Our current SCEC grant provides support for postdoc Delphine Fitzenz. She began the official period of SCEC support on October 1, 2004. We thus do not have detailed progress to report at this time. We will provide an update later once final results are in hand. Right now we are required to submit this report

Before coming to Stanford, she worked at the USGS on the interseismic behavior of faults [1]. She is studying compaction within fault zones and its effect on fluid pressure. In particular, fluid pressure may build up within the fault zone between earthquakes. This may allow earthquakes to occur at laboratory values ~0.7 of the coefficient of friction at relatively low shear traction. It is a viable mechanism for weak faults like the San Andreas.

So far she has concentrated in getting laboratory data into a physically well characterized form for export to crustal fault zones. She will develop an inverse method using repeated measurements or estimations of porosity and/or pore pressure in laboratory or field fault zones to derive the constitutive relationships, parameters and uncertainties controlling pore pressure evolution in faults. In this approach, which is complimentary to the forward modeling approach, the Bayesian framework allows us to make use of all available prior knowledge (e.g., lithology, permeability and porosity, as well as spatial heterogeneity in these parameters) and to take into account what we know about the data acquisition. This approach is limited by the fact that existing experimental data are rarely adequate to completely define a single constitutive relationship for a given fault gouge mineralogy and grain size distribution over temperature and effective confining pressures of relevance to actual fault zones.

She has made special effort to the tracking of the uncertainties. Indeed, all laboratory measurements contain a statistical error and some noise, as well as uncertainties associated with extrapolation to natural conditions. It is important to both know the error and the noise on sensitive "input" variables such as temperature, porosity, and gouge grain size, and on the derived model parameters, if we want to evaluate the robustness of the model results. Rather than using separate sets of data points to fit separately for the stress dependence, the temperature dependence and so on, she considers all of the data and their standard deviation within a Bayesian framework to determine the probability density functions of the model parameters.

The SCEC meeting in Palm Springs renewed Norm Sleep's interest in the evolution laws in rate and state friction. Two simple evolution laws have been proposed. The Ruina [3] law predicts that the fault zone or laboratory gouge does not strengthen while at rest, that is during a "hold". Neither does it compact during a hold. The Dieterich [4] predicts strengthening and compaction during holds. Interestingly, the Ruina law represents laboratory behavior at low humidity while the Dieterich law represents behavior at high humidity [4-6]. This is bothersome for those who wish to export laboratory results to crustal fault zones.

We have investigated the underlying physics of creep within gouge lattices. Basically very high stresses exist at contact asperties. These strain rates associated with these stresses scale to an invariant depending on the macroscopic normal and shear tractions.

$$r = \sqrt{\tau_m^2 + c^2 P_m^2} \quad \sqrt{\tau^2 + c^2 P^2} \quad (1)$$

where τ is shear traction, P is normal traction, c is a dimensionless constant of order 1, and the subscript m indicates microscopic quantities within the grain lattice while the macroscopic quantities lack subscripts.

It is generally agreed that friction on a molecular level is thermally activated exponential creep [e.g., 7-9]. A full tensor treatment probably with anisotropy is needed to fully represent gouge. Some simplification is possible if one wants the mesoscopic and macroscopic effects. This formalism allows us to represent exponential creep with parametric equations. The microscopic shear strain rate is [10, eqns. 20 and 22]

$$\varepsilon'_m = \gamma' \sin(\theta) \exp(r/s) \ , \quad (2)$$

where γ' is a material constant with dimensions of strain rate, s is a material property with dimensions of stress as in (12) on the order of 100 MPa, and the microscopic stresses are given by

$$\tau_m \equiv r \sin(\theta), \quad (3)$$

and

$$cP_m \equiv r\cos(\theta)\,. \quad (4)$$

The corresponding expression for compaction is

$$f'_m = \gamma'\left(\frac{E}{c}\right)\sin(\theta)\exp(r/s) + \beta\varepsilon'_m\,, \quad (5)$$

where $\beta\varepsilon'_m$ is a linear term representing dilatancy that is proportional to the shear strain rate. We obtain mesoscopic values by integrating over enough time and space to be a continuum or more productively over a probability density function. Skipping some bulky mathematics, a convenient function for the macroscopic shear strain rate is

$$\varepsilon' = \gamma'\int h(r)rdr\int\frac{\delta}{\sqrt{\pi}}\sin(\theta)\exp\left[-\delta^2(\theta-\theta_0-\lambda)^2\right]d\theta \quad (6)$$

where h is the r-dependent product of the weighting function and the invariant. The weighting function h is significant only for values of the invariant stress r near the yield stress. Extremely sluggish creep occurs at low values and rapid creep and stress relaxation precludes high values. The dimensionless constant δ is a large to keep the Gaussian distribution narrow. The parameters within the bracket are

$$\tan(\theta_0) \equiv \frac{\tau}{cP}\,, \quad (7)$$

which represents the tendency of the ratio of the microscopic stresses to scale with the mesoscopic stresses and λ represents the tendency of asperities with high shear traction to persist longer than those with high normal traction. We recover the Ruina compaction law,

$$f' = \varepsilon' C \left[\ln\left(\frac{\varepsilon'}{\varepsilon'_0}\right) + \ln\left(\frac{\psi}{\psi_{\mathrm{norm}}}\right) \right], \quad (8)$$

where C is a dimensionless constant, when (skipping more mathematics including some involving the effect of dilatation) obtain the Ruina law (7) when

$$b - a = \frac{\partial \lambda}{\partial (\ln \varepsilon')} \left(\frac{\mu_0^2 + c^2}{c} \right). \quad (9)$$

That is, λ must change with strain rate to change steady state properties. The stability parameter $b-a$ is related to tendency of shear-traction concentrations to persist longer relative to normal-traction concentrations with increasing slip rate. This and the definition of λ in (25) are simple kinematic interpretations of rate and state friction

Our key assumptions in deriving the Ruina law (7) and (14) were homogeneity so the microscopic stresses scaled with the macroscopic ones and the frictional sliding was happening so that (2) applies and the shear strain rate is much greater than the compaction rate. This leads to two exceptions where the Dieterich law applies. The first is heterogeneous material where hydrated material at really contacts facilitates shear [4-5, 11-12]. The second is material far from shear failure including hydrostatic compaction which follow the Dieterich law [13,14]. A third exception is that it does not predict the dilatancy of intact rock on initial sliding.

Overall, the probability density function formulation seems powerful in that it can be obtained by considering a modest number of grains over time rather than a full gouge layer with countless grains. See Figure 8 of [15] for an analogous calculation. We will see what can be done analytically and before going to numerical methods

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