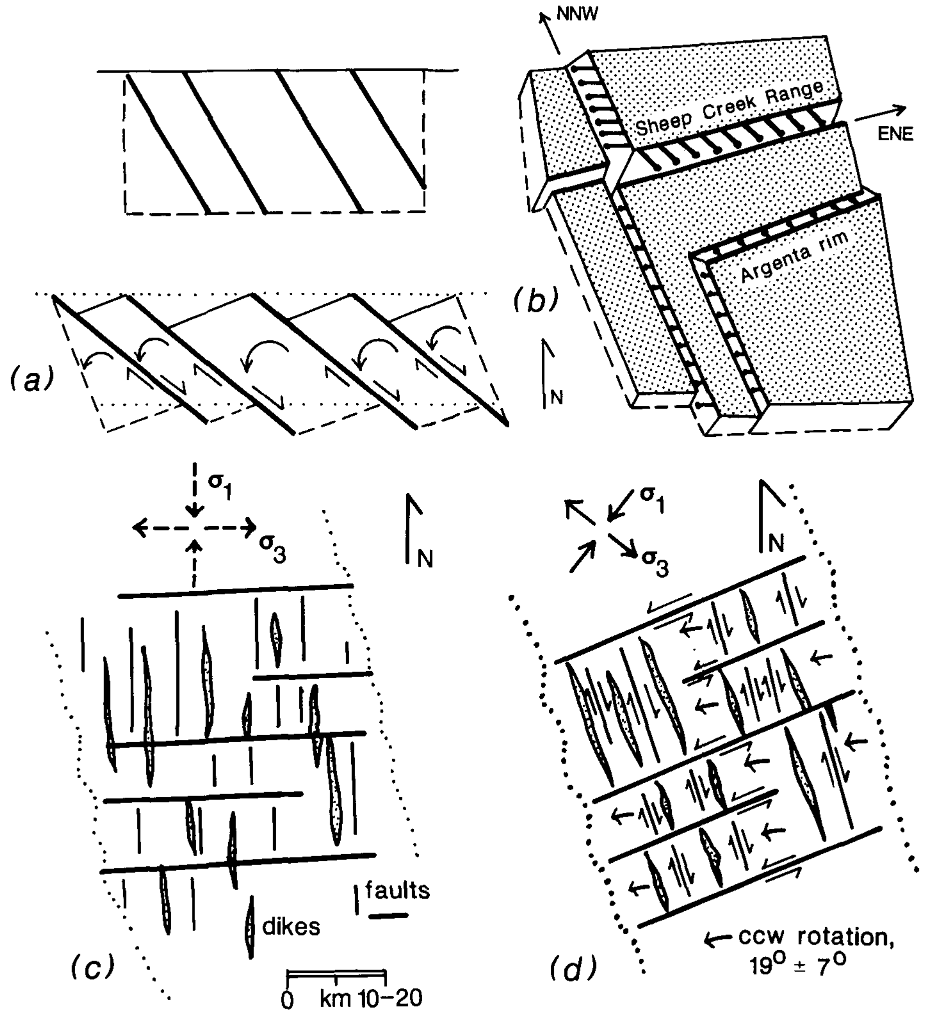

Figure 4. a: Block rotation model, after Ron et al. (1984). b: Schematic diagram showing fault relations typical of north Nevada rift; slip vectors on fault planes have been added to suggest general motion directions (modified from Zoback, 1978). c, d: Schematic two-dimensional block rotation model to explain observed rotations in north Nevada rift area before rotation (c), assuming approximately east-west least principal stress direction, and at present (d). Dotted lines = general rift boundaries. Note approximate nature of horizontal scale.

sponse to a subsequent stress system. Crustal rotations within the north Nevada rift must be rather localized in character: the present orientation of the rift, defined by a pronounced aeromagnetic anomaly (Blakely, 1988), field relations, and the alignment of the rift with extensional features in the eastern Columbia River basalt field (Zoback and Thompson, 1978), cannot be explained by wholesale rotation. We argue that the remarkable linearity of the aeromagnetic anomaly associated with the rift is maintained because dimensions of the rotating blocks are comparable to or smaller than the width of the rift. Mankinen et al. (1987) found no significant rotation of mid-Miocene basalts at Steens Mountain in southeast Oregon.

A rigorous solution to the magnitude of change, if any, in least principal stress direction in the northern Basin and Range province since mid-Miocene time may require more paleomagnetic data from areas where mid-Miocene least principal stress directions have been measured, as well as data from rock units younger than 6 Ma.

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