BLOCK ROTATIONS, FAULT DOMAINS AND CRUSTAL
DEFORMATION IN THE WESTERN U.S.

FINAL REPORT

09-15-87/02-28-90

Prepared by Amos Nur
Geophysics Department
Stanford University
Stanford, CA 94305-2215

This report contains a brief summary, new results, a list of publications and reprints for the project on "Block Rotations, Fault Domains and Crustal Deformation in the Western United States".

SUMMARY

The aim of the project was twofold :
1) Develop a 3D model of crustal deformation by distributed fault sets.
2) Test the model results in the field.

1. Block Rotation Modeling in 3D

In the first part of the project, Nur's 2D model (1986) was generalized to 3D. In Nur's model the frictional strength of rocks and faults of a domain provides a tight constraint on the amount of rotation that a fault set can undergo during block rotation. Domains of fault sets are commonly found in regions where the deformation is distributed across a region. The interaction of each fault set causes the fault bounded blocks to rotate. The following paragraphs briefly summarize the work that has been done towards quantifying the rotation of fault sets in a 3D stress field.

Estevez et al. (1990) developed a block rotation algorithm to analyze the 3D rotation path of faults, which describes the subsequent orientation of rotating, fault bounded blocks of a domain. The algorithm computes the rotation path in either the $\sigma_n - \tau$ space of the Mohr circle, or the Wulff stereoprojection representations. The former demonstrates the mechanical behaviour of faults during rotation whereas, the latter provides a geometrical picture of the rotating faults in space. The most important results of this study are:
a) Fault rotation may occur under "unstable" stress conditions (that is, slip and rotation of preexisting, poorly oriented faults may promote further slip and rotation).
b) Rotating faults may change their style of faulting as deformation continues.

Scotti et al. (1990) analyzed the geometry of distributed deformation across the domains of Southern California. The results show that active faults of the domains considered, can slip in accordance with friction criteria, in a homogeneous and stationary stress field, in spite of their diverse orientation and fault behaviour. The most important conclusions of the first part of this study are:
a) Reactivated fault sets are usually not well oriented in the stress field.
b) Even very poorly oriented fault sets can be reactivated in a stationary stress field.

In the second part of the study Scotti et al. (1990) analyzed the behaviour of rotating faults using the algorithm of Estevez et al. (1990). All three stress regimes were considered: normal, reverse and strike-slip. The results show that, for specific stress conditions and initial fault geometries, extreme changes in fault behaviour are possible during fault rotation. As an example the authors investigated the faulting history of the West Transverse Ranges, southern California. The 3D block rotation model predicts, in accordance with geological information, that the fault set of this domain may have been initially reactivated as normal faults. Upon rotation the fault set became strike-slip in nature and finally it rotated into the present-day high angle

reverse behaviour. The most important conclusions of the second part of this study are:

a) Fault sets become poorly oriented due to block rotation.

b) In general, faults and blocks will rotate about a mixture of vertical and horizontal axis. Therefore a vertical component of rotation is indeed expected in all three stress regimes.

c) Fault behaviour may change considerably as a fault set rotates in a stationary stress field.

Scotti and Nur (see abstract) developed a graphical algorithm to help visualize block rotation in 3D. The algorithm runs on an Ardent computer and utilizes its 3D Dore graphics package. This is an ongoing project aimed at developing a mechanical platform, on which both kinematics and mechanics of the block rotation model can be readily visualized and its implications understood. The final product will be a video tape, summarizing the 2D and 3D model results, as well as showing some applications to actual field examples (West Transverse Ranges, Mojave Desert, Lake Mead etc.).

2. Field examples

In the second part of the project, field studies were carried out in Israel, Nevada and China. These studies combined both paleomagnetic and structural information necessary to test the block rotation model results.

Li et al. (1990; 1989) present two field examples of block rotation: one from northwestern China and another from the North Nevada Rift Region. In the first field study, the authors found a discordance between the observed declination and expected declinations from the stable craton. Because the region is characterized by distributed reverse and strike-slip faults, the authors attribute the $30^0 - 40^0$ declination anomaly to counterclockwise tectonic rotation of the fault bounded blocks. In the second field study, paleomagnetic data from mid-Miocene dikes and flows indicate that some crustal blocks have rotated $\sim 20^0$ counterclockwise relative to stable North America. Rotation of blocks may have been accomodated along a system of right-lateral northwest-trending faults distributed across the region. The most important conclusions from these two field studies are:

a) Vertical axis rotation of crutal blocks in normal faulting environments does occur, as predicted by the 3D block rotation model.

b) Because regions of distributed deformation are characterized by tectonic block rotation, it is essential to study the paleomagnetic signature of dykes and single fault set domains before inferring stress directions from them.

The ambiguity between tectonic block rotation or stress field rotation is further addressed in Ron et al. (1989a). In this field study, the authors analyzed both paleomagnetic measurements and structural information from the Lake Mead fault system, Nevada. This region is characterized by distributed sets of strike-slip and normal faults. Multiple generations of faults have been identified. The main conclusions of this study are:

a) To unravel the combination of tectonic rotation of blocks and stress field rotation it is essential to combine structural and paleomagnetic studies.

b) Because of both tectonic rotation of blocks and stress field rotation, at least two generations of faults have contributed to crustal deformation in this region, as predicted by the block rotation model.

The existence of multiple generations of faults is further documented in field examples from Israel (Ron et al.; 1989b). As explained by Nur et al.

(1989a; 1989b; 1987), these and previous field studies provide a consistent picture that substantiates the block rotation model results. In accordance with the model, field studies demonstrate that faults and attending fault bounded blocks slip and rotate away from the direction of maximum compression when deformation is distributed across fault sets. Slip and rotation of fault sets may continue as long as the earth's crustal strenght is not exceeded. More optimally oriented faults must form, for subsequent deformation to occur. Eventually the block rotation mechanism may create a complex pattern of intersecting generations of faults.

NEW RESULTS

1. 3D BLOCK ROTATION IN THE WEST TRANSVERSE RANGES: THE KEY TO STRUCTURAL HISTORY AND BASIN DEVELOPMENT.

Oona Scotti and Amos Nur.

Abstract

Block rotation is widespread in regions of distributed shear. As rigid block-faulted domains rotate, "gaps" open up along their boundaries and sedimentary basins may develop. The evolution and the geometry of these basins is controlled by the slip history of the faults that bound them. To unravel their history, a 3D model was developed that combines the kinematics of block rotation with the mechanics of faulting.

As an example we present a 3D computer simulation for the history of rotation of the West Transverse Ranges domain, Southern California. A set of pre-existing faults, striking N-NE, is allowed to slip and rotate in accordance with known friction criteria. Rotation is assumed to occur in the strike slip stress regime. The principal stress axes are assumed fixed in the present day orientation throughout the deformation. Therefore, as faults slip and blocks rotate the sense of motion along the faults changes. This simulation predicts, in agreement with the observations, a initial period of normal motion along the reactivated faults. Upon fault slip and block rotation the same faults go through a phase of strike slip. With further slip and rotation they eventually become the E-W striking, oblique reverse faults that characterize the present day tectonics of this domain.

The model shows that a single set of faults can experience both dip slip and strike slip motion throughout its deformation history within a strike slip stress regime. It is not necessary to appeal to complex and arbitrary changes in the orientation of the stress field. Only by combining a 3D block rotation model with structural and paleomagnetic data it may be possible to unravel the complex tectonics of distributed deformation and basin evolution.

2. BLOCK ROTATION IN 3D.

Raul Estevez, Oona Scotti and Amos Nur

(in preparation...)

Abstract

Based on Mohr's Circles stress representation, *Coulomb-Navier criterion* for faulting and Wulff's stereographic projections, the basic mathematical tools for the description of block rotations in 3-D have been developed. These tools allow to follow the creation and dynamic evolution of individual faults within a bounded rotating fault domain. Mapping relations between Mohr's and geographic Wulff's representations let us "visualize" the state of stress and the geographic location of individual faults at each rotation event, as well as the direction of slip associated with these episodes. Three different models are considered for system stress increase and drop before and after each rotation occurs, corresponding to shear, normal and thrust faulting. Using parameter values, commomly found in the literature, theoretical models show several remarkable features, including, 1) the possibility of changes in faults's principal regimes (strike-slip, normal, thrust), 2)the existence of "unstable states" allowing rotations in the absence of major, if any, contributions from the system's stresses, and 3) notable differences in the evolution of stresses acting on the domain and those acting on individual faults during rotations.

PUBLICATIONS

Yianping Li, John Geissman, Amos Nur, Hagai Ron and Qing Huang; "Counterclockwise Block Rotation in the North Nevada Rift Region: Paleomagnetic Evidence", Geology, 18, 79-82, 1990.

Yianping Li, Robert Sharps, Michael McWilliams, Amos Nur, Yongan Li, Qiang Li and Wei Zhang; "Paleomagnetic results from Late Paleozoic dikes from the northwestern Junggar Block, northwestern China", Earth and Planetary Science Letters, 94, 123-130, 1989.

Amos Nur, Hagai Ron and Oona Scotti; "Kinematics and Mechanics of Tectonic Block Rotation", in Slow Deformation and Transmission of Stress in the Earth, eds. S.C.Cohen and P.Vanicek, Geophysical Monograph: 49/IUGG Series: 4, 1989a.

Amos Nur, Hagai Ron and Oona Scotti; "Mechanics of distributed fault and block rotation", in Paleomagnetic Rotations and Continental Deformation by Kluwer Academic Publishers , eds. C.Kissel and C.Laj, 209-228, 1989b.

Amos Nur and Hagai Ron; "Block Rotations, fault domains and crustal deformation", Annales Tectonicae, 1, 1, 40-47, 1987.

Hagai Ron, Amos Nur and Attila Aydin; "Stress Field Rotation or Block Rotation: an Example from the Lake Mead Fault System", submitted to Geology, 1989a.

Hagai Ron, Amos Nur and Y. Eyal; "Multiple Strike Slip Fault sets: a Case Study from the Dead Sea Transform", submitted to Tectonics, 1989b.

Oona Scotti, Amos Nur and Raul Estevez; "Distributed deformation and block rotation in 3D", submitted to Journal Geophysical Research, March 1990.