When and Where Does Aseismic Creep Stop Rupture Propagation?

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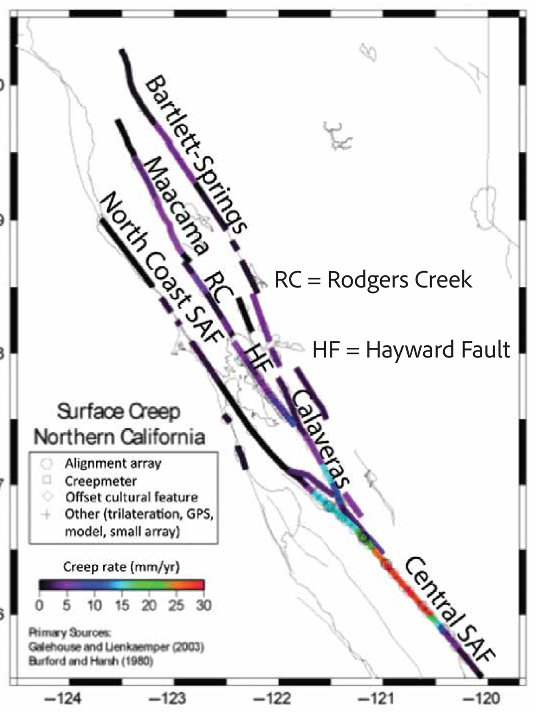
Introduction and Motivation

Aseismic creep is a process by which faults move slowly and regularly, without experiencing stick-slip events on or releasing seismic waves from the portions that are moving. Parts of many faults in the San Andreas fault system - within the San Francisco Bay Area in particular - exhibit regular aseismic creep. Because these partially-creeping faults are in close proximity to densely-populated areas, understanding how creep affects rupture length is a central issue for rupture hazard assessment and earthquake preparedness in northern California, and other places with similar fault behaviors.

Map of aseismic creep on faults in northern California, from Johnson et al. (2022).

Note that many of these faults have creeping patches of different speeds, which sometimes alternate along strike with locked patches.

Knowing whether creeping patches can stop ruptures is key for knowing how big earthquakes in the northern San Andreas system can become.



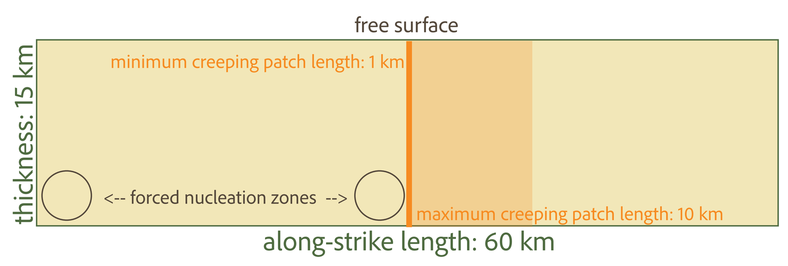
Aseismic creep on faults is characterized by rate-strengthening friction, which means that the fault actively resists movement as slip rates increase. This resistance to coseismic rupture velocities approaching from adjacent locked fault sections suggests that the frictional behaviors associated with creep can, in and of themselves, be barriers to rupture. But because creeping sections of faults are in motion during the interseismic period, they also consistently release at least some portion of the shear stress imparted by tectonic loading. This may mean that creeping areas also have low enough shear stress to cause a rupture front to die out, even independently of their frictional conditions. Thus, understanding which combinations of frictional resistance and shear stress retention, over what length of fault patch, are able to stop versus allow throughgoing coseismic rupture is critical for evaluating hazard associated with partially-creeping faults.

Here, I conduct dynamic rupture simulations on partially-creeping strike-slip faults under a range of stress conditions, varying frictional resistance and stress release in creeping patches of different lengths.

My eventual goal is to run enough models that I can develop a set of physics-based passing probabilities for partially-creeping faults. These will be useful for rupture forecasting, and for both probabilistic and deterministic hazard and scenario modeling.

Model Setup

My model fault is planar, vertical, and right-lateral strike-slip. It is mostly frictionally locked, though it has a central creeping patch of fixed thickness and variable along-strike length.



I embed the fault in a homogeneous fully-elastic half space with Vp = 6000 m/s, Vs = 3464 m/s, and ρ = 2670 kg/m³.

I use the 3D finite element software FaultMod (Barall, 2009) to conduct my dynamic rupture simulations. I also use FaultMod's internal mesher to build my hexahedral fault mesh (near field element size = 200 m; far-field element size: 400 m).

I nucleate my ruptures by raising the shear stress at a chosen hypocenter and forcing propagation over an area larger than the critical patch size required for self-sustaining rupture.

Acknowledgments

I would like to thank Rob Givler, Chris Madugo, and Steve Thompson for their interest in this project and their help in figuring out how to approach this in a way that will also be useful for engineering applications.
I would also like to thank Kenny Ryan for his help with implementing rate-state friction in FaultMod.

Frictional Parameters

I implement rate-state friction with a modified Dieterich-Ruina aging law (Dieterich, 1978, Ruina, 1983), which allows me to model active frictional resistance associated with aseismic creep:

$$\tau = a \arcsin h\left[\frac{V}{2V_0}\exp\left(\frac{\mu_0+\psi}{a}\right)\right] \quad \text{where state variable} \quad \psi = b\ln\left(\frac{\theta}{\theta_0}\right) \quad \text{and} \quad \frac{d\theta}{dt} = \frac{-1}{\theta_{ss}}(\theta-\theta_{ss})$$

The difference between unitless variables *a* and *b* controls whether the fault weakens (*a*-*b* < 0) or strengthens (*a*-*b* > 0) with increasing slip rate. At *a*-*b* = 0, the fault neither promotes nor resists slip.

I designate the locked portions of the fault as strongly rate-weakening for all models.
I only vary the frictional parameters in the creeping zone. The strong rate-weakening case represents a fully-locked fault, and isolates the effects of stress heterogeneity.

In all cases, I use $V_0 = 1\times10^{-6}$ m/s, $\mu_0 = 0.6$, and $\psi_0 = 0.135524$.

	a	*b*
Locked	0.008	0.012
Strong Rate-Weakening	0.008	0.012
Weak Rate-Weakening	0.01	0.012
Rate Neutral	0.012	0.012
Weak Rate-Strengthening	0.014	0.012
Strong Rate-Strengthening	0.016	0.012

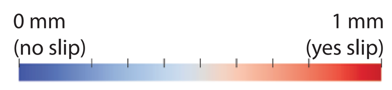
Stress Parameters

Aseismic creep releases on-fault shear stress during the interseismic period. Because dynamic rupture simulations do not cover the physics of the interseismic period, I account for this by reducing initial shear stress in the creeping zone by either 100%, 75%, 50%, 25%, or 0%. Initial shear stress is the same over the whole fault in the 0% reduction cases, which isolates the effect of frictional contrasts.

	σ	τ
Low Stress/Slow Rupture	30 MPa	19.2 MPa
Low Stress/Moderate Rupture	30 MPa	20.7 MPa
Low Stress/Fast Rupture	30 MPa	22.2 MPa
Medium Stress/Slow Rupture	75 MPa	48 MPa
Medium Stress/Moderate Rupture	75 MPa	51.75 MPa
Medium Stress/Fast Rupture	75 MPa	55.5 MPa
High Stress/Slow Rupture	120 MPa	76.8 MPa
High Stress/Moderate Rupture	120 MPa	82.8 MPa
High Stress/Fast Rupture	120 MPa	88.8 MPa

Rupture Behaviors

My simulations fit into five rupture behavior categories. I use a slip-vs-no-slip color scale here to best illustrate these slip patterns.
The symbol below each rupture behavior is how I represent them on my parameter space plots. Shaded areas with no symbols represent combinations of parameters for which I did not run models, but whose behavior is bracketed by surrounding simulations.



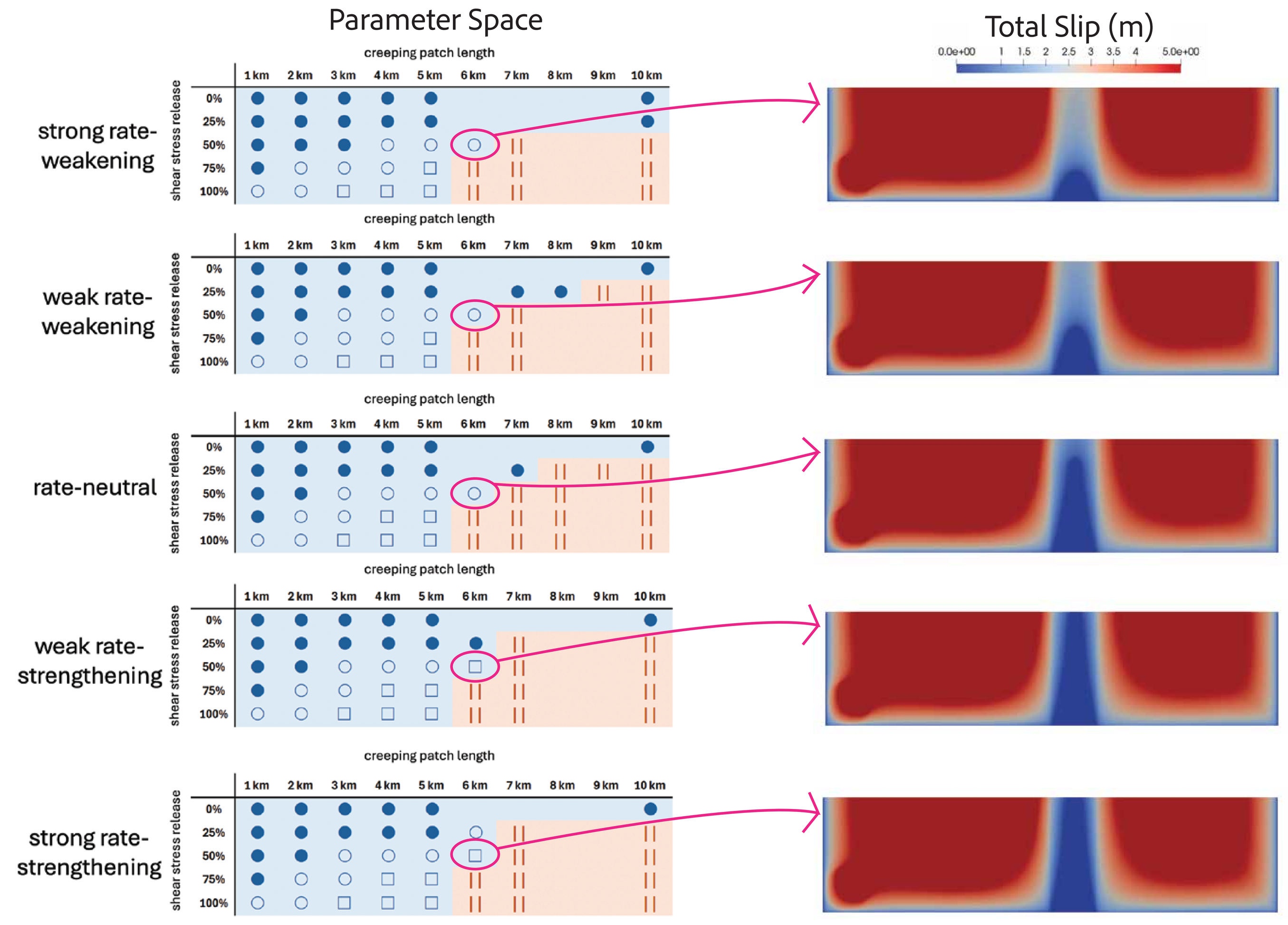
Complete rupture | Incomplete at depth | Jumping rupture | Triggered slip | Stopped rupture

I have run over 3000 simulations for this project so far. There is not room to show all of them legibly on this poster. I will focus on highlighting broad effects of specific parameters instead. If you would like to see the full parameter space, just ask!

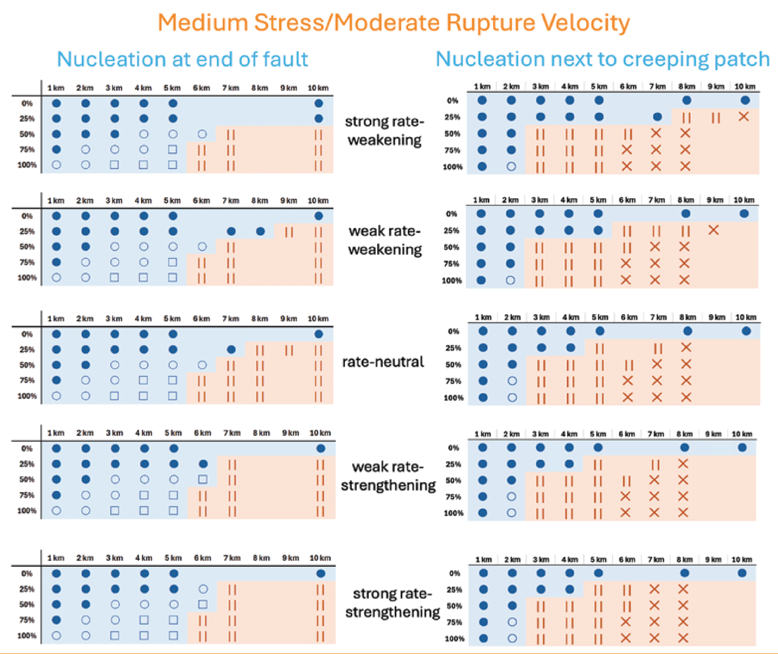
Shear stress release matters more than frictional contrast.

For every set of initial stress conditions I tested, the amount of shear stress release due to creep had a much stronger control over final rupture behavior/length than amount of frictional contrast did. I therefore only show one representative stress case here; they all follow the same basic pattern, though shifted based on overall stress level.

Frictional contrast has more of a second-order effect, specifically on the amplitude of slip in the creeping patch. Though this matters less for the what-allows-through-going-rupture question, it may have larger implications for aftershocks or afterslip.



Directivity helps ruptures go further.

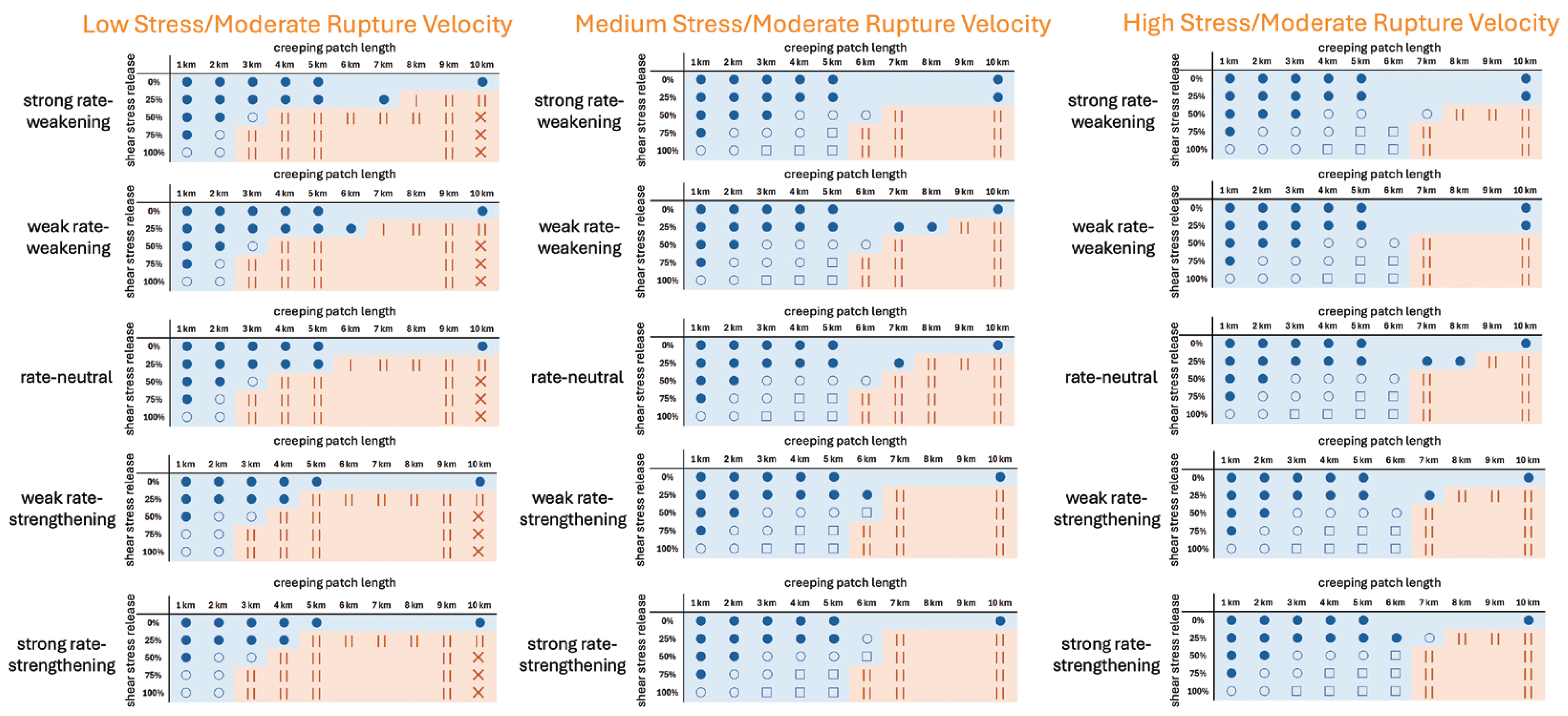


In general, ruptures with longer directivity can get through larger/more prohibitive creeping patches.

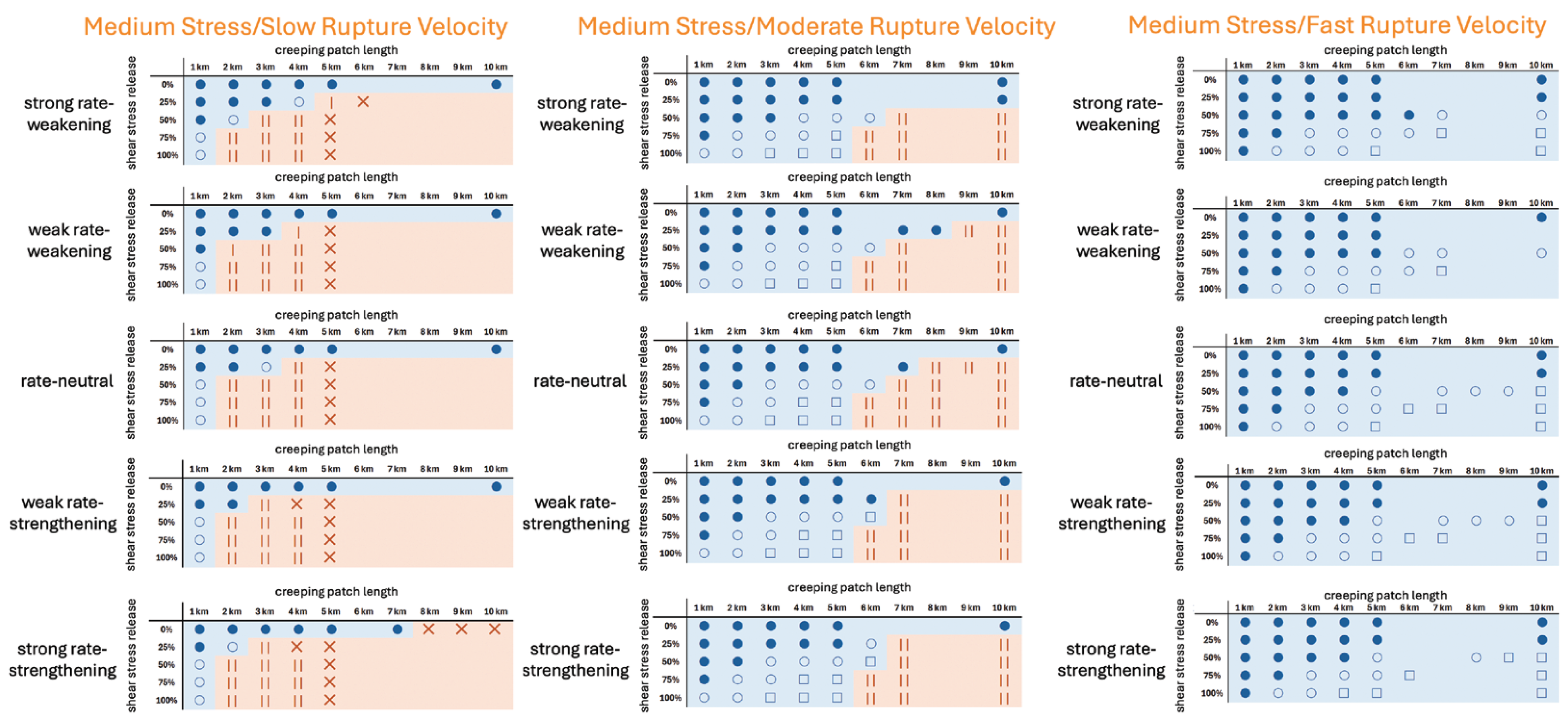
But, for small creeping patches, ruptures that nucleate adjacent to the patch go a little further. (This may be an effect of the initial forced nucleation process, though.)

I am currently running more simulations with even longer directivity to see how this effect scales.

Higher overall stresses allow ruptures to go further.



Rupture velocity has a larger effect than overall stress amplitude.



Some Implications

- Creeping patches can stop ruptures, and should be formally accounted for in rupture hazard forecasts.
- Rupture velocity is an important factor for how rupture negotiates on-fault complexities. This needs to be integrated into forecasts, somehow.
- When modeling coseismic ruptures on partially-creeping faults, the stress parameterization matters more than the frictional one.

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