USC University of Southern California

GEOL 534L: Mechanics of Lithospheric Deformation (3.0 units)

Calendar

Term-Day-Time: Spring Wed 9:00 – 11:25 am.
Location: ZHS 130 (Zumberge Hall).
Instructor: Prof. Sylvain Barbot (sbarbot@usc.edu).
Office Hours: Upon appointment, ZHS 105.

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

Regular communication will be conducted through Brightspace (https://brightspace.usc.edu). Ask for appointment with class instructor via email. All lectures slides will be posted on Brightspace well before the class.

Lectures

From Wednesday January 15th, 2025 to Wesnesday, April 30th, 2025, there will be 48 lectures. The lectures are 145 minute-long on Wednesdays in ZHS 130 (Zumberge Hall). All lectures slides will be posted on Brightspace before the class.

Academic Accommodations

Any student requesting academic accommodations based on a disability is required to register with Disability Services and Programs (DSP) each semester. A letter of verification for approved accommodations can be obtained from DSP. Please be sure the letter is delivered to me as early in the semester as possible. DSP can be reached at ability@usc.edu and is open 8:30am-5:00pm Monday through Friday. The phone number for DSP is 213-740-0776.

Academic integrity

University policies on academic dishonesty are printed in SCAMPUS. Because cheating negatively affects everyone in the class, we will follow USC guidelines and report all academic misconduct. USC policies on cheating are strict and the minimum punishment is failure in the class and possible expulsion. Please don't make us have to turn you in! And remember that even the appearance of impropriety can be a concern.
More information at https://policy.usc.edu/scampus/.

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.

Classes end on Friday, May 2nd, 2025.

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.

Barbot, S., 2023. Constitutive behavior of rocks during the seismic cycle. *AGU Advances*, *4*(5), p.e2023AV000972.

Barbot, S., 2024. Transient and steady-state friction in non-isobaric conditions. *Geochemistry, Geophysics, Geosystems*, *25*(2), p.e2023GC011279.

Barbot, S., 2024. Does the direct effect of friction increase continuously with absolute temperature?. *Proceedings of the National Academy of Sciences*, *121*(42), p.e2405111121.

Baumberger, T., Berthoud, P. and Caroli, C., 1999. Physical analysis of the state-and rate-dependent friction law. II. Dynamic friction. *Physical Review B*, *60*(6), p.3928.

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.

Dieterich, J.H., 1972. Time-dependent friction as a possible mechanism for aftershocks. *Journal of Geophysical Research*, *77*(20), pp.3771-3781.

Dieterich, J.H. and Linker, M.F., 1992. Fault stability under conditions of variable normal stress. *Geophysical Research Letters*, *19*(16), pp.1691-1694.

Dieterich, J.H., 1972. Time-dependent friction as a possible mechanism for aftershocks. *Journal of Geophysical Research*, *77*(20), pp.3771-3781.

Dieterich, J.H. and Kilgore, B.D., 1994. Direct observation of frictional contacts: New insights for state-dependent properties. *Pure and applied geophysics*, *143*, pp.283-302.

Dieterich, J.H. and Kilgore, B.D., 1996. Imaging surface contacts: power law contact distributions and contact stresses in quartz, calcite, glass and acrylic plastic. *Tectonophysics*, *256*(1-4), pp.219-239.

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.

Linker, M.F. and Dieterich, J.H., 1992. Effects of variable normal stress on rock friction: Observations and constitutive equations. *Journal of Geophysical Research: Solid Earth*, *97*(B4), pp.4923-4940.

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.

Shreedharan, S., Rivière, J., Bhattacharya, P. and Marone, C., 2019. Frictional state evolution during normal stress perturbations probed with ultrasonic waves. *Journal of Geophysical Research: Solid Earth*, *124*(6), pp.5469-5491.

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).

Wang, B. and Barbot, S., 2023. Pulse-like ruptures, seismic swarms, and tremorgenic slow-slip events with thermally activated friction. *Earth and Planetary Science Letters*, *603*, p.117983.

Yamashita, F., Fukuyama, E. and Mizoguchi, K., 2014. Probing the slip-weakening mechanism of earthquakes with electrical conductivity: Rapid transition from asperity contact to gouge comminution. *Geophysical Research Letters*, *41*(2), pp.341-347.

Statement on Academic Conduct and Support Systems

Academic Conduct:

Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in *SCampus* in Part B, Section 11, "Behavior Violating University Standards" policy.usc.edu/scampus-part-b. Other forms of academic dishonesty are equally unacceptable. See additional information in *SCampus* and university policies on scientific misconduct, http://policy.usc.edu/scientific-misconduct.

Support Systems:

Student Counseling Services (SCS) – (213) 740-7711 – 24/7 on call
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention. engemannshc.usc.edu/counseling

National Suicide Prevention Lifeline – 1 (800) 273-8255
Provides free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week. www.suicidepreventionlifeline.org

Relationship and Sexual Violence Prevention Services (RSVP) – (213) 740-4900 – 24/7 on call
Free and confidential therapy services, workshops, and training for situations related to gender-based harm. engemannshc.usc.edu/rsvp

Sexual Assault Resource Center
For more information about how to get help or help a survivor, rights, reporting options, and additional resources, visit the website: sarc.usc.edu

Office of Equity and Diversity (OED)/Title IX Compliance – (213) 740-5086
Works with faculty, staff, visitors, applicants, and students around issues of protected class. equity.usc.edu

Bias Assessment Response and Support
Incidents of bias, hate crimes and microaggressions need to be reported allowing for appropriate investigation and response. studentaffairs.usc.edu/bias-assessment-response-support

The Office of Disability Services and Programs
Provides certification for students with disabilities and helps arrange relevant accommodations. dsp.usc.edu

Student Support and Advocacy – (213) 821-4710
Assists students and families in resolving complex issues adversely affecting their success as a student EX: personal, financial, and academic. studentaffairs.usc.edu/ssa

Diversity at USC
Information on events, programs and training, the Diversity Task Force (including representatives for each school), chronology, participation, and various resources for students. diversity.usc.edu

USC Emergency Information
Provides safety and other updates, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible. emergency.usc.edu

USC Department of Public Safety – UPC: (213) 740-4321 – HSC: (323) 442-1000 – 24-hour emergency or to report a crime.
Provides overall safety to USC community. dps.usc.edu