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Fault rheology and earthquake dynamics

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Abstract

Investigations were undertaken on the following topics:

(1) Development of fault mechanics analysis procedures allowing fully elastodynamic simulations of long tectonic loading intervals during which sporadic earthquake instabilities occur. Their application has provided new perspectives on key questions in the physics of earthquakes, especially the nucleation process and the earliest phases of seismic radiation, the clustering of small events near transitions from stably sliding to locked regions, and the overall complexity of event sequences.

(2) Existence or not of continuum complexity in the elastodynamics of repeated fault ruptures (collaborative study with B. E. Shaw, LDEO). This has shown that small-event complexity can be a legitimate outcome, for ruptures on a uniform fault, if only in rather restricted parameter ranges.

(3) Rupture dynamics and self-healing slip pulses for faults between dissimilar materials.

(4) Development of high dynamic stressing off the main fault plane and consequences for fault branching and induction of secondary faulting. Here the dependence of off-fault stressing on rupture speed and the direction of principal stress in the prestress field have been inferred to be critical, in a manner that is apparently consistent with natural examples.

(5) Evaluation of fault zone pore pressure changes for Coulomb stress analysis of earthquake interactions (collaborative study with M. Cocco, Rome).

(6) Repeating earthquakes as low-stress-drop events at a border between locked and creeping fault patches (collaborative study with C. G. Sammis, Univ. So. Cal.).

(7) Flash heating at frictional asperity contacts as a possible basis for strong velocity weakening at high slip rates. Here a model for weakening in the small-slip regime prior to macroscopic melting has reasonable agreement with available experiments.

(8) Fracture energy of earthquakes and slip-weakening rupture parameters. A new perspective is provided by applying a crack model to interpret parameters of dynamic earthquake slip inversions, suggesting fracture energies of 0.3-5 MJ/m^2, with average of 2 MJ/m^2.

(9) Nucleation of slip-weakening rupture instability under non-uniform fault loading. For linear slip-weakening, the slipping zone length at nucleation has been proven to be independent of details of the loading stress distribution. Nucleation was also studied in the rate and state context, and seismic observations were used to help constrain slip-weakening.

Results (the numbering here corresponds to that of topics in the *Abstract*)

(1) We have developed (Lapusta et al., 2000) an efficient and rigorous numerical procedure for calculating the elastodynamic response of faults subjected to slow tectonic loading processes of long duration within which there are episodes of rapid earthquake failure. This is done for a general class of rate- and state-dependent friction laws with positive direct velocity effect. The algorithm allows us to treat accurately, within a single computational procedure, loading intervals of thousands of years and to describe, for each earthquake episode, initially aseismic accelerating slip prior to dynamic rupture, the rupture propagation itself, rapid postseismic deformation which follows, and also ongoing creep slippage throughout the loading period in velocity strengthening fault regions. The work is motivated by earlier but less efficient algorithms with similar aims, described and/or implemented by Zheng et al (*EOS Trans. AGU*, 1995), Rice and Ben-Zion (*Proc. Natl. Acad. of Sci. USA*, 1996) and Ben-Zion and Rice (*JGR*, 1997).

The algorithm first separates the elastodynamic stress transfer functional into its long-time static limit and a wave-mediated dynamic part. The latter localizes the effects of the prior deformation history in convolution integrals on slip velocity with rapidly decaying kernels. Truncation of these convolutions allows to simulate long processes without the necessity to deal with all prior deformation history at each time step. Throughout the calculation, time steps can vary by several orders of magnitude (as many as 9 in our examples). The choice of the time steps is dictated by the current values of slip velocities, parameters of the constitutive law and stability considerations. This variable time stepping makes the number of time steps during slow deformation periods numerically manageable while still capturing the details of both the nucleation and dynamic propagation phases. Proper space and time discretization, and a new second-order accurate updating scheme that we have developed, ensure the reliability of the results which can be verified through grid and time-step refinement. The methodology is developed in detail for the 2-D anti-plane spectral formulation but can be extended to the 2-D in-plane and 3-D spectral formulations and, with certain modifications, to the space-time boundary integral formulations as well as to their discretized development using finite-difference or finite-element methods.

We used that methodology to 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 (Lapusta and Rice, 2002). The methodology 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); see Figure 1. 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) These studies (Shaw and Rice, 2000) were directed to resolving long-standing debates about the origins of earthquake complexity, or at least about the kinds of fault models which do and do not predict aspects of complexity. The possibility that some aspects of the complexity displayed by earthquakes might be explained by stress heterogeneities developed through the self-organization of repeated ruptures had been suggested by some simple self-organizing models. The question of whether or not even these simple self-organizing models require at least some degree of material heterogeneity to maintain complex sequences of events has been the subject of some controversy. In one class of elastodynamic models previous work has described complexity as arising on a model fault with completely uniform material properties. Questions were raised, however, regarding the role of discreteness, the relevance of the nucleation mechanism, and special parameter choices, in generating the complexity that has been reported. In this work, we examined the question of whether or not continuum complexity is achieved under the stringent conditions of continuous loading, and whether the results are similar to previously claimed findings of continuum complexity or its absence.

The elastodynamic model we used consists of a one dimensional fault boundary with friction, a steady slowly moving one-dimensional boundary parallel to the fault, and a two dimensional scalar elastic media connecting the two boundaries. The constitutive law used involves a pair of sequential weakening processes, one occurring over a small slip (or velocity) and accomplishing a small fraction of the total strength drop, the other at larger slip (or velocity) and providing the remaining strength drop. The large scale process is motivated by a heat weakening instability. Our main results are:

(i) We generally find complexity of type I, a broad distribution of large event sizes with nonperiodic recurrence, when the modeled region is very long, along strike, compared to the layer thickness.

(ii) We find that complexity of type II, with numerous small events showing a power law distribution, is not a generic result but does definitely exist in a restricted range of parameter space. For that, in the slip weakening version of our model, the strength drop and nucleation size in the small slip process must be much smaller than in the large slip process, and the nucleation length associated with the latter must be comparable to layer thickness. This suggests a basis for reconciling different previously reported results.

(iii) Nucleation from slip weakening, precisely following the constitutive equation, and from a time dependent weakening algorithm (strength decreased linearly over a few subsequent time steps once threshold stress achieved) showed similar large scale behavior. However, not all constitutive laws are insensitive to all nucleation approximations; those making a model ``inherently discrete'' and hence grid dependent, in particular, can affect large scales.

(iv) While inherent discreteness has been seen to be a source of power-law small event complexity in some fault models, it does not appear to be the cause of the complexity in the attractors examined here, and reported in earlier work , fortuitously in that special parameter range referred to in *(ii)*, with the same class of continuum fault models and same or very similar constitutive relations. Continuum homogeneous dynamic complexity does indeed exist although that includes type II small event complexity only under restricted circumstances.

(3) Faults often separate materials with different elastic properties. Major faults have transported one terrain a great distance relative to its neighbor, so at least modest dissimilarity should be typical. Further, a mature fault zone has a thickened core, extending from many 10s of meters to a kilometer or more, in which properties have been altered by mechanical breakage and fluid interactions, and slip near the border of such a zone might lead to the same effects. Our studies of this topic are reported in Cochard and Rice (2000), Ranjith and Rice (2001), Rice (2001), and Rice, Lapusta and Ranjith (2001); see Figure 2.

Nonuniform slip on such faults induces a change in normal stress, suggesting the possibility of self-sustained slip pulses propagating at the generalized Rayleigh speed c_{GR} speed even with a Coulomb constitutive law, i.e., with a constant coefficient of friction, and a remote driving shear stress that is arbitrarily less than the corresponding frictional strength (Weertman, *JGR*, 1980). Following Andrews and Ben-Zion (*JGR*, 1997) (ABZ), we have studied numerically (Cochard and Rice, 2000), with a 2D plane strain geometry, the propagation of ruptures along such a dissimilar material interface. However, this problem has been shown to be ill-posed for a wide range of elastic material contrasts (Renardy, *J. Elasticity*, 1992; Martins and Simoes, *Contact Mech.*, 1995; Adams, *J. Appl. Mech.,* 1995). Ranjith and Rice (2001) showed that, when the c_{GR} wave speed exists, as is the case for the material contrast studied by ABZ, the problem is ill-posed for all values of the coefficient of friction, f, whereas when it does not exist, the problem is ill-posed only for f greater than a critical value.

We illustrated that ill-posedness by showing that, in the unstable range, the numerical solutions do not converge through grid size reduction. By contrast, convergence is achieved in the stable range but, not unexpectedly, only dying pulses are then observed. Ranjith and Rice (2001) showed that, among other regularization procedures, use of an experimentally based law (Prakash and Clifton, *ASME AMD Vol 165*, 1993; Prakash, *J.*

Tribology, 1998), in which the shear strength τ^s in response to an abrupt change in normal stress σ evolves continuously with time or slip towards the corresponding Coulomb strength $f\sigma$, provides a regularization. For example, a law with $d\tau^s / dt$ proportional to $-(\tau^s - f\sigma)$ provides such behavior. The specific form we use is of the form $d\tau^s / dt = -[(|V| + V^*) / L](\tau^s - f\sigma)$ where V is slip rate and where V^* and L are constants. (Classical slip weakening or rate- and state-dependent constitutive laws having the same kind of abrupt response as Coulomb friction also do not regularize the problem.)

Convergence through grid size reduction is then achieved in the otherwise ill-posed range. For sufficiently rapid shear strength evolution (small enough L), self-sustained pulses are observed. When the c_{GR} wave speed exists, they propagate essentially at that velocity and, consistently with the Weertman (1980) analysis, the propagation occurs only in one direction which is that of slip in the more compliant medium. When the c_{GR} wave speed does not exist, similar self-sustained pulses propagate at about the slower S-wave speed and in the same direction.

Ranjith and Rice (2001) also suggested that, for sufficiently high coefficient of friction, another kind of (less unstable) self-sustained pulses, propagating at a velocity close to the slower P-wave, and in the opposite direction, could also exist. Cochard and Rice (2000) numerically verified that.

Rice, Lapusta and Ranjith (2001) examined sliding on the dissimilar material interface in the framework of rate and state dependent friction, and showed that the positive "direct effect" included in such framework, and attributed to thermally activated creep at asperity contacts, could actually regularize the problem of sufficiently slow sliding even if there is an abrupt change in shear strength associated with an abrupt change in normal stress. Nevertheless, the situation remains unclear. To regularize the problem only means that a solution exists, but such a solution typically describes a very unstable progression of fault slippage and hence could predict slip rates which fall outside the "slow" range for which the positive direct effect regularizes the problem.

(4) Major earthquakes seldom rupture along single planar faults. Instead there exist geometric complexities, including fault bends, branches and stepovers, which affect the rupture process, including nucleation and arrest. In work initiated with help of this grant, we have addresses rupture interactions with possible branches in the rupture path and the induction of secondary faulting off the main fault plane.

Our theoretical stress analysis (Poliakov, Dmowska and Rice, 2002) for a propagating shear rupture suggests that the propensity of the rupture path to branch is determined by rupture speed v_r and by the preexisting stress state. Deviatoric stresses near a mode II rupture tip are found to be much higher to both sides of the fault plane than directly ahead, when rupture speed v_r becomes close to the Rayleigh speed.

However, the actual pattern of predicted Coulomb failure on secondary faults is strongly dependent on the angle ψ between the fault and the direction of maximum compression S_{max} in the pre-stress field. Steep S_{max} angles lead to more extensive failure on the extensional side, whereas shallow angles give comparable failure regions on both (Figure 3).

We have tested such concepts against elastodynamic boundary integral equation simulations of slip-weakening rupture through branches (Kame, Rice and Dmowska, 2001), Figure 4, and studied their correspondence to natural examples (Dmowska, Rice and Poliakov, 2001), Figure 5. For crustal thrust faults we may assume that S_{max} is horizontal. Thus nucleation on a steeply dipping plane, like the 53˚ dip for the 1971 San Fernando earthquake, is consistent with rupture path kinking to the extensional side, as inferred. Nucleation on a shallow dip, like for the 12˚ -18˚ of the 1985 Kettleman Hills event, should activate both sides, as seems consistent with aftershock patterns.

Similarly, in a strike-slip example, for the 1992 Landers rupture, S_{max} is inferred to be at approximately $\psi = 60^\circ$ with the Johnson Valley fault where it branched to the extensional side onto the Kickapoo fault (Hauksson et al., *JGR,* 2001), and this too is consistent. Further, geological examination of the activation of secondary fault features along the Johnson Valley fault and the Homestead Valley fault consistently shows that most activity occurs on the extensional side, as would be predicted. Another strike-slip example is the Imperial Valley 1979 earthquake. The approximate S_{max} direction is north-south, at around $\psi = 35^\circ$ with the main fault, where it branched, on the extensional side, onto the Brawley fault, again interpretable with the concepts developed. The association between steepness/shallowness of the S_{max} angle ψ and branching seems consistent with theoretical concepts.

Another test of predictions is based on detailed mapping of secondary faulting by Sowers et al. (*BSSA*, 1994). They show evidence for gradually diminishing slip on the upper Johnson Valley fault NW of the Kickapoo branch (on which the major rupture branched), and on the lower Homestead Valley fault SE of the Kickapoo branch (the main rupture went to the NW on the Homestead Valley fault). This suggests NW propagation on the upper JV fault, and SE propagation on lower HV fault. Our theoretical modeling says secondary faulting should occur primarily on the extensional side of a strike-slip fault. That means on the NE side of upper, and lower, JV fault, and on the SW side of the lower HV fault. The mapping of fault slip by Sowers et al. does confirm that expectation.

(5) Fault interaction is widely investigated using Coulomb stress changes on faults of specified orientation. We have studied (Cocco and Rice, 2002) the proper inclusion of pore pressure changes $\Delta p'$ in such analyses. 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.

We showed that on a short postseismic time scale, for which it could be assumed that the fault zone and its surroundings are 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 $c' \ll c(N'/N)^2$, 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.

(6) The source of repeating earthquakes on creeping faults was modeled by Sammis and Rice (2001) 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 (1-10 bars) 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. Streaks of microearthquakes observed on creeping fault planes are explained by the present model as alignments on the boundaries between locked and creeping patches.

(7) Flash heating at frictional asperity contacts has been suggested in engineering tribology as the key to understanding the slip rate dependence of dry friction in metals at high rates (e.g., Bowden and Thomas, *Proc. Roy. Soc.,* 1954; Ettles, *J. Tribol.,* 1986; Lim and Ashby, *Acta Met.,* 1987; Molinari et al., *J. Tribol.,* 1999). We have begun to analyze the concept for fault friction during rapid, possibly large, slips (Rice, 1999).

Let T_f be the gradually evolving average temperature along a sliding fault zone, and T be a local, highly transient, temperature at an asperity contact from flash heating during its brief lifetime $\theta = D/V$. Here D is contact size and V is slip rate. The contact shear strength τ_c must degrade continuously with increasing T. A simple yet informative first model that has been studied is to assume τ_c is constant with T up to a weakening temperature T_w, and then negligible for $T > T_w$. Then there will be a thermal effect on friction only if the time θ_w necessary for shear heating to raise T from T_f to T_w is less than the lifetime θ. We can estimate $\theta_w = (\pi\alpha/V^2)[\rho c(T_w–T_f)/\tau_c]^2$ by equating the heat input $\tau_c V \theta_w$ at the contact to the thermal energy storage $\rho c(T_w–T_f)$ over an effective distance $\sqrt{(\pi\alpha\theta_w)}$, based on 1D heat conduction, where α is thermal diffusivity and ρc is the specific heat. The expression given for θ_w is relevant if $\theta_w < \theta$. That occurs for $V > V_w = (\pi\alpha/D)[\rho c(T_w–T_f)/\tau_c]^2$, a characteristic weakening velocity.

To evaluate V_w, we take $\alpha = 1\ (\text{mm})^2/\text{s}$ and $\rho c = 4$ MJ/°Cm^3 for crustal rocks. D should be identified roughly with the state-evolution slip distance; $D =$ 10 μm is taken for illustration here. The weakening temperature T_w cannot be in excess of the inferred temperature of pseudotachylyte melts, 1000°C to 1450°C (Spray, 1993, 1995; Ray, 1999, O'Hara and Sharp, 2001), and should be closer to the lower limit of that range since here we are considering the pre-melt range, and T_w = 1000°C is considered here. T_f = 200°C gives an ambient fault zone temperature (before slip begins; T_f rises as a result of shear heating during slip) towards the mid level of the seismogenic zone. It could also represent experimental conditions after some amount of sliding that is still well before melting, a range studied (in addition to the melting range) by Tsutsumi and Shimamoto (*GRL,* 1997). So we take $T_w \pm T_f$ = 1000°C – 200°C = 800°C for illustration. Recent measurements of contact area in transparent materials, including quartz, by light scattering (Dieterich and Kilgore, *Pure Appl. Geophys.,* 1994, *Tectonophys.,* 1996) confirms earlier suggestions (Boitnott et al., *JGR,* 1992) that in brittle materials τ_c is of order 0.1 μ, where μ is the elastic shear modulus; 0.1 μ is a standard estimate of the theoretical shear strength. Thus we take τ_c = 3.0 GPa. This gives V_w = 0.4 m/s for onset of severe thermal weakening. The result scales with the most uncertain parameters, D, $T_w \pm T_f$ and τ_c, according to the expression for V_w above.

A similarly simple estimate of the effect on macroscopic friction is given by neglecting the statistics of D and other parameters, and noting that when $V > V_w$, $(\tau_c)_{avg} = \tau_c\theta_w/\theta$ (= $\tau_c V_w/V$) is the average shear stress borne by a contact. The macroscopic shear strength τ and normal stress σ on the fault satisfy $\tau/\sigma = (\tau_c)_{avg}/\sigma_c = f$, where σ_c is the local normal stress at the contacts and f is the friction coefficient. Thus, for $V > V_w$ the friction coefficient diminishes with rate as $f = f_o V_w/V$, where $f_o = \tau_c/\sigma_c$ is the coefficient at lower speeds. Unfortunately, there is very little data for rapid sliding, especially in the regime before so much slip has accumulated that macroscopic melting occurs. All that has been reported seems to be in a portion of the data set of Tsutsumi and Shimamoto (*GRL*, 1997) on gabbro, extending up to only V = 0.5 m/s; that is qualitatively fit by the form just given with f_o = 0.8 and V_w = 0.3 to 0.4 m/s, Figure 6.

(8) Studies have been done on constraining the fracture energy G of earthquakes (Rice, 2000). The breakdown process at a propagating fault tip may be characterized in terms of fracture energy 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 were 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 $G = 0.3\text{-}4.8$ 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 $G = 1\text{-}24$ MJ/m^2.

Estimating τ_p as 0.6 times the difference between overburden and hydrostatic 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 to range from 1-4 MPa. 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.

(9) In studies initiated under partial support of this grant, Uenishi and Rice (2002) analyzed the nucleation of instability on a slip-weakening fault subjected to a heterogeneous, locally peaked "loading" stress; see Figure 7. That stress is assumed to gradually increase due to tectonic loading but to retain its peaked character. The case of a linear stress versus slip law is considered in the framework of two-dimensional quasi-static elasticity for a planar fault. Slip initiates when the peak of the loading stress first reaches the strength level of the fault to start slip weakening. Then the size of the slipping region grows under increased loading stress until finally a critical nucleation length is reached, at which no further quasi-static solution exists for additional increase of the loading. That marks the onset of a dynamically controlled instability. We proved that the nucleation length is independent of the shape of the loading stress distribution. Its universal value is proportional to an elastic modulus and inversely proportional to the slip-weakening rate, and is given by the solution to an eigenvalue problem. That is the same eigenvalue problem as introduced by Dascalu, Ionescu and Campillo (2000) for dynamic slip nucleation under spatially uniform pre-stress on a fault segment of fixed length; the critical length we derive is the same as in their case. To illustrate the nucleation process and to verify its universal feature, we consider specific examples for which the loading stress is peaked symmetrically or non-symmetrically, by employing a numerical approach based on a Chebyshev polynomial representation. Laboratory-derived and earthquake-inferred data were used to evaluate the nucleation size.

Data defining the scaling of radiated energy and stress drop with earthquake size can, with certain assumptions as described by Abercrombie and Rice (2001), be used to define aspects of a slip-weakening relation for slips on earthquake faults, and implications of tha are being considered also for nucleation.

Other studies of nucleation were carried out in the framework of rate and state friction. Those occurrung naturally in the simulation of sequences of earthquakes under ralisticaly slow tectonic loading are described in Lapusta, Rice, Ben-Zion and Zheng (2000) and Lapusta and Rice (2002) discussed under topic **(1)** above. In addition, Perfettini, Schmittbuhl, Rice and Cocco (2001) analyzed nucleation of instability on sliding faults under small ascillations of the normal loading and showed that at conditions near critical stiffness that the effect of such oscillations was greatly amplified by a resonance. That can lead to instability at slightly higher than critical stiffness, but the parameter ranges or the resonance do not seem to be consistent with the mechanisam acting uder tidal excitation.

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The work descriped by Nadia Lapusta in **(1)**, also constituting the major portion of her June 2001 Ph.D. thesis, has led to her selection to receive the 2002 Nicholas Metropolis

Award of the American Physical Society for "outstanding doctoral thesis work in computational physics".

Nontechnical Summary

Theoretical modeling of rupture mechanics based on physically plausible and, when possible, lab-constrained friction laws seeks to model earthquake nucleation and propagation processes, to understand the mechanisms by which pore fluids in fault zones interact with the rupture process, and to explain the complex sequences by which failure occurs in rupture through arrays of interacting faults.

Scientific papers:

M. Cocco and J. R. Rice, "Pore pressure and poroelasticity effects in Coulomb stress analysis of earthquake interactions", *Journal of Geophysical Research*, in press, 2002.

A. Cochard and J. R. Rice, "Fault rupture between dissimilar materials: Ill-posedness, regularization and slip-pulse response", *Journal of Geophysical Research*, **105**, 25,891-25,907, 2000.

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H. Perfettini, J. Schmittbuhl, J. R. Rice and M. Cocco, "Frictional response induced by time-dependent fluctuations of the normal loading", *Journal of Geophysical Research*, **106**, 13,455-13,472, 2001.

A. N. B. Poliakov, R. Dmowska and J. R. Rice, "Dynamic shear rupture interactions with fault bends and off-axis secondary faulting", *Journal of Geophysical Research*, in press, 2002.

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R. E. Abercrombie and J. R. Rice, "Small earthquake scaling revisited: Can it constrain slip weakening?", *EOS Trans. Amer. Geophys. Union*, vol. 82, no. 47, Fall Meet. Suppl., Abstract S21E-04, 2001.
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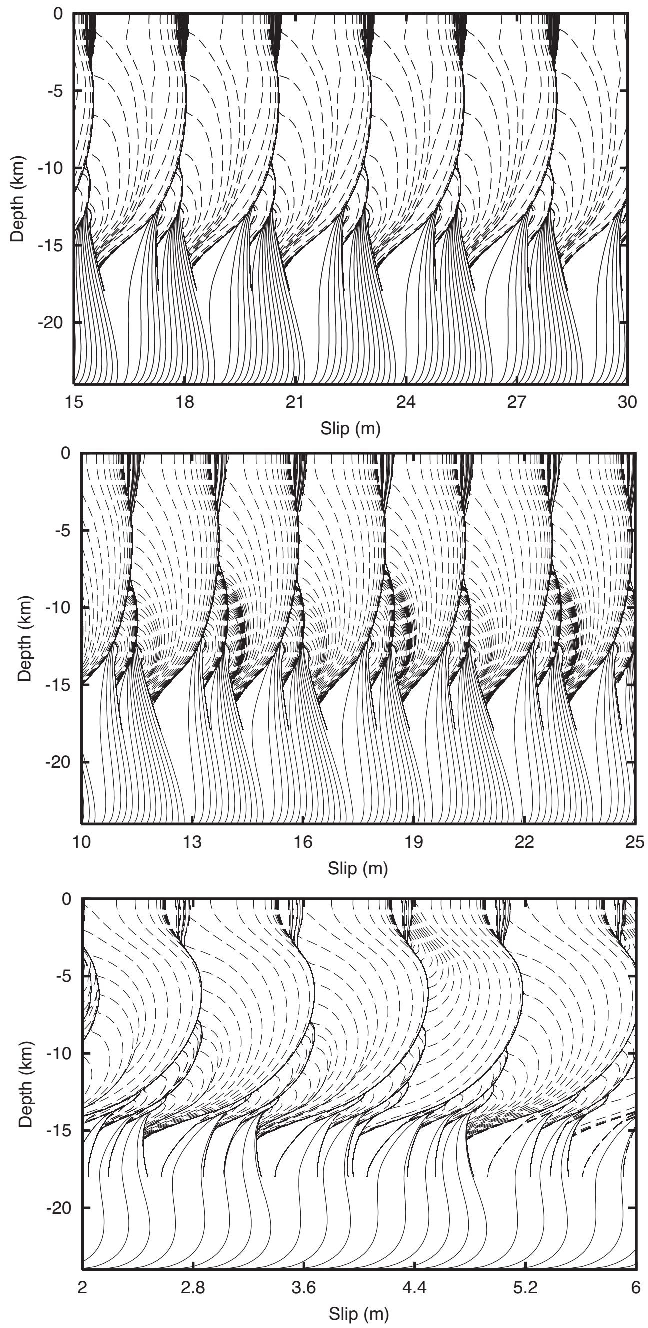
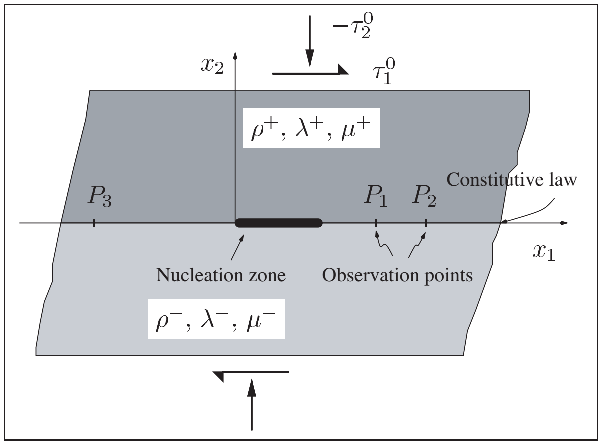


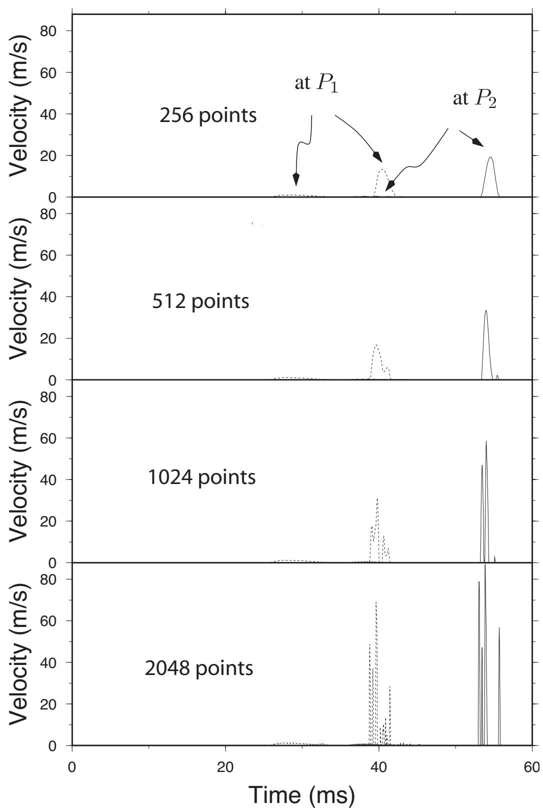
Figure 1. Accumulation of slip versus depth for the cases with $L = 2$ mm, all dynamic effects included (top); $L = 2$ mm, dynamic stress transfers ignored (middle); $L = 0.14$ mm, dynamic stress transfers ignored (bottom). The solid lines are plotted every 5 years. The dashed lines are plotted above 18 km depth every second if the maximum velocity anywhere on the fault exceeds 1 mm/s. Notice that small events appear at the transition from the creeping to locked behavior (sequences with larger L, e.g., $L = 8$ mm, do not have small events). For $L = 2$ mm (top, middle), the event sequence consists of a large and a small events. For $L = 0.14$ mm (bottom) the event sequence is more complex, consisting of a large event, a small event, an "intermediate" event, and another small event. (Modified from *Lapusta and Rice* (2002).)

Figure 2

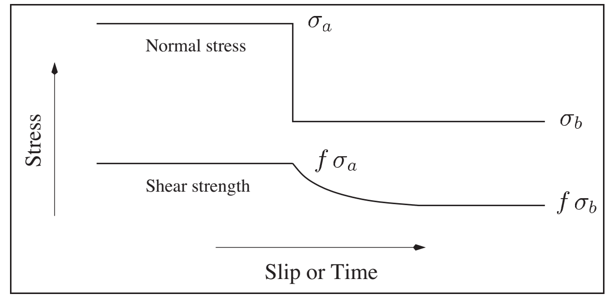
SLIP-RUPTURE ALONG BI-MATERIAL INTERFACES
A. Cochard, K. Ranjith and J. R. Rice



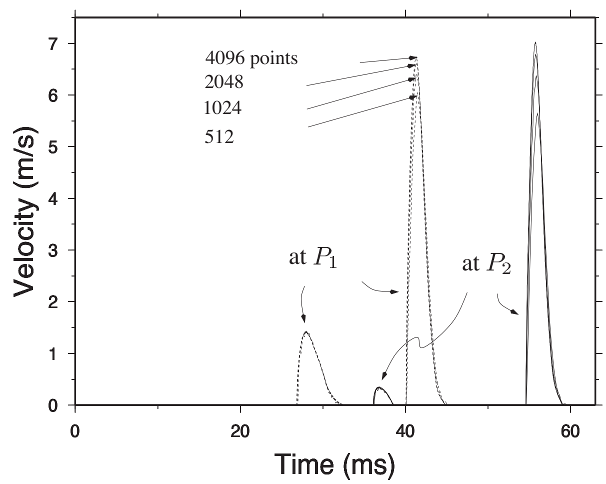
(a) Two dissimilar solids in frictional contact. Sub-critical pre-stress, below friction threshold. Slip rupture nucleated by reduction of normal stress in nucleation zone.



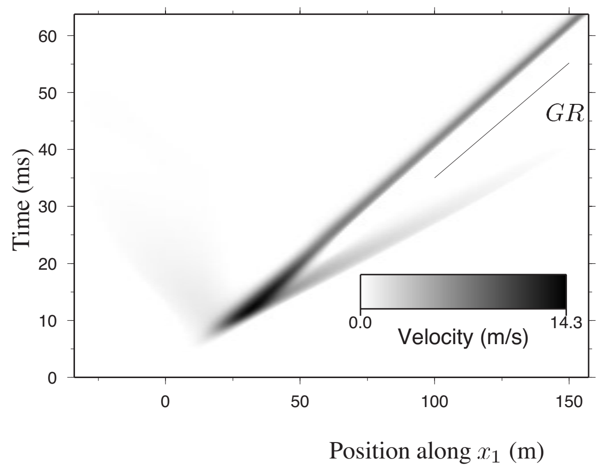
(b) Use of classical Coulomb friction, $\tau = f\,\sigma$, at the interface, with a constant coefficient of friction f, leads to a mathematically ill-posed problem, at least for the material parameters chosen here.; no solution exists. In the numerical simulation, this shows as a lack of convergence with increasing refinement of the grid. This simulation involves the same choice of parameters (with 20% mismatch of shear speeds and density, identical Poisson ratios 0.25, and f = 0.6) as in Andrews and Ben-Zion, J. Geophys. Res., 1997.



(c) A regularization suggested by the Prakash-Clifton oblique shock impact experiments. They find no sudden change of shear strength in response to a sudden change of normal stress. We thus modified the Coulomb law $\tau = f\,\sigma$ to $d\tau / dt = -(V / L)(\tau - f\,\sigma)$; V is slip rate and L a characteristic slip distance.



(d) With the modified friction law, the ill-posedness is removed (Ranjith and Rice, J. Mech. Phys. Solids, 2001). The numerical simulation then converges with grid refinement, and shows a rupture which propagates as a self-healing pulse of slip.



(e) The slip pulse propagates at a speed which closely approaches the generalized Rayleigh speed for the bi-material pair.

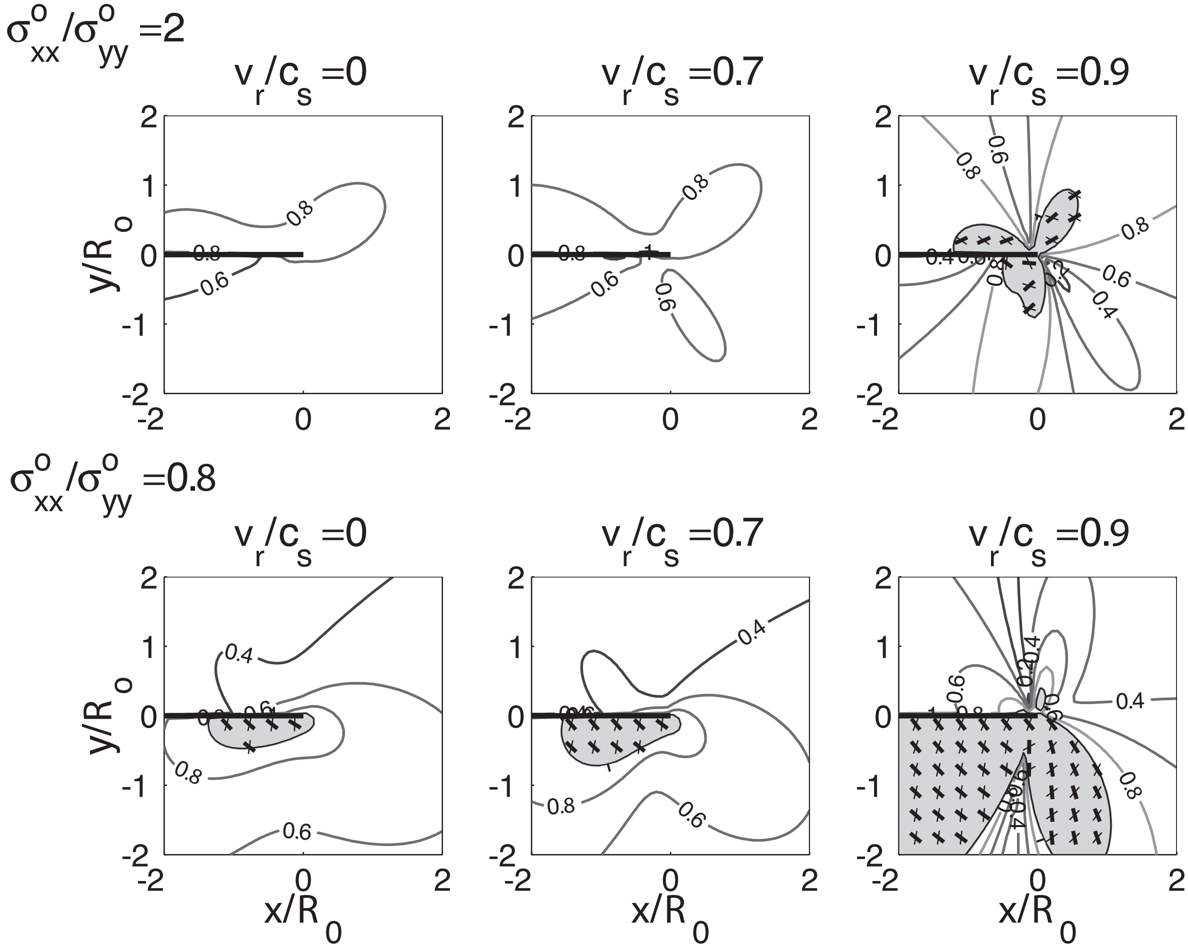


Figure 3: Predicted zones of Mohr-Coulomb rupture based on stress field of a rapidly propagating slip-weakening rupture in an otherwise elastic solid. Top row shows case of shallow angle ψ of principal stress S_{max} with the fault; bottom row is for a steep angle. Steep angle favors failure on the extensional side. Here v_r is rupture speed, c_s is shear wave speed. (Poliakov, Dmowska and Rice, 2002)

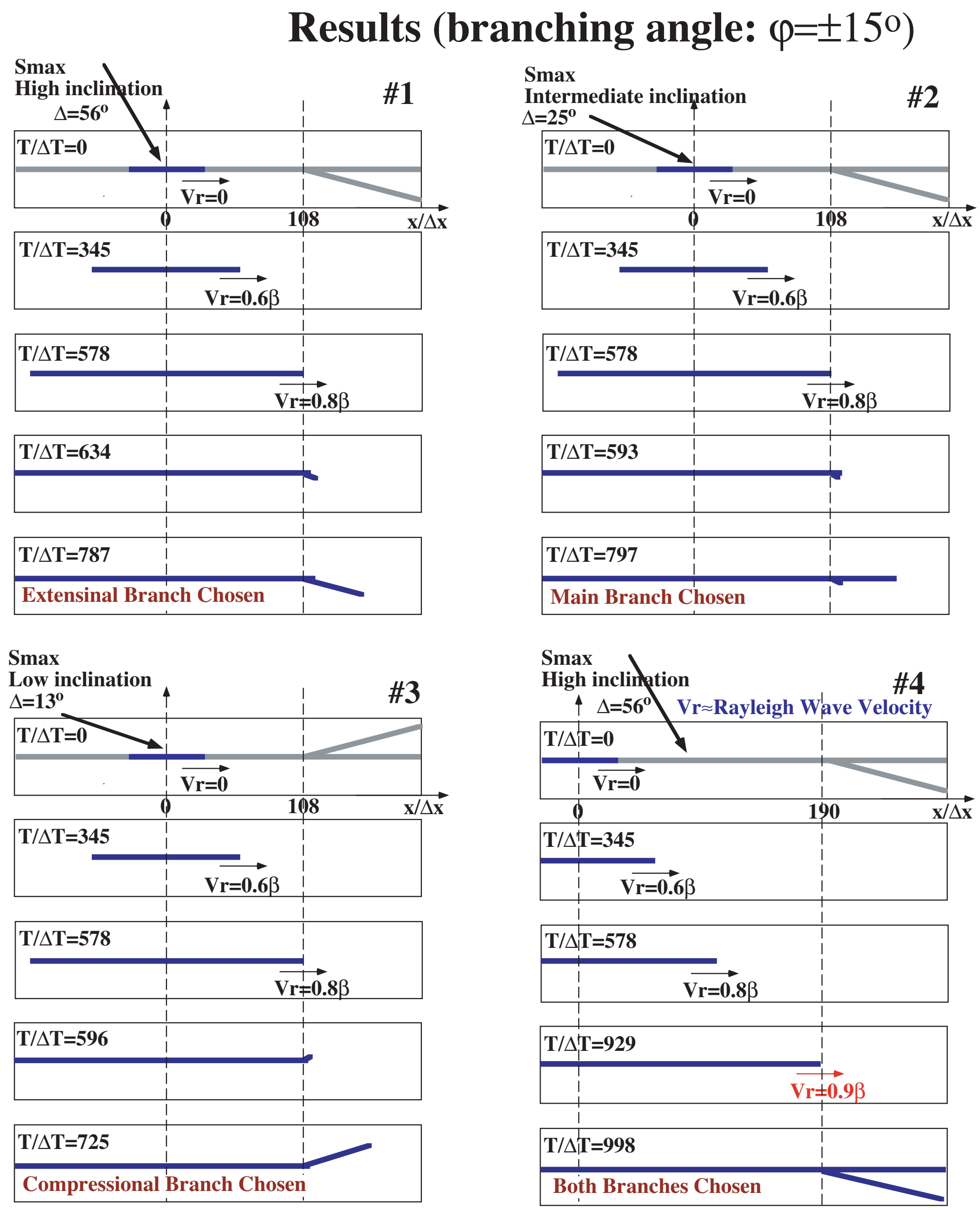


Figure 4: Four represesentative cases of boundary integral equation dynamic simulations (Kame, Rice and Dmowska, 2001), showing correlation of choice of branch direction with angle ψ (labeled Δ here) of principal stress S_{max}

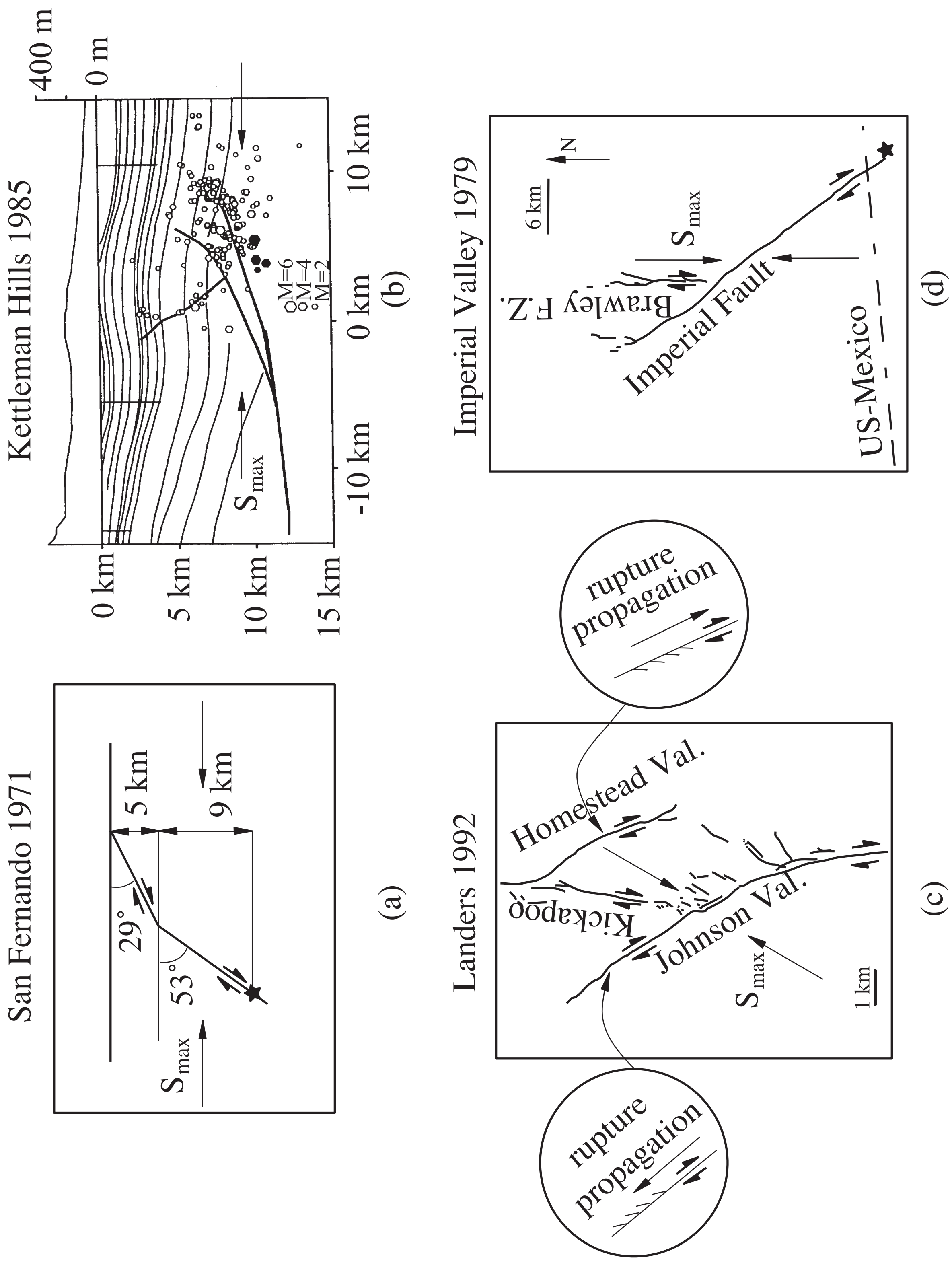


Figure 5: Natural examples of branching and correlation in terms of pre-stress direction (Dmowska, Rice and Poliakov, 2001; Poliakov, Dmowska and Rice, 2002)

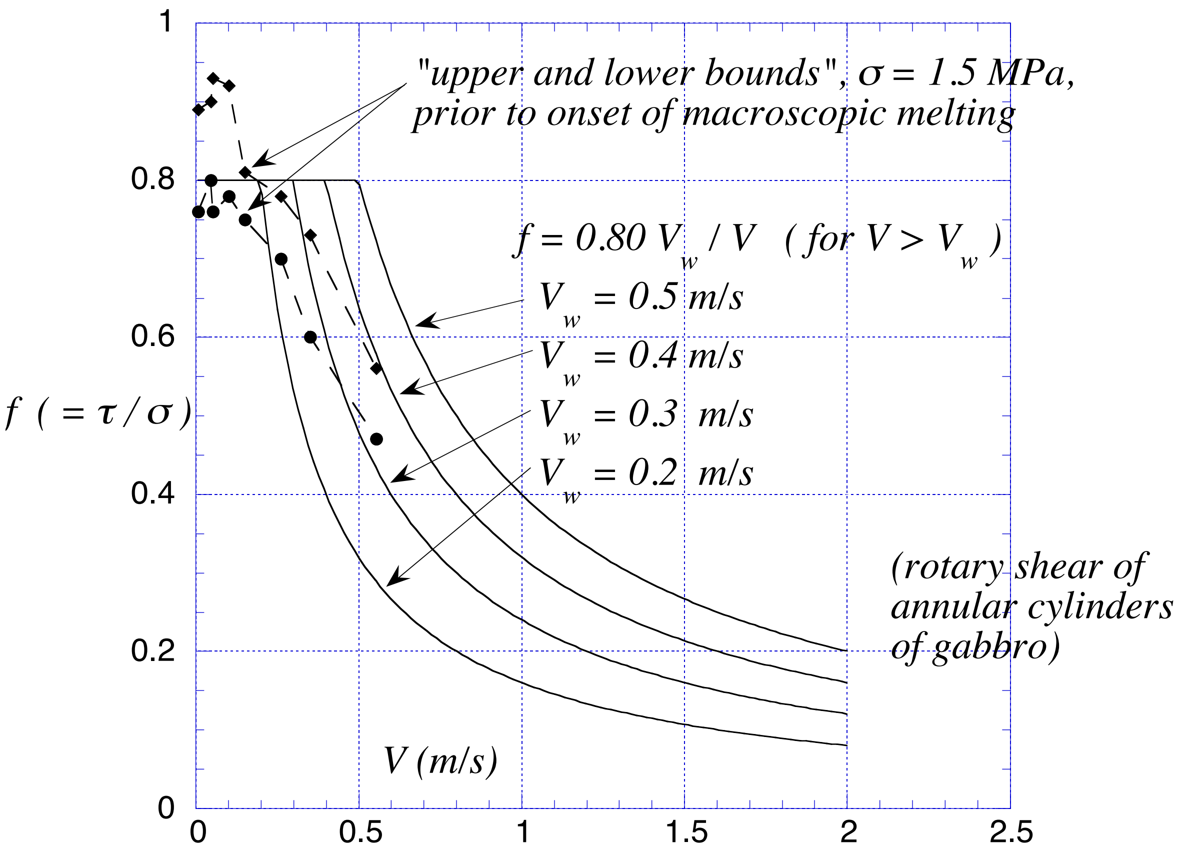
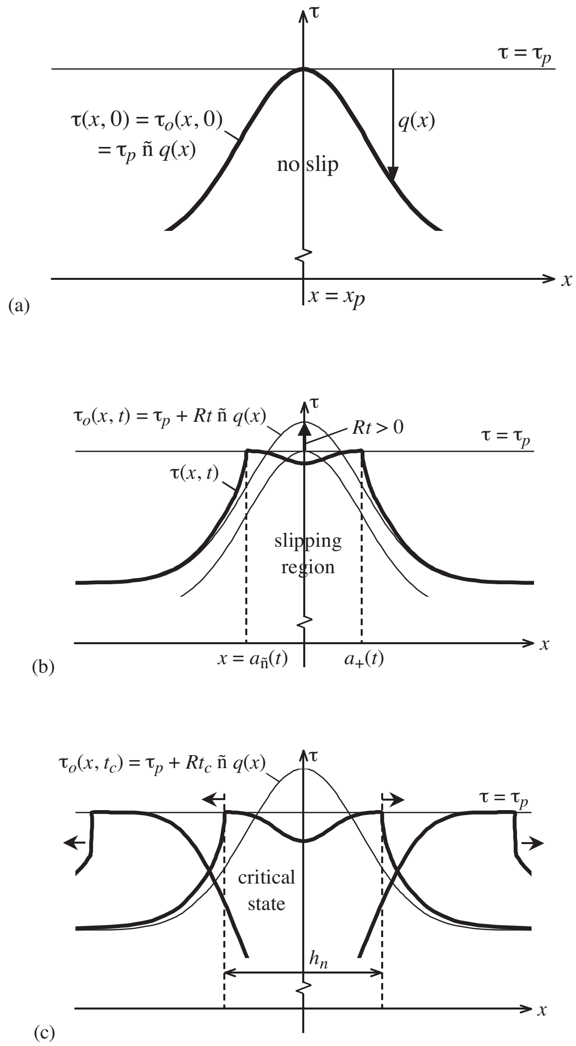
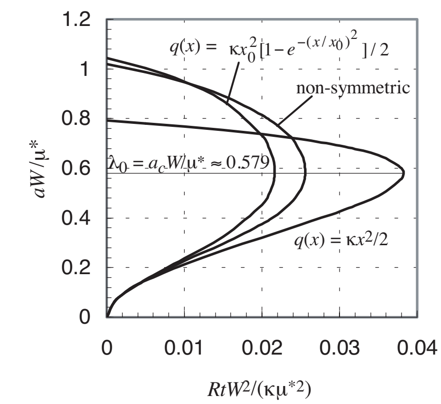


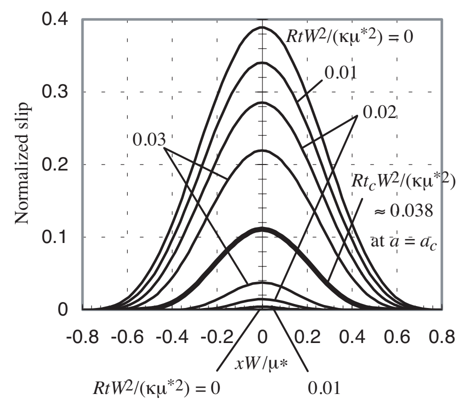
Figure 6: Data of Tsutsumi and Shimamoto (GRL, 1997) for frictional weakening as a function of slip rate in gabbro, for small slips prior to macroscopic melting, compared to solid lines showing the theoretical model presented here.



Development of the slipping region induced by the increasing loading stress. (a) At time $t = 0$, the peak of the stress distribution reaches the peak strength of the fault, τ_p. Prior to this stage, no slip has occurred; (b) At $t > 0$, part of the fault slips and the stress inside the slipping region drops according to the slip-weakening friction law; and (c) At a later stage, when the length of the slipping region reaches a critical value, h_n, the fault system becomes unstable and the slipping region will expand even without any increase of the loading stress. We show that h_n is independent of R and $q(x)$.



The development of the slipping region half-length a for three different loading distributions of $q(x)$. The parameter $x_0W/\mu^* = 1/3$ for $q(x) = \kappa x_0^2[1 - e^{-(x/x_0)^2}]/2$ and for the non-symmetric loading case. Only the lower branches of the curves are physically meaningful if the loading stress is monotonically increasing in time. Instability occurs when the slope becomes unbounded (right extremities of the curves; $da(t)/dt \to \infty$) all of which correspond to the same nucleation size.



The development of the normalized slip distribution, $W^3\delta/(\kappa\mu^{*2})$, for loading with $q(x) = \kappa x^2/2$. The heavy line is the unstable limit to the range of existence of quasi-static solutions under monotonic increase of the loading stress.

Figure 7: Analysis of rupture nucleation under non-uniform stressing of a slip-weakening fault surface (Uenishi and Rice, 2002). For a linear decrease of strength with slip, the length of the slipping region at nucleation is found to be independent of the form of the (locally peaked) loading stress distribution.