Energy budget of laboratory earthquakes

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Energy partitioning during EQs
Outline

• EQs in the lab.

• Heat generation – How hot does it get?
  (Aubry et al. GRL 2018)

• With water, pressure matters
  (Acosta et al., Nat. Comm. 2018)

• HF radiation, where the waves come from?
  (Marty et al. GRL 2019)
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Stick-Slip as a Mechanism for Earthquakes

W. F. Brace; J. D. Byerlee


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Fig. 1 (left). Force-displacement curve for the axial direction in a cylindrical sample of Westerly granite. Small diagram above the curve shows schematically how stress was applied to the sample. The sample fractured at point FR forming the fault which is shown as a dotted line in the small diagram. The exact shape of the curves during a stress drop (such as ab) is not known and is shown dotted. P is confining pressure. Fig. 2 (right). Same as Fig. 1 except that the sample contained a sawcut with finely ground surfaces as shown schematically (small figure) by a heavy line.
PREFACE:
A SHORT GEOPHYSICAL HISTORY OF WESTERLY GRANITE

C. H. Scholz

A number of rocks have achieved a kind of fame in geophysical circles because of their frequent

(...) 

It is ironic that many who use the well-worn quip "geophysicists think that the crust is made of Westerly granite" are probably unaware that Westerly granite was once designated by the U.S. Geological Survey and the Carnegie Institution as 'G-1', the type rock of the continental crust [Fairbairn et al., 1951].
The soft (Earthquake) machine...
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Measuring Heat

Frictional heat produced inferred from

- **45 MPa**
- **90 MPa**
- **180 MPa**

**Graphs showing temperature increase with time**

- **45 MPa**
  - Thermocouple data
  - Polynomial curve fitting
  - Best fit - thermocouple location: 5.5 mm
  - $Q_{th} = 5080 \text{ J/m}^2$

- **90 MPa**
  - $Q_{th} = 5882 \text{ J/m}^2$

- **180 MPa**
  - $Q_{th} = 37 \text{ kJ/m}^2$
Heating efficiency

When looking at heat, rupture becomes more efficient with increasing sliding

\[ R = \frac{Q_{th}}{E_{tot}} \]
Frictional heating is heterogeneous

Temperature maps of the interface during frictional sliding

Aubry et al. GRL 2018
Transition from asperity to bulk surface melting

Microstructural evidences of melting

45 MPa

90 MPa

180 MPa

Locally molten

Degree of melting

Fully molten

Aubry et al. GRL 2018
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Stick-slips and stress drops

the fluid version

Acosta et al. Ncomms, 2018
Stick-slips and stress drops

the fluid version

Acosta et al. Ncomms, 2018
Stick-slips and stress drops

_the fluid version_

Acosta et al. Ncomms, 2018
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Rupture velocity and HF radiation

Passelègue et al., Science 2013
Rupture velocity and HF radiation

- HF radiation are enhanced with both $P_c$ and $V_r$.
- Supershear ruptures are highly enhanced in HF radiation compared to sub-Rayleigh ruptures: Mach-wave signature

_Marty et al., GRL 2019_
HF radiation
Back projection of the HF content locates at rupture front

Marty et al., GRL 2019
Energy budget summary

Mw [-4, -3] earthquakes, AT THE LABORATORY SCALE IN THE RIGHT σ-P-T CONDITIONS

Transition from multiple asperities (low seismic efficiency, low rupture speed, small stress drop & low HF radiation) to a single asperity (high seismic efficiency, high stress drop, high rupture speed, & high HF radiation).
Conclusions

• During sliding, heat generation is limited to asperities. Flash melting on asperities (sliding velocities >m/s) drives the discrepancy between static and dynamic stress drop and generate high velocity ruptures.

• Flash melting is inhibited at large pore fluid pressure (thermodynamics of water matters).

• Faster (Supershear) ruptures are accompanied by HF radiation, which originates at (or close to) rupture front (dynamic off-fault damage triggering and/or breakdown zone).

Thanks for your invitation!
Thanks for your attention!

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@ EPFL: **François Passelègue**
@ IPGP: Frédéric Girault, Javier Escartin
@ Durham U.: Stefan Nielsen
Measuring Heat

Heat diffusion model - Thermocouple data inversion

- Constant heat rate during stick slip duration $t_{ss} = 20 \, \mu s$
- Heat produced on the fault and diffused within the sample

\[ \rho C_p h \frac{dT_{th}}{dt} = \dot{Q} + K \frac{d^2 T_{th}}{dy^2} \]

\[ h = 2\sqrt{\pi K t} \]

\[ Q_{th} = 2\dot{Q} t_{ss} \sqrt{\pi K t_{ss}} \text{ (J/m$^2$)} \]

Thermal diffusivity $K = 1.2 \times 10^{-6} \text{ m}^2/\text{s}$; Lockner et al., 2015.
Stick slip duration $t_{ss} = 20 \, \mu s$; Passelègue et al., 2016.

Aubry et al. GRL 2018
Heat dissipation...

Mapping the interface by the help of amorphous carbon

Calibration made with specific coated samples (other than these for experiments) heated in an oven during 10 s.

- The more advanced the process of carbonization and the higher the ratio $H_d/H_g$.
- We are aware of kinetic problem (10 s heating) compared to the duration of stick-slip (20 μs).
Heating efficiency

Rupture becomes more efficient with increasing sliding because heat is bounded by melting (or phase change) temperature and heat diffusion.
Static vs. dynamic stress drops

Passelègue et al. JGR 2016
Comparison with synthetics

2D steady state slip pulse model
(Dunham and Archuleta, 2005)

Sub-Rayleigh

\( \frac{R}{L} = 0.22 \quad \frac{V_r}{C_s} = 0.75 \)

Passelegue et al, 2013