Harvard EPS – Solid Earth Physics Seminar, March 11, 2008

Slip and depth dependent variations in fault strength and gouge properties: Insights from particle dynamics simulations

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Fault slip is accompanied by substantial fault rock damage and grain comminution, which can strongly influence the overall strength and behavior of the fault zone. Changes in wall rock damage and gouge thickness over time will also control the long-term fault zone evolution. We simulate the break down of fault blocks using particle dynamics methods in two-dimensions (2-D) to examine this evolution and its consequences on fault strength and behavior under a range of normal stresses (σ_n) corresponding to different fault depths, and a range of uniaxial compressive strengths (σ_{ucs}) corresponding to varying rock types and lithification states. Under most stress and strength conditions, initial loading generates extensional microfractures within the wall rocks at high angles to the pre-existing planar fault surface. Initially, the gouge zone thickens rapidly, as grains plucked from the wall rocks accumulate within the fault. Gouge grains also undergo progressive fracture and size reduction with shear. Fault strength evolves with shear strain due to changes in gouge thickness and grain characteristics. The balance among grain plucking, grain size reduction, and gouge thickening depends on the ratio of σ_n/σ_{ucs}. If this ratio is high, gouge grains are rapidly crushed, forming a relatively thin layer of weak, fine-grained fault gouge that cushions the wall rocks from further plucking. This results in a progressive decrease in fault strength with strain. If this ratio is low, comparatively large, angular gouge grains persist, grinding along the walls to pluck new grains, further increasing the thickness of the gouge. This causes a gradual increase in fault strength with shear strain.

The implications of such variations in gouge thickness and fault strength with σ_n/σ_{ucs} are significant. First, this belies a universal relationship between gouge thickness and shear strain, as the former is strongly dependent on both fault depth and wall-rock lithology. Second, for a uniform lithology, deeper portions of a fault zone will undergo rapid softening as fault gouge forms and degrades, whereas shallower portions of the fault will experience a gradual increase in strength as coarse, immature fault gouge accumulates. Such temporal and spatial heterogeneities in fault strength may result in changes in fault activity, and possibly seismicity, over time.