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Materials Physics of Faults in Rapid Shear and Consequences for Earthquake Dynamics (Louis Néel Medal Lecture)

J.R. Rice

Department of Earth and Planetary Sciences, and School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138 USA, rice@seas.harvard.edu

Field observations of maturely slipped faults show that despite a generally broad zone of damage by cracking and granulation, large shear deformation, and therefore heat generation, in individual earthquakes takes place with extreme localization to a zone of order 1 mm or less width within a finely granulated fault core. Relevant fault weakening processes during large crustal events are therefore likely to be thermally influenced, although a constraint to be met, from scarcity of pseudotachylite, is that melting within fault zones seems relatively rare, at least in the up per crust. Further, given the porosit y of damage zones, it seems reasonable to assume in-situ water presence. The lecture reviews current understanding of the materials physics underlying rapid shear of such fault zones, addressing questions like: Why is there severe localization? What are the dynamic relations between shear stress sustained by the fault and its slip history? How do those relations, taken to provide the boundary conditions on a rupturing interface between elastic regions of the earth, control key features of the dynamics of earthquakes?

Primary dynamic weakening mechanisms, expected active in at least the early phases of nearly all crustal events, are flash heating at highly stressed frictional micro-contacts and thermal pressurization of native fault-zone pore fluid, the latter with a net effect that depends on interactions with dilatancy. Other weakening processes may also become active at large enough T rise, still prior to bulk melting, including endothermic decomposition reactions releasing a CO_2 or H_2O fluid phase under conditions that the fluid and solid products would, at the same p and T, occupy more volume than the parent rock, so that the pore fluid is forced to undergo severe pressure increase. The endothermic nature of the reactions buffers against melting because frictional work is absorbed into enthalpy increase of the reactants. There may also be a contribution to the weakening linked to the typically nanoscale range of the solid product phases.

The results, applied to modeling of spontaneous slip ruptures, show how faults can be statically strong yet dynamically weak, and operate under low overall driving stress, in a manner that generates negligible heat and meets major seismic constraints on slip, stress drop, and self-healing rupture mode. They also shed light on how fault segments that normally shear stably, so as to not nucleate earthquakes, can nevertheless take part in major events when a high-slip rupture impinges from a bordering segment. The studies reviewed have been done collaboratively with, or draw on the separate insights of, N. Brantut, M. Cocco, E. Dunham, D. Garagash, D. Goldsby, N. Lapusta, H. Noda, J. Platt, A. Rempel, J. Rudnicki, P. Segall, T. Shimamoto, J. Sulem, T. Tullis and I. Vardoulakis.