A model for Neogene crustal rotations, transtension, and transpression in southern California

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ABSTRACT

Two episodes of crustal rotation have occurred in the regions of southern California and the Mojave Desert since the beginning of Miocene time. An early Miocene episode of clockwise crustal rotation is associated with widespread north-south to north-northeast-south-southwest crustal extension throughout southeast California and western Arizona. This episode is apparently related to changing subduction parameters of the Farallon plate. A middle Miocene and later episode of clockwise rotation in the Transverse Ranges and bordering areas is related to shear between the Pacific and North American plates. In both episodes, clockwise crustal rotations first occur in a deforming zone which has a component of extension across its trend and shear along its trend. The effects of extension are most pronounced in the earlier episode but clear in the later one also. The Pacific–North American deforming zone began contracting in width during Pliocene time, but clockwise rotations continued and are probably in progress today.

CRUSTAL ROTATIONS IN THE PACIFIC-NORTH AMERICAN PLATE DEFORMING ZONE

In their regional geometric model for Neogene tectonic rotations in the Transverse Ranges of southern California, Luyendyk and others (1980, 1985) assumed that both the deforming plate boundary zone in southern California containing the rotating crustal blocks and the Pacific–North American relative motion vector trended northwest-southeast parallel to each other. Dextral simple shear was proposed to occur within a zone of constant width. This geometry requires that the ends of rotating crustal beams thrust out of the deforming zone, an effect which apparently lacks geologic evidence (Luyendyk and others, 1980, 1985; Luyendyk, 1989). This problem is mitigated if the deforming zone is in fact widening in the northeast-southwest direction perpendicular to the zone trend (McKenzie and Jackson, 1986) while also undergoing dextral shear. Thus the zone is undergoing transtension (Fig. 1). The width changes because the Pacific–North American vector has an extensional component perpendicular to the trend of the boundary, and new crustal area is created. In the Luyendyk and others' (1980, 1985) model, crustal overthrusting is balanced by gapping between rotating and non-rotating crust, thereby conserving area. Another distinction between these two concepts is that in the original geometric model all crustal displacements during rotation occur on strike-slip faults, whereas displacements within a deforming zone undergoing either transtension or transpression occur on oblique slip faults (Fig. 1).

The Luyendyk and others (1980, 1985) models predicted that middle Miocene and younger clockwise tectonic rotations have occurred in the Northeast Mojave Block and in the Tehachapi Mountains Block (Fig. 2). In the Mojave region, Ross and others (1989, 1991) and Wells and Hillhouse (1989) found evidence for an early Miocene clockwise rotation outside of the Northeast Mojave Block. Further, Kanter and McWilliams (1982) and McWilliams and Li (1985) suggested that rotation in the Tehachapi block occurred before middle Miocene time. Therefore, the original models of Luyendyk and others (1980, 1985) incompletely predict and explain rotations east of the San Andreas fault.

TWO ROTATION EPISODES

Two rotation episodes are suggested, both of which involve simultaneous crustal extension and rotation at the onset of each episode. The concepts of McKenzie and Jackson (1986) can therefore be applied to understand the geometry and driving mechanisms for the rotations.

Early Miocene Mojave Episode

The following facts are believed known on the timing and locations of the clockwise rotations since Oligocene time (Fig. 3). An episode of early Miocene clockwise rotation has been discovered in the Mojave Desert (Ross and others, 1989; Wells and Hillhouse, 1989, Fig. 2). This rotation apparently occurred within a region which was being simultaneously extended in an approximately north-south or north-northeast–south-southwest direction. Clockwise rotations and related extension in the San Gabriel block (Terres and Luyendyk, 1985) and the Orocopia Mountains (Terres, 1984), and the Tehachapi Mountain Block (Kanter and McWilliams, 1982; McWilliams and Li, 1985), may have been simultaneous with the Mojave episode. The ages of the Orocopia and San Gabriel rotations are constrained only to be post–earliest Miocene time. In any case, northeastward-oriented extension was prevalent throughout southern California and western Arizona in early Miocene time, possibly due to back-arc spreading (Tennyson, 1989) or to "roll-back" to the southwest of the steepening and disintegrating downgoing Farallon slab (Atwater, 1989).

Middle Miocene and Later Episode

Rotations associated with the Pacific–North American transform boundary began after ca. 18–17 Ma (Hornafius and others, 1986; Liddicoat, 1990), when subduction ceased offshore southern California (Lonsdale, 1991). Diffuse crustal extension and basin formation preceded the rotation and strike-slip faulting by a few million years (Crowell, 1987; Atwater, 1989). A

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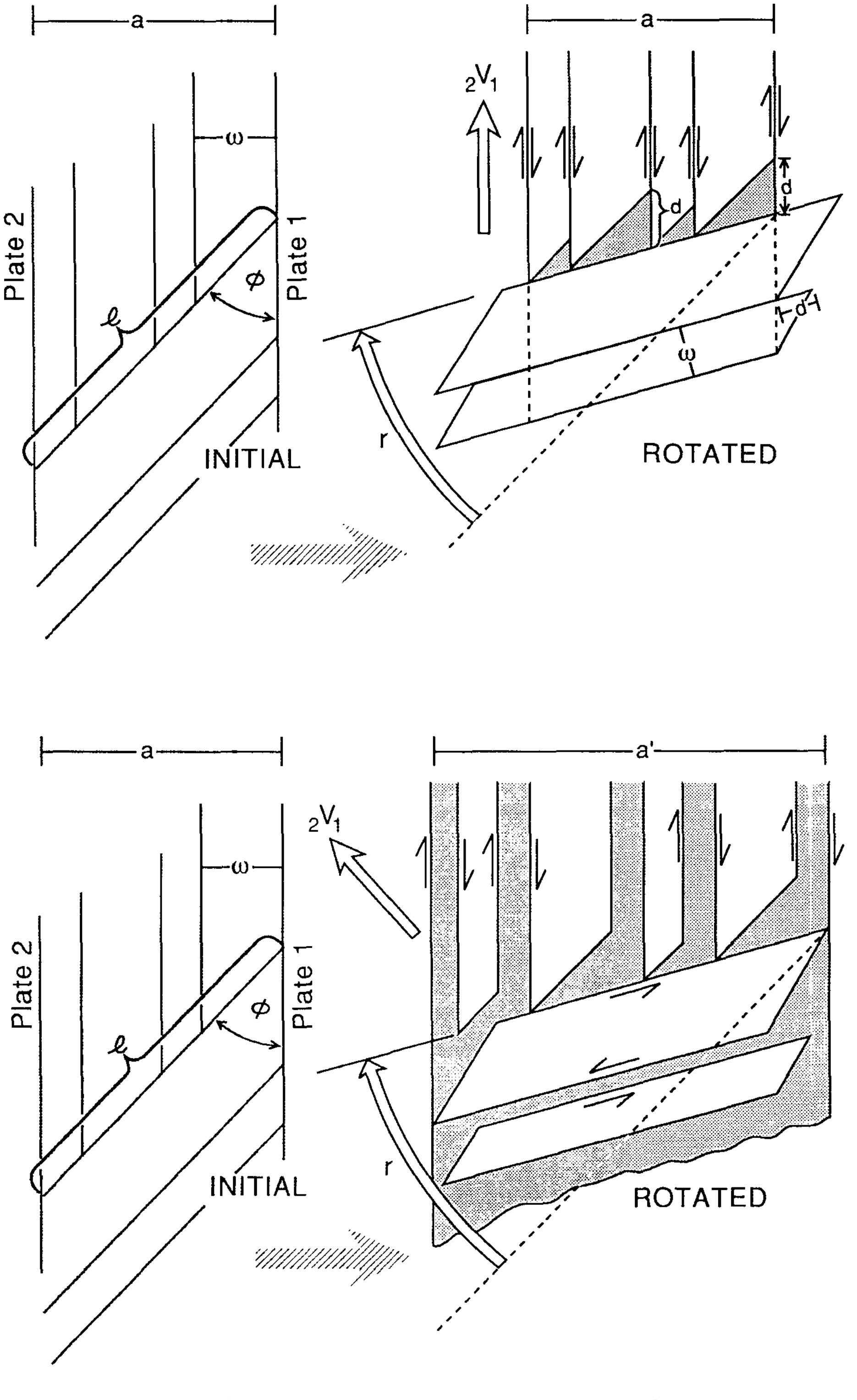


Figure 1. A geometric model showing rotation and simultaneous faulting. (top) Plate 1 moves parallel to deforming zone which maintains a constant width, a, and the rotating blocks thrust out of the zone. (bottom) Plate 1–2 motion is transtensional; the rotating blocks remain within the deforming zone, which is expanding from width a to a′: Definitions: r = rotation angle; ω = width of individual blocks; d = displacements on faults bounding blocks; ℓ = length of rotating blocks; φ = initial angle between rotated and nonrotated blocks. For equations to find d, see Luyendyk and others (1980). D = Σd_i is computed for California in Hornafius and others (1986) and Luyendyk (1990).

possible scenario is that the western Transverse blocks were created and began rotating in middle Miocene time as the Pacific–North American plate boundary zone both sheared dextrally in the northwest-southeast direction and extended in a perpendicular direction as the Pacific plate moved approximately west-northwest relative to North America (Atwater, 1989; Stock and Molnar, 1988). Garfunkel (1989) has shown in a theoretical treatment that the plate-motion vector must be at least 20 degrees oblique to the trend of the zone boundary for extensional faults to form in the deforming zone. In theory, these faults would trend at a high angle to the zone boundary. Laboratory experiments by Tron and Brun (1991) show extension faults forming at angles between 20 and 30 degrees to the transtension zone boundary for plate motion vectors 15 to 45 degrees oblique to the boundary. The faults bounding the rotating crustal blocks therefore may have formed when the zone deformed initially (Luyendyk and others, 1985). As the zone widened, the fault-bounded western Transverse Ranges blocks rotated clockwise (Fig. 4). Sediments were deposited in triangular basins, such as the Los Angeles basin, which formed as sphenochasms or transrotational basins (Ingersoll, 1988) opening between the rotating and nonrotating crust. In addition, the nonrotating crust in the deforming zone was being extended orthogonally to the zone, initiating long linear sedimentary basins parallel to the deforming zone trend. Faults between the rotating crustal beams and parallel to their strike were both sinistral and extensional, leading to the initiation of the Santa Barbara and Ventura basins, among others. The sedimentary basins described by Blake and others (1978), McCulloch (1987), and Crowell (1987) can all be attributed to these phenomena, as can rifting in the inner southern borderland as proposed by Yeats (1968) and extension in the Santa Maria basin discussed by Hornafius (1985).

During Pliocene time, the Pacific–North American vector changed direction, resulting in a component of contraction across the deforming zone (Harbert and Cox, 1989; Fig. 4). Clockwise rotation continued with the western Transverse blocks still contained within the deforming zone. This is possible because by this time the blocks had rotated beyond perpendicular to the zone trend. Crustal shortening in the California margin and borderland (McCulloch, 1987; Teng and Gorsline, 1989) and California Coast Ranges (Page, 1981; Crouch and others, 1984) occurred simultaneously with the rotation as the deformation zone narrowed.

Generally, rotations began first in the west in middle Miocene time, and later in the east; further, net rotations are larger in the west than

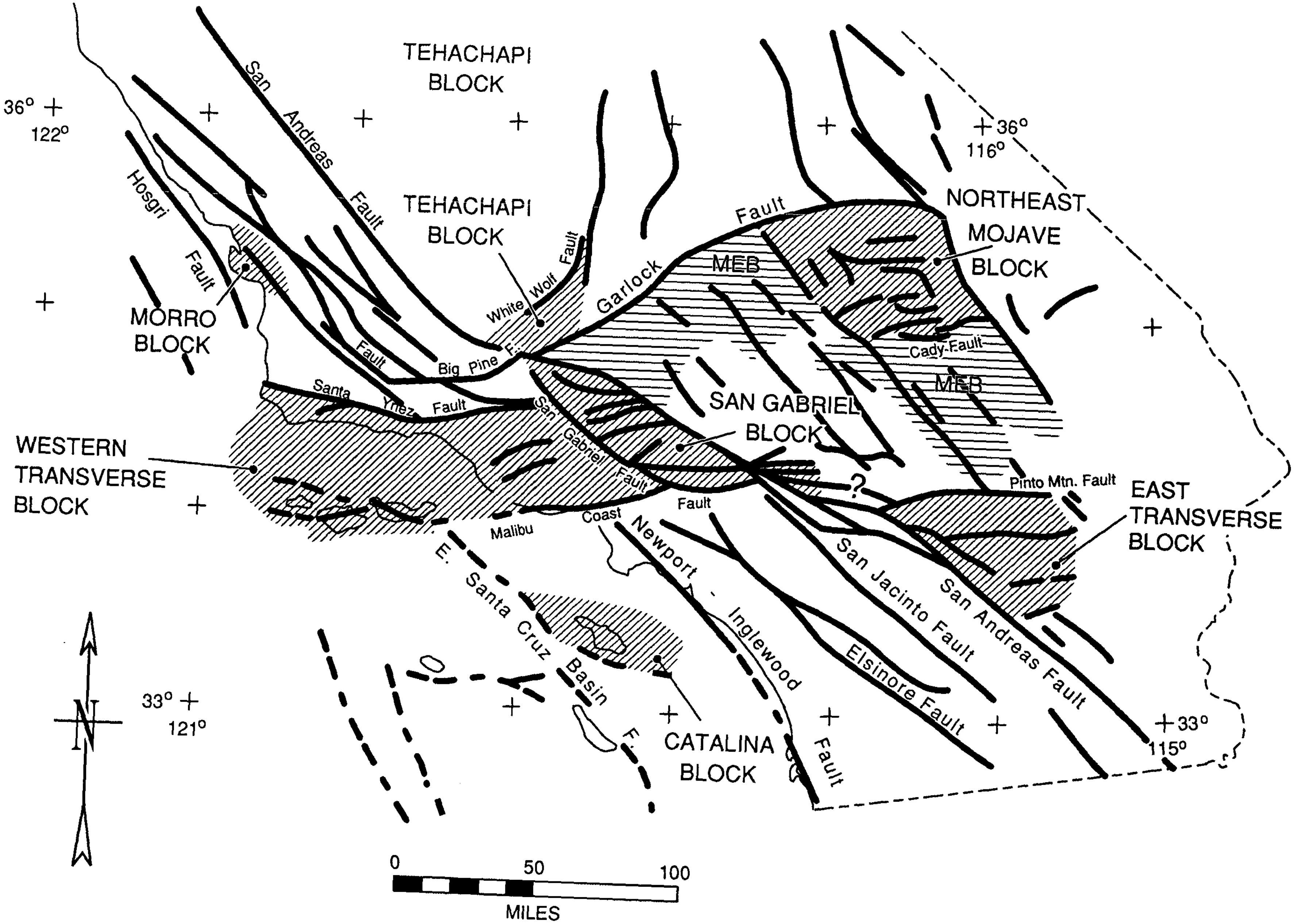


Figure 2. Areas believed to have been clockwise rotated in southern California and the Mojave Desert during Neogene time. The diagonal rules outline blocks rotated since the end of early Miocene time within the deforming zone between the Pacific and North American plates. the horizontal rules outline the Mojave Extensional Belt (Dokka, 1986, 1989). Ross and others (1989) found that blocks of the upper plate here were rotated clockwise in early Miocene time apparently simultaneously with crustal extension related to subduction beneath the North American plate.

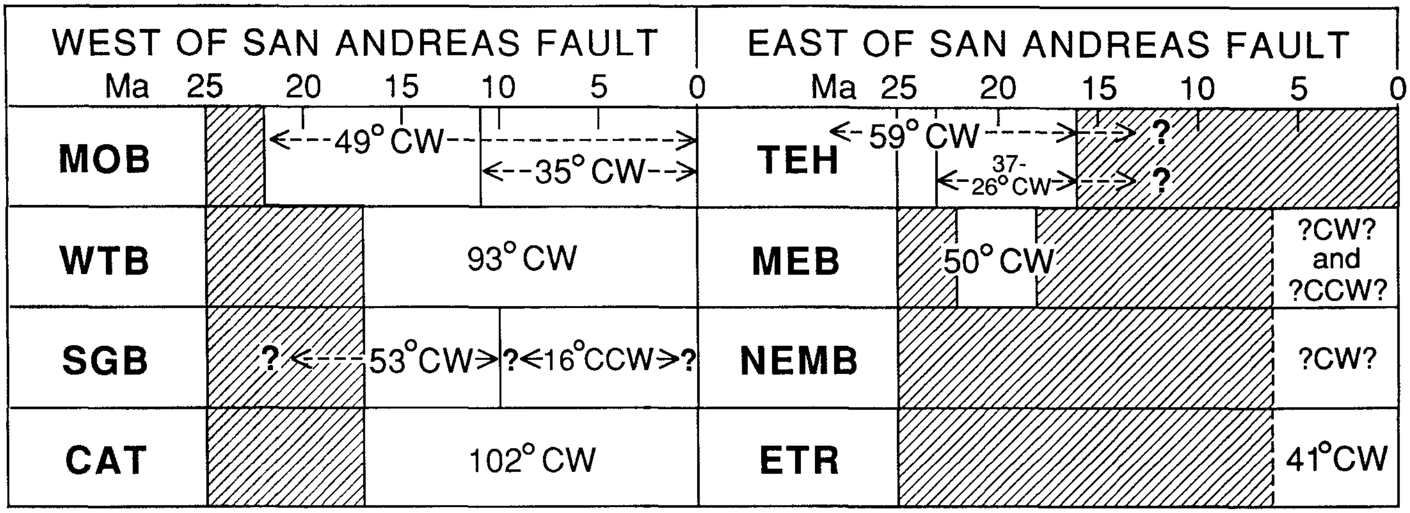


Figure 3. Schedule of rotation events in the southern California region. Time before present is across the top, and regions are divided by the San Andreas fault. Explanation: CW = clockwise rotation; CCW = counterclockwise. Age limits are the ages of the rocks studied and thus bracket only the timing of rotation. Where the ages are uncertain (MEB, NEMB, ETR), the limit is dashed. For WTB, SGB, CAT, the beginning of the rotation is believed to be estimated fairly accurately at 17 Ma. MOB = Morro Block with 49 degrees of post–22 Ma CW rotation (Greenhaus and Cox, 1978) and 35 degrees of post–11 Ma CW rotation (Khan and others, 1988). WTB = Western Transverse Block with 93 degrees of middle Miocene and later, CW rotation (Luyendyk, 1990; Hornafius and others, 1986; Liddicoat, 1990). SGB = San Gabriel Block with 53 degrees of post–21 Ma CW rotation (Terres and Luyendyk, 1985; Hornafius and others, 1986) and 16 degrees of post–11 Ma CCW rotation (Terres and Luyendyk, 1985). CAT = Santa Catalina Island with 102 degrees of middle Miocene and later CW rotation (Luyendyk and others, 1988). TEH = Tehachapi block. This block has probably undergone both block rotation and oroclinal bending. In the southwest, 59 degrees of post–77 Ma CW rotation was found (McWilliams and Li, 1985), along with 37 or 26 degrees of post–23 Ma CW rotation (J. Plescia, G. Calderone, and L. Snee, unpub. data; see text for discussion). To the northeast on this block, 16 Ma volcanic rocks show no significant rotation (Kanter and McWilliams, 1982). The time of the end of the rotation in the southwest is unconstrained. MEB = Mojave Extensional Belt with 50 degrees of CW rotation between 22 Ma and 18 Ma (Ross and others, 1989; and data of Golombeck and Brown, 1988), and a possible post-Miocene rotation event; CW and/or CCW (Luyendyk and others, 1980, 1985). NEMB = Northeast Mojave Block with a possible post-Miocene CW rotation (Luyendyk and others, 1980; Ross and others, 1989). ETR = Eastern Transverse Ranges Block with 41 degrees of CW rotation (Carter and others, 1987) which is now believed to be post-Miocene. All data from west of the San Andreas fault permit the interpretation of one middle Miocene and later rotation event. All data from east of the fault permit the interpretation of an early Miocene and a post-Miocene event. The TEH data permit this interpretation and also a middle Miocene and later event.

the east, but are generally less than 100 degrees. The western Transverse Ranges block rotated about 35 degrees clockwise during middle Miocene time (Fig. 5). The Tehachapi Mountains block possibly rotated clockwise during this same period. The timing of rotation of the Tehachapi block is poorly constrained. Unpublished paleomagnetic data (see caption to Fig. 3) from early Miocene lavas show a clockwise declination anomaly, but there are significant questions on whether secular variation and/or undetected tilts contaminate the result. During late Miocene time, the western Transverse Ranges blocks rotated more than 25 degrees. Since Miocene time, the eastern Transverse Ranges block (northeast across the San Andreas fault) and possibly parts of the northeast Mojave Desert north of the Cady or the Sleeping Beauty fault rotated clockwise (MacFadden and others, 1990) about 41 degrees while the western Transverse Ranges block again rotated about 35 degrees (Fig. 6). Ross and others (1991) found both pre– and post–16.5 Ma clockwise rotation in the southwest Cady Mountains in the Mojave Desert, but the areal extent of this pattern is unknown. Most of the western Mojave may have rotated about 15 degrees counterclockwise in post-Miocene time, also bending the adjacent portion of the San Andreas fault (Luyendyk and others, 1985), although this interpretation is poorly constrained. Comparison between Figure 5 (13–14 Ma) and Figure 6 (3 Ma) suggests that 80 to 90 km of extension (35%) occurred across the deforming zone west of the San Andreas fault during the transtension phase.

Simultaneous clockwise and counterclockwise rotations in the Mojave are best explained by northeast-oriented pure shear (compression; Carter and others, 1987), which could be due to Pliocene transpression within the Pacific–North American deforming zone (Fig. 6) and also to regional compression associated with the post-Miocene (?) restraining bend in the San Andreas fault formed when Baja began rifting from mainland Mexico. Because seismicity is apparent on both northwest-southeast and east-west faults in California, it is likely that rotations are continuing today both in the Mojave and the Transverse Ranges (Jackson and Molnar, 1990).

The progression of the rotation inland is probably a result of the widening of the contact length between the Pacific and North American plates as the Mendocino and Rivera triple junctions migrated apart. This effect was described in the analytical model of Sonder and others (1986).

RATE OF MIDDLE MIOCENE AND LATER ROTATION

Reviewing paleomagnetic data from the western Transverse Ranges, Hornafius and others (1986) suggested that the rate of rotation was not constant and decreased from 10 degrees/million years (10 deg./m.y.) in middle Miocene time, to a low rate or zero in late Miocene time, and increased again to 5 deg./m.y. in Pliocene time. In finding these rates, they used stratigraphic ages which have since been reassigned. Luyendyk (1990) found that with revised ages the data can be interpreted equally as well showing a steady rate of rotation of 5.79 deg./m.y. since early Miocene time (Fig. 7).

A constant rate of rotation is an unexpected result considering several factors, including theoretical models for rotations and possible variation in the Pacific–North American motion vector. In theory, the rotation rate is a result of complex interplay between plate motions, block geometry and orientation, and driving mechanisms. In their treatment, McKenzie and Jackson (1983, 1986) noted that elongate blocks in a deforming zone rotate at an instantaneous rate equal to the velocity gradient across the zone if the blocks are "pinned" or mechanically connected to the zone edges (see Fig. 4), but at half this rate if the blocks are disconnected from the boundaries or "floating" in the zone and are being driven mainly by viscous forces at the bottoms of the blocks. In middle Miocene time when rotation began, the crustal blocks would soon disconnect from the zone boundaries as the zone widened in a transtension regime. In Pliocene time or later, the blocks may have reconnected with the zone boundaries during transpression. In a crude sense then, this model suggests a lower rate in Miocene time and a higher rate in Pliocene and later time.

Lamb (1987) has treated finite rotations of "floating" elliptical (crustal) blocks in a deforming zone. Lamb (1987) assumes a constant relative motion vector across the deforming zone. His treatment shows that the rate of rotation varies with time and is dependent on the instantaneous orientation of the block, the aspect ratio of the block dimensions, and the plate relative motion vector. A constant rate is found only for crustal discs, which are a poor model for the elongate blocks of the western Transverse Ranges. Using his equations for the rate of rotation of an elongate inclusion suggests that the rate would decrease with time by a factor of two or more during transtension, then abruptly increase when the zone became transpressive, and steadily decrease thereafter.

Plate-motion studies for western North America suggest significant changes in the relative motion vector between the plates during Neogene time (Stock and Molnar, 1988; Harbert and Cox, 1989, Harbert, 1991). In addition, the velocity gradient across the zone decreases as the zone widens under transtension and increases as it contracts under transpression. The interaction of these effects on the rotation rate with the effects of block orientation on the rate (Lamb, 1987) are complex and speculative at this point. Nevertheless, it is consistent to suggest that the rate may have decreased during transtension and increased during transpression.

It is clear that theoretical models favor a change in rotation rate with time, and generally

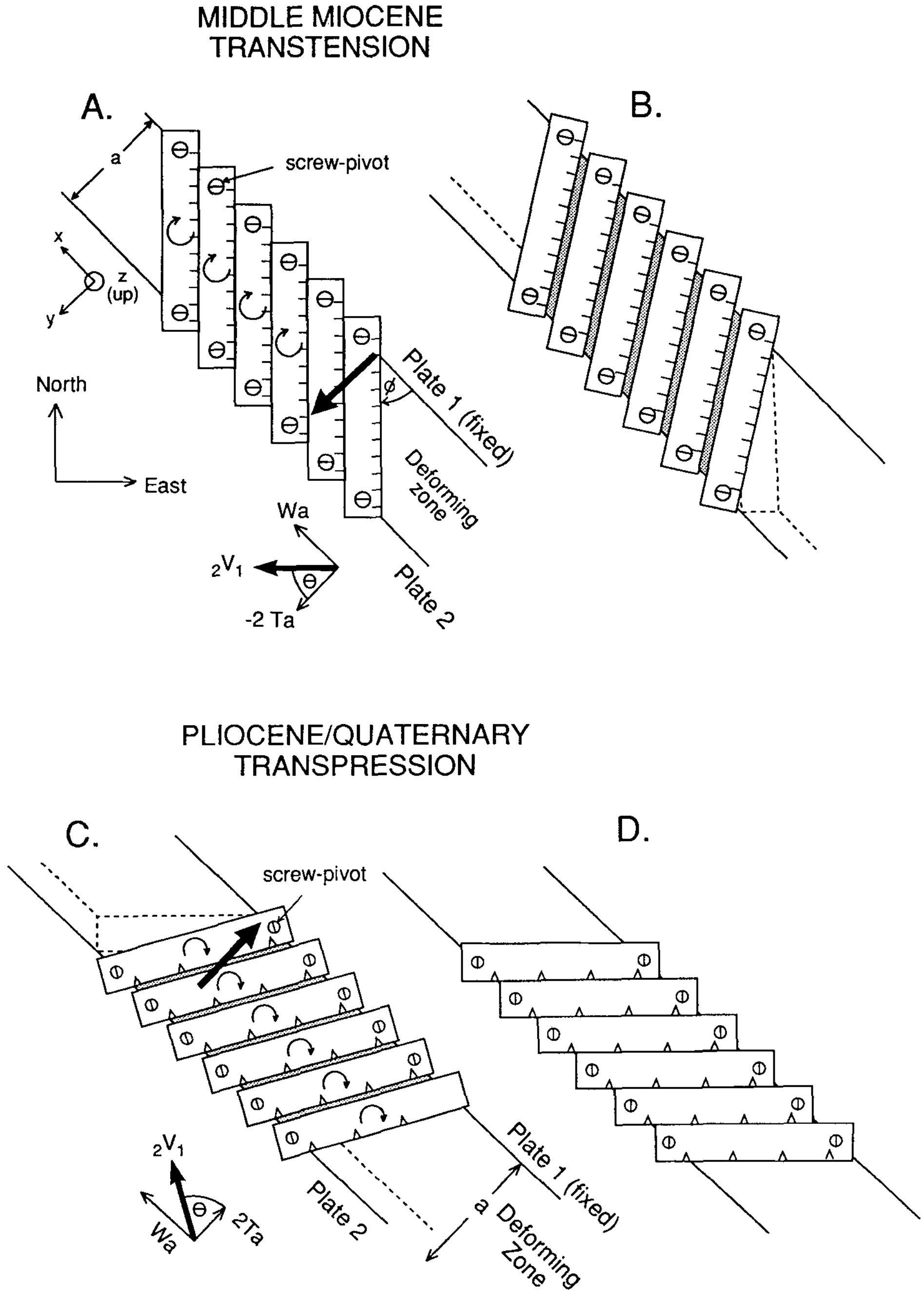


Figure 4. Models for the rotation of the western Transverse Ranges blocks during changing width a, of the deforming zone between Plate 1 (North American) and Plate 2 (Pacific); after McKenzie and Jackson (1983, 1986). The plate-motion vector is the heavy arrow with components Ta across the zone and Wa along it. The heavy arrow within the zones (Figs. 4A and 4C) is the direction of slip on faults bounding the rotating blocks. Figures 4A and 4B depict the transtensional situation in Miocene time; 4C and 4D, the transpressional situation in Pliocene time.

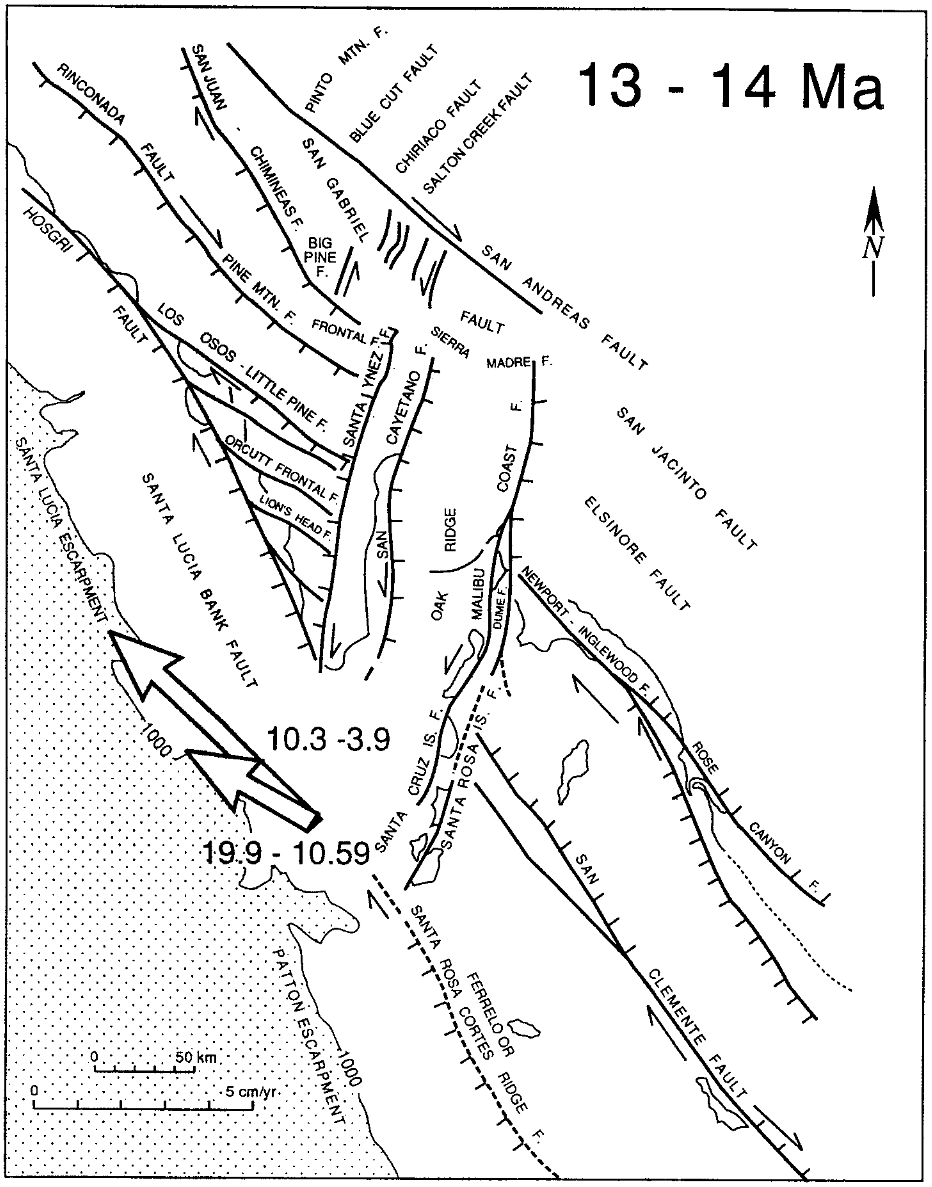


Figure 5. Reconstruction for southern California for the middle Miocene and later rotation episode at 13–14 Ma showing restored orientation of fault-bounded crustal blocks and proposed plate-motion vectors (modified from Luyendyk, 1989). The plate-motion vectors are calculated from the results of Stock and Molnar (1988) and Harbert and Cox (1989). The Pacific–North American vectors are 3.42 cm/yr, at 302 degrees for 19.9–10.59 Ma; and 6.2 cm/yr, at 314 degrees for 10.3–3.9 Ma; errors on vector magnitude and direction should be considered to be at least 20%. On this map, the names of faults are placed where they will appear in later time (Fig. 6).

an increased rate during the transpressional phase. This change in rate is opposite to that suggested by Hornafius and others (1986); Luyendyk (1990) considered modeling the data with only a constant rate and a rate decreasing steadily with time. The uncertainties in the data (Fig. 7) are large enough not to rule out rate changes of a factor of two. Considering uncertainties in the data and in the values for critical parameters of the theoretical models, an interpretation in terms of changes in the instantaneous rotation rate is inappropriate. Rather, it is best to conclude that the rotation progressed through middle Miocene and later time at an average rate of 5 to 6 deg./m.y.

FEATURES OF A REVISED MODEL FOR CALIFORNIA

The revised model recognizes two episodes of clockwise tectonic rotation in California: an early Miocene episode and a middle Miocene and later episode. The second episode has an early transtension phase followed immediately by a transpression phase. The revised rotation model emphasizes that extension and contraction of the zone of deformation is a critical controlling parameter for crustal block rotation of elongate crustal blocks which span the deformation zone; specifically, that rotation cannot *begin* unless the zone is first expanding.

An early Miocene episode of clockwise rotation in the Mojave is closely connected with crustal extension along detachment faults; both extension and rotation may be related to Farallon plate subduction. During middle and late Miocene time, the deformation zone between the Pacific and North American plates widens; it then contracts during Pliocene and Quaternary time. During rotation, the zone is also lengthening along strike due to the migration of the Mendocino and Rivera triple junctions in opposite directions.

This revised model has the following features:

1. Crustal extension and rotation can occur simultaneously within a widening plate deforming zone. Rotation can also occur during later contraction of the deforming zone.
2. During extension, linear basins form within the nonrotating parts of the plate-boundary deformation zone. These are bounded by dextral transtensional faults and are parallel to the zone trend.
3. Similar basins form along the trend of the clockwise-rotating blocks where they are bounded by sinistral transtensional faults.
4. Triangular or transrotational basins open at the join between rotating and nonrotating crust in the deforming zone.
5. Because rotations begin in a widening zone, the rotating block ends are always within the zone at first and do not necessarily thrust outside the zone as proposed in the original geometric model of Luyendyk and others (1980) for middle Miocene and later rotations. In fact, the zone boundaries may pull away from the rotating blocks, causing extensional faults at the end of the rotating crustal beams; this prediction needs testing.

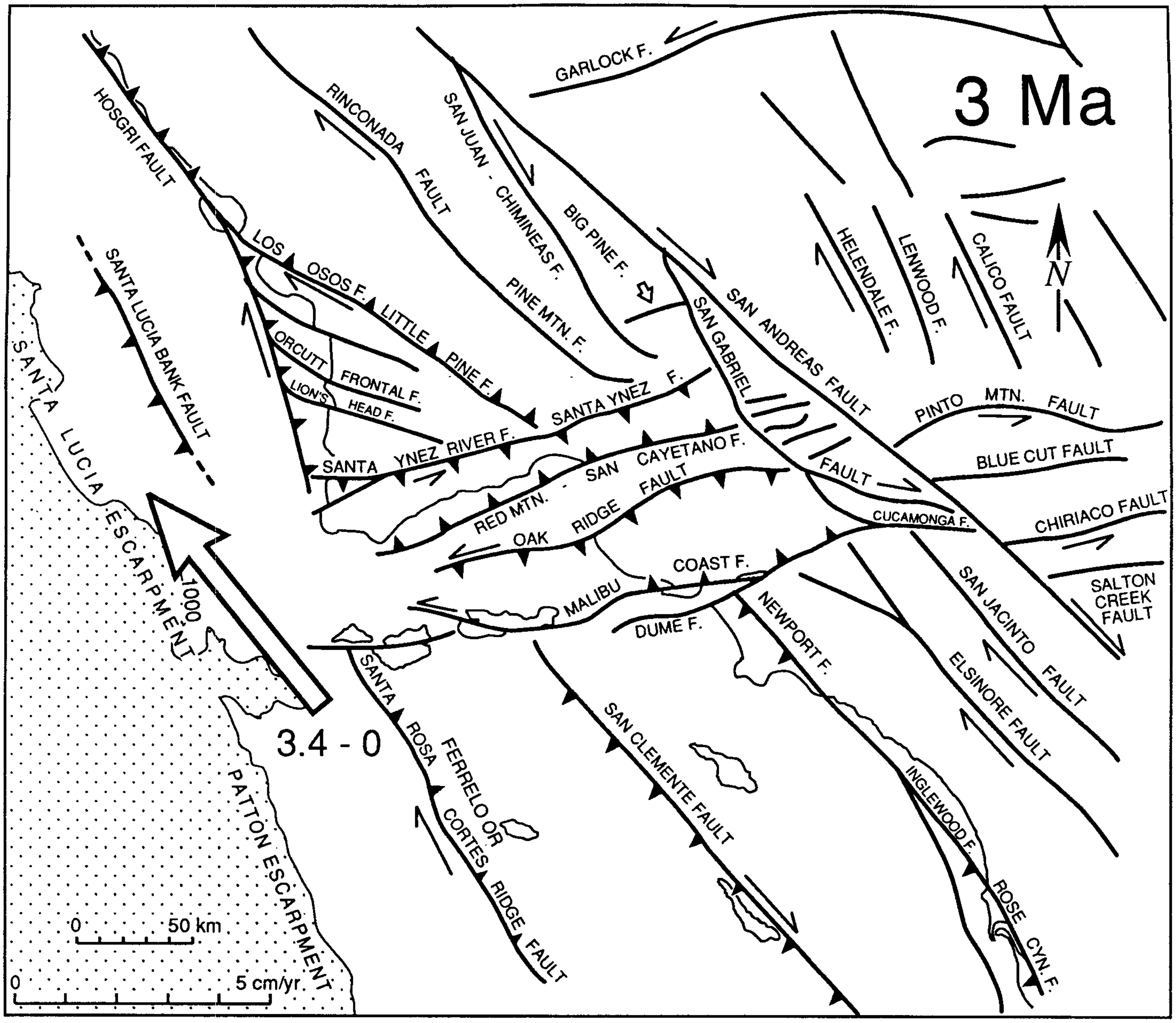


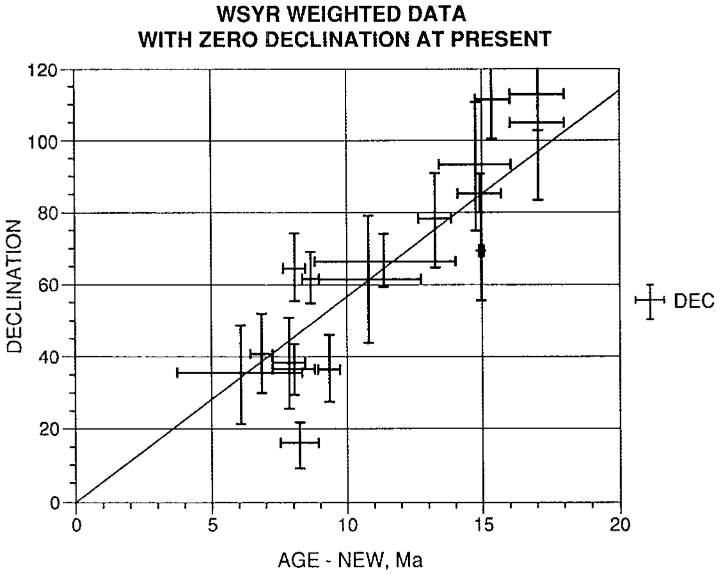
Figure 6. Reconstruction at 3 Ma showing proposed crustal blocks and plate vectors (modified from Hornafius and others, 1986). The plate motion vectors are calculated from results of Stock and Molnar (1988) and Harbert and Cox (1989). The Pacific–North American vector is 4.9 cm/yr, at 323 degrees since 3.4 Ma. This yields a transpressive component of about 0.7 cm/yr (minimum of 20% uncertainty), perpendicular to the trend of the San Andreas fault.

6. During the transtensional phase, the rotating blocks are most likely mechanically disconnected from the deforming zone boundaries, and so they are rotating at a rate of about half the velocity gradient across the zone. This results in half or less distributed shear north and south of the rotating blocks than is present between the plates. The remaining shear is taken up at the far edges of the deforming zone or on master faults within the zone.

7. There may be two episodes of Neogene clockwise crustal rotation in California: one associated with transtension caused by subduction of the Farallon plate, and a second due to transtension and transpression in the Pacific–North American plate boundary zone.

8. During Pliocene time contraction of the Pacific–North American deformation zone, all of the basins that formed in the earlier transtensional phase closed and formed fold belts as seen in the southern borderland and Central Coast

Figure 7. Declination data from the western Santa Ynez Range (WSYR) in the Transverse Ranges, from Hornafius and others (1986). Ages (new) are reassigned based on revised stratigraphy. The regression is computed for weighted data based on the number of sites in each data set (Hornafius and others, 1986). For an assumed constant rotation rate, declination = 5.79 deg./m.y. × Age-New; R^2 for fit = 0.95.



Ranges. Displacements occurred on transpressional faults.

REMAINING QUESTIONS AND FUTURE WORK

Within a deforming zone, the orientations of faults should determine which blocks rotate and which do not. It is not clear what the controls are on the origin of this faulting pattern. For example, Garfunkel (1989) has explained the origin of transtensional faults bounding rotating blocks, but the origin of faults bounding nonrotating blocks was not explained.

If transtension occurred in the southwestern United States during both the early Miocene and the later episode, then why are not more areas rotated, or are there other regions of undetected rotations? What is special, if anything, about the western Transverse blocks and the Mojave Extensional Belt? Although more basic data are still needed to understand the time-space boundaries of both episodes, the early Miocene episode is less well defined due to a lack of paleomagnetic data and a stratigraphic context for it.

The early Miocene rotations are apparently associated with extension and detachment faulting in a transtensional environment. Because the middle Miocene and later rotations also may be related to extension in a transtension environment, it can be hypothesized that these rotations are associated with (now buried) detachment faults. Detachment faults in various geometries have been described for the Transverse Ranges (for example, Yeats, 1981; Namson and Davis, 1988), but their relationship to crustal rotation is unclear.

In relating crustal rotation to detachment faulting, two questions arise. What is the timing of rotation relative to faulting, and do both upper and lower plates rotate or only the upper? Ross and others (1991) cited data which suggest that the early Miocene Mojave rotation followed the main faulting and tilting associated with extension. This is consistent with the experiments of Tron and Brun (1991), which show that considerable extension occurs early in deformation without rotation. On the other question, Janecke and others (1991) found rotations in the hanging wall of an extended area in the Lost River and Lemhi Ranges of Idaho. Their interpretation has the footwall fixed during the hanging-wall rotation. Clearly, these types of questions are only beginning to be addressed.

Lund and Bottjer (1991), among others, have proposed accretion of the Peninsular Ranges Terrane (or Baja-Borderland allochthon of Howell and others, 1987) against continental California in late Tertiary time. If this is so, how are terrane accretion and rotation episodes related?

The timing and extent of crustal rotations is still incompletely described. Specifically, virtually no data constrain rotations in the Northeast Mojave Block, the timing of the Tehachapi rotations is unclear, and the existence and timing of counter-clockwise rotations in the western Mojave Desert and San Gabriel Block are in question.

The rate of rotation is only crudely described in all regions, the best determined being the western Transverse blocks. Determining not only the rate, but also changes in the rate, is important in constraining theoretical models for tectonic rotations.

Rotations and slip on faults are geometrically related. It is not fully understood, however, which faults were active or existed at particular times in southern California. Understanding this will permit more accurate description of plate-boundary shear within the deformation zone.

Application of the transtensional model of McKenzie and Jackson (1986) predicts that the western ends of the western Transverse blocks are defined by mostly normal faults. These have not yet been mapped.

The transtensional model also predicts that all or most of the Miocene basins in southern California will have the same or very similar histories, and this prediction must be tested.

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