Technical Report

Constraining friction properties of mature low-stressed faults such as SAF

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1. Summary of the results

A number of observations suggest (section 3) that well-developed, mature faults such as the San Andreas Fault (SAF) are generally "weak," i.e. operate at low overall levels of shear stress in comparison with what would be expected from Byerlee's law and numerous laboratory experiments on quasi-static or low-slip-rate friction (e.g., Byerlee, 1978; Dieterich, 1979, 1981; Tullis and Weeks, 1986; Blanpied et al., 1991, 1995; Marone, 1998; Wibberley et al., 2008 and references therein). If typical low-slip-rate friction coefficients of 0.6-0.8 are multiplied by overburden minus hydrostatic pore pressure, ~150 MPa at the representative seismic depth of 8 km, one obtains shear strength values of ~100 MPa. Faults that operate at much lower levels of stress (~10-20 MPa) are called "weak" and their strength is called "low."

We have been simulating sequences of earthquakes and aseismic slip in different models for "weak" mature faults, aiming to determine which friction and other fault properties in such models are compatible with a range of available observations such as static stress drops of 1-10 MPa, the observed variations of the breakdown energy and radiated energy with the seismic moment, and the absence of pervasive melting in shear zones. Our eventual goal is to establish which among the acceptable models have behaviors specific to the SAF, including seismic quiescence between large events for some SAF segments and paleoseismic data.

We have continued developing methodologies for computing seismological parameters such as stress drop, breakdown energy, and radiation efficiency based on our simulations (Lin and Lapusta, 2018; Perry et al., 2019; Lambert et al., 2019), both (i) directly from the simulated earthquake sources and (ii) indirectly from other observables as it is done for natural earthquakes (e.g., Kanamori and Brodsky, 2004; Rice, 2006; Viesca and Garagash, 2015; Ye et al., 2016a-c). We have found that fault models with rate-and-state friction and moderate enhanced co-seismic weakening in the form of thermal pressurization are consistent with a number of observationally inferred trends including magnitude-independent stress drops, breakdown energy increasing with earthquake moment, and radiation ratios of about 0.5 (Figure 1; Perry et al., 2018). Moreover, we have established that the indirect, seismologically inferred values of breakdown energy and radiation efficiency are comparable, within a factor of two, to direct, source-based values for crack-like and moderately pulse-like ruptures, which result in the final levels of shear stress similar to the dynamic levels, with overshoots/undershoots small compared to the average stress drop (Figure 1; Perry et al., 2019). These results suggest that the rate-and-state fault models with moderate enhanced weakening due to thermal pressurization may be potentially plausible representations of mature faults. However, the conditions that we have found to reproduce the inferred trends and maintain temperatures below those at which one would expect pervasive melting of the fault core require low effective confining stresses (i.e., 25 MPa or less) and hence substantial chronic fluid overpressurization, in addition to enhanced weakening due to thermal pressurization.

Simulations including more pronounced enhanced co-seismic weakening, such as through more efficient thermal pressurization, allow for lower-heat operation of quasi-statically stronger faults, but result in sharper self-healing pulse-like ruptures, with pronounced undershoot (Figure 2). The indirect, inferred values of the breakdown energy and radiation efficiency for sharper pulse-like ruptures – the ones with the rise time much smaller than the overall rupture duration – can be quite different from the actual values (Figure 2; Lambert et al., 2019). The much higher radiated efficiencies of the simulated sharper pulses compared to the typical seismological inferences suggest that either large earthquakes are rarely sharply pulse-like, or the seismically estimated radiated energy from sharp pulse-like ruptures is several times underestimated (see section 5 for more details).

2. Relevance of the project goals to the objectives of SCEC

Our project addresses the following SCEC Research Priorities:
P1.c. Constrain how absolute stress and stressing rate vary laterally and with depth on faults
P3.c Assess how shear resistance and energy dissipation depend on the maturity of the fault system
P1.d Quantify stress heterogeneity on faults at different spatial scales
P5.a. Develop earthquake simulators that encode the current understanding of earthquake predictability.
Our study will determine which models of low-stresses faults are consistent with basic observations and hence put constraints on the absolute levels of both shear and effective normal stress at all depths, contributing to priority P1.c. Our efforts towards studying the seismological observables and energy budget for all our simulated events will contribute to P3.c. We will study which levels of roughness-motivated heterogeneity on faults is consistent with seismic quiescence observed for several SAF segments, thus contributing to priority P1.d. We will also contribute to P1.d by quantifying the resulting variability of stress before large events. Our goal to produce models of low-stressed SAF segments consistent with basic observations will help towards developing realistic earthquake simulators with predictive power, as in P5.a. The proposed modeling significantly contributes to a number of research priorities of FARM, including "Constrain how absolute stress, fault strength and rheology vary with depth on faults," and "Determine how seismic and aseismic deformation processes interact." Confirming that "weak" fault models with low shear stress values are compatible with available observations will contribute to the Community Stress Model.

3. Evidence for "weak" mature faults and two classes of models

The outflow of heat observed for SAF and other mature faults implies that shear stresses acting during sliding are of the order of 10 MPa or less (e.g., Brune et al., 1969; Henyey and Wassenburg, 1971; Lachenbruch and Sass, 1973, Lachenbruch, 1980, Nankali, 2011). Analyses of the fault core obtained by drilling through shallow parts of faults that have experienced major recent events, including the great 2011 Mw 9.0 Tohoku-Oki event, point to co-seismic friction coefficients as low as ~0.1 (e.g., Tanikawa and Shimamoto, 2009; Fulton et al., 2013). Low values for shear stresses acting on major faults including SAF are also supported by the inferences of steep angles between the principal stress direction and fault trace (e.g., Townend and Zoback, 2004; Zoback et al, 2007), significant rotations of principal stress directions due to stress drop in earthquakes as judged by the focal mechanisms of microseismicity (e.g., Wesson and Boyd, 2007), geometry of thrust-belt wedges (e.g., Suppe, 2007), and scarcity of pseudotachylytes, the products of solidifying rock melts (e.g., Sibson, 1975; Rice, 2006).

Two classes of models can explain earthquake occurrence under low shear stress. In the first class, the quasi-static friction is high on average, but fault resistance to slip weakens substantially at seismic slip rates as supported by lab experiments (Tullis, 2015 and references therein; Noda et al., 2009; Noda and Lapusta, 2010, 2013; Jiang and Lapusta, 2016). Earthquake rupture initiates in places of stress concentrations and/or statically weak spots and propagates over the rest of the low-stressed fault due to co-seismic weakening, making the fault appear weak. In the second one, the faults are chronically weak, both during slow (quasi-static) and fast (seismic) slip, due to either low friction coefficients, or low effective normal stress, or both. Such models are supported by low quasi-static friction coefficients for some minerals in the lab (although most of them are also rate-strengthening) and observations of fluid overpressure (e.g., Brown et al., 2003; Faulkner et al., 2006; Bellot, 2008; Bangs et al., 2009; Collettini et al., 2009; Fulton and Saffer, 2009; Carpenter et al., 2011; Lockner et al., 2011). Note that fluid overpressure may be confined to the immediate vicinity of the fault (e.g., Rice, 1992) (and hence not readily observable by bulk velocity studies), due to much higher along-fault permeability compared to the surrounding rock.

While both classes of models can explain fault operation under low shear stress, other aspects of their behavior should exhibit substantial differences. Chronically weak faults operate at the average shear stress levels close to the average static fault strength. For the statically strong but co-seismically weak faults, the average shear stress on the fault is much lower than its average static strength. One expected consequence of this difference is in the temporal and spatial patterns of microseismicity occurrence in the two models (e.g., Jiang and Lapusta, 2016; 2017). Another potential difference is in the energy budget and radiation efficiency that we have been studying in our models.

4. Models with rate-and-state faults and additional co-seismic weakening that produce crack-like ruptures

To enable quantitative comparison of our simulated earthquake sources with observations, we have been developing a methodology for computing source parameters based on our simulations both (i) directly from the simulated earthquake sources and (ii) from seismological observations as it is done for natural earthquakes (Noda and Lapusta, 2012; Noda, Lapusta, and Kanamori, 2013; Perry et al. 2019; Lambert et al., 2019). We can now compute (i) the actual energy balance for the simulated events in our models and the energy-related quantities, including the total strain energy released, total dissipated energy, breakdown energy, radiated energy, and radiation ratio (also called radiation efficiency), (ii) the actual source-based average stress drops, and (iii) estimates of stress drops, breakdown energy, and radiation efficiency as done for observations.

Comparing these values between our models and natural events has enabled us to gain valuable insights, and we will focus only on some of them here. In computing the radiation efficiency for natural events (e.g., Venkataraman and Kanamori, 2004), the intent is to compute η^R from (1) below, and it is estimated to be equal to η^R_{seis} using the standard energy analysis (without overshoot or undershoot):

$$\eta^R = \frac{E_R/A}{E_R/A+G}, \; \eta^R_{seis} = \frac{E_R/A}{(\frac{1}{2}\overline{\Delta u}\,\overline{\Delta\sigma})} \qquad (1)$$

where E_R/A and G are the total radiated and breakdown energies per unit rupture area, respectively, and $\overline{\Delta u}$ and $\overline{\Delta\sigma}$ are the average slip and stress drop, respectively, $E_R/A + G$ is the available energy for radiation and breakdown per unit area, and $\frac{1}{2}\overline{\Delta u}\,\overline{\Delta\sigma}$ is the estimate of the available energy based on no undershoot/overshoot. Clearly, $\eta^R \leq 1$, but its estimate η^R_{seis} does not have to be (e.g., Noda et al., 2013).

We found that models with moderate enhanced co-seismic weakening due to thermal pressurization of pore fluids result in either crack-like or moderately pulse-like ruptures, in which the local rupture duration (rise time) is comparable to or up to 4 times smaller than the overall rupture duration. Such ruptures have (Perry et al., 2019; Figure 1): (1) final shear stress comparable to the dynamic shear stress values, with minor overshoots/undershoots; (2) similar actual and seismologically estimated breakdown energies, radiated energies, and radiation efficiencies, generally within a factor of 2, (3) magnitude-invariant stress drops comparable to observations for a range of event sizes, and (4) increasing breakdown energies with average slip, similar to observations. However, to keep the shear-zone temperature in such models below melting, for model self-consistency (the models do not include constitutive relations for melting) as well as due to observations of scarcity of pseudotachylytes, the products of solidifying rock melts (e.g., Sibson, 1975; Rice, 2006), such models need to assume the effective normal stresses of ~25 MPa or less, for the range of other parameters studied, effectively combining the enhanced dynamic weakening with somewhat chronically weak faults.

5. Models with rate-and-state faults and additional co-seismic weakening that produce self-healing pulses

We have found that models with much more pronounced enhanced co-seismic weakening, such as through more efficient thermal pressurization and more reliably through flash heating, can keep the temperature below melting for statically stronger faults, but result in sharper self-healing pulse-like ruptures, with pronounced undershoot (Lambert et al., 2019; Figure 2), making the standard energy considerations (e.g., Kanamori and Brodsky, 2004) not accurate and yielding substantial discrepancies between seismologically-inferred energy estimates and actual on-fault quantities. The undershoot, which increases with the pulse sharpness, translates into extra available energy, in the words of the standard energy analysis. The work of Viesca and Garagash (2015) assumed that this extra energy goes into breakdown energy. However, in our models, it goes into radiated energy, making η^R_{seis} significantly larger than 1 and resulting in seismological estimates of the average breakdown energy that are negative (Lambert et al., 2019; Figure 2). Observations rarely report such large values of η^R_{seis}, with the observed values generally below one and sometimes slightly larger than 1 (Figure 1, bottom right).

This finding implies that (i) either the large natural earthquakes are rarely dominated by sharp self-healing pulses, or (ii) if such sharper pulse-like ruptures do often occur (e.g. Heaton 1990) their radiated energy is underestimated, by up to an order of magnitude. It is commonly suggested that large earthquakes propagate as slip pulses rather than continuously expanding cracks (Heaton 1990; Viesca and Garagash, 2015), therefore it is important to understand this inconsistency. We are working on expanding our simulations and energy analysis to 3D models with 2D faults and developing tools for computing seismological estimates or radiated energy based on our sources; currently, our analysis uses the exact values of the radiated energy from the simulations determined as the difference between strain energy released and dissipated energy.

Publications

Perry, S., V. Lambert and N. Lapusta, Magnitude-invariant stress drops and increasing breakdown energy in earthquake sequence simulations on rate-and-state faults with thermal pressurization, to be submitted to *J. Geophys. Res.*, 2019.

Lambert, V., Lapusta, N. and S. Perry. Connecting seismological estimates of radiation efficiency with the rupture style of large earthquakes. Manuscript in Preparation.

Lambert, V., and N. Lapusta. Models for the low-heat, low-stress operation of mature faults, Manuscript in Preparation.

Presentations

Lambert, V. and N. Lapusta. Modeling the low-stress operation of mature faults: Investigating the Relation Between Actual and Seismologically-Inferred Quantities using Dynamic Simulations of Earthquake Sequences (Oral presentation), NIED, Tsukuba, Japan, Mar. 2019.

Lambert, V. and N. Lapusta. Energy Budget of Earthquakes: Investigating the Relation Between Actual and Seismologically-Inferred Quantities using Dynamic Simulations of Earthquake Sequences (Oral presentation), 2nd International Symposium on Crustal Dynamics, Uji, Japan, Mar. 2019.

Lambert, V. and N. Lapusta. Modeling the low-heat, low-stress operation of mature faults (Oral presentation), SCEC Community Stress Model Workshop, Pomona, CA, Jan. 2019

Lambert, V., Perry, S., and N. Lapusta. Energy budget of earthquakes: connecting remote obsevations with local physical behavior (Oral presentation), AGU Fall Meeting, Washington DC, Dec. 2018.

Lambert, V., Perry, S., and N. Lapusta. Earthquake Sequences in Rate-and-State Fault Models with Thermal Pressurization (Poster presentation), SCEC annual meeting, Palm Springs, CA, Sep. 2018.

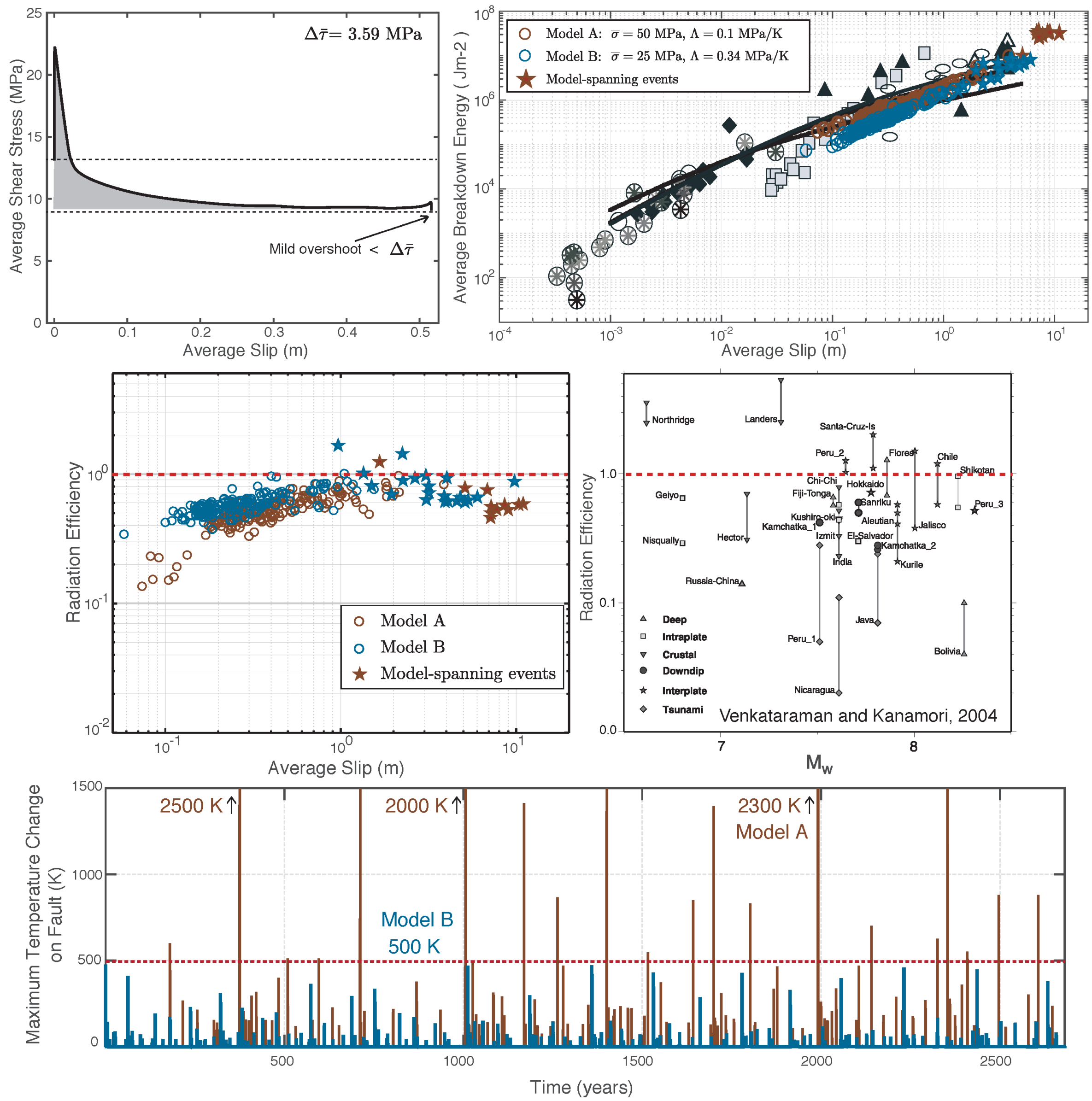

Figure 1: Models that combine chronic fault overpressure with moderate enhanced dynamic weakening produce predominantly crack-like ruptures that satisfy a range of generic observations (Perry et al., 2019). (top) Breakdown energies from our simulations compared to those inferred for natural events by Rice (2006). Our models are able to match the observed trend quite well. (center) Crack-like events with mild undershoot or overshoot have energy-based properties comparable to seismological observations, as demonstrated here for the values of radiation ratio (aka radiation efficiency), $\boldsymbol{\eta_{seis}^{R}}$; the values for the natural events are from Venkataraman and Kanamori (2004). (bottom) Crack-like ruptures require low effective confining stresses (e.g. < 25 MPa) to avoid melting of the shearing zone, suggesting substantial chronic fluid over-pressurization and/or more efficient thermal pressurization to maintain low enough temperatures to avoid pervasive melt production. The temperature evolution is shown for two models, with the interseismic effective normal stresses of 25 MPa (blue) and 50 MPa (red).

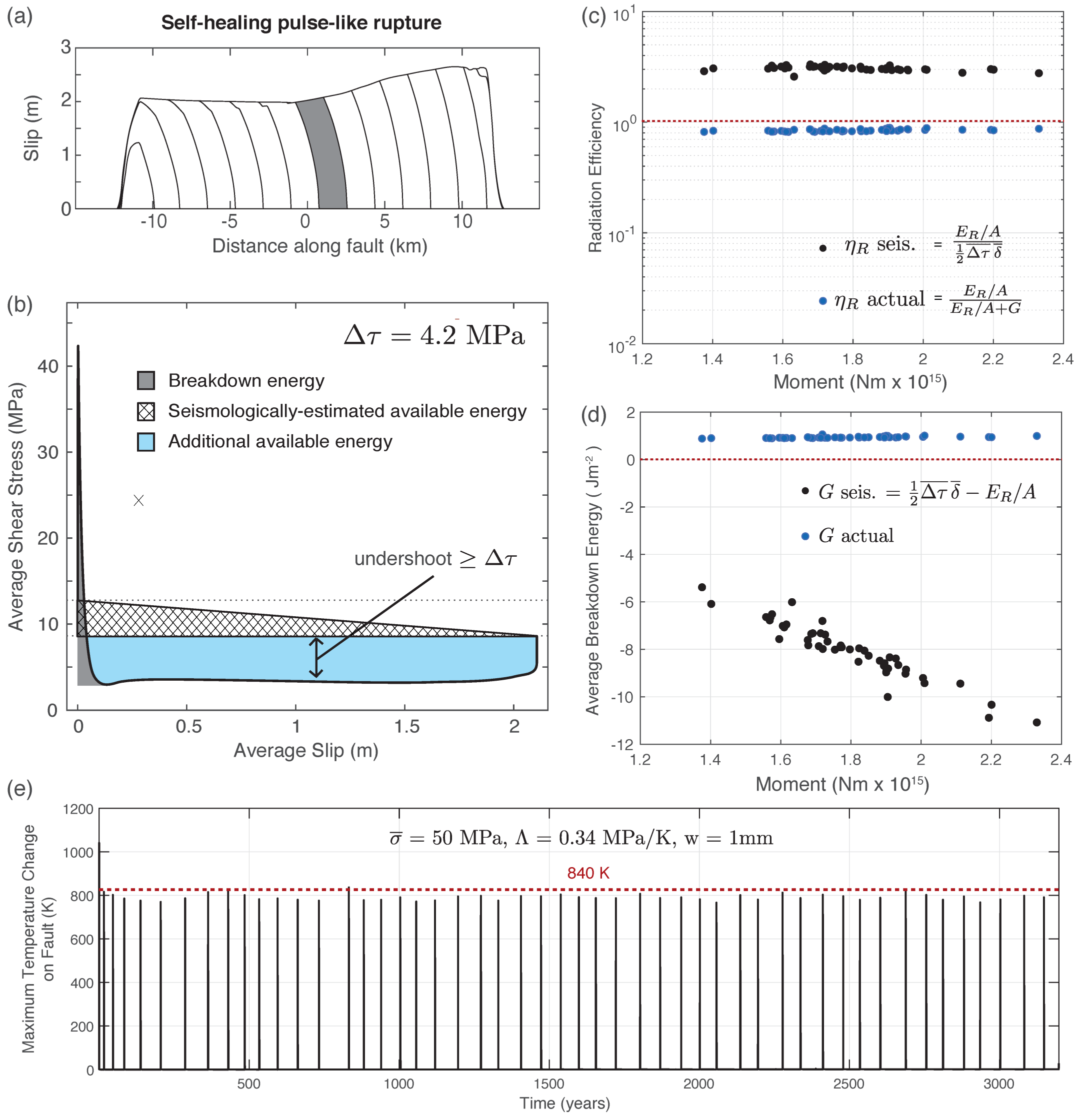

Figure 2: Increasing the efficiency of enhanced dynamic weakening in models leads to the generation of self-healing pulse-like ruptures which help maintain the fault temperatures below melting but have much larger radiation efficiencies than observed. (a) Slip evolution of a pulse-like rupture where the slipping region during a 0.5-s time interval during the rupture (shaded region) is small compared to the total ruptured region. (b) Such sharply pulse-like ruptures exhibit dynamic stress undershoots that are comparable to or larger than the static stress drop of the event and result in seismologically estimated radiation ratio/efficiency $\boldsymbol{\eta^R_{seis}}$ greater than 1 and seismological estimates of breakdown energy that are negative (d) (Lambert et al., 2018). e) As most slip occurs at lower levels of dynamic resistance, the degree of shear heating is reduced during the rupture allowing for lower heat operation for faults with higher quasi-static strength (i.e., higher interseismic effective normal stress) The example of the interseismic effective normal stress of 50 MPa is shown, to be compared to Figure 1, but higher effective normal stresses should be allowable as well, for even more efficient enhanced dynamic weakening, which is the subject of our current work.

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