Physical Processes within Major Fault Zones: Implementation to the Complete Cycle Including Rupture

USGS Award No.: 1434-HQ-98-GR-1028

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Program element: III. Understanding Earthquake Processes

Keyword: Fault dynamics

- **Investigations undertaken**

Our work has been motivated by two classes of observations: (1) fault sometimes fail sudden to produce major earthquakes; and (2) major crustal fault zones fail at relatively low shear tractions. Our objective has been to develop a unified treatment of fault zones that allows both topics to be addressed in a self-consistent manner. We have applied and extended a unified theory for fault gouge behavior developed from traditional rate and state friction by *Sleep* (1997). We briefly summary the results of that work.

The state variable which represents the effects of previous sliding on friction was explicitly related to the porosity of the fault zone. The porosity was increased by frictional dilatancy during sliding and decreased by compaction driven by the normal traction on the fault zone. The latter process is temperature dependent. To summarize the results, the traditional formula for the coefficient of friction is retained

$$\mu = \mu_0 + a \ln (V/V_0) + b \ln (\psi/\psi_0) \quad (1)$$

where μ_0 is the coefficient of friction of reference values of the sliding velocity $V = V_0$ and the state variable $\psi = \psi_0$ and a and b are small dimensionless constants. The normalizing constant ψ_0 depends on the normal traction and on the temperature. Sudden changes in either of these quantities, as is observed, result in sudden changes in the coefficient of friction.

We have found it advantageous to use strain rate within the fault zone rather than velocity as a variable to represent sliding. This makes analogies to other flow laws more evident. It also allows strain rate to vary within the fault zone and allows strain localization to be explicitly represented. This is important since localization is observed both in the laboratory and in exhumed faults. Localization is expected when $b > a$. Localization during the early part of sliding reduces the amount of porosity production by frictional dilatancy and hence the fluid pressure decrease within sealed fault zones. The tendency of frictional dilatancy to quench earthquakes within sealed zones is thus reduced.

We have concentrated on representing the physics of processes that are measurable in the laboratory and likely to occur in the Earth. Conversely, we have tried to recognize processes that occur in laboratory experiments but are unlikely to occur in real faults. Our work has been theoretical and we summarize the results below.

- **Results**

Gouge extrusion. The use of strain rate as a function of position within a fault zone has allowed us to investigate the effects of gouge extrusion on friction. We predict that gouge extrusion does not significantly affect experiments to measure *a* and *b*. The observed coefficient of friction is lowered below the intrinsic value by gouge extrusion when $a > b$. The behavior when $b > a$ is complicated by strain localization. In a real experiment, regions of high shear traction tend to trigger the formation of boundary Y-shears in the gouge. Gouge extrusion is driven by variations of gouge pressure and hence normal traction from its macroscopic value. Changes in normal traction may affect the strength of the fault if an experiment perturbs either the geometry of gouge extrusion or causes local values of normal traction to change.

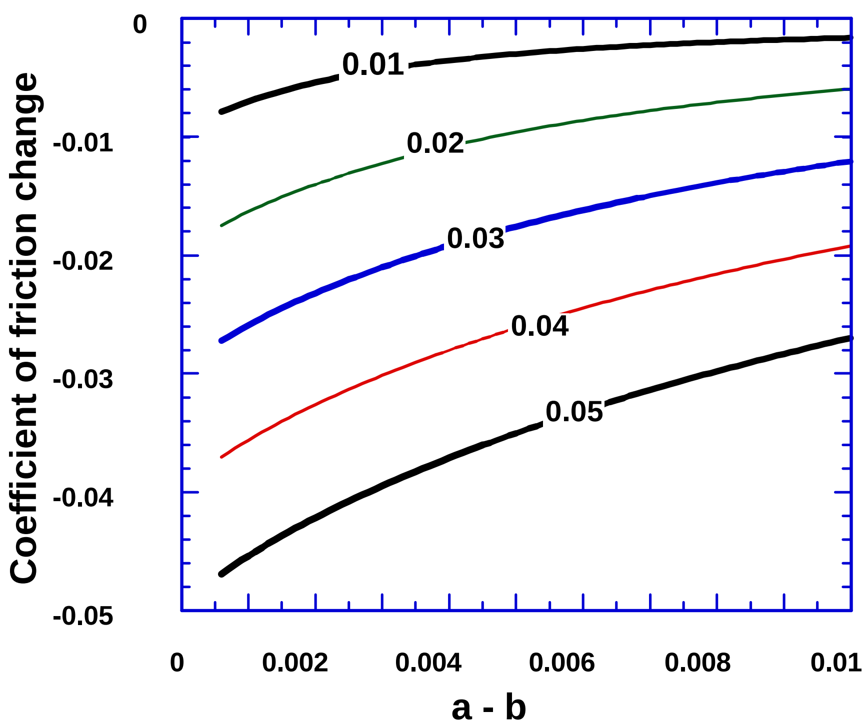

Figure 1: The predicted reduction of the steady state coefficient of friction from gouge extrusion is shown as a function of $a - b$. The numbers on the curves are the ratio of the width of the gouge zone to the distance from its center to its edge along the direction of shear. The curves extrapolate to these values at $a - b = 0$.

To the first order, gouge extrusion should not affect experiments to measure frictional dilatancy. Strain localization, however, may affect the results. The effects of sudden changes in normal traction should not affected be gouge extrusion provided the wall of the fault zone behave rigidly. We predict that compliant walls of a laboratory gouge zone may produce significant artifacts.

Variations is normal traction associated with extrusion of thick gouge or with the flow of thin gouge around constrictions in the fault zone may produce complicated effects when they interact with strain localization. In particular, strain localization may be disrupted by a reversal in the polarity of sliding. Experiments where the macroscopic shear traction is greatly reduced after slip may be vulnerable to these effects.

Rake-dependent friction. The scalar velocity and scalar strain rate have entered traditional rate and state friction theory. The direction of sliding within faults planes (the rake), however, is observed to change during earthquakes. To represent this effect, we used damage tensors to extend the state variable to include the effects of random variations in the orientation of strain history (*Sleep*, 1998). Once would expect that particles within gouge would become oriented during sliding and that fault surfaces would become grooved. In the simplest form of the theory, predicts strengthening more the rake of sliding changes. However, no strength change occurs when the polarity of sliding is exactly reversed. There are no relevant experiments with which to appraise the theory. It is possible that this polarity reversal relationship is true for ideal gouge where only uniform simple shear occurs. Oblique Riedel shears develop at intermediate stages of strain localization in real gouge. Such shears are disrupted by a reversal in sliding polarity We have not applied the theory in three dimensions to the difficult problem of the development and disruption of oblique shears.

Porosity-friction relationship. The state variable is directly related to the porosity in laboratory experiments. However, the general experience in rock mechanics is that tabular cracks weaken the material much more than equidimensional pores. The theory could have been extended by using the number density of cracks rather than the porosity to define the state variable. This more fundamental approach is awkward because the number density is not easily measured during sliding. We therefore modified the evolution equation for porosity to include both failure cracks which effect friction and equidimensional pores which do not. Shear produces failure cracks and converts equidimensional pores into failure cracks. Equidimensional pores are created when failure cracks close. The resulting theory has no unmeasurable parameters. It has been applied to the development of faults in rocks with high equidimensional porosity, like sandstones, and to the evolution of porosity as cracks close following an earthquake.

The relationship between porosity and friction did not properly extrapolate to the properties of intact rock. Rather, a coefficient of friction of over 6 was predicted for intact rock. This deficiency was fixed by using percolation theory to obtain a new relationship between porosity and the state variable which gives essentially the previous result of broken gouge. The state variable then has the form of

$$y = \left[1 - \frac{f}{M f_l} - \frac{f^2 (M f_l - f_c)}{M f_l f_c^2} \right]^M \tag{2}$$

where *f* is the porosity of failure cracks, *M* is the percolation theory exponent, ϕ_l constant which gives a linear relationship between porosity and the state variable in the limit approaching zero porosity, and ϕ_C is the critical porosity where all strength is lost. This relationship is useful for comparing intact rock experiments with gouge experiments. It has applications to the Earth in that faults often need to start at the expense of intact rock and as ruptures on existing faults may locally break into intact rock.

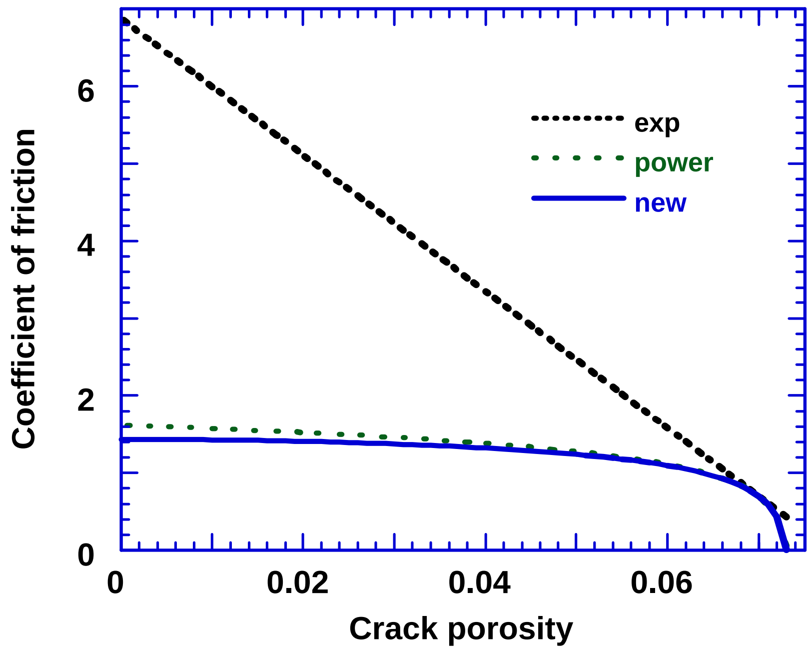

Figure 2: The computed coefficient of friction is shown as a function of porosity for three possible relationships between porosity and the state variable. An exponential dependence of state state variable on porosity implies an excessive coefficent of friction for intact rock. A power-law where $\psi = (\phi_C - f)^M$ and the new relationship in Figure 2 imply reasonable values for intact rock. The laws give similar predictions near at the high porosities where significant frictional sliding occurs.

- **Non-technical summary**

Earthquakes occur when broken rock of faults suddenly fails. This failure is believed to be proceeded by gradual deformation. Our objective has been to understand the grain scale physics of both slow sliding before earthquakes and rapid sliding after earthquakes. To do this, we have related empirical theories that represent the behavior of fault materials in the laboratory to theories developed in material science. This has allowed us to unify several previously separate theories. We are now able to represent fault behavior through the complete earthquake cycle in a self-consistent manner. We are also able to represent the effects of changes in the direction of sliding of faults on friction. This permits study of the physics of the complete earthquake cycle.

- **Reports published**

Sleep, N. H., Application of a unified rate and state friction theory to the mechanics of fault zones with strain localization, *J. Geophys. Res.*, *102*, 2875-2895, 1997.

Sleep, N. H., Rake dependent rate and state friction, *J. Geophys. Res.*, *103*, 7111-7119, 1998.

- **Data available**

None.