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Material and Stress Rotations: The Key to Reconciling Crustal Faulting Complexity with Rock Mechanics

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Rotations ... make nonsense of the two-dimensional reconstructions that are still so popular among structural geologists. (McKenzie, 1990, p. 109–110)

Abstract

A perennial problem in fault mechanics is that the fault geometries *in situ*—especially of strike-slip faults—often contradict theoretical predictions. According to experimental and theoretical rock mechanics as captured by Coulomb's law, fault directions and motions should correspond simply to stresses in the crust. However, the complex geometrical distribution and regional trends of observable faults in the crust often seem at odds with the regional state of stress. Fortunately, these discrepancies can be neatly reconciled with Coulomb's law if we recognize that many faults did not form in their current orientations, but have rotated over time, and/or the stress field has rotated as well.

We describe a comprehensive tectonic model for the strike-slip fault geometry, seismicity, material rotation, and stress rotation, in which new, optimally oriented faults can form when older ones have rotated about a vertical axis out of favorable orientations. The model was successfully tested in the Mojave region using stress rotation and three independent data sets: the alignment of epicenters and fault plane solutions from the six largest central Mojave earthquakes since 1947, material rotations inferred from paleomagnetic declination anomalies, and rotated dike strands of the Independence dike swarm.

The success of the rotation model in the Mojave has applications well beyond this special region alone. The implication for crustal deformation in general is that rotations—of material (faults and the blocks between them) and of stress—provide the key link between the geology of faults and the mechanical theory of faulting. Excluding rotations from the kinematica and mechanical analysis of crustal deformation makes it impossible to explain the complexity of what geologists see in faults, or what seismicity shows us about active faults. However, when we allow for rotation of material and stress, Coulomb's law becomes consistent with the complexity of faults and faulting observed *in situ*.

Faulting Geometry: Laboratory versus *in situ*

A PERENNIAL PROBLEM in fault mechanics is that fault geometries *in situ* are generally at great odds with theoretical predictions. According to experimental and theoretical rock mechanics, as formulated by Anderson (1951), fault directions and fault slip should correspond simply to stresses in the crust. However, the complex geometrical distribution and the complexity of regional trends of faults in the earth's crust often seem to have little to do with the regional state of stress.

In the laboratory, when a rock fails under differential stress, the resulting failure plane, or fault, generally forms at a predictable angle to the direction of the maximum principle stress. This angle—or the direction of optimal failure—depends on the rock's strength properties and is usually near 30°. In homogeneous materials, there are two equally likely failure planes, called conjugate fault planes (Fig. 1), with opposite senses of slip relative to the direction of the maximum stress. Each of these conjugate fault planes satisfies the failure criteria, known as Coulomb's law.

Because faults *in situ* are believed to form when rocks fracture under crustal stresses, geologic faults are expected to form according to Coulomb's friction

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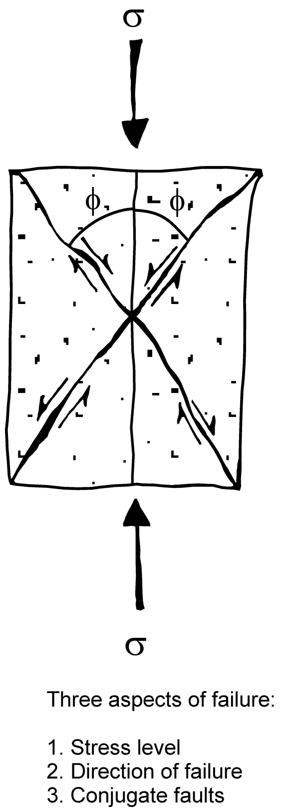


FIG. 1. A sketch of the standard Coulomb failure law for shear faulting, as supported by laboratory experiments. Shear faulting in unfaulted rocks occurs at an angle relative to the direction of maximum compression that depends only on the coefficient of friction and the strength of the rock. This plane of failure is called the optimal fault direction. Because of stress symmetry, faulting can be left- or right-lateral. This ambiguity gave rise to the concept of conjugate faults.

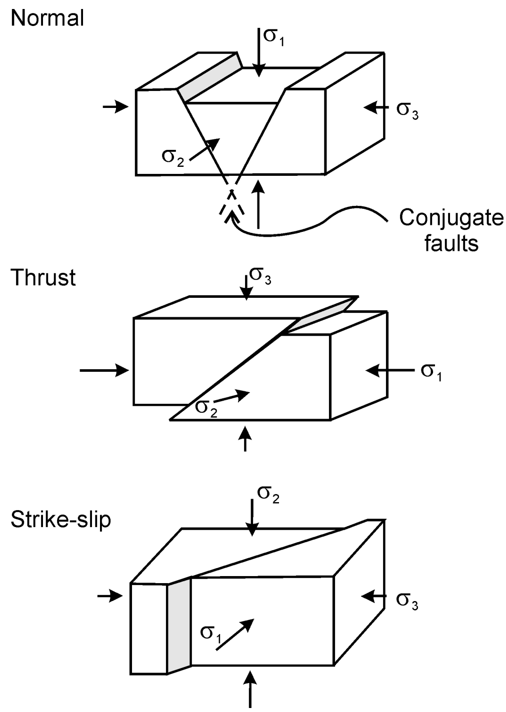


FIG. 2. Orientation of the three principal stress directions at some non-negligible depth for the prediction of the three types of shear failure. A. Normal faults are expected if the maximum compressive stress is vertical. B. Reverse faults are expected if the minimum compressive stress is vertical. C. Strike-slip faults are expected if the intermediate compressive stress is vertical. Tensional stresses are not required for the formation of these faults.

law. This was first proposed by Anderson (1951), and remains the assumption in nearly every textbook or tectonophysics papers on fault mechanics or crustal tectonics. As a result, most structural geology textbooks (e.g., Billings, 1972) have a figure similar to Figure 2, showing how faults are classified as normal, reverse, or strike-slip, depending on their orientation relative to the direction of stress. Note the similarity between Figure 2 and Figure 1 in the relationships between stress directions, sense of fault slip, and the occurrence of conjugate fault planes.

Unfortunately, most real faults in nature hardly correspond to the simple textbook point of view. Discrepancies are commonly observed in the geometry of fault systems in situ, including: (a) the angles between the direction of the maximum stress and the fault direction; or the angle between seemingly conjugate faults; and (b) the overall complexity of fault systems. One outstanding example is the current complex seismicity pattern in the New Madrid area. In Figure 3, each dot denotes the epicenter of an earthquake recorded during the past 20 years or so. The clustering of the epicenters delineates a complex active fault system that clearly cannot be simply reconciled with a set of two simple conjugate faults. The geometry of the New Madrid faults is bewilderingly complicated, far more so than Coulomb friction alone can possibly explain.

Figure 4 shows an example of wrong angular relations. In this example from northern Canada, a large region is faulted by two sets of numerous strike-slip faults, organized in two seemingly

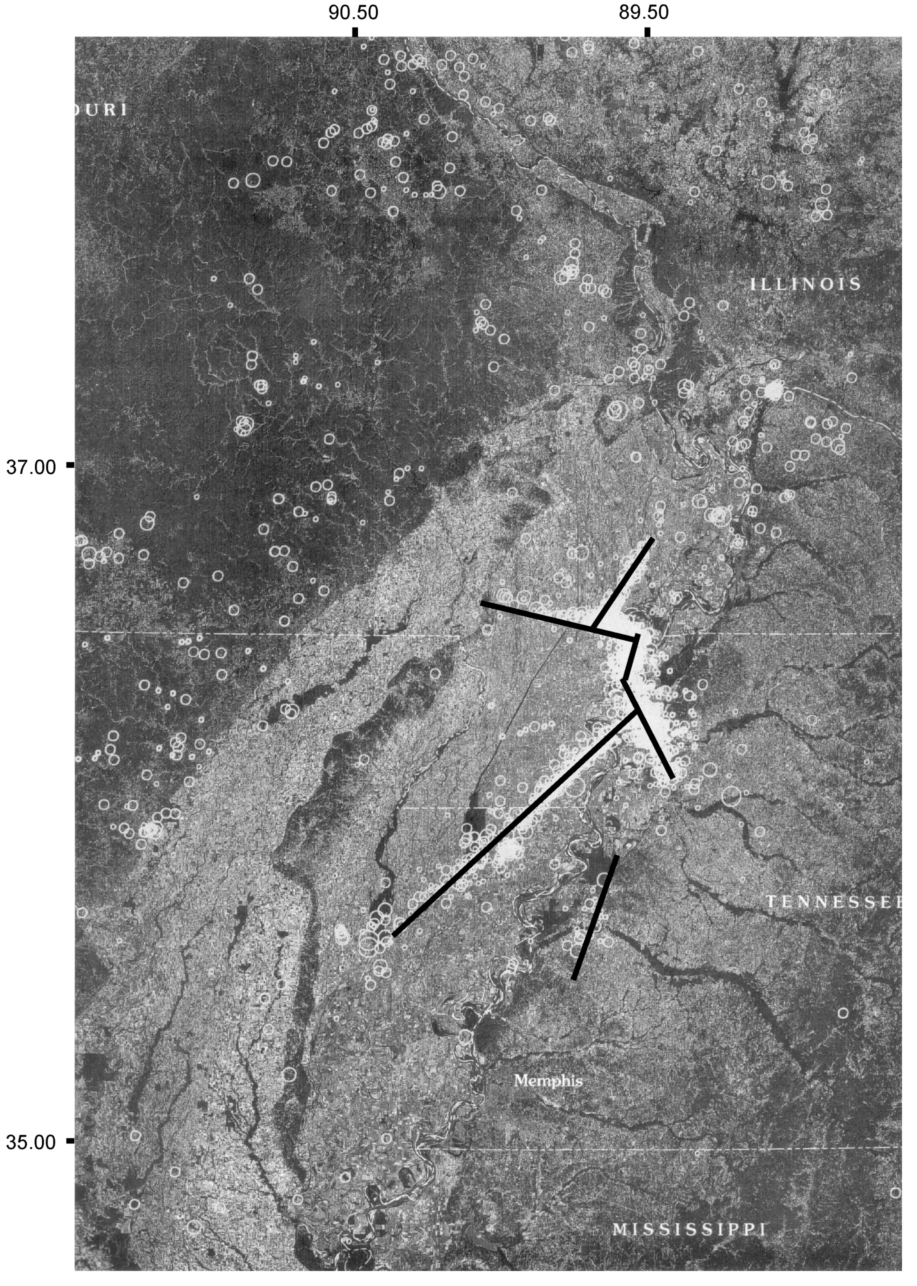


FIG. 3. Active faults in the New Madrid region. The complexity of this fault system cannot be reconciled with Mohr-Coulomb theory if we insist that active faults are optimally oriented in the current stress field.

conjugate fault domains. At first glance, the angle between the fault directions in the domains seems to display conjugate-fault behavior, with right-lateral slip on the NE-trending faults and left-lateral slip on the NW-trending faults. However, upon closer examination, with these senses of slip the angle between these sets of faults—100 to 120° degrees—is much larger than the ~60° expected from

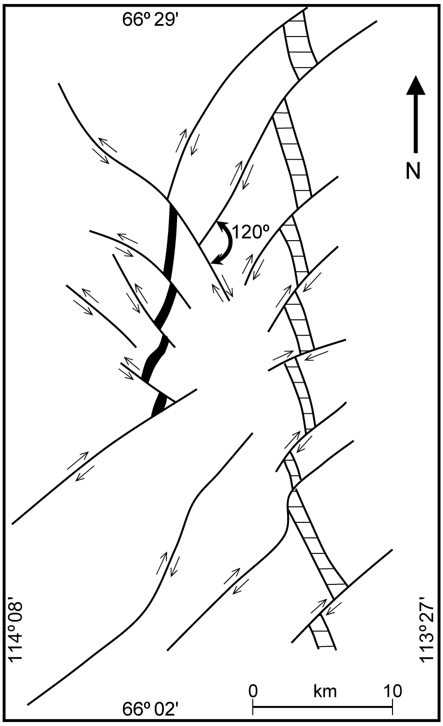


FIG. 4. Two domains of strike-slip fault offsets of beds in black and hatched pattern indicate the sense and amount of slip on the faults in these two domains. At first glance, the domains may seem "conjugate." However, the angle between the two fault set domains, measured through the direction of maximum compression, is around 120°, not 60°. Consequently, these fault sets could not have formed in their current relative orientation, and they most likely have rotated approximately 30° away from the optimal direction of faulting (modified from Hoffman et al., 1984).

Coulomb's law. In fact, this angular relation would be right for conjugate faults if the senses of slip were exactly reversed for the entire map.

Another set of examples of wrong angular relations is found in the San Francisco Bay area (Fig. 5). The figure shows a schematic line sketch of the major active faults of the Bay Area. Many faults in this region have widely varying strikes. Again at first glance it looks like some of the faults (e.g., the N-S–trending ones in the East Bay) may be conjugate to the San Andreas, with angles of 25 to 35° between them. But they are not; most of the faults in this map are right lateral. They are not conjugate to the San Andreas fault (SAF), because they all have the same sense of slip as the San Andreas fault itself rather than the opposite, conjugate sense.

It follows—assuming a uniform direction of principal stresses in the San Francisco Bay area—that if some of these faults are at present optimally oriented relative to the current stress direction, many others are not. For example, if the San Andreas is optimally oriented, then all of the East Bay faults are not, or vice versa.

Another example is the larger region of Southern California (Fig. 6). Again, there are many faults here oriented in such a multitude of different directions that it is difficult to imagine a pattern of any sort. Again the geometry and slip pattern and sense of slip for these faults do~~es~~ not even begin to mimic the simple geometry expected from the application of Coulomb's law. For example, consider the angle—approximately 120°—between the left-lateral Garlock fault and the right-lateral SAF at their point of intersection. While the senses of slip are conjugate, this angle is twice the value expected from Coulomb's law.

Relating Laboratory Behavior to Field Patterns

Can field situations like the examples above be reconciled with laboratory experiments, Coulomb friction, and Andersonian faulting? If as these examples suggest, faults can slip even when greatly mis-oriented relative to the current stress directions and to each other, there are two possible explanations. One is that Coulomb's law is simply irrelevant to faulting in the earth's crust; it is a simple, pleasing theory that yields nice experimental insights, but the earth just does not respond to stress in that way. The alternative is that many faults that criss-cross the earth's crust did not form in their current directions, or in their current geometrical relationships to the maximum principal stress; either the faults have rotated over time, or the stress field has rotated, or both.

Some researchers do in fact reject Coulomb failure as a model relevant to the earth (e.g., Duebendorfer and Simpson, 1994, p. 1057): "… There is no evidence that major strike-slip faults must form in response to regional stresses in accord with the Mohr-Coulomb theory…." In another example, Wernicke and Burchfiel (1982) defined a "chaos structure," where simple shear is accommodated by a chaotic, distributed network of faults. That simple shear is accommodated by "chaos structure" describes the complex fault patterns seen in situ, but it bypasses any explanation in terms of stress,

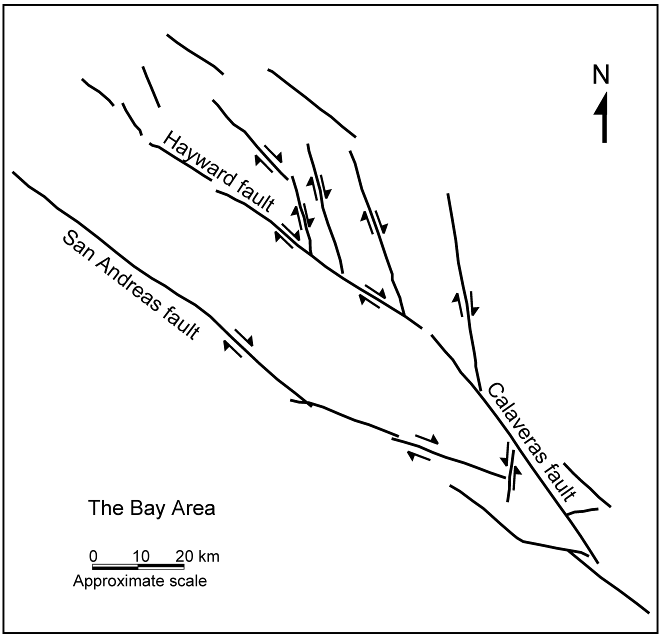


FIG. 5. Line sketch of seismically active faults in the San Francisco Bay area. At first glance faults in the East Bay Area seem conjugate to the Calaveras and Hayward faults. However, the sense of slip on *all* the faults is left-lateral, so they are *not* conjugate. Clearly some of these active faults are presently not optimally oriented relative to the current stress field.

mechanics, or rock properties. If such fault systems cannot be related to rock properties and stress, then rock mechanics must be considered truly irrelevant to crustal faulting.

It turns out that one way to save rock mechanics, and at the same time gain a real understanding of what we see in the field, is to examine the limits for slip on non-optimally oriented faults. According to Coulomb's law, when a rock with a pre-existing cut is subjected to non-hydrostatic stress, the pre-existing cut can slip, even if it is not oriented in the direction of optimal failure (Fig. 7). The pre-existing cut can be at an angle quite different from the optimal direction of failure as long as the shear stress on it is high enough and the normal stress sufficiently low. Here it is convenient to define a critical angle, øc, as the angle between the optimal direction of failure and the fault direction, beyond which the fault cannot slip. When the cut is oriented beyond that angle, and the applied stress is sufficiently large, a new failure plane must form to accommodate further brittle deformation. Typically this critical or locking angle is on the order of ϕ_c about 30° beyond the optimal failure direction.

This suggests that in principle it is possible to have an active, pre-existing fault in situ that is not optimally oriented to the current state of stress in the crust. The only consideration added to Coulomb's law is that when the fault formed, it was optimally oriented in the stress field at the time. Presumably such a non-optimally oriented fault over time has rotated away from its optimal direction of formation, as first elaborated by Freund (1974). The question now is whether we can find actual evidence for such material rotations (rotation of faults and the blocks they bound) *in situ*.

Rotation of Blocks and Multiple Fault Sets

We have shown in the past (Nur et al., 1986, 1989, 1993a, 1993b; Ron et al., 2001) that one place to investigate material rotation is in the Mojave region (Fig. 8). Faults here are organized in domains: The central Mojave domain (CM) consists of sets of parallel, right-lateral strike-slip faults trending northwest. In contrast, in the eastern Mojave (EM) and eastern Transverse Range (ET) domains, sets of left-lateral strike-slip faults are

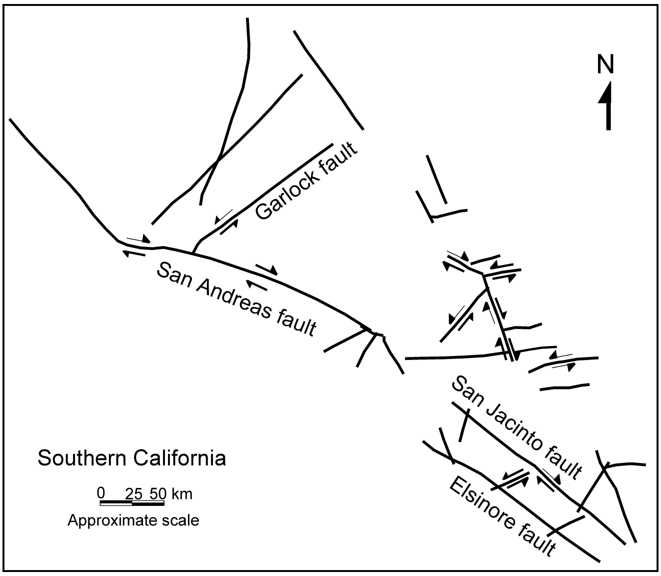


FIG. 6. Line sketch of seismically active faults in Southern California. Directions and senses of slip are so diverse that most of the faults cannot be optimally oriented relative to the current stress direction.

oriented east-west. As in the case of the Garlock-SAF system, one might at first glance think these to be conjugate sets of faults. However, the relevant angle between them is approximately 120°, rather than the optimal 60°. Furthermore, none of these fault sets are optimally oriented to the current stress field (Fig. 8) as independently determined for the Mojave. So, if Mohr-Coulomb theory is to be relevant, these faults, which are all about the same age, must have once formed at optimal angles to the maximum principal stress, but have since rotated (or the stress- field has rotated) out of alignment.

To start with, let us first think of how faults might rotate if there is slip on a set of parallel faults in a domain as shown in Figure 9. A region in the crust is under N-S compression. Two domains of optimally oriented conjugate faults develop, one with NE-trending, left-lateral strike slip, the other with NW-trending, right-lateral strike slip (Fig. 9B). The angle between the two conjugate fault is on the order of 60° (or 30° in either direction from maximum compression). As slip progresses under continual compression, the faults and the blocks between them also begin to rotate, always away from the direction of compression toward the direction of extension (like books on a shelf when the bookend is removed). It is easy to see that, as they slip and rotate, there is a simple geometrical relationship between the amount of slip and the amount of rotation (e.g., Ron et al, 1984). The right-lateral faults rotate counter-clockwise, whereas the left-lateral faults rotate clockwise (Fig. 9C). Gradually, as slip and rotation increase, the faults become more unfavorably oriented relative to the direction of principal compression. When the rotation becomes large enough (on the order of half the fault spacing), faults cease to slip. Then a new set of optimally oriented faults must form to accommodate continued compression. The slip on these new faults will offset the old, locked faults (Fig. 9D). Coulomb's law predicts the angle between the old and new sets. Typical values are between 25 and 40°, depending on the coefficient of friction and the cohesive strength of the rock involved (Nur et al., 1986).

In places where this process continues over geologically significant times, the rotation, locking, and formation of new faults can happen repeatedly and easily lead to very complicated, seemingly chaotic fault patterns, with generations of older faults being offset by younger ones. In this process, the one parameter that remains clearly linked to Coulomb's law is that the angle between any two conjugate fault sets of the same age is always bisected by the direction of the maximum compression at the time of formation.

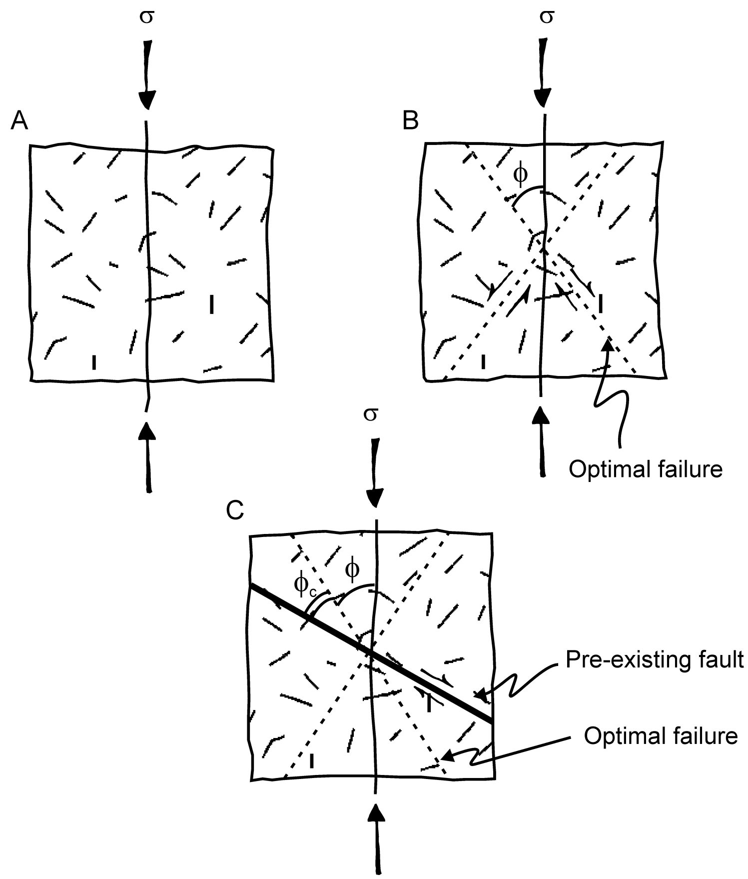


FIG. 7. Slippage can occur on a preexisting cut or fault even when it is not optimally oriented, as long as the angle with respect to the direction of optimal failure is less than a critical angle ϕ_c. Typically ϕ_c is on the order of 25° to 40°. *In situ*, the preexisting fault must be inherited from an earlier failure situation.

Block Rotation in the San Gabriel Mountains

Published work suggests that something like the process described above actually seems to happen in the crust. Figure 10 (Carter, 1982; Nur et al., 1989) shows an example of younger faults offsetting older ones, together with material rotation, from the San Gabriel block, situated between the San Andreas and San Gabriel faults. Based on cross-cutting relations *in situ*, the strike-slip faults marked with broken lines are relatively young, whereas the ones marked with heavier lines are older. The implied rotation is supported by paleomagnetic data obtained from measured declination anomalies (Terres and Luyendyke, 1985) that show approximately 53° of clockwise rotation—large enough to require new faulting. Because the slip on all faults is left-lateral, this sense of clockwise rotation is consistent with our fault rotation model. We believe therefore that the main aspects of the fault and block rotation model are present here: sense of slip, a younger fault system cutting an old one that is now frozen, and material rotation of the correct sense and magnitude. Also it is noteworthy that no alternative model has ever been advanced to explain both the fault pattern (fault geometry, cross-cutting relationships) and the material rotation independently obtained from paleomagnetic data.

Block Rotation in the Mojave Region

Consider again the Mojave region (Fig. 8) including the direction of maximum compression (NNE) as

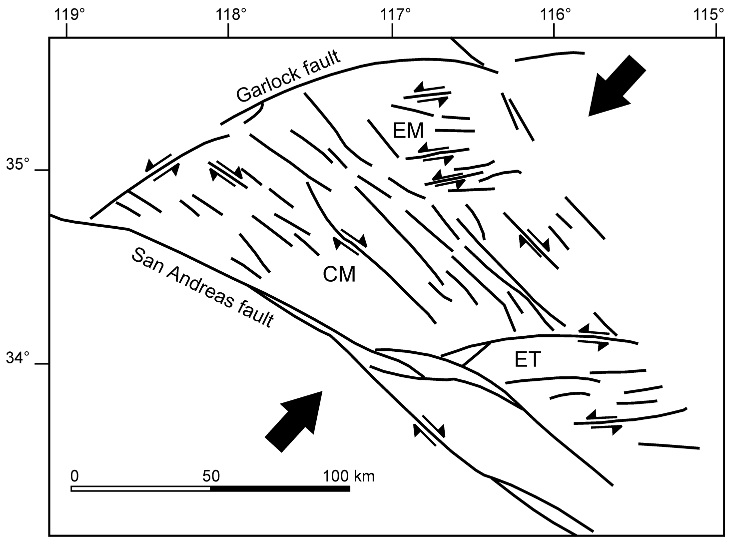


FIG. 8. Details of the central Mojave Desert (CM), the eastern Transverse Ranges (ET), and the eastern Mojave Desert (EM). Each domain consists of roughly parallel fault sets of consistent sense of slip, which is expected to be directly associated with block and fault rotations: counterclockwise rotation with right-lateral slip in the CM, and clockwise rotation with left-lateral slip in the EM and the ET. Arrows indicate current direction of maximum tectonic compression.

shown by arrows (Zoback et al., 1987). Given this stress field, none of the faults are optimally oriented in accordance with Coulomb's law. It was for this reason that we first put forward in 1989 (Nur et al., 1989, p. 38) what may still be the only published anticipation of a significeant earthquake in the United States:

> We suggest that the direction of faulting in the central Mojave… might very well be part of a developing new fault set, which is gradually replacing the older, now rotated out of favor strike-slip faults in the central Mojave domain.

In making this suggestion or prediction, we argued that the geologically developed (and well-documented) NW–trending faults in the central Mojave domain are almost perpendicular to the direction of the current compression, and therefore may be locking up.

Our prediction was originally based on two events, the Homestead earthquake of 1979 and the Galway Lake earthquake of 1975, to which we subsequently added the 1963 Calico and 1947 Manix earthquakes (Figs. 11A and 11B). There are four remarkable aspects of these four earthquakes that are relevant to our block and fault rotation model: (1) all four earthquakes have fault-plane solutions consistent with right-lateral strike-slip on N-trending (not NW-trending) faults; (2) their N-directed rupture directions clearly cross-cut the older NW-trending Central Mojave faults; (3) the earthquakes and their fault planes fall consecutively on a single line; and (4) this line is not a known, thorough-going regional fault. Based on these facts, we proposed in 1989 that a new major fault system is emerging heree, and suggested that, if this is true, future earthquakes will occur on this line (Fig. 12).

Then, in 1992, the Joshua Tree and Landers earthquakes surprisingly did just that. Both earthquakes fell exactly on the line we had proposed in 1989 as the newly emerging fault system that was later termed "The Mojave-Landers Line." The fault-plane solution for the Joshua Tree earthquake, like the previous four events, was again consistent with a right-lateral strike-slip event. The rupture pattern associated with the Landers quake was even more interesting: some of the slip occurred on several segments of the older NW-trending faults, whereas some of the slip took place along the segments of a N-trending line we had proposed. This was the sort of behavior the block-rotation model anticipates: slip is partitioned between new, optimally oriented faults and old, well-developed but unfavorably

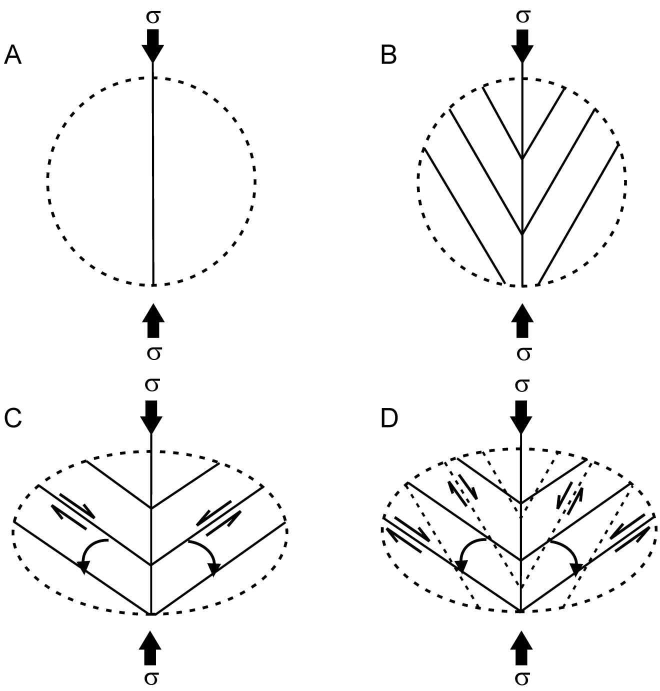


FIG. 9. A 2-D model illustrating the development of faulted domains by the simultaneous activity of strike-slip displacement and rotation of the fault blocks. (A) Tectonic stress is applied to (B) the initial fault configuration. C. After deformation, the set of left-lateral faults have rotated clockwise and the set of right-lateral faults have rotated counterclockwise. D. As faults rotate beyond ϕ_c, new, optimally oriented faults form, while the older, now rotated faults cease to slip. During the transition from old, rotated to new, optimally oriented faults, earthquake slip can be partitioned between the two fault sets. The Landers rupture may be an example.

oriented ones. According to the model, this happens when old faults, rotated away from the stress direction , are locking up, and the new or young faults are beginning to emerge.

From a teleseismic point of view, this geography and pattern of earthquakes and faulting would imply the existence of a major (200 km long) fault trending N-S in the Mojave (Fig. 13). On the other hand, from a local geological point of view, there is no throughgoing fault here; the events are six separate earthquakes, and the Mojave earthquake line was never before considered capable of producing a magnitude 7.6 earthquake.

To test our model and its ability to account for the faults and earthquakes in the Mojave, we turn to another and independent aspect that is predicted: the rotation of blocks and faults. Fortunately, quite a number of relevant paleomagnetic data sets have been collected in the Mojave region over the years. A compilation of the most reliable declination anomaly data in fact reveals that large rotations actually occurred here (Fig 14B), a ~50° clockwise rotations in the two domains of right-lateral slip—the eastern Transverse Range and the eastern Mojave. Remarkably, these rotations are greater than the expected 30°. Furthermore the left-lateral slip on the faults in the two domains implies clockwise rotation, which fits the model perfectly.

On the other hand, paleomagnetic data in the central Mojave domain of the NW-trending right-lateral faults show no rotation at all, in an apparent contradiction of the counterclockwise rotation predicted by the model (for a summary see Nur et al., 1993a; Ron et al., 2000, 2001). Somehow, while the eastern Mojave and eastern Transverse domains have both rotated more than expected from the model, the central Mojave domain has not rotated at all. The asymmetry does not agree with the version of the material rotation model of Figure 9.

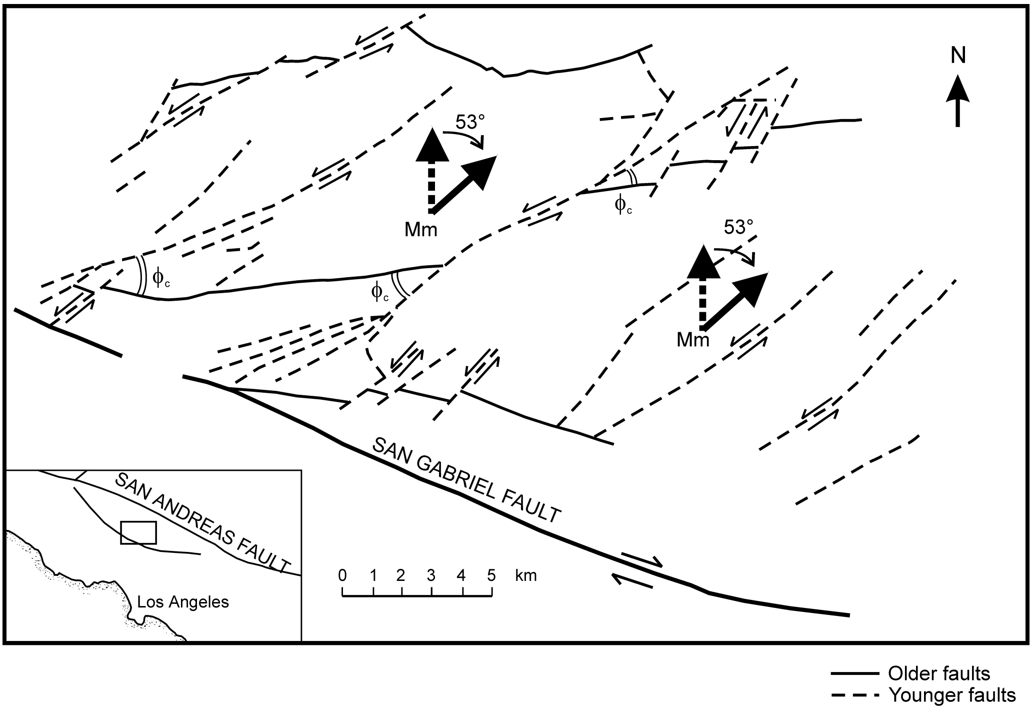


FIG. 10. Multiple strike-slip fault sets in the San Gabriel Mountains (after Carter, 1982). Note the younger NE-trending strike-slip faults offsetting the older E-W–trending ones. Both sets have the same left-handed sense of motion and are therefore not conjugate sets. The paleomagnetically determined clockwise rotation of 53° (from Terres and Luyendyke, 1985) is consistent with the observed left-handed slip.

The same pattern of rotation asymmetry is inferred also from geological evidence derived from the geometry of the Independence dike swarm. This Late Jurassic swarm extends from the central Sierra Nevada area through eastern California to the Mexican border (James, 1989). The swarm runs right through the Mojave region, and being much older than the Mojave faults, can be used as a passive indicator of material rotations. Specifically we expect dike strands in this swarm to be rotated where the paleomagnetic data show rotation, and not rotated elsewhere.

In the central Mojave (Fig. 14A), where paleomagnetic data show no rotation, the dikes on average follow the general NW trend common for the entire dike system; they appear not to have rotated (Ron and Nur, 1996). In contrast, in the eastern Mojave and the eastern Transverse Range where paleomagnetic data show a 40° to 50° clockwise rotation, the average trend of the dike strands is equally rotated—about 40°—relative to the rest of the dike system.

In the Mojave region, we have thus encountered something that is quite rare in tectonic analysis: three independent inputs that all produce mutually reinforcing data: earthquake locations and fault plane solutions, paleomagnetic data, and by sheer serendipity, dikes. These inputs are based on measurements that were made by unrelated teams of researchers who designed and obtained their results without ever considering each other's data.

Adding Stress Rotation

Whereas the data above show remarkable internal consistencies, one major problem remains: our model predicts a symmetric rotation pattern, such that faults and blocks in the central Mojave should have rotated counterclockwise by the same amount that the faults and blocks in the eastern Mojave and eastern Transverse Range domain rotated clockwise. However, as we have shown above, the paleomagnetic and dike data yield a clear asymmetric pattern. Obviously, our model of material rotation as

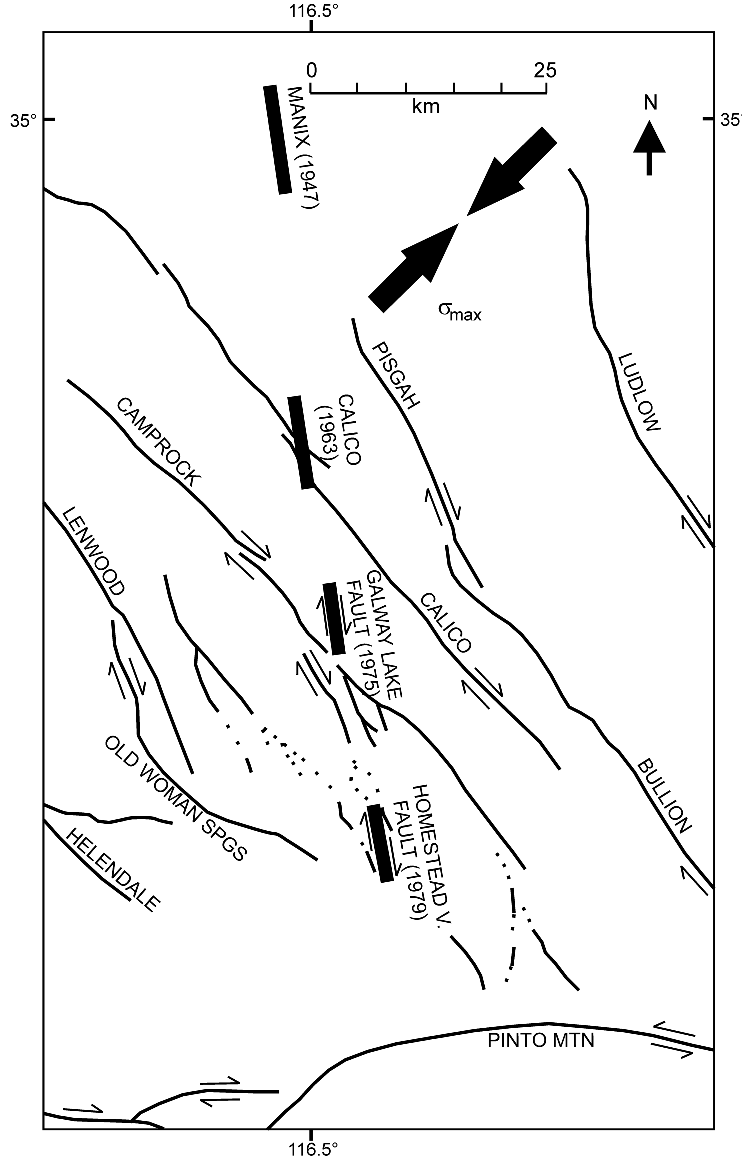


FIG. 11. Reproduction of the Nur et al. (1989) figure showing the nearly fault-normal orientation of the Mojave compression to the older faults and its optimal orientation to the Manix, Calico, Homestead Valley, and Galway Lake ruptures, suggesting the emergence of a new fault line and the gradual locking of the older faults.

it stands is not consistent with this asymmetry—with exceedingly large clockwise rotation in the eastern Mojave and eastern Transverse Range range domains *and* no counterclockwise rotation in the central Mojave domain.

One way to reconcile the observed asymmetry in rotation, is to consider the possibility that the stress field may have rotated as well. Figure 15 shows the block diagram from Figure 9, but removes the (arbitrary) restriction that the stress is fixed in time. Instead stress is allowed to rotate. Here we envision again that all original faults (left-lateral and right-lateral) form in their optimal directions relative to the applied stress (Figure 15B). However, in

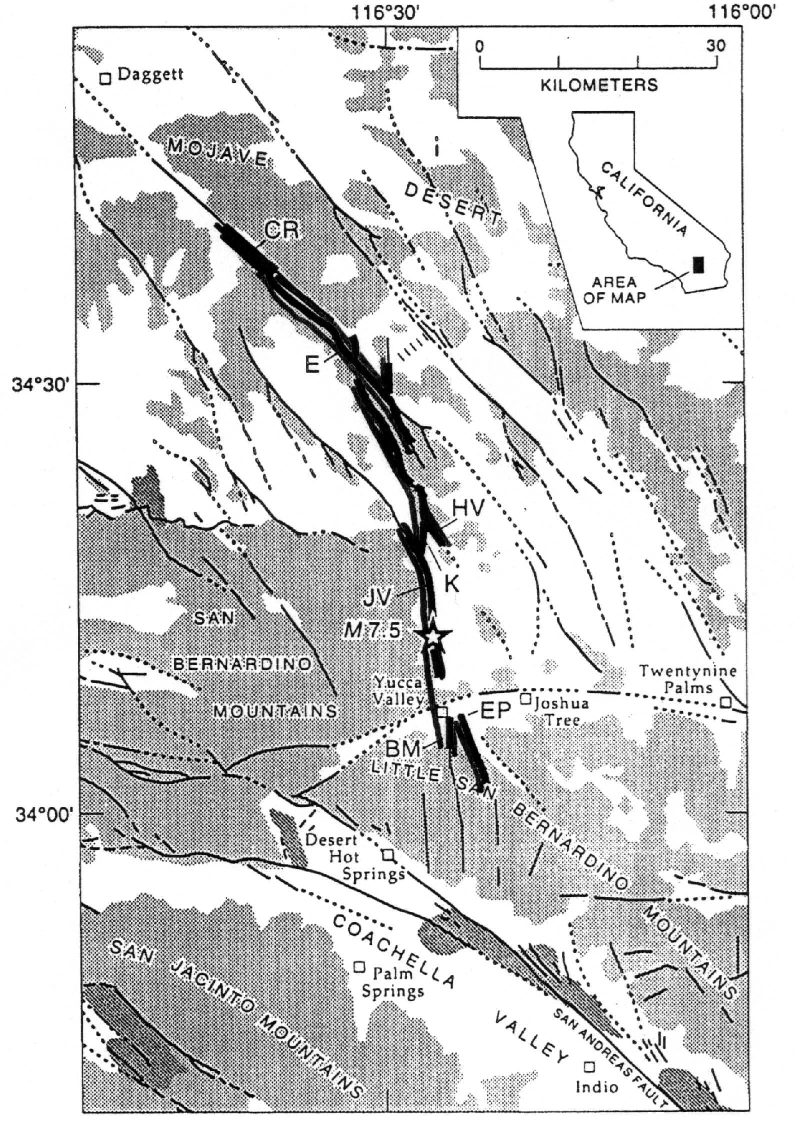


FIG. 12. Surface fault slip associated with the Landers earthquake is partly on existing NW-trending faults and partly on fresh or young N-trending faults.

contrast to Figure 9, the principle stress direction is not fixed in time as deformation progresses. Instead, we allow the direction of the principal stress to rotate while faults and the blocks they bound also rotate. This directly leads to an asymmetry in material rotation: in one domain (as reflected, e.g., in paleomagnetic declinations or dike strand orientation) is the *sum* of the block rotation relative to the direction of compression and the stress rotation, whereas in the other domain it is the *difference* between material and stress rotation. In the special case where the stress field rotates clockwise at the same rate as the blocks rotate, there should be no rotation in the domain with right-lateral faults, whereas rotation should be double in the left-lateral fault domain. Figure 16 shows what this might look like for the Mojave region.

Is there any supporting evidence that stress rotation actually occurred in the Mojave? Little is known about the history of stress direction in the

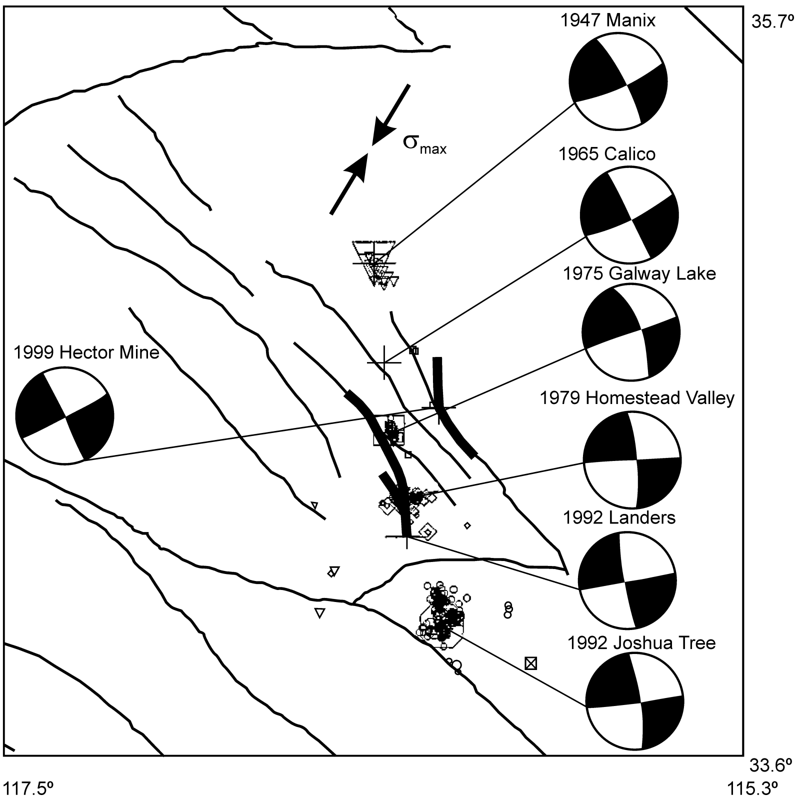


FIG. 13. Epicenters and fault-plane solutions of the six largest central Mojave earthquakes since 1947. Because the directions of these events approximately coincide with the alignment of their epicenters, it is proposed that this Landers-Mojave line may be a new or young fault. This fault crosscuts the older, well-documented and well-developed N45°W-trending central Mojave faults. At its kink, the Landers rupture was partitioned between these old faults and the Landers-Mojave direction.

Mojave over time. However, Zoback and Thompson (1978) have convincingly shown that the principal stress direction-in the Great Basin region has rotated clockwise by about 30° since the Miocene. If this regional stress behavior is controlled (as Zoback and Thompson suggest) by the large-scale relative motion of the Pacific, Farallon, Juan-de-Fuca, and North American tectonic plates, then it probably applies to the Mojave region as well. This sense of clockwise stress rotation is exactly what our material-plus-stress model requires to explain the apparent asymmetry in material rotation.

For the Mojave, a 20° to 30° clockwise stress rotation can reconcile the asymmetry: Approximately 30° of material rotation should have occurred in each of the conjugate Mojave domains of faults between the time of their formation and when they began to lock up. In the central Mojave, with its right-lateral faults, the expected counterclockwise material rotation was approximately canceled by the clockwise rotation of the stress field. In contrast, the domains with left-lateral faults, underwent a 30° clockwise material rotation, plus the stress-field rotation, for total of ~50–60°.

Figure 17 shows how the slip might be partitioned between old and new fault sets at transition, when the old faults begin to lock. This type of slip partitioning was noted for both the Landers and the more recent Hector Mine earthquakes. Over time, say a few tens of thousands of years, this kind of partitioning will cease as the slip becomes confined to the new fault sets.

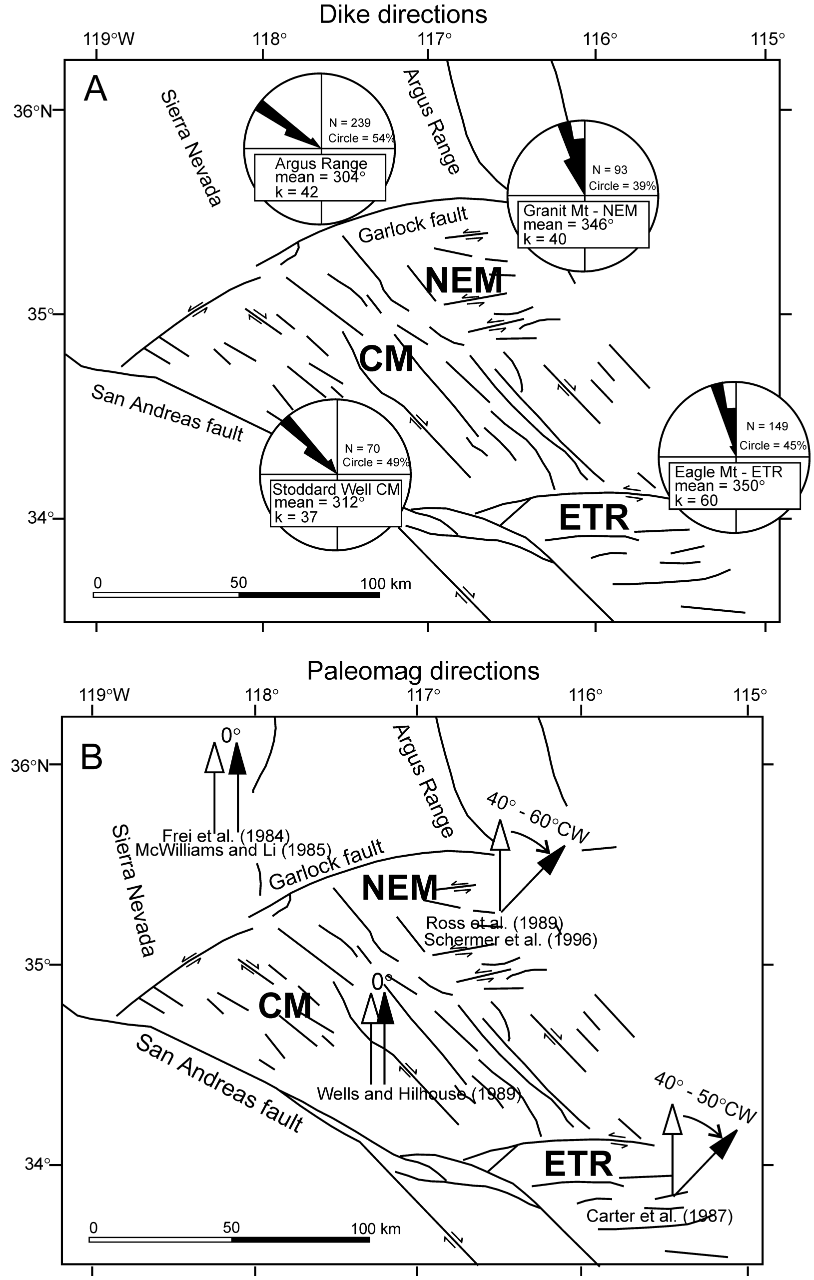


FIG. 14. Map of the Mojave showing its three fault domains: northeastern Mojave (NEM), central Mojave (CM), and eastern Transverse Range (ETR). A. Rose diagrams and statistics of Independence dike swarm populations in each domain. B. Paleomagnetically derived rotations of each domain.

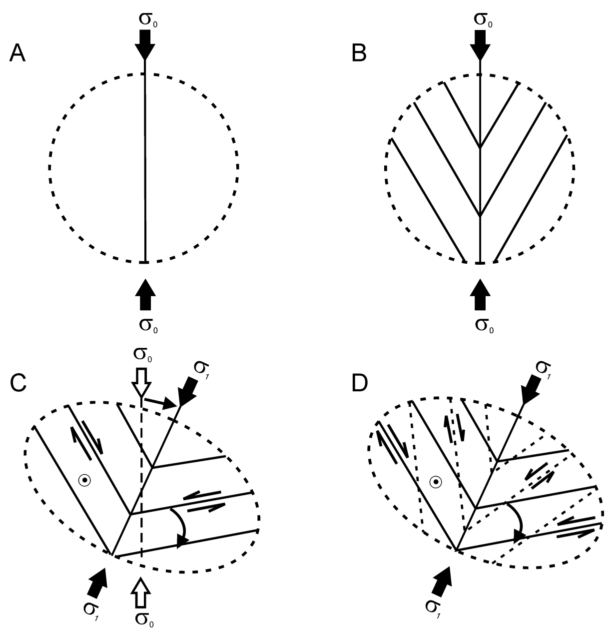
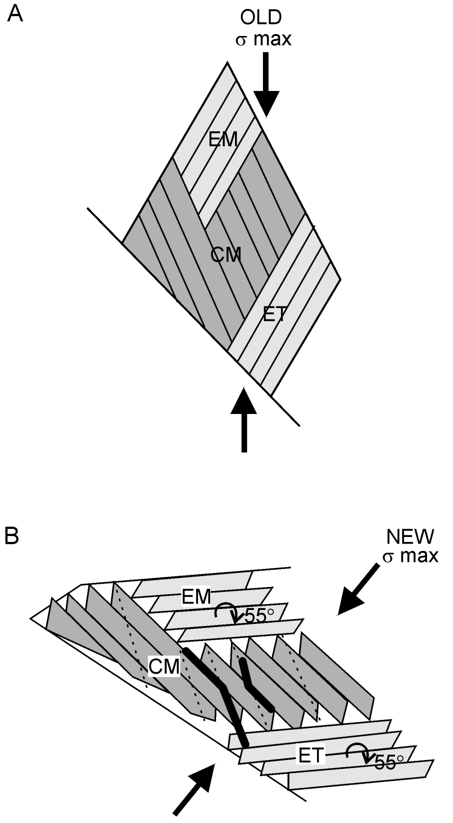


FIG. 15. The block and fault rotation model of Figure 9 with the addition of stress rotation.



Earthquake Migration

The idea that the Mojave Landers earthquake line is an emerging new or young fault system is supported by one additional observation, which goes beyond the Mojave to span the larger Eastern California shear zone as shown in Figure 18. We plot the location of the epicenters of the Mojave earthquakes as measured from the San Andreas vs. time, including, in addition to the Mojave 1947 to 1998 events, also the 1908 Death Valley and the 1872 Owens Valley earthquakes. The epicenters show roughly a southward propagation from the northwest to the southeast, with an average propagation velocity of about 2.5 km/yr.

FIG. 16 (to left). Block rotation in domains, stress-field rotation, and the formation of optimally oriented new faults in the Mojave region. A. In the initial configuration, the east Mojave (EM) and eastern Transverse Range (ET) domain faults are oriented at 30°. B. In the present-day configuration, paleomagnetic evidence and some structural data suggest a 55° or so clockwise rotation of blocks and faults in the EM and ETR domains, and no counterclockwise rotation in the CM domain. These material rotations imply a stress field rotation of 15°–25°, into today's direction of N15°W. Because the existing faults are so unfavorably oriented relative to the current stress, new ones should form (broken lines in the CM and the Landers-Mojave line may be such faults.)

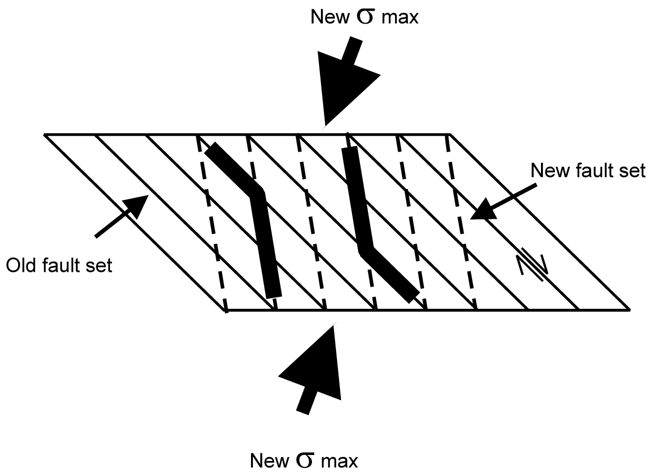


FIG. 17. Schematic diagram showing the slip partitioning of the Landers and Hector Mines earthquakes. Heavy segments show rupture that bends from the old faults (solid lines) into the direction of the proposed new faults (broken lines).

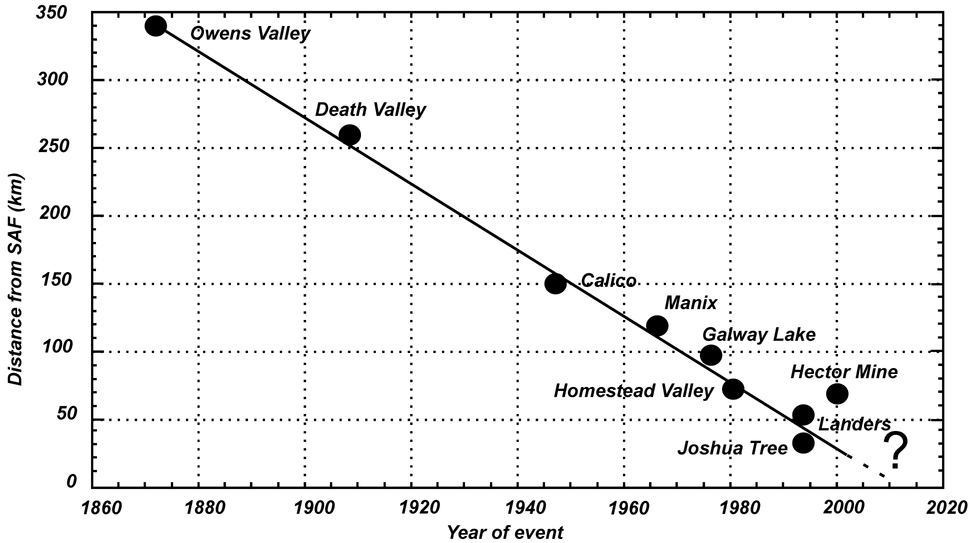


FIG. 18. Propagation with time of earthquakes in the Eastern California shear zone, along what we call (1989) the Mojave fault system. The position of the earthquakes (measured from the intersection of the propagation line with the SAF) is plotted vs. time in years. Propagation velocity is approximately 130 km in 50 years, or 2.5 km/yr. Extrapolating back in time to include also the 1872 Owens Valley and 1908 Death Valley earthquakes, the velocity remains the same (320 km in 120 years). Extrapolating forward, this line of activity will intersect the San Andreas Fault sometime between 2006 and 2008. Whether this implies that a large earthquake will occur on the SAF is anybody's guess at this time—if only because we do not understand the physical process responsible for this sort of propagation.

This pattern again suggests that, projecting the earthquake propagation trend into the future, seismicity will intersect the San Andreas fault between 2005 and 2010. Could this lead to a major earthquake on the SAF? It remains a distinct possibility. This question cannot be answered without understanding the mechanics of this sort of propagation. One thing we do know however, is that this type of

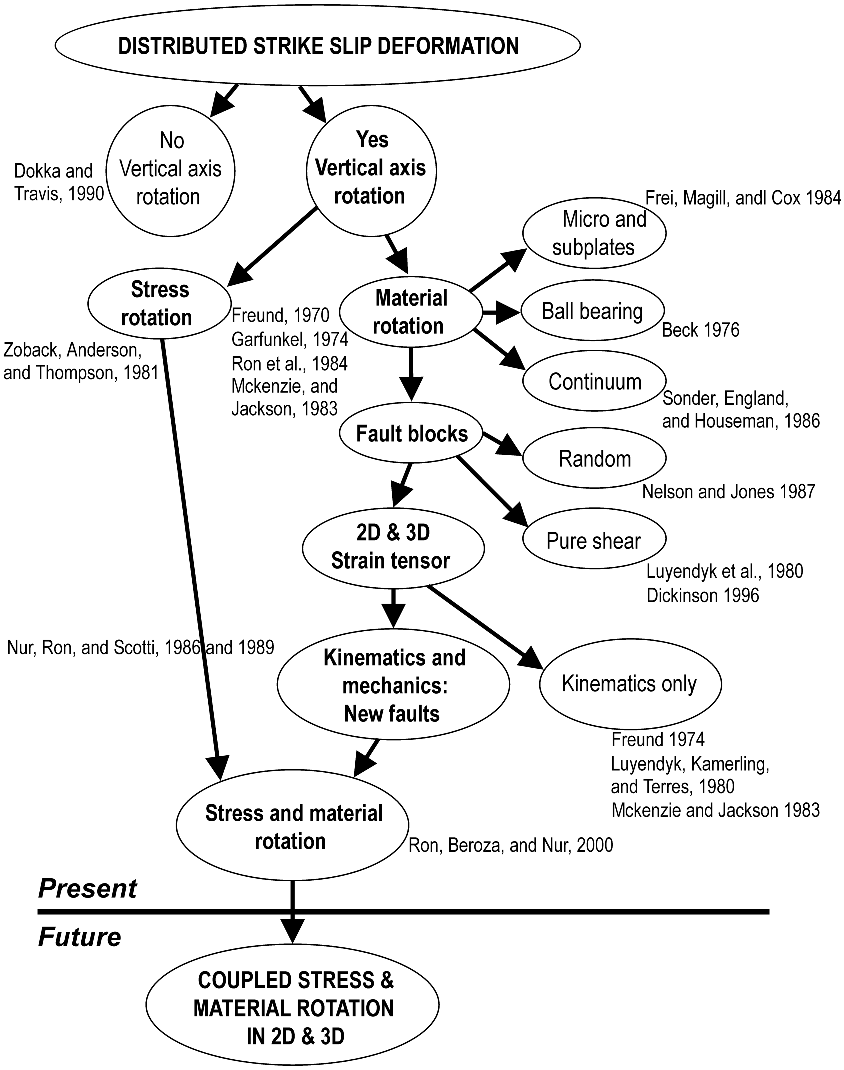


FIG. 19. A summary of the history and trends of thought about material and stress rotations in crustal deformation, including key references to studies relevant to the debate about rotations in crustal deformation. A theory of coupled stress rotation and material rotation remains to be developed.

earthquake propagation has been observed along other fault systems, e.g., the North Anatolian fault between 1939 and present and the San Jacinto fault in Southern California between 1925 and 1987 (Sanders, 1993; Rydelek and Sacks, 2001). Again, the exact implications of this sort of propagation at present are unclear, but it seems that some sort of very long range mechanical interaction—perhaps tectonic forces that are transmitted below the brittle part of the crust—are related to yielding not only along existing major faults (with lengths much greater than the thickness of the brittle crust) but also along emerging ones.

Conclusions

We believe that the complexity of the tectonics of the Mojave region and the Landers and Hector Mine earthquakes can be reconciled with mechanics by invoking rotations both of material and stress. Otherwise this complexity will remain totally enigmatic. This strongly supports the necessity of including rotations for understanding crustal deformation in general. The general implication is that the rotation of material—the faults and the blocks between them—and the rotation of stress together provide the key linking the geometry of faults and faulting *in situ* and the mechanics of faulting. Without rotations, it appears that it is impossible to explain the complexity of what geologists see *in situ*, or what seismicity shows about active faults.

Unfortunately, some stubbornly resist the notion that rotations may be such a key aspect of crustal deformation. Said Greg Davis (pers. commun., 1993): "As it is impossible to measure a regional stress tensor in the field … any interpretation which depends on such a tensor is at best a gross simplification. Thus the so called 'mechanical' evidence cited … cannot form the basis for startling new ideas about the birth of faults." Rockwell et al. (1995) questioned our analysis of the Landers earthquake: "Is this a new fault, or business as usual?" The phraseology of the question makes his skepticism clear.

Many more crustal deformation investigators have simply paid little attention to rotations (e.g., Sibson. 2002, Yeats et al., 1997). This is especially perplexing because, as a research community, we seem to have adhered to the totally arbitrary assumption of irrotational crustal deformation. However, there is absolutely no *a priori* reason to make such a limiting assumption. There is no logical reason, and as this study shows, no factual reason to ignore or exclude rotations in crustal deformation.

Fortunately a few have already come to recognize how important kinematic mechanical rotations are for a fuller understanding of crustal deformation. This was best said by McKenzie (1990, p. 109–110) in *Nature* a few years ago: "Rotations … make nonsense of the two-dimensional reconstructions that are still so popular among structural geologists."

In the future, to fully model crustal deformation that includes *both* material and stress rotations, we will have to look at stress and material rotations not separately but as a coupled process (see Fig. 19 for a summary). In our current version of the model, we impose stress rotation and material rotation separately. Eventually, what will be needed is a fully coupled theory, where stress rotations cause but also are caused by material rotations. That is work for future researchers.

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