Annual Report for 2007 SCEC Research (Feb 1, 2007 to Feb 1, 2008)

Numerical Models of Static Stress Evolution in Active Fault Systems

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Proposal Category B: Integration and Theory

Interdisciplinary Focus Area: III Crustal Deformation Modeling

Research Area A: A11 and A3

I proposed a two-part plan for SCEC-funded research in 2007. The first part involved investigating the significance of heterogeneous viscoelastic and elastic lithosphere structure on stress evolution in the upper crust. The goal was to evaluate whether uniform elastic dislocation models that reproduce elastic strain and strain rates at the Earth's surface are suitable for modeling coseismic and interseismic stress changes at seismogenic depths. If realistic heterogeneity in elastic and viscoelastic parameters plays an important role in such stress transfer, then we will know that the full finite-element treatment is required to model stress evolution among faults in California over temporal and spatial scales of interest to the CDMG.

The second part of my proposed research involved continuing projects in cooperation with Yuri Fialko (Scripps/UCSD) on deformation of compliant zones in the Mojave Desert, and with Yehuda Ben Zion (USC) on the formation and evolution of strike-slip fault systems. It turns out that this research took up most of the funding period, and it has resulted in two submitted manuscripts (as of mid-June 2008). It also turns out that the findings of these two projects are directly relevant to the goals stated in the first part of my research plan. Specifically, we found that both the spatial extent of significant damage-induced elastic heterogeneity in the upper crust, and the influence of such heterogeneity on stress transfer, are of limited regional significance. Larger-scale, permanent heterogeneities associated with differences in lithology are a more important target for research on regional-scale stress transfer.

Mojave Compliant Zone Modeling

Geodetic and seismic observations have revealed long-lived zones with reduced rigidity along active crustal faults in the Mojave region (e.g., Li et al., 1999; Peng et al., 2003; Fialko et al., 2002). A fault zone trapped wave study of one of these compliant zones shows that it softened further in response to the Hector Mine earthquake (Vidale and Li, 2003). This means that coseismic strain of this, and likely other Mojave compliant zones must result from two contributions: one from coseismic stresses acting on permanently soft material, and another from coseismic softening (and hence strain) under the influence of the total background stress. The softening term is proportional to background stress and percentage drop in the shear modulus. The coseismic stress term is proportional to coseismic stress (which is well constrained) and compliant zone softness.

In this project, we used finite-element models to investigate whether coseismic strain of compliant zones in the Mojave Desert can place limits on their geometry and more importantly, on stresses in the upper crust. Models based on currently understood compliant zone properties yield dramatic contraction and subsidence under lithostatic stress, of individual compliant zones and the surrounding region. InSAR LOS displacement profiles and GPS data show no signs of such subsidence. The simplest explanation for this lack of subsidence is that the compliant zones are incompressible. Assuming this, we assessed the relative contributions of coseismic stress and coseismic softening to compliant zone deformation, and found that background deviatoric stress contributes significantly to deformation of compliant zones around the Pinto Mountain and Camp Rock faults. The softening contribution appears to be broadly consistent with a Mohr-Coulomb stress state, with a static friction coefficient of at least 0.7. Our results differ from previous studies which explain compliant zone strain in terms of just the coseismic stress contribution (Fialko et al., 2002).

Because of uncertainties and trade-offs in model parameters, we were not able to assess the maximum depth of the compliant zones, nor could we precisely pin down the friction coefficient. We did find that heterogeneity in both rigidity and coseismic softening were needed to model InSAR range change profiles across Mojave fault zones. An alternative, but unlikely, explanation would be extremely heterogeneous stresses over length scales of kilometers to tens of kilometers. With more seismic studies (specifically, measurements of compliant zone depth, rigidity, and coseismic softening), we are convinced that our approach could provide useful estimates of total crustal stress.

Damage Models of Fault System Formation and Evolution

My PhD student, Yaron Finzi, modeled the formation and development of strike-slip fault systems, in a brittle layer with a thermodynamically-based damage rheology, underlain by a viscoelastic substrate. As strain is imposed on the system at a constant rate, the model produces timedependent, three dimensional patterns of strain rate and damage (elasticity degradation), which are interpreted as fault structures and regions of distributed deformation. Geometry of the resulting fault zones may be compared with observations from natural faults. Only the portion of this project which is relevant to SCEC is described below.

Along fault segments, the damage evolution models produce a broad zone of damage in the top 5 kilometers of the crust, and highly localized damage at depth (Figure 1). We cannot define the width of this deeper damage zone because the smallest elements for most of our models (from 2007) are about 0.4 km in dimension. The shallow, distributed damage zone forms during an early evolutionary stage of the fault system (before a total offset of about 0.05 to 0.1 km has accumulated), and persists as continued deformation localizes along a narrower slip zone. The more highly damaged parts of the shallow "flower structures" correspond to the geodetically-observed shallow compliant zones around active faults. The rigidity of this shallow material does not evolve much between large earthquakes. The narrower, active zone which penetrates deeper into the crust corresponds to seismic wave-trapping structures. Damage in the deeper parts of this narrow zone increases coseismically and decreases (heals) interseismically.

Our models yield segmented faults, with releasing stepovers which are locations of ongoing interseismic deformation and seismicity. During the entire earthquake cycle, material within the fault stepovers remains damaged (with a significantly reduced rigidity and shear wave velocity) to depths of 10 to 15 km. This deep and persistent damage could have important implications for earthquake rupture propagation and strong motion predictions.

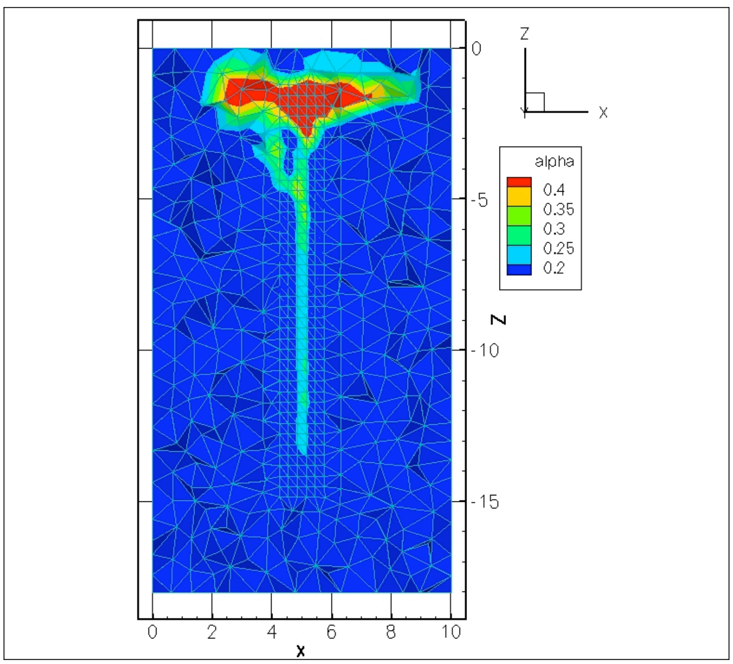

Figure 1. Distribution of modeled damage around a strike-slip fault segment (profile view). This pattern is not very sensitive to time in the earthquake cycle, except immediately after a large earthquake. Values of alpha inversely correlate with rigidity reduction. We are investigating factors controlling compliant zone width with higher-resolution models.

Synthesis and Relevance to SCEC Objectives

If compliant zones are shallow (per Finzi et al., 2008) and do not undergo significant coseismic volume changes (per Hearn and Fialko, 2008), their influence on stress transfer is limited to the local scale and to the uppermost crust (i.e., they have less effect than shown on Figure 2). At stepovers, where they extend deeper into the crust, they could locally influence stresses in the seismogenic zone. We suggest that *compliant zones probably do not contribute significantly to* *regional-scale stress transfer at seismogenic depths. More studies are needed to assess conditions for which compliant zones could locally affect stress transfer at seismogenic depths.*

If some coseismic strain results from background tectonic stress (i,e., if the coseismic softening contribution to compliant zone strain is significant), inversions of surface deformation data for coseismic slip could also be off the mark. Fortunately, since contributions to surface deformation from coseismically-softened compliant zones appears to be spatially limited, *Hector Mine and Landers earthquake coseismic slip inversions were probably not affected significantly by compliant zone strain*.

Our damage models concur with geologic and seismic observations suggesting that tectonic strain is concentrated along the highly damaged cores of fault zones. Thus, it is entirely suitable to represent faults as surfaces in finite-element stress transfer models, except at stepovers or kinks. Furthermore, adding a continuum damage rheology to deformation modeling codes like PyLith may not be warranted, because properties of the km-scale, shallow damage zones evolve so little between earthquakes that a low-rigidity (or plastic) material could be used to represent them. The narrower, active part of the damage zone may be modeled equivalently using rate-and-state friction (Lyakhovsky et al., 2005). Thus, *stress evolution in southern California may be modeled with existing FE codes (without continuum damage rheology)*. Damage models of fault system evolution, with different boundary conditions (specifically, transpression rather than simple shear strain), will be required to determine the robustness of this conclusion for all parts of southern California.

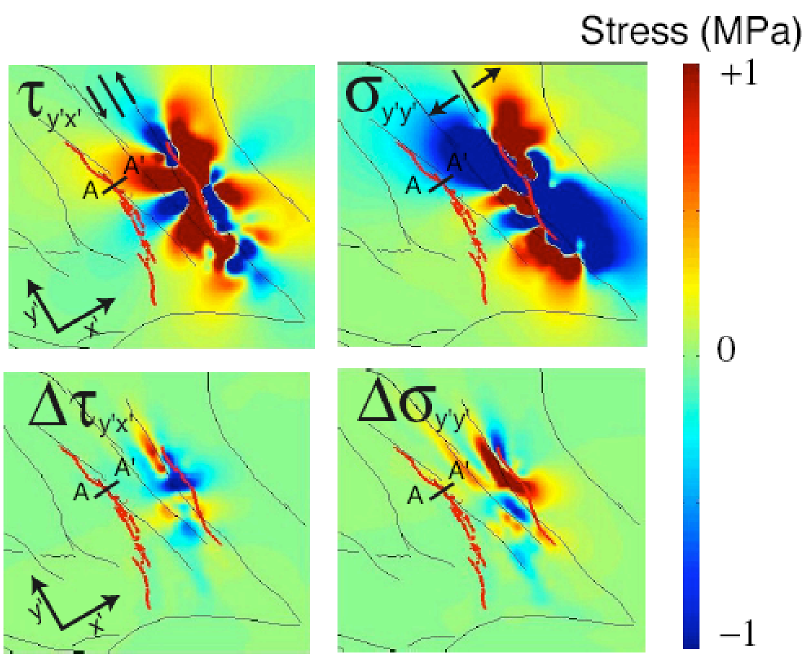

Figure 2. Effect of compliant zones on coseismic stresses (at a depth of 7.5 km). Top panels: Hector Mine earthquake coseismic shear and normal stress. Bottom panels: residual stresses (model with compliant zones minus model without them). Modeled compliant zones are 10 km deep and 2 km wide, and are 50% softer than their surroundings. They are centered on the Landers rupture segments, and the Pinto Mountain, Emerson, Calico, and Rodman faults. If compliant zones are shallow per Finzi et al. (2008), the stress differences will be smaller and more localized than shown here.

Papers Resulting From This (and Prior) SCEC Funding

Finzi, Y., E. H. Hearn, Y. Ben Zion, Y., and V. Lyakhovsky, Structural properties and deformation patterns of evolving strike-slip faults: Numerical simulations incorporating damage rheology, submitted to *Pure Appl. Geophys.*, May 2008.

Hearn, E. H. and Y. Fialko, Can compliant fault zones be used to measure absolute stresses in the upper crust?, for *J. Geophys. Res.*, June 2008.

Other References

Fialko, Y., D. Sandwell, D. Agnew, M. Simons, P. Shearer, and B. Minster, Deformation on nearby faults induced by the 1999 Hector Mine earthquake, *Science*, 297, 1858-1862, 2002.

Li, Y.-G., K. Aki, J. Vidale, and F, Xu, Shallow structure of the Landers Fault Zone from explosion-generated trapped waves, *J. Geophys. Res.*, 104, 20,257-20275, 1999.

Li, Y.-G., P. Chen, E. Cochran, J. Vidale, and T. Burdette, Seismic Evidence for Rock Damage and Healing on the San Andreas Fault Associated with the 2004 M 6.0 Parkfield Earthquake, *Bull. Seis. Soc. Am*., 96, doi: 10.1785/0120050803, pp. S349–S363, 2006.

Lyakhovsky, V., Y. Ben-Zion and A. Agnon, A viscoelastic damage rheology and rate- and state-dependent friction , *Geophys. J. Int.*, 161, 179-190, doi: 10.1111/j.1365-246X.2005.02583.x, 2005.

Peng, Z., Y. Ben Zion, Y. Zhu, and A. Michael, Inference of a shallow fault zone layer in the rupture zone of the 1992 Landers, California earthquake from locations of events generating trapped waves and travel time analysis, *Geophys. J. Int.*, 155, 1021-1041, 2003.

Vidale, J. and Y.-G. Li, Damage to the shallow Landers fault from the nearby Hector Mine earthquake, *Nature*, 421, 524-526, 2003.