Mechanisms of unsteady shallow creep on major crustal faults

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Investigator: Yuri Fialko (SIO/UCSD)

I. Project Overview

Abstract

A number of active continental strike-slip faults are associated with geodetically detectable shallow creep, while other faults appear to be locked all the way to the surface over the interseismic period (*Harris* 2017). Faults that exhibit shallow creep also often host episodic accelerated creep events (e.g., *Linde et al.* 1996; *Murray and Segall* 2005; *Wei et al.* 2009; *Jolivet et al.* 2015; *Bilham et al.* 2016). Diverse geophysical observations now offer a more complete picture of the behavior of certain strike-slip faults that host transient creep events. Spatially dense InSAR observations and temporally continuous creepmeter records, taken together, indicate that shallow creep events can involve large fault areas (up to tens of km long and several km down-dip) (*Wei et al.* 2009; *Rousset et al.* 2016) and persist throughout much of interseismic periods.

The physical mechanisms and fault zone properties giving rise to shallow transient aseismic slip remain poorly understood. A traditional interpretation of shallow creep in terms of a velocity-strengthening (VS) layer atop the velocity-weakening (VW) seismogenic zone (SZ) fails to explain spontaneous, episodic creep events. Special subsurface structure and lithological conditions, e.g., a thin VW layer within the VS shallow crust (*Wei et al.* 2013), may promote transient slip but seems unlikely to be always present to explain the large-scale and widespread occurrence of shallow unsteady creep events on many major crustal faults. In this project we have started to explore the rheologic controls on aseismic episodic slip events and their implications for seismic faulting in models of faults governed by laboratory-based constitutive laws, motivated by observations from the San Andreas and Superstition Hills faults in Southern Californa.

SCEC Annual Science Highlights

FARM, SDOT

Exemplary Figure

Figure 3.

SCEC Science Priorities

1d, 3g, 5a

Intellectual Merits

Our main findings are:

- We reproduce spontaneous slow slip events, with displacements of millimeters and periods of years that are consistent with interseismic observations from SHF and NAF, in a fault zone model having monotonic depth variations in rate-and-state friction parameters at shallow depths—a transition zone with mildly VW properties between the VS surface layer and the VW deeper seismogenic zone. Simulated slow slip events occur in the transitional layer due to recurring aseismic frictional instability in a region with a large nucleation size, with their characteristics controlled by frictional parameters, a, b, L, the nucleation zone size h^*, and layer thickness W.
- Simulations of long-term fault slip history over hundreds of years suggest significant overlap and interactions between seismic and aseismic slip within different layers and over different periods. For example, shallow VS layer modulates the behavior of slow slip events, as well as the fault failure potential during earthquake ruptures and the ensued afterslip. Additional fault strengthening mechanisms, such as dilatancy, may be needed to reconcile model results with postseismic observations from SHF and NAF.
- Our models demonstrate two physically plausible scenarios for the long-term behavior and seismic potential of shallow crustal faults. In the first scenario, slow-slip areas are purely friction-controlled, susceptible to earthquake penetration and capable of limited afterslip. In the second scenario, slow-slip regions are also subject to additional fluid-related strain-strengthening processes, thus acting as a more effective barrier to earthquake rupture and producing larger afterslip.

Broader Impacts

Overall, the modeling and parameter estimation schemes developed in this project provide new ways to probe depth-dependent fault friction properties and assess the extent of surface rupture of potential earthquakes. The framework of connecting observations of different seismic-cycle phases to fault zone properties for the two selected strike-slip faults also provide insights relevant to studying shallow sections of subduction zones. The developed numerical models will ultimately improve our understanding of seismic hazard to populated areas in Southern California. This project has provided training and support for one postdoctoral scholar (Junle Jiang).

II. Technical Report

1 Shallow slow slip in 2D frictional fault models

To understand slip behavior of major crustal faults, we developed 2D models of faults with monotonic transition in rate-and-state friction properties, from VS properties at the surface to mildly VW properties at greater depths, above the deeper VW seismogenic zone (SZ) (Figure 1). We adopt near-hydrostatic effective normal stress gradient (13 MPa/km) and choose a total thickness of 4 km for the two shallow layers atop the SZ, based on estimates for the NAF in *Bilham et al.* (2016). Our simulations includes aseismic periods that last decades to centuries and occasional dynamic ruptures of major earthquakes, with the coupled equations of elastodynamic stress and frictional resistance solved using the methodology of *Lapusta et al.* (2000).

To reproduce realistic interseismic slow slip in such a fault model, we first identify and explore critical model parameters that control the maximum slip velocity, V_{max}, and characteristic periods, T, of recurring

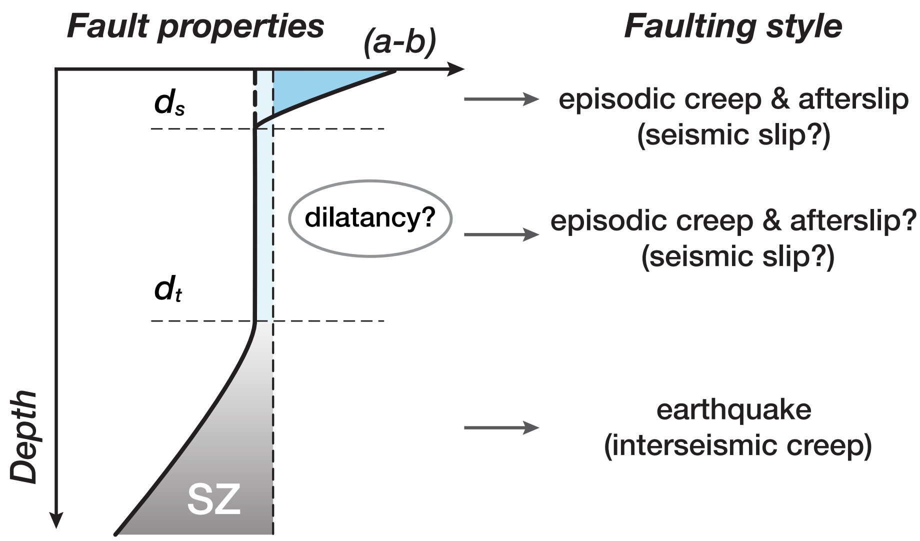

Figure 1: A model of shallow fault zone with (left) layered distributions of frictional properties and (right) the corresponding depth-dependent fault slip behavior. The topmost layer (blue) is frictionally stable (velocity-strengthening, $(a-b)>0$) and accommodates steady creep and potential afterslip following earthquakes. The deeper seismogenic zone (SZ, gray) is frictionally unstable (velocity-weakening, $(a-b)<0$) and hosts large earthquakes. The transition zone in-between is "conditionally stable" (mildly velocity-weakening, $(a-b)\approx 0$) and produces episodic creep events between large earthquakes. Earthquake slip may propogate all the way to the surface; interseismic creep may erode into the SZ.

slow slip events. As a first step, we consider slightly modified fault models that do not include the surface VS layer, i.e., the shallow fault zone has uniform mildly VW properties. In this model, we find that the nucleation zone size with respect to the shallow layer thickness and the ratio of frictional parameters a/b (more than the absolute values of a and b) control $V_{\max}$ and T (Figure 2). On the one hand, the critical nucleation size, h^* on a 2D strike-slip fault can be estimated for $0.5 < a/b < 1$ (*Ampuero et al.* 2008): $h^* = \frac{2}{\pi}\frac{\mu b L}{(b-a)^2\bar{\sigma}}$, where μ is shear modulus and $\bar{\sigma}$ is the local effective normal stress. On the other hand, 1D spring-slider modeling at neutral stability suggests that $T \approx 2\pi\left(\frac{1}{b/a-1}\right)^{1/2}\frac{L}{V_{\mathrm{pl}}}$ (*Rubin* 2008), where V_{pl} is the plate loading rate. Since the characteristic slip distance L trades off with other parameters σ, a/b, b in the two equations and cannot be uniquely constrained when other frictional parameters are unknown, we choose a fixed value, $L = 0.45$ mm, which is close to laboratory values of 1–100 µm and numerically tractable.

We then consider the more complex model setup that has a VS layer at the surface. Through a grid search of model parameters, we find that larger a/b or larger thickness of this layer leads to smaller $V_{\max}$ and smaller T (not shown), and therefore directly trades off with the parameters, W/h^* and a/b, that characterize the deeper, mildly VW layer. For simplicity, we choose a thickness of 0.5 km for the VS layer and only allow frictional parameters, a/b and L, of the layer to change. With tuned model parameters, our model can indeed reproduce interseismic slow slip events with amplitudes on the order of mm and recurring periods of several years, which are largely consistent with observations from NAF and SHF.

When extended to simulate longer fault slip history that includes earthquake ruptures, our numerical models sometimes yield qualitatively different interseismic behavior due to interactions of fault slip in different regions across various phases of the seismic cycle. While being capable of producing interseismic slow slip, the mildly VW region generally facilitate, rather than impede, coseismic earthquake rupture, due

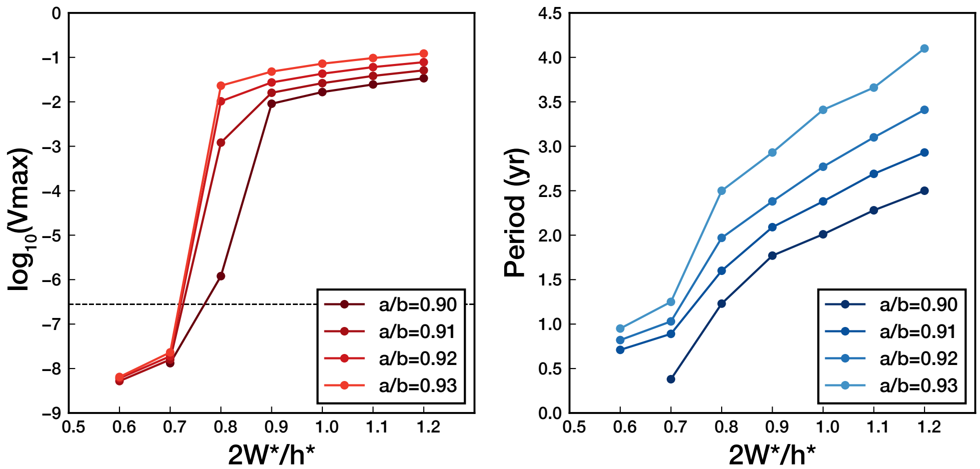

Figure 2: The effect of model parameters W/h^* and a/b on maximum velocity, $V_{\max}$ and recurrence intervals, T, of simulated interseismic slow slip events. W is the thickness of the shallow VW layer and h^* is the nucleation zone size. The horizontal dashed line indicate the deeper creeping rate (plate loading rate).

to small stress drop and hence small break-down energy. For the deeper seismogenic zone, we choose VW properties so that the maximum coseismic slip reaches $\sim$3 m, comparable to the expected coseismic slip amplitude at the SHF and NAF. For shallow part of the fault, we choose VS frictional properties that can reduce the extent of coseismic failure and allow slip budget for aseismic slip, and VW properties accordingly that enables the occurrence of slow slip events ($a = 0.040$, $b = 0.029$, and $L = 1.00$ m for the first layer, compared to $a = 0.0030$, $b = 0.0035$, $L = 0.45$ mm, for the second layer).

The long-term evolution of fault slip rates and postseismic/interseismic slow-slip behavior in a typical model are shown in Figure 3. Small-amplitude afterslip occurs at the surface following large earthquakes. The amplitude and characteristic periods of slow slip events increase toward the end of the interseismic period, indicating the effect of large-scale, time-varying loading rates on these transient events. The recurrence intervals of simulated events, $\sim$5 yr, are larger than those of the observed transients at NAF ($\sim$1 yr), because we cannot use too small a value for L due to numerical considerations.

2 Scenarios for earthquakes and slow slip on crustal faults

Observations of limited surface slip during prior events and rapid afterslip on the NAF and SHF provide important constraints on the properties of shallow fault layers. The logarithmic time dependence of postseismic displacements in the two cases (*Bilham* 1989; *Kaneko et al.* 2013; *Bilham et al.* 2016) is consistent with VS friction (*Marone et al.* 1991). Large $(a-b)$ in the top VS layer can reduce coseismic slip at the Earth's surface but would also impede propagation of episodic creep events to the surface, as shown in Figure 3. This aspect of model behavior is inconsistent with surface observations of slow slip in short-aperture creepmeters.

To better reconcile observations and models, we considered an additional mechanism that may be at play at shallow faults, dilatant strengthening that occurs at increasing slip rates. Using the formulation in *Segall* (1995), we solve for the coupled evolution of the state variable and porosity, which in turn affects pore pressure and the effective normal stress. Since increased slip rates decrease the state, increase porosity, and then decrease pore pressure, leading to larger fault strength, this means that earthquake rupture would

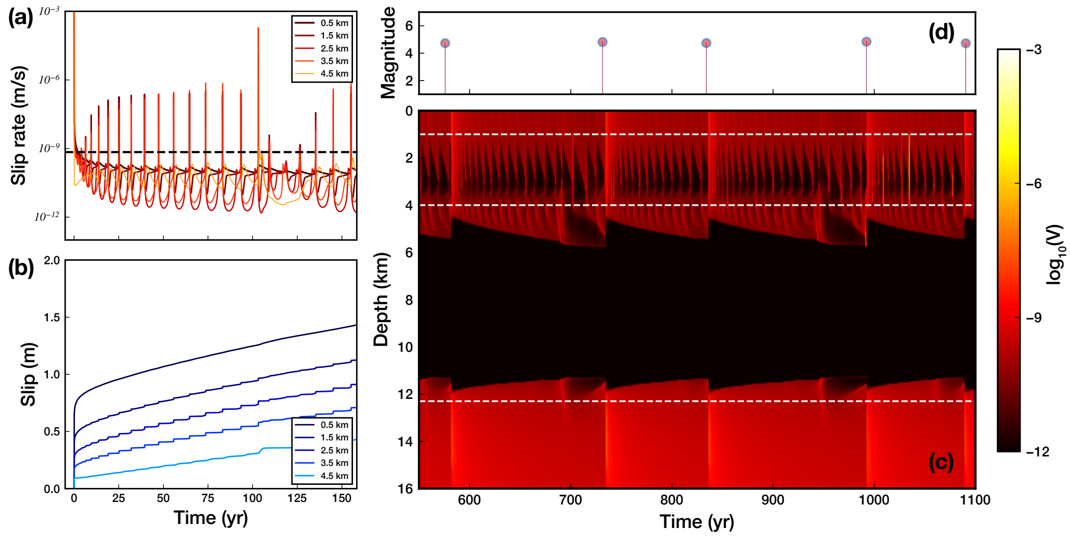

Figure 3: Shallow unsteady creep in a rate-and-state fault model. (a–b) The evolution of fault slip rates and slip at different depths following a large earthquake rupture. (c) The evolution of fault slip rates along depth with time. The fault slip rates, color-coded on a logarithmic scale, are averaged over one day and hence smaller than actual peak slip rates during transient events. Horizontal dashed lines indicate the interfaces between different layers. (d) Moment magnitudes of simulated large earthquakes at corresponding time.

be discouraged in fault areas where such a process is active. Our models incorporating dilatancy effect demonstrate how the negative feedback loop can help reduce earthquake propagation into the slow-slip regions (Figure 4). Due to reduced coseismic slip, more pronounced afterslip is produced in such a model, while the interseismic slow slip is qualitatively similar compared to those in purely frictional models.

Comparisons of the purely frictional and coupled-friction-dilatancy models suggest two qualitatively different scenarios of long-term behavior for faults where shallow slow slip occurs (Figure 5). In the former case, shallow fault areas are ineffective barriers to earthquake rupture, leaving reduced postseismic slip, and prominent slow slip appears later in the interseismic periods. In the latter case, earthquake propagation to the surface is discouraged due to strain-strengthening process and hence pronounced afterslip is produced and accompanied by earlier occurrence of slow slip events. Our modeling results suggest that the second scenario is more consistent with the seismic-cycle observations from the NAF and SHF.

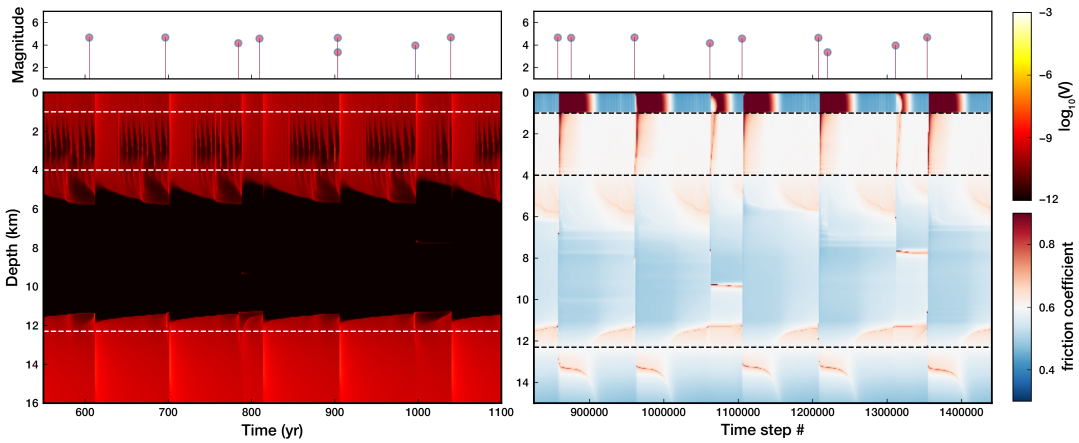

Figure 4: Time-dependent behavior of a fault governed by rate-and-state friction coupled with dilatancy. (Left) The evolution of fault slip rates along depth in time. The fault slip rates, color-coded on a logarithmic scale, are averaged over one day and hence smaller than actual peak slip rates during transient events. (Right) The evolution of the coefficient of friction on the fault with increasing time steps (nonuniform time intervals). Regions in red and blue indicate higher and lower stresses compared to the reference state.

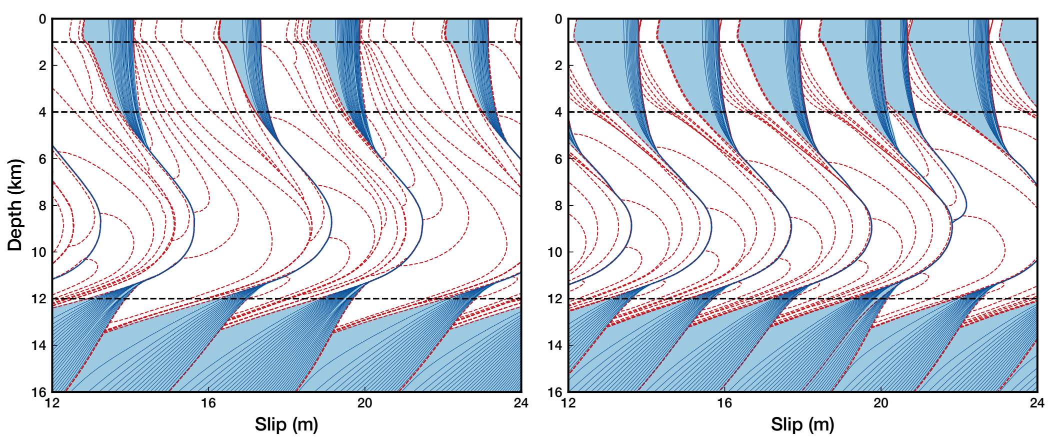

Figure 5: Depth profiles of cumulative slip in rate-and-state fault models (left) without and (right) with dilatancy. Regions in white indicate seismic periods where the maximum slip rate on fault exceeds 0.1 m/s, with red dashed lines drawn every 1 sec; regions in blue indicate aseismic periods where the maximum fault slip rate is below 0.1 m/s, with blue lines drawn every 5 yr.

3 Related presentations/publications

Jiang, J., & Fialko, Y. (2018, 08). Probing mechanisms of unsteady shallow creep on major crustal faults. Poster Presentation at 2018 SCEC Annual Meeting (SCEC Contribution #8568).

Jiang, J., & Fialko, Y., Probing mechanisms of unsteady shallow creep on major crustal faults, in preparation for *Journal of Geophysical Research - Solid Earth*.

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