Dynamic Weakening Mechanisms Workshop
September 12-13, 2009

Summary

An outstanding question of earthquake mechanics is to explain the multiple lines of evidence suggesting that major faults operate at stress levels far lower than those suggested by the combined assumptions of hydrostatic pore fluid pressure and laboratory values of friction at slow slip speeds. A leading explanation is dynamic weakening, in which faults have static strengths compatible with low speed friction experiments but offer very little frictional resistance during coseismic slip. Dynamic weakening has been the recent subject of many new high-velocity friction experiments, as well as a number of modeling studies. This workshop was convened in order to discuss the state of knowledge surrounding these issues and identify promising directions for future research. The workshop was jointly organized by Eric Dunham and Judi Chester, and was attended by 126 participants [IS THAT THE RIGHT NUMBER?].

About half of the workshop was devoted to experimental results concerning fault friction at coseismic slip rates. Most of these experiments show extreme weakening of friction at speeds exceeding ~0.1 m/s for a wide variety of rock types, though there were a few counterexamples presented at the workshop of experiments showing negligible decrease of friction at high speeds. The particular form of the rate-dependence of friction was debated; some experiments show friction to be proportional to the inverse of slip velocity, which is consistent with the theoretical flash heating model, while others show milder velocity dependence. Giulio Di Toro presented a compilation of over 100 experimental results for a wide variety of rock types showing how universal dynamic weakening is, though most of these experiments are limited to either low normal stresses or slip rates only just entering the coseismic range. In addition, Vikas Prakash gave examples from experiments at much higher normal stresses and velocities that show very low friction coefficients.

A feature of many high velocity friction experiments is the appearance of oscillations that some have attributed to machine compliance. This view is supported by new results presented by David Goldsby that demonstrate how changing machine stiffness influences the amplitude of the oscillations. Ze'ev Reches presented results from a new high speed friction apparatus that show weakening of friction down to ~0.3 at ~0.01 m/s followed by strengthening to ~0.7 at ~0.1 m/s; this non-monotonic behavior of friction with velocity has evidently been seen before in other tribology experiments. In addition to the previous explanation of fault weakening due to flash heating, several new weakening mechanisms were proposed. These include distributed high strain rate plastic flow at asperity contacts (discussed by Kevin Brown) and the production of nanoscale particles that adhere to the sliding surfaces. A new microstructural study of laboratory samples after high speed friction experiments by Hiroko Kitajima linked the onset of dynamic weakening with the development of particular structural units with the gouge layer. Establishing a theoretical understanding of experimental results and identifying distinguishing characteristics of dynamic weakening that can be mapped in the field both remain top research priorities. Additionally, future experiments are needed that involve controlled pore fluid pressure and finite gouge layers. One proposed dynamic weakening mechanism, thermal pressurization, is becoming more widely used in the modeling community but has no experimental basis as of yet.

The other half of the workshop focused on modeling. Constitutive equations describing dynamic weakening were discussed; these ranged from physics-based descriptions of melting

and shear of viscous melt layers at asperity contacts by Alan Rempel to more empirical formulations capturing a broad set of experimental results by Nick Beeler. Jim Rice presented results of numerical simulations of rupture propagation with flash heating and thermal pressurization using parameters derived directly from laboratory measurements. While presently limited by computational constraints to very small earthquakes, the resulting stress drop and scaling of slip with propagation distance appear to be consistent with natural events, lending support to the dynamic weakening model of fault mechanics. Nadia Lapusta presented earthquake cycle simulations with rate-and-state friction and thermal pressurization, showing how dynamic weakening from thermal pressurization can permit ruptures to propagate on rate-strengthening portions of the fault. Using numerical simulations, Joe Andrews suggested that efficient thermal pressurization in the shales at the north end of the Chi-Chi earthquake might explain the low levels of spectral acceleration relative to spectral velocity observed in the strong ground motion records.

The workshop also had several discussion periods. In particular, there were two discussion sessions for the two parts of the workshop that were led by Terry Tullis and Nadia Lapusta. In addition, the workshop concluded with a panel discussion featuring Jim Evans, Bruce Shaw, Greg Hirth, Paul Segall, and Bill Ellsworth. Several interesting ideas emerged from the discussions. Some participants suggested supplementing high velocity friction experiments with controlled studies to isolate and better understand particular processes that are thought to be occurring during dynamic weakening (e.g., high strain rate deformation of molten layers). Another suggestion expressed in the discussions was to test the dynamic weakening model by isolating and studying particular locations where it is difficult to argue for alternative explanations (like overpressurized fluids) for fault weakness. Other places to focus are where measured stresses are very close to those suggested by Byerlee's law and the assumption of hydrostatic pore pressure. How are such faults different from those that operate at low stress levels? Slow slip events might also provide constraints on fault mechanics and dynamic weakening. Models of these events suggest very high pore pressures at depth, something that is supported by seismic data. Another potential area of focus is induced seismicity, where the forcing function is known. Finally, there is a clear need to identify, through modeling efforts, potential seismic signatures of dynamic weakening mechanisms. This effort should be coordinated with future instrumentation efforts to ensure that seismometers are placed in locations that will be able to record the necessary signals (e.g., stations close to or on the fault might help constrain rise time).

Agenda

10:00-10:10 am	Introduction, Eric Dunham and Judi Chester
10:10-10:40 am	Overview of Dynamic Weakening Mechanisms, Jim Rice

Session I: High Velocity Experiments and Understanding Weakening Mechanisms

10:40-11:10 am	David Goldsby *Experimental constraints on coseismic slip*
11:10-11:40 am	Vikas Prakash *Laboratory experiments to understand slip weakening due to flash heating at seismic slip rates*
11:40-12:10 pm	Kevin Brown *Fault plasticity at seismic slip rates: Experiments and theory*
12:15-1:45 pm	Lunch
1:45-2:15 pm	Ze'ev Reches *Dynamic weakening by gouge lubrication: Experimental observations of granite friction at velocity range of 0.001-1.0 m/s*
2:15-2:45 pm	Hiroko Kitajima *High-speed friction of Punchbowl Fault ultracataclasite in rotary shear: Characterization of frictional heating, mechanical behavior, and microstructure evolution*
2:45-3:30 pm	Session I Discussion, led by Terry Tullis
3:30-3:45 pm	Coffee break

Session II: Interpreting Observations and Integrating Dynamic Weakening into Rupture Models

3:45-4:15 pm	Alan Rempel *Flash weakening and the onset of melting*
4:15-4:45 pm	Nadia Lapusta *3D earthquake-sequence simulations with thermal pressurization of pore fluids: Effect of heterogeneous fault properties on slip complexity and interseismic stress*
4:45-5:00 pm	Day 1 wrap-up
5 pm	Cocktails
6 pm	Dinner

Sunday, September 13

Continuation of Session II

8:30-9:00 am	Giulio Di Toro *High-velocity friction experiments simulating seismic slip: An overview*
9:00-9:30 am	Nick Beeler *Semi-empirical constitutive relations for dynamic weakening based on high speed friction experiments*
9:30-9:45 am	Coffee Break
9:45-10:15 am	Joe Andrews *What can ground motion in the Chi-chi earthquake tell us about dynamic weakening?*
10:15-11:30 am	Session II Discussion, led by Nadia Lapusta

Moving Forward - What earthquake physics science priorities should SCEC 4 pursue?

11:30-12:00 pm	Open Discussion and Wrap-up of Day 2, Eric Dunham and Judi Chester

People Attending Workshop

Organizers
Eric Dunham
Judi Chester

Invited Speakers
David Goldsby
Vikas Prakash
Kevin Brown
Ze'ev Reches
Hiroko Kitajima
Alan Rempel
Emily Brodsky
Nick Beeler
Hiro Noda
Joe Andrews
Giulio Di Toro