Fault Properties and Slip Processes

C. Marone, Penn State

With help from: Demian Saffer, Derek Elsworth, Andre Niemeijer, Cristiano Collettini, Massimo Cocco, Paul Johnson, Sam Haines, Igor Faoro, Andy Rathbun, Jon Samuelson, Matt Ikari, Matt Knuth, Harold Tobin, Bryan Kaproth and others

Workshop for an EarthScope Science Plan

Building on Breakthroughs
Fault Properties and Slip Processes

C. Marone, Penn State

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Workshop for an EarthScope Science Plan

Building on Breakthroughs that the EarthScope Facility is poised to push forward
Fault Properties and Slip Processes

C. Marone, Penn State

1. PHYSICAL PROPERTIES OF AN ACTIVE, SEISMOGENIC FAULT

Frictional, hydrologic, poromechanical, elastic properties
2. THE SPECTRUM OF FAULT SLIP BEHAVIORS

Tremor, Slow Slip, Swarms, Low frequency earthquakes, Creep, Geodetic transients, Dynamic triggering, Postseismic slip

PBO, USArray: Flex & T-array
Fault Properties and Slip Processes

3. DATA DRIVES SCIENCE

Laboratory and theoretical work motivated by seismic, geodetic, and geologic observations
Fault Properties and Slip Processes

C. Marone, Penn State

3. DATA DRIVES SCIENCE

Laboratory and theoretical work motivated by seismic, geodetic, and geologic observations

Frictional, thermal, and pore-fluid processes in fault zones and the physics of slow and fast slip

Paul Segall, Stanford
Fault Zone Properties

Frictional, hydrologic, poromechanical, elastic properties

- Fault zone width. How wide is the zone of active shear?
- Physical properties of the fault zones
- Additional coring?

Cross section: Thayer & Arrowsmith (2005)
Core image: SAFOD Phase III Core Atlas
Shear Zone Micrograph: D. Moore
Fault Zone Properties

- Multiple Fault Strands, each of which is several meters wide
- Physical properties
- Interlab Comparison: www.geosc.psu.edu/~cjm/safod

Logging data: SAFOD data repository and Phase III Core Atlas
SAFOD Phase III Hole G, Run 2 Section 7

The '10,480' fault

Thayer & Arrowsmith (2005)

SAFOD Phase III Core Atlas
Fault Zone Properties

- Core Samples from Phase I & II drilling
- Cuttings from Phase III drilling
- Outcrop samples

Tembe et al., GRL 2006
Solum et al., GRL 2006
Morrow et al., GRL 2007
Moore and Rymer, Nature 2007

Carpenter, Marone, and Saffer, GRL, 2009
SAFOD and surrounding rock

Shear Stress/Normal Stress (μ)

Carpenter, Marone, and Saffer, GRL, 2009
SAFOD and surrounding rock

Carpenter, Marone, and Saffer, GRL, 2009
Surface-slip distribution along the 1857 Fort Tejon earthquake rupture trace derived from “B4” LiDAR data

Zielke and Arrowsmith, 2008
2. THE SPECTRUM OF FAULT SLIP BEHAVIORS

Tremor, Slow Slip, Swarms, Low frequency earthquakes, Creep, Geodetic transients, Dynamic triggering, Postseismic slip

Stick Slip vs. Stable Sliding
2. THE SPECTRUM OF FAULT SLIP BEHAVIORS

Sticky Slip vs. Stable Sliding

Tremor, Slow Slip, Swarms, Low frequency earthquakes, Creep, Geodetic transients, Dynamic triggering, Postseismic slip
Tectonic Tremor is modulated by Love wave shear stress (Denali) and Tides

Rubinstein et al., Science, 2008
Remote Triggering of Tectonic tremor

Remote triggering of tremor along the San Andreas Fault in central California

Peng et al., JGR 2009

Gomberg et al., Science 2008
The Salton Trough routinely has large swarms of earthquakes with time scales of a few days. The largest of these occurred in 1975, 1981, 2005, 2008, and 2009.

The Salton Trough also routinely has large (M ~5+) creep transients where large (10-20 km), shallow portions of strike slip faults fail over periods of a few days.

Sometimes the swarms and strain transients coincide, sometimes they do not.
Migration velocities of 0.1-1 km/hr characterize both small and large swarms in the Salton Trough and on EPR transform faults.

Lohman and McGuire, 2007
Roland and McGuire, 2009
Effects of acoustic waves on stick–slip friction

Laboratory Evidence for Complex Friction Behavior

- 5 MPa normal stress
- background shearing rate of 5 μm/sec
Stress drop in slow, quasi-stick-slip events scales with acoustic vibration amplitude

Johnson and Marone, ms. In prep, 2009
Typical stick-slip sequence, ‘interseismic’ dilation and compaction upon stress drop.
Typical Stick-slip, millisecond duration

Triggered, slow slip event, 5-10 second duration

Johnson and Marone, ms. In prep, 2009
Laboratory Evidence for Complex Friction Behavior

Long term friction: From stick–slip to stable sliding

Voisin, Renard, and Grasso, GRL 2007
Laboratory Evidence for Complex Friction Behavior

Long term friction: From stick-slip to stable sliding

Voisin, Renard, and Grasso, GRL 2007
Faults exhibit a wide spectrum of slip behaviors

EarthScope Facility:

- Fault Mechanics
- Frictional Rheology
- Earthquake Physics
- Earthquake Hazzard
3. DATA DRIVES SCIENCE
Laboratory and theoretical work motivated by seismic, geodetic, and geologic observations

Fault zone fabric and weakness
Role of surface coatings
Frictional strength of mixtures of strong & weak materials
Zuccale Fault is part of a system of low angle normal faults in central Italy.
Cutting Sculpting Samples for friction tests, in-situ shear geometry

C. Collettini, A. Niemeijer, C. Viti and C. Marone
Foliated fault rocks, sheared in their in-situ geometry, are much weaker than their powdered equivalents.

C. Collettini, A. Niemeijer, C. Viti and C. Marone
Foliated fault rocks are much weaker than their powdered equivalents!

Fabric is important, even under cataclastic conditions.

Foliated fault rocks are much weaker than their powdered equivalents.

Comparison of fault rock and powdered gouge

Microstructures
fine grained foliation
Interconnected phyllosilicate-rich network (talc, smectite) embedding isolated crystals of tremolite

Fault zone fabric and fault weakness,

Mixtures of strong and weak materials vs. layers

Niemeijer, Marone, and Elsworth, ms. in prep
Homogenous mixtures of talc & quartz are much stronger than layered synthetic fault zones.

Niemeijer, Marone, and Elsworth, ms. in prep. 2009
Homogenous mixtures of weak and strong materials are frictionally strong.

Layered synthetic fault zones.

Niemeijer, Marone, and Elsworth, ms. in prep. 2009
Frictional, thermal, and pore-fluid processes in fault zones and the physics of slow and fast slip

Paul Segall, Stanford

With a little help from my friends: A. Rubin, J.R. Rice, A.M. Bradley, S. Schmitt, T. Matsuzawa, E. Dunham
Dilatancy greatly expands slow slip range

Slip law

\[ a/b = 0.9 \]
\[ a/b = 0.8 \]

Rubin, 2008

With Dilatancy

Normalized Fault Width

[Graph showing normalized moment rate versus normalized fault width with data points for different conditions]
Building on Breakthroughs Fault Properties and Slip Processes

1. Physical properties of active, seismogenic faults
   Fault rocks can be very weak: Homogeneous mixtures of weak/strong materials are strong, but fabrics and clay coatings can make things extremely weak. Fault zones have finite width.

2. Spectrum of fault slip behaviors
   What is the source of this complexity? Friction laws, fluids, material properties, heterogeneity. Physics of slow and fast slip. What will we discover next?

3. Data drives science
   Laboratory and theoretical works feeding off EarthScope data stream. Multidisciplinary science. Frictional, thermal, and poromechanical response.
Thanks!

Penn State Rock and Sediment Mechanics Lab