**Annual Report for 2008 SCEC Research (Feb 1, 2008 to Jan 31, 2009)**

**Lithosphere Heterogeneity and Static Stress Transfer**

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Proposal Category B: Integration and Theory

Interdisciplinary Focus Area: III Crustal Deformation Modeling

Research Area A: A2, A3, and A11

This year, we continued investigating the effects of rheological heterogeneity on fault zone formation and earthquake-cycle deformation. Motivated by new studies suggesting a wide range of interseismic damage levels along active fault zones, we added a project on how variations in fault zone healing effectiveness influence the distribution of damage and the longevity of geometrical complexities.

## Fault system evolution in upper crust with damage-controlled rheology

My PhD student, Yaron Finzi, has been modeling the formation and development of strike-slip fault systems, in a brittle upper crustal layer with a thermodynamically-based damage rheology, underlain by a viscoelastic substrate. As strain is imposed on this system at an essentially constant rate, time-dependent, three dimensional patterns of high strain rate and damage (elasticity degradation) develop in the upper crust. These patterns are interpreted as fault structures and regions of distributed deformation. The amount of damage is expressed in terms of parameter $\alpha$, which may vary from 0 (for a pristine elastic material) to 1 (for a thoroughly cracked brittle material, with no shear strength). The geometry of fault zones that emerge in the models may be compared with observations from natural faults. This year, Yaron focused on two research questions. First, he investigated the effect of fault zone healing efficiency on the longevity and complexity of extensional stepovers. Next, he began to model fault propagation into regions with lateral rheological contrasts. This research is in coordination with Yehuda Ben Zion at USC and Vladimir Lyakhovsky at the Geological Survey of Israel.

*Longevity of fault complexities, and damage distribution, depend on healing efficiency*
After a rapid episode of postseismic healing, damage levels in modeled fault zones asymptotically approach a steady-state value (e.g., Lyakhovsky et al., 1997 and 2001, Finzi et al., 2009a and b). Though damage levels vary laterally and with depth in shallow fault zones, and estimates of damage are associated with large uncertainties, recent studies suggest that fault zone damage varies significantly, even along individual faults (e.g., Cochran et al., 2009; Hearn and Fialko, 2009; Barbot et al., 2009). We define healing "effectiveness" in terms of a characteristic, residual fault zone damage level in the interseismic period, $\alpha_{ch}$. "Effective" and "ineffective" healing refer, respectively, to low and high values of $\alpha_{ch}$. Our exploration of how healing affects fault complexity is a departure from previous studies showing that the rate of early postseismic

damage healing (relative to the rate of loading) governs fault zone complexity (Ben-Zion et al., 1999; Lyakhovsky et al., 2001).

We find that healing effectiveness controls both the spatial extent of damage zones and the long-term geometrical complexity of strike-slip fault systems. Specifically, simulations with highly-effective healing form localized intensively damaged fault cores that interseismically extend only a few kilometers deep, and are bracketed by wider zones of distributed off-fault damage. Ineffective healing yields deeper zones of intense damage that persist throughout the interseismic interval, and narrower zones of distributed off-fault damage (Figure 1). In both cases, shallow damage remains localized within a few kilometers of the fault and is very limited in the host rock. At depth, it localizes to a one-element-wide zone for all values of $\alpha_{ch}$.

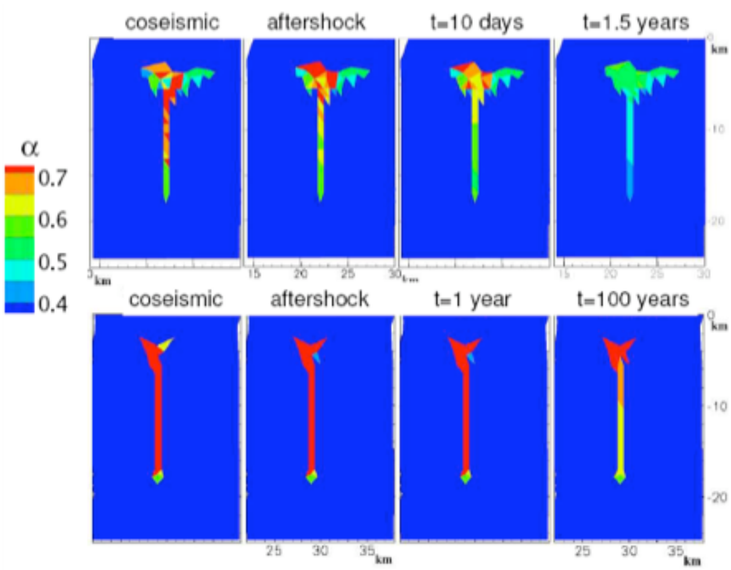



**Figure 1.** Cross-sections displaying evolving damage levels along two strike-slip faults representing effective (top, $\alpha_{ch}$=0.4) and ineffective (bottom, $\alpha_{ch}$=0.7) healing conditions. The damage zone is narrower, deeper, and longer-lived for fault zones with ineffective healing. Note the difference in time epochs for the two sets of models: after 100 years, damage in the $\alpha_{ch}$ = 0.4 case is completely healed (i.e. blue) below a depth of 5 km. From Finzi et al., 2009b.

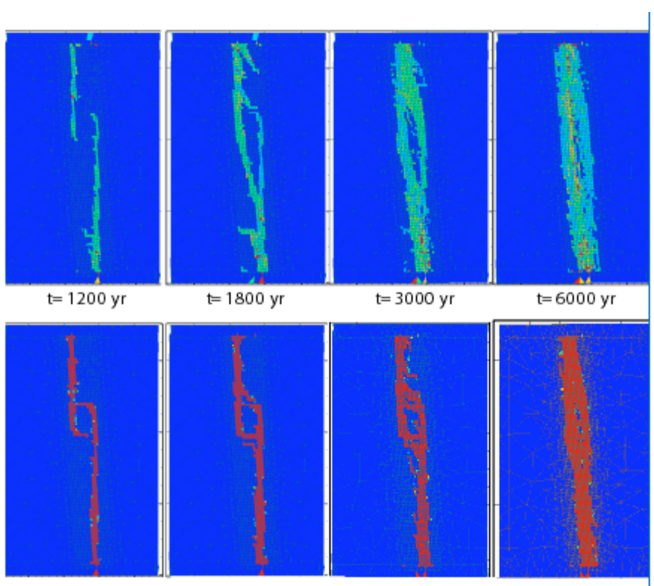


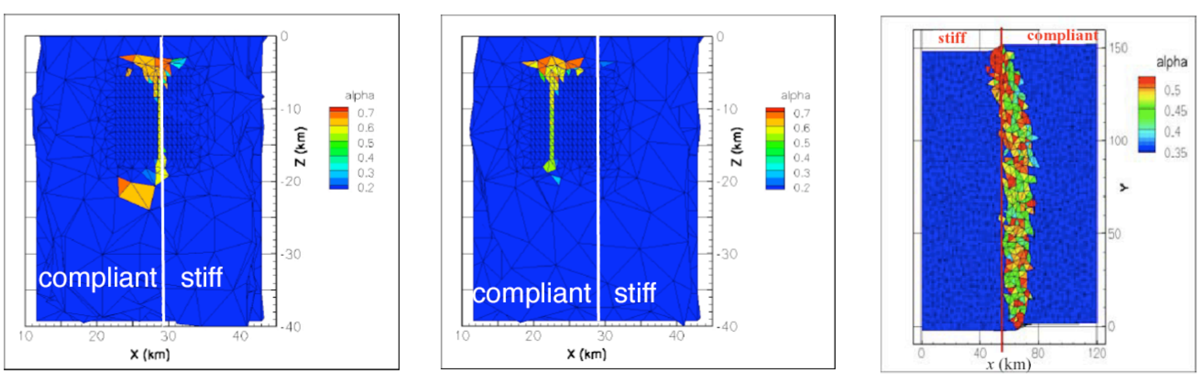

**Figure 2.** Damage maps (depth = 5 km) displaying two evolving stepovers along segmented strike-slip faults with effective (top, $\alpha_{ch}$ = 0.4) and ineffective (bottom, $\alpha_{ch}$ = 0.7) healing. While effective healing (top) leads to rapid smoothing of the fault system and turns the stepover into an inactive structure, ineffective healing keeps the stepover structure active and the fault system remains segmented throughout the duration of the simulation. The region shown is 40 by 70 km and damage levels range from 0.2 (blue) to 0.55 (red). From Finzi et al., 2009b.

In addition, we find that highly effective healing leads to a rapid evolution of an initially segmented fault system to a simpler through-going fault, while ineffective healing along a segmented fault preserves complexities such as stepovers and fault jogs, resulting in long-lasting distributed deformation (Figure 2). This is because in the case of effective healing, a stepover is permanently weak to only a shallow depth. Below a few kilometers, confining stresses are large and the fault zone heals rapidly to a low damage level. The stepover has less of an influence on the propagation of large ruptures, which break through it, eventually allowing a through-going fault to form. These results, based on fully 3D simulations and wide range of healing parameters (both timescale and effective residual $\alpha_{ch}$), provide important refinements to the earlier general findings of Lyakhovsky et al. (2001) Ben-Zion et al. (1999), which were based on simpler analytic models of a 2D region with an initially uniform strain rate.

*Faults appear to localize on the "weaker side" in areas with contrasting effective plate thickness*
Our preliminary models with a lateral contrast in the shear modulus indicate that the damage zone of a fault at the contrast may be more broad than it is for comparable, laterally homogeneous models. If the weak side is in the tensional quadrant during rupture propagation, a wider damage zone results. After the fault zone has formed, the weak side may be either in a tensional or compressional quadrant during large earthquakes, but the asymmetry of the damage zone left over from the propagation period lingers. Also, our preliminary models suggest that elasticity contrasts do not "attract" propagating fault zones, and that asymmetry in compliant zone width is not present if the fault zone is not located near the elasticity contrast (Figure 3).

We are currently running models with contrasts in viscous structure, both parallel and oblique to the imposed regional shear. We will begin to evaluate the model results to address whether viscous rheology contrasts at depth can cause asymmetric damage distribution and whether strain (and hence faulting) localizes along such contrasts. Thin viscous sheet models with power-law flow and oblique indentors require a large stress exponent (n=10) to reproduce observed strain rate localization (Dayem et al., 2009). Our models may do the same with reasonable power-law flow laws (lower n) below the upper crust. If significant damage asymmetry results from a contrast in effective plate thickness across a fault, this should be taken into consideration when attempting to relate damage distribution with rupture directionality. We are also investigating fault system and damage zone evolution in models with permanent, low-viscosity channels in the lower crust and uppermost mantle.

**Figure 3.** Damage along a strike-slip fault segment for preliminary models with an elasticity contrast at the white dashed line. Left panel (cross section) shows asymmetry resulting from a lateral contrast of 40% in shear modulus at the white line. Center panel (cross section) shows that if the contrast is further away, a symmetric damage pattern results. Right panel shows (plan view at 3 km depth) non-localized damage in the weaker material (this time, on the right). The different colors result from varying times since the failure of individual model elements (i.e., simulated earthquakes).

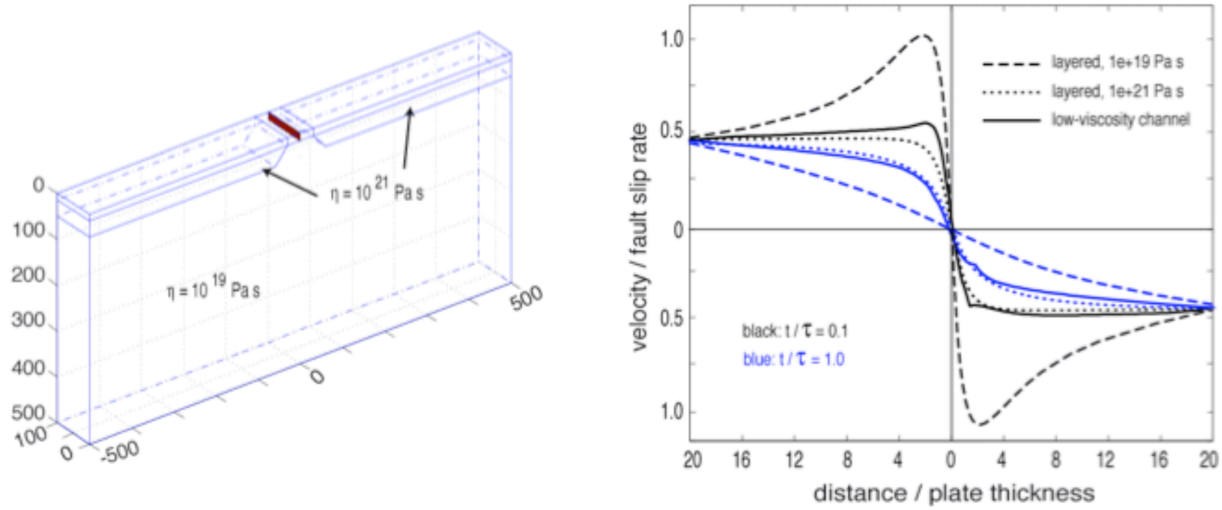


## Earthquake cycle models with laterally heterogeneous viscosity

Models of postseismic deformation following large strike-slip earthquakes rule out the classical idea of an elastic upper crustal layer overlying low-viscosity lower crust and upper mantle with a linearly viscoelastic rheology (e.g. Freed et al., 2006, Hearn et al., 2002). This has led several researchers to propose that the effective viscosity of the lower crust or upper mantle varies with time after an earthquake, due to either a transient (Hetland and Hager, 2005, Hearn et al., 2009) or power-law rheology (Freed et al., 2006). Several examples are summarized by Burgmann and Dresen (2008). Based on studies of exhumed shear zone rocks (e.g., Mehl and Hirth, 2008; Warren and Hirth, 2006) it seems likely that permanent lateral heterogeneities in effective viscosity may be present at plate boundaries. We would like to know whether such heterogeneous models, for a variety of geologically reasonable rheologies and shear zone geometries, yield interseismic deformation similar to that observed around major strike-slip faults.

The first step in this project was to set up new earthquake cycle models in GeoFEST (Parker et al., 2008), to supplement our previous models (Hearn et al., 2006). Figure 4 summarizes fault-parallel velocities early and late in the earthquake cycle, for two simple (layer over uniform viscoelastic halfspace) models with different viscosities, and a model with a low-viscosity channel embedded in higher-viscosity lower crust and uppermost mantle (as suggested by Mehl and Hirth [2008] and Warren and Hirth [2006]). Both early and late in the earthquake cycle, the channel model surface velocities look somewhat like those for a high-viscosity, uniform halfspace (Figure 4), though differential stresses in the lower crust and mantle are much lower. We are currently running a suite of strike-slip earthquake cycle models with different channel geometries and rheologies, including power-law flow outside the shear zone and (in the shear zone) at high strain rates (Billen and Hirth, 2007).

**Figure 4.** *Left:* FE earthquake-cycle model with a low-viscosity channel embedded in higher-viscosity lower crust and upper mantle. The model extends 500 km along strike (100 km is shown). The relative velocity of the sides is 20 mm/year, the top model boundary is free, and the front, back, and bottom boundaries are free to move in the fault-parallel direction. The crust is 15 km thick and the high-viscosity layer extends to 50 km depth on either side of the channel, which is 50 to 100 km wide. Earthquakes are modeled every 300 years and the domain is a Poisson solid



with G = 30 GPa. *Right:* fault-parallel velocities early (black) and late (blue) in the earthquake cycle, for the channel model, and two reference models with uniform lower crust / upper mantle viscosities.

Kaj Johnson has found (using BEMs) that viscoelastic relaxation beneath a complex system of faults adds a long-wavelength feature to the interseismic velocity field (pers. comm., 2009). If we get a similar result for these somewhat more realistic FEM's, we may be able to come up with a way to assess the need to "spin up" models of interseismic stress transfer for southern California fault system models. This could save SCEC researchers a tremendous amount of simulation time, and obviate the need to address stability problems that are being faced by FE modelers who are incorporating the SCEC CFM in their simulations (B. Aagaard, pers. comm. 2009). Faster simulations would allow us to run more models and better assess model sensitivity to poorly-constrained parameters (as alluded to by T. Becker at the June 2009 SCEC retreat). Ali and I are also exploring whether a coseismic stress perturbation in nonlinear or transient lithosphere can lead to a detectable component of postseismic deformation driven by the background tectonic stress, as discussed by Hearn et al. (2009). Greg Lyzenga has been assisting us with GeoFEST during this research.

## Education and Outreach

Michael Bostock and I taught our new UBC undergraduate Earthquakes class (EOSC 256) for the first time this spring. Several SCEC products proved highly useful for developing homeworks, in-class exercises, and lectures. These included the online exercises on seismicity statistics and aftershocks, ShakeOut information, and the SCEC velocity field. With these materials and up-to-the-minute online products from the USGS, GeoEarthscope, and other sources, we were able to put together an exciting course. Student ratings for this course were very high (4.4/5). EOSC 256 has raised awareness of SCEC among our students, and will continue to do so as the enrollment increases in coming years.

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