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MATERIAL AND STRESS ROTATIONS: THE KEY TO RECONCILING CRUSTAL FAULTING COMPLEXITY WITH ROCK MECHANICS

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Abstract

The most common test of breaking rocks in the laboratory under compression has provided the basis for most of the widely used modeling of faulting and the earthquake instability in the earth's crust. But it has not been able to explain the actual complexity of fault systems insitu. However a greatly generalized lab experiment - widely overlooked for decades - provides the missing links needed to begin to understand the actual complexity of fault systems insitu.

Keywords: *earthquakes, faults, domains.*

A perennial problem in fault mechanics is that 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 (Figs 1, 2).

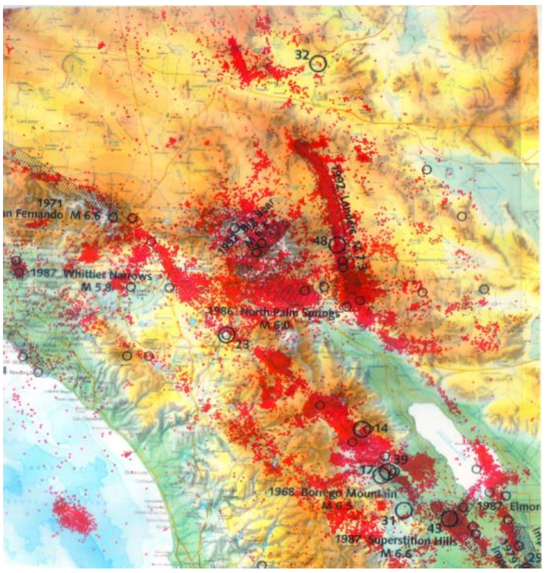

Fig. 1 - Earthquake hypocenter distribution in Southern California shows a bewildering complexity in delineating fault directions.

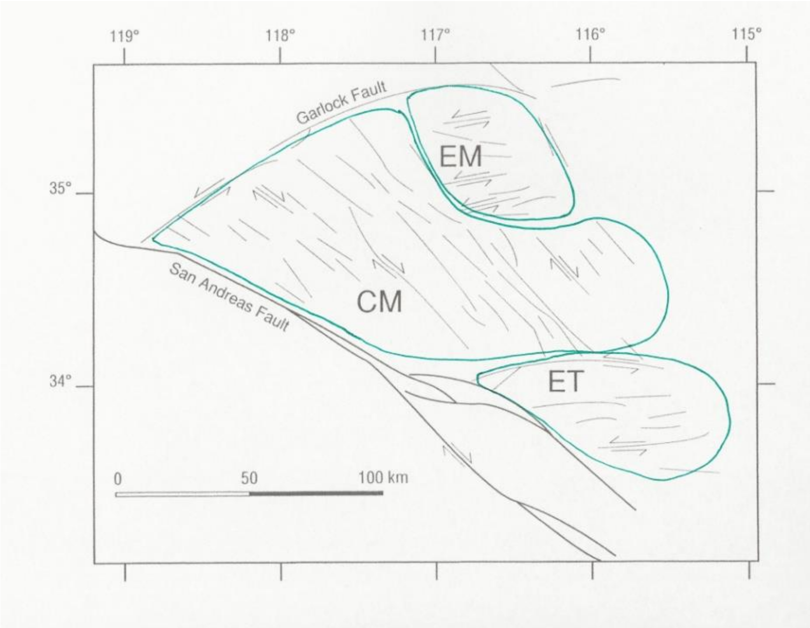

Fig. 2 - The late tertiary fault systems in the Mojave region of Southern California are organized in domains of sub parallel fault sets. The sense of slip in neighboring domains is akin to conjugate faults observed in lab failure of rocks.

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.

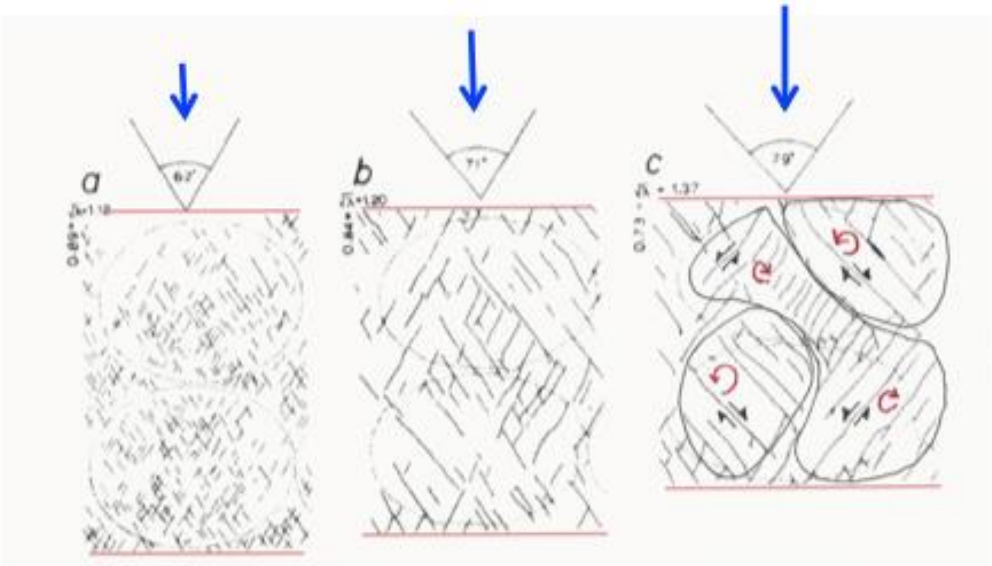

Fig. 3 - Non rotational plane strain experiments in clay distorted by a sheet of rubber beneath it showing the gradual progression of rotation, bending, coalescence, and domain formation with growing NS shortening and EW extension (Freund1974, after Hoeppener, 1969).

Following Hoeppener's model (Fig.3) 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 (Fig. 4), material rotations inferred from paleomagnetic declination anomalies, and rotated dike strands of the Independence dike swarm (Fig. 5).

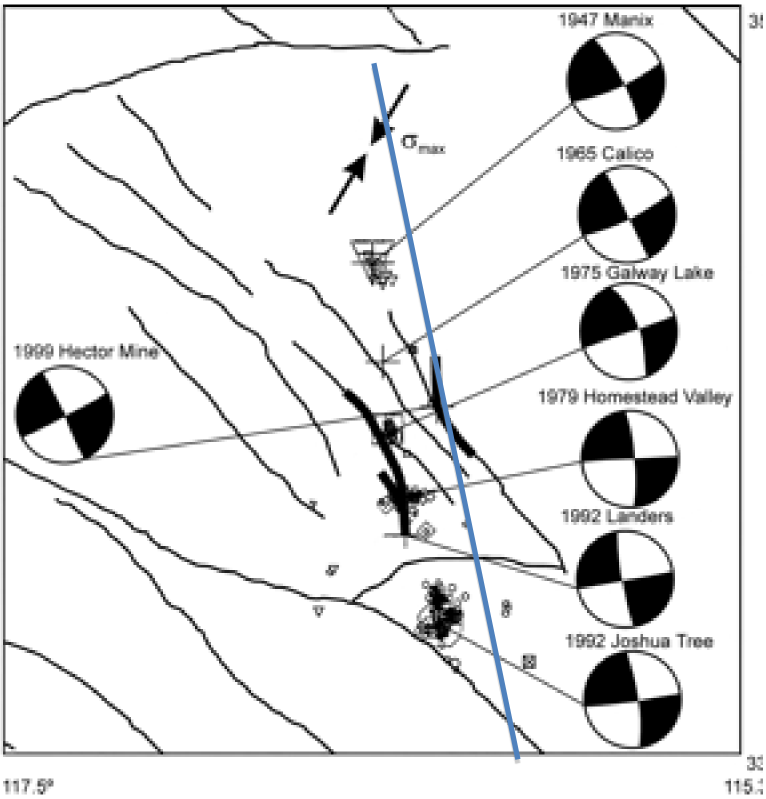

Fig. 4 - Reproduction of the Nur *et al.* (1989) figure showing the nearly fault-normal orientation of the Mojave compression to the older faults and its optimal orientation to the Manix, Calico, Homestead Valley, and Galway Lake ruptures, suggesting the emergence of a new fault line (in blue) and the gradual locking of the older faults.

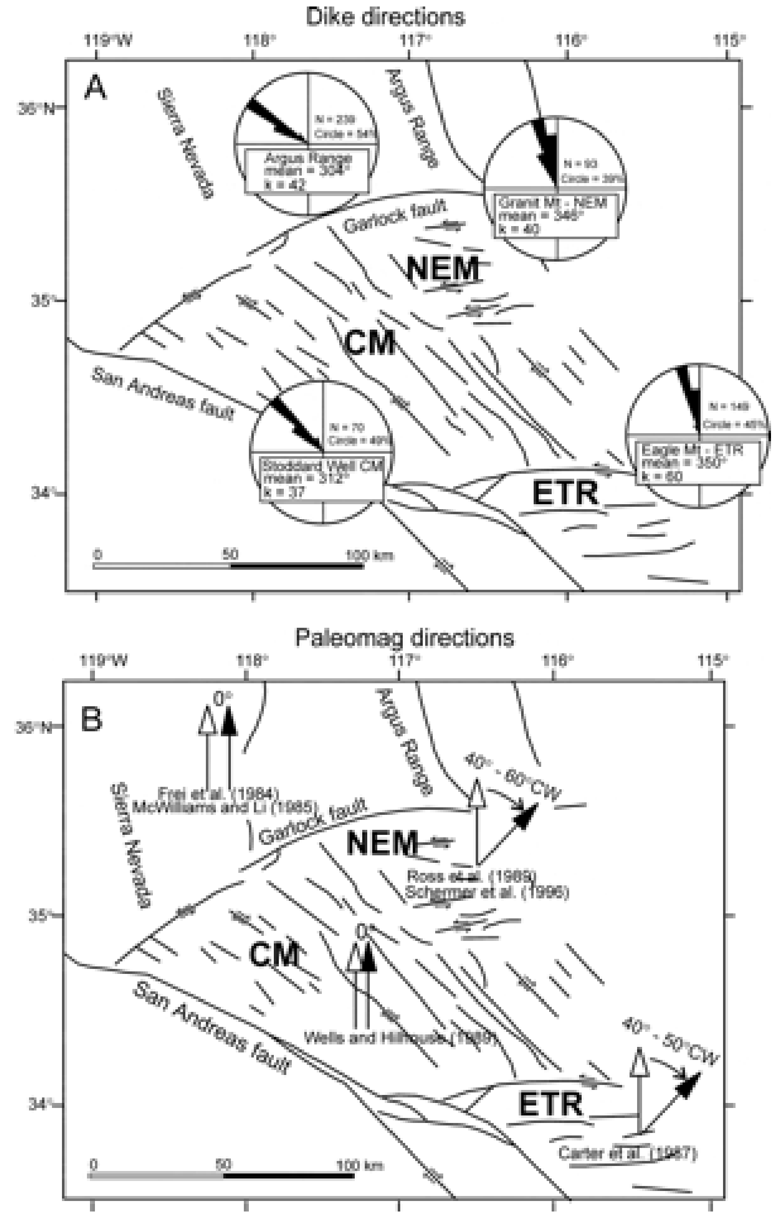

Fig. 5 - Map of the Mojave showing its three fault domains: northeastern Mojave (NEM), central Mojave (CM), and eastern Transverse Range (ETR). A. Rose diagrams and statistics of Independence dike swarm populations in each domain. B. Paleomagnetically derived rotations of each domain.

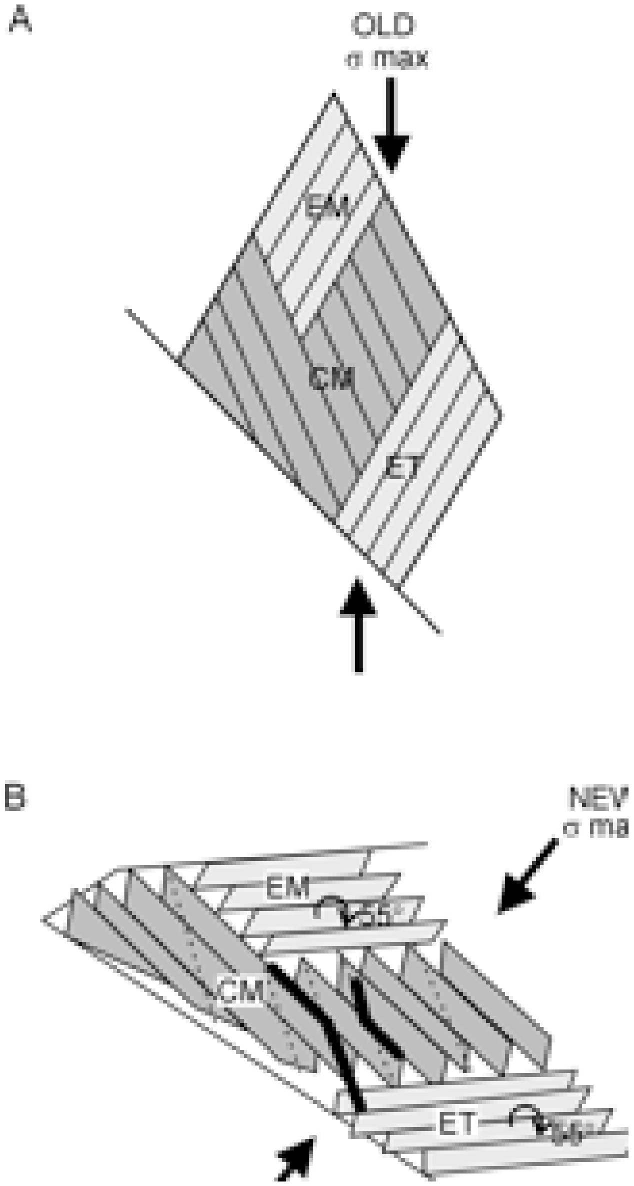

Fig. 6 - Block rotation in domains, stress-field rotation, and the formation of optimally oriented new faults in the Mojave region. A. In the initial configuration, the east Mojave (EM) and eastern Transverse Range (ET) domain faults are oriented at 30°. B. In the present-day configuration, paleomagnetic 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 cur- rent stress, new ones should form (broken lines in the CM and the Landers-Mojave line may be such faults.)

The success of the rotation model in the Mojave (Fig. 6) 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 kinematics 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*.

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 … couldn't 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 exclude rotations in crustal deformation.

Fortunately a few (Fig. 7) have already come to recognize how important kinematic mechanical rotations are for a fuller understanding of crustal deformation. McKenzie "Rotations make nonsense of the two-dimensional reconstructions that are still so popular among structural geologists" best said this. (McKenzie, 1990) are caused by material rotations. That is work for future research.

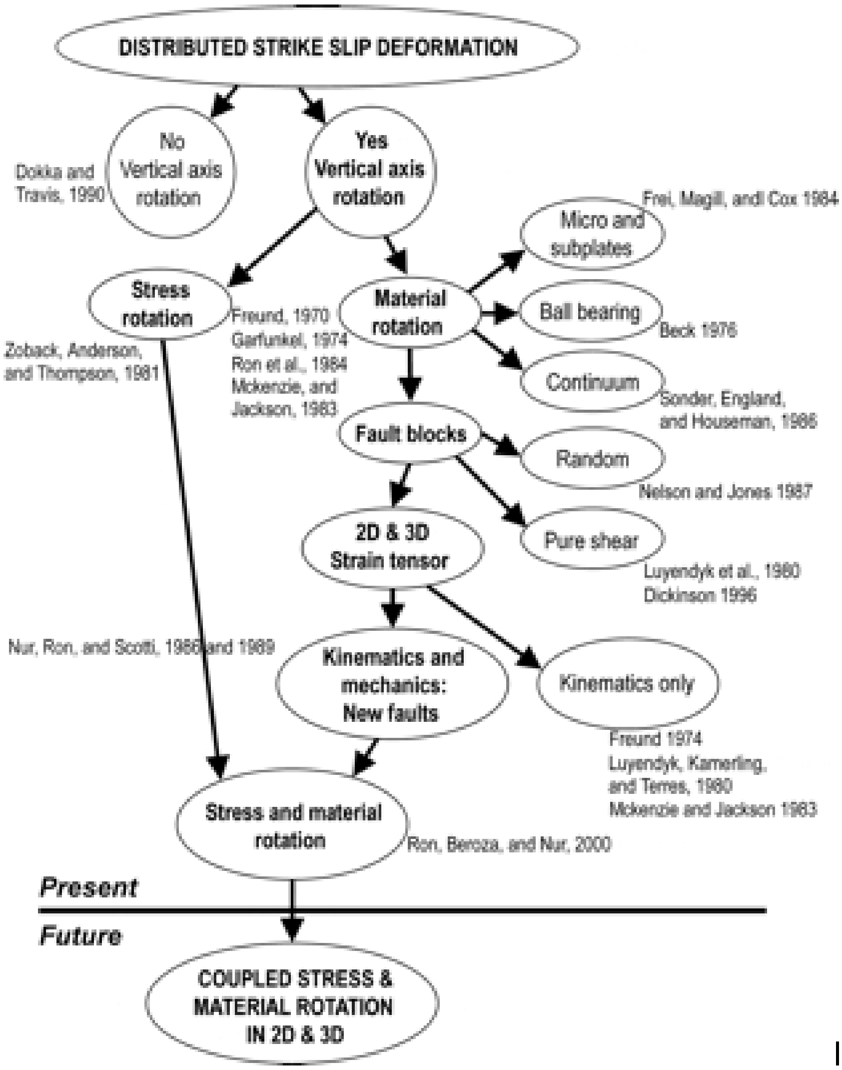

Fig. 7 - A summary of the history and trends of thought about material and stress rotations in crustal deformation, including key references to studies relevant to the debate about rotations in crustal deformation. A theory of coupled stress rotation and material rotation remains to be developed.

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