Fault rheology and earthquake dynamics

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Investigations undertaken

(1) Earthquake nucleation and early propagation as affected by prior events.

(2) Fracture energy of earthquakes and slip-weakening rupture parameters.

(3) Pore pressure transitions in Coulomb stress analysis of earthquake interactions.

(4) Development of high dynamic stressing off the main fault plane and induction of secondary faulting.

(5) Fault encounters with bends and stepovers.

(6) Repeating earthquakes as low-stress-drop events at a border between locked and creeping fault patches

Results

(1) We study earthquake nucleation and early propagation during sequences of model earthquakes in a 2-D model of a vertical strike-slip fault with standard depth-variable rate and state friction. The methodology (Lapusta et al., *JGR*, 2000) incorporates both truly slow, tectonic loading and all dynamic features. It allows us to treat accurately, within a single computational procedure, loading intervals of thousands of years and to calculate, for each earthquake episode, initially aseismic accelerating slip (nucleation process), the resulting dynamic rupture break-out and propagation, post seismic deformation, and ongoing slippage throughout the loading period in creeping fault regions.

Rate and state friction incorporates a characteristic slip distance L for evolution of frictional strength. For fixed other parameters, the nucleation size (size of the quasi-statically slipping patch that precedes the dynamic rupture break-out) is proportional to L. We study how earthquake sequences change as we decrease L, approaching the laboratory range of tens of microns (too small to be computationally feasible). As L decreases, small events appear near the brittle-ductile transition at the bottom of the seismogenic (velocity-weakening) zone. For the particular depth-variable fault model studied by Lapusta et al. (*ibid*), a simulation with L = 8 mm produces a periodic sequence of large events (sequence I), while a simulation with L = 2 mm results in the sequence of a large and a small event (sequence II), as do the simulations with L = 1 mm and 0.5 mm. In the case with L = 0.14 mm (done so far only quasi-dynamically; we intend to redo it with full dynamics), the sequence is more elaborate, with large events interspersed by three smaller events.

The nucleation of the large and small events is very similar, as manifested by plots of slip, slip velocity, moment rate, and moment acceleration. This means that observing the nucleation and beginning of a model earthquake, it is impossible to tell whether the final size of the event will be large or small. The final size of the event is determined by the conditions on the fault region that the event is propagating into, rather than by the nucleation process.

We observe that moment acceleration during initial stages of dynamic rupture propagation can have "bumps" and subsequent "speed-ups". This is consistent with observations, e.g. as reported by Ellsworth and Beroza (*Science*, 1995), who attribute these features to either processes in the preslip region or a special cascade structure of the fault. Our simulations show that such irregular moment acceleration (to which velocity seismograms are proportional) can be caused by heterogeneous stress distribution left by previous events. For the large event of the sequence II, moment acceleration grows initially, then decreases almost to zero during rupture propagation over the region that slipped in the previous small event, and then again abruptly grows, even faster than initially, when the rupture reaches the region of stress concentration left by the arrest of the previous event. Such a "bump" and "speed-up" is not observed for an event of the sequence I which does not have small events.

(2) The breakdown process at a propagating fault tip may be charcaterized in terms of a fracture energy G, at least when the dynamic shear strength τ_d along well-slid parts of the rupture can be considered uniform over scales that are a few or more times the size of the breakdown zone. If breakdown is interpreted as slip-weakening on the main fault plane (ignoring the effect of high off-main-fault stresses), G can be equated to $(\tau_p - \tau_d)\delta_1$. Here τ_p is the peak shear strength and δ_1 is a characteristic slip in a parameterization of weakening by $\tau = (\tau_p - \tau_d)\exp(-\delta / \delta_1) + \tau_d$. (Such parameterization emerges from the Sibson-Lachenbruch description of weakening by undrained adiabatic shear heating of a fluid-infiltrated fault.) Seismic estimates of G are used here to constrain δ_1.

That is done with the Freund (*JGR*, 1979) 2D shear rupture model for which the friction stress is constant (at τ_d) on the sliding surface, an elastic crack singularity occurs at the leading edge, and there is smooth closing at the trailing edge. This describes a self-healing rupture, although the model has no description of what promotes healing. Nevertheless, using the model, it is possible to estimate the energy flux G, per unit new fault area, to the leading edge in terms of the width L_s of the slipping portion, the seismic slip Δu, and the propagation velocity V_r. The form is $G \propto \mu\,(\Delta u)^2 / L_s\, F(V_r)$ where μ is shear modulus and $F(V_r)$ is an elastodynamic crack function which varies from 1 at $V_r = 0^+$ to ∞ as V_r approaches a limit speed c_{lim} (shear speed for mode III, Rayleigh for mode II). Estimates of L_s, Δu, and V_r are given in earthquake slip inversions. Using average values reported for each of the seven events with inversions summarized by Heaton (*PEPI*, 1990), we obtain G = 0.3-4.8 MJ/m^2, with average of 1.9 MJ/m^2. These are generally consistent with other estimate of G (e.g., Rudnicki and Wu, *JGR*, 1995) based on the arrest of large ruptures. Heaton also reports estimates of L_s and Δu at asperities; using average values of V_r, these lead to peak G within an event of G = 1-24 MJ/m^2.

Estimating τ_p as 0.6 times the difference between overburden and hydostatic pore pressure, averaged over the rupture depth range, results in 50-240 MPa, much higher than the dynamic stress drops $\propto \mu \Delta u / L_s F(V_r)$ inferred from the Freund model, which range from 1-4 MPa for the seven events. Assuming from heat flow arguments that $\tau_d << \tau_p$, one then estimates characteristic weakening slips δ_1 for individual events as 4-49 mm, with average of 20 mm; the numbers increase in proportion to $\tau_p / (\tau_p - \tau_d)$ for non-negligible τ_d.

Limitations are that G and δ_1 may be mis-estimated for reasons such as the following: (1) self-healing is not a prediction of the model used, but rather has been imposed on it; (2) L_s may be poorly estimated from the seismic inversions (which are based on records from which high frequency information has been filtered); (3) the average V_r may represent a highly irregular local rupture speed which may be near to either c_{lim} or 0 (in which case G would be overestimated); (4) a significant part of G involves dissipation in faulted border regions off the main fault plane; (5) the approximation of constant τ_d fails due, e.g., to strong velocity weakening at seismic slip rates; (6) rupture takes place with significant local reduction of normal stress, e.g., due to modest dissimilarity of properties across the fault planes.

(3) Fault interaction is widely investigated using Coulomb stress changes on faults of specified orientation. Pore pressure changes $\Delta p'$ within the fault should be included in these calculations, because the proper measure of stress change is $\Delta\sigma_{31} + f(\Delta\sigma_{33} + \Delta p')$. Here f is the friction coefficient, σ_{33} is the stress component acting normal to the fault, which lies in the x_1, x_2 plane, and σ_{31} is the shear stress component in the slip direction ; both of those take the same values within a narrow fault zone as in the adjoining crust but some other stress components, like σ_{11}, need not do so.

Previously we showed (Cocco and Rice, *EOS*, 1999) that on a short postseismic time scale, for which it could be assumed that the fault zone and its surroundings were undrained, that $\Delta p'$ was negatively proportional to a linear combination of $\Delta\sigma_{33}$ and $\Delta\sigma_{kk} / 3$, where $\sigma_{kk} / 3$ is the first invariant of the stress tensor in the adjoining crust. We considered a narrow fault zone whose poroelastic parameters were different from those in the adjoining medium, which was assumed to be isotropic. In cases of a fault zone which is much more compliant than its surroundings (e.g., low fault zone wave speeds), or which has a strongly anisotropic texture, the dependence of $\Delta p'$ on $\Delta\sigma_{33}$ is much stronger than on $\Delta\sigma_{kk} / 3$.

However, if we consider moderately longer time scales than those for undrained response, we should expect a sufficiently narrow and permeable fault to come to local pressure equilibrium with its surroundings even while that surrounding region is still effectively undrained at larger distances from the fault than those of order of fault zone thickness. In such cases, $\Delta p'$ approaches Δp with time, where p is the pore pressure in those surroundings. Thus $\Delta p'$ approaches $\Delta p = -B \, \Delta\sigma_{kk} / 3$, where B is the Skempton poroelastic coefficient in the surroundings. Hence there is a transition from dependence (primarily) on $\Delta\sigma_{33}$ to dependence on $\Delta\sigma_{kk} / 3$.

Adopting the model of a fault zone of thickness *h* with uniform poroelastic properties *c′*,*N′*, in uniform surroundings with properties *c*,*N* (here *c′*,*c* are diffusivities and *N′*,*N* are storage moduli), we solve mathematically for the time dependence of $\Delta p'$ in its transition towards Δp. That transition is shown to be approximately halfway complete at time $t_d = [1 / c' + (N / N')^2 / c]h^2 / 8$. For *h* ranging from 10 cm to 10 m, and for the minimum of the two permeabilities in the range of a nano- to a micro-darcy, this ranges from a few seconds to a year. Further, unless $c' << c(N' / N)^2$, the time scale for close approach to the limit Δp can be several times t_d. Thus it must be expected that the fault population has members at various stages of transition between $\Delta p'$ being dependent on (primarily) $\Delta\sigma_{33}$, versus dependent on $\Delta\sigma_{kk} / 3$, during the time scale of earthquake interactions in aftershock sequences.

(4) We consider singular crack or slip-weakening rupture models for which the residual dynamic shear strength τ_{res} on the fault can be considered as effectively constant at distances from the rupture tip larger than the the slip-weakening (process) zone size. An important feature of the dynamic near-tip stress field is the growth of the maximum off-fault shear stress τ_{off} with an increase of velocity of rupture propagation v_r. At least according to the leading term in the singular crack solution, the ratio of τ_{off} to the stress τ_{main} on the main fault plane, at a fixed distance from the rupture tip, approaches infinity as v_r approaches the limiting crack speed c_{lim} (which is the Raleigh speed c_R for mode II and the shear speed c_s for mode III). For example, for mode III, if we evaluate τ_{off} along a line perpendicular to the crack plane and passing through the crack tip, this ratio is

$$\tau_{off} / \tau_{main} = (1 - v_r^2 / 2c_s^2)^{1/2} / (1 - v_r^2 / c_s^2)^{3/4} .$$

High off-fault stress may contribute to the explanation of the following: (i) secondary faulting (activation of damaged border zone, like observed along the exhumed San Gabriel and Punchbowl faults), (ii) bifurication of fracture path and self-arrest of a crack as $v_r \to c_{lim}$, and (iii) jump of a rupture to a sub-parallel segment (e.g., Landers and Izmit events).

To study the location and directions of highest stressing on secondary faults we plot, for the singular crack model, (i) isolines of the maximum ratio of shear stress to Coloumb shear strength for the local normal stress, and (ii) directions of potential fractures (planes on which that ratio is maximum) around a crack tip. This augments a study by Rubin and Parker (USGS O-F Rpt. 94-228). Coordinates are scaled with what would be the length of the slip-weakening zone (ω_o) at $v_r = 0^+$, which is estimated to be 5 to 100 m (based on 0.5 - 5 MJ/m^2 fracture energy and 50 - 100 MPa peak to residual strength drop). For given pre-stress states, we varied v_r and τ_{res}.

For both rupture modes we found that the zone of potential secondary faulting (i) contracts in front of the rupture while (ii) it stretches in the direction perpendicular to the main fault as $v_r \to c_{lim}$ and (iii) decreases (in all directions) with an increase of τ_{res}. At low τ_{res} (relative to the slip-weakening strength drop), directions of the secondary faults tend to be perpendicular to the main fault, and for high τ_{res} they tend to be parallel. The main difference between modes is an asymmetry of secondary faulting for mode II compared to symmetrical faulting for mode III.

To conclude, our calculations predict activation of faults in the damage zone of the size in the range of (0.1 - 1) ω_o (i.e. 0.5 - 100 meters) in vicinity of the main fault. The directions of secondary fractures depending on the mode of rupture, τ_{res} and pre-stress state.

The study is in preparation for numerical modelling of spontaneous activation of secondary faults during dynamic rupture. For that we are developing two approaches. First, in work with visiting scientist A. Poliakov, we are adapting to shear ruptures the finite element procedures of Xu and Needleman (1994), in which element boundaries are potential surfaces of decohesion which follow relations between tractions and displacement discontinuities. Our formulation reduces to classical slip-weakening when there is only sliding displacement, but it allows for local tensile opening too if the stress field demands that. The second approach is our work with postdoctoral fellow N. Kame, who has developed elastodynamic boundary integral equation methods for faults with non-planar, possibly branched, paths.

(5) In studies related to the last topic, we investigate how earthquake ruptures jump to neighboring faults or overcome a bend in the fault system, and how that depends on the type of fault, geometry, etc. That is, we study the propensity of the rupture path to jump or bend, or to do neither and arrest, in different tectonic conditions.

A dip slip rupture can be approximated by a mode III crack at its ends along strike; a strike slip rupture by a mode II crack. Thus a start is to compare Coulomb stress changes ahead of crack tips for those two crack types. We do that based on singular field approximations for the crack tip region where stress changes are on the order of the stress drop, full field solutions for simple 2D and 3D cracks in unbounded media, and numerical 3D models for specific fault geometries in a half space.

We analyze the stress changes caused by a main rupture which would encourage jumping of unbroken barriers so as to continue rupture on a parallel fault, or kinking onto a sub-fault which bends away from the main fault. For all models, we find that for a given rupture dimension and stress drop, the mode III stress field encourages jumping or bending over a broader range ahead of the tip than does the mode II field.

For jumping, we find from the singular field that Coulomb stress changes on parallel planes with an amplitude equal to the stress drop extend over more than twice the distance perpendicular to a mode III rupture than for mode II, when the friction coefficient $f = 0.5$. In the full-field solution for the 2D tunnel crack, the zone of increased fault-parallel Coulomb stress ahead of the rupture tip is more than twice as wide for mode III. However, stress changes have mirror symmetry about the crack plane for mode III and are point symmetric with respect to the crack center for mode II, in which case a lobe of stress increase extends to each side of the rupture. The characteristics of the mode III stress field in those simpler models are reproduced in 3D numerical solutions for dip-slip faults, except for free surface effects which are most pronounced at shallow depths.

For bends, the mode III near-tip field gives favorable stressing over a wide angular range, extending beyond –90˚ to 90˚ from the crack plane. By contrast, the mode II rupture is conducive to bending over a more restricted range, from ≈ –90˚ to 30˚ when $f = 0.5$. However, the Coulomb stress change, of stress drop amplitude, extends slightly further from the tip in mode II (in the region of highest mode II stressing, ≈ –40˚) than for mode III.

In applications, it must be remembered that the zone of stress increase scales with the characteristic length dimension, which we are trying to more fully quantify from the 3D studies.

Thus, a shallow-depth normal fault rupture, despite its mode III ends, may have less potential to jump than does a strike slip rupture (mode II ends) which penetrates much deeper. For equal depths, the normal fault should be harder to stop. It should be most difficult of all to stop a large subduction earthquake which has, in addition to mode III ends, a broad down-dip zone, which would enter the scaling. That might help explain why the earthquakes which extend furthest along strike are typically subduction events.

(6) The source of repeating earthquakes on creeping faults is modeled as a weak asperity at a border between much larger locked and creeping patches on the fault plane. The $x^{-1/2}$ decrease in stress concentration with distance *x* from the boundary is shown to lead directly to the observed scaling $\langle T \rangle \propto \langle M_0 \rangle^{1/6}$ between the average repeat time and average scalar moment for a repeating sequence. The stress drop in such small events at the border depends on the size of the large locked patch. For a circular patch of radius *R* and representative fault parameters, $\Delta\sigma = 7.6(m/R)^{3/5} MPa$, which yields stress drops between 0.1 and 1.0 MPa (1-10bars) for *R* between 5 km and 100 m. These low stress drops are consistent with estimates of stress drop for small earthquakes based on their seismic spectra. However, they are orders of magnitude smaller than stress drops calculated under the assumption that repeating sources are isolated stuck asperities on an otherwise creeping fault plane, whose seismic slips keep pace with the surrounding creep rate. Linear streaks of microearthquakes observed on creeping fault planes are trivially explained by the present model as alignments on the boundaries between locked and creeping patches.

Non-technical summary

Theoretical modeling of rupture mechanics based on lab-constrained friction laws seeks to identify models consistent with fault operation at low overall driving stress, to understand the mechanisms by which pore fluids in fault zones interact with the rupture process, to model the nucleation and propagation of dynamic rupture, and to explain the complex sequences by which failure occurs in rupture through arrays of interacting faults.

Reports

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