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The Mechanics of Slow Slip and Lab Earthquake Prediction

Chris Marone
The Pennsylvania State University, Dept. of Geosciences, University Park, United States (cjm38@psu.edu)

Earthquake science is in the midst of a revolution. Our understanding of tectonic faulting has been shaken to the core by discoveries of seismic tremor, low frequency earthquakes, slow slip events, and other modes of fault slip. These phenomena represent modes of failure that were thought to be non-existent and theoretically impossible only a few years ago. The origin of slow earthquakes and in particular the processes that limit their rupture propagation speed remain unresolved, despite the fact that they have been observed at every major plate boundary and can trigger catastrophic large earthquakes.

In this lecture, I summarize recent laboratory work showing that we can produce slow, quasi-dynamic rupture under controlled conditions and that the same fault can host the full spectrum of fault slip modes observed in nature. The lab slow slip events represent quasi-dynamic rupture, rather than simple creep relaxation, and occur for conditions near the stability boundary between stable creep and elastodynamic rupture. Slow slip occurs when the elastic energy release rate during failure becomes equal to the fracture energy. In the lab, we impose this condition by matching the fault unloading stiffness K to the frictional weakening rate with slip Kc $\approx$ (b-a)/Dc, where (b-a) is the friction rate parameter and Dc is the critical friction slip distance. Slow slip can also arise from stress or strength heterogeneity along the fault, as shown by the works of others. We find that slow slip is favoured by conditions that yield low rates of interseismic fault healing and by fault rocks for which dKc/dV is negative, where V is slip velocity. Lab studies document the nature of changes in Kc with slip velocity due to both increasing critical slip distance with slip velocity and/or reduction in the friction rate parameter (b-a) with increasing slip rate. Numerical work shows that the condition dKc/dV < 0 is sufficient to promote slow rupture; that is, Kc does not have to change sign from positive to negative for a range of conditions appropriate for the lab faults.

Our lab work documents the spectrum of failure modes from stable creep to elastodynamic rupture. Remarkably, this range of events can be predicted using machine learning (ML) techniques to analyze acoustic emissions emanating from the fault. The labquakes are preceded by a cascade of micro-failure events that radiate elastic energy in a manner that foretells catastrophic failure. The ML methods predict the time of failure, the slip duration, and for some events the magnitude of slip. These predictions demonstrate a mapping between fault strength and statistical attributes of the fault zone elastic radiation that it is valid throughout the duration of the lab seismic cycle and also correctly describes both dynamic rupture and slow slip events. The work I review has been achieved thanks to collaboration with a number of people who I have had the fortune of learning from. I celebrate their input, help, and discoveries in this talk.