Dilatancy Stabilization of Frictional Sliding as a Mechanism for Slow Slip Events

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Slow slip events and associated non-volcanic tremor have been discovered in a number of tectonic settings, yet the processes giving rise to these phenomena are as yet not understood. One proposal is that friction changes from rate weakening behavior at low slip speeds to rate-strengthening at higher slip speeds, as has been observed in halite [Shibazaki and Iio, GRL, 2003; Shibazkai and Shimamoto, GJI, 2007]. This mechanism does not appear to be supported by lab data on silicates, however there is a prominent lack of data for mafic rocks under appropriate pressure and temperature conditions.

Transient slip in subduction zones appears to occur between the locked megathrust and the steadily creeping fault below, suggesting that slow slip occurs in regions near frictionally neutral stability [Kuroki et al, BSSA, 2004; Liu and Rice, JGR 2005; JGR 2007]. However, the width of the transiently slipping zone W must be large enough to allow non-steady slip ($W > h^*$, where h^* is the critical nucleation dimension) but not so large that the rupture becomes dynamic. The size range for which transient, quasi-static slip occurs is small, particularly for the slip-law form of rate-state friction, which is favored by velocity stepping experiments. If W is only slightly larger than h^*, than h^* must be of the order of several tens of km in order to satisfy geodetic observations. Kuroki et al, [BSSA, 2004] achieve this with slip weakening distance d_c, three to four orders of magnitude larger than observed in lab experiments. An alternative, at least consistent with some seismic tomography results, is that high pore pressures lead to low effective normal stresses, and hence large h^* [Liu and Rice, JGR, 2007] .

A further possibility is that rate-state friction nucleates slip under drained conditions but that as slip accelerates deformation becomes effectively undrained, and dilatancy induced pore-pressure reductions quench the instability. This idea was described briefly in Liu and Rice [JGR, 2007], see also Liu and Rice [AGU Abs, 2005], and builds on much earlier work in the context of slip weakening models [Rice, 1975; Rudnicki, 1979]. We have studied this process assuming 2D elasticity, rate-state friction and a highly simplified dilatancy law [Segall-Rice, 1995, JGR]. Pore-pressure fluctuations are governed either by simplified, isothermal *membrane diffusion*: $dp/dt = (p^\infty - p)/t_f + (1/\beta)d\phi/dt$, where p and p^∞ are fault and remote pore-pressure, t_f a characteristic diffusion time, β pore and fluid compressibility and ϕ fault zone porosity, or by one-dimensional (fault normal) diffusion into the surrounding medium computed by finite difference.

For the membrane diffusion model, dimensional analysis shows that dilatant strengthening scales with $E \equiv f_0\epsilon/\beta b(\sigma - p^{\infty})$, where$f_0$ is nominal friction and b the rate-state parameter. Linearized stability analysis [Segall-Rice, 1995, JGR] suggests that $E = 1 - a/b$ defines a boundary between slow and fast slip. Indeed, numerical simulations with $E < 1 - a/b$ accelerate to radiation damping limits for sufficiently large W/h^*, whereas for $E > 1 - a/b$ the maximum slip-speed is well below inertial for a very wide range of W/h^*. This suggests that stable slip is favored by low effective stress, consistent with some seismic observations. It may be that what ultimately controls whether slip is fast or slow depends on whether dilatancy limits maximum slip-speeds to values below where thermal pressurization rapidly degrades fault strength.

The physical mechanism for tremor is far from clear, however spatial variations in permeability, due for example to fractures intersecting the principal slip surface, could play an important role. 2D simulations show that slow slip accelerates in regions that drain faster than the surrounding fault. Seismic radiation will result if slip rates become fast enough for thermal pressurization to become significant.

An important societal rationale for studying slow slip is that stress transfer to the locked mega-thrust could trigger a damaging earthquake. We note in this regard that slow slip events on Kilauea volcano, the Boso Peninsula Japan, and the north island of New Zealand are associated with microseismicity. Further study of these localities could lead to a better understanding of triggered earthquakes and what controls their ultimate size.