Stress field rotation or block rotation: an example from the Lake Mead fault system

Hagai Ron([1]), Amos Nur([2]) and Atilla Aydin([3])
([1]) *The Institute for Petroleum Research and Geophysics, Holon Israel*
([2]) *Department of Geophysics, Stanford University, Stanford, CA*
([3]) *Department of Applied Earth Sciences, Stanford University, Stanford, CA*

Abstract
The Coulomb criterion, as applied by Anderson, has been widely used as the basis for inferring paleostresses from *in situ* fault slip data, assuming that faults are optimally oriented relative to the tectonic stress direction. Consequently if the stress direction is fixed during deformation so must be the faults. Freund has shown however that faults, when arranged in sets, must generally rotate as they slip. Nur *et al.* showed how sufficiently large rotations require the development of new sets of faults which are more favorably oriented to the principal direction of stress. This leads to the appearance of multiple fault sets in which older faults are offset by younger ones, both having the same sense of slip. Consequently correct paleostress analysis must include the possible effect of fault and material rotation, in addition to stress field rotation.
The combined effects of stress field rotation and material rotation were investigated in the Lake Mead Fault System (LMFS) especially in the Hoover Dam area. Fault inversion results imply an apparent 60° clockwise (CW) rotation off the stress field since mid-Miocene time. In contrast structural data from the rest of the Great Basin suggest only a 30° CW stress field rotation. By incorporating also paleomagnetic and seismic evidence, the 30° discrepancy can be neatly resolved. Based on paleomagnetic declination anomalies it is inferred that slip on NW rending right-lateral faults caused a local 30° counterclockwise (CCW) rotation of blocks and faults in the Lake Mead area. Consequently the inferred 60° CW rotation of the stress field in the LMFS consists of an actual 30° rotation of the stress field (as for the entire Great Basin) plus a local 30° CCW material rotation of the LMFS fault blocks.

1. Introduction

The Coulomb criterion, as applied by Anderson (1951) to faulting, gave rise to the widely used concepts of faulting mechanics in rocks. Accordingly faults form at angles of 45° or less (depending on the frictional properties of rocks) from the maximum compressive stress. It is the orientation of the principle stress axes relative to the earth free surface which thus defined the three types of standard faults: normal, reverse, and strike slip.

Anderson's approach has provided the basis for methods to infer paleostress directions from *in situ* fault strike and dip, sense of slip, and related strain indicators (Choukroune, 1969;

Hancock and Atiya, 1979; Zoback *et al.*, 1981; Letouzey and Tremolieres, 1980; Marshak *et al.*, 1983; Eyal and Reches, 1983; and others). Improved estimates were introduced during the last decade (Angelier, 1979, 1984; Michael, 1984; Ellsworth, 1982, and others) based on the added assumption that fault slip is in the direction of maximum shear stress resolved on the fault plane: here fault slip data is used to determine that paleo-orientation of the principle stresses which minimizes the angular deviations between the observed slip direction along a fault and the direction of the maximum resolved shear stress. Reches (1987) introduced a further improvement in which the fault's coefficient of friction and cohesion are also constrained.

2. Stress rotation *vs.* material rotation

A key assumption in all the inversion methods mentioned above is that fault orientation remains unchanged relative to the principal stress directions during fault slip. However in a seminal paper, Freund (1974) explored the consequences of relaxing this assumption by adding rotation of crustal blocks bounded by slipping faults. On the basis of simple 2D kinematic analysis Freund showed that rotations are not only possible, but generally unavoidable. Furthermore he showed that the sense of these rotations is directly controlled by the orientation of the faults (arranged in sets) relative to the direction of the principle tectonic shortening, and that the magnitude of the rotation of crustal blocks is controlled by the magnitude of the crustal shortening.

Significant evidence has accumulated by now to suggest that block and fault rotations due to crustal shortening and extension are widespread. For example, Ron *et al.* (1984) showed that depending on fault orientation adjacent fault domains experienced clockwise and counterclockwise rotations in a single tectonic setting of northern Israel. Similar interpretations were suggested for the Mojave area, California (Garfunkel, 1974), the Transverse Range, California (Terres and Luyendyk, 1985), central America (Menton, 1987), Alaska (Stamatakos, 1988), the Lake Mead, Nevada region (Ron *et al.*, 1986; Geissman, 1986), and northern Greece (Pavlides and Kilias, 1987). According to Freund's (1974) model the blocks and their bounding faults always rotate away from the direction of shortening and toward the direction of elongation.

It was shown by Nur *et al.* (1986) that, when rotation becomes sufficiently large, slip on the rotating faults ceases because the resolved shear stress on them has decreased and the normal stress has increased to the point where the frictional resistance is too great for further slip. If crustal deformation is to proceed it must be accommodated by a set of new faults, more favorably oriented to the principle direction of the regional stress field. As a result, domains of multiple sets are formed in which the younger faults systematically offset the older ones. This simple process of crustal deformation by multiple sets of rotating faults and blocks thus results in complex fault patterns which do not require stress field rotations. Consequently tectonic and structural analysis of complex fault systems, using fault plane inversion methods which exclude fault rotation, can lead to unduly complicated and often erroneously inferred paleostress histories. Although in many cases stress field rotations actually take place over geological time, these rotations are probably slow and gradual. As a result, much of the observed complexity of the fault pattern observed *in situ* could very well be due to multiple fault sets formed by material rotation of blocks and their bounding faults, not by stress field rotation.

To resolve the relative importance of the two rotations – stress field rotation *vs.* material rotation – they must be determined independently. Stress rotations must be inferred indirectly from regional structural and tectonic features (*e.g.*, Zoback *et al.*, 1981). In contrast material rotations can be determined directly from paleomagnetic declination and inclination anomaly measurements.

The purpose of this paper is to analyze a case of combined material rotation and stress field rotation in the Lake Mead fault system, Nevada. The evidence is based on three types of information: structural evidence (Zoback *et al.*, 1981; Angelier *et al.*, 1985), paleomagnetic data (Ron *et al.*, 1986; Geissman, 1986) and seismicity (Rogers and Lee, 1976; Rogers *et al.*, 1983).

3. Data

Structures. The 30 by 80 km Lake Mead fault system (fig. 1) includes a few long northeast-trending left-lateral strike slip faults (set #1 in fig. 1 and 2). Based on offsets of Lake Neogene volcanic rocks (Anderson, 1973; Bohannon, 1983) the total horizontal slip across this system is approximately 65 km. Geological evidence shows that strike slip faulting has begun 13.5 to 11.3 Ma ago and continued through Miocene to early Pliocene and possibly to Pleistocene times (Anderson, 1973; Bohannon, 1983).

Bohannon (1983) suggests specifically that most of the left-lateral faulting occurred during late Miocene time. This phase of intense faulting was followed by decreasing volcanic and plu-
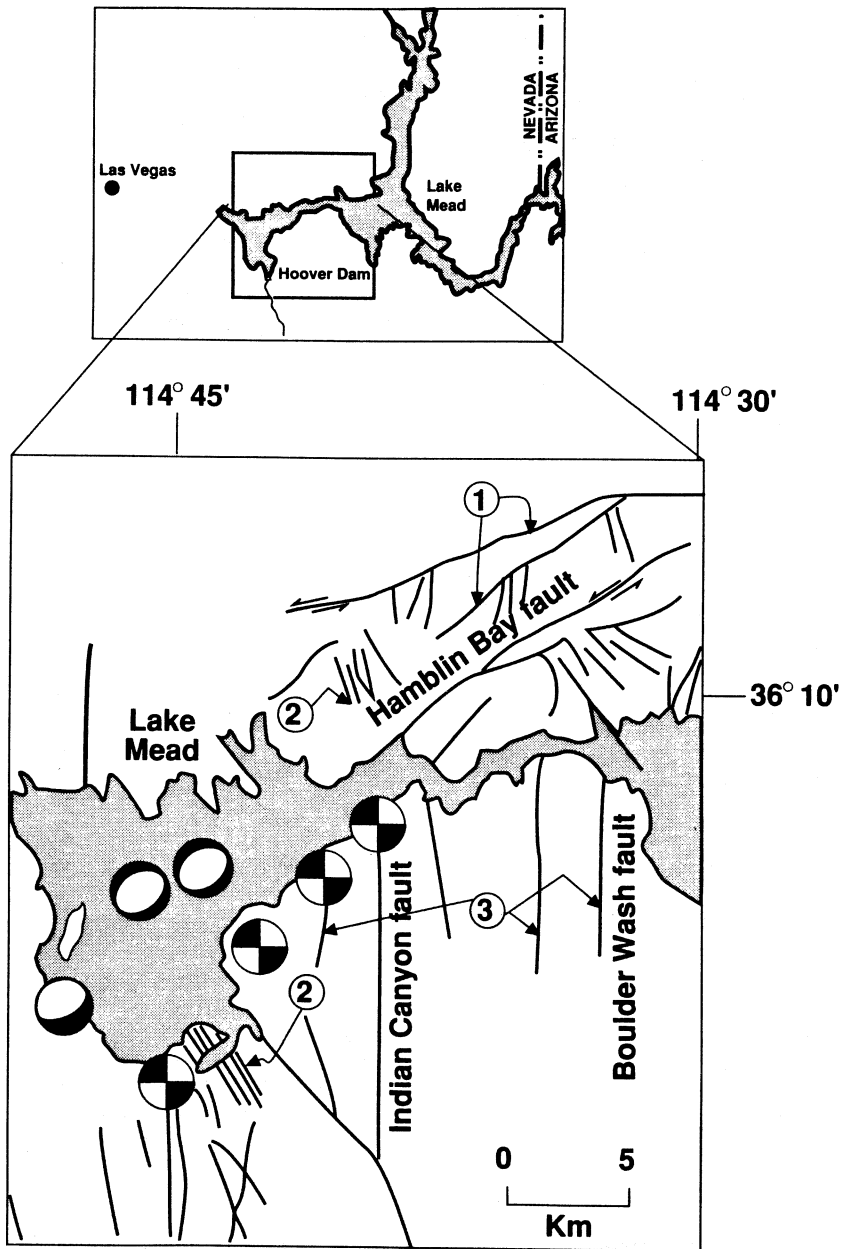
Fig. 1. The main fault sets in the Lake Mead Fault System (modified after Rogers and Lee, 1976): 1) large NE-trending left-lateral strike slip faults (set #1); 2) short NW-trending right-lateral strike slip faults (sets #2); and 3) N-trending seismically active faults (set #3). Although these faults are mapped as normal faults, the fault plane solution indicates right-lateral strike slip.

HAMBLIN-CLEOPATRA DOMAINS
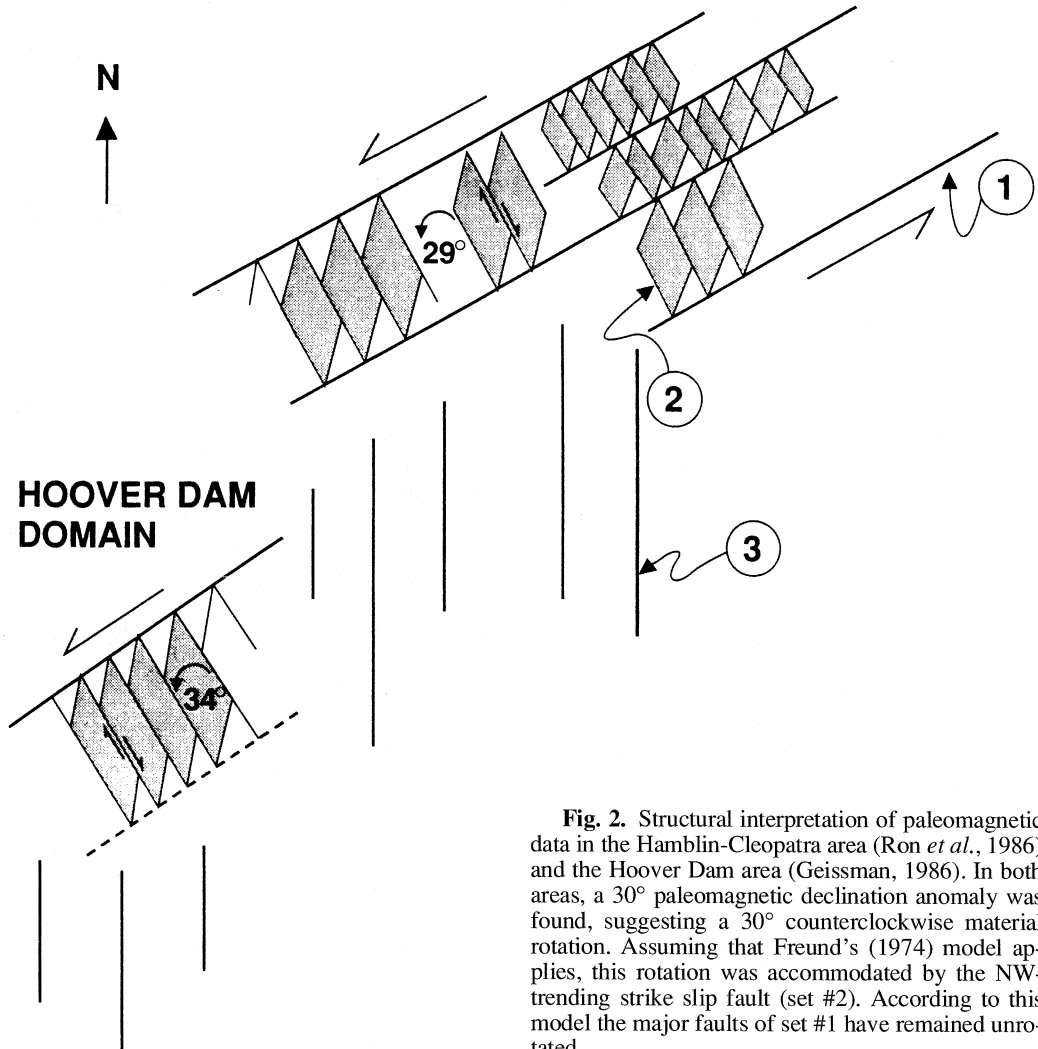
N

HOOVER DAM DOMAIN

Fig. 2. Structural interpretation of paleomagnetic data in the Hamblin-Cleopatra area (Ron *et al.*, 1986) and the Hoover Dam area (Geissman, 1986). In both areas, a 30° paleomagnetic declination anomaly was found, suggesting a 30° counterclockwise material rotation. Assuming that Freund's (1974) model applies, this rotation was accommodated by the NW-trending strike slip fault (set #2). According to this model the major faults of set #1 have remained unrotated.

tonic activity and by normal faulting that formed broadly spaced basins and ranges (Anderson *et al.*, 1972). Results by Ron *et al.* (1986) and by Li (personal communication, 1989) suggest that sets of smaller faults, trending NW and showing right-lateral slip are bounded by the larger NE-trending faults.

A more detailed and local study of the geometry and nature of faulting of the LMFS was completed by Angelier *et al.* (1985) in a small area near Hoover Dam. The data, in the form of density distributions (the numbers of faults in a given set) have shown that a) the most prominent fault set is the one striking northwest (Angelier

et al., 1985; fig. 6); b) the rake distribution of this NW-trending fault set is bimodal, with groups of dip slip and right-lateral strike slip faults striking 290°-325°(north-west) (Angelier *et al.*, 1985; fig. 6 and 9); c) a few left-lateral faults striking 350°-30° (north to northeast) are also found here (Angelier *et al.*, 1985; fig. 9).

Together these results suggest that the north-west-trending right-lateral faults (set #2 in fig. 1 and 2) probably accommodated most of the internal deformation of the LMFS region and are therefore reliable stress indicators in this region.

Angelier *et al.* (1985) used the fault data above to determine the paleostress history of the Southern Great Basin. By assuming that any cluster of fault orientations is associated with a corresponding orientation of the stress field (and excluding material rotation), Angelier *et al.* (1985) inferred a clockwise (CW) stress field rotation of about 60° since mid-Miocene time. The CW sense of this paleostress rotation is clearly consistent with the sense of stress rotation proposed for the entire Basin and Range by Zoback *et al.* (1981).

However the magnitude of the stress rotation is in remarkable disagreement with the Zoback *et al.* (1981) suggested 30° CW rotation of the principal paleostress direction since mid-Miocene throughout the Basin and Range. The resulting 30° discrepancy is too large for scatter of the data. Angelier and co-workers consequently suggested that rocks in the Hoover Dam study area may have experienced, in addition to the regional Basin and Range stress field rotation, also some local material rotation associated with shearing along the Lake Mead fault system.

Seismicity. Rogers and Lee (1976) inferred from fault plane solutions for earthquakes in the Lake Mead region that many faults are right-handed strike slip in nature, with north-south strikes (set #3, fig. 1 and 2). It is noteworthy that this seismic activity is not associated with the large northeast left-lateral strike slip faults (set #1), or the shorter NW-trending right-lateral faults (set #2). The prevalence of the NW-trending, now inactive faults (set #2) and the N-trending seismic faults (set #3) led us to suggest (Ron *et al.*, 1986) that active crustal deformation in this area was and is being still accommodated by the

sets of the smaller fault with right-lateral strike slip (fig. 2 and 3), situated within the larger left-lateral shear zones. The extension direction inferred from the seismically active fault plane solutions is oriented northwest-southeast, in agreement with the direction of the current least horizontal principal stress throughout the entire Basin and Range Province (Zoback *et al.*, 1981; Carr, 1984).

Paleomagnetism. Two sets of paleomagnetic data are directly relevant to our analysis, one from the Hamblin-Cleopatra volcano area (Ron *et al.*, 1986), a second from the Hoover Dam area (Geissman, 1986, Wells and Hillhouse, 1989). The Hamblin-Cleopatra volcano area results, according to Ron *et al.* (1986), show that

1) based on *in situ* field inclination data, paleomagnetic analysis yields negligible local block rotation about horizontal axis. This implies insignificant tilting by normal faults.

2) The data reveals a declination anomaly of −29.4° ± 8.5°. This implies a counterclockwise rotation of blocks in this area about a vertical axis of about 30°.

In the same Hoover Dam area, where Angelier *et al.* (1985) obtained their structural data, paleomagetic data collected by Geissman (1986) imply that

1) paleomagnetic declination implies a counterclockwise rotation of approximately 30° of the Hoover Dam area relative to the unrotated region to southeast. This rotation is close both in sense and magnitude to Ron *et al.* (1986) results for the Hamblin-Cleopatra area.

2) The tilting of fault blocks found inferred from inclination data in the Hoover Dam area as inferred from inclination data occurred most probably before the left-lateral strike slip faulting of the Lake Mead system. This is in good agreement with Angelier *et al.* (1985), who suggested on the basis of structural evidence that tilting occurred before or very early in the strike slip faulting history. Wells and Hillhouse (1989) also report on CCW rotation of ~10°presumably on NW-trending left-lateral faults at the SW end of the LMFS, about 40 km away from the Hoover Dam area.

4. Discussion

The results reviewed above can be summarized as follows:

1) the structural data suggests that the short NW-trending right-lateral faults (set #2 in fig. 1 and 2) accommodated much of the deformation of the region (Angelier *et al.*, 1985).

2) The seismic data shows the active faulting takes place along short north-south–trending right-lateral strike slip faults (set #3) (Rogers and Lee, 1976; Rogers *et al.*, 1983), not along the NW-trending older ones, or the major NE faults.

3) The paleomagnetic data reveals that the NW-trending right-lateral strike slip faults (set #2) were most probably involved in a 30° counterclockwise material rotation of blocks and faults (fig. 2). This has led us to suggest (Ron *et al.*, 1986) that the original orientation of these faults was approximately nourt-south as shown in fig. 3. Presumably, as a consequence of their rotation they locked up, and a new, NS-trending set of currently seismically active faults has developed.

4) As shown in fig. 4, the structural paleo-stress indicators from the Lake Mead fault system yield, assuming no material rotation, a 60° clockwise stress field rotation since mid-Miocene (Angelier *et al.*, 1985). In contrast, paleostress indicators throughout the Basin and Range suggest only a 30° clockwise stress field rotation (Anderson and Ekren, 1977; Zoback *et al.*, 1981).

5) The current maximum horizontal stress as inferred from earthquakes fault plane solutions, is oriented N30°E. This direction is good agreement with stress orientation derived from post mid-Miocene structures in other parts of the Great Basin.

Figure 3 presents our proposed model for the fault geometry, the sense of horizontal slip, and the nature of block rotation (Ron *et al.*, 1986) beginning about 11 My ago and still in progress today: overall left-lateral shear in Miocene times caused right-lateral strike slip displacement on set #2 of local faults, initially trending north-south. The strike slip on these faults led to their counterclockwise rotation together with the intervening blocks. The faults locked up following the 30° CCW rotation from their initial direction (Nur *et al.*, 1986). Assuming that the stress field
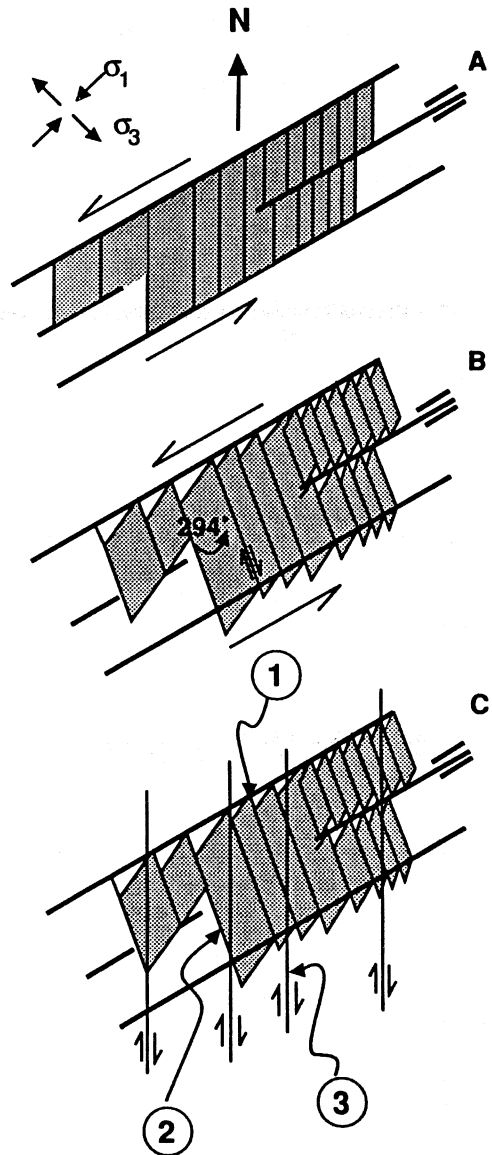

Fig. 3. Structural model for the development of multiple faults sets due to the material rotation in the Lake Mead fault zone: left slip on the irrotational faults of set #1 caused right slip on the faults of set #2, as well as rotation of the blocks bounded by these faults. When these right-lateral faults rotated approximately 30° CW away from the direction of maximum compression 1, they locked up. Further deformation is now accommodated by the new set #3 of right-lateral faults.
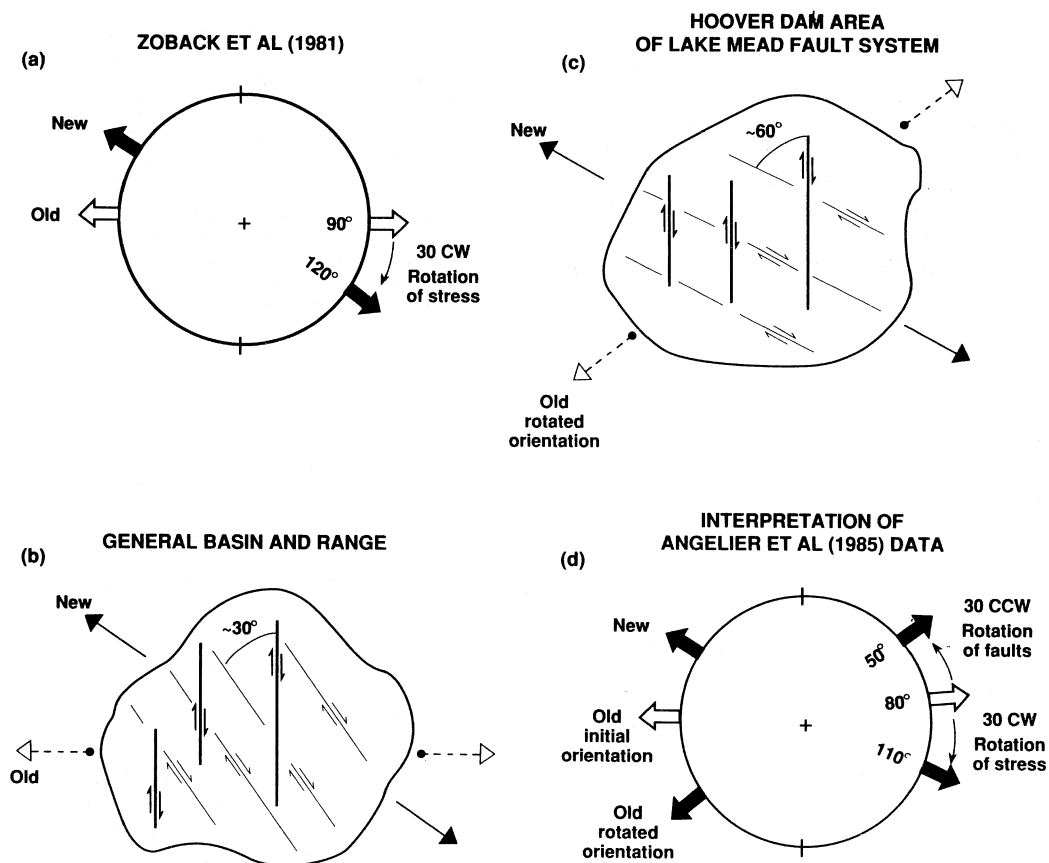
Fig. 4. Combined material rotation and stress field rotation in the Lake Mead Fault system *vs.* stress field rotation only in the Basin and Range province: a) old (90°) and new (120°) extension directions in the Basin and Range province, according to Zoback *et al.* (1981). b) Expected old and new optimal directions of strike slip faults in the Basin and Range province subject to the stresses in a). Note that the angle between them should be 30°. c) Directions of old and new strike slip faults observed in the Lake Mead Fault zone (MFZ) and Hoover Dam area (set #2 and #3, respectively of fig.1 and 2). The angle between them is close to 60°. d) The apparent rotation of 60° is a combination of a 30° clockwise stress field rotation plus a 30° counterclockwise material rotation.

orientation remained constant over 11 My (Zoback *et al.*, 1981) subsequent crustal deformation was and is still being accommodated by the new set #3 of the more favorably oriented north–south–trending right-lateral strike slip faults.

5. Conclusion

Taken together, these results provide a neat and simple explanation for the puzzling discrepancy between the apparent 60° clockwise stress field rotation inferred from the Angelier *et al.* (1985) data from the Hoover Dam area, and the known 30° clockwise stress field rotation established for the entire Basin and Range province. We suggest that the 60° rotation consists of a 30° CW stress field rotation plus a 30° CCW material rotation. Consequently local material rotation in the LMES has been superimposed on the regional

71

Basin and Range stress field rotation.

There must exist other regions where the tectonic history involved both *stress* field rotation and material rotation. Consequently our analysis here may prove effective in solving faulting complexities elsewhere: examples include central Japan (Angelier and Huchon, 1987), where large differential paleomagnetic rotations have been found (Yasuto, 1988), northern Greece (Pavlides and Kilias, 1987), Southern California (Nicholson *et al.*, 1986).

Acknowledgements

REFERENCES

ANDERSON, E.M. (1951): *The dynamics of faulting* (Oliver and Boyd, Edimburgh), Vol. **206**.

ANDERSON, R.E. (1973): Large-magnitude late tertiary strike slip faulting north of Lake Mead, Nevada, *US Geological Survey Professional Paper*, Vol. **794**.

ANDERSON, R.E., R.C. LONGWELL, R.L. ARMSTRONG and R.F. MARVIN (1972): Significance of K-Ar ages of tertiary rocks from the Lake Mead region, Nevada-Arizona, *Geol. Soc. Am. Bull.*, **83**, 273-288.

ANDERSON R.E. and E.B. EKREN (1977): Comment on late Cenozoic fault patterns and stress field in the Great Basin and westward displacement of the Sierra Nevada block, *Geology*, **5**, 388-389.

ANGELIER, J. (1979): Determination of the mean principal directions of stress for a given fault population, *Tectonophysics*, **56**, T17-T26.

ANGELIER, J. (1984): Tectonics analysis of fault slip data set, *J. Geophys. Res.*, **89**, 5835-5848.

ANGELIER, J., B. COLLETT and E.R. ANDERSON (1985): Neogene paleostress changes in the Basin and Range: A case study at Hoover Dam, Nevada-Arizona, *Geol. Soc. Am. Bull.*, **96**, 347-361.

ANGELIER, J. and R. HUCHON (1987): Tectonic record of convergence changes in a collision area; the Boso and Miura peninsulas, Central Japan, *Earth Plan. Sci. Lett.*, **81**, 3997-4008.

BOHANNON, R.G. (1983): Geologic map, tectonic map and structure sections of the Muddy and northern Black Mountains, Clark Country, Nevada, *US Geological Survey Miscellaneous Investigation Series*, Pap I-1406.

CARR, W.J. (1984): Regional structural setting of Yucca mountain, southwestern Great Basin, Nevada and California, US Geological Survey Openfile Report, 84-854.

CHOUKROUNE, P. (1969): Un example d'analyse microtetocnique d'une series calcaire affectee de plis isopaque («concentique»), *Tectonophysics*, **7**, 57-70.

ELLSWORTH, W.L. (1982): A general theory for determining the state of stress in the earth from fault slip measurements, *Terra Cognita*, **2**, 170.

EYAL, Y. and Z. RECHES (1983): Tectonic analysis of the Dead Sea Rift region since the Late Cretaceous based on mesostructures, *Tectonophysics*, **2**, 167-185.

FREUND, R. (1974): Kinematics of transform and transcurrent faults, *Tectonophysics*, **21**, 93-134.

GARFUNKEL, Z. (1974): Model for the late Cenozoic tectonic history of the Mojave Desert, California, and for its relation to adjacent regions, *Geol. Soc. Am. Bull.*, **85**, 1931-1944.

GEISSMAN, W.J. (1986): Paleomagnetism and strike slip tectonism in the Hoover Dam area, southeast extension of the Lake Mead Fault Zone, Nevada and Arizona, *EOS*, **67**, 922.

HANCOCK, P.L. and M.S. ATIYA (1979): Tectonic significance of the mesofractures systems associated with the Lebanese segment of the Dead Sea transform fault, *J. Struct. Geol.*, **1**, 143-153.

LETOUZEY, J. and P. TREMOLIERES (1980): Paleostress around the Mediterranean since the Mesozoic from microtectonic: Comparison with plate tectonic data, *Rock Mech.*, **9**, 173-192.

MARSHAK, G., P.A. GEISER, W. ALVAREZ and T. ENGELDER (1983): Mesoscopic fault array of the northern Umbrian Apennine fold belt, Italy: Reactivation of joints by pressure-solution slip, *Geol. Soc. Am. Bull.*, **93**, 1013- 1022.

MENTON, W.I. (1987): Tectonic interpretation of the morphology of Honduras, *Tectonics*, **6**, 533-651.

MICHAEL, A.J. (1984): Determination of stress from slip data: faults and folds, *J. Geophys. Res.*, **89**, 517-526.

NICHOLSON, C., L. SEEBER, P. WILLIAMS and L.R. SYDES (1986): Seismic evidence for conjugate slip and block rotation within tha San Andreas Fault system, Southern California, *Tectonics*, **5**, 629-648.

NUR, A., H. RON and O. SCOTTI (1986): Fault mechanics and the kinematics of the block rotations, *Geology*, **14**, 746-749.

PAVLIDES, S.B. and A.A. KILIAS (1987): Neotectonic and active faults along the Serbomacedonian zone (SE Chalkidike, Northern Greece), *Ann. Tect.*, **1**, 97-104.

RECHES, Z. (1987): Determination of the tectonic stress tensor from slip along faults that obey the Coulomb yield condition, *Tectonics*, **6**, 849-861.

ROGERS, A.M. and W.H.K. LEE (1976): Seismic study of earthquakes in the Lake Mead, Nevada-Arizona region, *Bull. Seismol. Soc. Am.*, **66**, 1631-1657.

ROGERS, A.M., S.C. HARMSEN, W.J. CARR and W. SPENCE (1983): Southern Great Basin seismological data report from 1981 and preliminary data analysis, US Geological Survey, Open File Report, pp. 83-669.

RON, H., R. FREUND, Z. GARFUNKEL and A. NUR (1984): Block rotation by strike slip faulting: Structural and paleomagnetic evidence, *J. Geophys. Res.*, **89**, 6256-6270.

RON, H., A. AYDIN and A. NUR (1986): Strike slip faulting and block rotation in the Lake Mead Faulty system, *Geology*, **14**, 1024-1026.

STAMATAKOS, J.A., K.P. KODAMA and T.L. PAVLIS (1988):

Paleomagnetism of Eocene plutonic rocks, Matanuska Valley, Alaska, *Geology*, **16**, 618-622.

TERRES, R.R. and B.P. LUYENDYK (1985): Neogene tectonic rotation of the San Gabriel region, California, suggested by paleomagnetic vector, *J. Geophys. Res.*, **90**, 12 467-12 484.

WELLS, RAY. and JOHN W. HILLHOUSE (1989): Paleomagnetism and tectonic rotation of the lower Miocene Peach Springs Tuff: Colorado Plateau, Arizona to Barstow, California, *Geol. Soc. Am. Bull.*, **101**, 846-863.

YATSUTO, I. (1988): Differential rotation of the eastern part of soutwest Japan inferred from paleomagnetism of Cretaceous and Neogene rocks, *J. Geophys. Res.*, **93**, 3401-3411.

ZOBACK, M.L., R.E. ANDERSON and G.A. THOMPSON (1981): Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western US, in «Extensional tectonics associated with convergent plate boundaries», organized by F.J. VINE and A.G. SMITH, *Royal Society of London Proceedings*, pp. 189-216.