Frictional Sliding, Shock Waves and Granular Rotations

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We offer a sketch of the physics and geophysics of the seismic cycle of a single earthquake fault in terms of the dynamics of fracture in a major earthquake and its interaction with the material in its neighborhood.

The nature of sliding friction in the dynamic regime of rupture is unclear. Part of the difficulty can be attributed to the absence of laboratory information on friction at large enough velocities. The modeling community is also responsible for some of the difficulty: The experimentalists usually measure friction on prepared surfaces and the theoreticians prefer to describe friction on a planar surfaces for theoretical convenience. The familiar rate/state model of strength weakening is valid in a quasistatic regime of low slip-velocity. Yamashita and Knopoff (YK; 1987) showed that a stress corrosion breakdown model of many asperities in a plane leads to a critical point instability in the fracture. X.-X. Ni and L. Knopoff have shown that the YK model and the rate/state model are equivalent in the regime of high densities of cracks.

By a simple model, Z.-L. Wu and L. Knopoff have shown that the terminal fracture in the dynamic regime releases most of the stress, and moment as well. Most important they show that a linear velocity weakening process is appropriate in the dynamical regime for fractures with small topographic roughness. This result has an unexpected consequence. The theory of ruptures in elastic media in the dynamical regime under the influence of velocity-weakening, shows that there is a limiting value to the rate of weakening of stress as a function of slip velocity, $d\sigma/dv$. This quantity must always be less than the acoustic impedance ρc, where ρ is the density of the elastic medium and c is the S-wave velocity. While slip rates given by the ratio of the stress drop to the acoustic impedance are appropriate for the interiors of sliding cracks remote from the edges, they are not appropriate for the edges where they can be considerably higher. It is simple to show that no solutions are possible physically for $d\sigma/dv > \rho c$. A paradox ensues: If only slow slip rates are allowed by elasticity theory, then how can strong earthquakes develop sharp onsets? The answer is clear: If $d\sigma/dv > \rho c$, then the medium adjacent to a fault is no longer linear. Indeed, this condition is exactly that needed for the development of a shock wave, in which the rate of loading exceeds the rate at which stress energy can be removed by elastic waves: in this case the particle velocity exceeds the shock wave velocity. Thus if strong earthquakes are to develop, the application of a theory of linear elasticity extending from infinity up to the fault surface is not possible for large earthquakes.

What are the consequences of a supersonic shock in the crack tip region on the material nearby the fault? Clearly the material must shatter. But for recurrent large

earthquakes on a given fault, we require that the adjacent region have been shattered many times over, with repeated healing in the intervals between the large earthquakes. The shattered material in the neighborhood of a fault must be a weakened region that supports many aftershocks. We have argued elsewhere that aftershocks are produced by a two-stage process. First, a shattering of the material nearby the fault takes place, which we now attribute to the consequence of the shock wave. It is the distribution of sizes of shards and asperities in the shattered zone that gives rise to the observation of the Gutenberg-Richter (G-R) law for aftershocks (M.W. Lee). The second stage involves the presence of subcritical crack growth and stress corrosion of the asperities between the shattered fragments, a process that gives rise to the Omori rate-of-occurrence law. The process is abetted by fluids which we assume are derived from the slip in the fault trapped-mode zone during the initial shock. The depletion of fluids leads to rapid self-healing of the slip in the main shock.

Observations of the geometry of aftershock zones, as well as modeling of the aftershock process, give corroboration of the above view of the role of shock waves in the generation of a detrital zone nearby a main fault. Evidence from aftershock and main shock distributions indicates the width of this zone is about 3 km in Southern California. Large aftershocks outside this zone do not obey the Omori law, and have only a short duration of sequence. Most aftershock series terminate After some time; after a long time, the quiescent episode itself terminates, and "background" reactivation of earthquakes has been identified, and is an indicator of "active" faults, i.e. those faults that are likely to rupture in future great earthquakes.

The presence of shock wave excitation of the cemented, but weakened adjoining region, means that stress drops and moments are underestimated by inversions using elastic wave Green's function. It therefore follows that use of moment-tensor catalogs underestimate tectonic (fracture) moment release in large earthquakes and these quantities should be re-evaluated.

The development of a highly fractured zone astride the main fault rupture is a zone of loss of fracture energy. This means that not only must we take elastic wave radiation and sliding friction into account as dissipative processes that retard continued slip, but also we must take fracturing and, as we now argue, granular rotations and collisions in the trapped mode zone into account as well. All are important; radiation and sliding are often taken into account in more usual models.

We discuss the role of rotations in the dissipative process. We start with the proposal above, that the elastic properties of the remote medium do not extend up to the fault itself. A central force model suffices to model the elastic system. We review the properties of the central force model and the contributions of Cauchy, Poisson, Voigt and Epstein. We show that the conventional assumption that rotational forces can be neglected in traditional elasticity is not valid in a coarse graining approximation. However the inclusion of rotations in the central force model, does not introduce elastic anisotropy, but it does change the Poisson's ratio. More important, it does not introduce dissipation under conditions of elastic deformation. Classical central force models of large slips are also not dissipative, and hence these produce no heat in fracturing. The only way to introduce dissipation in these systems of large motions is to allow both slip and rotation simultaneously. Thus rotational energy in the sliding,

rotating granular system, for example, is an essential component of the dissipative process in fracture.

We have the following model: The central part of a major earthquake fault is identified with the trapped mode zone in which the macrorupture itself takes place. We envision the trapped mode zone to be a granular medium of varying grain sizes; the grains have a high pore pressure due to the presence of trapped zone fluids. The fracture is irregular in this zone because if its highly granular nature. Under very high deformational stress, the large event begins to nucleate; it does so by the generation of tensile fractures in the granular medium; the scale size of these fractures is limited by the width of the trapped mode zone. As the density of tensile fractures increases, they link up to form irregular shear cracks with many lateral small scale cracks. The damage to the trapped mode zone creates a melange of moving grains of various sizes, all of which have significant rotation, especially due to the shear. These features of deformation under the release of the very high stresses in the process zone excite a shock wave that travels to the adjoining medium, which has itself been shattered in the past, but is now locked because of low pore pressure. The shock wave, shatters the adjoining medium creating a high density of shards, with a strong gradient of slip across the adjoining zone: these become the sites for subsequent aftershock activity under the influence of water expelled from the core zone in a hydrofracture process. As large scale sliding develops, inelastic collisions among grains and between coherent units against topographic irregularities produce friction and frictional heating. Rotation of grains in the core zone remains an essential part of the process of frictional heating. The fracture comes to rest by self-healing of slip due to the energy loss in radiation and frictional heating, and by the encounter of the fracture with large-scale topographic irregularities in the fault zone. Aftershocks are induced in the adjoining shattered region under the influence of the residual stress and irregular slip on the main shock region; stress corrosion is an integral part of this aftershock process. As fluids diffuse back into the core zone, the adjoining region hardens, and the aftershock region ultimately becomes quiescent. When the tectonic stress builds up once again to a sufficiently strong value, the region is reactivated into a set of infrequently occurring foreshocks. Under continued buildup of stress from both tectonic sources and redistribution from other large earthquakes nearby, small earthquakes begin to occur that probably have tensile mechanisms; these fractures remain "open" under high pore pressure, i.e. have low normal stress. Continued excitation of foreshocks, causes linkage of the tensile cracks in the nucleation zone, thereby completing the cycle.