Vertical axis rotations in the Mojave: Evidence from the Independence dike swarm

Hagai Ron* Institute for Petroleum Research and Geophysics, P.O. Box 22286, Holon 58122, Israel
Amos Nur Department of Geophysics, Stanford University, Stanford, California 94305-2215

ABSTRACT

The 500-km-long Late Jurassic Independence dike swarm in California extends from the central Sierra Nevada through the Mojave Desert to the Eastern Transverse Range. The dikes are mostly vertical, and their azimuth in the Sierra Nevada is ~315°. However, in the Mojave region, their azimuth varies significantly: 300°–320° in the Argus Range, the Spangler Hills, and the Stoddard Well and Soda Mountain areas, and 340°–350° in the Granite Mountain, Alvord Mountain, and Eagle Mountain areas. Apparently the dikes in the Granite, Alvord, and Eagle mountains areas have rotated ~50° clockwise about vertical axis relative to the Sierra Nevada and the Stoddard Well area. These rotations are remarkably consistent with known post–early Miocene paleomagnetically derived rotations. The clockwise rotations are associated with the east-west–trending left-lateral strike-slip faults in the northeastern Mojave and the Eastern Transverse range regions. In contrast, the data show that little or no rotation occurred in the central Mojave domain, which is characterized by northwest-trending faults.

DEBATE ABOUT VERTICAL AXIS ROTATION IN THE MOJAVE

It has long been recognized that significant shear deformation has and still is taking place away from the San Andreas in the Mojave's eastern California shear zone (Savage et al., 1990). Many have realized that this deformation of the brittle crust is accommodated by slip distributed on numerous faults arranged in domains with common fault orientations, but the exact mechanism of this deformation has remained controversial. One of the most debated parts of the controversy is the role of fault and block rotations in domains.

In the Mojave portion of the eastern California shear zone, there are three such domains, each consisting of sets of subparallel strike-slip faults (Dibblee, 1961, 1968; Hope, 1969; Garfunkel, 1974; Powell, 1981; Dokka, 1983): (1) the Eastern Transverse Range, (2) the northeastern Mojave, which has domains of east-west–trending left-lateral faults, and (3) the central Mojave domain, which has northwest-trending right-lateral strike-slip faults. In terms of their sense of faulting, the central Mojave and the Eastern Transverse Range domains and the northeastern Mojave can be thought of as conjugate fault domains. Garfunkel (1974) showed that late Cenozoic crustal deformation in the Mojave was accommodated by strike-slip faulting accompanied by fault and block rotation about the vertical axis. This led ultimately to four distinct models based on various combinations of geologic, kinematic, paleomagnetic, and mechanical evidence.

1. Garfunkel's (1974) model, based on fault geometry and geologic offsets, assumes that the Garlock fault direction has remained fixed, and consequently predicts that the northwest-trending faults of the central Mojave domain must have rotated 40° to 50° counterclockwise, whereas the east-west–trending faults of northeastern Mojave and Eastern Transverse Range remained unrotated.
2. Luyendyk et al. (1985), using paleomagnetic declination anomalies, proposed a 30° to 50° clockwise rotation of the now east-west–trending faults in the northeastern Mojave and Eastern Transverse Range, and no rotation of the northwest-trending one in the central Mojave.
3. Dokka (1983) and Dokka and Travis (1990), on the basis of geologic field studies, concluded that no systematic or significant rotations of blocks and faults about a vertical axis have taken place in the Mojave, and whatever local rotations that occurred are secondary, possibly due to drag on transfer faults that accommodate differential extension.
4. Our model (Nur et al., 1989) introduced mechanical considerations, especially the limits on slip-related fault rotation imposed by fault strength and shear stress. We showed that the rotation of faults in the conjugate domains must be symmetrical about the principal stress direction. Consequently, we thought that the northwest-trending fault should have rotated ~25° to 30° counterclockwise, whereas the east-west–trending fault should have rotated an equal amount clockwise.

With only paleomagnetic data being used to infer rotations, these four models appear unreconcilable. However, as we show in this paper, separate evidence for rotation is provided by the geographic variations of the trends of dikes of the well-known Independence dike swarm. The details of these variations are used to identify the correct model and reconcile all the relevant facts with the models. We use the orientations of individual dikes within the swarm as indicators, unrelated to paleomagnetic data or fault pattern, for regional crustal vertical axis rotation. Taking the azimuth of the dike swarm in the presumably unrotated Sierra Nevada (Frei, 1985) as a reference direction, we obtain the local senses and magnitudes of rotations in the three Mojave domains.

INDEPENDENCE DIKE SWARM

The 148 Ma Late Jurassic Independence dike swarm in California (Chen and Moore, 1979; James, 1989) is ~500 km long (Fig. 1). It extends from the central Sierra Nevada through the Mojave Desert domains to the Eastern Transverse Range and possibly into Sonora, Mexico. The dike rocks are fine-grained diorite porphyry to granodiorite in composition (Moore and Hopson, 1961; Smith, 1962). The swarm is as wide as 30 km, and typical widths of the individual dikes are 3–30 m. The dip of the dikes is typically 80°E. As first suggested by Smith (1962), the general azimuth of both the swarm and its dikes is west-northwest north of the Garlock fault (in the Sierra Nevada, Inyo Mountains, and Argus Range) and north-northwest south of the Garlock fault (in Granite Mountain, Tifort, and Alvord Mountain). This difference led Smith (1962) to suggest that the area to the south of the Garlock fault has undergone a clockwise rotation about a vertical axis relative to the area north of the Garlock fault. Consequently, the Independence dikes may be good indicators for the amounts of both rotation about a vertical axis by inference strike-slip faulting and crustal pure shear deformation, and rotation about horizontal axis (tilt), by inference of crustal extension.

DIRECTIONAL ANALYSIS OF INDEPENDENCE DIKE SWARM DIKES

We have used the Independence dike orientations to determine which of the four models above best describes the Mojave's

*E-mail: hagai@iprg.energy.gov.il.

late Cenozoic crustal deformation. To this end we measured the directions of about 600 dikes in four areas that have especially good dike exposures (Fig. 1): (1) the Argus Range and Spangler Hills areas north of the Garlock fault, (2) the Granite Mountain and Alvord Mountain areas in the northeastern Mojave left-lateral fault domain southeast of the Garlock, (3) the Stoddard Well area southwest of Barstow in the central Mojave right-lateral fault domain, and (4) the Eagle Mountain area in the left-lateral fault domain of the Eastern Transverse Range.

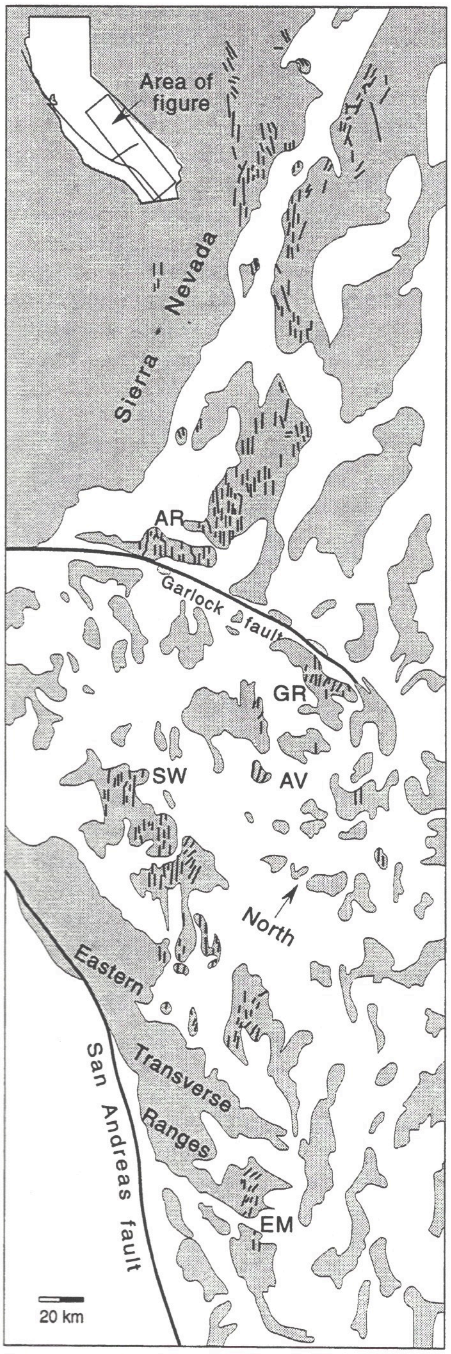

Figure 1. Independence dike swarm (lines) and pre-Tertiary igneous and metamorphic rocks (in gray) in eastern California. EM—Eagle Mountain, SW—Stoddard Well, AV—Alvord Mountain, GR—Granite Mountain, AR—Argus Range (after James, 1989).

The dike's directions were obtained from 1:45 000 aerial photographs, purchased from the U.S. Geological Survey. Using image-processing software we highlighted the individual Independence dikes (Fig. 2). In each of the four areas, each covering several hundreds of square kilometres, we measured 70–240 individual dikes—enough for good estimates of their mean directions and their scatter statistics (Table 1). For ground truthing, we also measured the azimuths and dips of several tens of dikes in the field. The combined data were then plotted for each area on a rose diagram and statistical parameters were calculated (Table 1, Fig. 2).

The statistical analysis (Table 1) implies that (1) the sampling in each of the study areas was random; (2) each data set adequately represents the actual local Independence dike population; and (3) that the Independence dike directions have small dispersion and a well-determined mean, and can serve as reliable markers for directional analysis.

The measured mean dike directions imply that the 40° to 50° difference in the azimuths between the mean trends of the dike populations in the Argus Range and Stoddard Well areas and the Granite Mountain and Eagle Mountain areas is statistically significant. Consequently, a 40°–50° *relative* vertical axis rotation between these two groups of areas must have taken place. Because the Sierra Nevada is known to have undergone little or no vertical axis rotation (Frei, 1985; McWilliams and Li, 1985), we take the mean trend of the Independence dikes in the Sierra Nevada as a fixed reference against which we compare the mean trends in the Mojave domains. This implies that the eastern Mojave and Eastern Transverse Range domains (with the Granite Mountain and the Eagle Mountain areas) underwent an *absolute* vertical axis rotation of 40° to 50° clockwise. In contrast, the data imply that the central Mojave domain (with the Stoddard well area) did not rotate (Fig. 3).

COMPARISON WITH PALEOMAGNETIC DATA

We now compare the dike data with rotations inferred in the past from declination anomalies derived from paleomagnetic studies in the Mojave. For this comparison, we consider data only from post–early Miocene rocks that are young enough to have recorded the young strike-slip phase of deformation in the Mojave, yet old enough to show the accumulated declination anomaly where it exists.

Left Lateral Domains

On the basis of paleomagnetic declination anomalies from post–6 Ma rocks (Ross et al., 1989) in the Eastern Transverse Range domain, Terres (1984) and Carter et al. (1987) reported a 40° to 50° clockwise rotation of blocks bounded by the east-west–trending left-lateral faults of this region. Carter et al. (1987) also found good agreement between paleomagnetically derived rotations and the rotation calculated from fault displacement and spacing (Freund, 1974; Ron et al., 1984).

Ross et al. (1989) also suggested a post–6 Ma 53° ± 10° clockwise rotation of left-lateral fault blocks in the Alvord Mountain and north Cady Mountain areas of the northeastern Mojave domain. This paleomagnetically derived rotation is in good agreement with the dike rotation value based on the mean direction of 43° ± 5° clockwise for 16 dikes of the Alvord Mountain area, in agreement with Schermer et al. (1996). An older rotation inferred by Ross et al. (1989) is apparently the consequence of remagnetization and therefore these data cannot be used for our analysis.

It is clear that the paleomagnetic results for the Eastern Transverse Range and northeastern Mojave domains are remarkably consistent with the dike evidence, implying a 40° to 60° clockwise vertical axis rotation associated with the now left-lateral east-west–trending strike-slip faults during the past few million years.

Right Lateral Domain

Wells and Hillhouse (1989) showed that the magnetic declination in the 18 Ma Peach Spring Tuff in the unrotated western Colorado Plateau is the same as in the central Mojave, implying that fault blocks in the central Mojave domain did not undergo significant vertical axis rotations. Similarly, paleomagnetic directions obtained from the middle Miocene Barstow Formation north of Barstow (MacFadden et al., 1990) also

TABLE 1. DIRECTIONAL ANALYSIS OF THE IDS IN THE FOUR STUDY REGIONS

Area	Number of dikes	Mean direction (degrees)	Percent between azimuth	K	d_0 (°)
Argus Range	239	304	54 (300°–310°)	42	1
Granite and Alvord mt.	93	346	39 (340°–350°)	40	2
Stoddard well	70	312	49 (310°–320°)	37	2
Eagle mt.	149	350	45 (340°–350°)	60	1

Note: K is the precision parameter, and d_0 is the confidence limit about the mean direction in degrees.

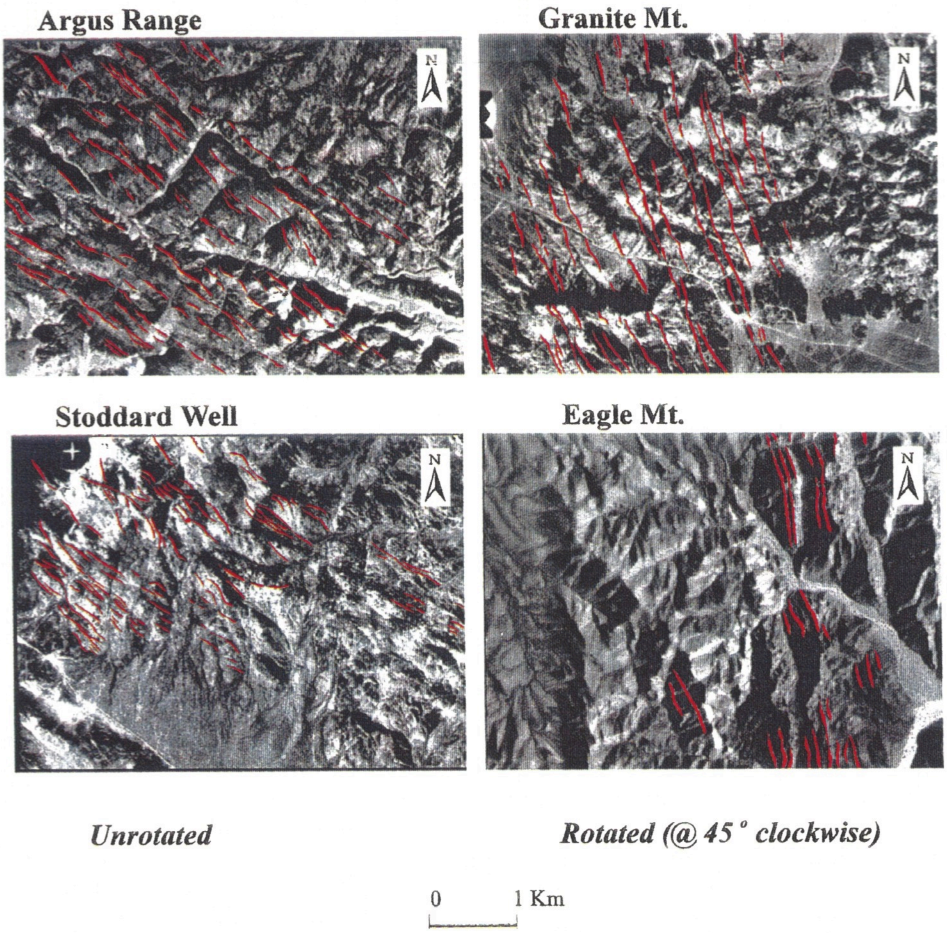

Figure 2. Representative aerial photographs of four studied regions. Individual dikes are shown in red following digital processing of these photos.

imply little or no rotation about a vertical axis in the central Mojave domain. Consequently, there is good agreement between the paleomagnetic and the dike-inferred rotations about the absence of rotations.

CONCLUSIONS

Earlier models and analyses of fault patterns, offsets, and paleomagnetic declination anomalies have strongly suggested that block and strike-slip fault rotations about a vertical axis are the dominant mechanism of late Cenozoic to recent crustal deformation of the Mojave. The direct and unambiguous Independence dike swarm directional data prove that these rotations have occurred, because both the sense and magnitude of rotations inferred from the paleomagnetic data for the three Mojave domains are remarkably consistent with the values derived from the Independence dike swarm directions. Both show little or no rotation in the Sierra Nevada, the Argus Range, and the central Mojave domain, and both show 40° to 60° clockwise rotations of the northeast Mojave and the Eastern Transverse Range domains.

The results also show that of the four models proposed in the past for the deformation by distributed faulting and fault-block rotation of the Mojave domains (Table 1), that of Luyendyk et al. (1985) is the correct one: a 40° to 60° clockwise rotation of the domains with east-west–trending strike-slip faults and little or no counterclockwise rotation of the northwest-trending fault domain. Garfunkel's model, based on fault geometry and offsets, erred by assuming a priori that the Garlock fault (and hence all the east-west–trending faults) have not rotated. Dokka's conclusion that no systematic material rotations occurred in the Mojave is clearly inconsistent with both the Independence dike swarm and the paleomagnetic rotation results. In addition, the vertical orientation of most of the dikes implies an absence of significant or systematic tilting and suggests limited extension in the Mojave since Late Jurassic time, at least in the areas where the Independence dike swarm is exposed.

In our model (Nur et al., 1986, 1989), we erred by assuming that the direction of the tectonic stress remained fixed in time. Because in our model stress and strength considerations require symmetrical rotation away from the maximum horizontal compression, we expected rotations of equal magnitude but of opposite sense in the conjugate central Mojave and the Eastern Transverse Range and eastern Mojave domains. The dike evidence shows, however, that the rotation has been asymmetrical, implying that in addition to the clockwise rotations of the east-west faults in the Mojave, the direction of stress must have also rotated clockwise (by an amount equal to half the fault rotation) (see Nur et al., 1993a, 1993b).

The results imply that (1) the fixed or irrotational direction in the Mojave region is approximately that of the San Andreas fault, and (2) material rotation about vertical axes is the dominant mechanism by which the pure shearing of the eastern California shear zone has been and is being accommodated. In contrast, the pervasive vertical orientation of the dikes of the Jurassic swarm implies little or no rotation about the horizontal axis (tilt), and therefore casts some doubt about presumed large pre–middle Miocene extension in the Mojave.

ACKNOWLEDGMENTS

Although they may not agree with our conclusions, we are grateful to George Thompson, Stanford University, for alerting us to the use of dikes and dike systems to test for the presence (or absence) of material rotation about a vertical axis, and Greg Davis, University of Southern California, for prodding us to pay more attention to geologic evidence. Ran Bachrach helped process the digital images.

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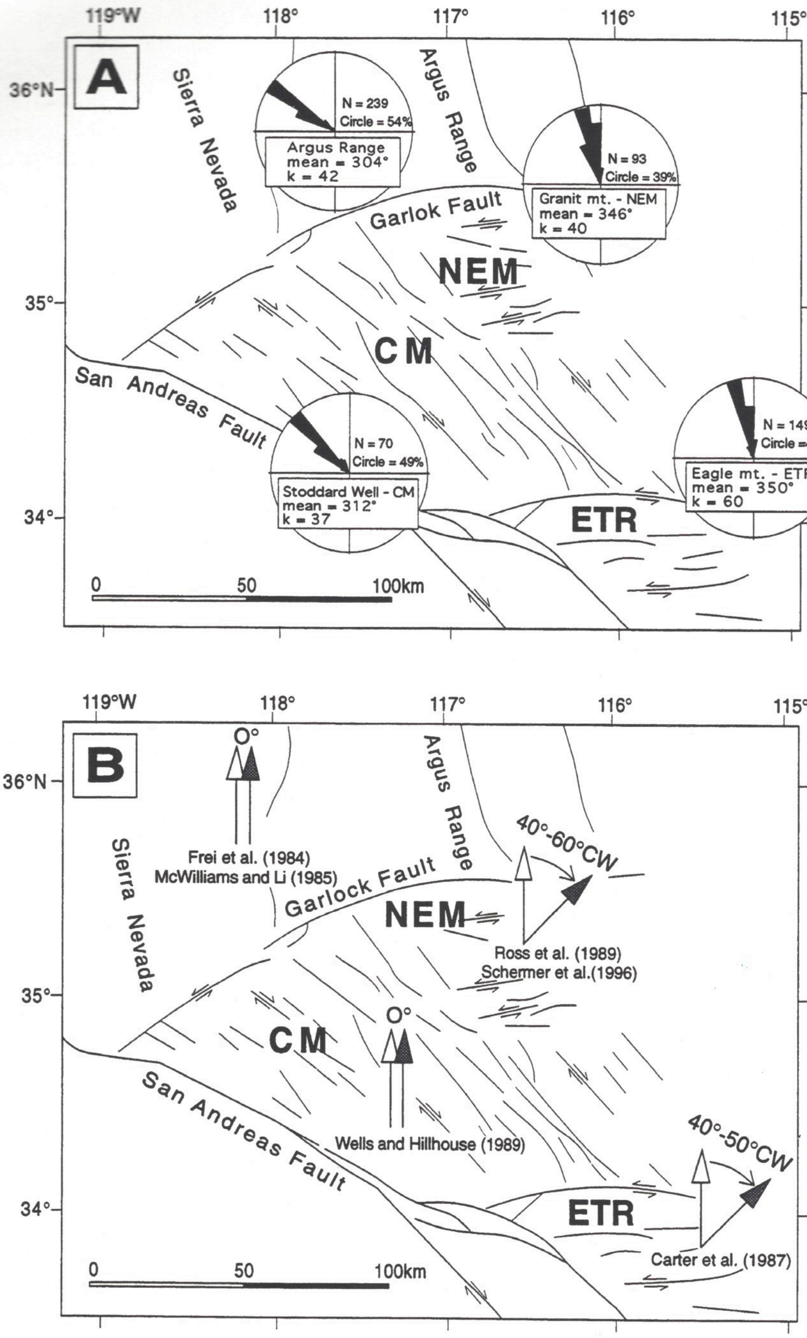

Figure 3. Fault map of Mojave showing its three fault domains: northeastern Mojave (NEM), central Mojave (CM), and Eastern Transverse Range (ETR). A: Rose diagram and statistics of Independence dike swarm populations in each domain (for explanation of statistical parameters see Table 2). B: Paleomagnetically derived rotations of each domain.

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Manuscript received March 25, 1996
Revised manuscript received August 1, 1996
Manuscript accepted August 19, 1996

Printed in U.S.A.