High-velocity shear experiments with possible implications to earthquake physics

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2015, Application of Mechanics to Geophysics

Earthquakes are governed by a complex of interrelated, transient processes along active fault-zones at (almost) inaccessible depth

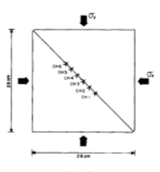
The experimental approach:
Shearing faults at conditions relevant to earthquakes:

1. Characterization of earthquake processes
2. Testing theoretical models/concepts
3. Measuring dynamic strength of active faults

Experimental design

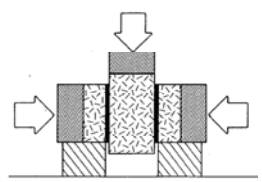
Stick-slip (e.g., Brace & Byerlee, Ohnaka):

1. Spontaneous slip
2. Tiny slip distance (< 100 micron)
3. Modest slip velocity (< 0.1 m/s)
4. High accelerations (a few km/s^2)
5. Rupture propagation monitored



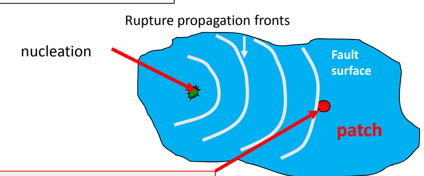
Direct-shear (e.g., Dieterich, Marone):

1. Controlled, stepping slip velocity
2. Small slip distance (~ 1 mm)
3. Low slip velocity (0.01-10 micron/s)
4. Rate-and-state friction law



Limitations
DiToro et al. (Nature, 2011) stated:
"Given the low slip rates [and short distances], these experiments lack a primary aspect of natural seismic slip: a large mechanical work-rate … [that] can be so large as to grind and mill the rock…., trigger mechanically and thermally activated chemical reactions, and, eventually, melt the rock."

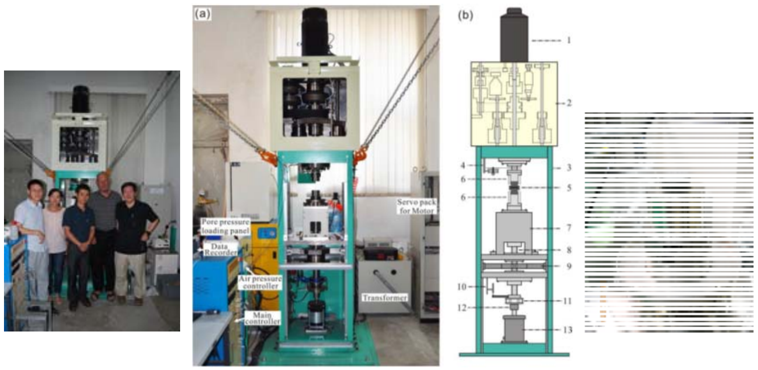
Thus, experiments of low velocity/short distance provide insight to nucleation processes, but cannot simulate the high velocity/high energy slip of a fault patch during its short rise time



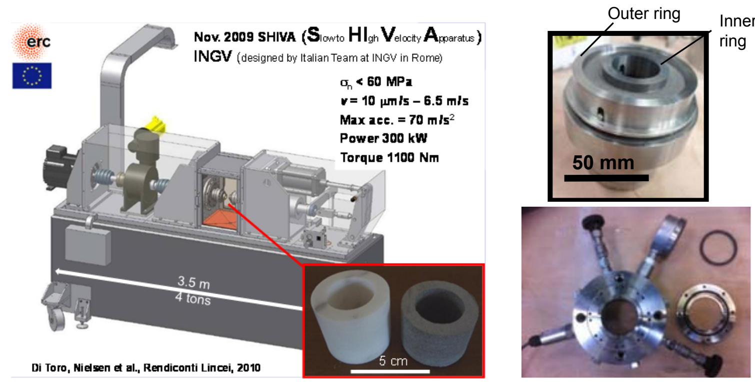
High-velocity experiments attempt to simulate earthquake conditions

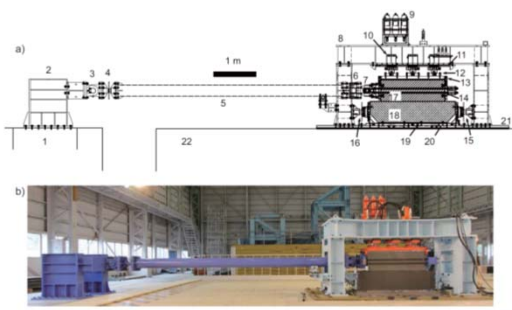
1. Slip velocity of ~1 m/s
2. Slip of a few meters
3. Loading by a propagating rupture front
4. Normal stress of tens to hundreds MPa
5. Gouge powder
6. Elevated fluid pressure
7. Elevated ambient temperature

Simultaneous application of these conditions requires a "dream apparatus" which does not exist yet…

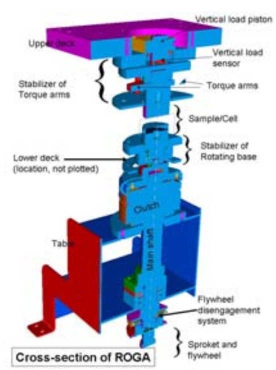


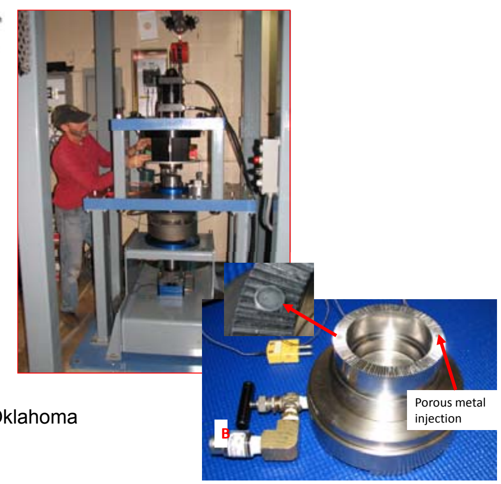
LHVR-Institute of Geology, China Earthquake Administration, Beijing (Shimamoto et al., 2014)





Biaxial friction experiments using a large shaking table, NIED, Japan (Fukuyama et al., 2014)





ROGA at the University of Oklahoma (Reches & Lockner, 2010)

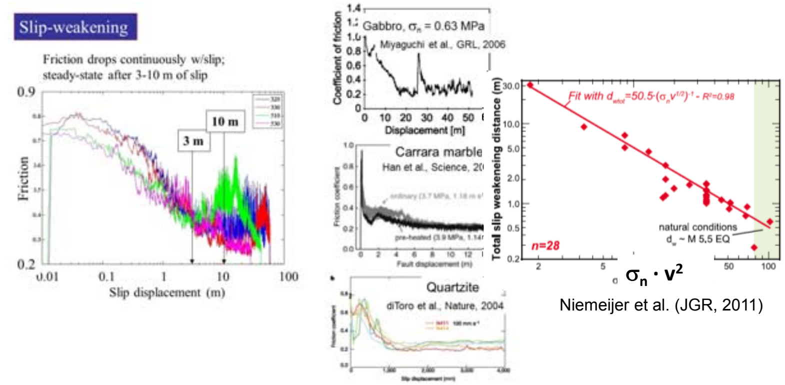
High-velocity shear experiments results

Macroscopic observations:
1. Dynamic weakening (distance, velocity, acceleration)
2. Dynamic strengthening (lithology dependence)

Microscopic observations:
1. Pulverization into sub-micron particles forms a highly reactive gouge powder (thermally, mechanically and chemically)
2. Slip localization in sub-mm zones intensifies the deformation

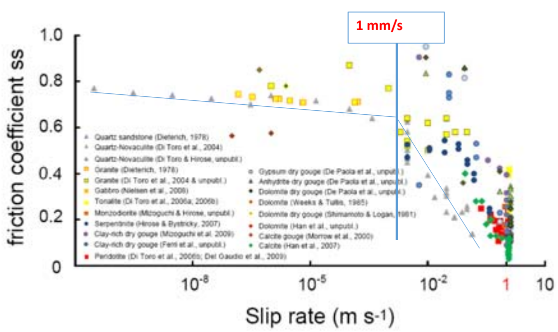
Interpretations and model testing:
1. Mechanisms of dynamic weakening
   a. Thermal activation
   (melting, flash heating, thermal pressurization, phase transform, superplasticity)
   a. Lubrication (silica gel, powder, rolling)
   b. Composition dependence (shale, talc, carbonates, granite vs gabbro)
   c. Geometry (smoothing, wear, localization)
2. Loading style (steady-state vs impact, velocity control, power control)

Slip weakening, thermally activated

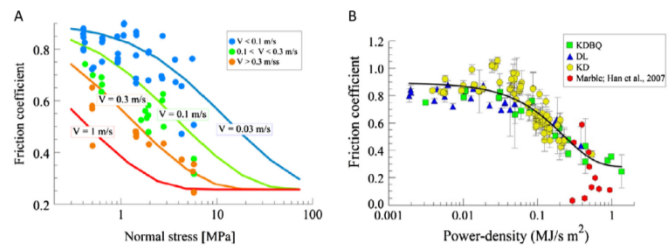


Niemeijer et al. (JGR, 2011)

Velocity weakening, thermally activated



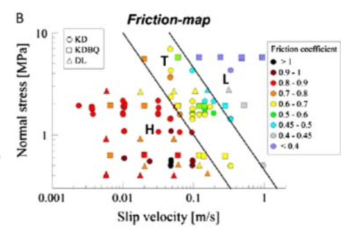
Di Toro et al. (Nature, 2011)



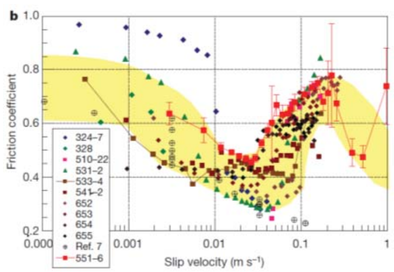
1. Friction is better viewed vs power density=shear stress x velocity

2. Or as a friction map with axes of slip velocity and normal stress

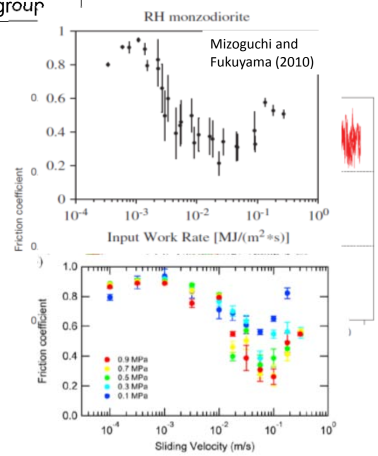
Boneh et al. (EPSL, 2013)



Non-monotonic strength evolution:
Thermally activated strengthening, granite group



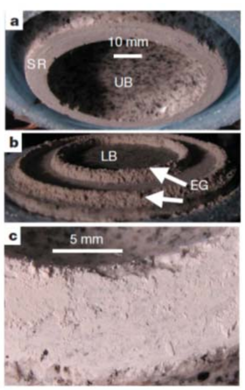
Reches and Lockner (Nature, 2010)



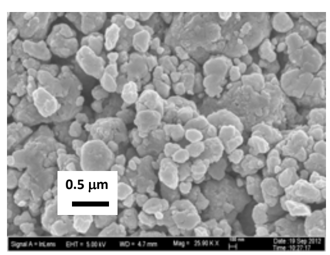
Kuwano and Hatano (2011)

Fault-zone ultra-microscopic structure

Pulverization into ultrafine gouge powder during experimental faults shear



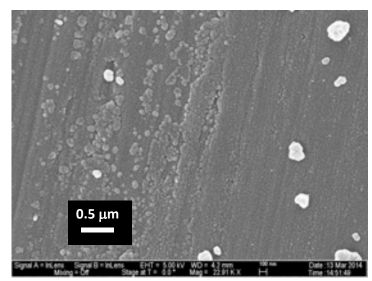
Niemeijer et al. (JGR, 2011)

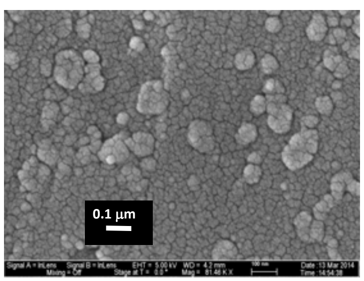


Reches and Lockner (Nature, 2010)

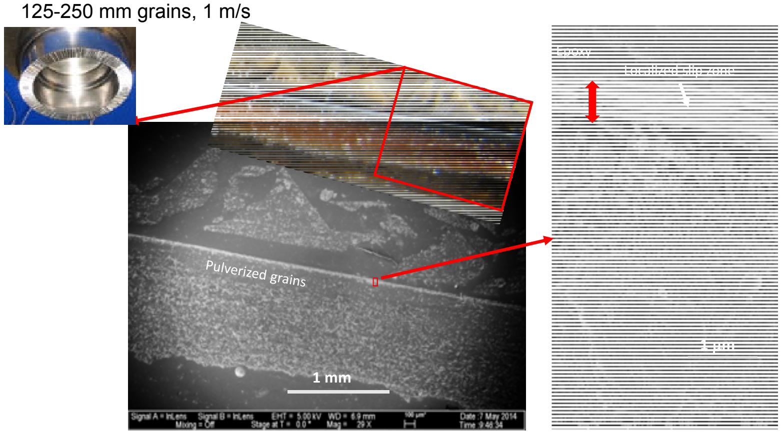
Pulverization and localization.
Shear of Kasota dolomite sand of 125-250 µm grains, in confined cell, v = 1 m/s

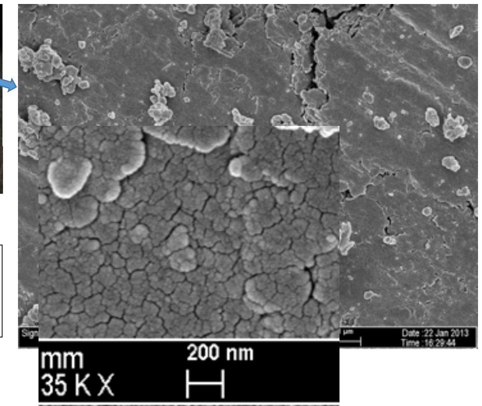
(Harry Green talk)





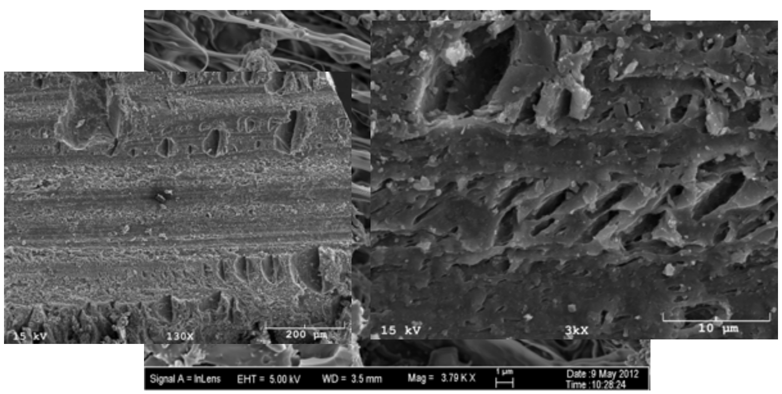
Pulverization and localization
Kasota dolomite, granular
125-250 mm grains, 1 m/s



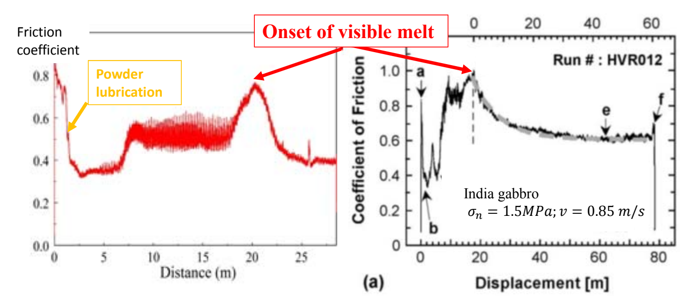


Slip localization along highly smooth surface within a 3 mm thick SAFOD gouge (SDZ) sheared at
v = 1 m/s, σ_n = 2.9 MPa

Localized melt in Sierra White Granite
$\sigma_n = 1.2\ MPa; v = 0.045\ m/s$



Melting in steps:
1. **weakening** (gouge formation);
2. **Strengthening** (local melt);
3. **Weakening** (full scale melt)

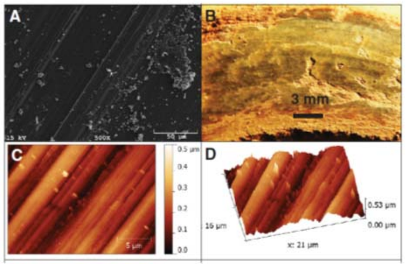


Chen et al.,(poster).

Hirose and Shimamoto (JGR, 2003)

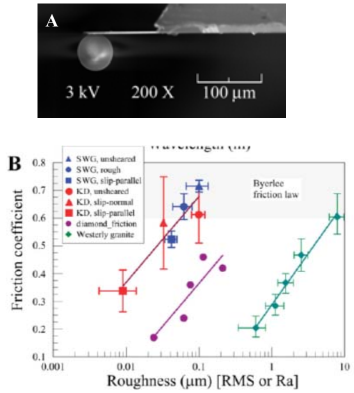
Direct, sub-microscopic observations of dynamic weakening mechanisms

Weakening due to smooth surfaces of localized slip

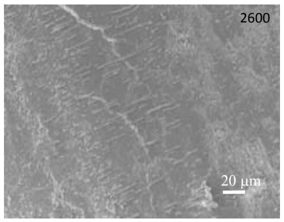


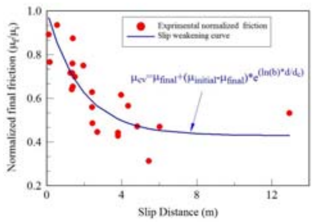
Using AFM to measure friction at sub-micron scale as function of surface roughness

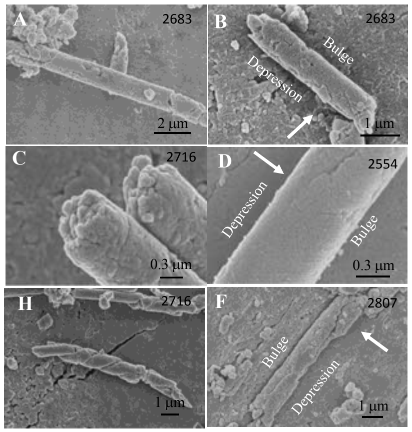
Chen et al. (Geology, 2013)



Weakening by <u>rolling-friction</u> in powder zones



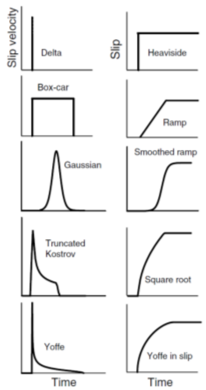




Chen et al., (poster)

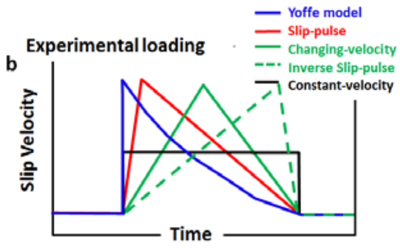
Loading modes of a fault patch

Conceptual views of slip velocity during earthquake rupture (Tinti et al., GRL 2005)

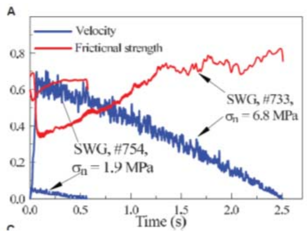


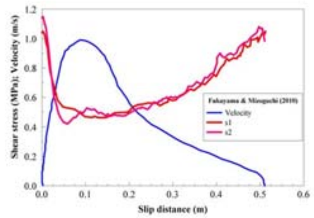
Loading modes

- Constant-velocity
- Slip-pulse (impact)
- Changing-velocity
- Inverse Slip-pulse

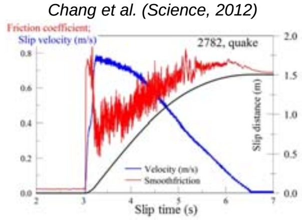


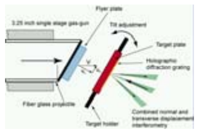
Liao et al. (EPSL, 2014)

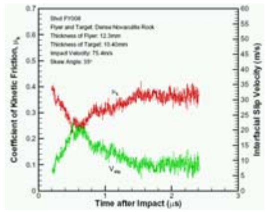




Chang et al. (Science, 2012) *(Fukuyama & Mizoguchi, 2010)*



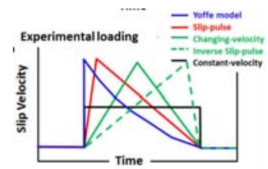


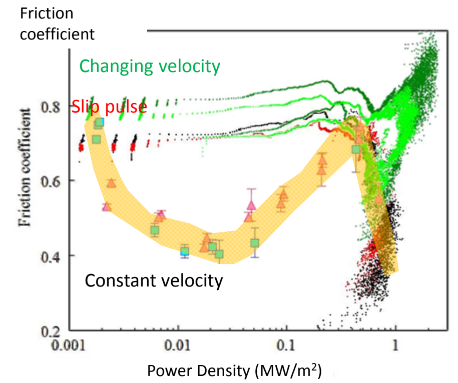


Vicar Prakash lab
(courtesy of Terry Tullis)

Liao et al. (EPSL, 2014)

Frictional strength depends on the loading modes



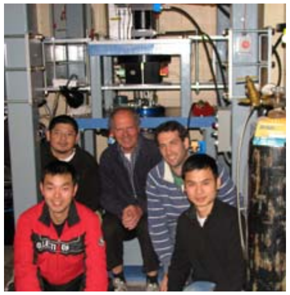


What did high-velocity shear experiments reveal about earthquakes?
Macroscopic observations
Microscopic observations
Interpretations and model testing

Future research

1. Testing at real in-situ conditions (a dream apparatus)
2. Explore for direct, physical evidence of conceptual weakening mechanisms
3. Investigate the effects of loading modes, and move away from velocity control
4. Develop comprehensive constitutive relations for fault frictional strength that will span the full range of velocity/acceleration/normal stress
5. Apply above experimental results to reduce seismic hazard
   (e.g., better links to seismology, fault stability, rupture simulation)

Thanks



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