The evolution of shear-zone thickness and fault strength during earthquakes.

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During the three months that I was hosted by Takahiro Hatano at ERI, my primary research focus concerned the controls on shear-zone thickness during earthquakes. Earlier kinematic models (e.g. Rempel and Rice, 2006) predict that fault rocks should melt during moderate earthquakes if deformation is accommodated over the sub-mm thicknesses that are often inferred from field observations (e.g. Chester et al., 1993, 2003). An unpublished analysis referenced by Rice et al. (2005) and Platt et al. (2010) showed that a shear zone of finite thickness is stable to infinitesimal perturbations in width if the frictional resistance increases with strain rate. It has long been established that the nucleation of earthquakes requires rate-weakening friction, so the hypothesis pursued here proposes that the frictional character changes subsequently to become rate-strengthening, which leads to an expansion of the shear zone thickness so that heat is dissipated over a sufficiently broad region to prevent bulk melting.

Two separate mechanisms were considered as likely to cause a change in the frictional rate dependence. The first follows from results reported in recent papers by Hatano and Kuwano (2011a, 2011b) that describe experimental and theoretical investigations of rate-strengthening granular friction at relatively low effective stresses. The effective friction coefficient is shown to be proportional to the inertial number I, which increases with slip rate V and depends inversely on the square root of effective stress $\bar{\sigma}$. Since $\bar{\sigma}$ must decrease from ambient levels (typically $O(10-100)\,\mathrm{MPa}$) to zero when bulk melting takes place, I becomes large as melting conditions are approached and this granular rate-strengthening gains increasing importance. The second mechanism follows from an analysis of the effects of flash heating at microscopic asperity contacts (e.g., Rempel and Weaver, 2008). An extension of this model predicts that the flash weakening that has been observed in numerous laboratory experiments (e.g. see Goldsby and Tullis, 2011 and references therein) should lead to rate-strengthening behavior when the shear resistance along asperity contacts decrease over their lifetimes and the duration of contact becomes ever more brief. The transition from rate-weakening to rate-strengthening is expected to depend on the ratio of V to the characteristic weakening velocity V_w, which decreases as the temperature T rises so that the transition comes at lower and lower V as T increases towards melting conditions. The essential behavior that each of these basic mechanisms predicts is a transition to rate-strengthening friction as melting conditions (low $\bar{\sigma}$, high T) are approached.

The first step towards making quantitative predictions of shear-zone thickness involved extending the linear stability analysis of Rice and coworkers, referred to above, to consider cases where the frictional resistance depends on effective stress and temperature. The behavior is particularly sensitive to the value of the hydraulic diffusivity α_{hy} that controls the rate of fluid escape from the thermally pressurized shear zone and the expansion parameter Λ that gauges the changes in density and pore volume due to temperature and effective stress changes. Shear thicknesses of $O(1 - 10\,\mathrm{mm})$ are predicted with moderate rate strengthening when $\Lambda \leq 0.1\,\mathrm{MPa}/^{\circ}\mathrm{C}$ and $\alpha_{\mathrm{hy}} \geq 10\,\mathrm{mm}^2/\mathrm{s}$; both of these parameters tend to evolve to promote thicker shear zones as $\bar{\sigma}$ falls. These thicknesses are very large in comparison to the typical size of gouge particles (i.e. $O(1\,\mu\mathrm{m})$) and confirm that the basic hypothesis has merit, but further efforts were needed to construct a dynamic model of shear-thickness changes. An analysis of flash heating enabled the more uncertain controlling parameters to be fit to the empirical data reported by Goldsby and Tullis (2011) and extended to estimate the degree of flash-strengthening as fault conditions change. University of Oregon PhD student, Jiangzhi Chen, was enlisted to develop a numerical treatment that has now generated preliminary results from a model that tracks changes in effective stress due to thermal pressurization of pore fluids and solves for the changes in strain rate and shear-zone thickness needed to satisfy force equilibrium as the temperature rises and the inter-particle friction evolves. This work will be presented at the upcoming SCEC annual meeting this September and the AGU fall meeting in December as we endeavor to summarize the results for a future publication in the Journal of Geophysical Research.

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