Landers-Mojave Earthquake Line: A New Fault System?
Amos Nur, Hagai Ron,* Greg Berza
Department of Geophysics, Stanford University,
Stanford, CA 94305-2215

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°-15°W across the central Mojave region. This previously unrecognized line, which we call the Landers-Mojave earthquake line, may be a geologically young, through-going 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.

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 been before recognized as a through-going 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 faults 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 Manx earthquakes (Fig. 1). We call this 120 km earthquake line the Landers-Mojave line.

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 1988, 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 palaeomagnetic, geological, and mechanical evidence at the time suggested that the well-developed north-west-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
most 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 co-linearity of these two ruptures sug-
gests 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. Rymar, personal com-
munication), it was not recognized as a throughgoing, coherent and seismo-
genetic 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 rup-
ture apparently crosscuts the presum-
ably young east-trending Pinto Moun-
tain fault. This crosscutting relation prompted us to reconsider the 1947 M 6.5 Manix, with its N20°W aftershock alignment (Richet, 1938), 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°S-W-trending faults, not on N45°W-trending ones. Thus, the

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

The Landers earthquake can also be explained by our model. First, the southeast pattern 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 mechan- ical model, because it suggests that slip can be partitioned during the transition from old, poorly oriented faults to new, optimally oriented ones (Fig. 5). In situ observations in fact reveal new rock fractures on some north-south seg- ments 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 assumptions: 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 breakout 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 McKenzie, 1980). 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. Rotation and Paleoseismology. Although using paleoseismic declina- tion anomalies to infer rotations of continental blocks is not a new idea, the practice, the mechanics 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, 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 dis- missed by some as due to secular varia- tion, unknown age of magnetization, hydrothermal effects, and unreliable or sparse sampling. However, it is essen- tially beyond dispute that a relative rotation of 55° to 75° between the eastern Transverse Ranges and eastern Mojave domains and the central Mod- ojave 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; Layendyk 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 90° compression at 3 Ma, the fault azimuths at that time were 30° and 30°, respectively. Taking a 45° clockwise rotation of the eastern Transverse Ranges and eastern Mojave blocks and a 15° counterclockwise rotation (rotation) of the central Mojave blocks (Fig. 5) yields a present-day compression direction of 22.5°, and a 17.5° clockwise stress rotation (rotation) 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 "naïve" 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 dat- ing of faults on geological faults is usually difficult, some argue that it is hard to prove the formation of new ones, because they are 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 large earthquakes must organize themselves out of a multitude of shorter faults. Furthermore, systematic crossing over 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, with which no sensible and rigorous interpretation of past and present crustal deformation by faulting will ever be possible.

CONCLUSION

The kinematic and mechanical considerations described above lead us to our attempt to analyze active faulting in the central Mojave with the model proposed earlier that can explain the main Landers and Mojave observations, touch on several important seismic-tectonic, 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, pass- ive controlled by the ductile deforma- tion at depth, or is the former controlling the latter?
6. Can the incorporation of fault sets in domains, conjugate double rotations, and the formation of new faults and fault sets lead to an advance- ment of faulting theory (which has remained, at least in our textbooks,
GEO-DIVERSITY FROM SPRINGER

The book will be of particular interest to students and teachers working in all areas of life sciences and to those with an interest in the history of science.

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