How fault creep makes its way

(to an instability)

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Dynamic rupture

Instability

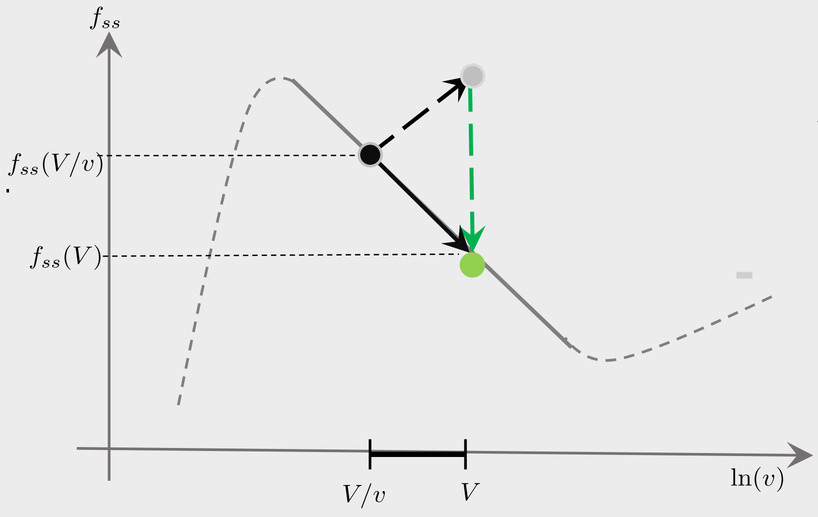
Creep propagation

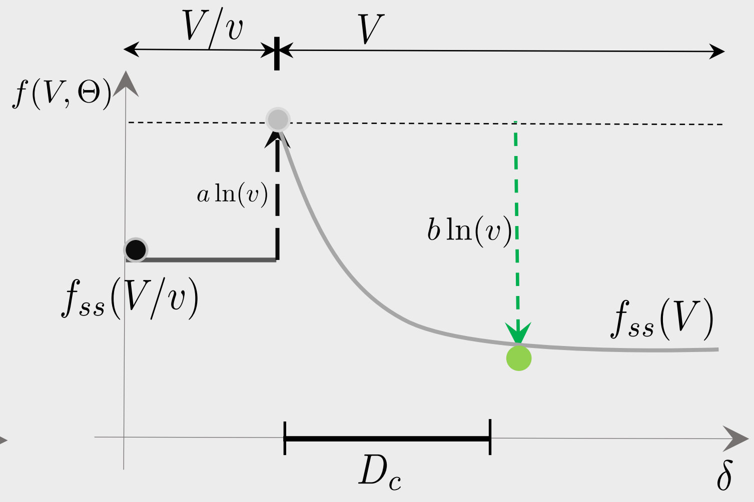
The content in this presentation is under preparation. Please contact the authors for questions and suggestions.

Introduction

We model mechanics of an aseismic fault creep propagation and conditions when it may lead to the initiation of seismic slip. We do so by considering fault bounding medium to be elastically deformable and fault's interfacial strength to be slip rate- and state-dependent characterized by the steady-state rate-weakening. The fault is considered to be initially locked: a state of slip when interfacial slip velocity is considerably low and arbitrarily less than the steady-state sliding rate for given uniformly distributed prestress.

We find solutions for creep penetration into the fault under geologically relevant loading scenarios (e.g., that of a plate-bounding strike-slip faulting driven by the slip at depth, or that of a rate-weakening patch of a fault loaded by a creep on an adjacent rate-strengthening part due to, e.g., anthropogenic fluid injection). In all the cases, the creep makes its way as a self-similar traveling front characterized by high stress owed to the direct effect; however, the remaining creep profile exhibits a steady-state sliding. Further, we find that the prestress, close to or far from steady-state sliding stress, controls the rate and manner of the creep penetration.





Friction

$$f\left[V(x,t),\Theta(x,t)\right] = f_o + a\ln\left(\frac{V(x,t)}{V_o}\right) + \Theta(x,t)$$

$$\partial_t\Theta(x,t) = -\frac{1}{D_c}\Psi\left(f - f_{ss}(V)\right)$$

$$f_{ss}[V(x,t)] = f_{ref} + (a-b)\ln\left(\frac{V(x,t)}{V_{ref}}\right)$$

Proximity from steady-state sliding for all sliding rates

$$\Phi(x,t) = \frac{1}{V(x,t)}\Psi(f - f_{ss})$$

$\Phi < 0$	$\Phi = 0$	$\Phi > 0$
Sliding below steady-state	at steady-state	above steady-state

$\mathbf{\Phi(x,t)}$ is just velocity-normalized $\mathbf{\Psi(x,t)}$

- Extent to which the pre-stress is far from steady-state frictional strength is specified by $\Phi(x,t=0) = \Phi_{in}$
- Φ_{in} (times normal stress) is related to the stress drop after an earthquake and at the beginning of a new creep → instability → dynamic rupture sequence.
- Φ_{in} allows to introduce variability in the creep penetration extent and rate before the next instability. In a way, Φ_{in}(renewed after each earthquake) allows to introduce variability in the recurrence time.

From slow-creep to instability to dynamic rupture

Elasticity

$$\tau(x,t) = \tau_o + \mathcal{H}[\partial_x \delta(x,t)] - \frac{\mu'}{2c_s}\partial_t \delta(x,t).$$

$\mathcal{H}[\cdot]$: Hilbert transform of its argument

τ : Shear traction

c_s : Shear wave speed

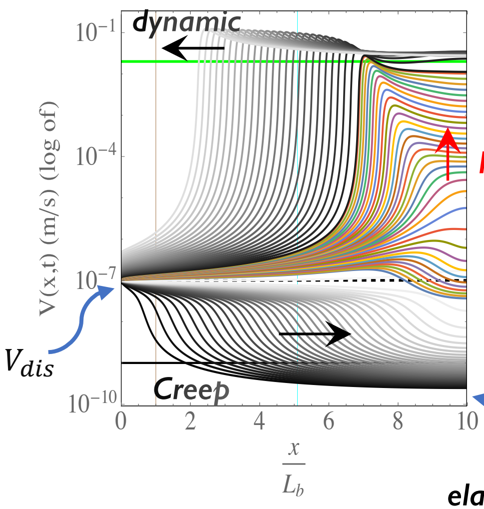
We study slip propagation from an imposed dislocation accrued at a constant rate at one end of a homogeneous fault with the other end either at:

1a. the free surface of an elastic half-space,

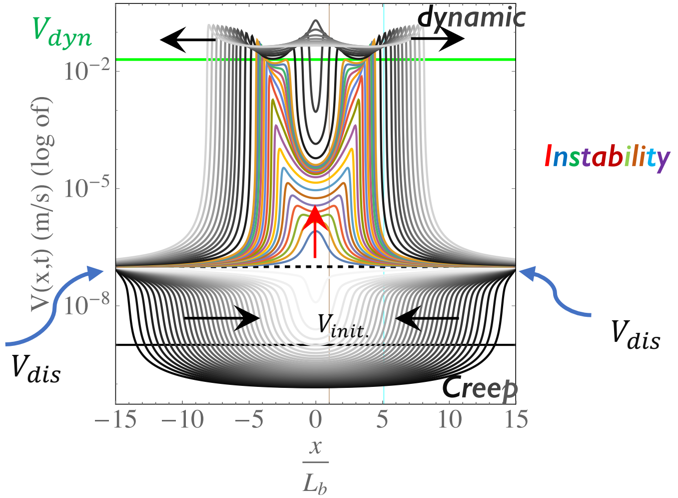
1b. similarly driven

2. strictly locked (buried) in the elastic full space

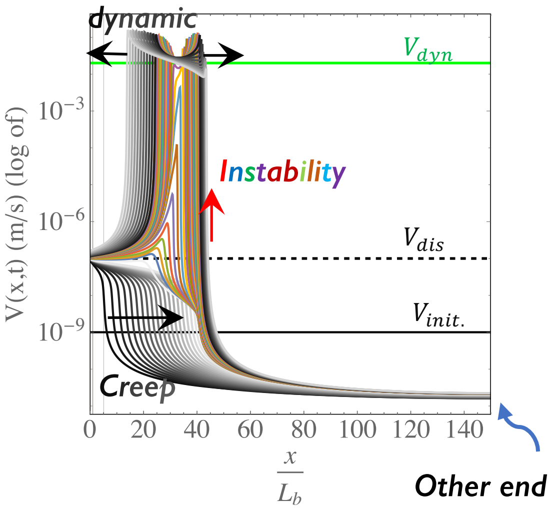
3. at far enough distance



the free surface of an elastic half-space (case 1a),



Imposed dislocations accrued at constant rate (case 1b),



Other end at far enough distance (case 3).

Dynamic rupture

No attempt at this transition so far!

Brener, Aldam, Barras, …(2018)

Instability

(localized sliding crack or pulse like nucleation)

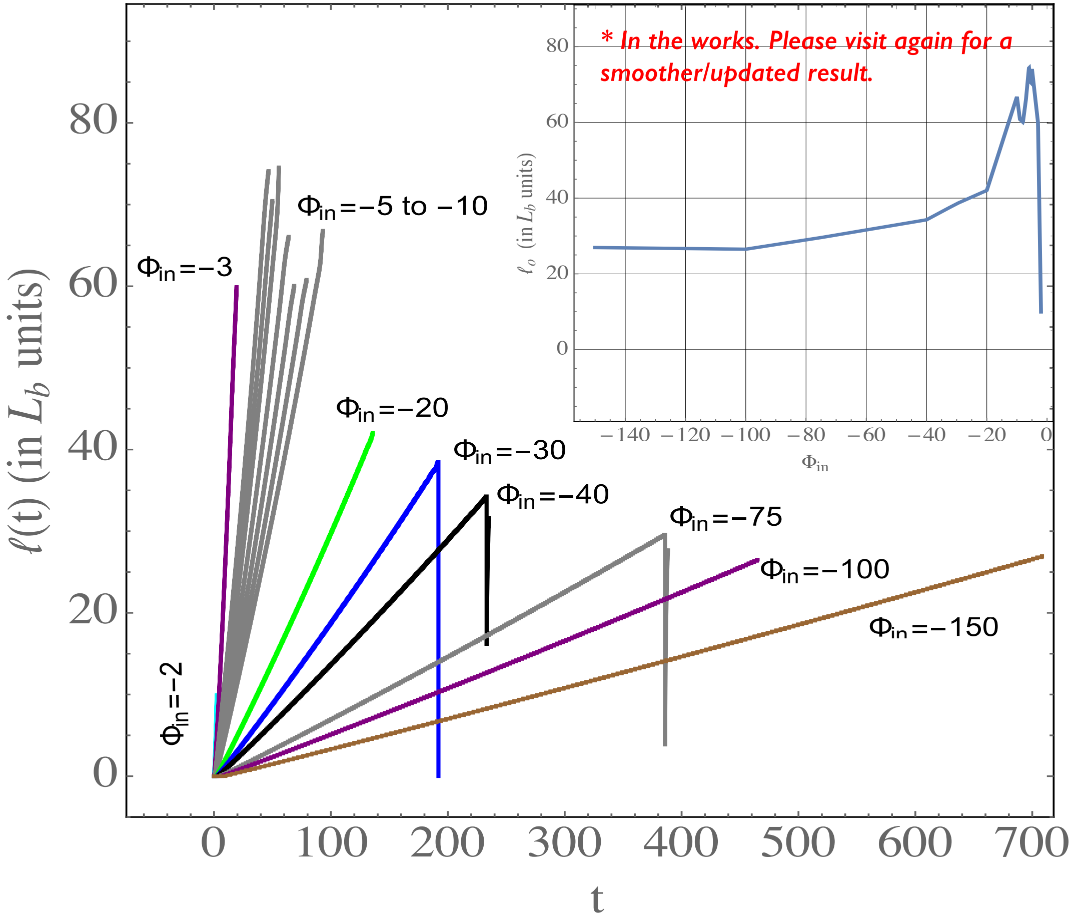
Creep propagation

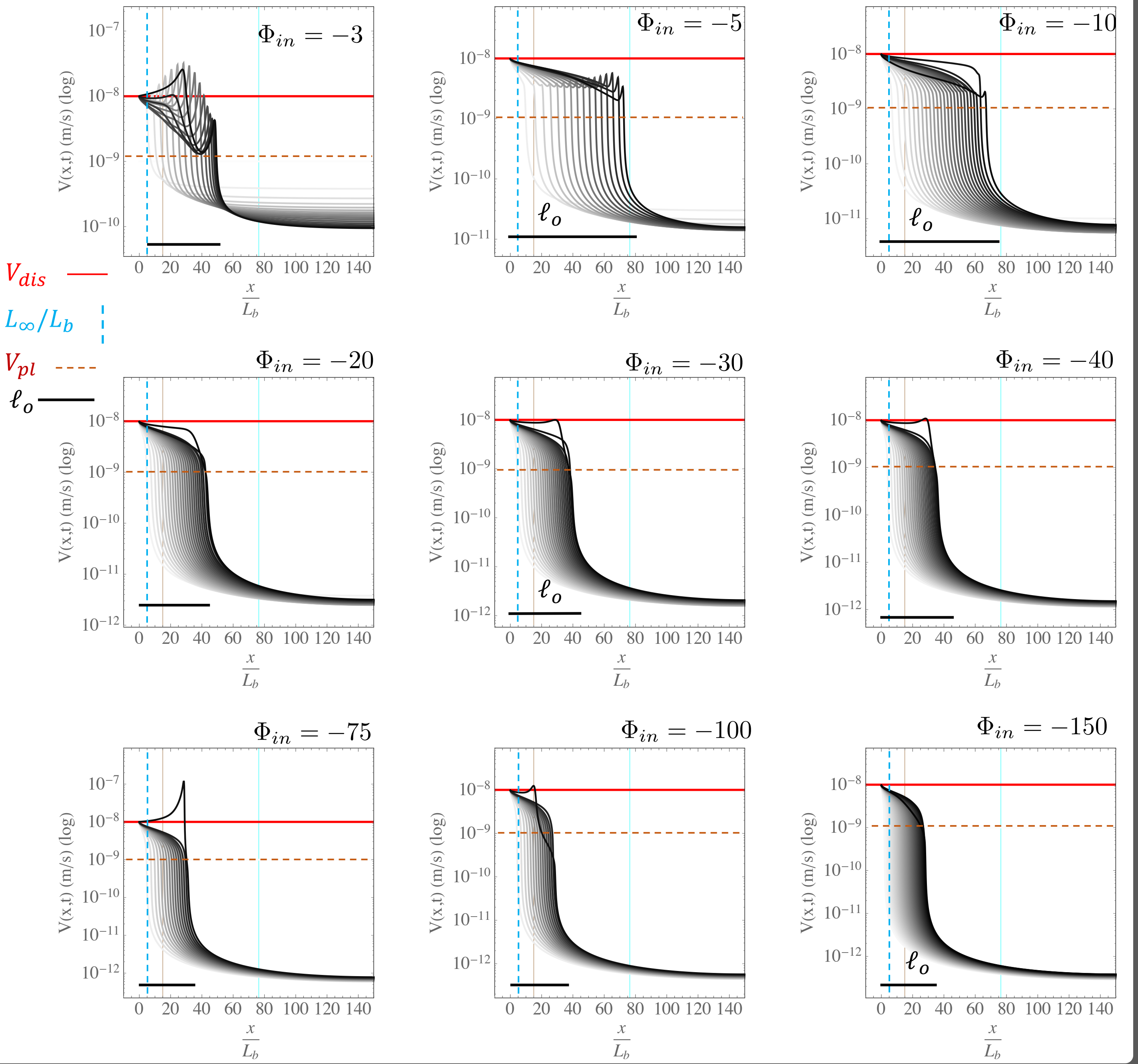
Kaneko & Ampuero (2011)
Cattania & Segall (2019)

(Rubin & Ampuero 2005, 2009)
(Viesca, 2016)

Creep penetration extent and rate (1a): dislocation-driven and with free surface ends

- *Extent to which creep penetrates before provoking an instability is a non-monotonic function of the initial deviation below steady-state sliding:* $\Phi(x, t = 0) = \Phi_{in}$
- *However, the creep propagation rate, which remains constant with time, monotonically decreases with the initial deviation below steady-state sliding,* Φ_{in}





When creep does not lead to an instability

We study slip propagation from an imposed dislocation accrued at a constant rate at one end of a homogeneous **rate-weakening** fault with the other end either at:

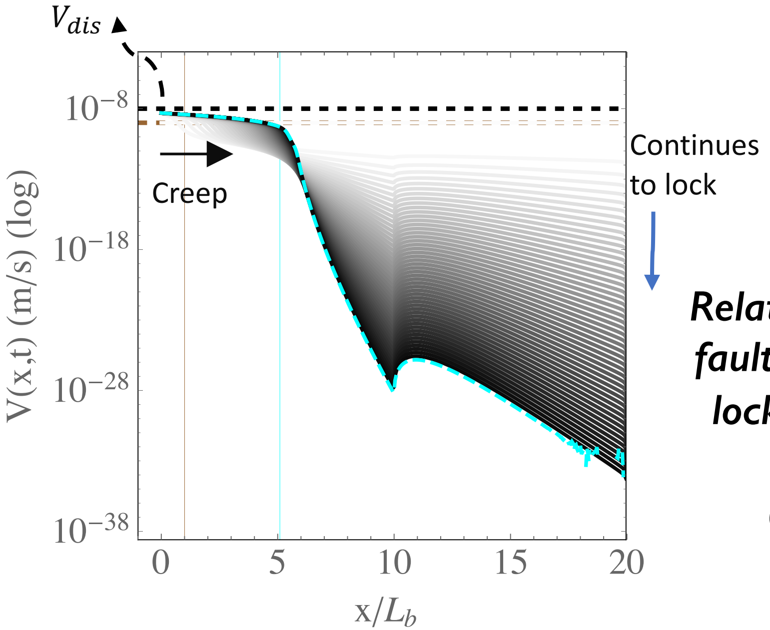
1a. the free surface of an elastic half-space,

1b. similarly driven

2. strictly locked (buried) in the elastic full space

3. at far enough distance

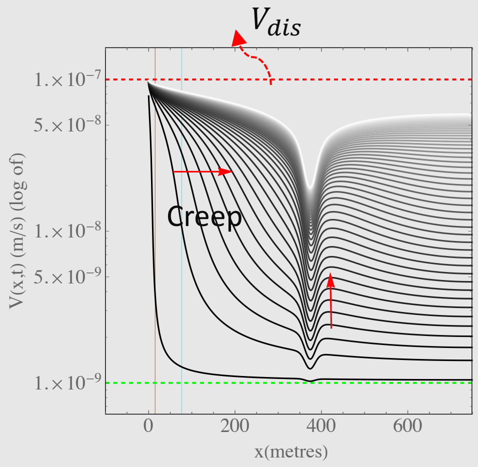
The creep front traverses nearly the entire length of the fault, but, instead of nucleating a dynamic event, the front arrests at some distance from the buried fault end, followed by the continual accumulation of aseismic slip without ever nucleating a dynamic event.

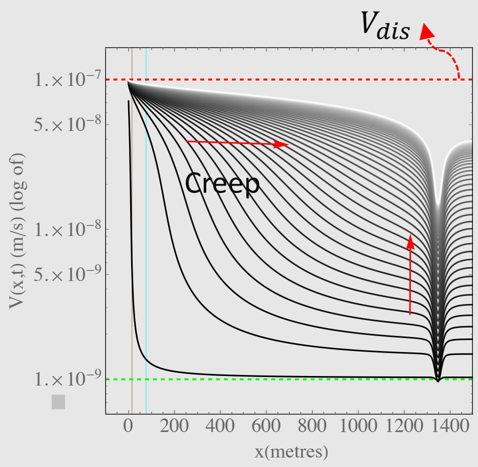


Relatively smaller fault with strictly locked (buried) end (case 2),

A reduced model

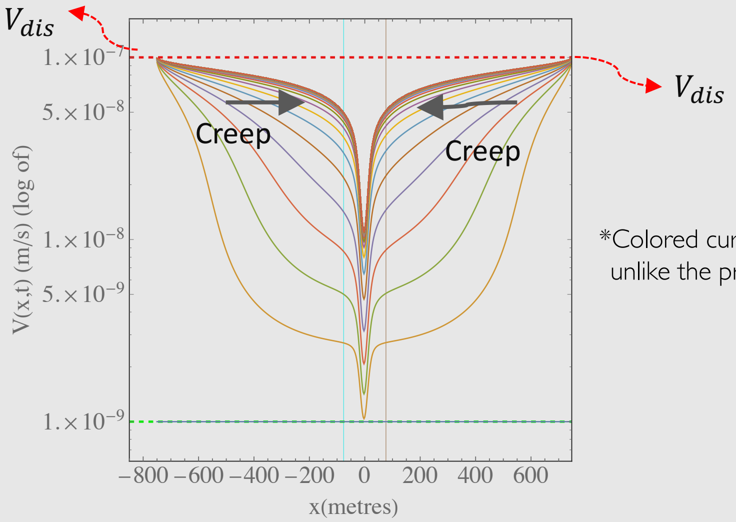
The convenient state variable $\mathbf{\Phi(x)}$ is considered frozen in time. Doing so, indicates that velocity profiles are enslaved to the prescribed distribution of (negative) $\mathbf{\Phi(x)}$. This, in turn, suggests that a continued creep propagation could be due to below steady-state sliding.





*Solid red arrows indicates creep's progression

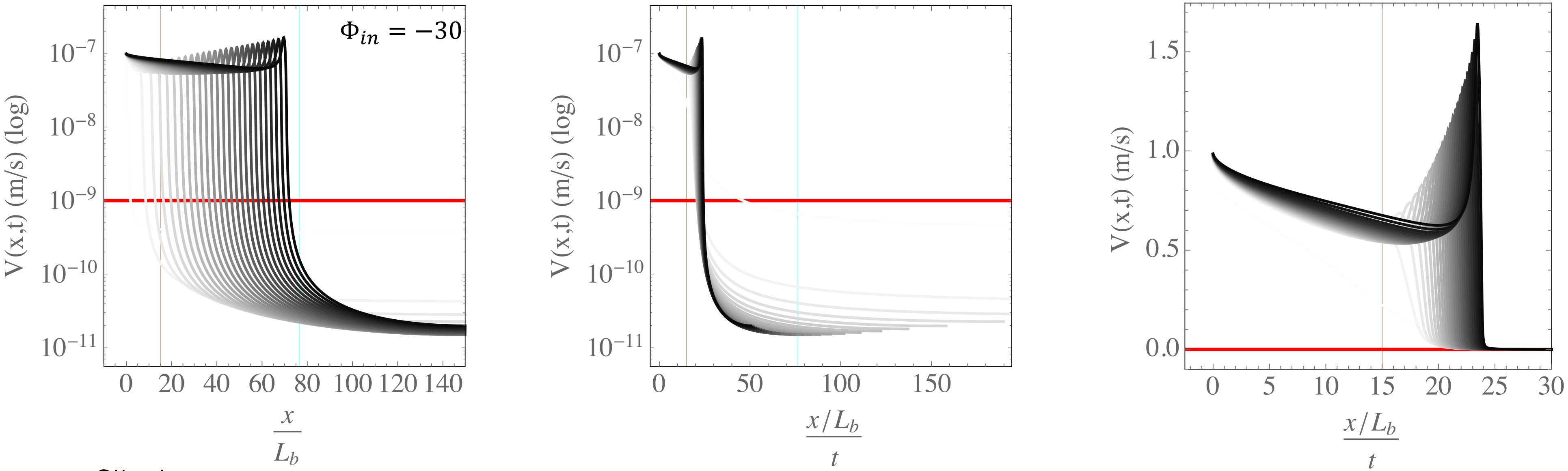
$$\Phi(x) = -C\, e^{(x-x_o)^2} \text{ (negative)}$$



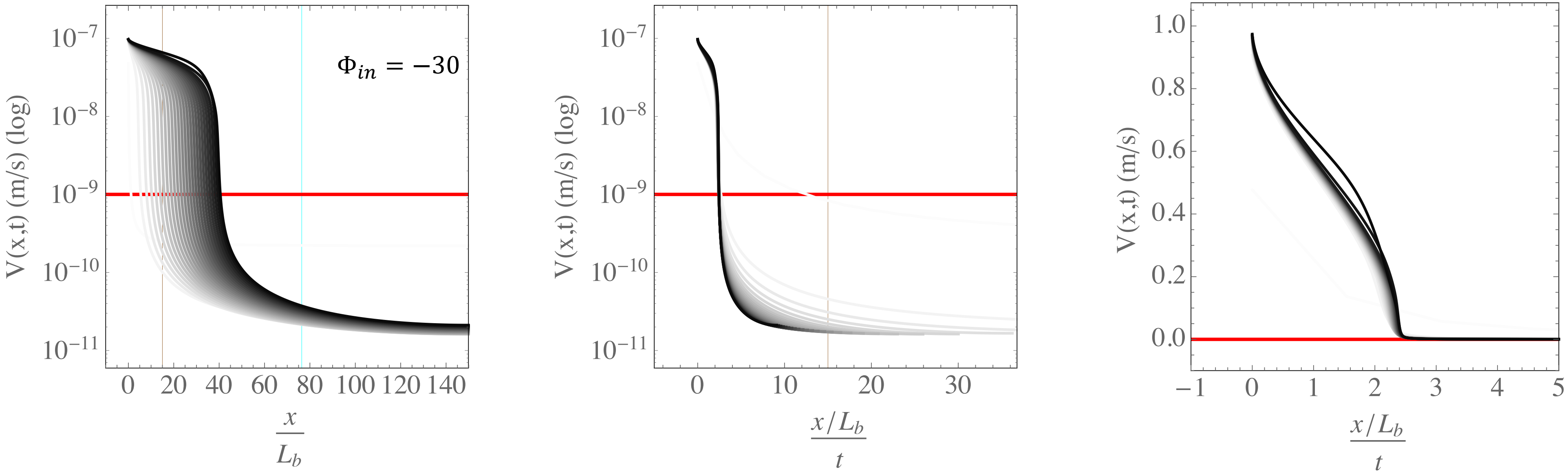
*Colored curves are creep unlike the previous cases

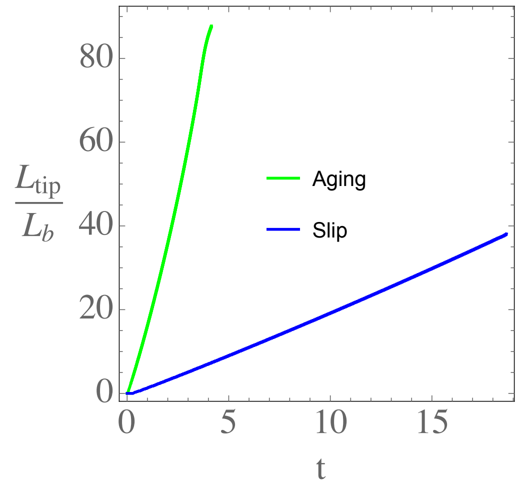
Creep propagation: Slip law vs. Aging law

Aging Law



Slip Law





Creep propagates larger distance and faster with aging law when driven with $\phi_{in} \ll 0$.

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Abstract

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We study slip propagation from an imposed dislocation accrued at a constant rate at one end of a homogeneous fault with the other end either at (1) the free surface of an elastic half-space or (2) strictly locked (buried) in the elastic full space. In both scenarios, no slip instability takes place over aseismic creep propagation distances relatable to the usual elasto-frictional nucleation lengthscale. Instead, in the first case creep propagation leads to the nucleation of the first and all subsequent dynamic events of the emerging cycle at/near the free surface after the creep traversed the entire length of the fault (for smaller faults).

In the second case, the creep front traverses nearly the entire length of the fault, but, instead of nucleating a dynamic event, the front arrests at some distance from the buried fault end, followed by the continual accumulation of aseismic slip without ever nucleating a dynamic event. These results may be owed to the physical and geometrical invariance of the considered homogeneous fault and may signal the essential role of fault strength heterogeneity, either that of the normal stress and/or frictional properties , in defining its seismogenic character, i.e. under which conditions and where on the fault the earthquake slip instability can take place

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References

1. Rubin and Ampuero (2009)
2. Kaneko and Ampuero (2011)
3. Brener et. al. (2018)
4. Bar-Sinai et. al. (2019)
5. Cattania and Segall (2019)
6. Garagash (2020, in preparation)

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