SCEC award 15009 – The role of seismogenic depth on rupture across stepovers and damage zone thickness - Final report

Summary

The goal of this project was to determine relations between fault zone structure and earthquake source properties by elucidating the mechanical connections between long-term fault zone evolution and earthquake dynamics. Here, we specifically addressed two questions: What controls the width of the splay fault fan at the tip of major faults? Does the systematic decrease of fault zone maturity along strike that results from long-term fault growth affect earthquake slip distribution and rupture speed? Empirical observations that motivate these questions were synthesized and fundamental aspects of the problem were studied by combining theoretical fracture mechanics and large-scale 3D simulations.

Inner damage zone thickness

Faults are typically surrounded by an "inner damaged zone" characterized by distributed fractures and micro-cracks. Its thickness is defined from geological field observations as a characteristic length of the decay of fracture density as a function of distance from the fault core (e.g. Mitchell and Faulkner, 2009; Savage and Brodsky, 2011). It also corresponds to the low velocity or compliant fault zones identified by seismological and geodetic methods (e.g. Huang and Ampuero, 2011; Yang, 2015).

Our dynamic rupture studies indicate that the presence of a damaged zone can affect rupture dynamics in significant ways. Trapped and guided waves in a low-velocity fault zone can interact with the rupture to generate healing fronts and promote pulse-like rupture or premature rupture arrest, periodic modulation of slip rate and off-fault dynamic damage, transition to supershear rupture at relatively low background stress, and rupture at speeds that are theoretically unexpected for steady ruptures in homogeneous media (Huang and Ampuero, 2011; Huang et al., 2014, 2015; Pelties et al., 2014). One of the key fault zone parameters controlling these phenomena is the thickness H of the damaged zone. Field observations show that H is roughly proportional to accumulated slip (S) for faults with small S, but tends to saturate at a few 100 m for mature faults with large S (Mitchell and Faulkner, 2009; Savage and Brodsky, 2011).

We proposed a mechanical explanation of the origin of this maximum fault zone thickness $\boldsymbol{H_{max}}$ (Ampuero and Mao, 2016). In particular, we showed that H_{max} is a small fraction of the seismogenic zone depth (W). We assumed that the dominant mechanism sustaining the inner damage zone is coseismic off-fault damage. Fracture mechanics provides the following estimate of the thickness of an off-fault yielding zone: $H \approx K^2/(\tau_s - \tau_0)^2$ where K is the stress intensity factor characterizing the concentration of stresses near the rupture tip ($\sigma \sim K^2/\sqrt{\pi r}$). We found quantitative agreement between this estimate and the results of 2D dynamic rupture simulations with off-fault plasticity (Xu et al, 2014a, b). In 3D, an elongated rupture of length L much longer than its width W in an elastic half-space has $K \sim \Delta\tau\sqrt{W}$ at its lateral tips: stress concentration is controlled by the shortest rupture dimension W (Day, 1982). Hence, for large strike-slip earthquakes, the seismogenic depth places a limit on the width of coseismic off-fault yielding: $H_{max} \approx \left(\frac{\tau_0-\tau_d}{\tau_s-\tau_d}\right)^2 W$.

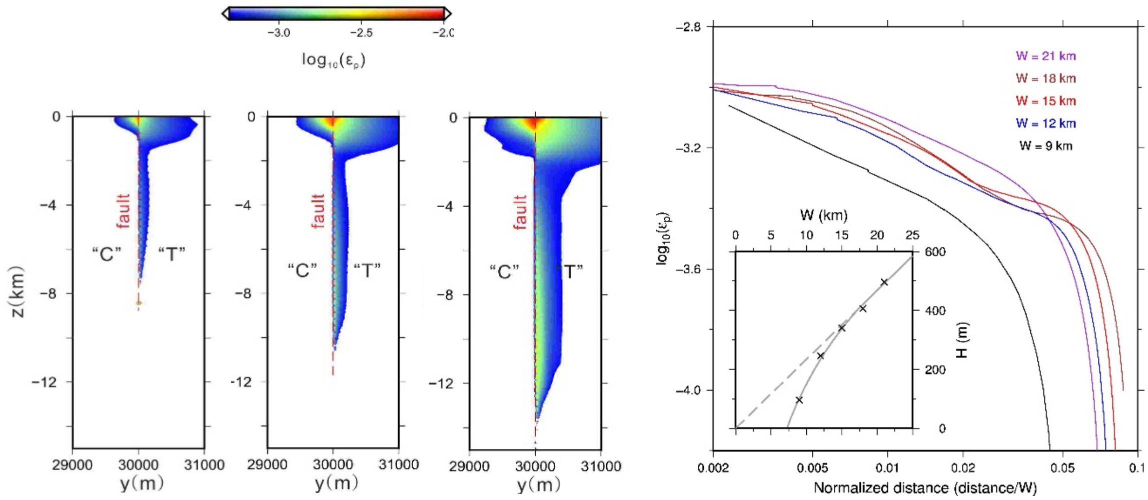

Figure 1. Left: depth cross-section view of plastic strain generated by ruptures with different seismogenic depths, W=9, 12 and 15 km, respectively. Fault length is much larger in all cases. Right: cross-fault decay of plastic strain at 5 km depth for five cases with different W. Inset: Damage zone thickness H at middle depth (defined here by a threshold of plastic strain ∼ 0.001) increases linearly with W, asymptotically when W is large.

We conducted 3D dynamic rupture simulations to study off-fault damage distributions generated by rupture propagation on strike-slip faults with large aspect ratios L/W. The off-fault plastic response is described by the Drucker-Prager yield criterion with visco-plastic regularization. The simulations included the effect of the free surface and a reasonable depth-dependent distribution of stress and strength. Our simulations confirmed that H_{max} is linearly related to W, asymptotically when W is large (see inset in figure 1-right). The predicted H_{max} is about two orders of magnitude smaller than W, that is, a few 100 m. For faults shorter than *W* the predicted *H* scales instead with *L*. Both predictions are consistent with field observations synthesized by Savage and Brodsky (2011).

Outer **damage zone thickness**

Faults grow laterally over geological time scales as they accommodate increasing deformation. They typically develop a network of macroscopic secondary fault branches. The younger fault branches often organize near the tips of the main fault into splay fault fans (Figure 2). We refer to the splay fault zone as the “outer damage zone”, to distinguish it from the “inner damage zone” defined through micro-fracture observations. By analyzing mapped traces of multiple active fault networks, Perrin et al. (2015) found that the width (W_{sp}) of splay fault fans scales with the main fault length *L*, and does not saturate (Figure 2-bottom).

We proposed a fracture mechanics model to explain this observation. Lehner et al. (1981) developed approximate expressions for the stress intensity factor at the tips of a fault cutting through the whole depth of an elastic plate (the lithosphere) that overlies a linear viscoelastic half-space (the asthenosphere). They found that at short times $\propto \sqrt{W}$, the scaling expected in an elastic half-space, as in the previous section. However, at times much longer than the characteristic viscous relaxation time of the asthenosphere they found $K \propto \sqrt{L}$, the scaling of a through-going crack in an elastic plate decoupled from the mantle, essentially a 2D plane strain configuration (see figure 5 of Lehner et al., 1981). The growth of splay fault fans is a long-term process. If it is driven by stress concentration near the propagating tip of the main fault under the long-term scaling of K, we predict a scaling law $W_{sp} \propto L$ qualitatively consistent with the geological observations.

These different predictions of scaling behavior help us identify aspects of fault zone evolution that are controlled by either short-term or long-term damage processes. Our insight indicates that short-term damage processes are essential in the evolution of fault zone structure, in particular of the inner damage zone. While our dynamic rupture simulations emphasize inner damage occurring over co-seismic time scales, a similar saturation of damage zone thickness is predicted for slower, quasi-static damage processes, because the static stress intensity factor K_0 is also limited by W. However, if inner damage were controlled by time scales longer than deep afterslip and longer than the relaxation time of the asthenosphere, the relevant model would be a through-going crack in a thin elastic slab and the inner damage zone thickness would not saturate. This would contradict the observations.

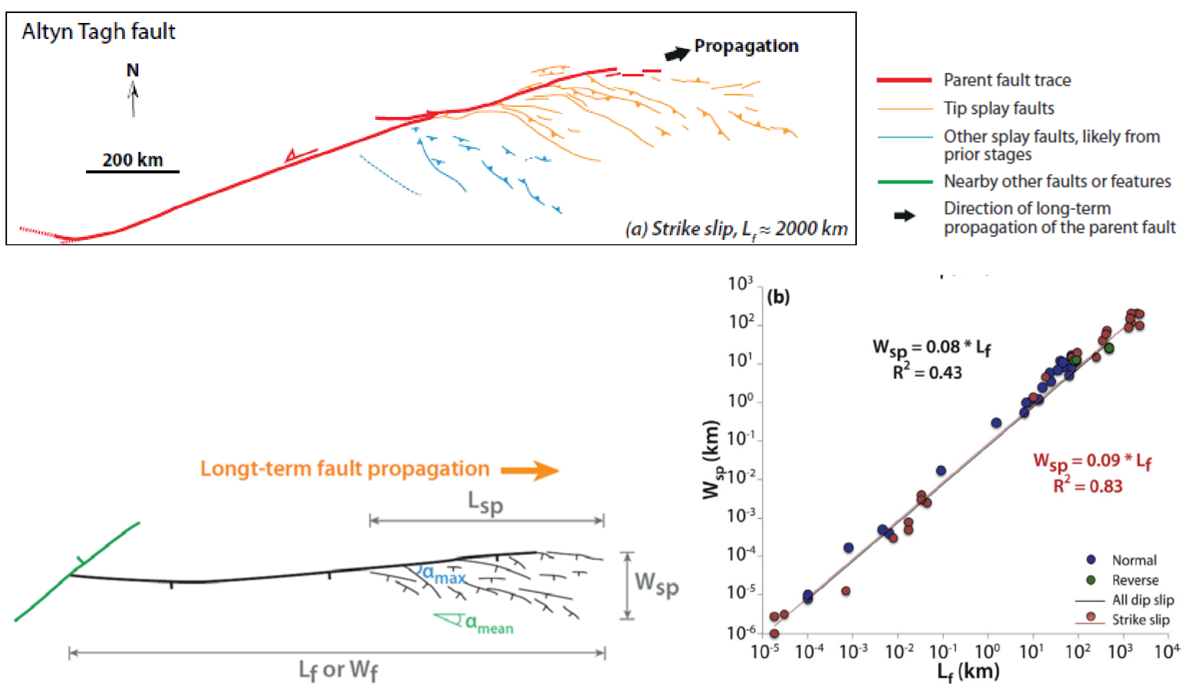

Figure 2. Splay fault fans (defined here as the "outer damage zone") and their relation to long-term fault growth. The width of the outer damage zone Wsp for a number of mapped faults is found to scale with the length of the main fault L (Perrin et al., 2015).

We also aimed at developing this conceptual model into a quantitative prediction that can be compared to observations. This was attempted by conducting 3D simulations of stresses near the tips of growing faults under kinematic boundary conditions, considering a finite elastic layer over a non-linear viscous half-space. Analysis of the stress outputs of these kinematic models are helping us calibrate simplified relations between K, W, L and time with a mathematical form inspired from the approximate results for linear viscosity of Lehner et al. (1981). An initial set of simulations with prescribed slip was done with the community code Relax available through the Computational Infrastructure for Geodynamics (https://geodynamics.org/cig/software/relax/). A more complete set of simulations prescribing a stress drop instead and varying the rheology is still ongoing.

We anticipate to progressively expand the modeling scope in order to examine how the geometry of the outer damage zone is affected by the ratio between recurrence time of characteristic earthquakes and the viscous relaxation time scale. This should provide a mechanical characterization of the role of tectonic slip rate on the maturity and structural evolution of fault networks.

Role of fault maturity on earthquake dynamics

The presence and orientation of a splay fault fan is an indicator of the direction of long-term fault propagation (figure 2-top). Fault growth induces a systematic distribution of maturity (age and cumulated slip) along the fault: the younger fault segments with shorter total slip naturally lie near the propagating tip(s). Here we have studied the implications of this systematic maturity variation on earthquake source properties.

In Perrin *et al.* (2016), in collaboration with Géosciences Azur (France), we analyzed the along-strike distribution of coseismic slip of more than 30 earthquakes and the structure of the fault networks that hosted them. We found that the area of largest slip systematically lies in the portions of the rupture that are farther away from the long-term fault propagation tip, that is, on relatively older fault sections (figure 3-right). We also found a tendency for rupture speeds to be faster along these older sections of the ruptured faults, although with fewer cases and larger uncertainties (figure 3-right). We proposed that both larger slip and faster rupture on older fault segments are related to the more intense damage expected in the inner damage zone of more mature segments. In fact, our 2D dynamic rupture simulations on pre-damaged fault zones (Huang *et al.*, 2014, 2015) showed that zones with higher damage (older, lower elastic rigidity) facilitate the transition to supershear rupture. Moreover, for a given stress drop, a lower shear modulus (older, more damaged fault) leads naturally to larger slip.

To turn this conceptual model into a quantitative one, we have set up the computational tools to do simulations of dynamic rupture with inner damaged fault zones that have lateral (along-strike) distributions of damage. We have developed a spectral representation of the 2D elastic stress transfer kernel on a fault surrounded by a damage zone for implementation in our quasi-dynamic earthquake cycle simulator QDYN (http://ydluo.github.io/qdyn/). We can postulate a convenient functional form with few parameters to describe the spatial along-strike distribution of damage, and seek parameter values leading to simulated slip profiles that match the observed degree of asymmetry of coseismic slip distributions. Such simulations can also address the question of rupture speed, and can be complemented with 2D earthquake cycle simulations with fixed damaged zone structure (Kaneko et al, 2011). A parametric study of the problem is ongoing.

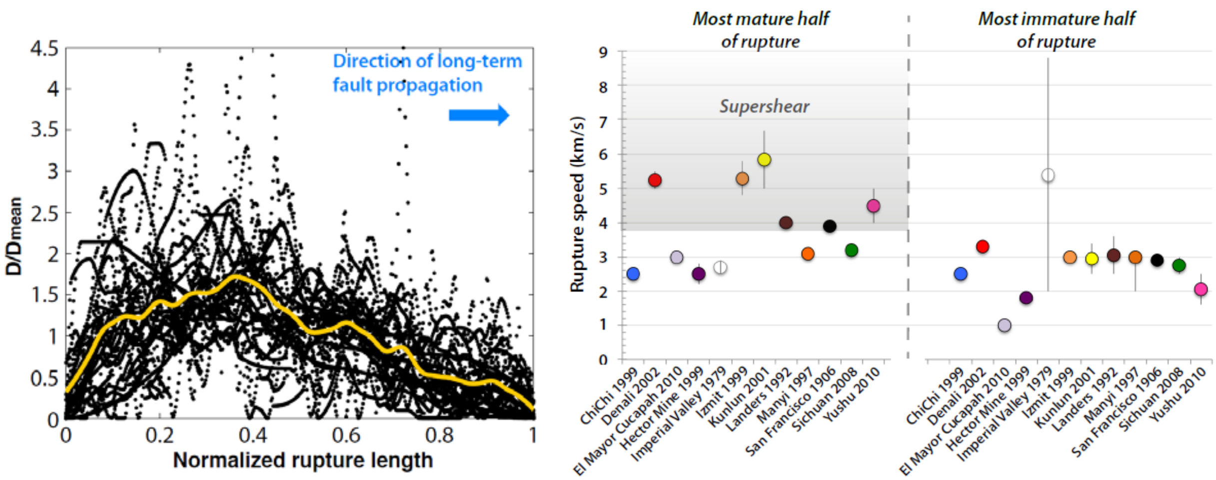

Figure 3, from Perrin et al (2016). Left: Surface slip profiles from 30+ earthquakes, normalized by their rupture length and mean slip, and oriented so that the direction of long-term fault propagation (inferred from splay fault fans and other structural indicators) is on the right of the figure. In yellow is the running average curve for the entire collection of slip profiles. Right: Rupture speeds estimated for 12 earthquakes, along the most mature and along the most immature halves of the ruptures. There is a tendency for faster propagation, sometimes with supershear speed, along the most mature part of the ruptures.

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