Dynamic rupture at low mean shear stress initiated with rate/state friction and sustained by thermal pressurization

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INTRODUCTION

Reconciling the frictional behavior of faults during nucleation and seismic slip remains a challenge in the study of fault mechanics. Multiple lines of evidence indicate that earthquakes frequently occur at low shear stress τ, and for effective normal stresses σ at seismogenic depths, the friction coefficient $f = \tau/\sigma$ must therefore be quite small (< 0.2) during seismic slip. Yet nearly all laboratory rock sliding experiments show that slip initiates at $f \sim 0.6$ to 0.9.

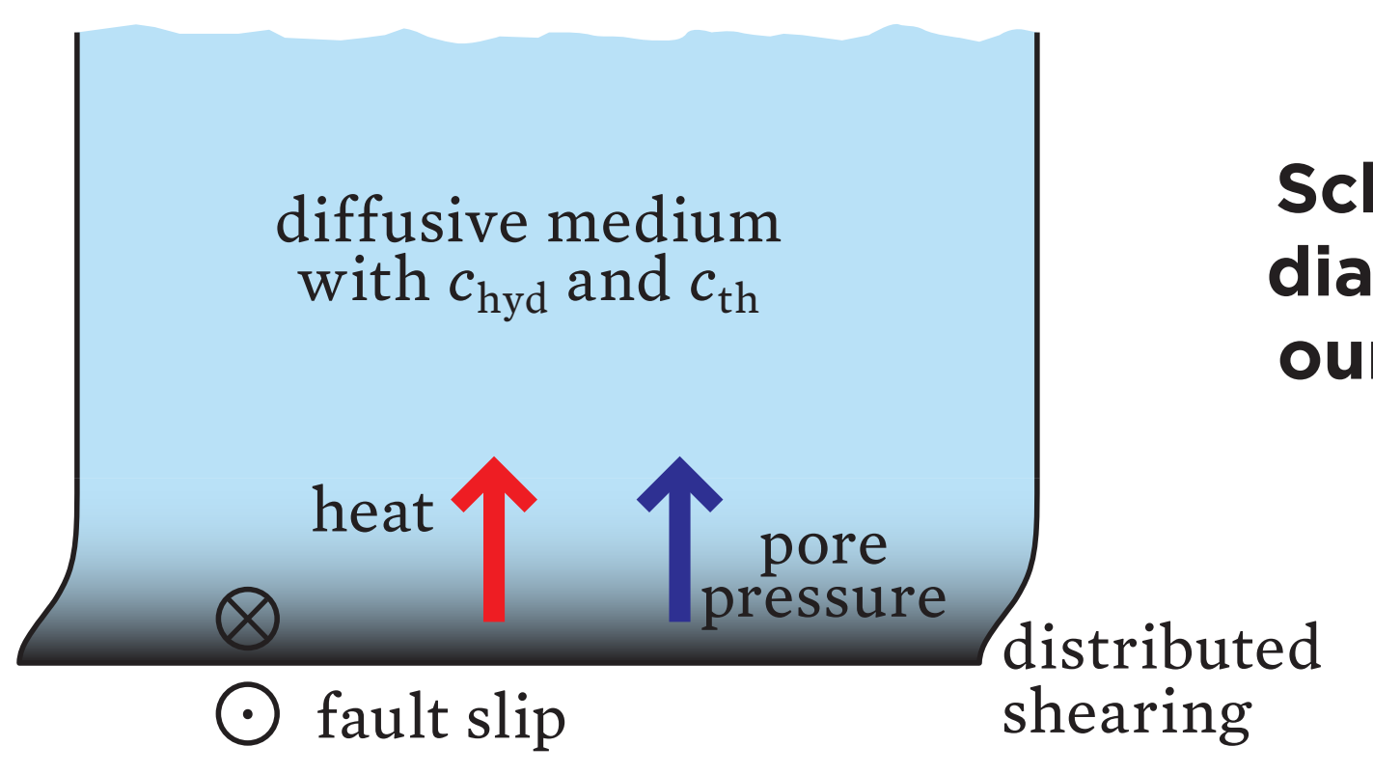
In order for sustained rupture to occur at low mean f, a likely scenario is that earthquakes nucleate where f is locally high and then propagate into regions of lower f. For a rupture to be self-sustaining, a strong weakening mechanism must operate during fast slip. One candidate mechanism is thermal pressurization, in which frictional heating pressurizes pore fluid in the fault zone and causes σ to drop, thereby weakening the fault.

Recent work has shown that thermal pressurization may, however, become the dominant weakening mechanism during quasi-static nucleation, well before the onset of seismic radiation [*Schmitt, Segall, & Matsuzawa*, JGR, 2011]. Thermal pressurization is effectively a slip weakening mechanism that feeds back into itself.

Because of the potential significance of thermal pressurization during nucleation, we have performed a suite of numerical simulations on 1D faults in which thermal pressurization is modeled during both quasi-static rate/state nucleation and dynamic rupture. We consider two idealized nucleation conditions—one called "high stress" in which σ is uniform and τ is locally high, and another called "low strength" in which τ is uniform and σ is locally diminished. Our simulations show that slip with thermal pressurization can produce some of the behavior observed in natural earthquakes.

MODEL & METHODS

In our model, a 1D fault hosts antiplane slip in a 2D continuum. Fault slip satisfies a periodic boundary condition. Initial conditions include a uniformly low slip speed and varied stress states and loading histories. Fault friction is defined in the regularized ("arsinh") rate/state friction framework with state evolution obeying the slip law.



Schematic diagram of our model

The fault is a boundary of a 2D finite-difference diffusion grid. Heat and pore pressure diffusion are calculated separately. Shear heating appears as a source term in the diffusion equation with magnitude $\tau\gamma(y)/\rho c_v$, where $\gamma(y)$ is a Gaussian distribution of shearing with half-width h and ρc_v is the heat capacity of the fault material. Thermal pressurization is a source term given by $\Lambda\, dT/dt$, where Λ is the thermal pressurization coefficient.

For the nucleation phase, we use the quasi-static code *FDRA* [*Bradley & Segall*, AGU, 2010], which is capable of integrating the coupled diffusion system rapidly during times of little evolution. Shortly before seismic radiation becomes significant, we export values of slip, fault state, stress, temperature, and pore pressure to *MDSBI*, an elastodynamic code [*Noda & others*, JGR, 2009]. Apart from the stress interaction term, both codes solve the same governing equation. *FDRA* uses an implicit time step for the diffusion equation while *MDSBI* uses adaptive substepping for diffusion during elasticity time steps. Both codes use the spectral boundary integral equation method for elasticity.

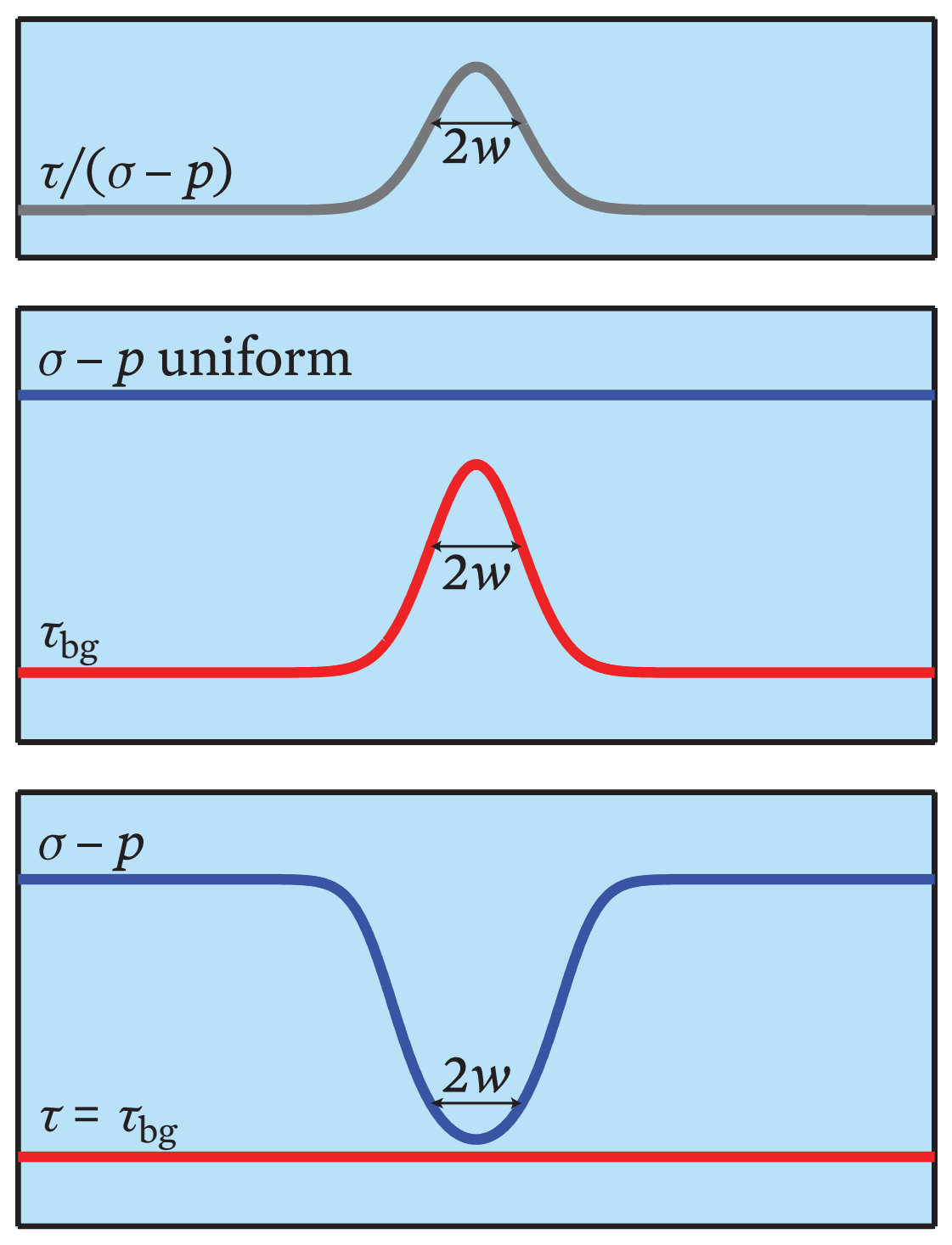
Fault parameters

G	shear modulus	30 GPa
v_s	s-wave velocity	3700 m/s
$\sigma - p_0$	ambient eff. normal stress	126 MPa
f_0	nominal friction	0.7
a	friction velocity effect	0.016
b	friction state effect	0.020
d_c	slip weakening distance	20 μm
h	shear zone thickness	100 μm
c_{th}	thermal diffusivity	0.7 mm²/s
c_{hyd}	hydraulic diffusivity	2.988 mm²/s
ρc_v	density × heat capacity	2.86 MPa/°C
Λ	thermal coupling param.	0.468 MPa/°C
w	width of heterogeneity	
L_{min}	minimum nuc. zone size	
θ	frictional state	
v	slip speed	
T	temperature (change)	
p	pore pressure (change)	
σ	normal stress	
τ	shear stress	

HETEROGENEOUS STRESS MODELS

A given $\tau/(\sigma - p)$ heterogeneity can be resolved into two endmember stress models. In the first of our simplified models, we specify a concentration of shear stress, while effective normal stress is uniform. We call this the **high-stress model**. In the other, shear stress is uniformly low, while there is a region of diminished effective normal stress. We call this the **low-strength model**.

Simple stress heterogeneities



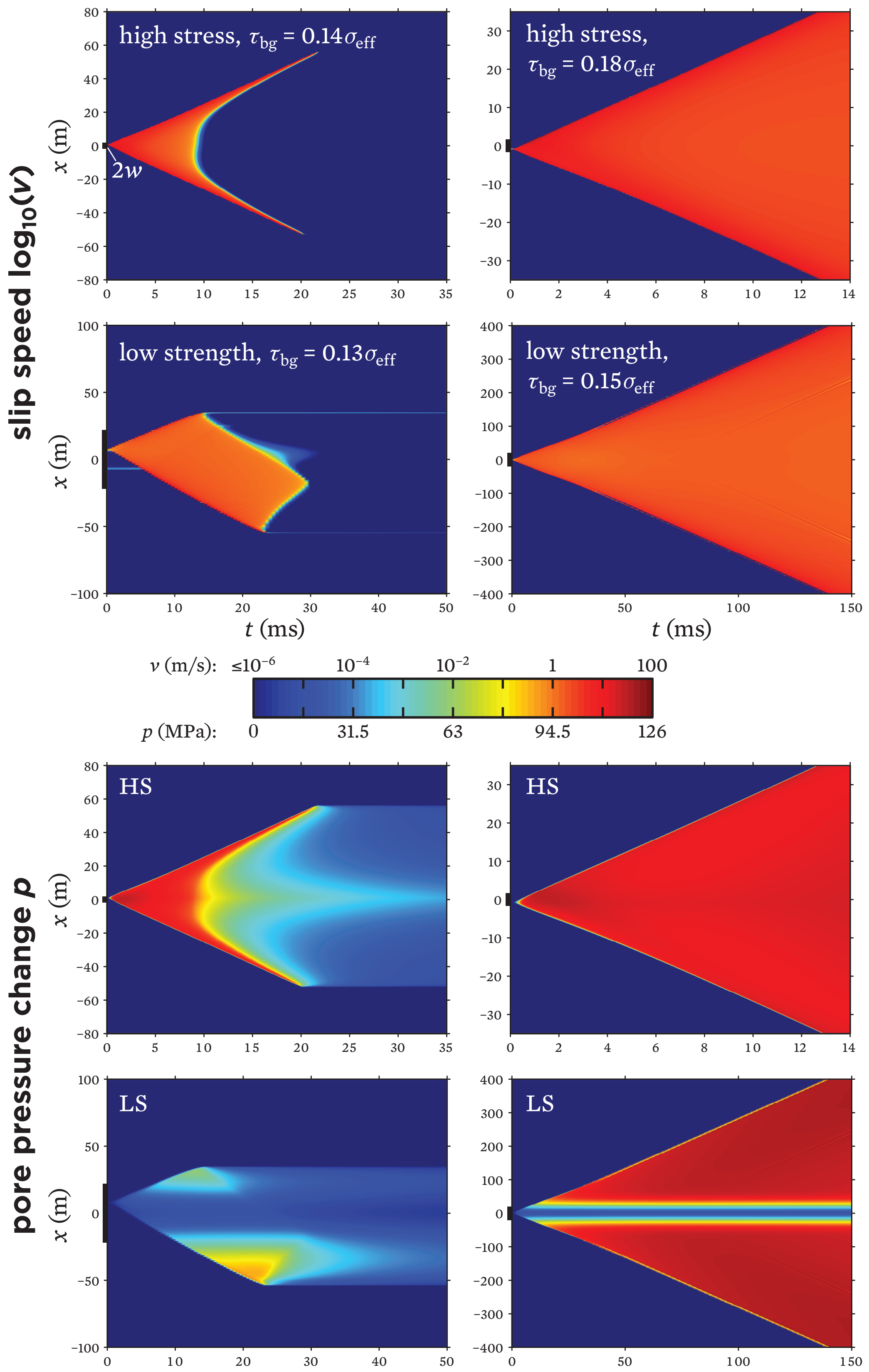
High-stress model

Low-strength model

For slip to nucleate, the fault loading must change gradually with time. In some of our simulations, we impose uniform loading after setting heterogeneous initial conditions. In others, we start with uniform initial conditions and gradually increase the amplitude of heterogeneities in τ_{remote} or $\sigma - p_0$. The two methods produce similar outcomes during dynamic rupture.

HIGH STRESS V. LOW STRENGTH

In high-stress ruptures, thermal pressurization is substantial within the nucleation zone and is capable of producing a self-sustaining rupture that propagates far into low-τ_{bg} regions. At sufficiently low τ_{bg}, high-stress ruptures possess a pulse-like character, which has been inferred for many natural earthquakes. In low-strength ruptures, thermal pressurization is modest within the nucleation zone, but becomes significant as slip propagates outside of the low-σ region. With weak thermal pressurization inside the nucleation zone, slip there is less energetic and more prolonged than at the rupture tips so earthquakes are generally more crack-like in character.

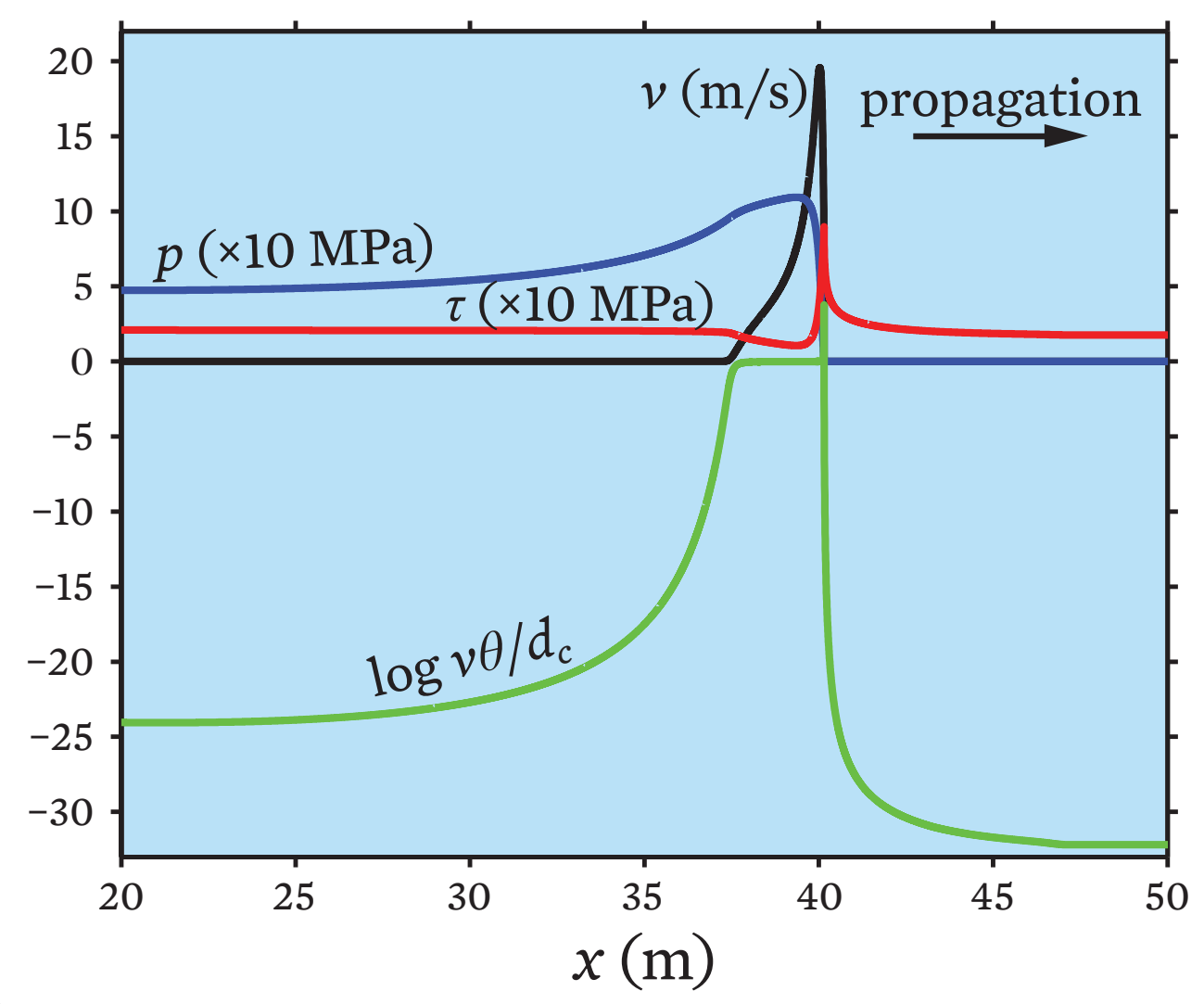


SUSTAINED DYNAMIC SLIP UNDER T. P.

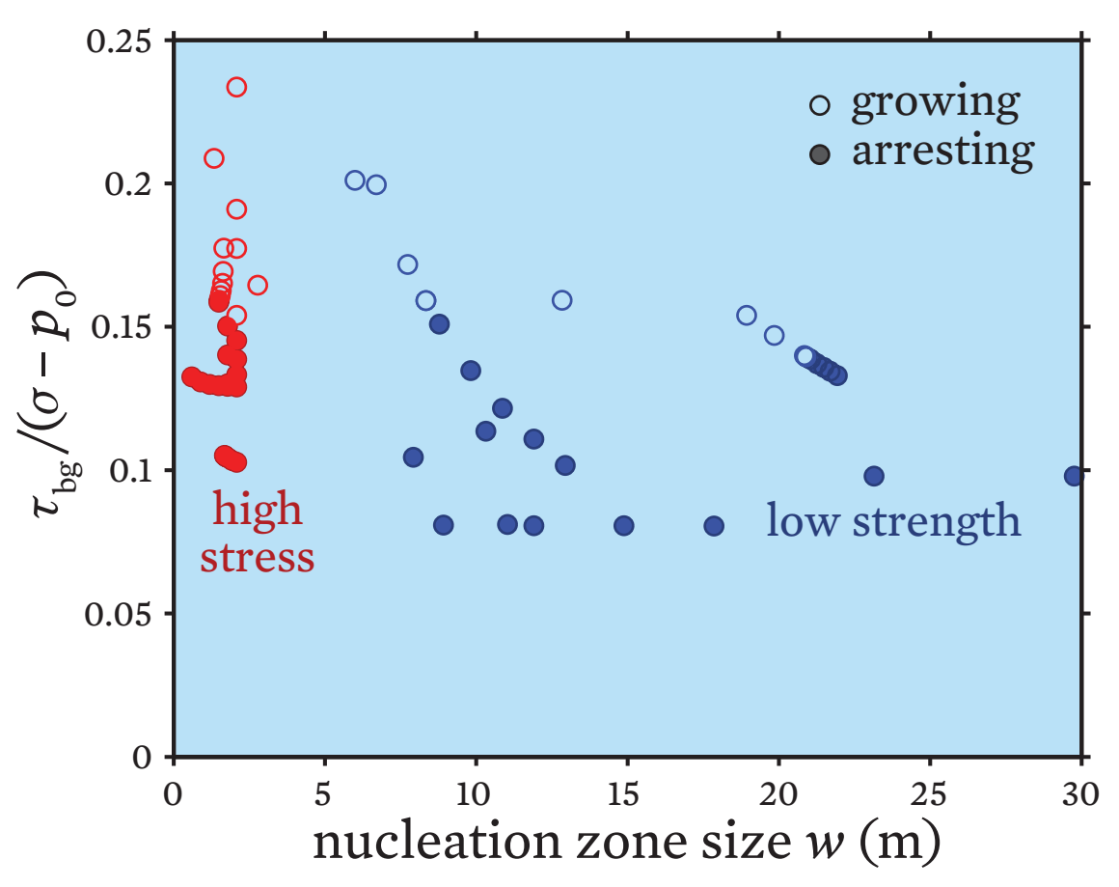
Propagation of slip into the low-τ_{bg} region can be sustained by the reduction in σ_{eff} due to thermal pressurization. The rupture tip's abrupt rise in slip speed v causes a trailing rise in pore pressure p. That elevated p yields a large stress drop behind the rupture tip, which in turn sustains its large rise in v.

Without strong thermal pressurization, the stress drop behind the rupture tip is smaller so lower slip speed v is attained. The rupture therefore arrests rapidly.

Behind the tip, slip occurs at steady state so f increases with the decay in v. Diffusion also causes σ_{eff} to climb, so the fault restrengthens behind the shear stress minimum. In many cases, the restrengthening is sufficient to cause slip to halt and the rupture assumes the form of a slip pulse.

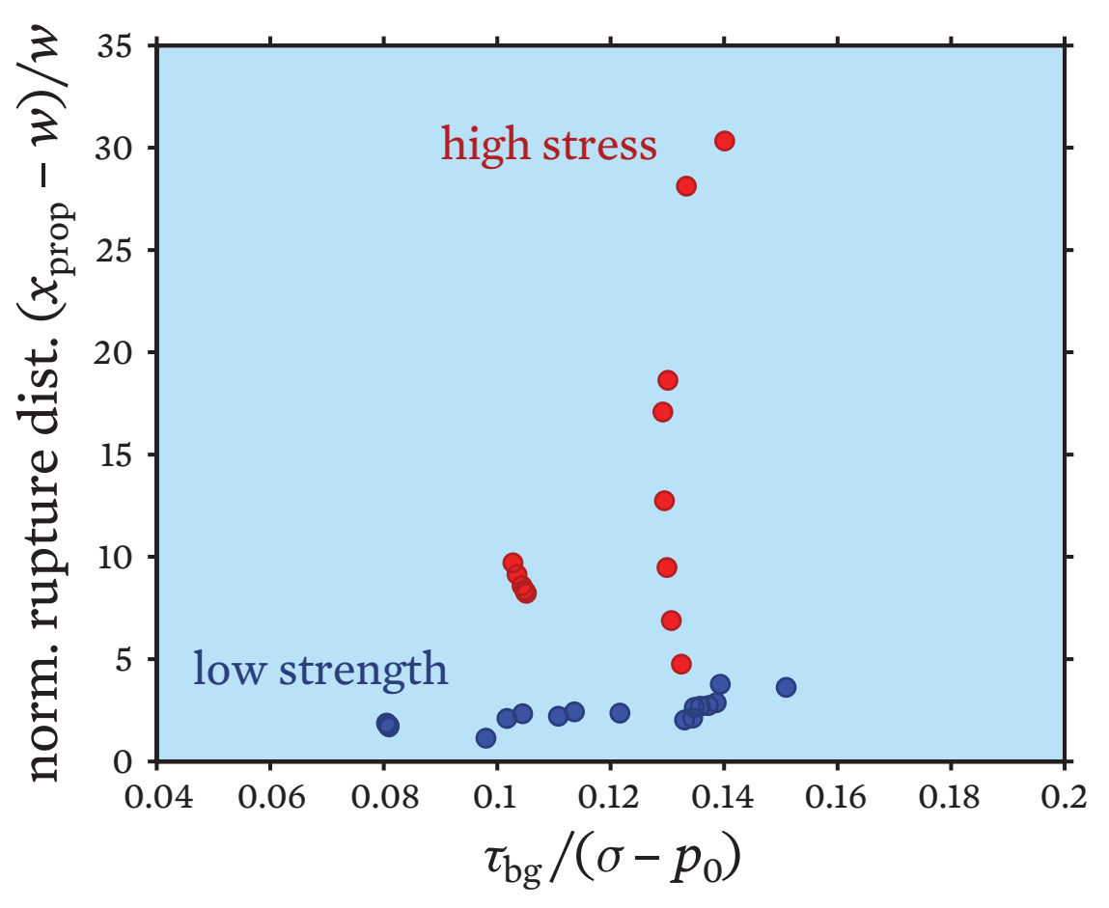


ARREST VERSUS GROWTH



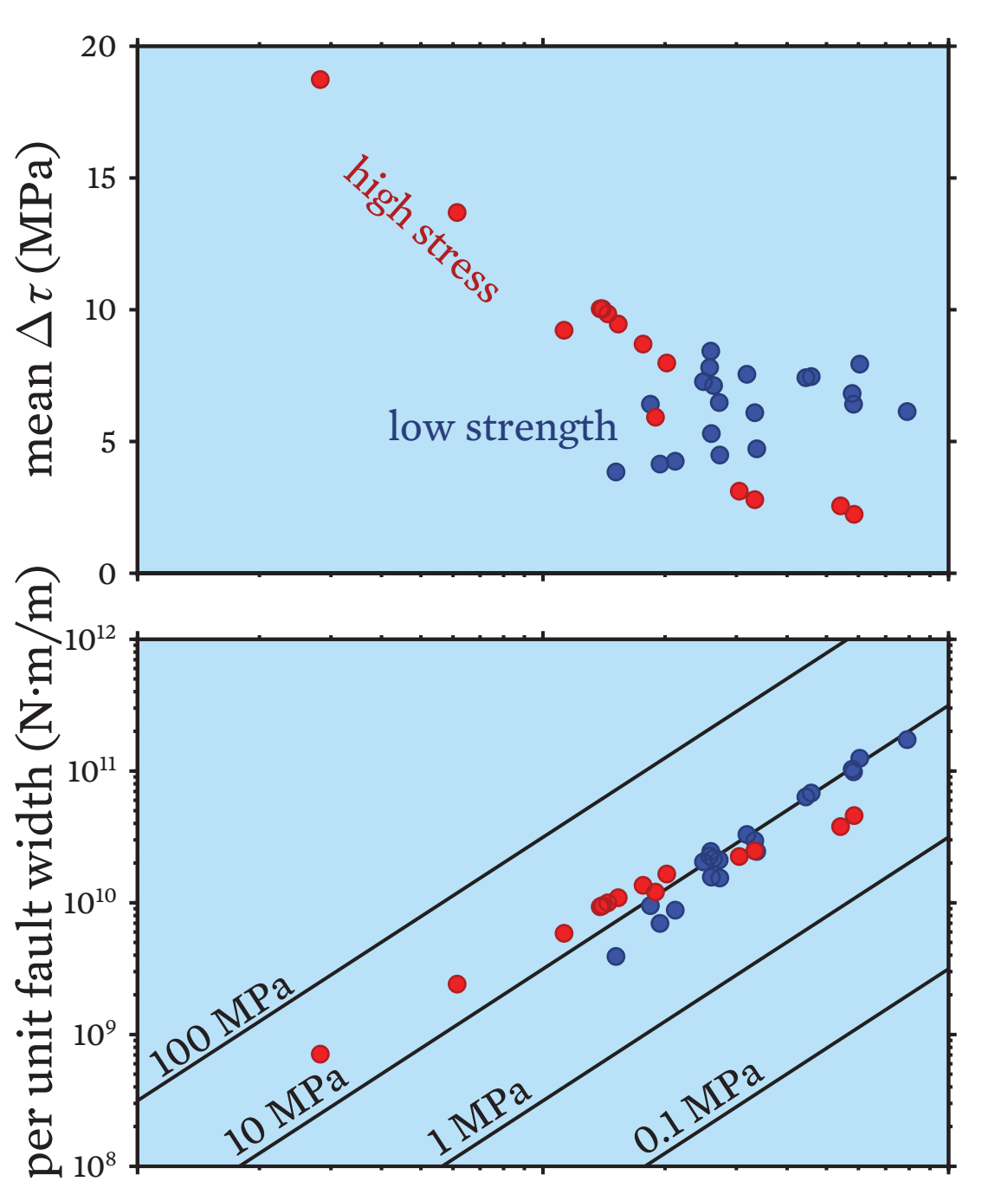
For a given set of material properties, the most significant control over whether a rupture arrests is the background shear stress τ_{bg}. Yet the intensity of thermal pressurization in the nucleation zone also has an effect.

EARTHQUAKE SOURCE PARAMETERS



For arresting ruptures, we may extract common earthquake source parameters, such as rupture length x_{prop} and moment M, from the simulation output. For rupture length, a significant difference exists between high-stress and low-strength ruptures. Because of the enhanced thermal pressurization inside the nucleation zone, high-stress ruptures can propagate far into the low-τ_{bg} region. Low-strength arresting ruptures, however, only reach a few w beyond the nucleation zone.

Because high-stress ruptures are capable of penetrating far into the low-τ_{bg} region, their mean stress drops $\Delta\tau$ are less affected by the nucleating heterogeneity as x_{prop} increases.



Our simulated ruptures show a moment-length relationship of $M \propto x_{prop}^2$ for low-strength arresting ruptures and a weaker proportionality for high-stress ruptures. Moment-length relationships for populations of earthquakes are often interpreted in the framework of constant stress drop cracks. For 1D uniform stress-drop cracks, $M = \pi a^2 \Delta\tau$, where a is the crack half-length ($\approx x_{prop}$). Lines of constant stress drop are shown in the lower right plot. In a crack model, our simulated ruptures would be modeled as having stress drops of ~10 MPa. Within uncertainty, that is consistent with observed source parameters for small earthquakes.