Caltech

Ge 193: Fault dynamics: from frictional experiments to seismic cycle simulations

Calendar

Term-Day-Time: Winter Friday 9:00 – 11:25 am.
Location: 251 Arms
Instructor: Prof. Sylvain Barbot (sbarbot@usc.edu).
Office Hours: Upon appointment.

Course Description

The source characteristics, rupture style, and recurrence patterns of earthquakes are shaped by the mechanical properties of rocks embedded in active faults zones. The frictional behavior of rocks is complicated, nonlinear, and varies abruptly with slip-rate, effective normal stress, pore-fluid pressure, and temperature. In addition, the frictional response of rocks maintains a memory of previous conditions. Understanding this complex mechanical behavior in the context of major faults in the continental or oceanic crusts, or along megathrusts at subduction zones, is key to better understanding the seismic cycle. In this class, we will review the historical development of rock friction, encompassing static and kinematic friction, slip-rate- and state-dependent friction, lubrication and melting and high slip speed, or effects that are known to modulate fault strength. We will converge toward a physical understand of fault friction that allows interpolation and extrapolation of laboratory data. We will also review methods to simulate seismic cycles numerically, focusing on the boundary integral method with its natural and spectral variants. The class provides a mathematical treatment of friction and reviews the key laboratory measurements that underpin physical models.

Learning Objectives

The class will provide a historical perspective on the development of friction and evolutions laws. The class will highlight key laboratory experiments in the last 60 years that have shaped our understanding of friction. We will also discuss the frontier of current knowledge and review observations that have no mechanical explanation yet. The class requires reading of milestone publications. By the end of the class, the student will have a wide perspective on rheology of rocks in the brittle field, with knowledge of remaining unknowns and possible fruitful avenues of research.

Prerequisites:

Knowledge of calculus (partial differential equations and integration) will be useful. Interest and basic knowledge of earthquake science is recommended.

Communication

Ask for appointment with class instructor via email. All lectures slides can be provided on demand.

Lectures

From Friday January 10th, 2025 to Friday, March 7th, 2025, there will be 9 lectures.

Classroom norms

Student participation during lecture is encouraged. Always feel free to ask questions and clarifications. The comments that you make (asking for clarification, sharing critiques, expanding on a point) should reflect that you have paid attention to the instructor comments.

Lecture outline

- Introduction to the phenomenon of friction and faulting
- Byerlee's (1978) law, adhesion theory (Bowden & Tabor 1950), aging (Dieterich & Kilgore 1994)
- Slip-rate and state-dependent friction (Dieterich 1972, 1979; Ruina 1983)
- Governing equations of fault dynamics and dimensional analysis
- Effects of varying normal stress (Linker & Dieterich 1992; Hong & Marone 2005)
- Normal stress dependence of the friction coefficient (Barton 1973; Byerlee 1978; Gonzalez et al. 2024)
- Direct and evolutionary temperature effects (Chester 1994)
- Review of laboratory experiments in hydrothermal conditions (e.g., Blanpied et al. 1995)
- Strong weakening by lubrication (Di Toro et al. 2011), thermal pressurization (Noda & Lapusta 2013)
- Thermal decomposition of carbonates (Sulem & Famin 2009)
- Thermally activated creep theory (Baumberger 1997, Sleep 1997, Baumberger et al. 1999, Nakatani 2001, Rice et al. 2001)
- Review of thermal effects in friction experiments (e.g., Sawai et al. 2016; Liu & He 2020)
- Constitutive behavior of rocks in isothermal conditions (Barbot 2019a; Barbot 2024a)
- Constitutive behavior of rocks in non-isothermal conditions (Barbot 2022; Barbot 2023)
- Evolution laws in non-isothermal, non-isobaric conditions (Barbot 2024b)
- Relationship between physical and empirical friction and evolution laws
- Plastic deformation fault gouge (pressure-solution creep, subcritical crack growth) as the origin of healing
- Thermobaric activation of the brittle-ductile transition (Zhang & He 2023)
- Kinematics of lubrication with absolute rate theory
- Review of rate of chemical reaction, melting/freezing as isochemical reaction
- Phase equilibrium of common rocks (using software PerpleX)
- Governing equations of fault dynamics in three dimensions (Barbot 2019b)
- Dimensional analysis and the Dieterich-Ruina-Rice number (Barbot 2019b)
- Emergence of period-n cycles and chaos in fault dynamics (Barbot 2019b)
- Numerical methods for seismic cycle modeling: Runge-Kutta quadrature
- Numerical methods for seismic cycle modeling: boundary integral method
- Numerical methods for seismic cycle modeling: spectral boundary integral method
- Workshop on open-source software Motorcycle (Barbot 2021; Barbot 2023c)
- Workshop on open-source software Unicycle (Barbot 2018; Barbot 2019)

Lecture content is subject to change without warning.

References

Barbot, S., 2019. Modulation of fault strength during the seismic cycle by grain-size evolution around contact junctions. *Tectonophysics*, *765*, pp.129-145.

Barbot, S., 2022. A rate-, state-, and temperature-dependent friction law with competing healing mechanisms. *Journal of Geophysical Research: Solid Earth*, *127*(11), p.e2022JB025106.

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Blanpied, M.L., Lockner, D.A. and Byerlee, J.D., 1995. Frictional slip of granite at hydrothermal conditions. *Journal of Geophysical Research: Solid Earth*, *100*(B7), pp.13045-13064.

Byerlee, J., 1978. Friction of rocks. *Rock friction and earthquake prediction*, pp.615-626.

Chester, F.M., 1994. Effects of temperature on friction: Constitutive equations and experiments with quartz gouge. *Journal of Geophysical Research: Solid Earth*, *99*(B4), pp.7247-7261.

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Di Toro, G., Han, R., Hirose, T., De Paola, N., Nielsen, S., Mizoguchi, K., Ferri, F., Cocco, M. and Shimamoto, T., 2011. Fault lubrication during earthquakes. *Nature*, *471*(7339), pp.494-498.

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Nagata, K., Nakatani, M. and Yoshida, S., 2012. A revised rate-and state-dependent friction law obtained by constraining constitutive and evolution laws separately with laboratory data. *Journal of Geophysical Research: Solid Earth*, *117*(B2).

Noda, H. and Lapusta, N., 2013. Stable creeping fault segments can become destructive as a result of dynamic weakening. *Nature*, *493*(7433), pp.518-521.

Ruina, A., 1983. Slip instability and state variable friction laws. *Journal of Geophysical Research: Solid Earth*, *88*(B12), pp.10359-10370.

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Sulem, J. and Famin, V., 2009. Thermal decomposition of carbonates in fault zones: Slip-weakening and temperature-limiting effects. *Journal of Geophysical Research: Solid Earth*, *114*(B3).

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