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STRESS FIELD ROTATION OR BLOCK ROTATION: AN EXAMPLE FROM THE LAKE MEAD FAULT SYSTEM

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ABSTRACT

The Coulomb criterion, as applied by Anderson (1951), has been widely used as the basis for inferring paleostresses from insitu fault slip data, assuming that faults are optimally oriented relative to the tectonic stress direction. Consequently if stress direction is fixed during deformation so must be the faults. Freund (1974) has shown however that faults, when arranged in sets, must generally rotate as they slip. Nur et al., (1986) 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 of 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 trending 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° CW rotation of the **stress field** (as for the entire Great Basin) plus a local 30° CCW **material** rotation of the LMFS fault blocks.

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 earths free surface which thus defines 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 insitu 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 the fault's coefficient of friction and cohesion are also constrained.

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 2-D 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 adjacent conjugate fault domains experienced both clockwise and counterclockwise rotations in a single tectonic setting of northern Israel. Similar interpretations were suggested for the Mojave area in California (Garfunkel, 1974), the Transverse Range, California (Terres and Luyendyk, 1985) central America (Manton, 1987), Alaska (Stamatakos et al., 1988), Lake Mead, Nevada region (Ron et al., 1986; Geissman, 1986,) and northern Greece (Pavlides et al., 1988). 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. Furthermore 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 further 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 relatively 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 it is most probable that 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 insitu 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 determine the relative importance of the two rotations - stress field rotation vs. material rotation they have to 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 short paper is to report on a probable 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 a., 1981; Angelier et al., 1985), paleomagnetic data (Ron et al., 1986; Geissman, 1986), and seismicity (Rogers and Lee, 1976; Rogers et al., 1984).

DATA

Structures. The 30 by 80 km Lake Mead fault system (figure 1) includes a few long northeast-trending left-lateral strike slip faults (set #1 in figure 1 & 2). Based on offsets of Late Neogene volcanic rocks (Anderson, 1973; Bohannon, 1983) the total 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 plutonic activity and by normal faulting that formed broadly spaced basins and ranges (Anderson et al., 1972; Angelier et al., 1985). 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 (Anglier et al., 1985, Figure 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 figure 6 and 9); (c) a few left-lateral faults striking 350°-30° (north to northeast) are also found here (Anglier et. al., figure 9).

Together these results suggest that the northwest-trending right lateral faults (set #2 in figure 1 & 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. Assuming that any one cluster of fault orientations is associated with a corresponding orientation of the stress field (and excluding material rotation) Anglier et. al., (1985) inferred a clockwise (CW) stress field rotation of about 60° since mid-Meocene time. Although the CW **sense** of this paleostress rotation is very consistent with the sense of stress rotation proposed for the entire Basin and Range (Ekren, 1977; Zoback et al., 1981), the **magnitude** of this stress rotation is in remarkable disagreement with values elsewhere: Zoback et al., (1981) suggested a 30° CW rotation of the principal paleostress direction since mid-Miocene throughout the Basin and Range, whereas the results by Anglier et al., (1985) seemingly imply a 60° CW stress field rotation for the Hoover Dam and presumably the entire Lake Mead area. The resulting 30° discrepancy led Anglier and co-workers to actually suggest 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 & 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 figures 1 & 2). It is noteworthy that this seismic activity is **not** associated with the large northeast left-lateral strike slip faults (set # 1), nor is it associated with the shorter NW trending right lateral faults (set #2). From the prevalence of the NW trending, now inactive faults (set #2) and the N trending seismic faults (set #3) we have suggested (Ron, et. al.,1986) that active crustal deformation in this area was and is still being accommodated by the sets of the smaller fault with right-lateral strike slip, situated within the larger left-lateral shear zones. The tension or 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 paleomagnetic data sets 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). Supporting evidence is found also in 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 in situ field data revealed 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°.

Similarly, paleomagnetic data collected by Geissman (1986) in the same Hoover Dam area, where Angelier et al (1985) obtained their structural data, imply that

(1) Paleomagnetic declination data imply 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's et al., (1986) results for the Hamblin-Cleopatra area.

(2) The tilting of fault blocks in the Hoover Dam and adjacent areas as inferred from inclination data occurred most probably prior to 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 independent structural evidence that tilting occurred before or very early in the strike slip faulting history.

Wells and Hillhouse (1989) also report on CCW rotations 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.

DISCUSSION

The results reviewed above can be summarized as follows:

(1) The structural data suggests that the shorter NW trending right-lateral faults (set #2 in figure 1 & 2) accommodated much of the deformation of the region (Angelier et al, 1985).

(2) The seismic data shows that current fault slip takes place along short north-

south trending right-lateral strike slip faults (set #3) (Rogers and Lee, 1976; Rogers et al., 1984) and not along the NW older trending 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 (Figure 2). This has led us to suggest (Ron et. al., 1986) that the original orientation of these faults was approximately north-south as shown in figure 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 figure 4 the structural paleostress 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 a., 1981).

(5) The current maximum horizontal stress as inferred from earthquakes fault plane solutions, is oriented N30° E. This direction is in 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 in the study area (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 lead 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 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.

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 for 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 LMFS it has been superimposed on the regional Basin and Range stress field rotation. This local rotation obeys the rules of the kinematics. (Freund 1974; Ron et al., 1984), and mechanics (Nur et al., 1986) of block and fault rotation model. In this model, simultaneous strike slip faulting and rigid block rotation about the vertical axis take place. A key feature is that the sense of rotation is opposite to the sense of slip (e.g., counterclockwise rotation associated with right-lateral slip and clockwise rotation associated with left lateral slip). Equivalently the material rotation is always away from the direction of maximum compression. Consequently, when structural markers are used to infer rotation, a **clockwise stress field** rotation is indistinguishable from a **counterclockwise material rotation**, and vice versa.

SUMMARY

We suggest that the Lake Mead - Hoover Dam area experienced the same 30° CW tectonic **stress field rotation** that presumably affected the entire basin and range province (Zoback et al., 1981). In addition this region has also experienced a 30° CCW **material rotation** of blocks and faults (Figure 4) giving rise to the apparent discrepancy between the stress history of the LMFS and the rest of the Basin and Range province.

There must exist other regions where the tectonic history involved both paleostress field rotation and material rotation. Consequently our analysis here may prove effective in solving faulting complexities elsewhere: Examples include central Japan (Angelier & Huchon, 1987), where large differential paleomagnetic rotations have been found (Yasuto, 1988), in northern Greece (Pavlides and Kilias, 1987, Pavlides et al., 1988) southern California (Nicholson et al., 1986), and New Zealand (Walcott, 1988), to name but a few.

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FIGURE CAPTIONS

Figure 1. The main fault sets in the Lake Mead Fault System (modified after Rogers & Lee, 1976): (1) Large NE trending left lateral strike slip faults, (set #1); (2) Shorter 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 indicate right handed strike slip.

Figure 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.

Figure 3. Structural model for the development of multiple faults due to the material rotation in the Lake Mead fault zone: Left slip on the irrational 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 handed faults rotated approximately 30° CW away from the direction of maximum compression σ_1, they locked up. Further deformation is now accommodated by the new set #3 of right handed faults. Presumably, when these fault will reach a CCW rotation of 30° in the future, they will lockup, and another set of rotating faults may have to develop.

Figure 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 (090°) 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 figure 1 & 2). The angle between them is close to 60°, not 30° as expected from (a) and (b); (d) explaining the LMFZ 60° apparent rotation as a combination of a 30° clockwise stress field rotation plus a 30° counterclockwise material rotation, as inferred from the paleomagnetic declination anomalies of Ron et. al., (1986) and Geissman (1986).

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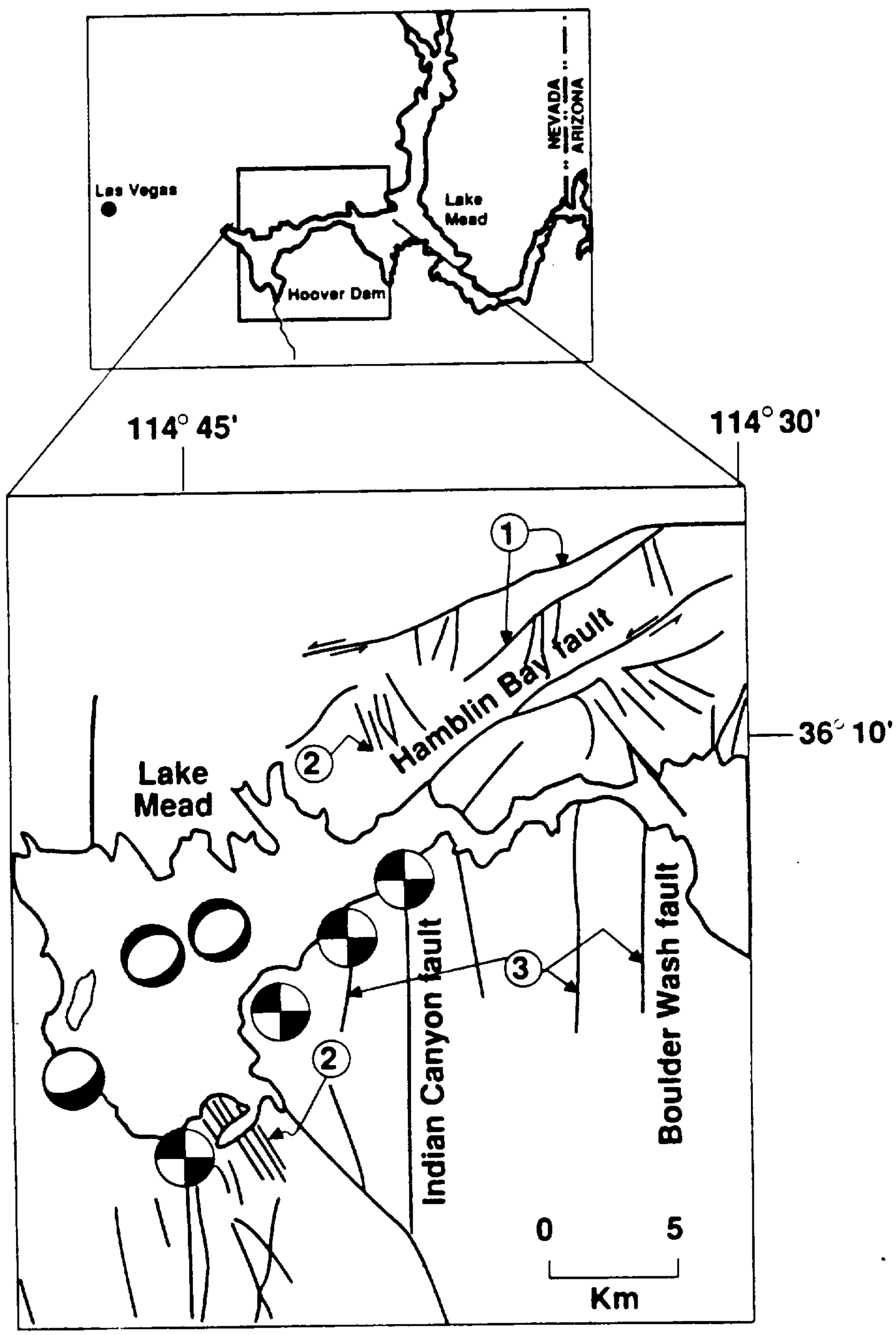


Las Vegas
Lake Mead
Hoover Dam
NEVADA
ARIZONA
114° 45'
114° 30'
36° 10'
Hamblin Bay fault
Lake Mead
Indian Canyon fault
Boulder Wash fault
1
2
3
0
5
Km

fig 1

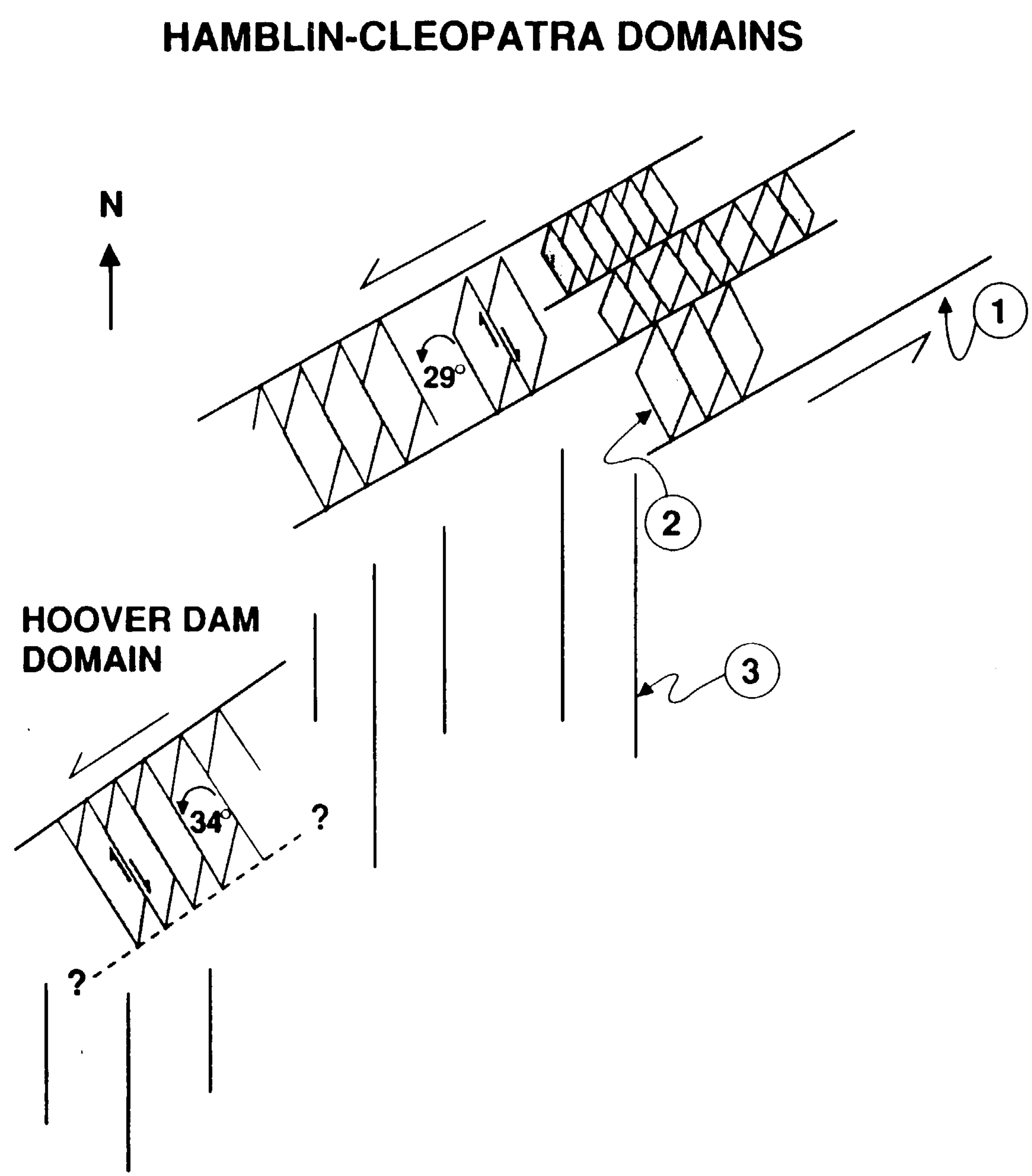
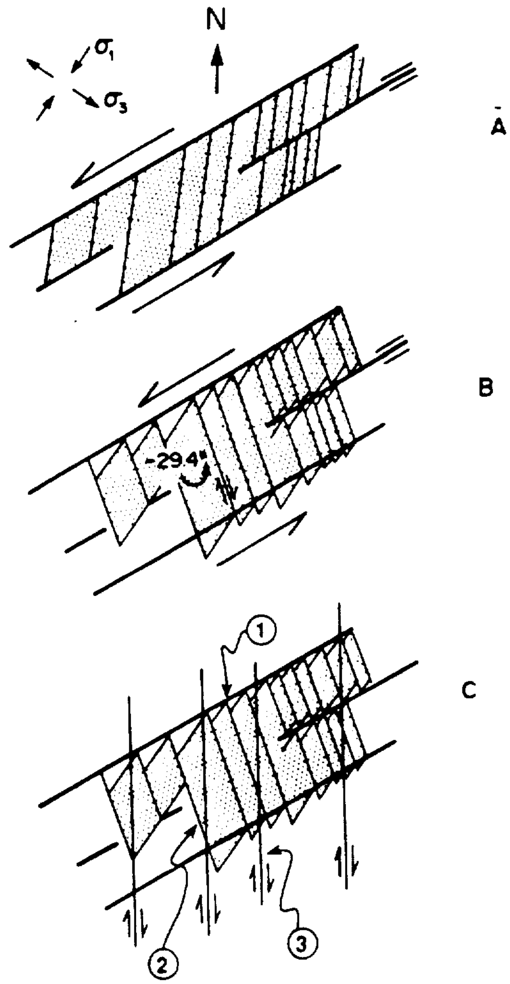
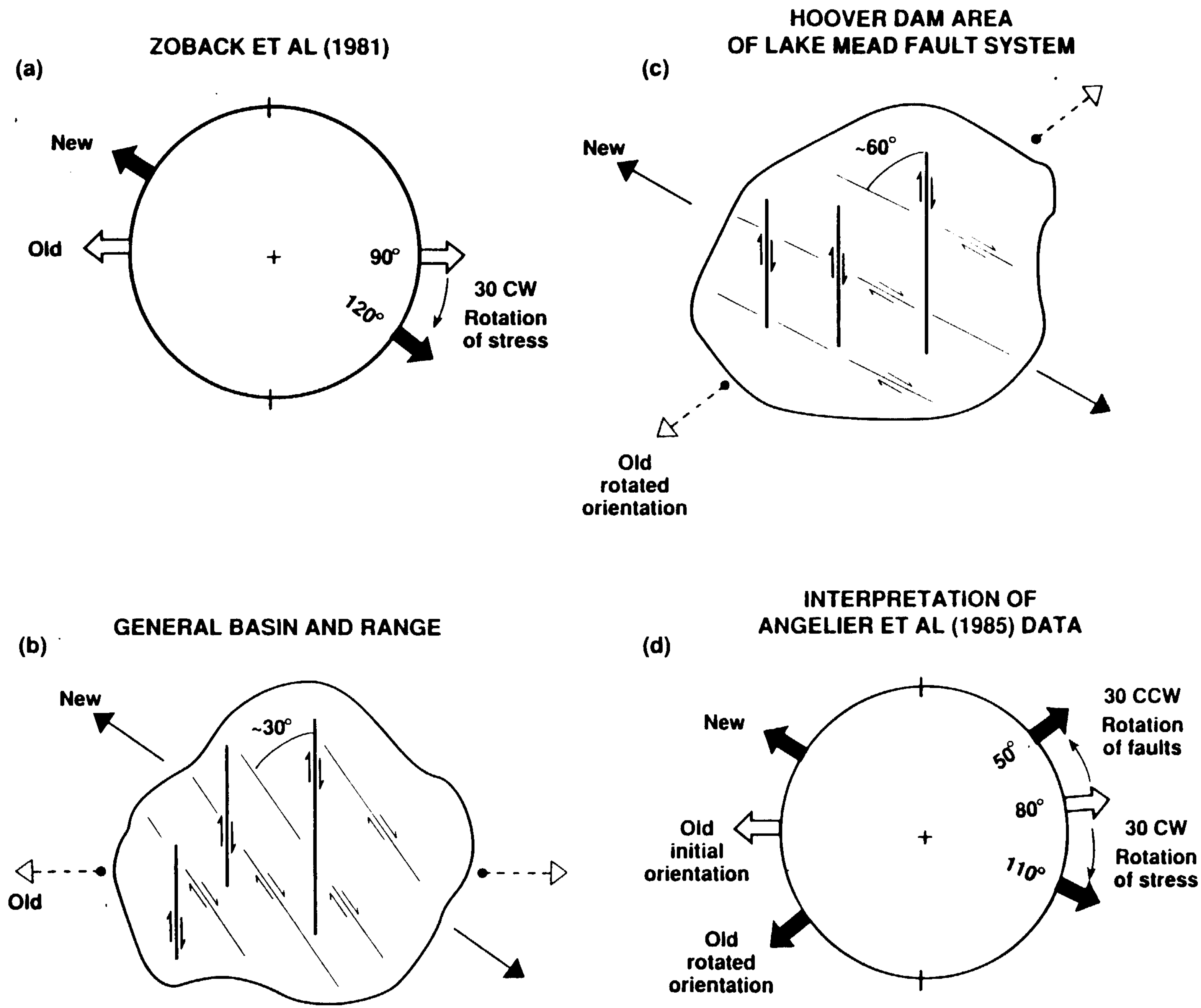


fig 2



N
σ1
σ3
A
-29.4°
B
1
C
2
3


(a)
ZOBACK ET AL (1981)
New
Old
90°
120°
30 CW
Rotation
of stress
(c)
HOOVER DAM AREA
OF LAKE MEAD FAULT SYSTEM
New
~60°
Old
rotated
orientation
(b)
GENERAL BASIN AND RANGE
New
~30°
Old
(d)
INTERPRETATION OF
ANGELIER ET AL (1985) DATA
New
50°
80°
110°
30 CCW
Rotation
of faults
30 CW
Rotation
of stress
Old
initial
orientation
Old
rotated
orientation