Towards simulating sequences of seismic and aseismic slip across scales: Initial benchmarks and future directions

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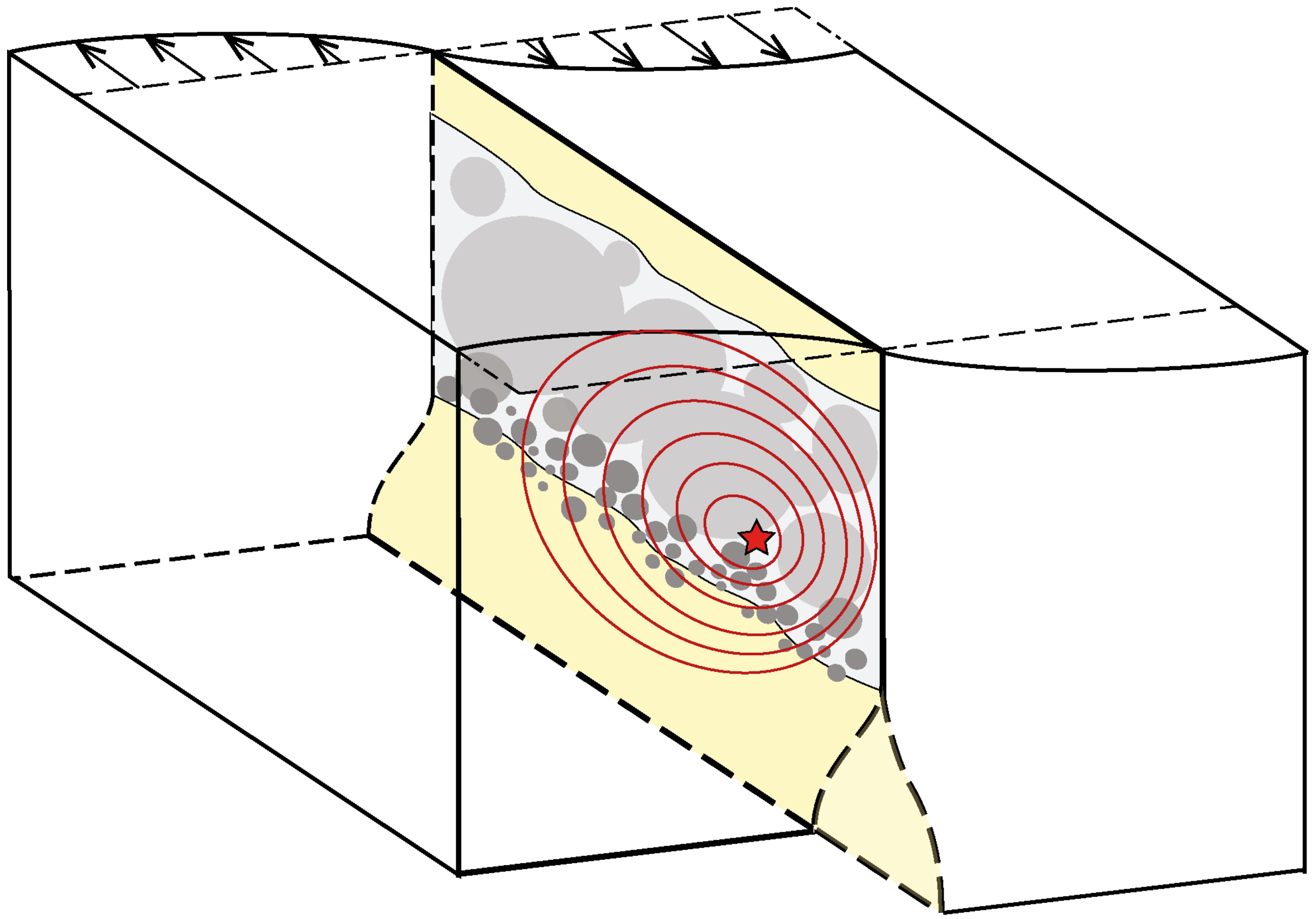

Seismological Laboratory California Institute of Technology

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Seismic cycle simulations

Seismic cycle simulations have made great progress over the past decades to address important questions in earthquake physics and fault mechanics…

…however, significant challenges remain in resolving earthquake nucleation, dynamic rupture, and multiscale interactions.

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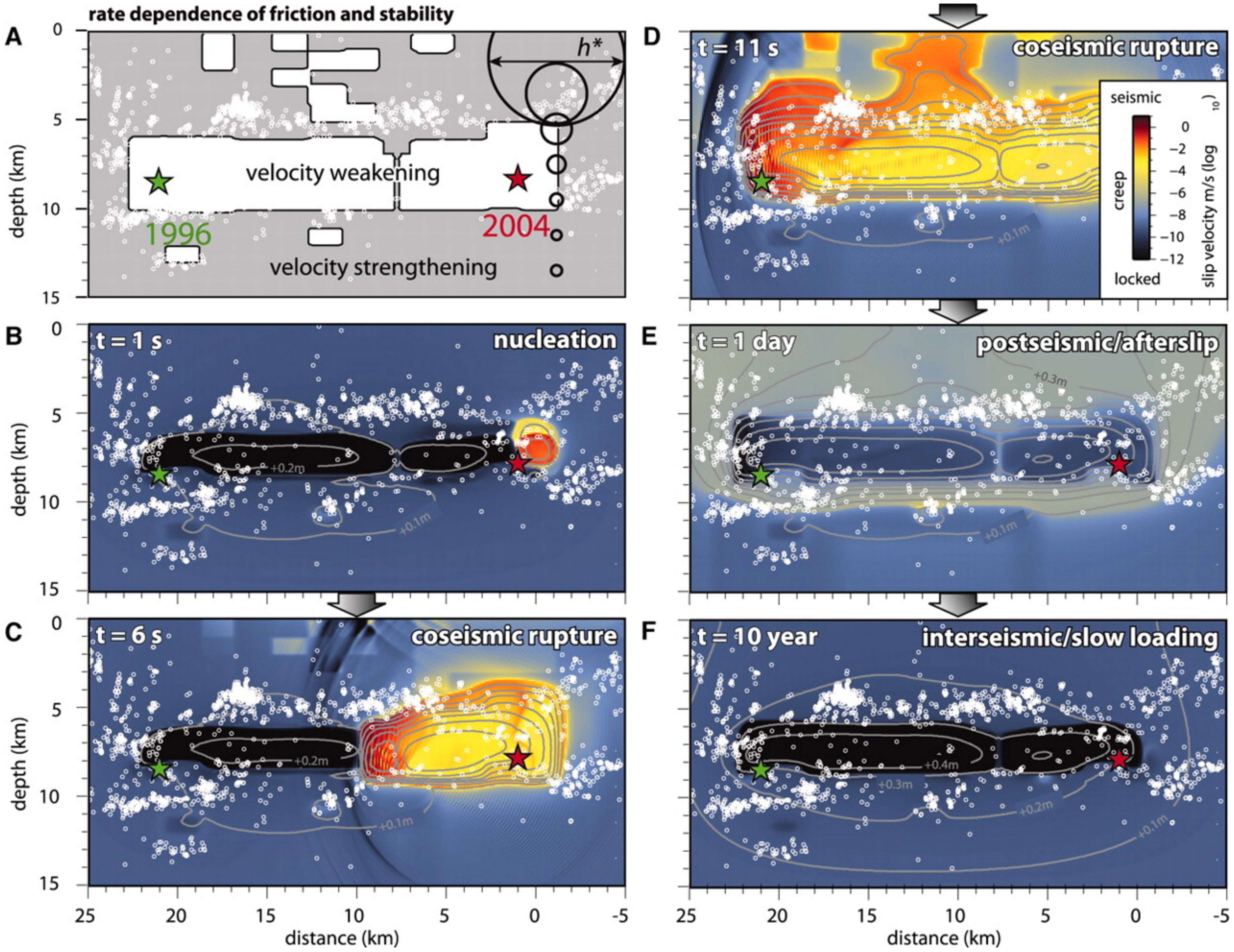
Understanding physical factors controlling observables such as seismicity and ground deformation.



Barbot et al., 2012

Community code-verification by the Southern California Earthquake Center (SCEC)

SCEC Southern California Earthquake Center
AN NSF+USGS CENTER

The increasing capability and complexity of Sequences of Earthquakes and Aseismic Slip (SEAS) modeling calls for extensive efforts to verify codes and advance these simulations with **rigor, reproducibility, and broadened impact.**

In 2018, the Southern California Earthquake Center (SCEC) initiated a "community code-verification exercise" for SEAS simulations

SEAS goal:

“The goal of the SEAS initiative is to promote advanced models with robust physical features — a large spectrum of rupture styles and patterns, including slow-slip events, complex earthquake sequences, fluid effects, dynamic stress changes, and inelastic deformation”

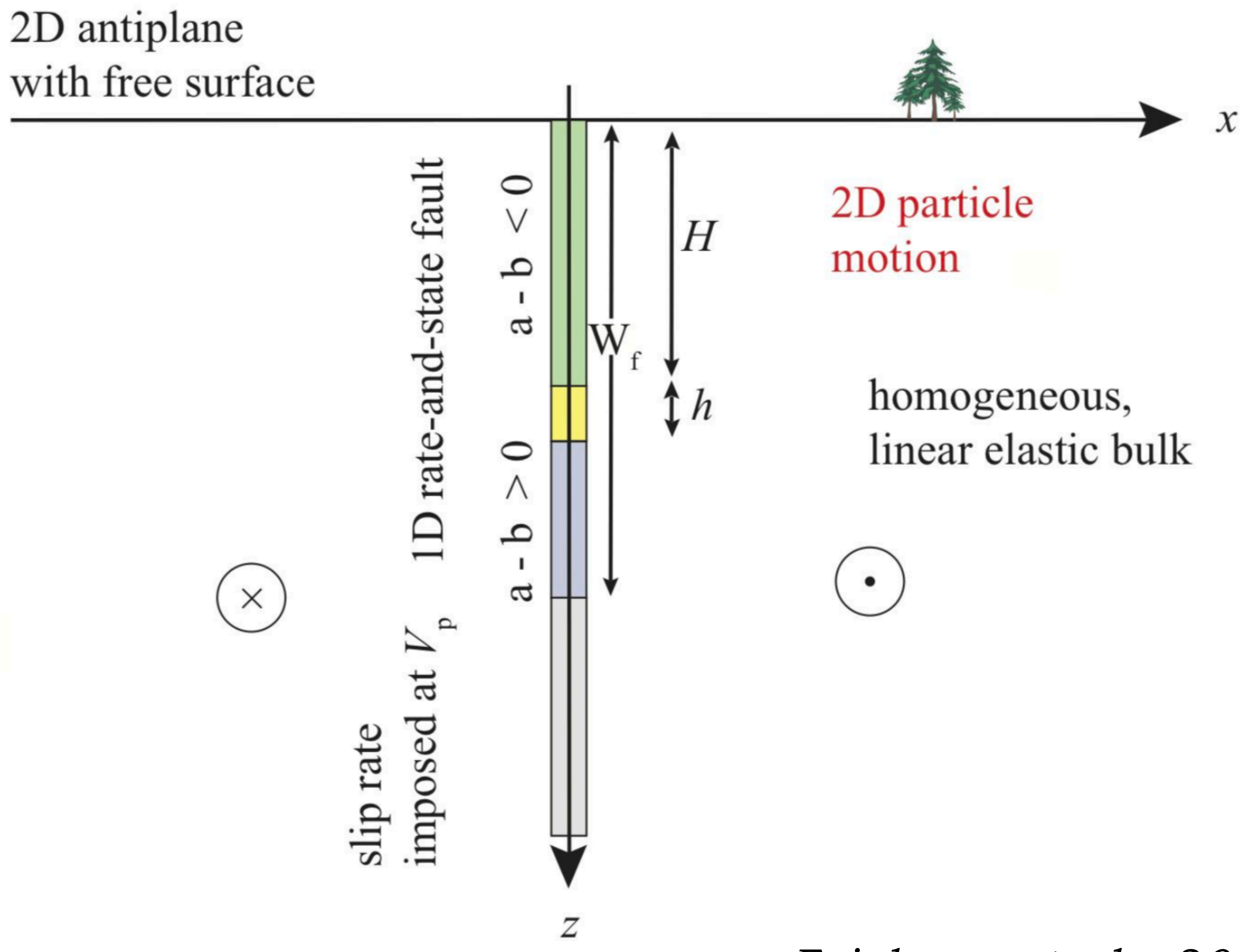
Erickson and Jiang, 2019, SCEC annual report

BP1 and BP3 benchmarks

2D antiplane problem, with a 1D planar vertical strike-slip fault obeying rate-and-state friction, embedded in a 2D homogeneous, linear elastic half-space.

The fault has a shallow seismogenic region with **velocity-weakening friction** and a deeper **velocity-strengthening region**, below which a relative plate motion rate is imposed.

- Cell size: ~25 m
- L = 8 mm
- σ = 50 MPa
- a = 0.01-0.025
- b = 0.16



Erickson et al., 2020

BP1 and BP3 benchmarks

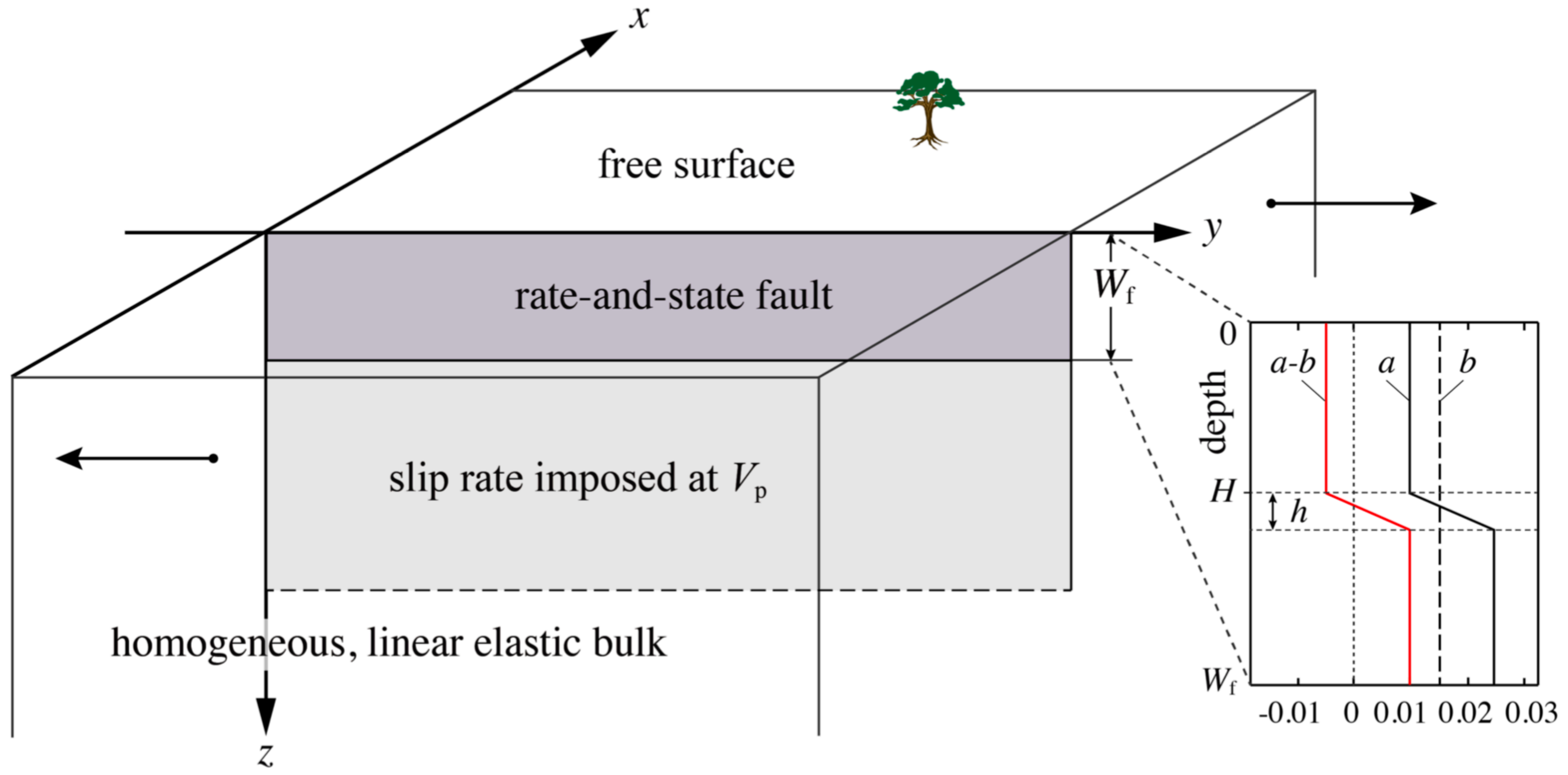
BP1: Quasi-dynamic (no inertia) + radiation damping

BP3: Fully-dynamic (inertia effects)

$$\tau(t) = \tau_0 + a\,\sigma_n \sinh^{-1}\left(\frac{1}{2}\frac{V(t)}{V_0}\exp\left(\frac{\mu_0}{a} + \frac{b}{a}\log\left(\frac{V_0\,\Theta(t)}{D_c}\right)\right)\right) + \underline{\eta\,V(t)}$$

$$\dot{\Theta}(t) = 1 - \frac{1}{D_c}V(t)\Theta(t)$$

$\eta \qquad G/c_s/2 \approx 4.6\ 10^6$



Erickson et al., 2020

GARNET

EARTH SCIENCES

GENERAL ALGORITHM · REGULAR GRID RESIDUAL-BASED ROOT-FINDING · NEWTON-KRYLOV NONLINEAR N-DIMENSIONAL · TIME-DEPENDENT TIGHTLY-COUPLED TOOLBOX

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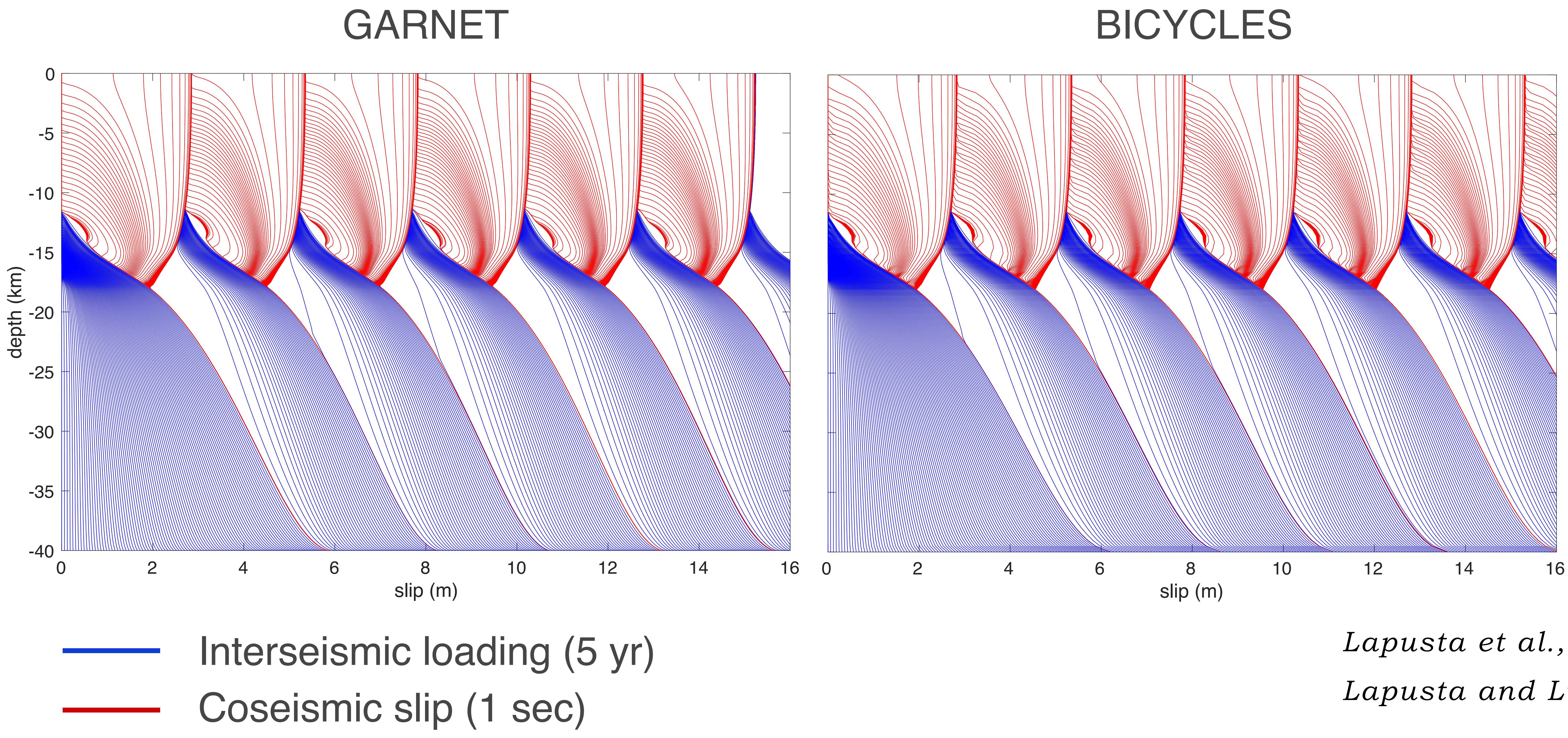
c++ library for the solution of coupled, non-linear, time-dependent continuum problems in geosciences

- Finite difference code / fully staggered spatially adaptive grid
- Automatic discretization algorithm combining different physical ingredients, including:
  - visco-elasto-plastic rheology
  - quasi- and fully dynamic formulation of inertial effects
  - absorbing boundary conditions
  - adaptive time stepping to resolve time scales ranging from years to milliseconds during the dynamic rupture propagation

\+ PETSc and Kokkos libraries are included for parallel computing

Results — BP1



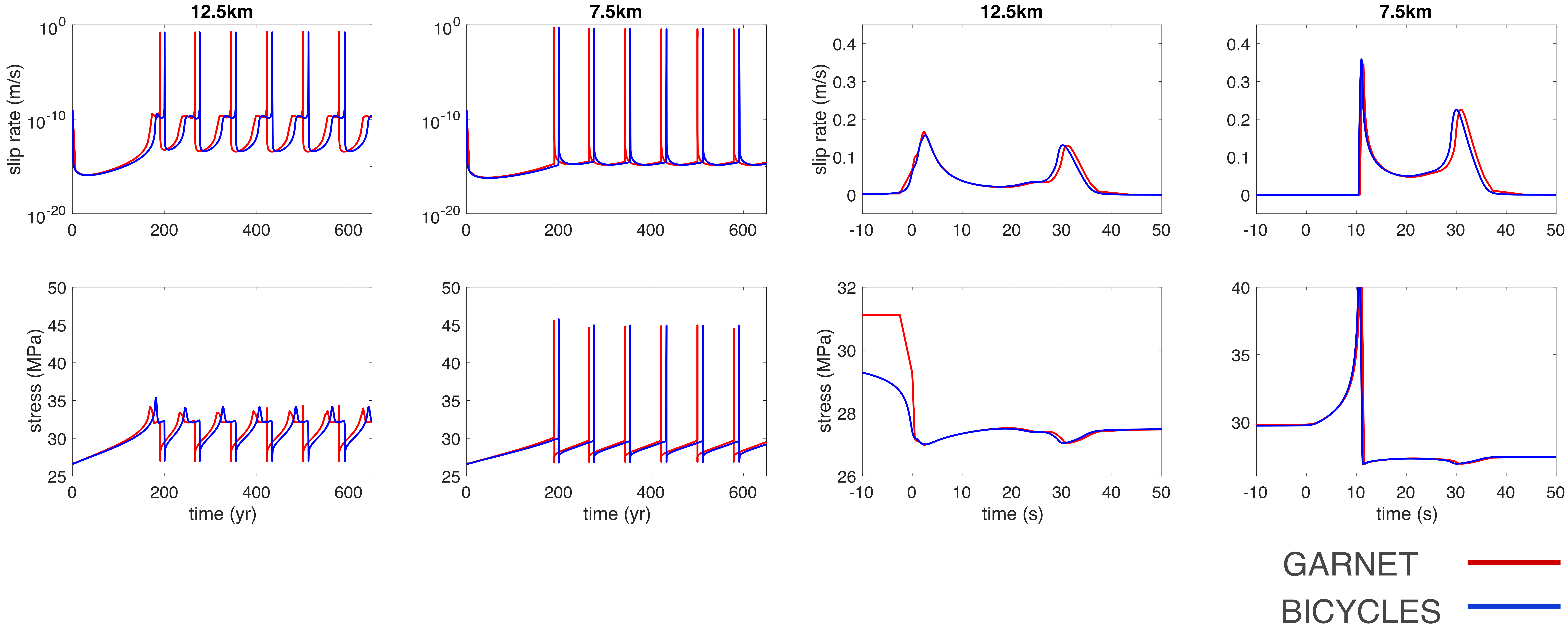
Lapusta et al., 2000

Lapusta and Liu, 2009

Results — BP1

Stress and velocity evolution at depths of 7.5 km and 12.5 km (nucleation zone)

Two peaks of slip velocity in the coseismic phase, the second due to surface reflection

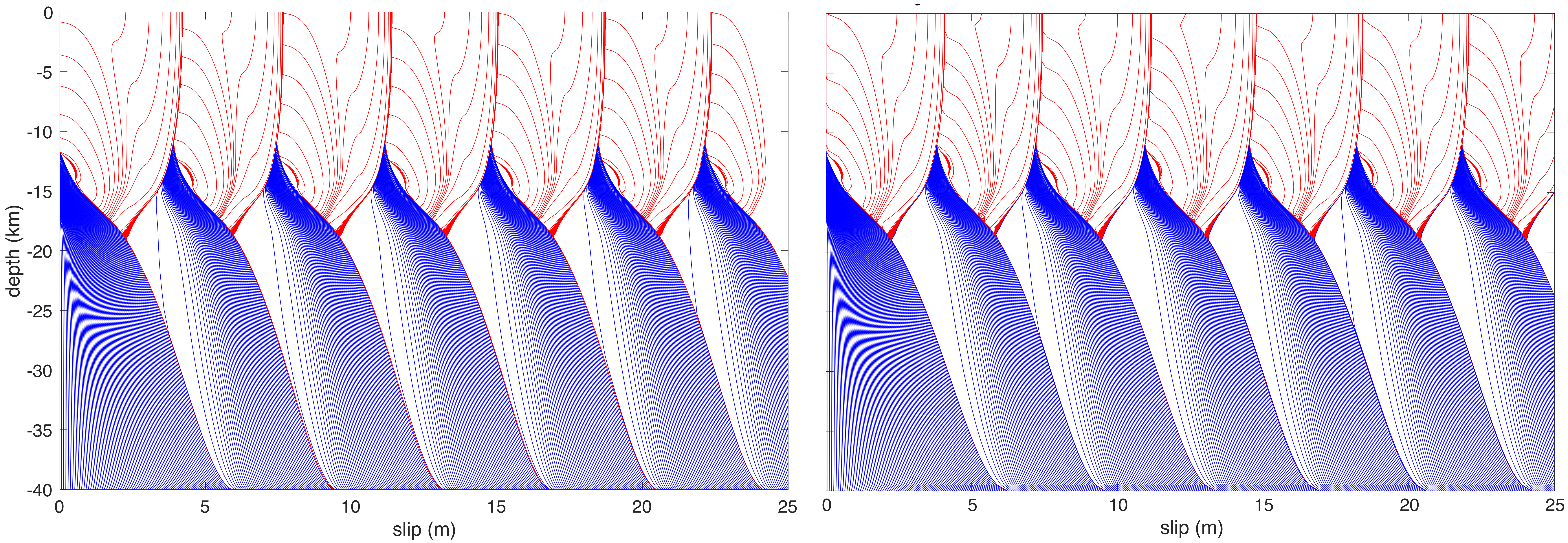


Results — BP3

More slip with each event compared with quasi-dynamic counterpart

GARNET

BICYCLES



Interseismic loading (5 yr)

Coseismic slip (1 sec)

Lapusta et al., 2000

Lapusta and Liu, 2009

Results — BP3

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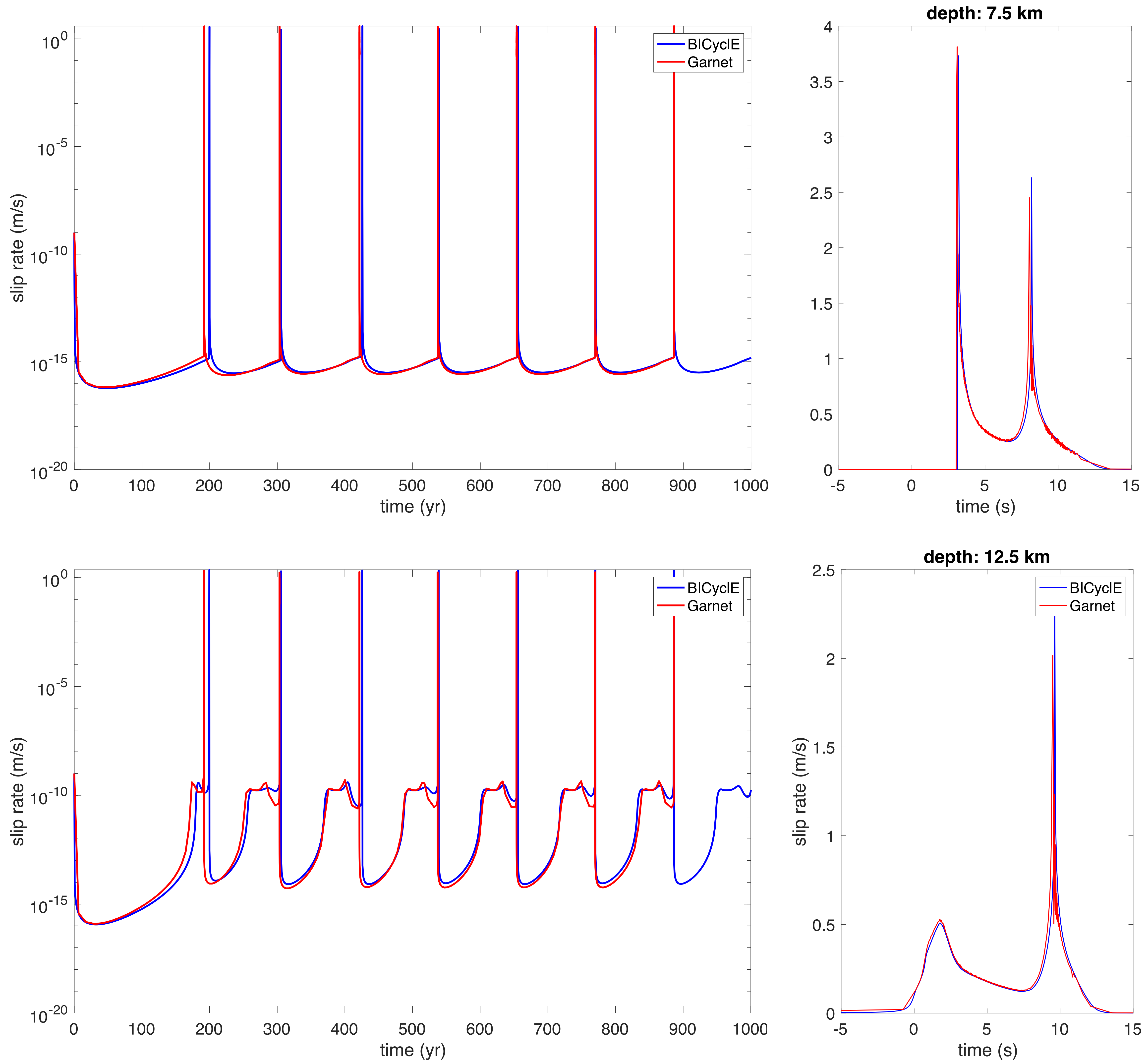
Full dynamics yields

- higher peak values in shear stress and slip rate
- faster rupture speeds
- longer recurrence times



Preliminary conclusions

Poor numerical resolution can result in the generation of artificial complexity, impacting simulation results (of potential interest for characterizing seismic hazard), including:

(1) earthquake size distributions, (2) moment release, and (3) earthquake recurrence times

Our result shows a good similarity in terms of recurrence period, total slip and cumulative slip profile compared to the results from BICycIE.

However, when compared to BiCycIE results, the output of GARNET still lacks a bit of slip and the event recurrence period is slightly shorter, which is probably due to periodic boundary conditions used in BICycIE.