EGU2020-10210 | D1295 | Tue, 05 May 2020 |

Dynamic and quasi-dynamic modelling of earthquake sequences from zero to three dimensions: choose model complexity as needed

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Objectives

- Simulate and compare seismic cycles on a strike-slip fault with rate-and-state friction law in 0D, 1D, 2D (and 3D), with and without inertia,
- Validate numerical code in different dimensions within the community by solving benchmark problems,
- Clarify the advantages and limitations of these models, identify the appropriate model complexity to solve a specific problem,
- Provide reliable and efficient forward models within a well-structured code library to contribute to the preparatory work for data assimilation to understand seismicity.

Methodology

- Rate-and-state friction

$$\tau_s = \mu\sigma_n = \left[\mu_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{\theta V_0}{L}\right)\right]\sigma_n$$

$$\theta_{ss} = \frac{L}{V}, \quad \mu_{ss} = \mu_0 + (a-b)\ln\left(\frac{V}{V_0}\right)$$

- Aging law $$\frac{\mathrm{d}\theta}{\mathrm{d}t} = 1 - \frac{V\theta}{L}$$

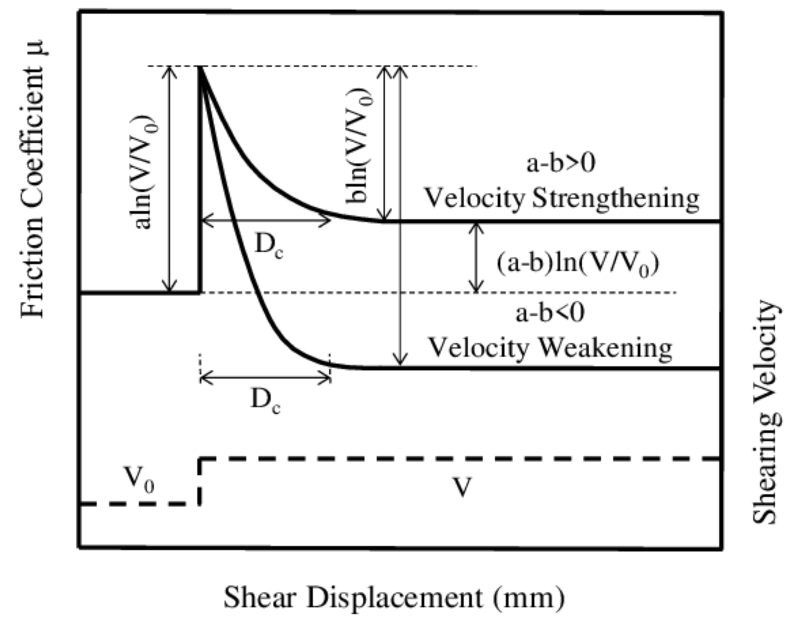

Figure: Rate and state friction law.

Methodology

- Medium behavior
  - Elastic rheology
  - Mass conservation
  - Momentum conservation
- Boundary condition
  - Rate-and-state friction
  - Aging law
- Adaptive time stepping

e.g.: in 2D, fully dynamic or Quasi-dynamic model

$$\dot{\tau}_{xy} = G\frac{\partial v_y}{\partial x}\,,\qquad \dot{\tau}_{yz} = G\frac{\partial v_y}{\partial z}\,,\qquad \dot{v}_y = \frac{1}{\rho}\left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z}\right).$$

or

$$\dot{\tau}_{xy} = G\frac{\partial v_y}{\partial x}\,,\qquad \dot{\tau}_{yz} = G\frac{\partial v_y}{\partial z}\,,\qquad 0 = \frac{1}{\rho}\left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z}\right).$$

$$\tau_s = \mu\sigma_n = \left[\mu_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{\theta V_0}{L}\right)\right]\sigma_n$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = 1 - \frac{V\theta}{L}$$

$$dt = \max\left(\min\left(dt_{pl}, dt_{por}, dt_{dx}, dt_{dy}, dt_{vxschange}, dt_{vyschange}\right), dt_{\min}\right)$$

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Garnet

Pranger, 2020

- General Root-finding Algorithm for Time-dependent, Tightly-coupled, Nonlinear problems arising in Earth sciences:
  - a public-domain code library with
  - a central finite difference discretization in
  - a staggered grid for
  - solving coupled nonlinear multi-physics systems in
  - any number of spatial dimensions [1-3]
- Kokkos and multi-threading on data structure level parallel computing (GPU)
- PETSc and MPI point-to-point communication on solver level parallel computing

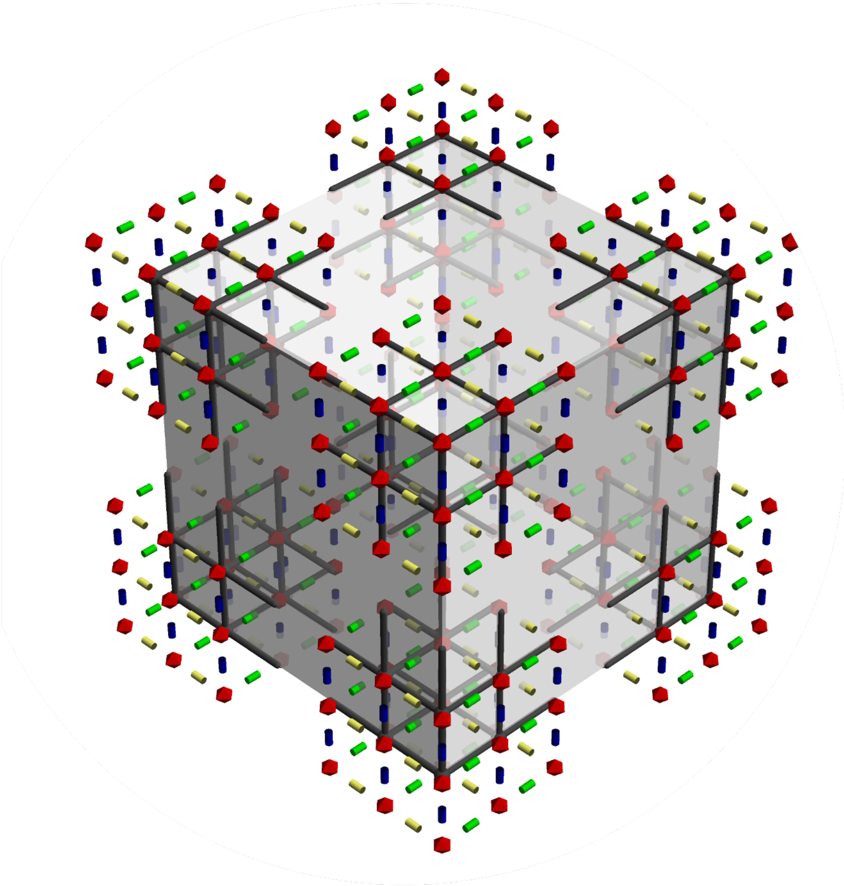

Figure: Staggered spatial discretization in 3D.

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SCEC benchmark problem

Erikson et al, 2019

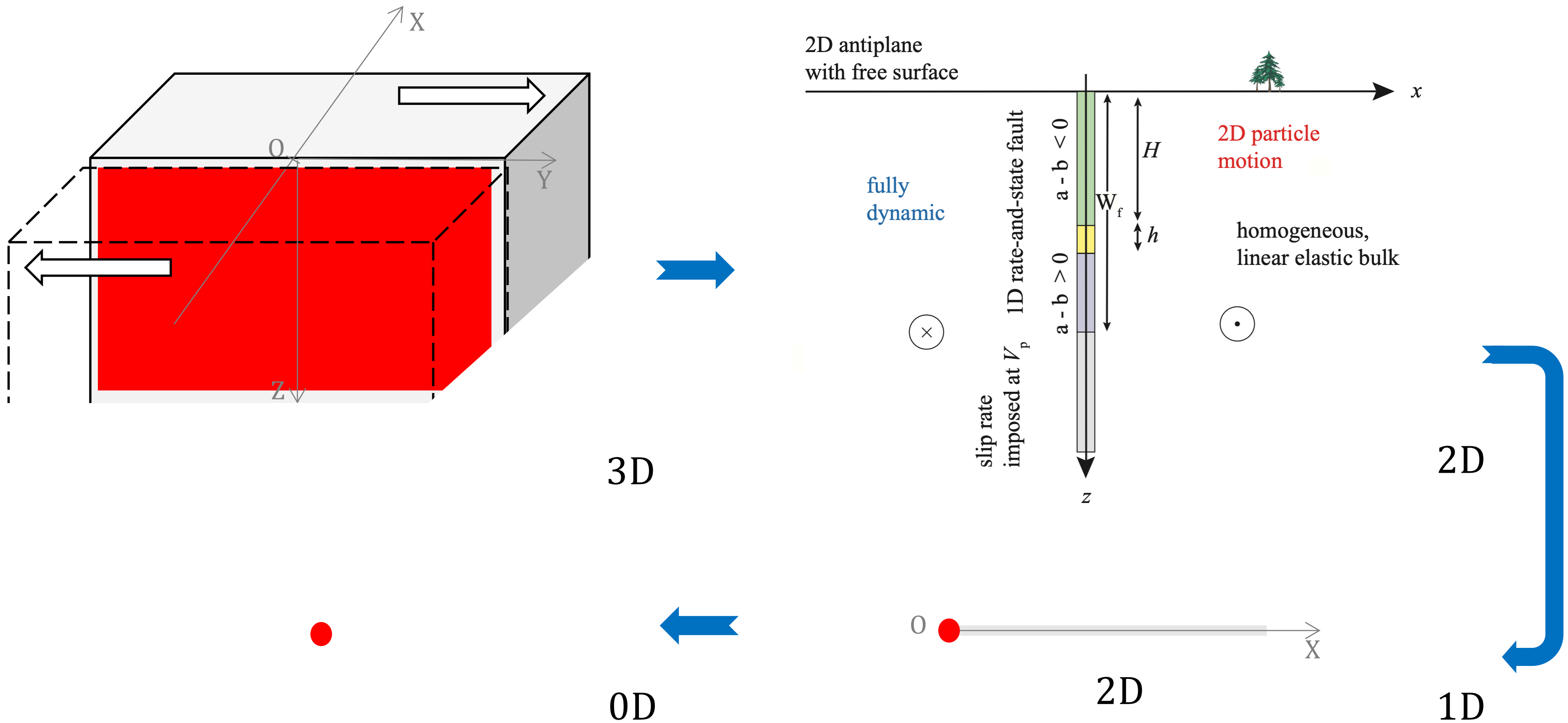


Figure: The benchmark problem model setup.

Comparison

- 0/1/2D quasi-dynamic:
  - In 0D, only quasi-dynamic model exists,
  - In 0/1D, nucleation phase does not exist,
  - in 2D, event repeats faster than in 0/1D,
  - Max/min stress and slip rates, are modeled accurately in lower dimensional models, which are much faster than higher dimensional models.

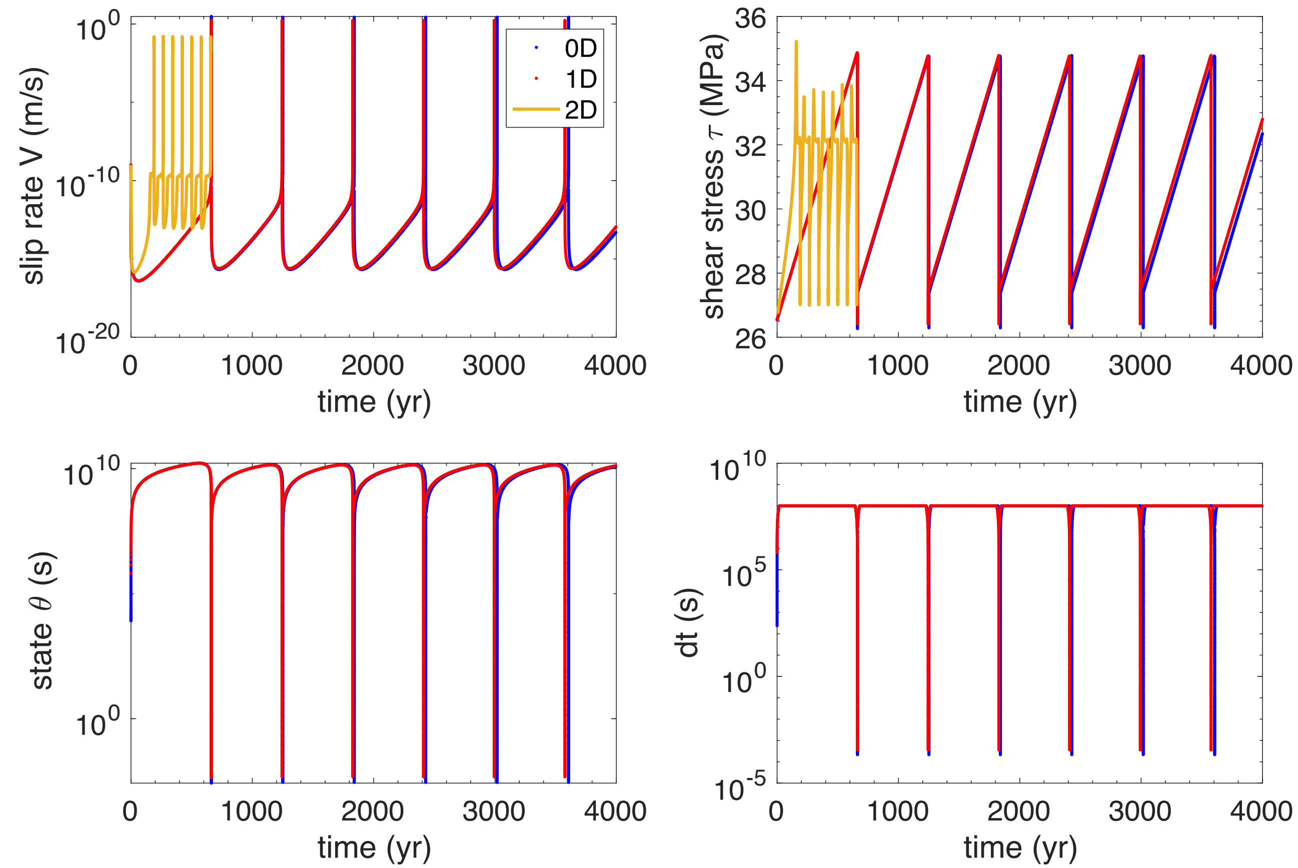
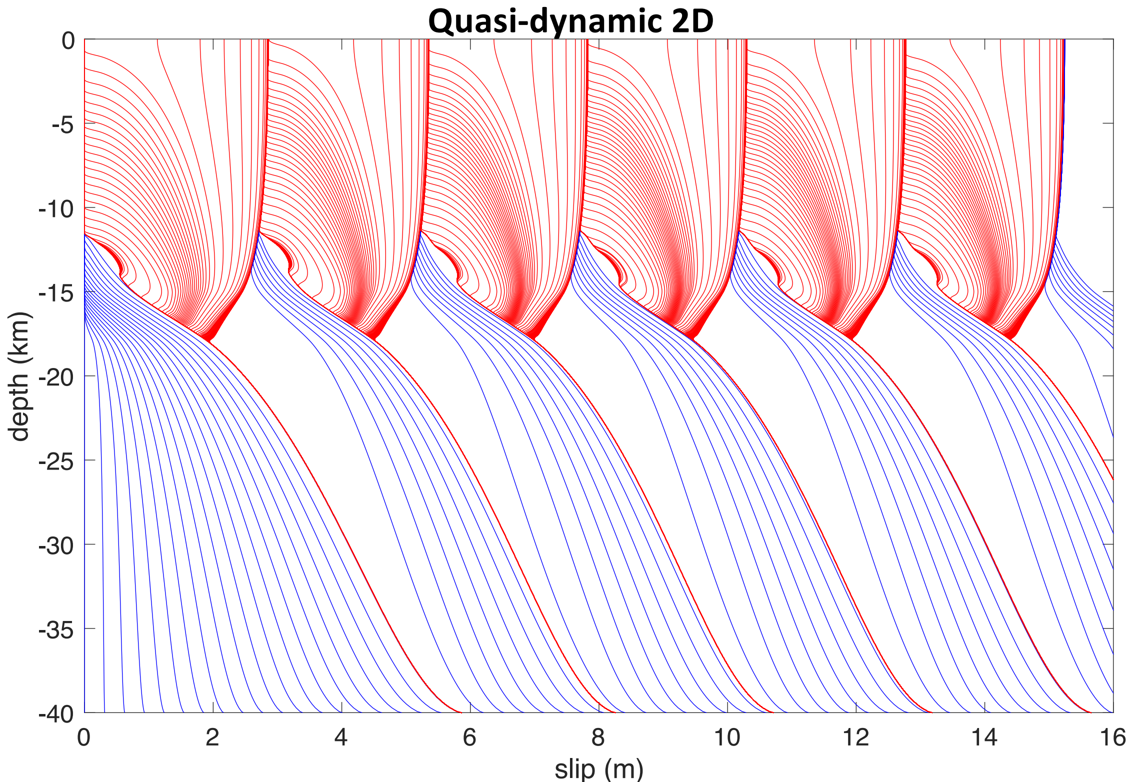
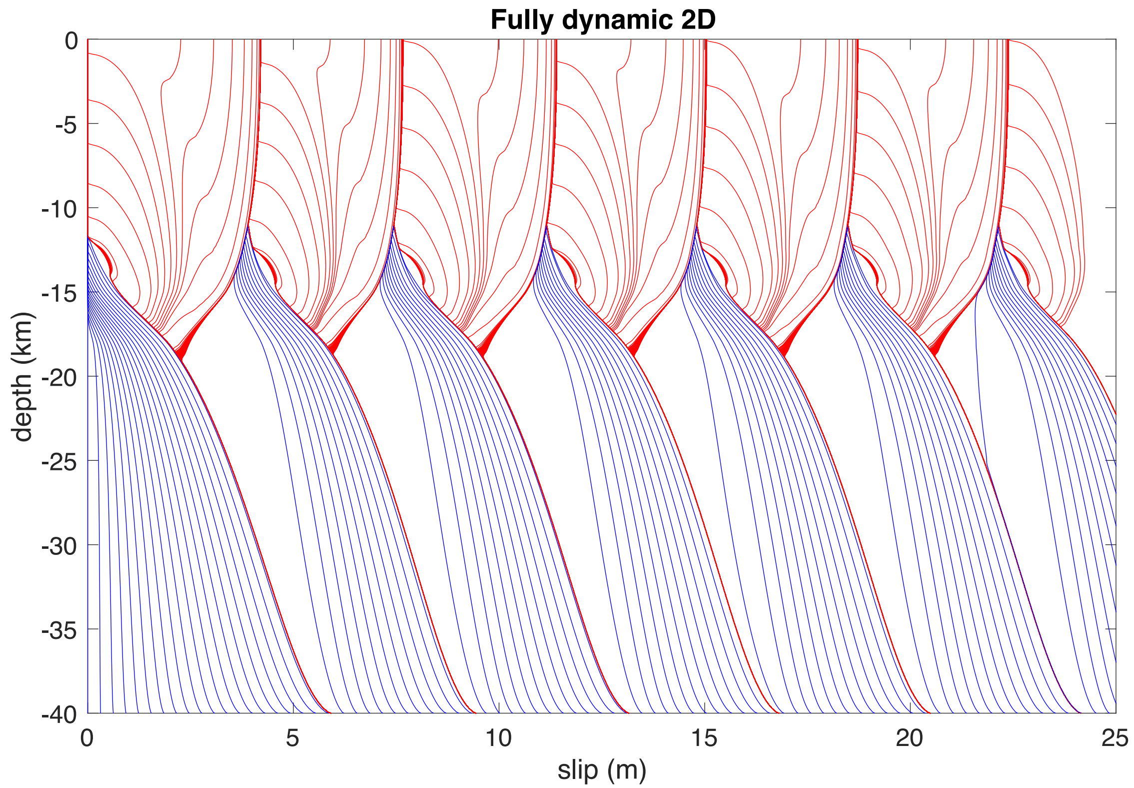


Figure: The slip velocity in 0/1/2D quasi-dynamic simulations.

Comparison

- Quasi- and fully dynamic 2D:
  - Fully dynamic models show larger maximum slip velocity and total slip,
  - Fully dynamic models show sharper wave front and surface reflection phase, as well as larger rupture speed. This makes the coseismic duration in fully dynamic models much shorter.





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Code validation: quasi-dynamic 2D

Lapusta et al, 2000, 2009

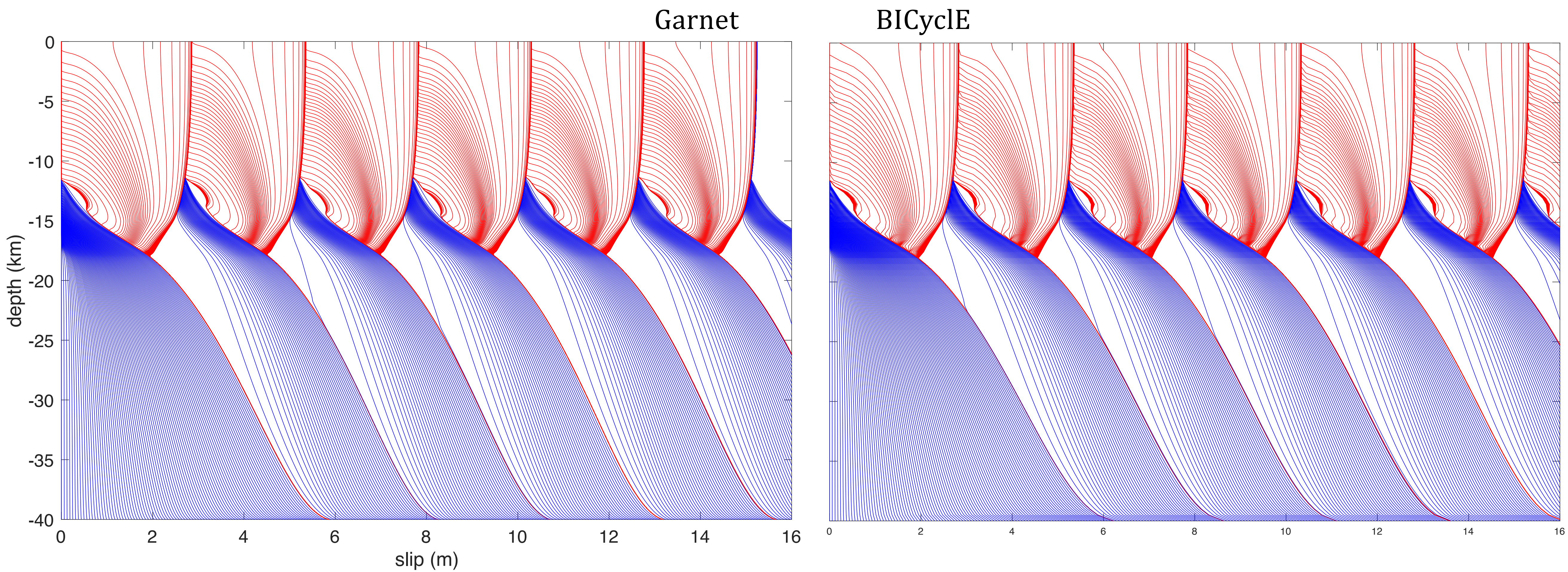


Figure: The comparison of 2D quasi-dynamic seismic cycle modeling between Garnet and BICyclE (provided by Valère Lambert, Caltech).

Code validation: fully dynamic 2D

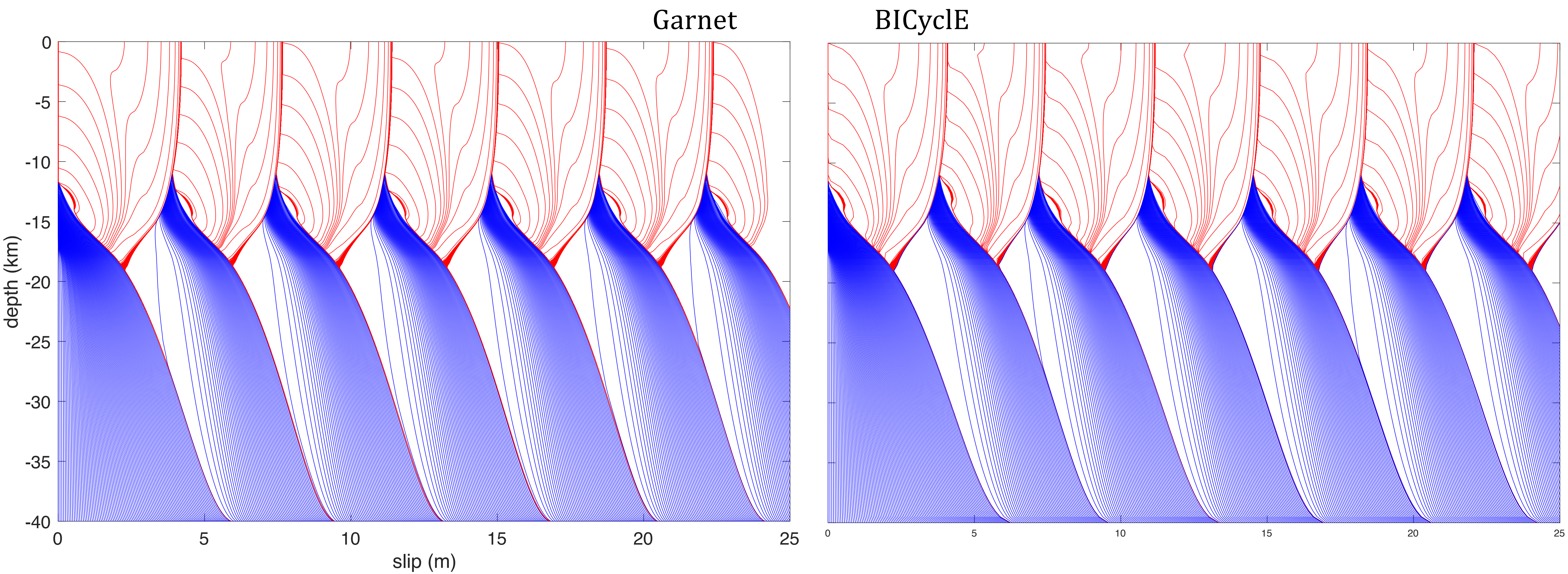
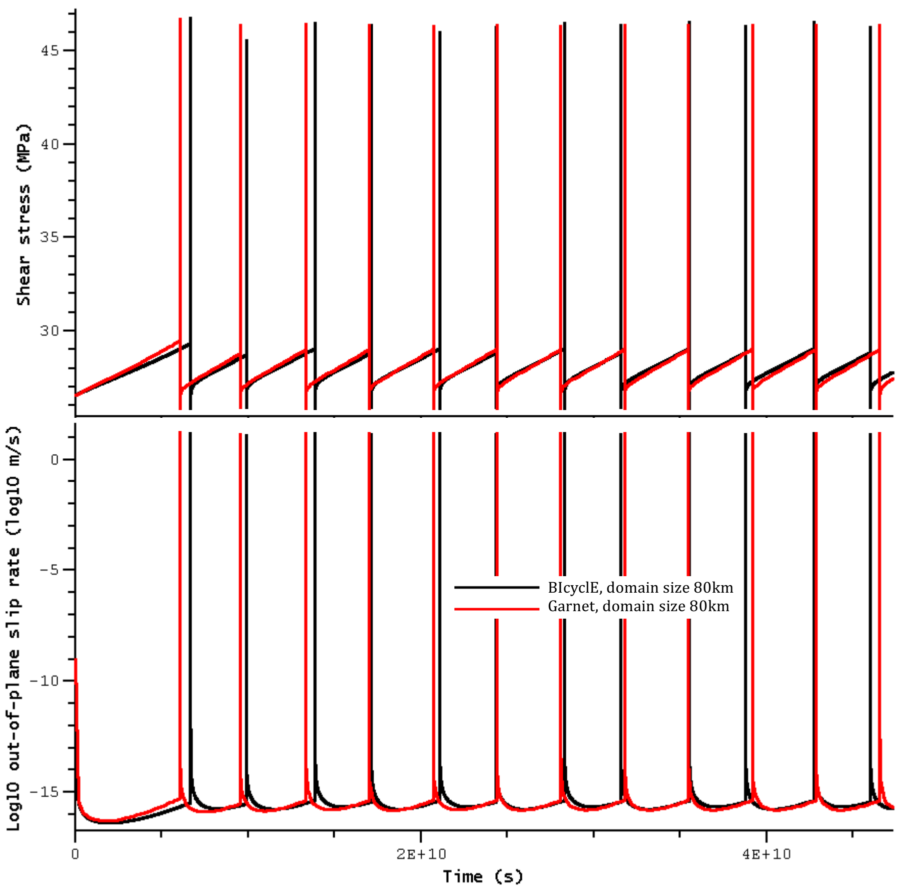
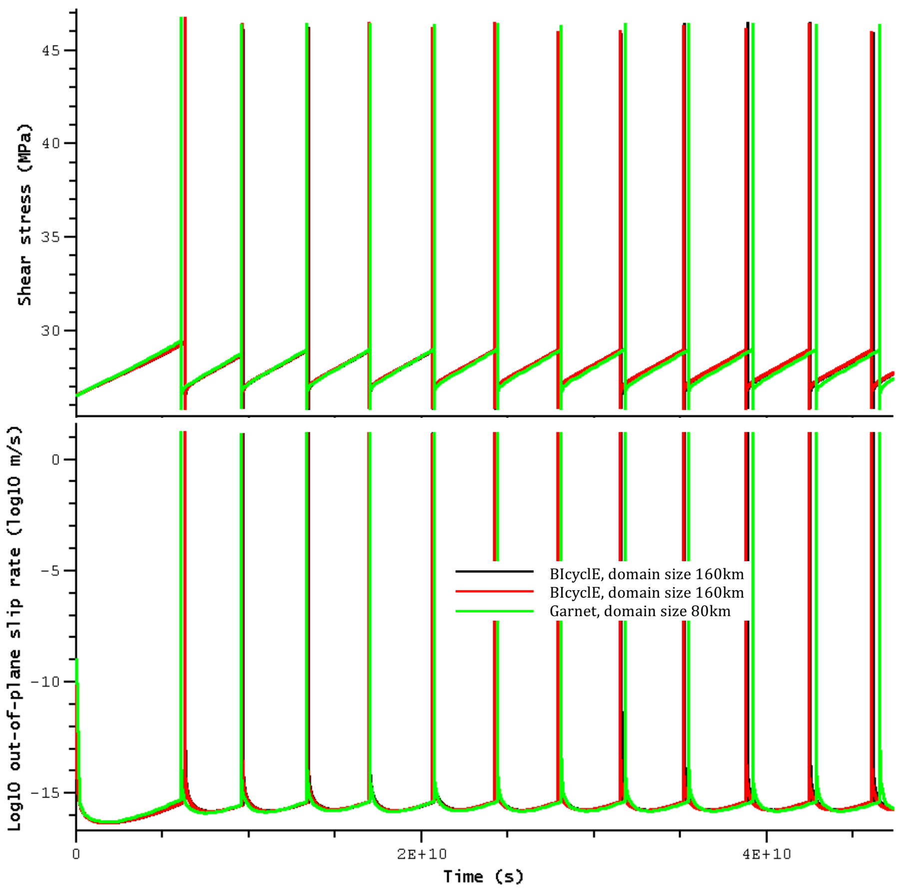


Figure: The comparison of 2D fully dynamic seismic cycle modeling between Garnet and BICyclE (provided by Valère Lambert, Caltech).

Code validation: fully dynamic 2D

- Garnet and BIcyclE show similar results, in both quasi- and fully dynamic models.
- Garnet shows more homogeneous events in terms of size and recurrence interval.
- BIcyclE results get closer to Garnet's when the computational domain is enlarged.





Code validation: quasi-dynamic 2D

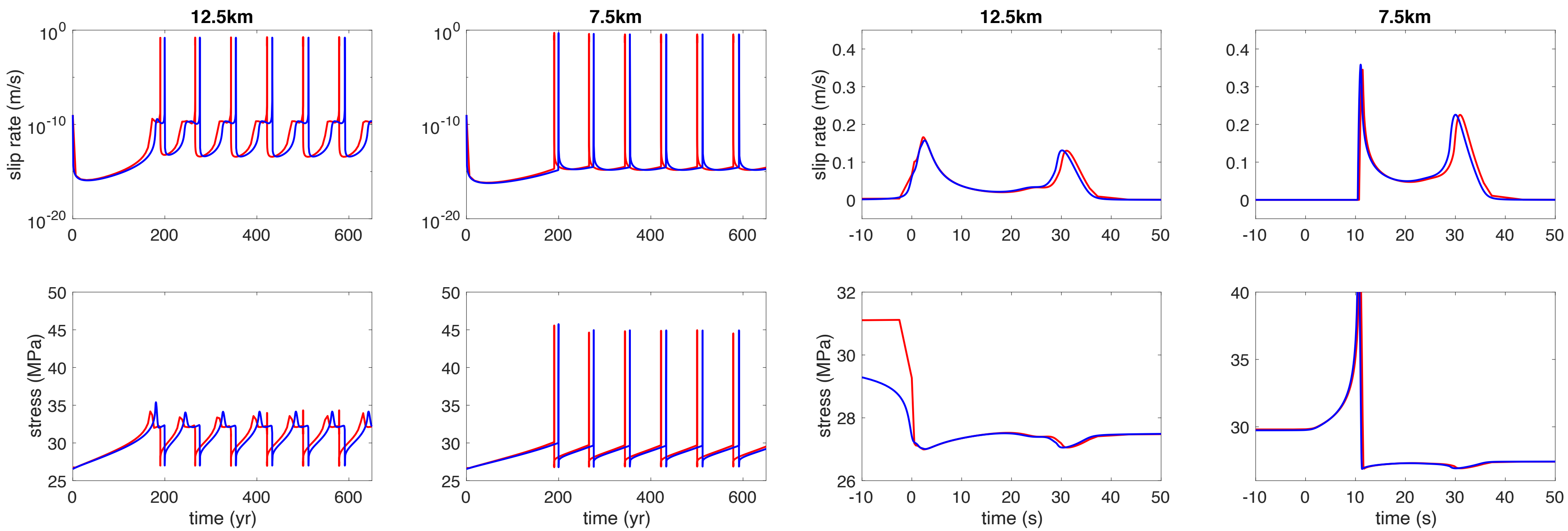


Figure: The comparison of 2D quasi-dynamic seismic cycle modeling between (red) Garnet and (blue) BICyclE. Left: The overall time series of slip rate and shear stress; Right: the coseismic time series with time origin reset to the rupture initiation time of the third event at the depth of 12.5 km for better comparison.

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Code validation: fully dynamic 2D

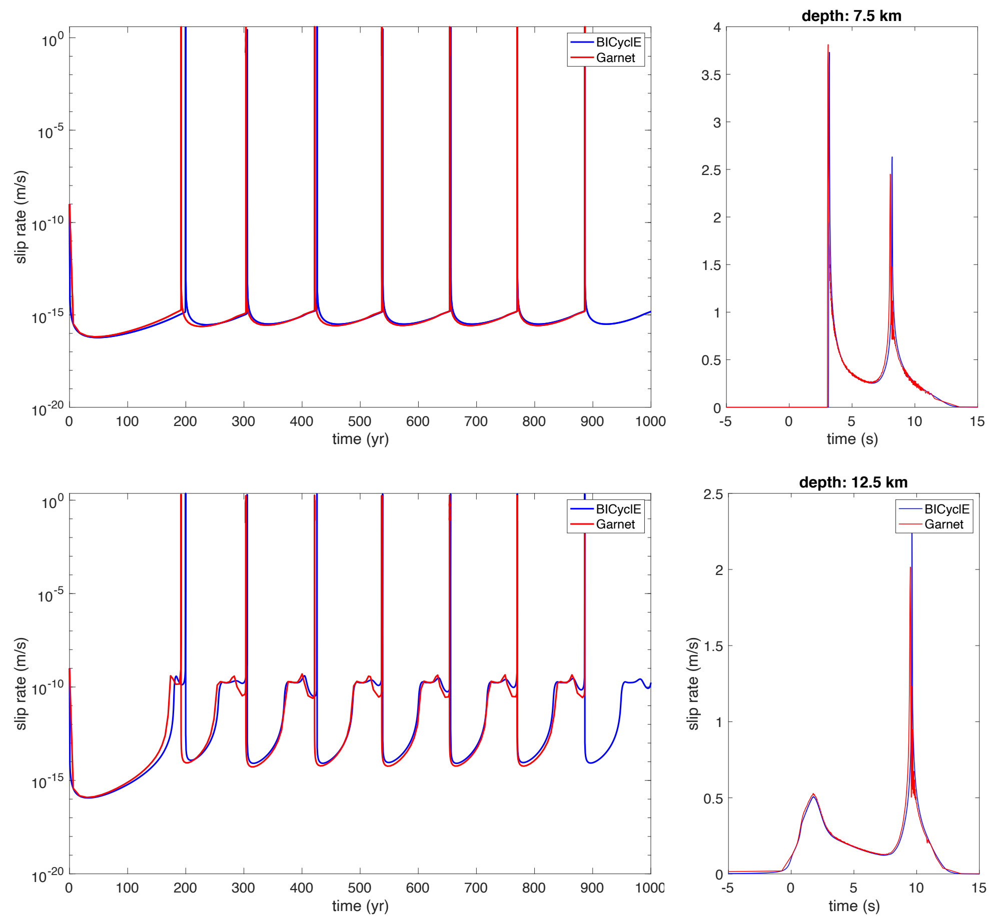

Figure: The comparison of 2D fully dynamic seismic cycle modeling between (red) Garnet and (blue) BICyclE. Left: The overall time series of slip rate; Right: the coseismic time series with time origin reset to the rupture initiation time of the third event at the depth of 12.5 km for better comparison.

Summary

- Garnet is validated by comparing its results of a benchmark within the community.
  - Garnet shows more homogeneous events in terms of size and recurrence interval, which BIcyclE achieves with larger computational domain.
  - Garnet will be further validated in off-fault plasticity in our future researches.

- Choose model complexity based on problem statement and objectives.
  - To validate data assimilation codes, a 1D quasi- or fully dynamic model is fast.
  - To implement data assimilation on a laboratory setup, a 2D quasi-dynamic model is useful while a 3D model is still required when the third dimension comes into interest.
  - One could use fast quasi-dynamic model instead of full dynamic one for certain purpose, with in mind that fully dynamic models tend to show larger maximum slip velocity and total slip.

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