Laboratory-Derived Friction Laws and The Rheology Of Brittle Fault Zones

Chris Marone

Department of Earth, Atmospheric, and Planetary Sciences,
MIT, Cambridge, MA USA 02139 cjm@westerly.mit.edu

Despite recent progress in some areas there is no general understanding or unified theory for rock friction or brittle faulting. In the preceding paper, *Scholz* discusses this problem in the context of fault strength and the state of stress within the crust. I focus on the second-order aspects of brittle failure that relate to the stability of frictional sliding, fault slip, and earthquakes. The presentation is divided into three sections covering friction laws, field observations of the rheology of brittle fault zones, and current directions in laboratory research. A generic theme is the question of what is the minimum level of complexity in terms of parameters and mechanisms needed to describe laboratory observations, seismic data, and other field observations of faulting.

1) Friction laws. What level of complexity?

A central goal in fault mechanics and problems involving brittle deformation at plate margins is to put forth a reasonably complete description of the strength and constitutive properties of lithospheric faults and, in particular, the seismogenic zone. Constitutive laws for brittle failure are necessary for describing and understanding the field observations and theoretical results used to construct and test hypotheses for crustal deformation. In the context of the seismic cycle, constitutive descriptions should describe failure criteria and their variation with strain rate, characteristics of aseismic creep and earthquake nucleation, aspects of dynamic slip during earthquakes (possibly including spectral characteristics of the emanating seismic waves), and postseismic transient behavior such as afterslip. Ideally, this would be done in a single law or minimum set of laws, with appropriate modification for variability in ambient conditions, strain rate, and fault properties.

I plan to introduce this section by illustrating why the simplest friction laws are fundamentally incapable of meeting a minimum set of these goals. A static-dynamic (or "high school") friction law does not adequately describe laboratory observations of stick-slip nor key aspects of the seismic cycle, since it does not explain basic aspects of these phenomena such as: (1) repetitive failure, (2) time-dependent frictional strengthening, (3) fault healing, and (4) the observation that a given fault may undergo either stable (aseismic) or unstable sliding (seismic). Slightly more complex laws, such as slip-weakening or purely velocity-dependent friction satisfy some observations but are incapable of describing the three key aspects of the seismic cycle: nucleation of instability, dynamic slip, and restrengthening. Recent laboratory research shows that, at a minimum, constitutive descriptions of frictional sliding must include memory effects and, for a given state of the frictional surface (or shear zone) explicit velocity (or strain-rate) dependence of frictional strength.

At the current forefront in unified descriptions of frictional shear, so-called rate and state friction laws are capable of describing repetitive stick-slip and a wide range of complex behavior. These laws include memory effects and slip history dependence, strain rate dependence of sliding friction and static friction, and time- or slip-dependent frictional aging. As such, rate and state friction laws describe a *rheology* of brittle deformation. I review laboratory observations that form the basis for rate and state friction theory, including the apparent equivalence of time-dependent static friction (aging) and velocity weakening sliding friction. Finally, I argue that the syntax '*rheology of brittle faulting*' is necessary, rather than an oxymoron, because the observations satisfy definitions for both brittle failure (pressure sensitive deformation mechanisms and normal stress dependent strength) and flow (shear occurs within a zone of finite thickness and strength is history- and strain-rate dependent).

2) The Rheology of Brittle Fault Zones. Seismic and Geodetic Observations.

Recent field-based observations of faulting indicate a rich variety of behaviors ranging from seismic to aseismic faulting. This includes slow and silent earthquakes, nucleation events, tsunamogenic earthquakes, earthquake afterslip, and creep events. The data show that a given fault can fail both seismically and aseismically at different times. I summarize these data with the goal of addressing the question: what level of complexity in the friction law is required to explain the observations? I argue that seismic and aseismic faulting are end members of a continuous spectrum of slip behaviors.

A second area of critical importance to the Margins mission is that of understanding controls on seismogenic zone boundaries. *Ruff* and *Hyndman* cover this topic in full on day 2 of our TEI. I focus on the up-dip limit of the seismogenic zone and show that for mature transcurrent faults in continental crust this stability transition can be explained by the state of consolidation and shear localization in granular fault gouge. The same mechanism may be significant in determining the upper stability transition in subduction zone accretionary prisms; however, in that case additional mechanisms related to the presence of clays may be important.

The seismogenic zone and stability transitions at its boundaries are defined in terms of where earthquakes nucleate. However, other information such as aseismic behavior and whether events propagate out of the seismogenic zone can also be used to infer characteristics of the fault zone. I show how such data have been used in the case of continental faults.

3) Friction Laws for Faulting. Applications and Current Directions.

Recent laboratory-based research is summarized including work on fault healing and frictional aging. I present results from direct shear experiments on quartz powder at high applied normal stress and for shearing velocities of a few to several hundred micron/s at room temperature and humidity. The primary goals here are to show the effect of loading rate on frictional healing and to explore the relationship between healing, creep relaxation, and mechanical consolidation within granular gouge. I focus on the independent roles of time and slip as related to frictional aging, including details of the effects of consolidation and dilation. Also, I demonstrate that frictional healing obeys the same friction law as used to describe active frictional shear. In each case the coefficient of friction depends on past slip, normal stress history, and the current slip rate. I use healing data to constrain the empirical rate- and state-dependent constitutive laws in two ways. First, time-series of aging tests are fit, including the relaxation history, static friction and reapproach to steady sliding. In addition, aggregate data from multiple tests are modelled, such as the aging rate (rate of increase of static friction with waiting time during quasi-stationary contact) at a given loading velocity. By comparing constitutive parameters determined from different types of tests, I critically evaluate the internal consistency of current rate and state friction laws. Finally, I compare field observations of fault healing with laboratory-based predictions.

Preliminary results will be presented from recent work on smectite clay. Direct shear experiments at room temperature and humidity show a stability transition in which velocity-weakening frictional behavior at low effective normal stress changes to velocity strengthening behavior at normal stresses above 20 MPa. The potentially important implications of these data for the stability transition within accretionary prisms are discussed and future work in this area is outlined.

The presentation will close with a summary of recent work on the effects of humidity on second-order aspects of friction. The work is aimed at illuminating the fundamental crystal-scale processes that give rise to the macroscopic behaviors described by the empirical rate and state friction laws and related work will be discussed.

References

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