Three-Dimensional Elastodynamic Simulations of Seismic and Aseismic Slip History of a Planar Strike-Slip Fault

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Abstract

Simulations of spontaneous slip accumulation in three-dimensional (3D) models enjoy a lot of interest because of their ability to clarify earthquake physics. We have been developing a 3D methodology for simulating the entire seismic and aseismic slip history of a fault subjected to slow tectonic loading. The algorithm, extended from the 2D study by Lapusta et al. (2000), allows us to resolve all stages of spontaneous slip accumulation in a single computational procedure, including quasi-static nucleation process, dynamic rupture propagation, post-seismic deformation, and aseismic processes throughout the loading period. Simulating long-term deformation histories while accounting for dynamic effects of occasional earthquakes is quite challenging due to a variety of temporal and spatial scales.

We consider a vertical strike-slip fault embedded in an elastic half-space and governed by rate and state friction. On the fault, there is a seismogenic region, 30 km long and 15 km deep, with steady-state rate-weakening properties. It is surrounded by steady-state rate-strengthening regions that stably slip (creep) under loading. We observe the following interesting phenomena:

(1) The simulations produce realistic earthquakes and complicated patterns of interseismic slip. The earthquakes propagate with rupture speeds comparable to the shear wave speed of the surrounding bulk and have average slip rates of order of 1 m/s. After each large earthquake, there is an accelerated post-seismic creep in the surrounding rate-strengthening regions. During interseismic periods, we observe very interesting patterns of aseismic slip, with accelerating and decelerating patches and slow propagation of faster creep along the interface. These patterns result in occasional small events.

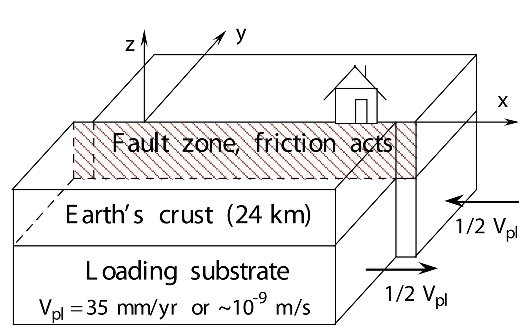
(2) The quasi-dynamic model, which ignores wave-mediated stress changes and hence significantly simplifies the computation of dynamic response, qualitatively captures most features of the fully dynamic computation, but produces more sluggish earthquake behavior and seems unable to reproduce some dynamic features such as the supershear burst.

(3) An asperity (a small circular region 20% stronger than the surrounding fault) causes a supershear burst for the first earthquake in the simulation but not for subsequent events. This indicates that single-earthquake simulations, due to their strong dependence on initial conditions, may in some cases reach conclusions that would not be sustained over a longer history of the fault.

(4) All simulated large events have similar initial stages of their moment-rate function.

In future studies, we plan to (i) adopt more realistic friction laws, by combining rate and state friction with pore pressure evolution and flash heating effects during the dynamic rupture; (ii) incorporate the bimaterial configuration into our earthquake sequence simulations, to investigate its statistical influence on rupture propagation direction over many earthquake cycles; (iii) determine the model response for a wider range of frictional parameters, such as more realistic characteristic slip distance of rate and state friction; (iv) investigate the possibility of determining frictional parameters by comparing our simulations with observations; (v) study whether complicated patterns of aseismic slip that we observe can explain recent observations of slow earthquakes and other interseismic phenomena.

Model of a vertical strike-slip fault



3D earthquake simulations help us to:

1. Study effects of earthquake physics and fault geometry, independently of initial conditions.
2. Understand how earthquakes nucleate, propagate and arrest, and how these stages interact.
3. Understand how heterogeneitites influence fault behavior in earthquake sequences vs. single earthquakes.

In simulations, we use rate-and-state friction law:

$$\tau = \sigma f = \sigma\left[f_o + a\ln\frac{V}{V_o} + b\ln\frac{V_o\theta}{L}\right] \qquad \frac{\partial\theta}{\partial t} = 1 - \frac{V\theta}{L}$$

a, b are friction parameters, of the order of 0.01.

If $a < b$, the fault exhibits steady-state velocity weakening;

if $a > b$, the fault exhibits steady-state velocity strengthening.

Basic friction f_o = 0.6 at the sliding velocity $V_o = 10^{-6}$ m/s.

Main challenge in simulations of earthquake sequences: multiscale nature

Multiple scales in time (dynamic cracks + slowing loading)

Loading time	100 to 1000 years
Duration of dynamic event	10 to 100 seconds
Time for rapid change of variables at the crack tip	fraction of a second

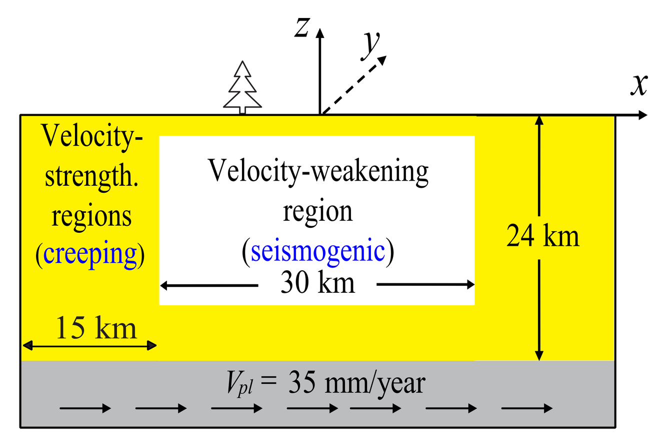
Multiscale in space

Fault dimensions	100 km
Nucleation size on faults	1 to100 meters (if L ~ 10 to 100 μm)
Distance of rapid changes at the rupture tip	fraction of a meter

Case I: Fault with homogeneous seismogenic region

Model Geometry

We simulate earthquake sequences on a fault embedded in an infinite elastic half space, subjected to slow tectonic loading V_{pl} = 35 mm/yr. The fault properties are extended from 2D studies (i.e. Lapusta et al. 2000), where a steady state velocity-weakening region of a = 0.015 and b = 0.019 is surrounded by seatdy state velocity-strengthening regions of a = 0.019 and b = 0.015. Nucleation starts in the strip -15 km < x < -10 km as the initial shear stress there is set to be 10% higher than $\tau_{ss|V=V_0}$. L is 8 mm, and the estimated critical nucleation sizes for an in-plane problems are (Rice Ruina, 1983; Rubin and Ampuero, 2005):

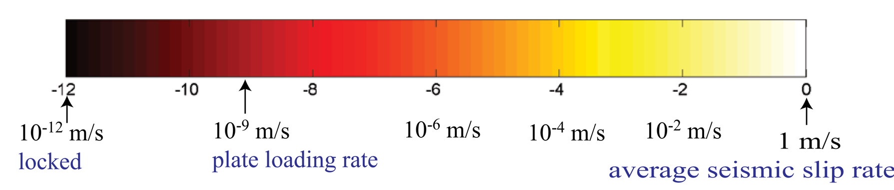


$$h^*_{RR} = \frac{\pi}{4}\frac{\mu}{1-\nu}\frac{L}{\sigma(b-a)} \approx 1.1 \text{ km} \qquad h^*_{RA} = \frac{1}{\pi}\frac{\mu}{1-\nu}\frac{Lb}{\sigma(b-a)^2} \approx 2.5 \text{ km}$$

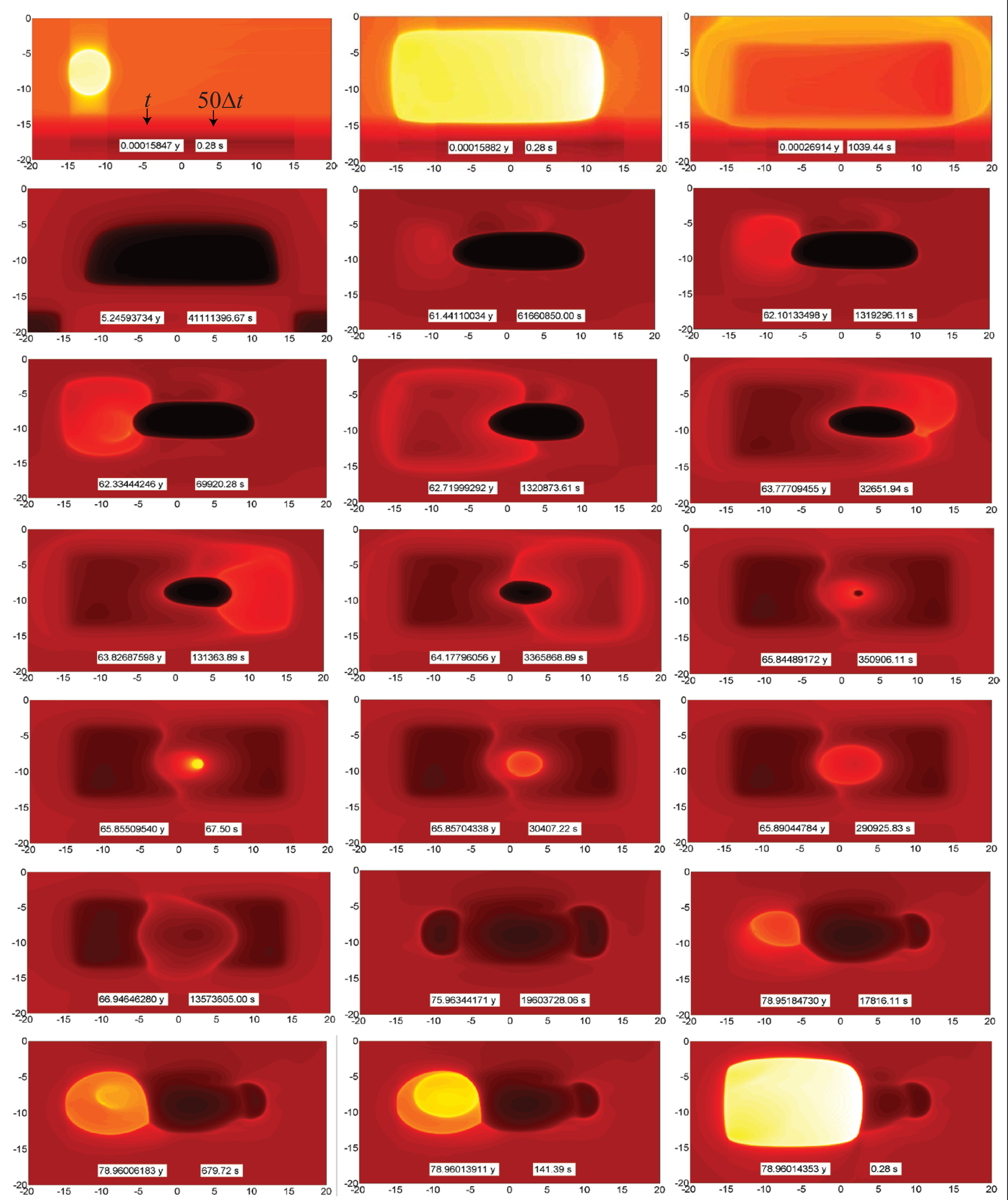
The calculation is implemented using spectral boundary integral method. Since the analytical integral kernels are available only for the whole infinite space, we make a mirror image of the simulated fault to approximately represent the effect of the free surface.

We use variable time stepping. Throughout the computation, time steps change by more than 10 orders of magnitude, allowing us to do relatively few steps through the quasi-static slow-loading periods, and to consider carefully earthquake nucleation and dynamic rupture propagation periods.

Snapshots of slip rate distribution during 1st and 2nd events



The color scheme depicts the slip rate in m/s on a logarithmic scale. Each snapshot has two time markers. The first one is simulated time t in years. The second one is the current time step Δt multiplied by 50.



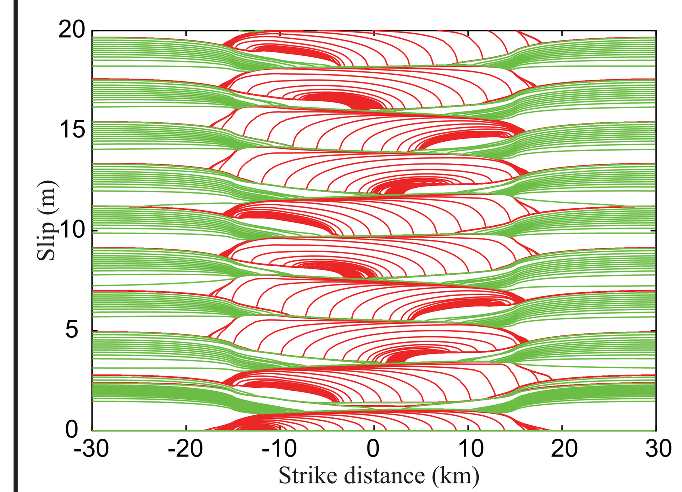


Fig 1: Accumulation of slip vs. strike, along the line z = -8 km. The red lines are plotted every 1 second when the maximum slip rate exceeds 1 mm/s. The green lines are plotted every 5 years.

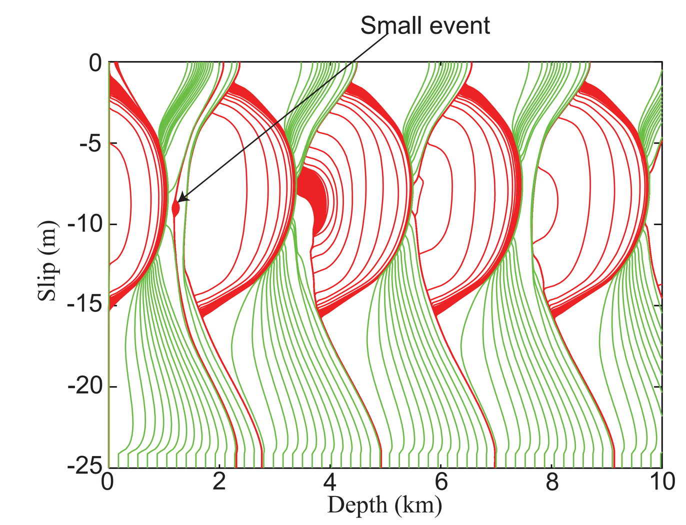
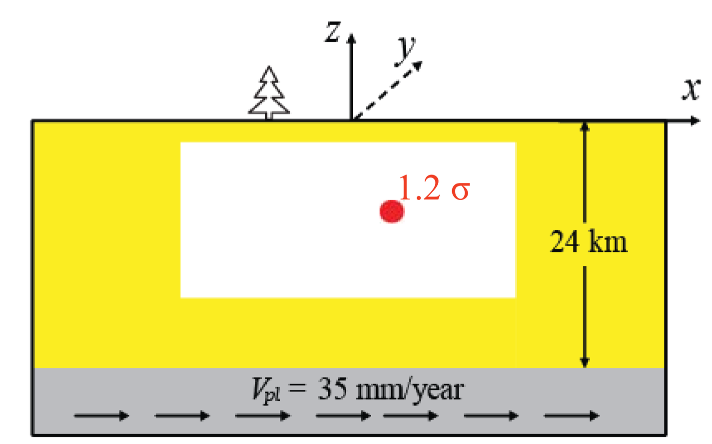


Fig 2: Accumulation of slip vs. depth, along the line x = 3 km. The red lines are plotted every 1 second when the maximum slip rate exceeds 1 mm/s. The green lines are plotted every 5 years.

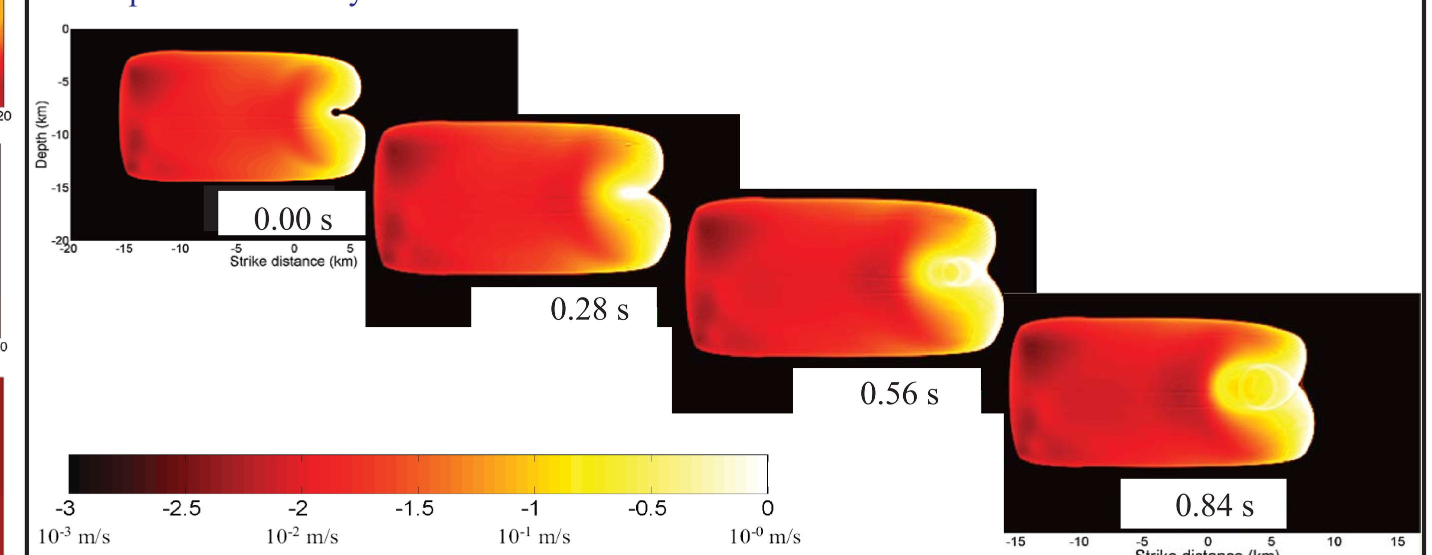
Case II: Fault with a compact heterogeneity

We add a circular patch of 1 km radius, centered at the point (3 km, -8 km). The effective normal stress σ in the patch is 20% larger than on the rest of the fault. The other parameters are the same as in Case I. We find that the heterogeneity causes a supershear burst for the first earthquake but not for subsequent events.



Supershear Burst in the First Event

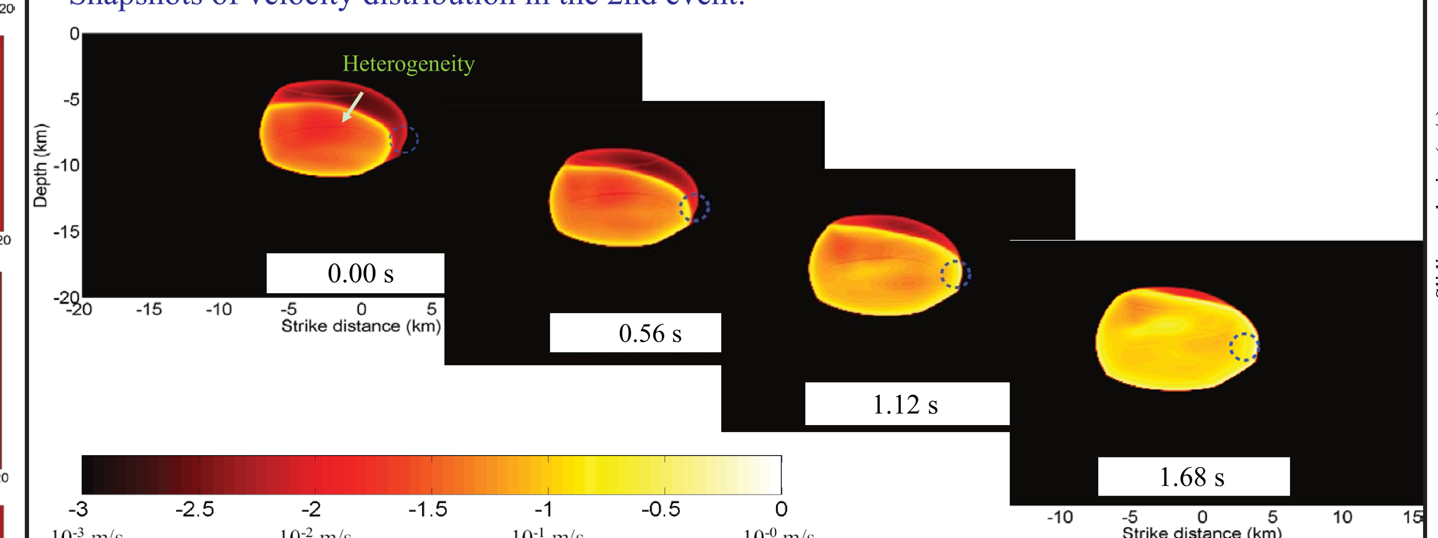
Snapshots of velocity distribution in the 1st event:



Average rupture speed during the time shown is c = 4.6 km/s which is larger than c_s = 3 km/s. Dunham et al. (2003) studied this kind of supershear bursts in single-event simulations; rupture surrounds the heterogeneity and creates a supershear burst after breaking it.

No Supershear Burst in the Following Events

Snapshots of velocity distribution in the 2nd event:



Supershear burst due to this heterogeneity is not repeatable in subsequent events due to redistribution of stress.

Comparison between fully-dynamic and quasi-dynamic models for Case II

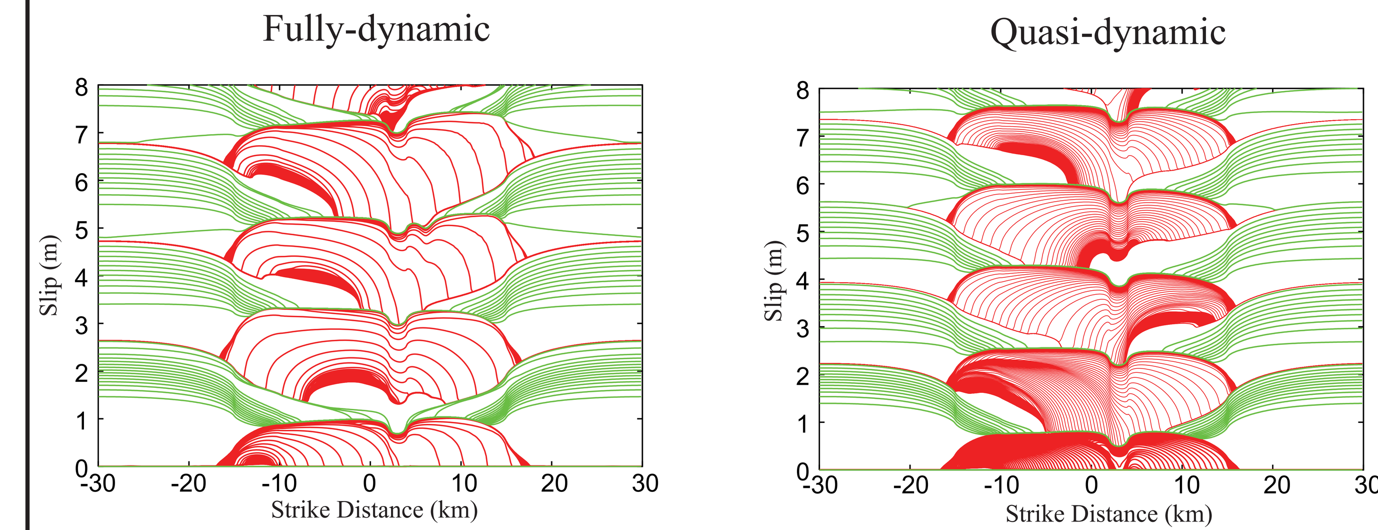


Fig 3: Accumulation of slip vs. strike, along the line z = -8 km that passes through the center of the heterogeneity. The red lines are plotted every 1 second when the maximum slip rate exceeds 1 mm/s. The green lines are plotted every 5 years.

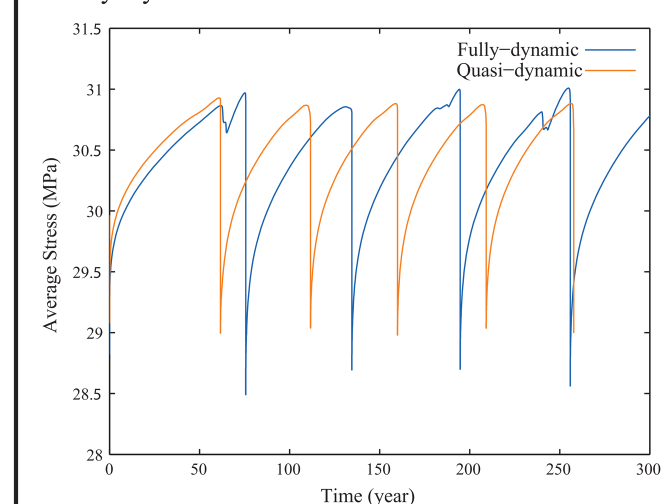


Fig 4: Comparison of average stress drop between fully-dynamic and quasi-dynamic models.

Quasi-dynamic simulation has some qualitatively similar features:

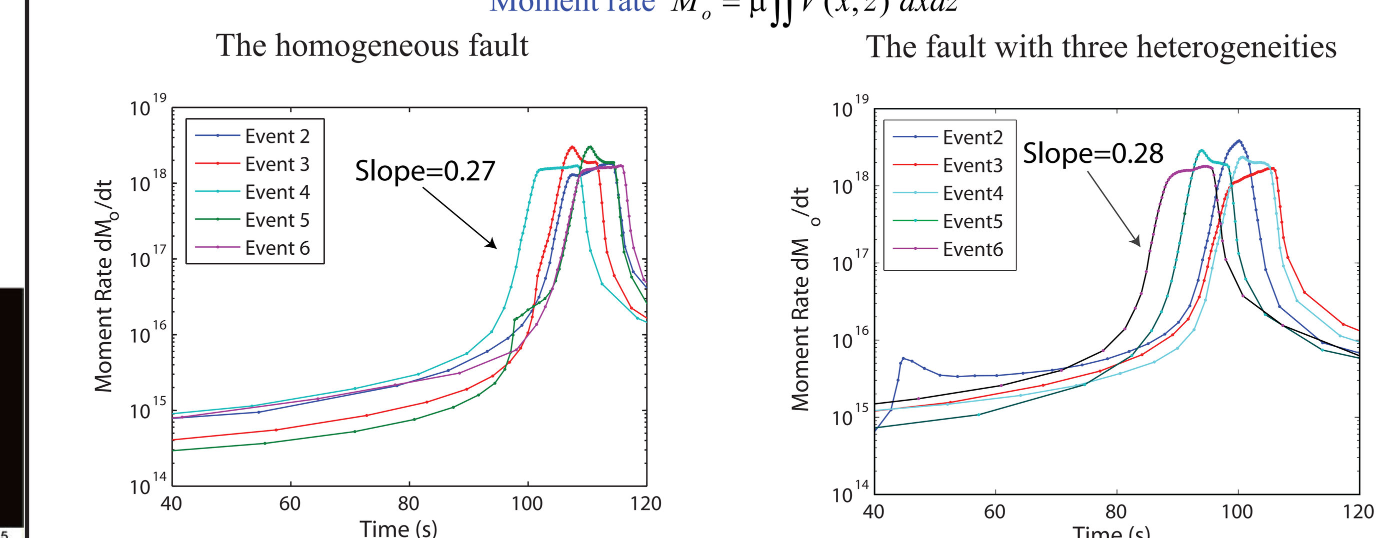
- slow nucleation process
- fast rupture propagation
- postseismic slip
- interseismic slip

Quasi-dynamic simulation has important differences with the fully-dynamic simulation:

- slower rupture propagation speed
- smaller slip rate and slip in events
- smaller earthquake period
- smaller stress drop in events

Similar moment rate function for large events

Moment rate $\dot{M}_o = \mu\iint V(x,z)\,dxdz$



Different events have almost the same slope of growth S.
What is the physical meaning of the slope? Some discussion in Ampuero (2003).
Can it be inferred from seismic observation?

Influence of L on earthquake period T

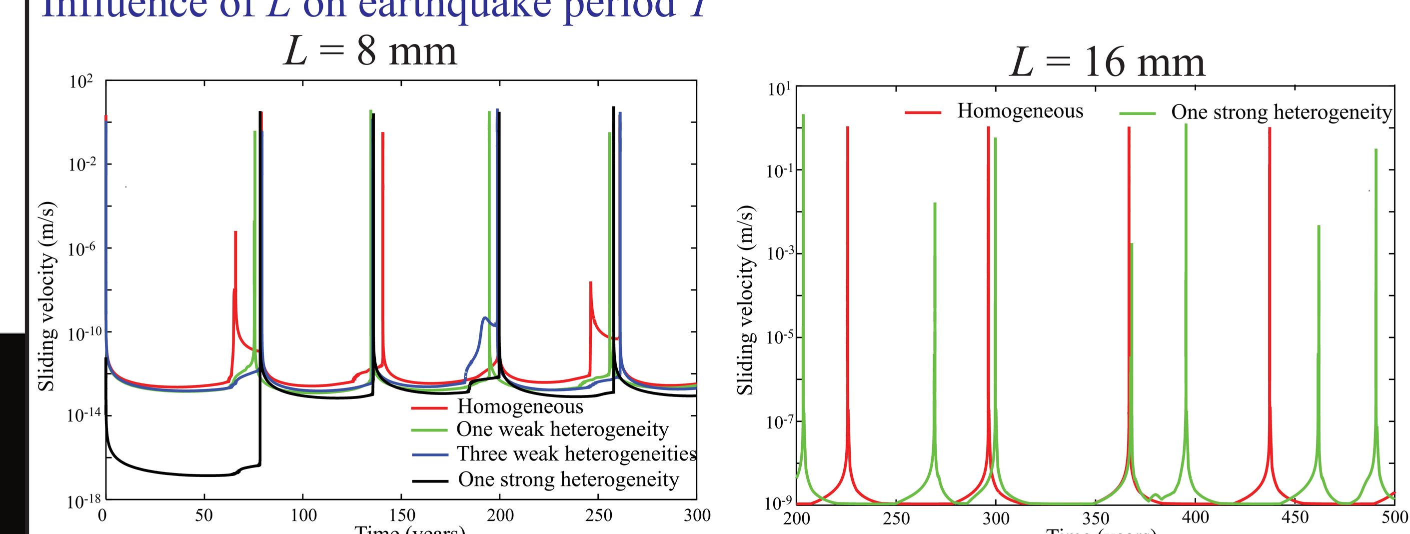


Fig 5: Sliding velocity evolution for several simulated cases with different heterogeneities on the fault. Every vertical line represents an event, and the time itervals between vertical lines are earthquake periods T. For L =16 mm, T is different for different cases. For L =8 mm, T is almost the same.

What happens for even smaller L?
Will T become insensitive to the existence of heterogeneities for small enough L?