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# Landers-Mojave Earthquake Line: A New Fault System?

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## ABSTRACT

**The M 7.4 Landers earthquake of June 28, 1992, like most twentieth century California earthquakes, did *not* fall on the San Andreas fault. Instead, it is the latest of six M ≥5 earthquakes in the past 50 years whose epicenters and slip directions appear to define a 120-km-long alignment running approximately N15° ±5°W across the central Mojave region. This previously unrecognized line, which we call the Landers-Mojave earthquake line, may be a geologically young, thoroughgoing fault system that cuts obliquely across numerous older but still active strike-slip faults. According to a simple kinematic and mechanical model of block rotation and new fault formation, these older faults may be gradually losing their ability to accommodate upper crustal deformation because they have become stresswise unfavorably oriented. The model and the debate it generated about crustal stress, rotations, and the formation of new faults touch on several unresolved issues in tectonics, seismotectonics, crustal deformation, earthquake prediction, and structural geology.**

Fault surface associated with the 1992 Landers (California) earthquake rupture along the Emerson fault, south of Galway Road.

## INTRODUCTION

Like most twentieth century larger California earthquakes, the 1992 M 6.1 Joshua Tree and the M 7.4 Landers events did *not* fall on the San Andreas fault. This highlights a puzzling aspect of California seismotectonics, especially because both events had pure strike-slip motion presumed to be typical for the San Andreas. In addition, the Landers earthquake surprised many for other reasons: (1) The southern part of the Landers and Joshua Tree earthquake ruptures define a line ~30 km long which has not before been recognized as a throughgoing and capable seismogenic fault (Ad Hoc Working Group Report, 1992). (2) The Landers 30° rupture kink (Fig. 1) is puzzling because some earthquake models assume that seismic rupture stops at kinks, and does not propagate through them. (3) The southern Landers and Joshua Tree ruptures fell on a line that has had at least four previous earthquakes with similar rupture directions: the M 5.4 1975 Galway Lake, the M 5.3 1979 Homestead Valley, the M 5.2 1965 Calico, and the M 6.5 1947 Manix earthquakes (Fig. 1). We call this 120 km earthquake line the *Landers-Mojave* line.

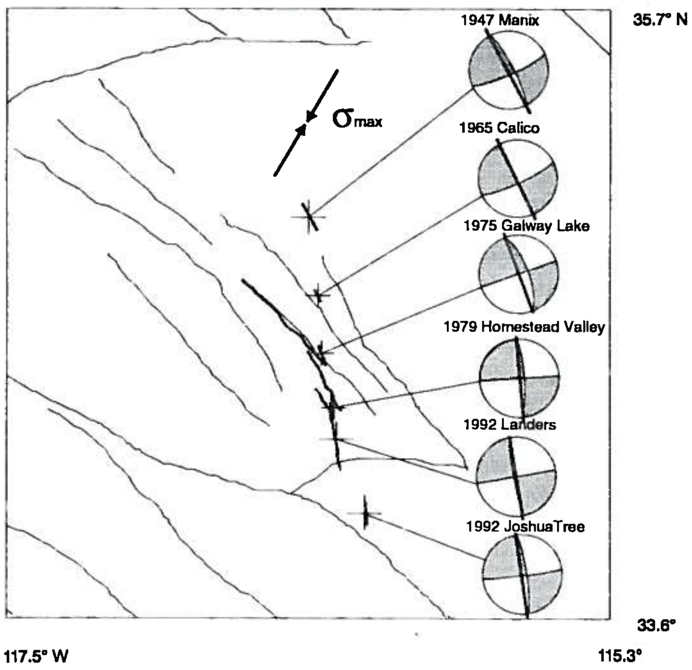

**Figure 1.** Epicenters and fault-plane solutions of the six largest central Mojave earthquakes since 1947. Because the directions of these events (shown in red) approximately coincide with the alignment of their epicenters, it is proposed that this Landers-Mojave line may be a new or young fault. This 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.

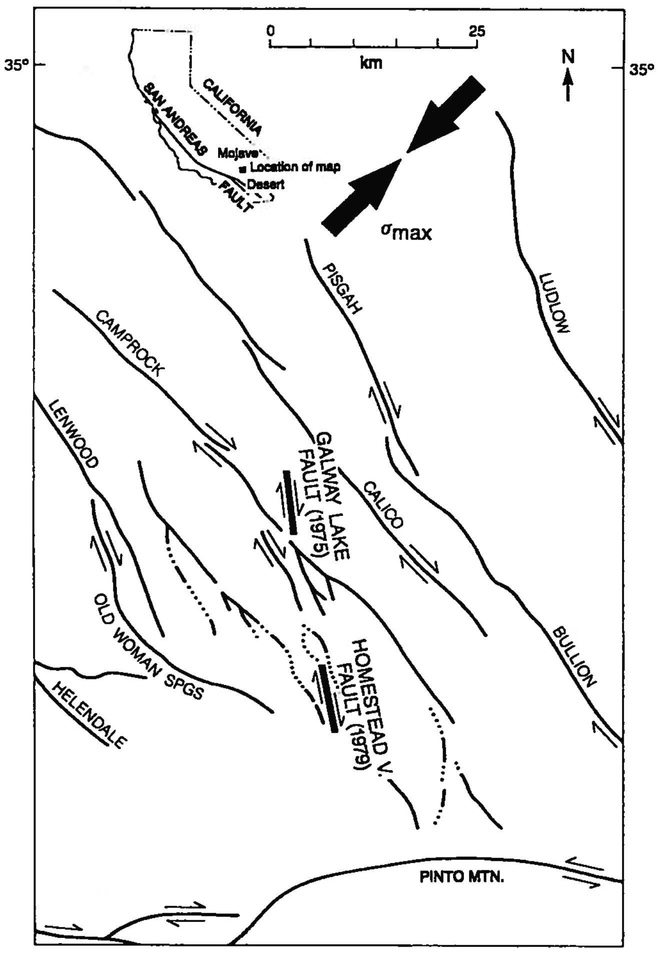

**Figure 2.** Reproduction of the Nur et al. (1989) figure showing the nearly fault-normal orientation of the Mojave compression of the older faults and its optimal orientation to the Homestead Valley and Galway Lake ruptures, suggesting the emergence of a new fault line and the gradual locking of the older faults.

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## LANDERS-MOJAVE LINE

The Landers-Mojave line falls within a broad region of distributed deformation (commonly referred to as the eastern California shear zone (Dokka and Travis, 1990; Savage et al., 1990), as inferred from geological and geodetic data. It is widely thought that distributed faulting is the main mechanism for this shearing. However, a fuller understanding of the *mechanics* of this distributed deformation in the Mojave remains elusive.

In 1989, we proposed, on the basis of an earlier kinematic and mechanical model for crustal deformation by fault sets (Ron et al., 1984; Nur et al., 1986, 1989) "that a new set of faults trending N-S may be in the process of formation" in the central Mojave region (Fig. 2). We thought that existing paleomagnetic, geological, and mechanical evidence at the time suggested that the well-developed northwest-oriented strike-slip faults in the central Mojave region had rotated counterclockwise or/and the stress had rotated clockwise (H. Ron, A. Nur, and A. Aydin, unpublished) so they are at present *mechanically* unfavorably oriented relative to the direction of maximum tectonic compression (Fig. 3). This direction at present is N10° to 30°E, and at an angle of 55° to 75° to the northwest-trending faults (for references see Stein et al., 1992; Zoback, 1991). Consequently, we suggested, a new fault system trending N15°W or so

**New Fault** *continued on p. 256*

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**New Fault** *continued from p. 253*

must develop to accommodate ongoing deformation. As we pointed out in 1989 the 1975 Galway Lake and the 1979 Homestead Valley earthquakes ruptured previously unmapped faults oriented roughly N15°W, not the well-developed N45°W-trending faults. The colinearity of these two ruptures suggests also that they may have occurred on a seismically single, unmapped fault 30 km long (Fig. 2). Although segments of this fault were identified in the field before 1992 (M. Rymer, personal communication), it was not recognized as a thoroughgoing, coherent and seismogenic fault.

The azimuth and sense of rupture of the Joshua Tree earthquake were similar to the 1975 and 1979 events (Fig. 1), and its epicenter fell roughly on the extension of their line to the south. Moreover, the Joshua Tree rupture apparently crosscuts the presumably young east-trending Pinto Mountain fault. This crosscutting relation prompted us to reconsider the 1947 M 6.5 Manix, with its N20°W aftershock alignment (Richter, 1958), and the 1965 M 5.2 Calico earthquakes, over 100 km north of the Joshua Tree epicenter. The focal mechanisms of these earthquakes also seem consistent with right-lateral strike slip on unmapped ~N15°±5°W–trending faults, not on N45°W-trending ones. Thus, the

*continued on p. 257*

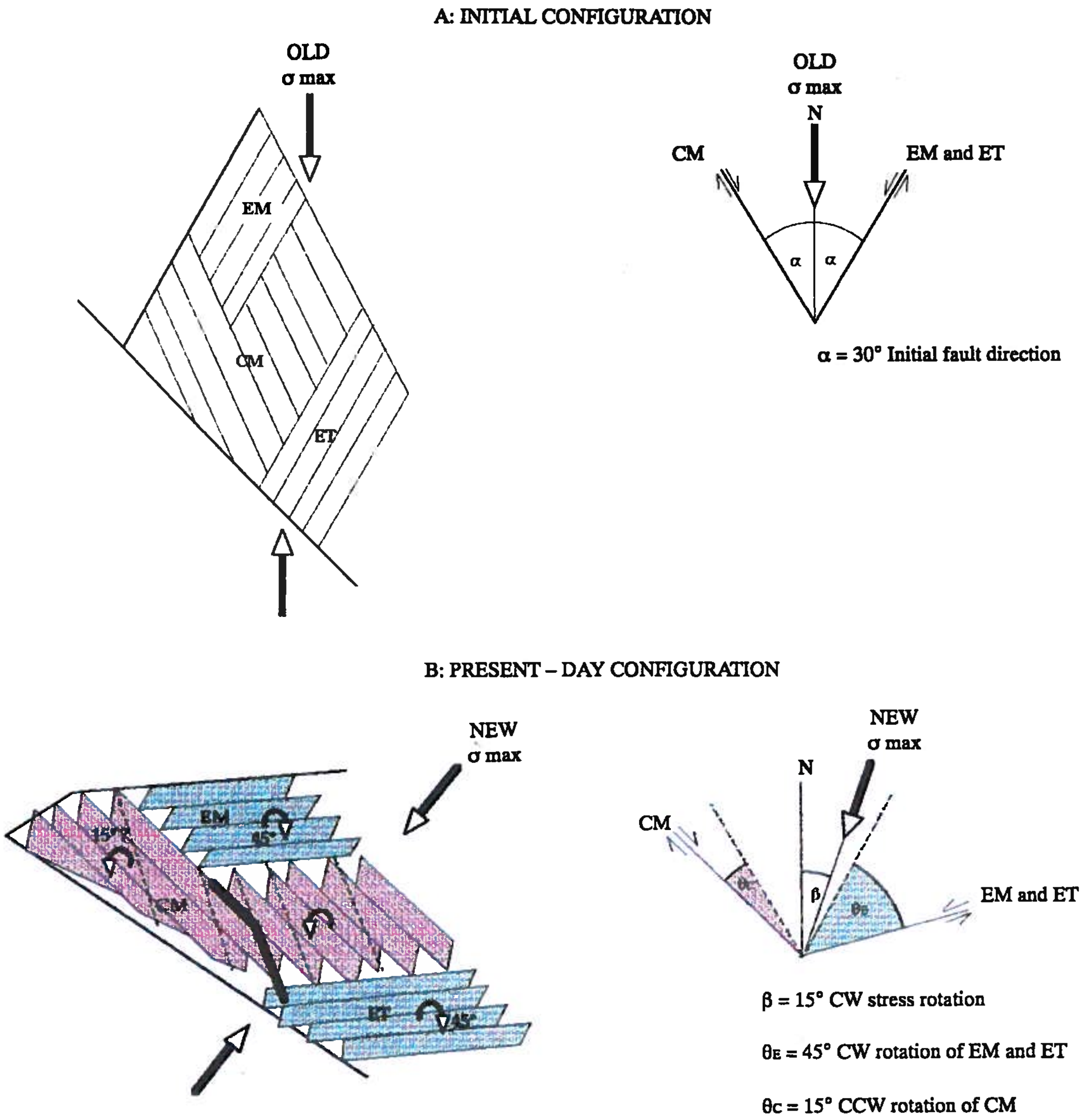
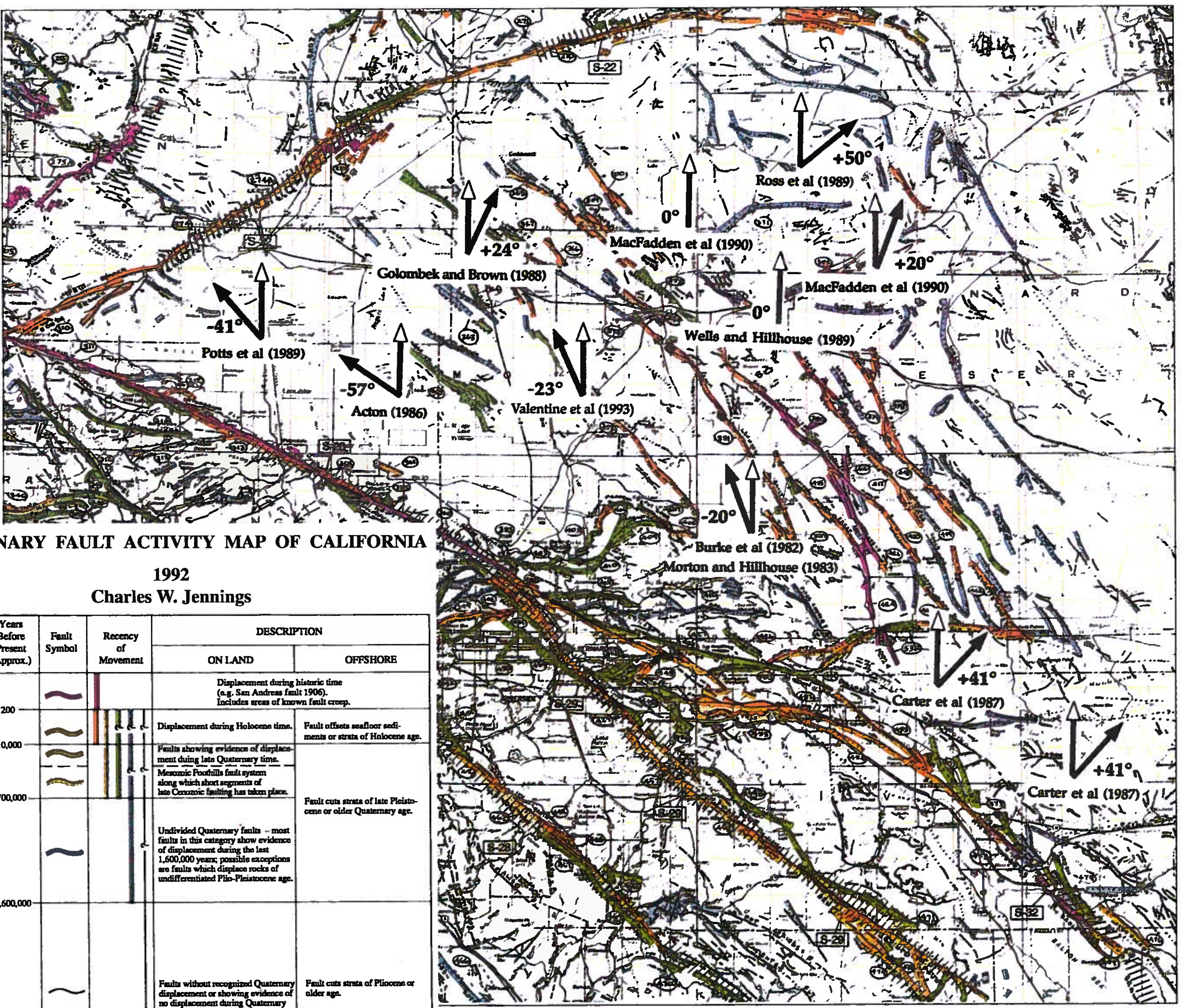


**Figure 3.** Block rotation in domains, stress-field rotation, and the formation of optimally oriented new faults in the Mojave region: A: In the initial configuration, the east Mojave (EM) and eastern Transverse Ranges (ET) domain faults are oriented σ = 30° from the direction of the north-trending stress, and the central Mojave (CM) faults are oriented σ = 30°. B: In the present-day configuration, paleomagnetic evidence and some structural data suggest a 45° or so clockwise rotation of blocks and faults in the EM and ETR domains, and possibly 15° or so counterclockwise rotation in the CM domain. These material rotations imply a stress field rotation σ = 15°, 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 [heavy line]), and the Landers-Mojave line may be such faults.



**PRELIMINARY FAULT ACTIVITY MAP OF CALIFORNIA**

**1992**

**Charles W. Jennings**

| Geologic Time Scale | | | Years Before Present (Approx.) | Fault Symbol | Recency of Movement | DESCRIPTION ON LAND | DESCRIPTION OFFSHORE |
|---|---|---|---|---|---|---|---|
| Quaternary | Late Quaternary | Historic | | ∼ | | Displacement during historic time (e.g. San Andreas fault 1906). Includes areas of known fault creep. | |
| | | Holocene | 200 | ∼ | | Displacement during Holocene time. | Fault offsets seafloor sediments or strata of Holocene age. |
| | | Pleistocene | 10,000 | ∼ | | Faults showing evidence of displacement during late Quaternary time. | Fault cuts strata of late Pleistocene or older Quaternary age. |
| | | | | ∼ | | Mesozoic Foothills fault system along which short segments of late Cenozoic faulting has taken place. | |
| | Early Quaternary | | 700,000 | ∼ | | Undivided Quaternary faults – most faults in this category show evidence of displacement during the last 1,600,000 years; possible exceptions are faults which displace rocks of undifferentiated Plio-Pleistocene age. | |
| Pre-Quaternary | | | 1,600,000<br>4.5 billion (Age of earth) | ∼ | | Faults without recognized Quaternary displacement or showing evidence of no displacement during Quaternary time. Not necessarily inactive. | Fault cuts strata of Pliocene or older age. |

**Figure 4.** Rotation about vertical axes, as inferred from paleomagnetic declination anomalies in the Mojave region. Results show clockwise rotation in the eastern Mojave (where the associated faults are oriented east-west), and generally no or counterclockwise rotation in the central Mojave (where the faults are oriented N45°W). The relative rotation *between* the faults in the two domains is on the order of 55° to 75°.

**New Fault** *continued*

line defined by the 1975, 1979, and 1992 (Joshua Tree) events (Fig. 1) is possibly an emerging thoroughgoing seismogenic fault ~120 km long.

The Landers earthquake can also be explained by our model. First, the southern part of its rupture, coincident in both the location and sense of slip with the previous N15°W ruptures, provides further evidence for a thoroughgoing fault. Second, the kink in the rupture is consistent with our mechanical model, because it suggests that slip can be partitioned during the transition from old, poorly oriented faults to new, optimally oriented ones (Fig. 3). In situ observations in fact reveal new rock fractures on some north-south segments of the Landers rupture (Ken Lajoie, personal communication), lending some direct support to the idea of new faulting.

## THE CONTROVERSY: STRESS, ROTATION, NEW FAULTS

The application of our model to the Mojave and Landers events has been sharply criticized for its three key aspects: stress, rotation, and new faults.

1. *Stress.* Two principal objections to the use of crustal stress to interpret active faulting were raised: (1) that it is immeasurable (can be inferred only indirectly from deformation measurements) and is spatially too heterogeneous; however, results from borehole breakouts and hydraulic fracturing provide clear evidence for systematic regional patterns of stress, especially principal stress directions (Zoback and Zoback, 1980); and (2) stress in the shallow brittle and weak continental crust is controlled by deformation of the ductile but strong middle crust, and merely reflects continuous deformation at depth (Jackson and Molnar, 1990). This is important in the context of the thin viscous sheet model for crustal (or lithospheric) deformation (England and McKenzie, 1982), which prohibits both clockwise and counterclockwise rotations in a single tectonic environment (Sonder et al., 1986). The opposing rotations of the Mojave domains suggest, therefore, that the thin viscous sheet model is inadequate here and that it is shallow faulting in the brittle crust that controls deformation of the deeper ductile regions (Zoback, 1991), not the other way around.

2. *Rotations and Paleomagnetism.* Although using paleomagnetic declination anomalies to infer rotations of crustal blocks about vertical axes is common practice, the mechanisms of these rotations remain uncertain. It is commonly assumed that rotations are controlled by the sense of shear in a given region. Thus, many have assumed that in the dextral San Andreas system, rotations must all be clockwise. However, paleomagnetic data indicate counterclockwise rotations in some areas of the western United States, notably the Mojave region (Fig. 4). For that region, about a dozen studies to date show clockwise rotations in the eastern Mojave and eastern Transverse Ranges (e.g., Carter et al., 1987) where faults are oriented east-west, and counterclockwise or no rotation in the central Mojave where active faults are oriented northwest (e.g., Morton and Hillhouse, 1983).

The evidence for counterclockwise rotations in Figure 4 has been dismissed by some as due to secular variations, unknown age of magnetization, hydrothermal effects, and unreliable or sparse sampling. However, it is essentially beyond dispute that a *relative* rotation of 55° to 75°, between the eastern Transverse Ranges and eastern Mojave domains and the central Mojave has taken place during the past few million years, and that this rotation must be related to the direction of faults within these domains (Garfunkel, 1974; Luyendyk et al., 1980). Taking the initial angle between the eastern Transverse Ranges and eastern Mojave faults, and those in the central Mojave close to the optimal failure direction with N0°E compression at 3 Ma, the fault azimuths at that time were 30°E and 30°W, respectively. Taking a 45° clockwise rotation of the eastern Transverse Ranges and eastern Mojave blocks and a 15° counterclockwise rotation of the central Mojave blocks (Fig. 3) yields a present-day compression direction of 22.5°E, and a 17.5° clockwise stress rotation (similar in sense to the Basin and Range stress rotation; Zoback and Zoback, 1980).

3. *Formation of New Faults.* That new faults may be forming now has been our most controversial issue, termed "naive" by Greg Davis (personal communication) and "bizarre" by others. Some argue that the crust contains enough older faults, so that any deformation can be accommodated without new faults being required. Because dating slip on geological faults is usually difficult, some argue that it is hard to prove the formation of new ones, because they may be old faults that simply have not been recognized.

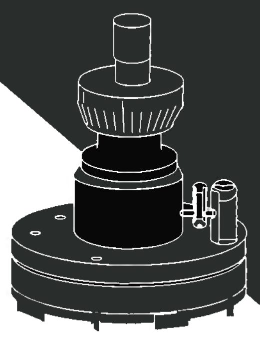
However, it cannot be disputed that faults must form at some time, and that long and coherent faults capable of generating larger earthquakes must organize sometimes out of a multitude of shorter faults. Furthermore, systematic crosscutting relations between faults provide compelling evidence that some are younger than others—e.g., the cutting of the young Pinto Mountain fault by the Joshua Tree and Landers rupture. In fact we believe (in contrast with some of our critics) that the *mechanics* of fault and fault set formation is a crucial subject for research, without which no sensible and rigorous interpretation of past and present crustal deformation by faulting will ever be possible.

## CONCLUSION

The kinematic and mechanical considerations discussed above, and our attempt to analyze active faulting in the central Mojave with the only model proposed so far that can explain the main Landers and Mojave observations, touch on several important seismotectonic, crustal deformation, and structural geology problems (and controversies).

1. How do new faults form or become organized?
2. Why and how is crustal deformation accommodated in so many regions by distributed faulting in domains?
3. How can we hope to predict earthquakes if we cannot even identify in advance the faults on which they can occur?
4. Is the Landers earthquake a characteristic one?
5. Is the deformation of the brittle crust, including block rotations, passively controlled by the ductile deformation at depth, or is the former controlling the latter?
6. Can the incorporation of fault sets in domains, conjugate domains, rotations, and the formation of new faults and fault sets lead to an advancement of faulting theory (which has remained, at least in our textbooks,

**New Fault** *continued on p. 258*



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**New Fault** *continued from p. 257*

unchanged for 40 years or more) by providing explanations for crosscutting fault sets, oblique slip, and mixed-mode deformation, for example?

## ACKNOWLEDGMENTS

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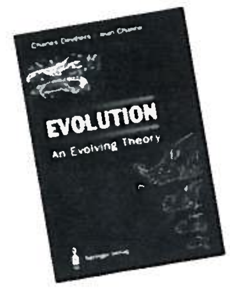

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