Earthquake fault dynamics: Insights from laboratory experiments

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This research is funded by the European Research Council
Acknowledgements

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G. Pennacchioni (2),
F. Di Felice (1),
G. Romeo (1),
R. Han (7),
T. Hirose (7),
K. Mizoguchi (7),
M. Cocco (1),
T. Shimamoto (3),
...

This research is funded by the European Research Council
Earthquakes are caused by fracture and frictional slip on faults. Friction is a key parameter in understanding the physics seismic source. Let's investigate friction under Earth crust conditions.

Fault surface in dolomite, Southern Alps, Italy
Arrest or propagation of dynamic rupture

Friction law

Energy balance: dissipation, heat, seismic radiation

Rupture velocity

Slip velocity, rise time
Friction and energy

- **steady-state**
- **peak**
- **recovery**
- **decay**

shear stress (friction)

\[ y \]

\[ D/2 \]

slip
No direct access to the “earthquake engine”...

Let's try to re-create it in the lab?
Synopsis

- Friction controls earthquake physics
- No direct access to the “earthquake engine”
- Earthquake simulation in the lab: friction machines
- Examples of experiments and typical results
- Lubrication processes and rock types
- Extrapolating the results: faults are weak during earthquakes
- Conclusions and future research
Experimental machines

LOW STRAIN (old-style shear or rotary)
- 
HVRF (High-velocity, Rotary Shear machines)
- 
SHIVA (Slow to High Velocity Apparatus)

Experimental machines are NOT designed to predict earthquakes!!
They help our understanding of earthquake physics and thus improve modeling and risk assessment.
Shear stress, GPa

Normal stress, GPa

Low friction during EQs?

"Byerlee's law"

µ = τ / σ

Byerlee, PAGEOPH, 1978

MAXIMUM FRICTION

µ = τ / σ

τ = 0.5 GPa
\[ \mu = \mu_0 + A \ln \left( \frac{V}{V^*} + 1 \right) + B \ln \left( \frac{\Theta}{\Theta^*} + 1 \right), \]

\[ \frac{d\Theta}{ds} = \frac{1}{V} - \frac{\Theta}{D_c}, \]

\[ \theta(s) \text{ state variable} \]

\[ V \text{ slip rate - s slip} \]

\[ D_c \text{ critical slip } 10^{-6} - 10^{-4} \text{ m} \]

\[ \mu \text{ friction coeff.} \]

\[ A \ & B \text{ constants} \]

friction drop is small
velocity dependance is small
stress and velocity cover only part of seismic faulting conditions

[from Marone, 1998]
The principle of ROTARY machines

Rotating shaft (torque act.)

Axial shaft (normal load act.)

PAIR OF CYLINDRICAL SAMPLES
Experimental conditions

Slip velocity (m/s)

Normal Stress (MPa)

“Traditional” machines

SHIVA

still out of reach...
Experimental conditions and earthquake conditions

- Shallow earthquakes
- "Typical" crustal earthquakes
- Deep earthquakes

Slip velocity (m/s) vs. Normal Stress (MPa)
Machine “1”, Kyoto Univ., Japan, ca. 1990 (T. Shimamoto)
\[ \sigma_n < 20 \text{ MPa} \]
\[ v = 0.1 \, \mu \text{m/s} - 10 \, \text{m/s} \]
\[ d = \text{infinite} \]
SHIVA, Italy, Sept 2009
(designed by an Italian Team at INGV)

\[ \sigma_n < 50 \text{ MPa} \]
\[ v = 1 \mu\text{m/s} - 9 \text{ m/s} \]
\[ d = \text{infinite} \]

Seismic accelerations
SERVO-CONTROL 200kW drive
Video examples of the experimental dynamics
Dry, slicatic rocks

--> melting

Natural faults

Lab
What do we measure?

FRICIONAL resistance of the sample while it is sliding
SHORTENING of the sample under the effect of frictional wear
GAS EMISSIONS during the sliding
TEMPERATURES in or around the sample close to the slip surface
SLIDING VELOCITY is retrieved from rotative motion and sample radius
Example:

**s051 - rings of gabbro at 3 m/s and 20 MPa**

\[
\text{Acceleration} = \text{deceleration} = 6 \text{ m/s}^2
\]
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High velocity friction; lubrication

Large slip & slip-rate
Intermediate normal stress
Considerable WEAKENING
Lubrication effect

Byerlee friction

H-V friction

theory

experiments

Nielsen et al., 2008
After Di Toro et al., 2005
The key is high work rate generating heat density

Heat density

Temperature increase

Specific heat of water, evaporation, fluid pressurization

Latent heat of chemical processes and phase transitions (decarbonation, gelification, dehydration, serpentinization, poorly known tribolchemical processes...)

Dynamic fault slip, heat and friction:

- Large, fast slip means concentrated heat
- Heat triggers a variety of weakening mechanisms
- Under favourable conditions melt is produced
In its most straightforward manifestation, elevated heat density induces temperature rise and eventually yields to melting...

But not always!

( maybe even seldom )
Observed processes in HV rock friction:

- Silica gel lubrication (quartz rocks)
- Thermal decomposition and nanopowders (limestones)
- Thermal decomposition and pressurization (dolostones)
- Clay-gouge weakening, dehydration and press. (clay-gouges)
- Flash heating (small slip amounts)
- Melt lubrication (all silicate built rocks)
A very incomplete classification of rock types and frictional processes

<table>
<thead>
<tr>
<th></th>
<th>Cohesive</th>
<th>Non-cohesive &amp; clays</th>
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| **Silicatic** | Melting
Silica gel lubrication
Flash heating
Dehydration |                      |
| **Carbonatic** | Decarbonation
Plastic yielding
Dehydration
Flash heating
Nanopowder lub. | Flash heating
Decarbonation
Nanopowder lub. |

*For most process and rock types lubrication is observed at high velocity*
Not much weakening..
Significant weakening around 0.1 m/s

Different rock types (carbonates, silicates, ...)

Di Toro et al., in preparation

Seismic slip rates

Di Toro et al., in preparation
Work rate or power density
Cohesive Rocks: desaggregation in the results for various compositions suggest different thermal activation mechanisms.
with gouge - Brantut et al., 2008

- Fault zone rich in kaolinite
- Dehydration at ~1 m/s, ~1 MPa
Clay-clast aggregates (FE-SEM image)  
(e.g., Bouteraud et al., 2008)
MELTING: glass and survivor clasts (SEM image)

- Glass
- Vesicles
- Pyroxene with embayment
- Feldspar clast
- Glass

Scale: 20 µm
Friction controls earthquake physics

No direct access to the “earthquake engine”

Earthquake simulation in the lab: friction machines

Examples of experiments and typical results

Lubrication processes and rock types

Extrapolating the results: faults are weak during earthquakes

Conclusions and future research
Extrapolation

How to upscale lab to EQ conditions?
Larger $\sigma_n$, $V$, accelerations
Larger size than sample
Complex slip time-history
Complex geometry
Different petrology/chemistry
Different fabric
Extrapolation
SEISMICITY, statistics of a fault population, correlations, criticality....: the process from a global point of view – YESTERDAYS TOPIC

LAB:
small portion of a fault - scale 2 - 5 cm

SISMO:
“global” rheology of the whole fault
Conclusions

- No direct access to the “earthquake engine”
- Earthquake simulation in the lab: friction machines
- High POWER (high slip vel. and normal load combined) yields lubrication
- Various lubrication processes depending on rock types
- Extrapolating the results: power laws and geometry problems
- We barely start to measure and understand...