SEAS Benchmark BP1 Results

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April 24th, 2018

Plan for this discussion:

- Benchmark set-up, overview of codes/numerical methods etc.
- Results - slip contours and time series.
- Issues like boundary conditions, spin-up. Discussion of metrics and how to determine a successful verification exercise.

After lunch:

- Discussion of future SEAS plans: benchmarks, platform, proposals, relationships with other working groups.

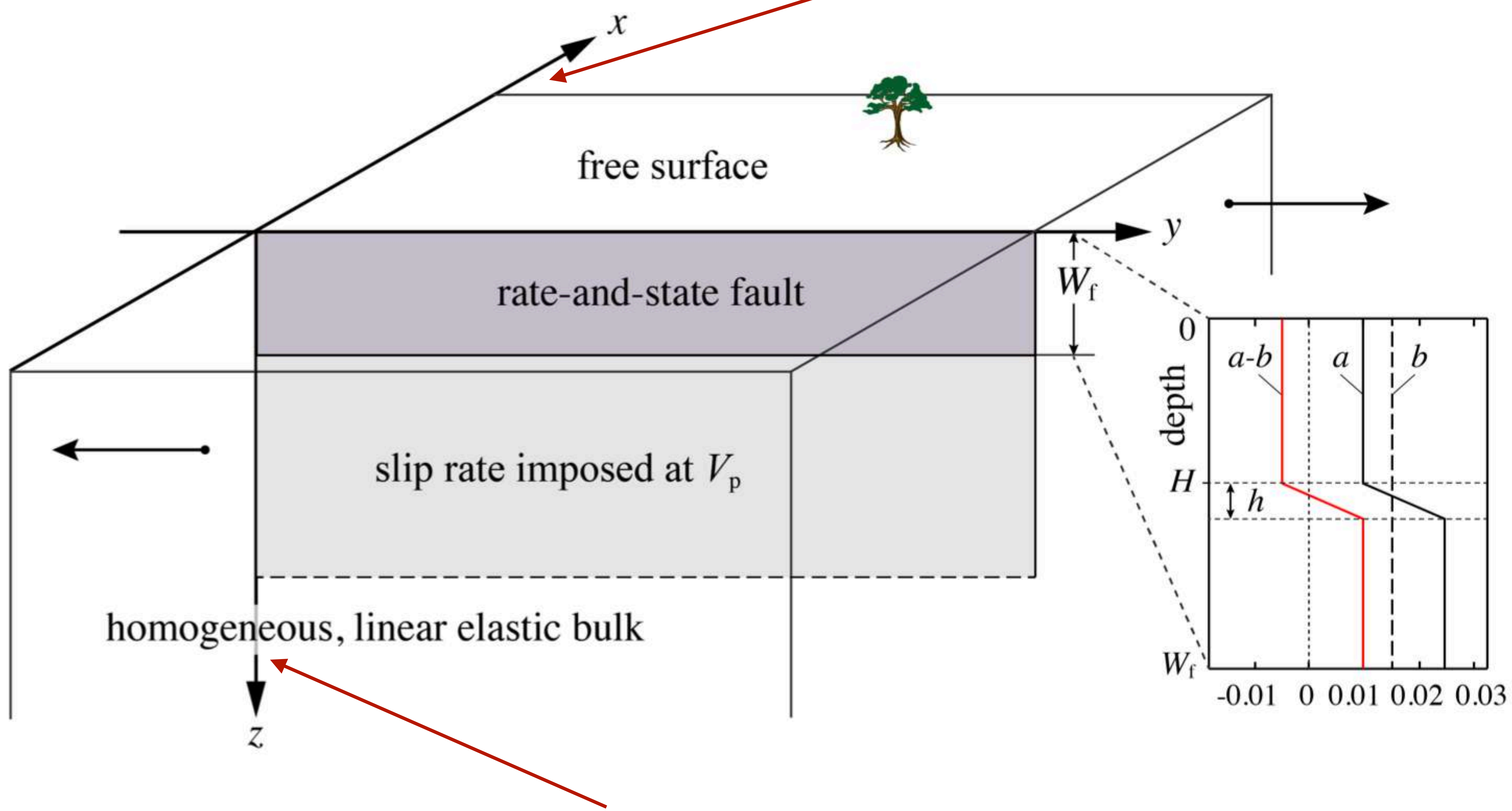
Summary of Participating Modelers and Codes:

	Method	Time stepping	Cell size	Domain size (Lx, Lz) (Ly)	Outer B.C.
Jiang	BEM (BICYCLE)	*Lapusta et al., 2000*	dz = 25 m	(∞, 80/160 km)	
Lambert	BEM (BICYCLE)	*Lapusta et al., 2000*	dz = 25/50 m	(∞, 50/80 km)	
Ma	BEM	*Lapusta et al., 2000*	dz = 25/50 m	(∞, 80 km)	
Luo/Idini	BEM (QDYN)	Bulirsch-Stoer ODE solver	dz = 19.53 m	(∞, ∞)	
Barbot	BEM	R-K adaptive stepping	dz = 25 m	(∞, ∞)	
Cattania	BEM		dz = 25/19 m	(∞, ∞/160/640 km)	
Erickson	2nd-order FDM	*Erickson and Dunham, 2014*	dz = 25 m (<40 km)	(80 km, 80 km)	traction-free
Abrahams	4th-order FDM	*Erickson and Dunham, 2014*	dz = 25 m (dx variable)	(100 km, 80 km)	traction-free/ displacement
Kozdon	DG FEM	*Erickson and Dunham, 2014*	dz = 25-50 m (near fault)	(160 km, 80 km) (800 km, 400 km)	traction-free/ displacement
Liu	BEM	R-K adaptive stepping	dz = 25 m	(∞, ∞) (720 km)	
Wei	BEM	R-K adaptive stepping	dz = 25 m	(∞, ∞) (720 km)	

Ly=∞ unless specified

Benchmark Problem Details:

L_x denotes fault-perpendicular extent of computational domain.



L_z denotes down dip extent of computational domain.

2D anti-plane problem: a homogeneous, isotropic linear elastic half-space

$$0 = \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial z}, \quad \sigma_{xy} = \mu \frac{\partial u}{\partial x}; \quad \sigma_{yz} = \mu \frac{\partial u}{\partial z}$$

Boundary condition: free surface on the top of the model domain

$$\sigma_{yz}(x, 0, t) = 0.$$

Interface conditions:

$$\sigma_{xy}(0^+, z, t) = \sigma_{xy}(0^-, z, t), \qquad \tau = F(V, \theta),$$

Friction laws on fault:

$$F = \sigma_\mathrm{n} f(V, \theta) \qquad f(V,\theta) = a \sinh^{-1}\left[\frac{V}{2V_0} \exp\left(\frac{f_0 + b \ln(V_0 \theta / D_\mathrm{c})}{a}\right)\right] \qquad \frac{d\theta}{dt} = 1 - \frac{V\theta}{D_\mathrm{c}},$$

Initial conditions: uniform slip rate V_init and uniform prestress τ^0

$$\tau^0 = \sigma_\mathrm{n} a_\mathrm{max} \sinh^{-1}\left[\frac{V_\mathrm{init}}{2V_0} \exp\left(\frac{f_0 + b_0 \ln(V_0 / V_\mathrm{init})}{a_\mathrm{max}}\right)\right] + \eta V_\mathrm{init}\,.$$

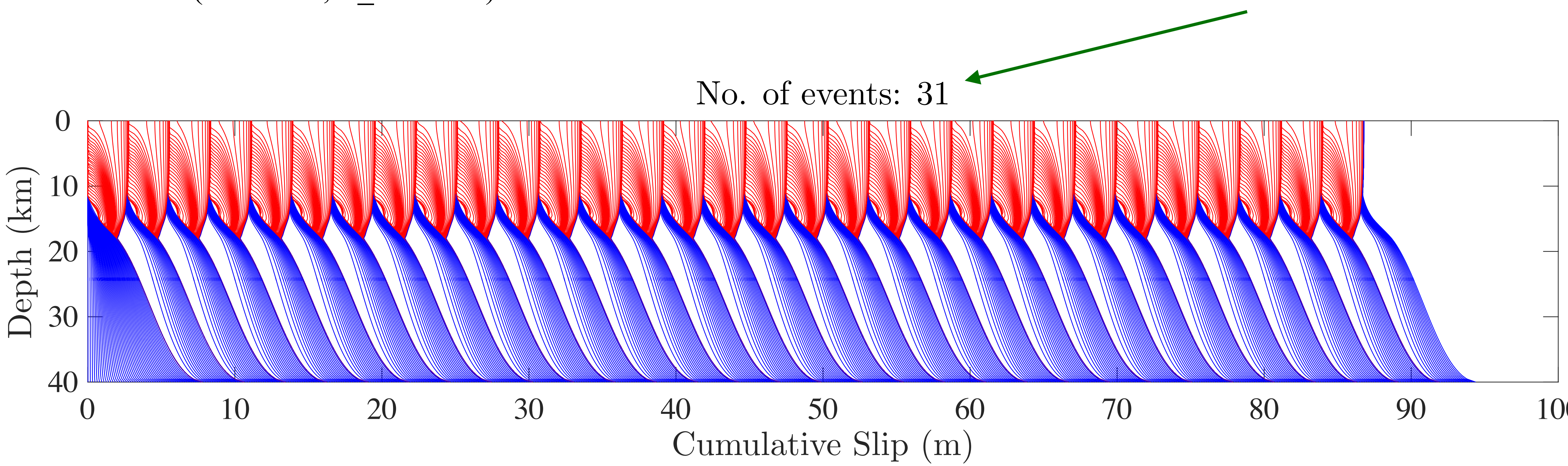
Table 1: Parameter values used in first benchmark problem

Parameter	Definition	Value, Units
ρ	density	2670 kg/m^3
c_s	shear wave speed	3.464 km/s
σ_n	effective normal stress on fault	50 MPa
a_0	rate-and-state parameter	0.010
a_{max}	rate-and-state parameter	0.025
b_0	rate-and-state parameter	0.015
D_c	critical slip distance	0.008 m
V_p	plate rate	10^{-9} m/s
V_{init}	initial slip rate	10^{-9} m/s
V_0	reference slip rate	10^{-6} m/s
f_0	reference friction coefficient	0.6
H	depth extent of uniform VW region	15 km
h	width of VW-VS transition zone	3 km
W_f	width of rate-and-state fault	40 km
Δz	suggested cell size	25 m
t_f	final simulation time	$3,000$ years

Slip Profiles

(nearly all data interpolated to plot every 5 years during interseismic, every second during coseismic phase)

Lambert (dz = 25m, L_z =50km): 31 events.



Lambert (dz = 50m, L_z = 80km): 35 events.

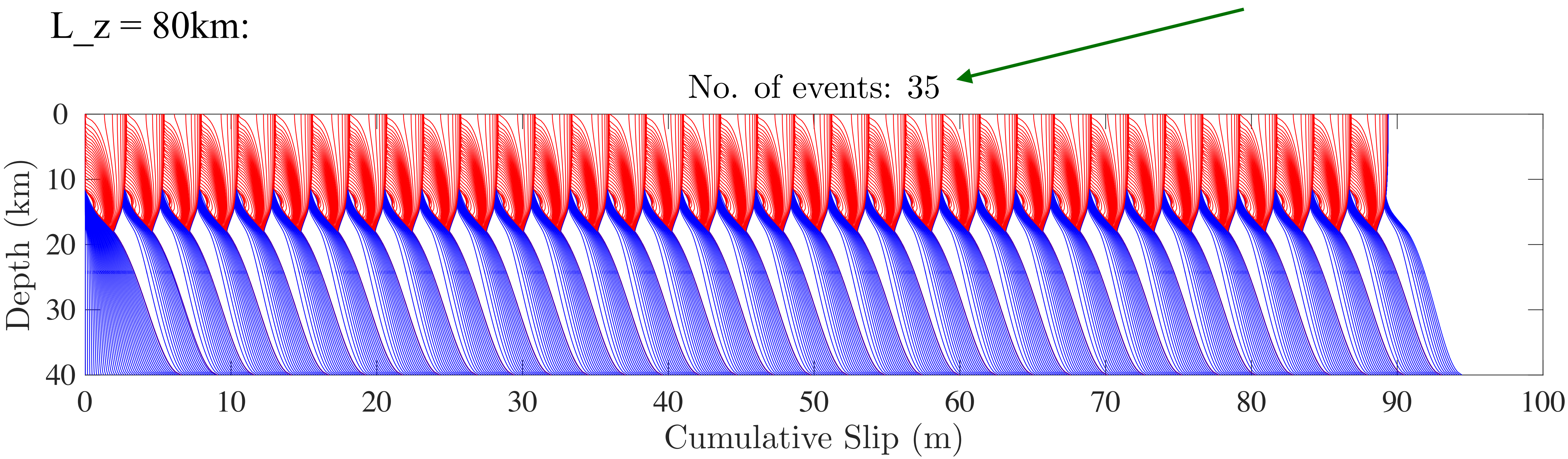
Lambert (dz = 25m, L_z = 80km): 35 events.

These results suggests there is a computational domain size dependency; dz = 25m, 50m yield similar results.

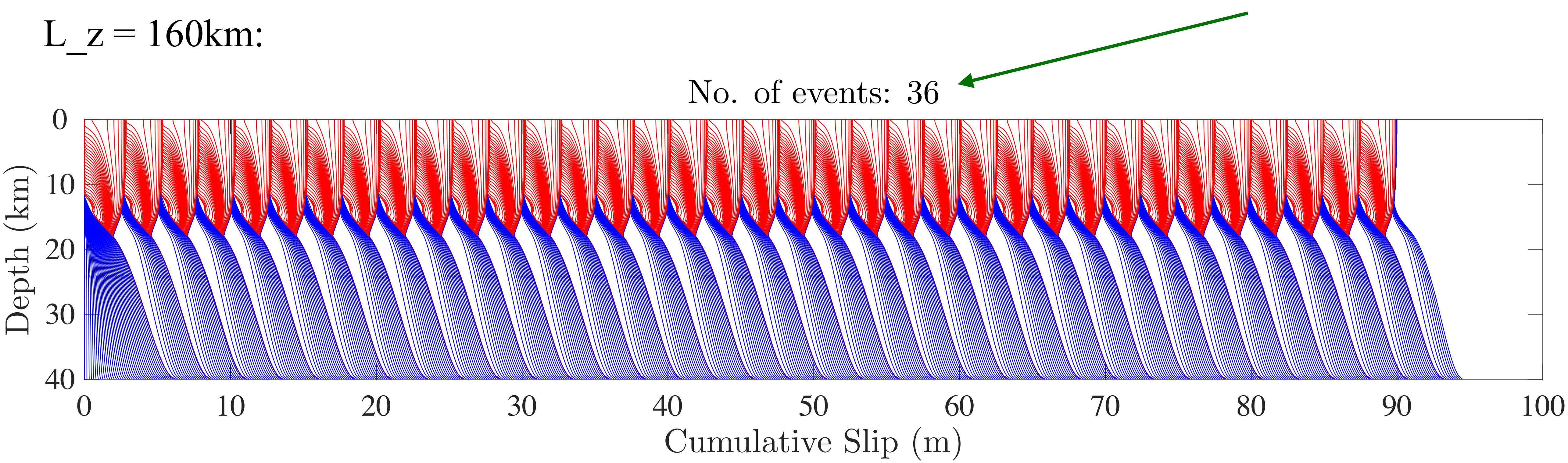
*Note: for most of the results from this benchmark, we see the models equilibrate after ~2-3 events.

Jiang: SBIM, time stepping from Lapusta et al., 2000. dz = 25m.

L_z = 80km:

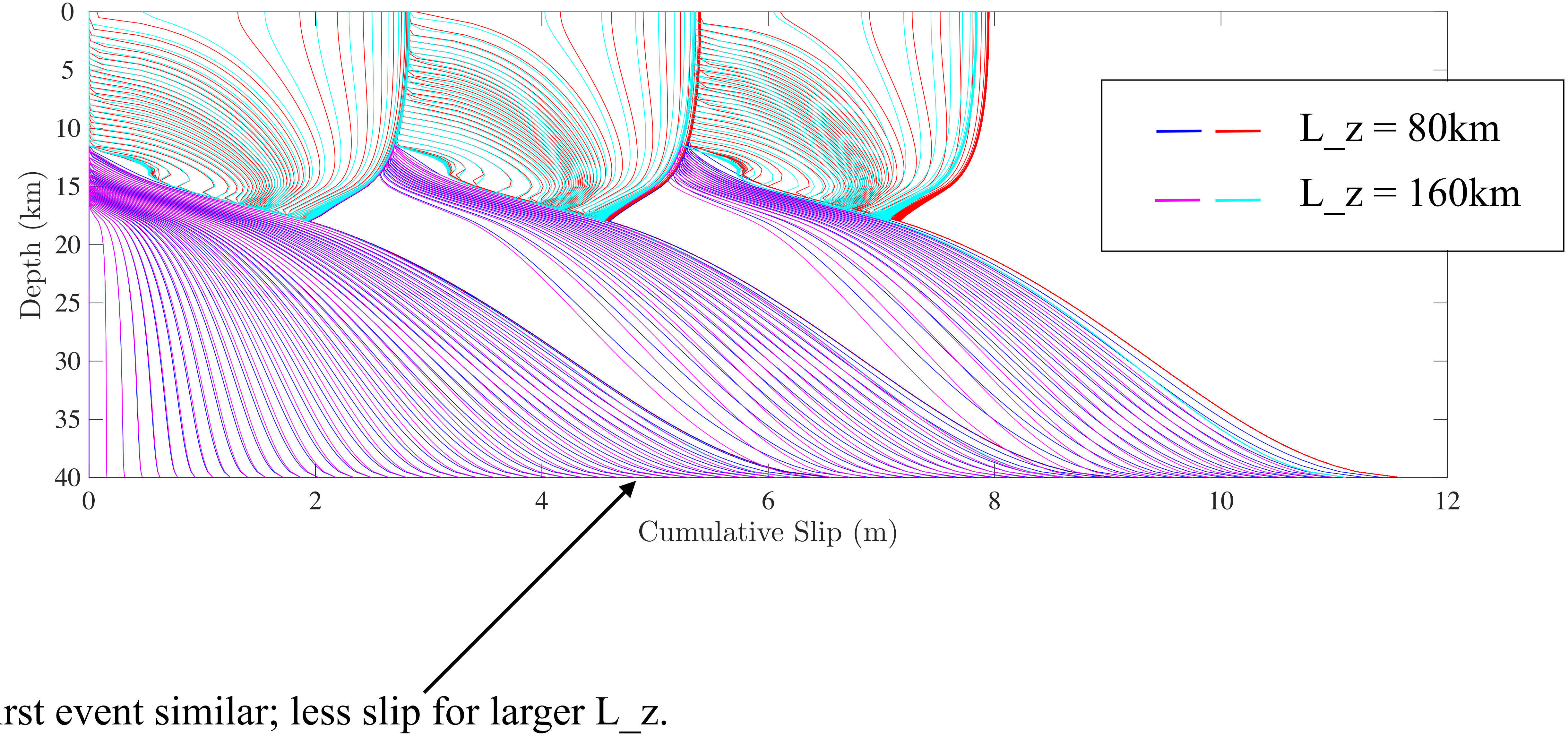


L_z = 160km:



Suggests longer fault length yields shorter recurrence interval.

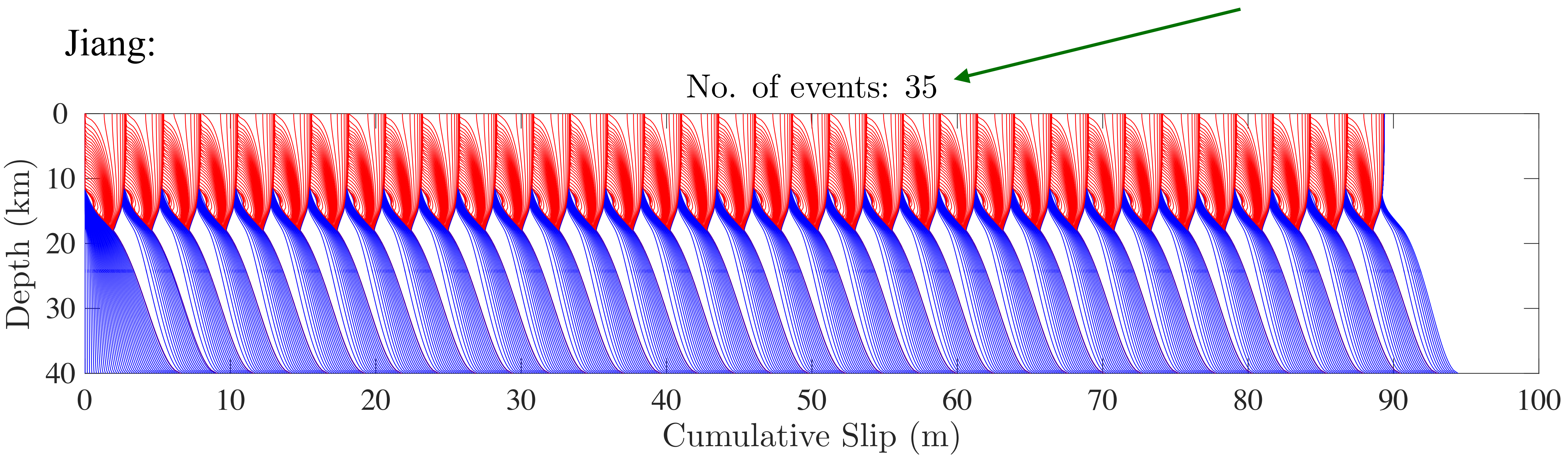
Jiang comparison: first three events



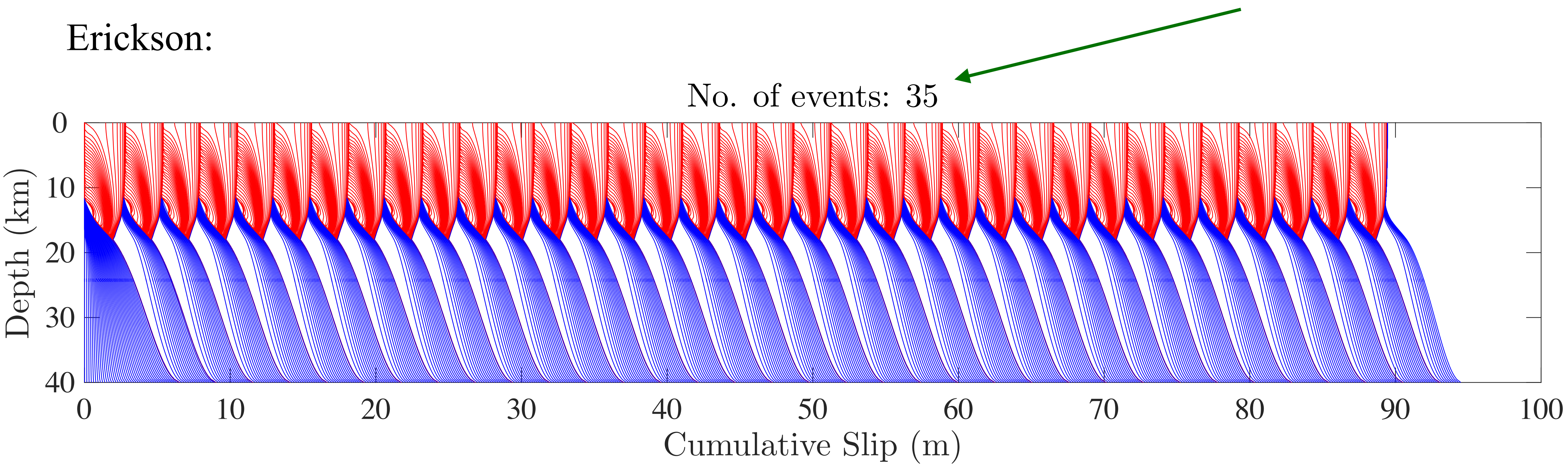
First event similar; less slip for larger L_z.

Jiang compared to Erickson (FDM, ode45, dz = 50m down to depth of 40 km, then variable. L_z = 80km, L_x = 80km, *far-field free boundary*):

Jiang:



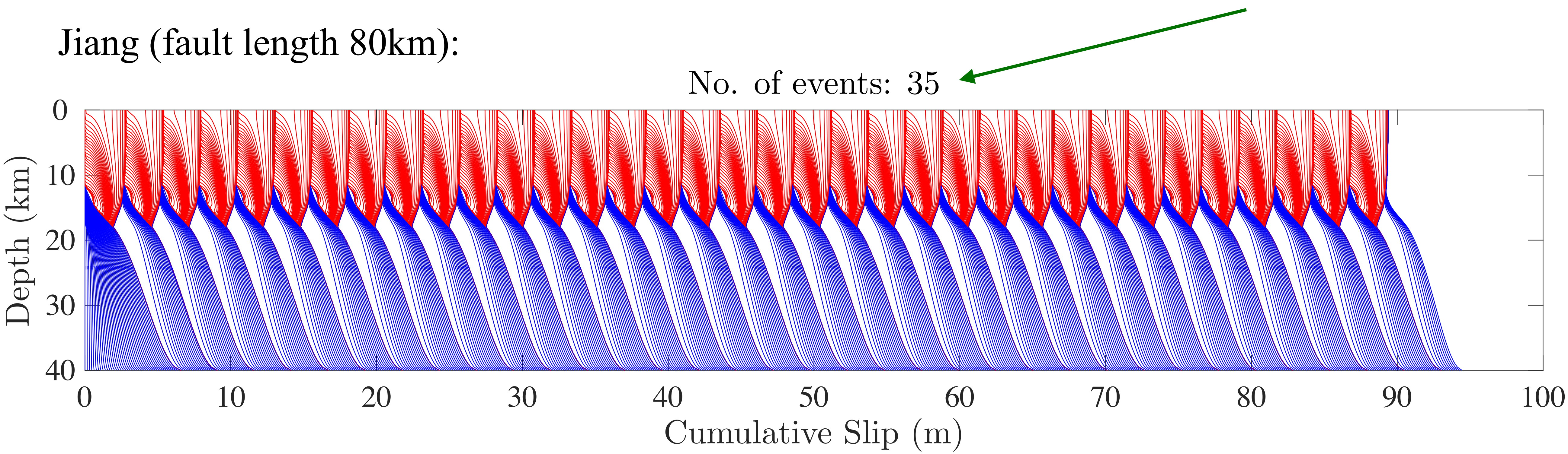
Erickson:



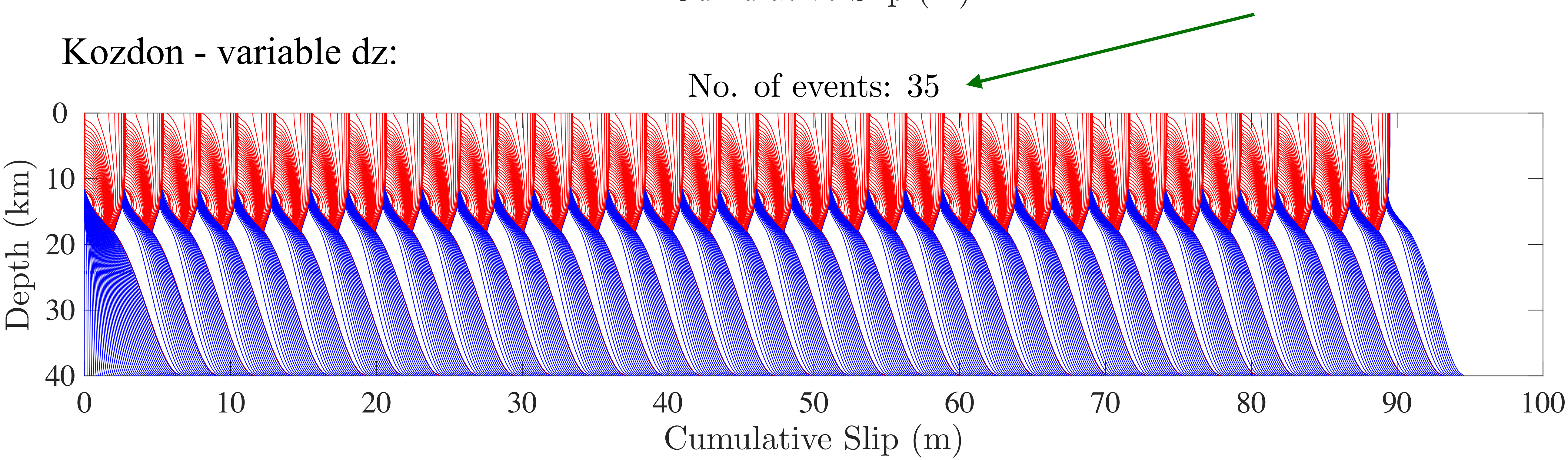
Suggests same L_z yields quite similar results for SBIM vs. FDM (with far-field free boundary for FDM).

Jiang compared to Kozdon (dG, ode45, dz = variable, L_z = 80km, L_x = 80km, *far-field free boundary condition*):

Jiang (fault length 80km):



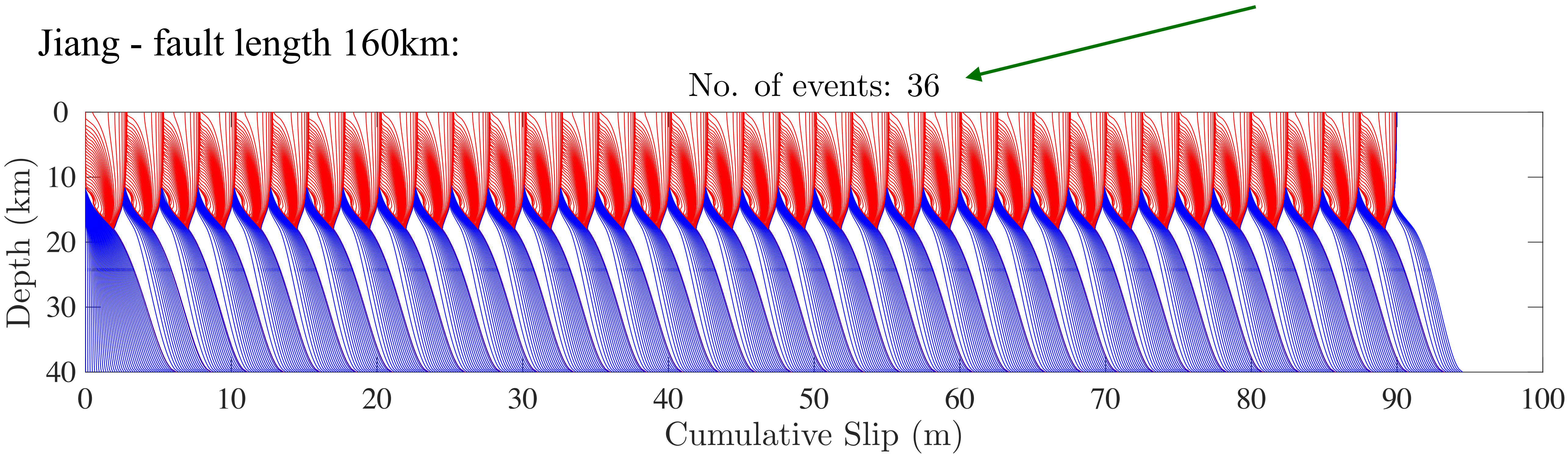
Kozdon - variable dz:



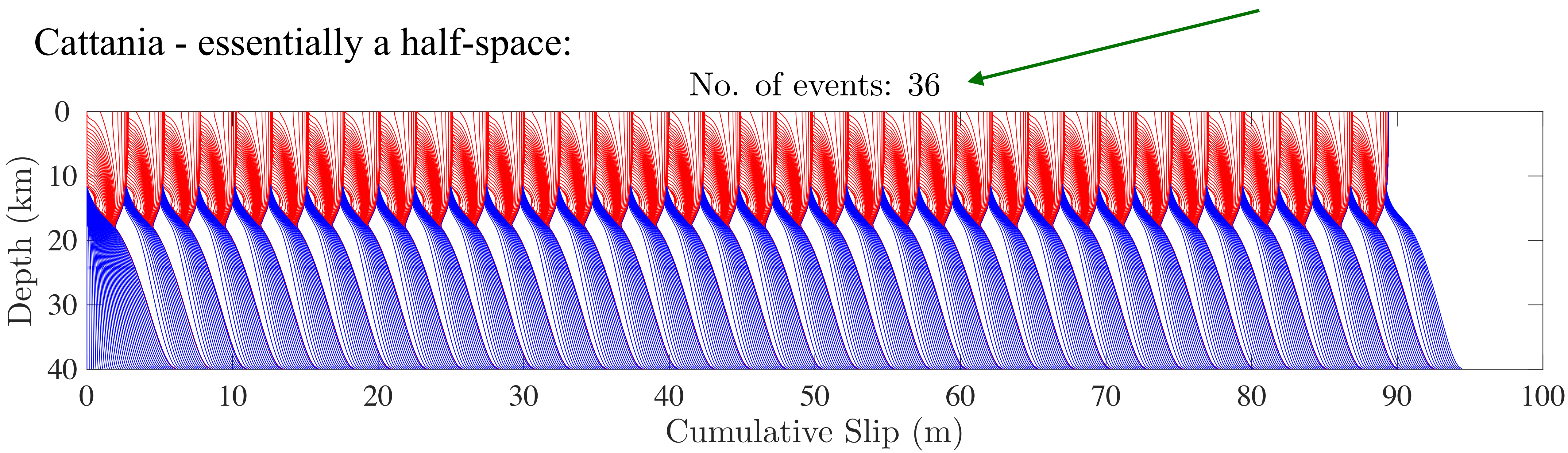
Suggests dG with variable grid spacing with dz = 25m (near the fault) compares well to SBIM (and to FDM), with far-field free boundary condition.

Jiang compared to Cattania (BIM, z = W_f treated at dislocation so domain is half space):

Jiang - fault length 160km:



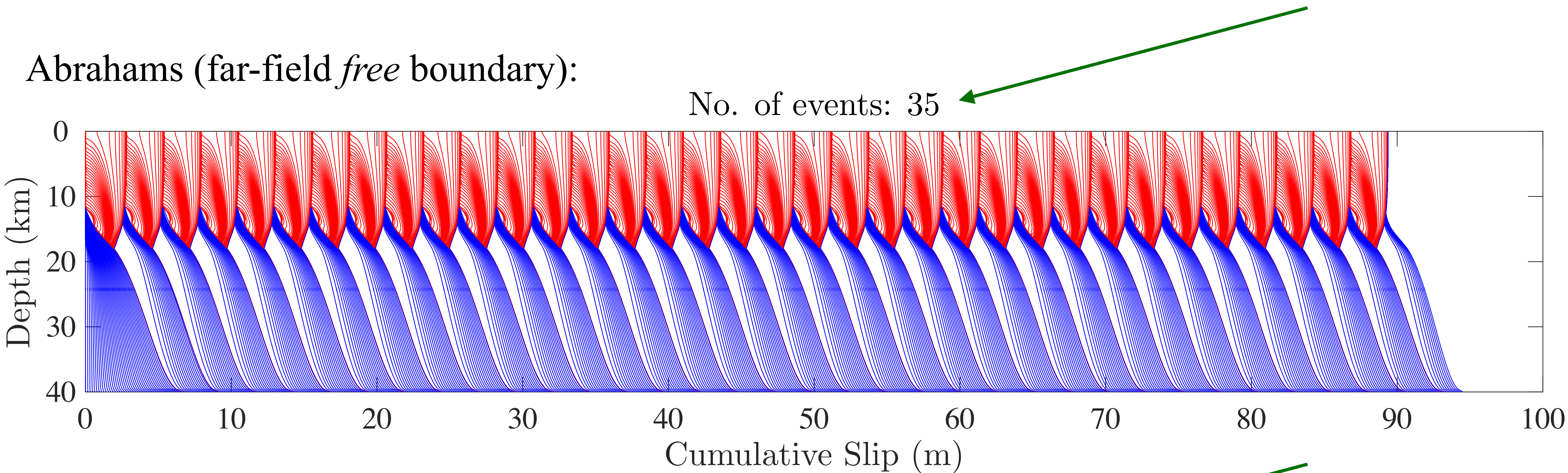
Cattania - essentially a half-space:



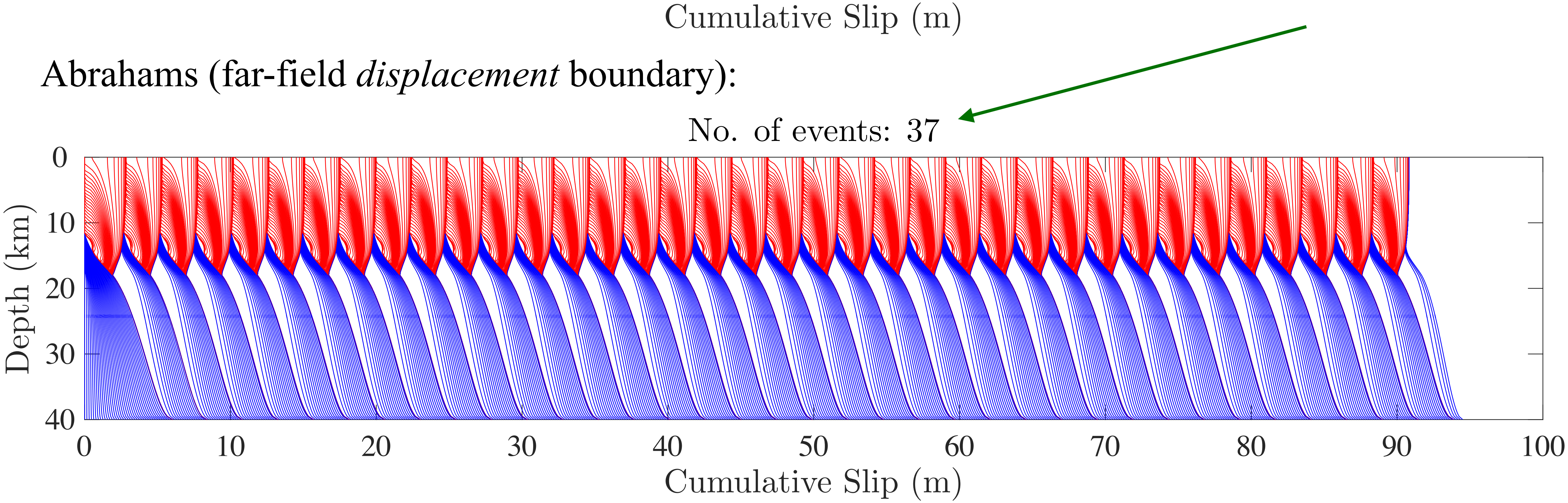
Suggests BIEM with fault length of 160 km yields similar results to that of half-space solution.

Abrahams (FDM, ode45, dz = 25m, L_z = 80km, L_y = 100km, *far-field displacement/free boundary condition*):

Abrahams (far-field *free* boundary):

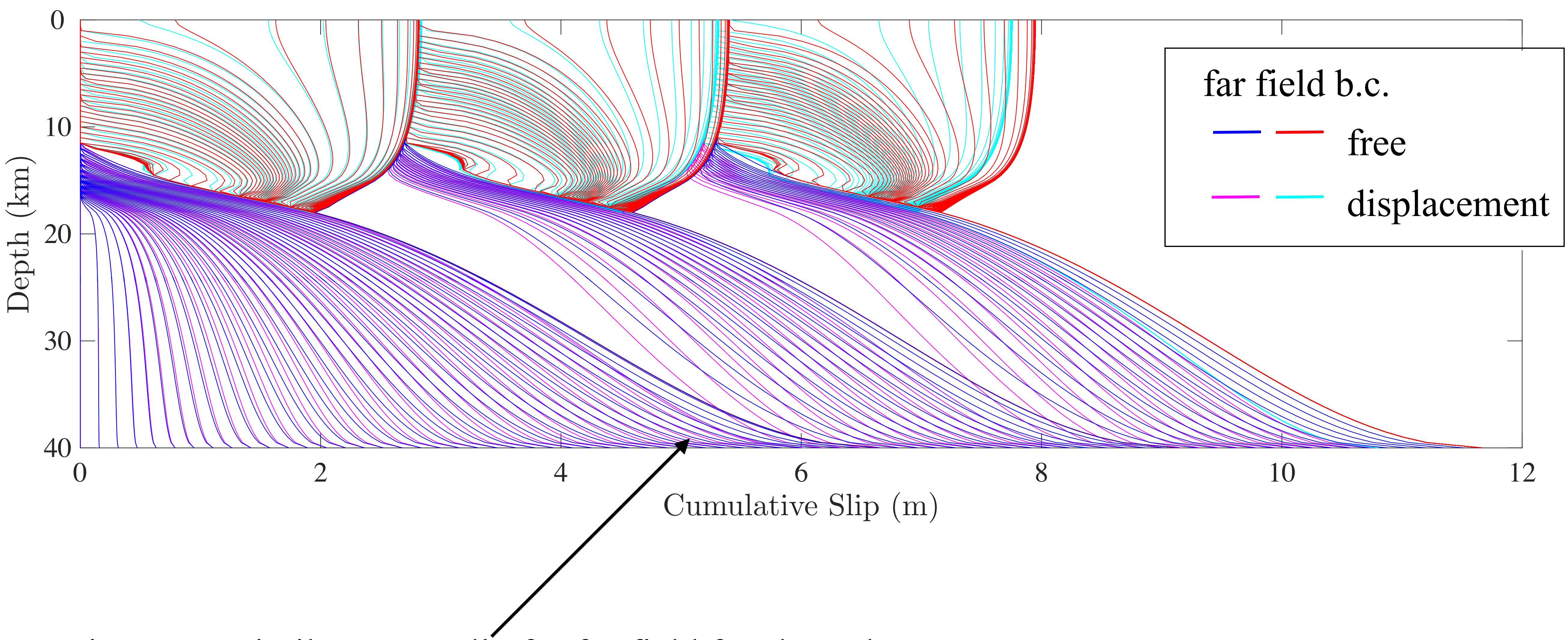


Abrahams (far-field *displacement* boundary):



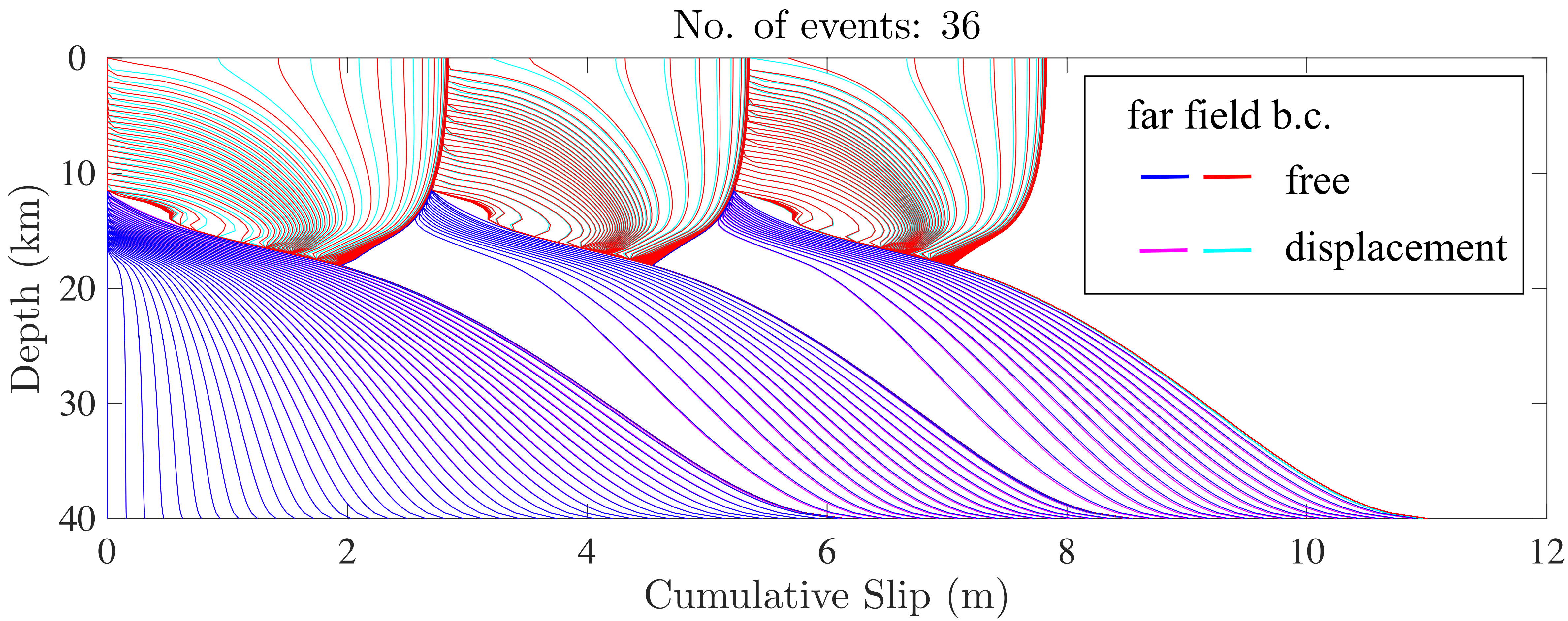
Suggests results dependent on far-field boundary conditions (for this domain size). Results with free boundary more comparable to Jiang with L_z = 80km.

Abrahams comparison: first three events



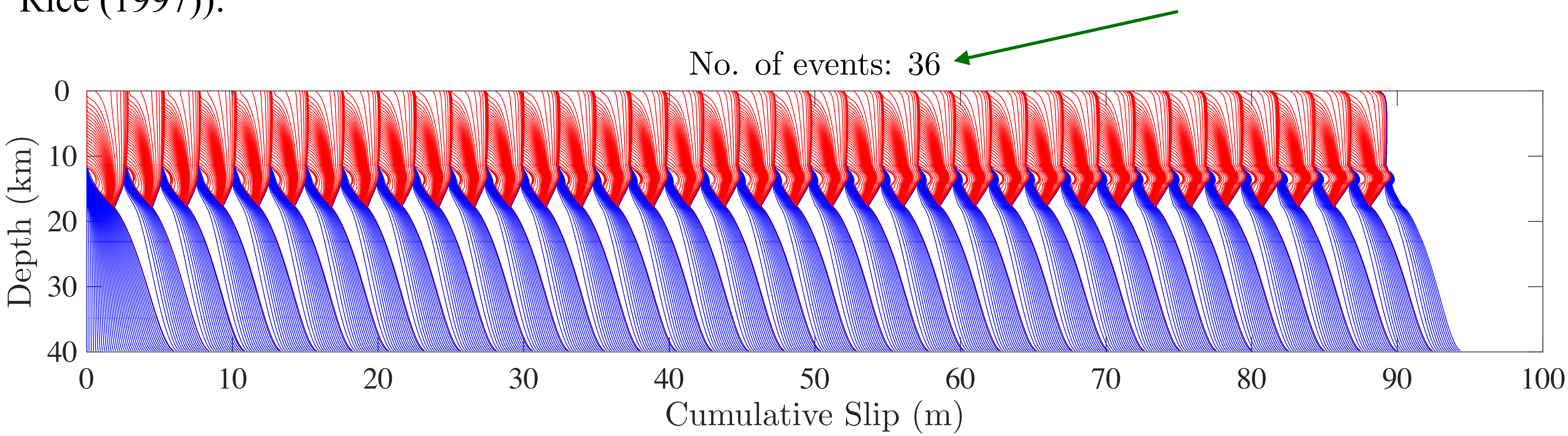
First event similar; more slip for far-field free boundary.

Kozdon, L_z = 400km, L_x = 400km, with different far field boundary conditions.

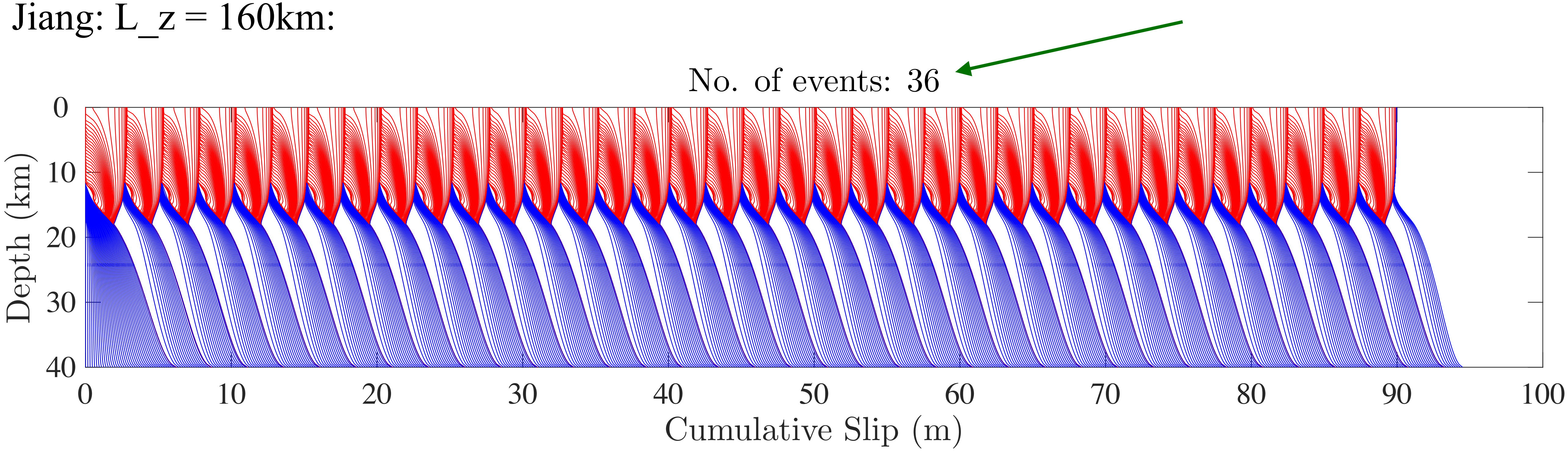


Suggests there is a "large enough" domain size for volume discretization method to yield similar results to that of half-space solution, independent of far-field boundary conditions.

Luo (BIEM, static stress transfer is computed via Fourier domain following Cochard and Rice (1997)):

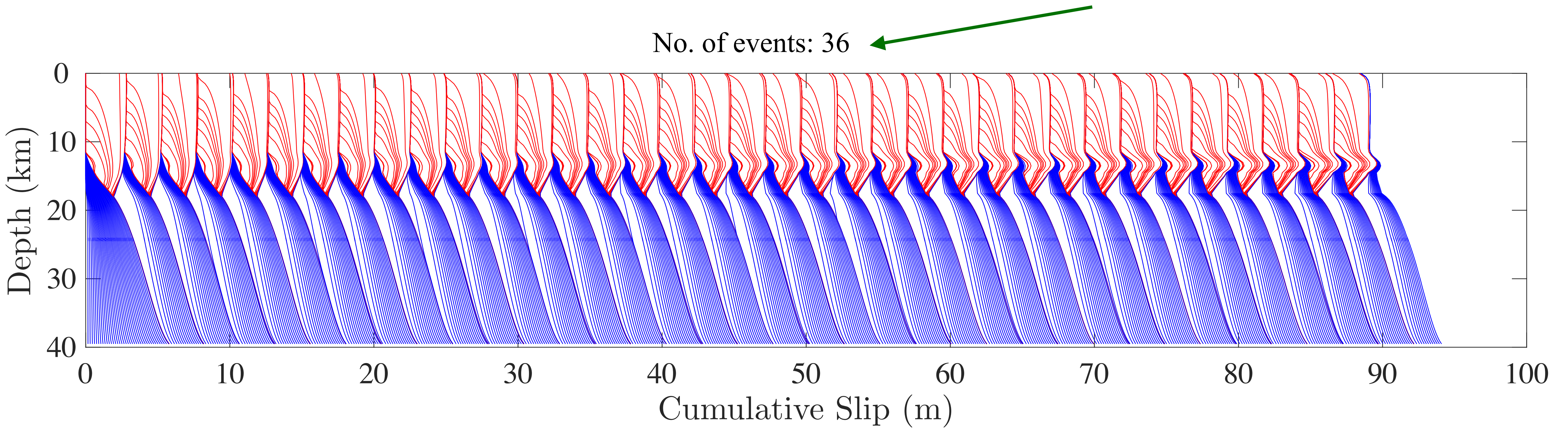


Jiang: L_z = 160km:

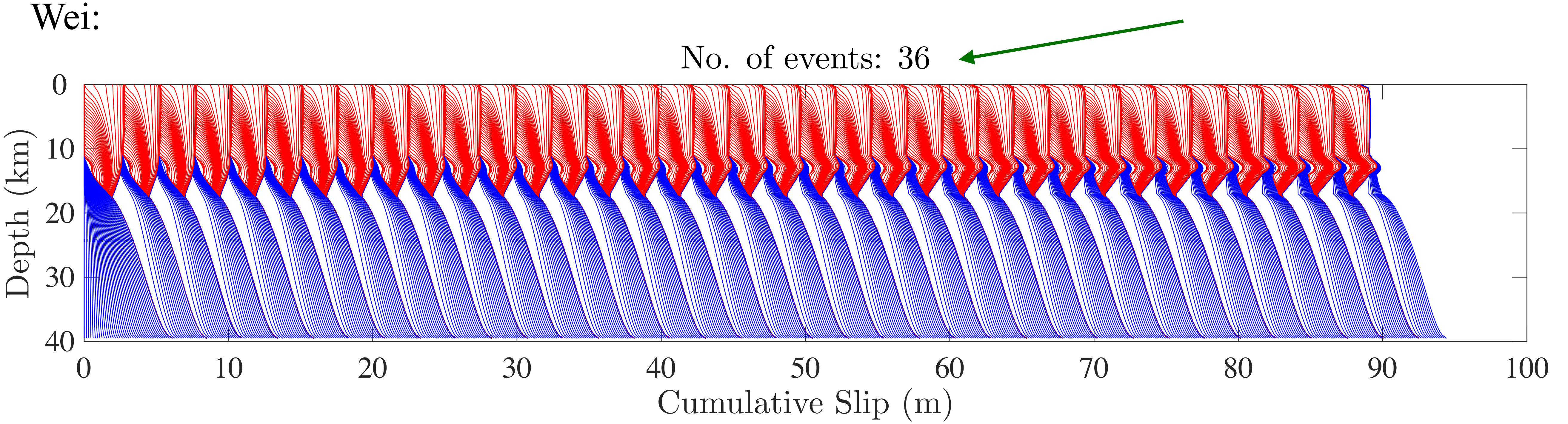


A kink in the slip profile tends to develop, but other features appear qualitatively similar (i.e. nucleation depth, amount of slip, recurrence).

Liu (no interpolation), L_z = 720km (similar to 1000km), dz = 25m :



Wei:



Some take-aways:

- for these parameters, dz = 25m, 50m yield comparable results.

- L_z = 80 km not sufficient to capture half-space features (160 km seems sufficient, but probably also depends on L_x).

- for codes with volume discretization, far field boundary condition matters for smaller domain sizes. Far field free condition seems to match BIEM in this case.

    - we need to explore dependency on far-field boundary condition on domain lengths. Do we need to take large L_x, large L_z, or both?

Time Series

`fltst_dp000`: $z = 0$ km (at the free surface)
`fltst_dp025`: $z = 2.5$ km
`fltst_dp050`: $z = 5$ km
`fltst_dp075`: $z = 7.5$ km
`fltst_dp100`: $z = 10$ km
`fltst_dp125`: $z = 12.5$ km
`fltst_dp150`: $z = 15$ km
`fltst_dp175`: $z = 17.5$ km
`fltst_dp200`: $z = 20$ km
`fltst_dp250`: $z = 25$ km
`fltst_dp300`: $z = 30$ km
`fltst_dp350`: $z = 35$ km

The SCEC Sequences of Earthquakes and Aseismic Slip Project

[Benchmark Comparison Tool]

[Benchmark Descriptions]

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Benchmark Comparison Tool

Go --> Public Area

Go --> Login to View Data

Go --> Login to Upload Files

Go --> Administrative Login

[Exit to SEAS Project Home Page]

Select Benchmark

Active Benchmarks

Name	Date	Description	Action
bp1	4/14/2018 8:08 AM	2D Antiplane Shear	Select

Logout

Upload Data Files

Benchmark: bp1 (2D Antiplane Shear)

Version: jiang (Junle Jiang (25 m; 80 km)) Change Version

On-Fault Stations

Name	Upload	Description	Action
fltst_dp000	4/19/2018 6:41 PM	z = 0.0 km	Upload Delete View Graph
fltst_dp025	4/19/2018 6:41 PM	z = 2.5 km	Upload Delete View Graph
fltst_dp050	4/19/2018 6:41 PM	z = 5.0 km	Upload Delete View Graph
fltst_dp075	4/19/2018 6:41 PM	z = 7.5 km	Upload Delete View Graph
fltst_dp100	4/19/2018 6:41 PM	z = 10.0 km	Upload Delete View Graph
fltst_dp125	4/19/2018 6:42 PM	z = 12.5 km	Upload Delete View Graph
fltst_dp150	4/19/2018 6:42 PM	z = 15.0 km	Upload Delete View Graph
fltst_dp175	4/19/2018 6:42 PM	z = 17.5 km	Upload Delete View Graph
fltst_dp200	4/19/2018 6:42 PM	z = 20.0 km	Upload Delete View Graph
fltst_dp250	4/19/2018 6:42 PM	z = 25.0 km	Upload Delete View Graph
fltst_dp300	4/19/2018 6:42 PM	z = 30.0 km	Upload Delete View Graph
fltst_dp350	4/19/2018 6:42 PM	z = 35.0 km	Upload Delete View Graph

Data visibility: Restricted Edit

Back to Benchmark List Logout

Benchmark BP1 Participation

Total submissions:

11 modelers

22 model runs

different B.C.

different cell sizes

different domain sizes

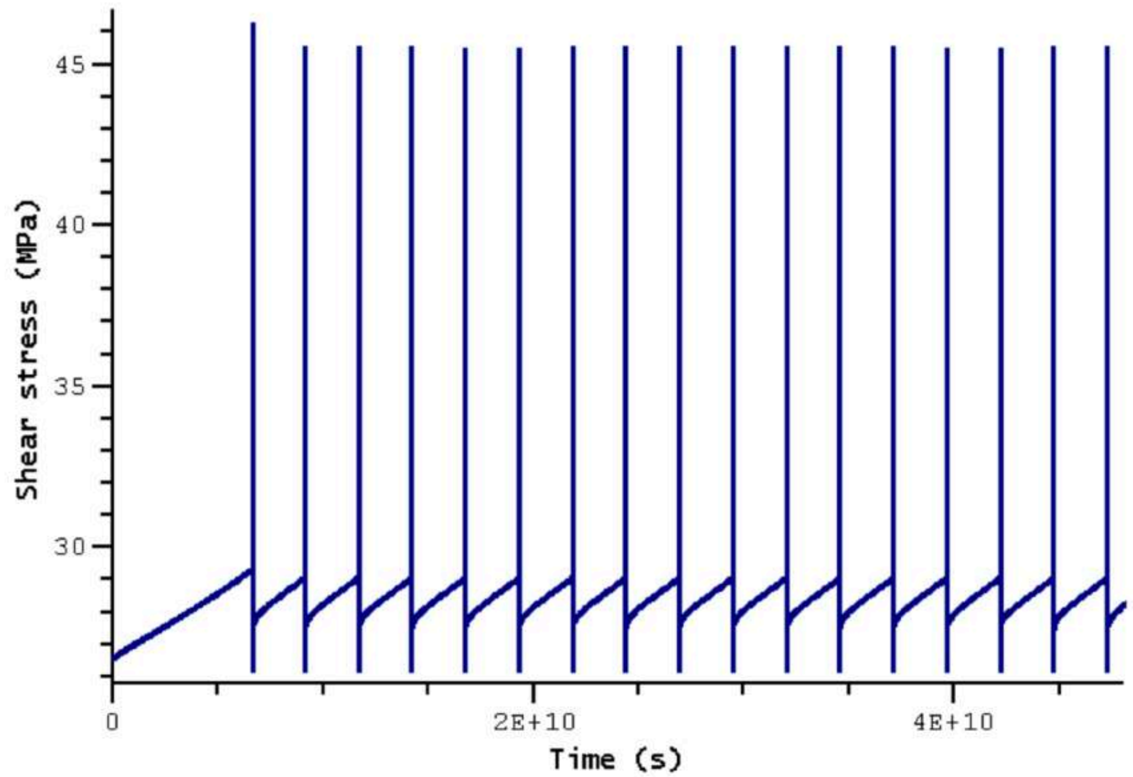
Users Select Checked Select All

	Name	Description	Action
☐	abrahams	100 km X 80 km: Free surface outer BC	Select
☐	abrahams.2	100 km X 80 km: Vp/2 outer BC	Select
☐	barbot	Sylvain Barbot (Fortran90)	Select
☐	barbot.2	Sylvain Barbot (Matlab)	Select
☐	cattania	Camilla Cattania - fdra (bem)	Select
☐	cattania.2	Camilla Cattania - fdra (fft, 160 km)	Select
☐	cattania.3	Camilla Cattania - fdra (fft, 640 km)	Select
☐	erickson	Brittany Erickson	Select
☐	erickson.2	Brittany Erickson	Select
☐	jiang	Junle Jiang (25 m; 80 km)	Select
☐	jiang.2	Junle Jiang (25 m; 160 km)	Select
☐	kozdon	SIPG :: 800 km X 400 km :: Vp/2 outer BC	Select
☐	kozdon.2	SIPG :: 160 km X 80 km :: Vp/2 outer BC	Select
☐	kozdon.3	SIPG :: 800 km X 400 km :: free surface outer BC	Select
☐	kozdon.4	SIPG :: 160 km X 80 km :: free surface outer BC	Select
☐	lambert	Valère Lambert - 25 m, 80 km domain	Select
☐	lambert.2	Valère Lambert - 50 m, 80 km domain	Select
☐	lambert.3	Valère Lambert - 25 m, 50 km domain	Select
☐	liu	Yajing Liu	Select
☐	luo	QDYN - Yingdi Luo, Ben Idini and Pablo Ampuero	Select
☐	wei	Matt Wei	Select
☐	xma	MSC-Cycle_25m_80	Select
☐	xma.2	MSC-Cycle_50m_80	Select

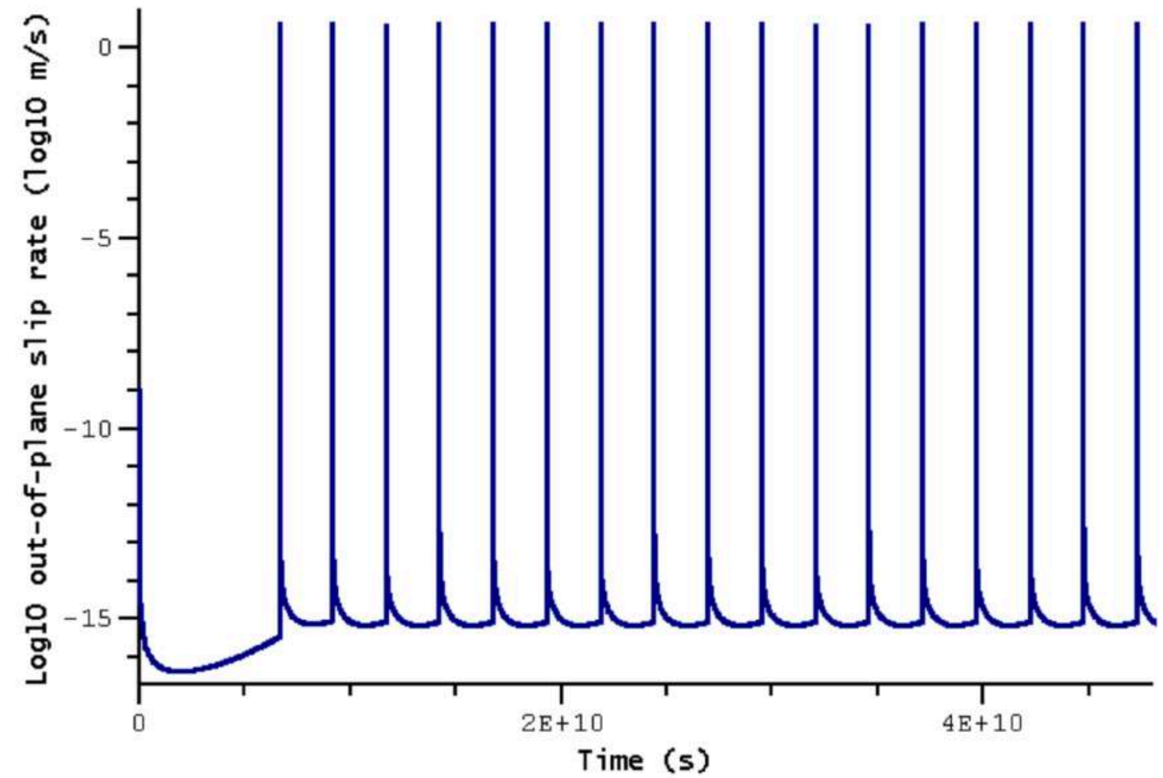
Select Checked Select All

Different physical variables: stress, rate, slip, & state

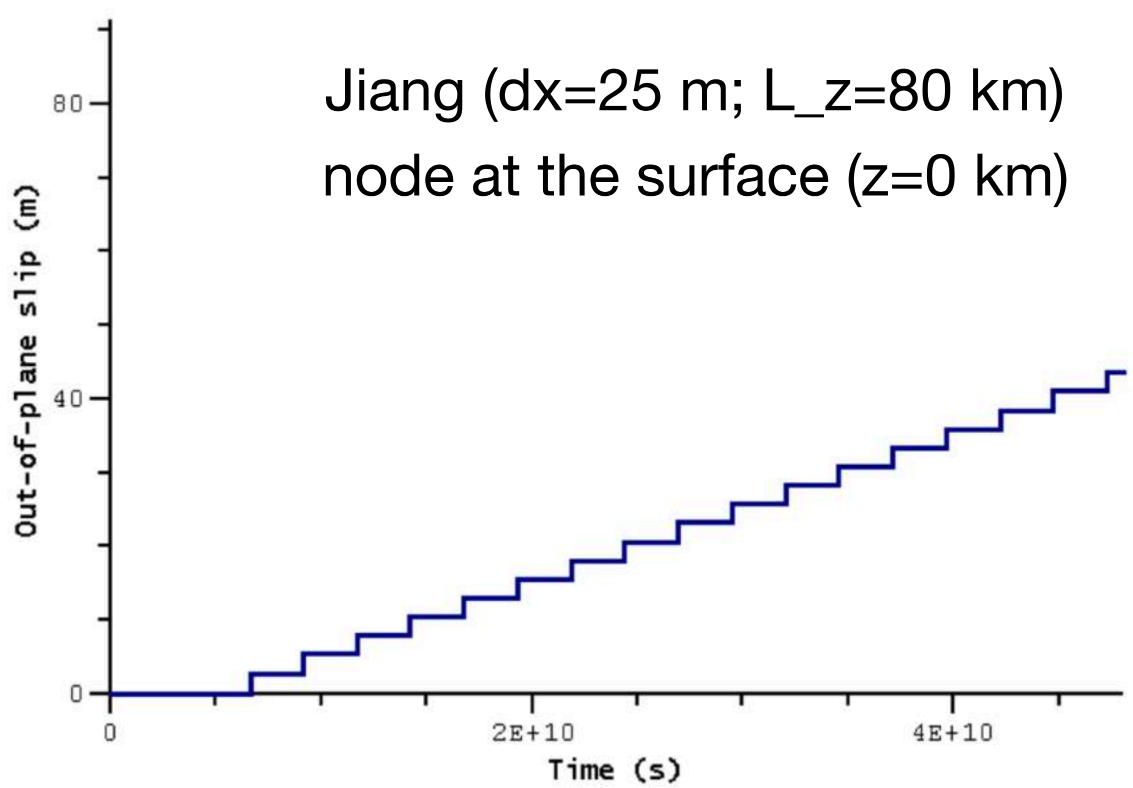
Field: shear_stress (Shear stress (MPa))



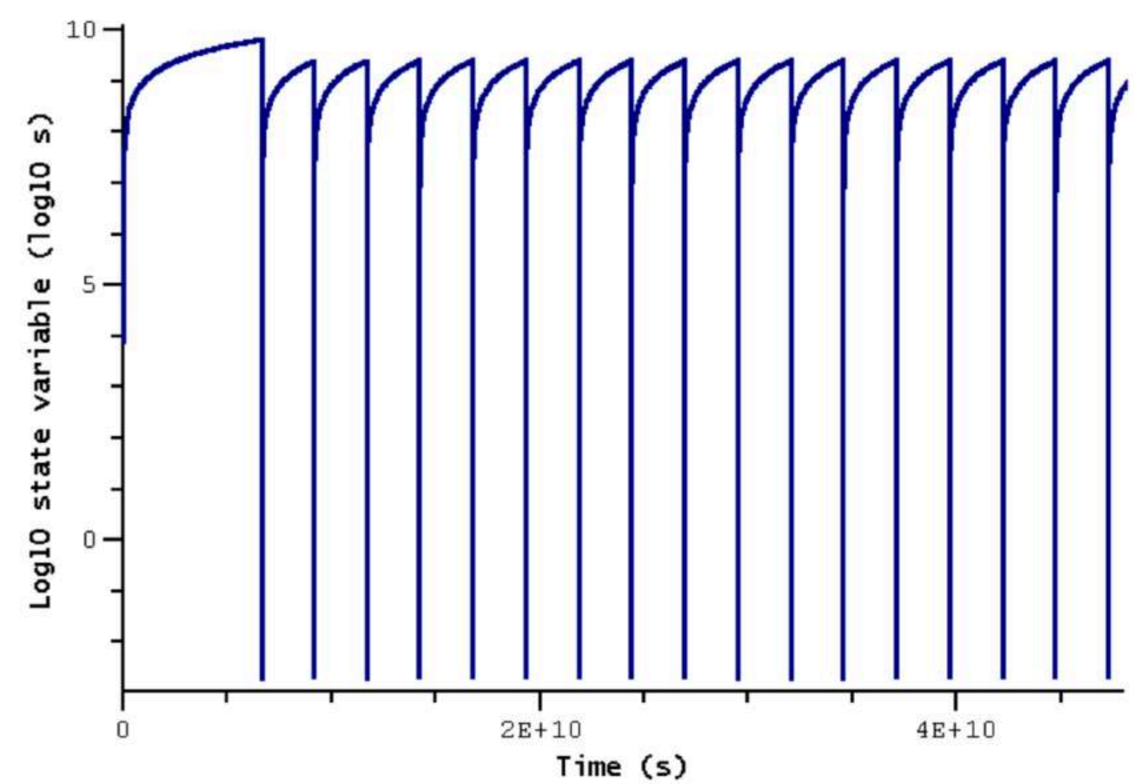
Field: slip_rate (Log10 out-of-plane slip rate (log10 m/s))



Field: slip (Out-of-plane slip (m))



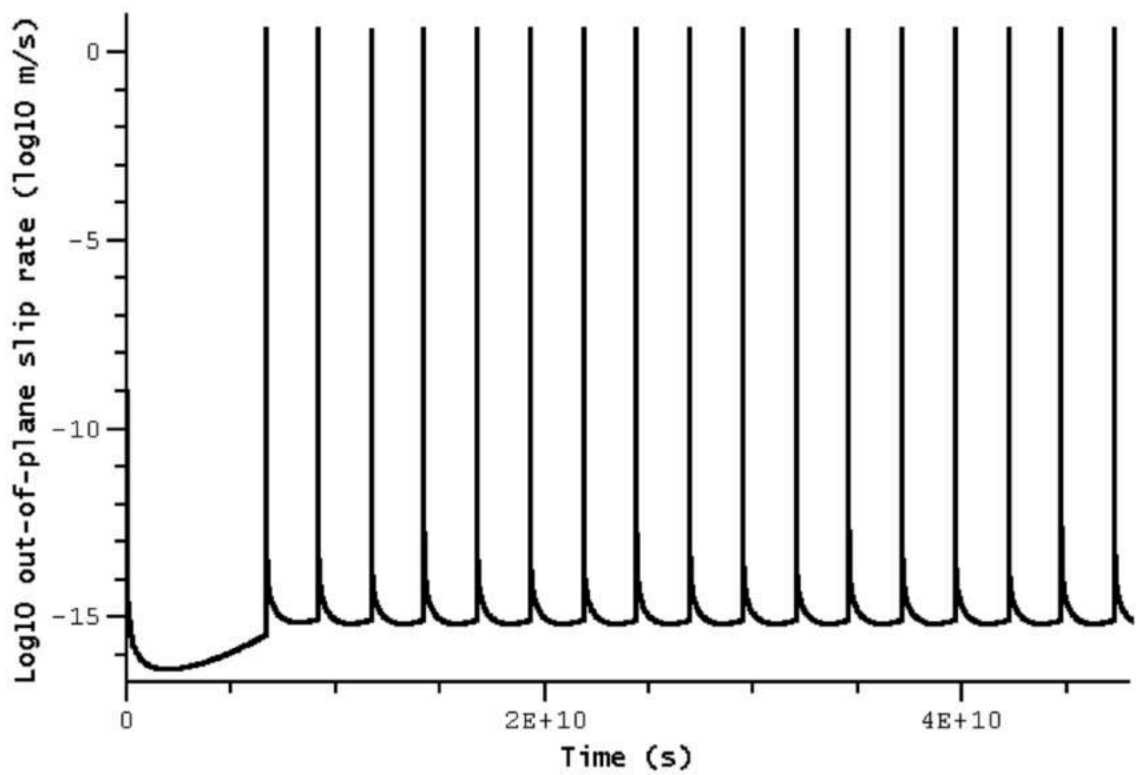
Field: state (Log10 state variable (log10 s))



Different depths on the fault: slip rate

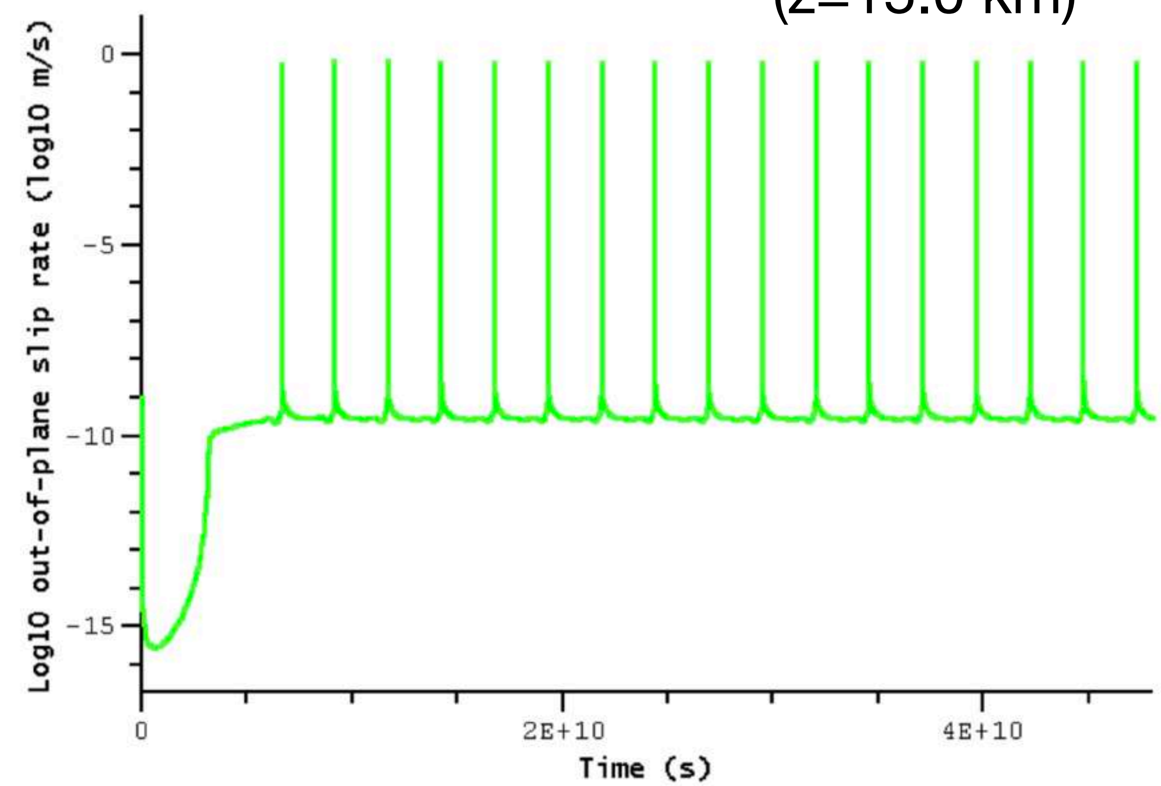
File: fltst_dp000 (z = 0.0 km)

surface (z=0 km)



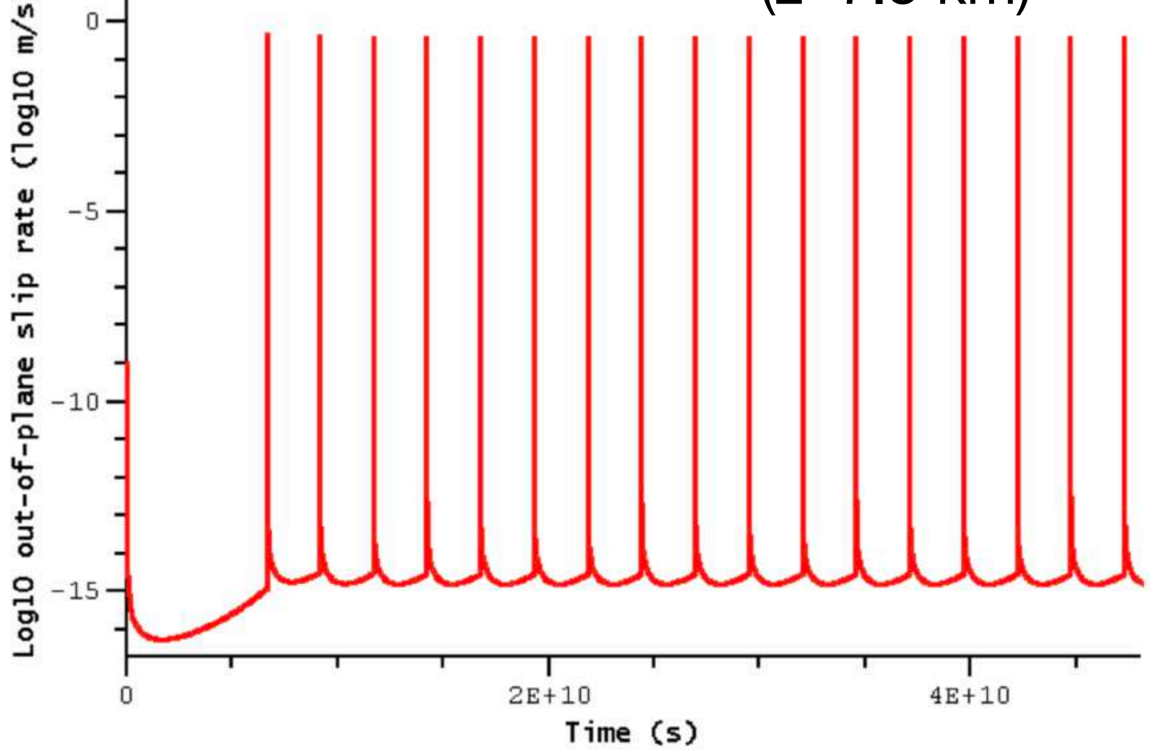
File: fltst_dp150 (z = 15.0 km)

VW/VS transition (z=15.0 km)



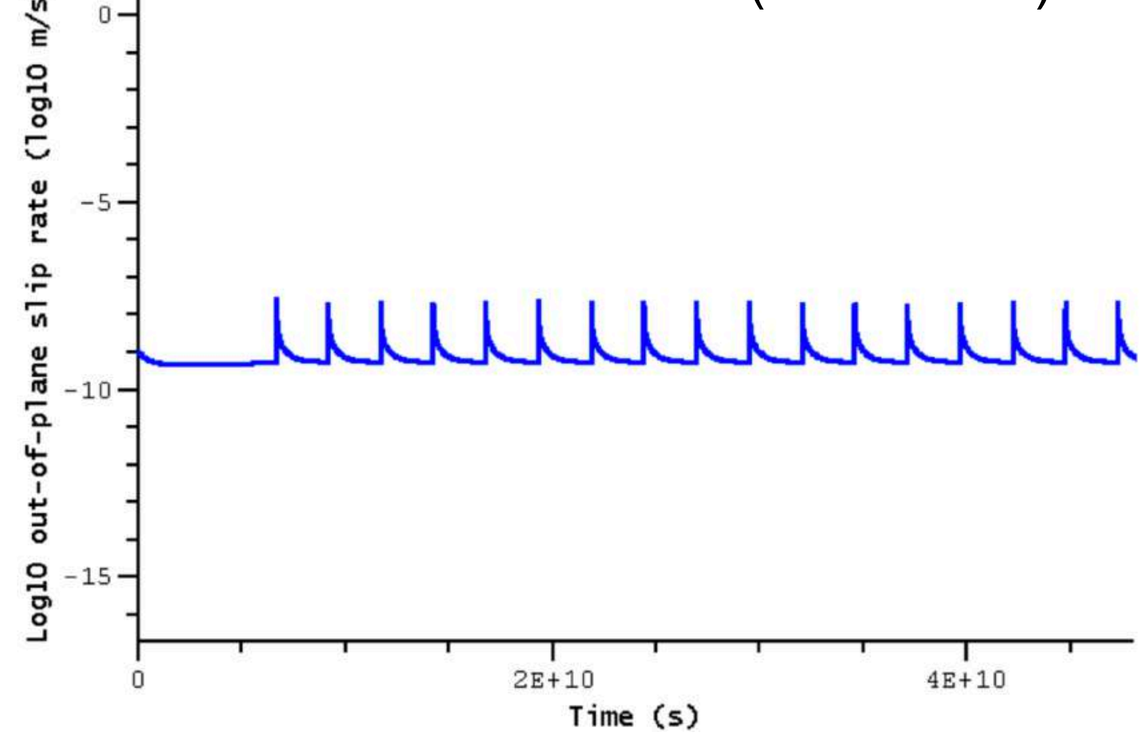
File: fltst_dp075 (z = 7.5 km)

mid-seismogenic depth (z=7.5 km)



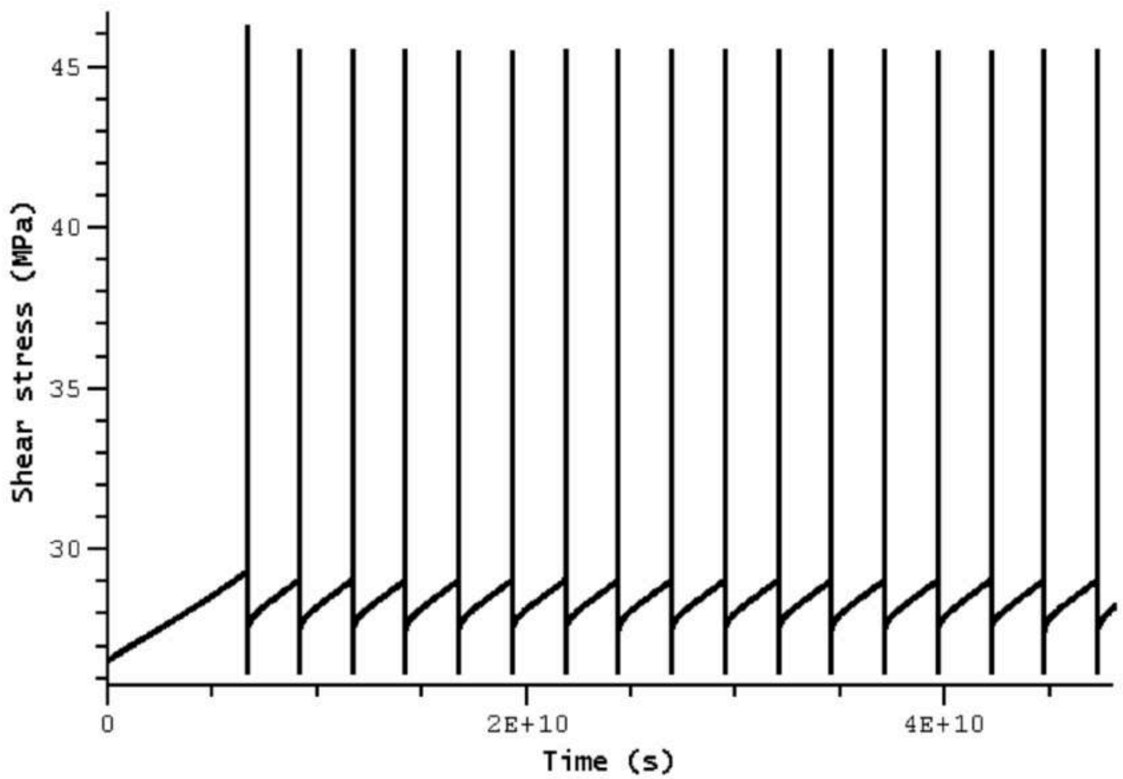
File: fltst_dp250 (z = 25.0 km)

VS region (z=25.0 km)

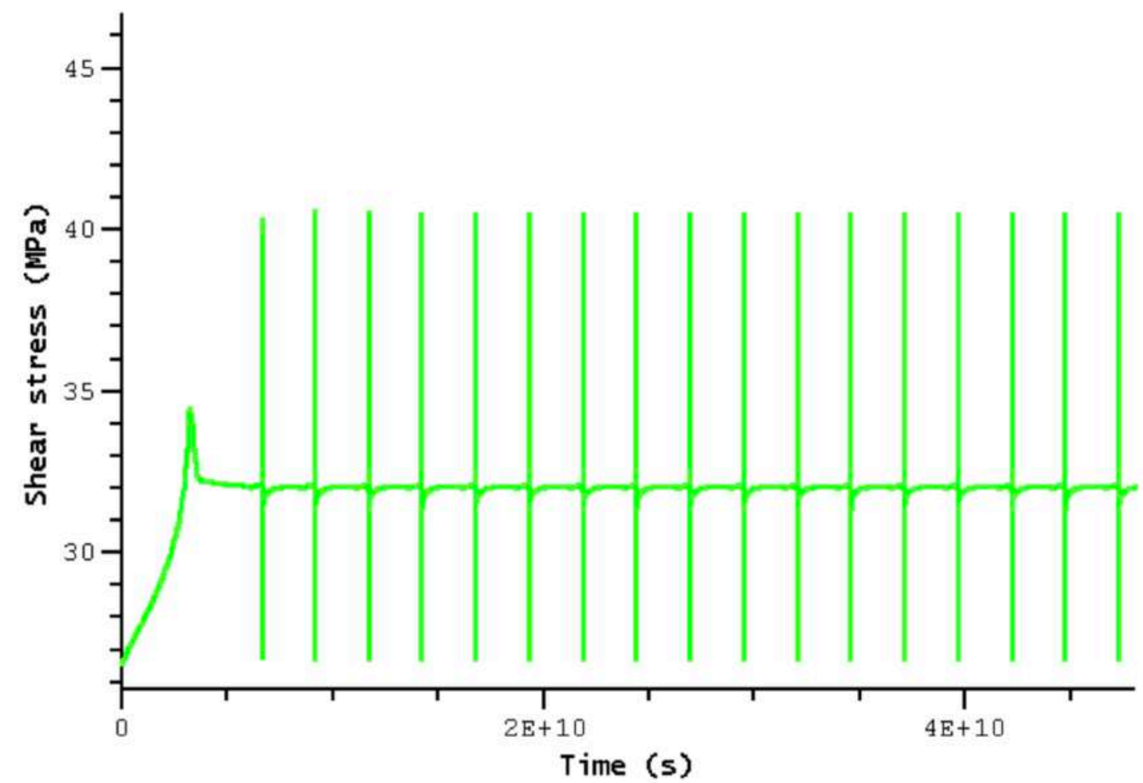


Different depths on the fault: shear stress

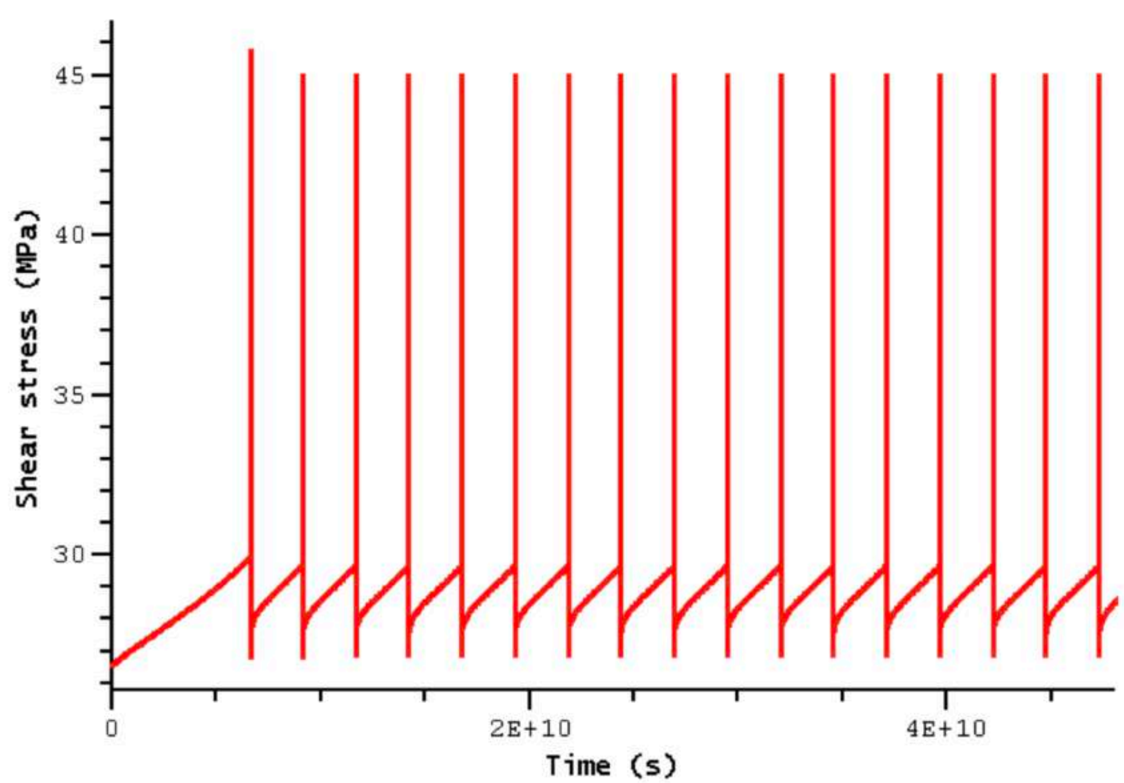
File: fltst_dp000 (z = 0.0 km)



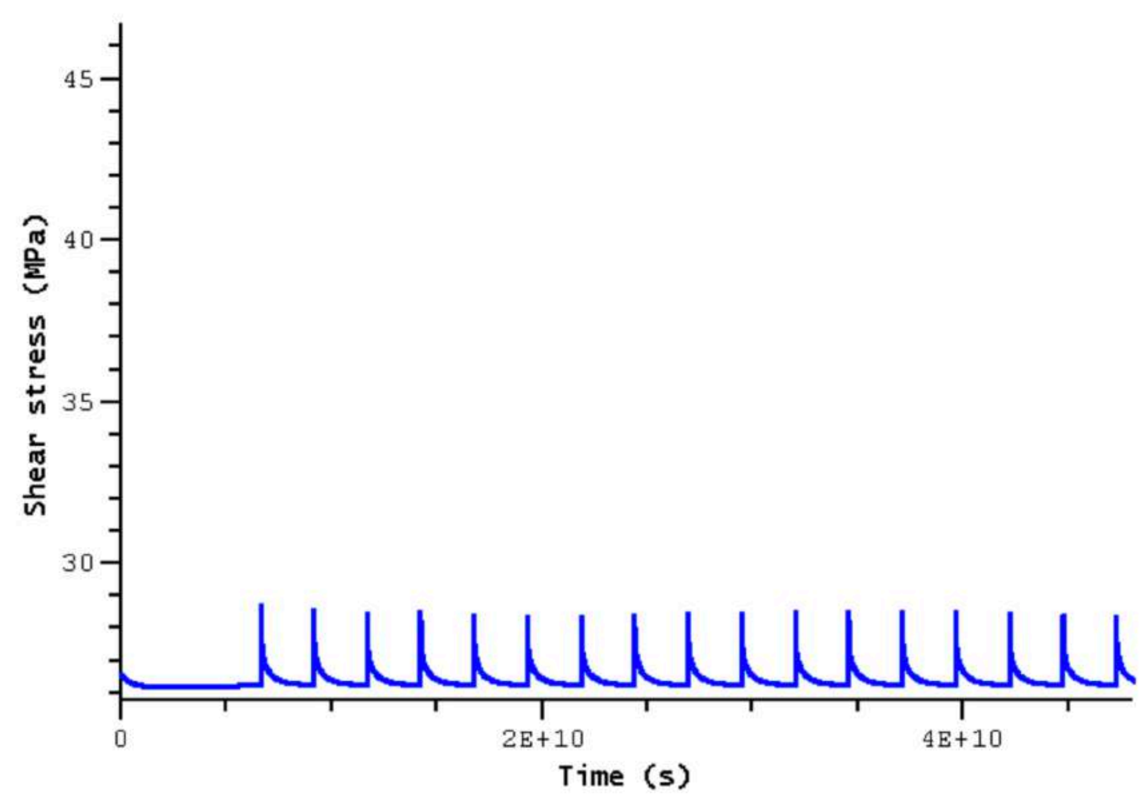
File: fltst_dp150 (z = 15.0 km)



File: fltst_dp075 (z = 7.5 km)

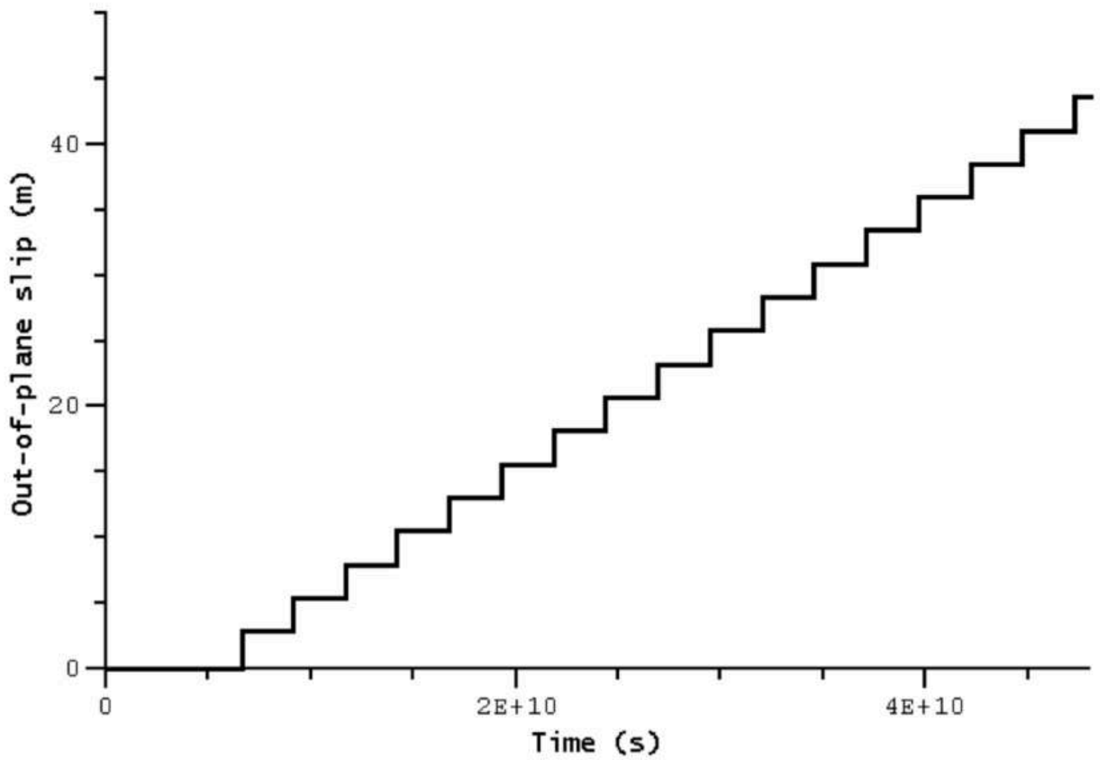


File: fltst_dp250 (z = 25.0 km)

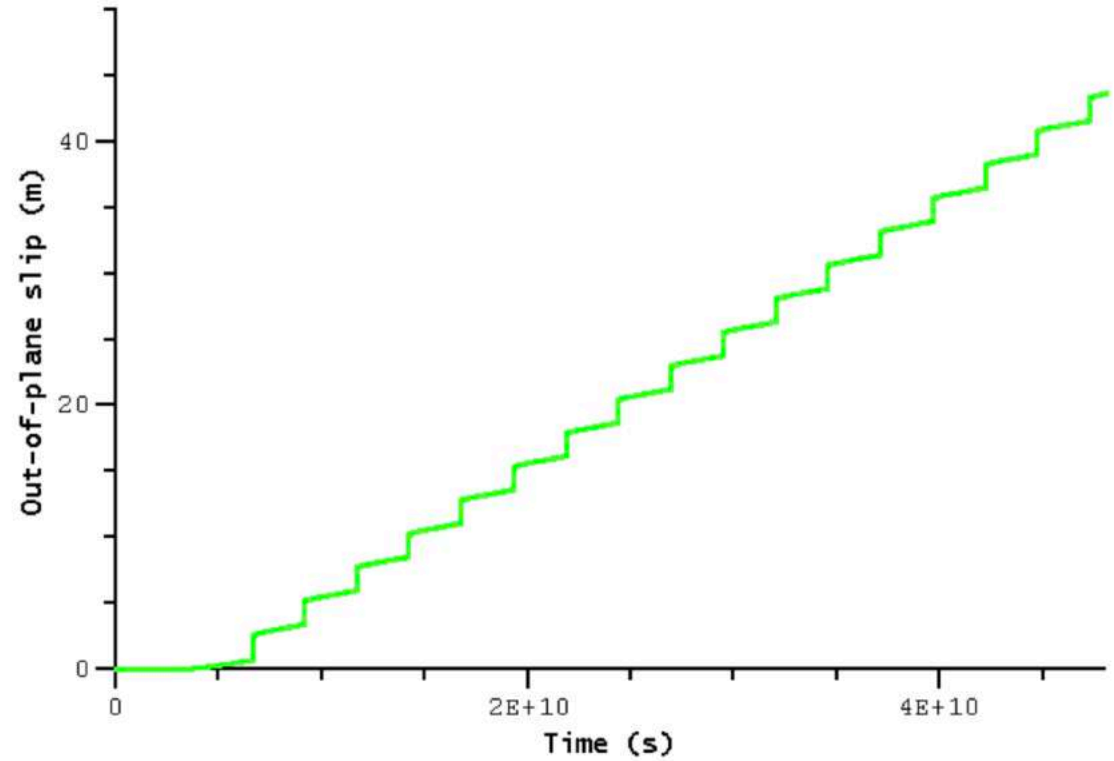


Different depths on the fault: slip

File: fltst_dp000 (z = 0.0 km)



File: fltst_dp150 (z = 15.0 km)



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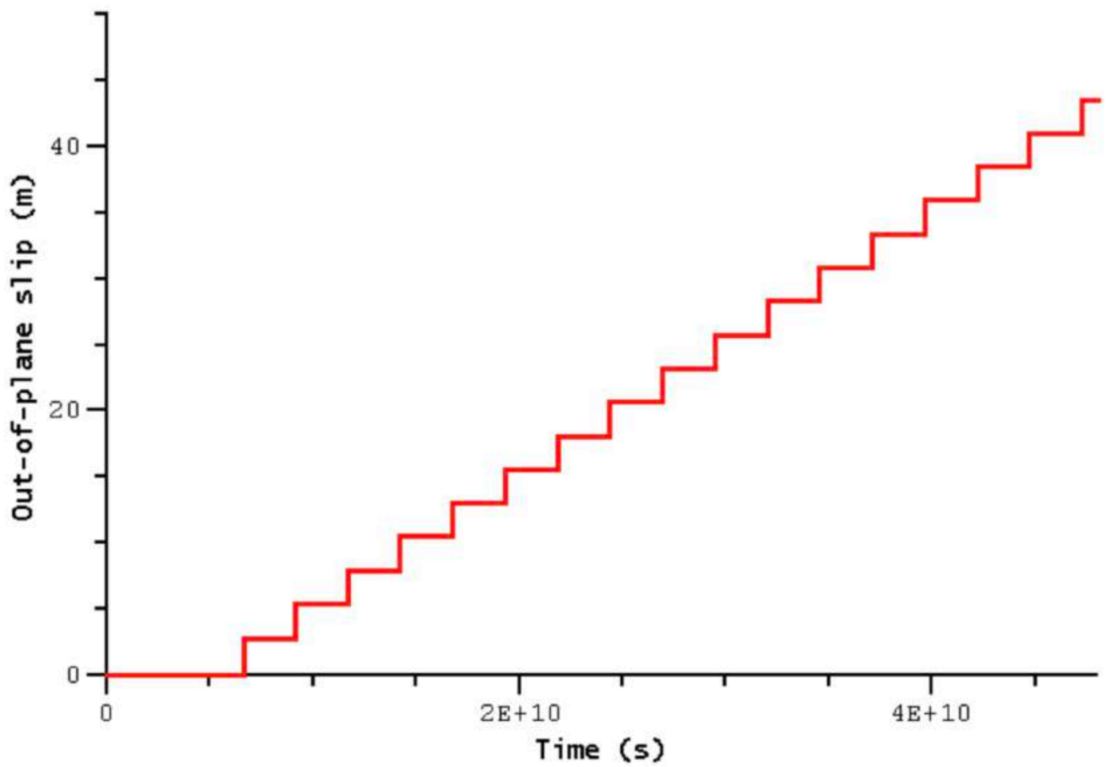

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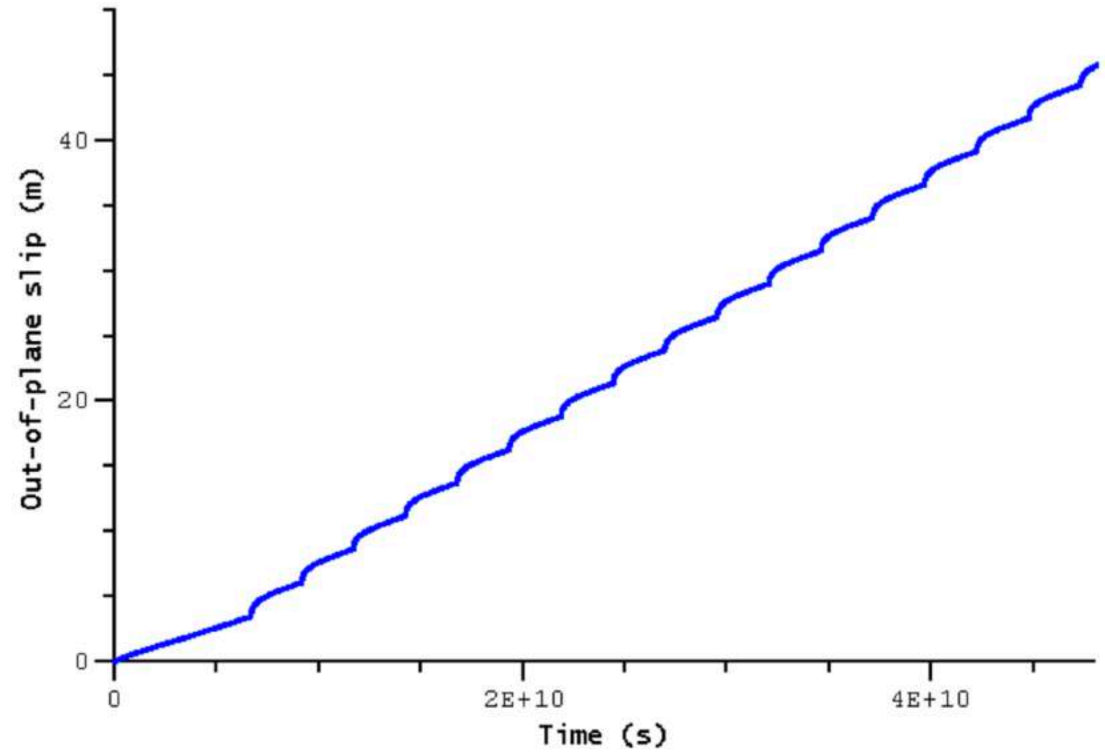
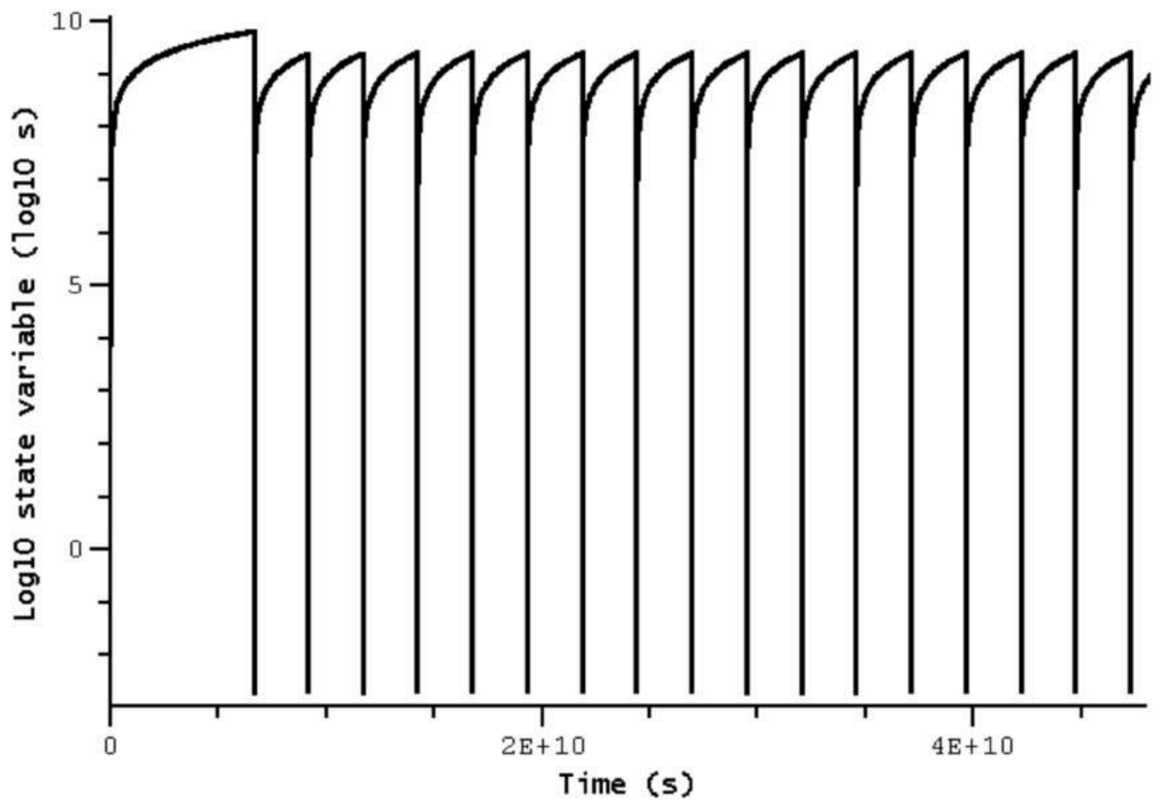
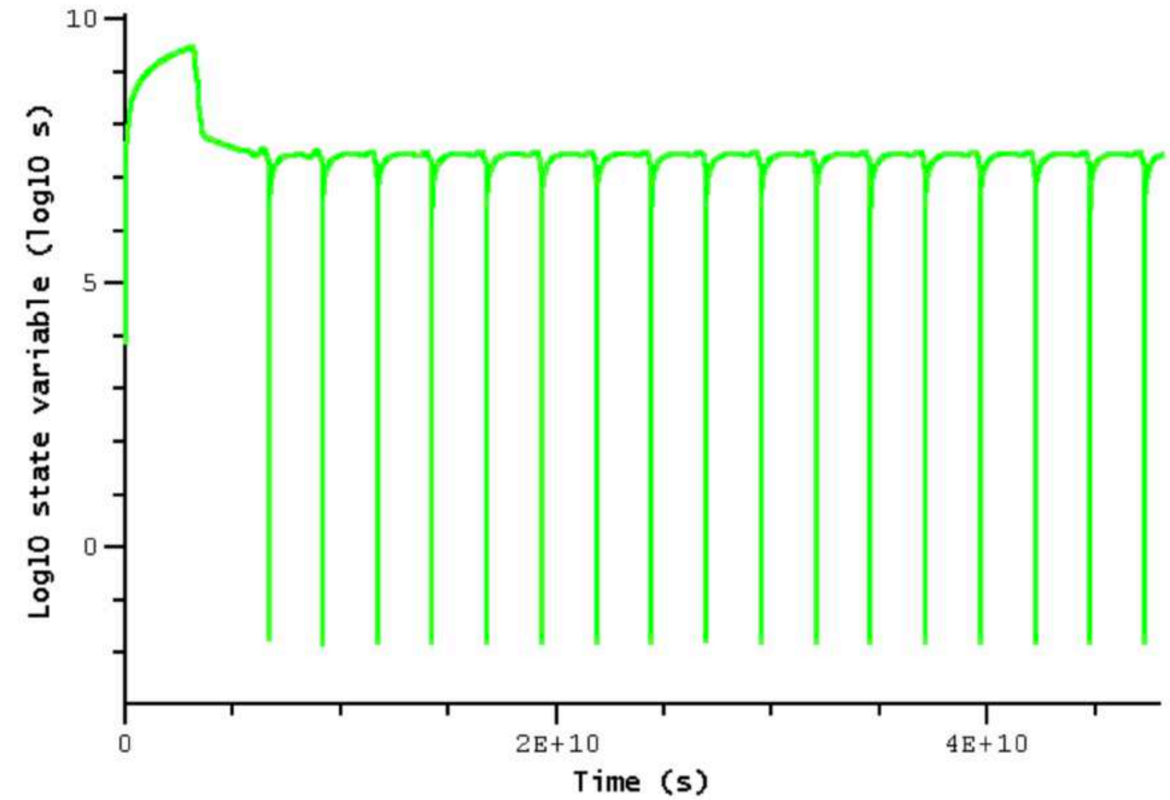


Different depths on the fault: state

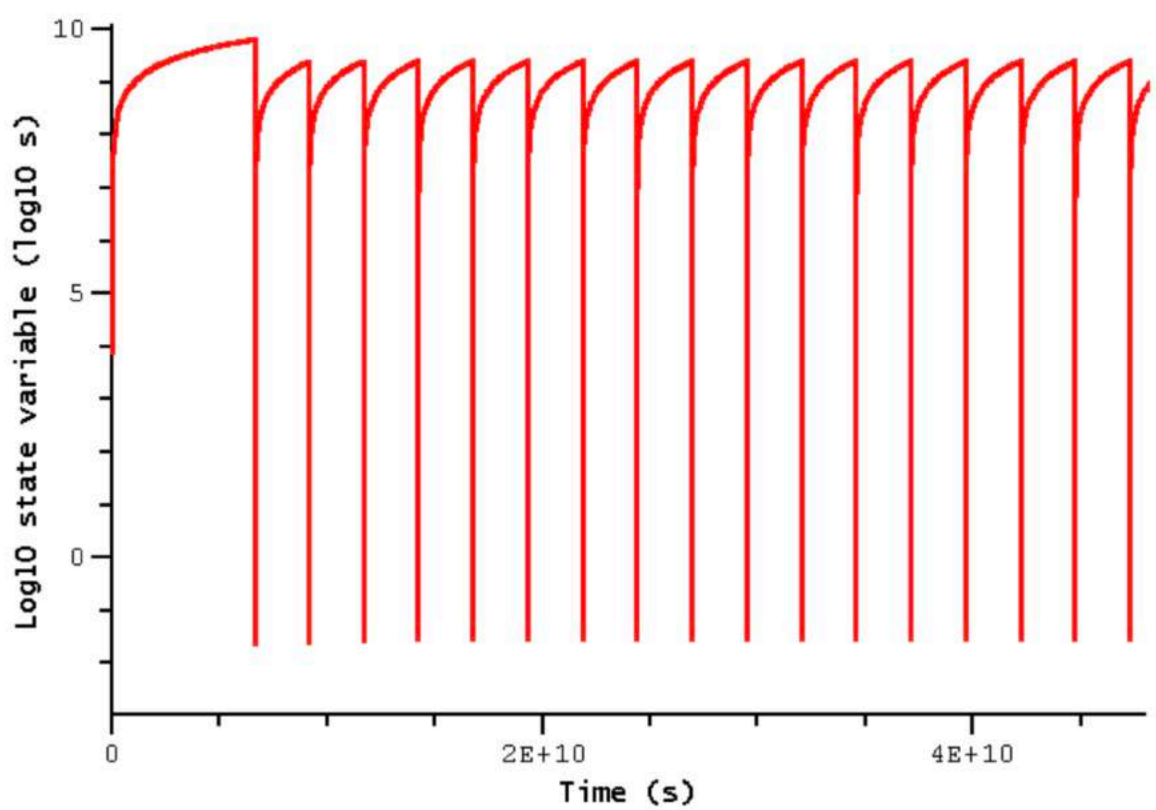
File: fltst_dp000 (z = 0.0 km)



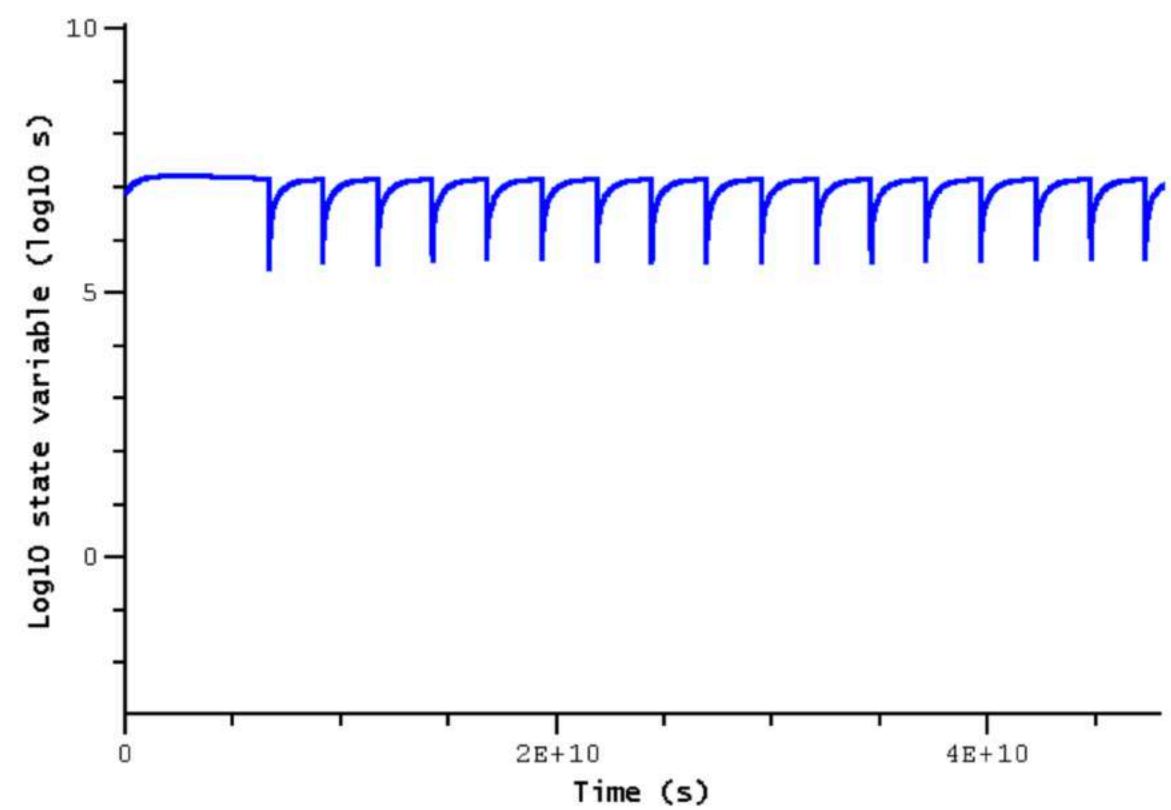
File: fltst_dp150 (z = 15.0 km)



File: fltst_dp075 (z = 7.5 km)

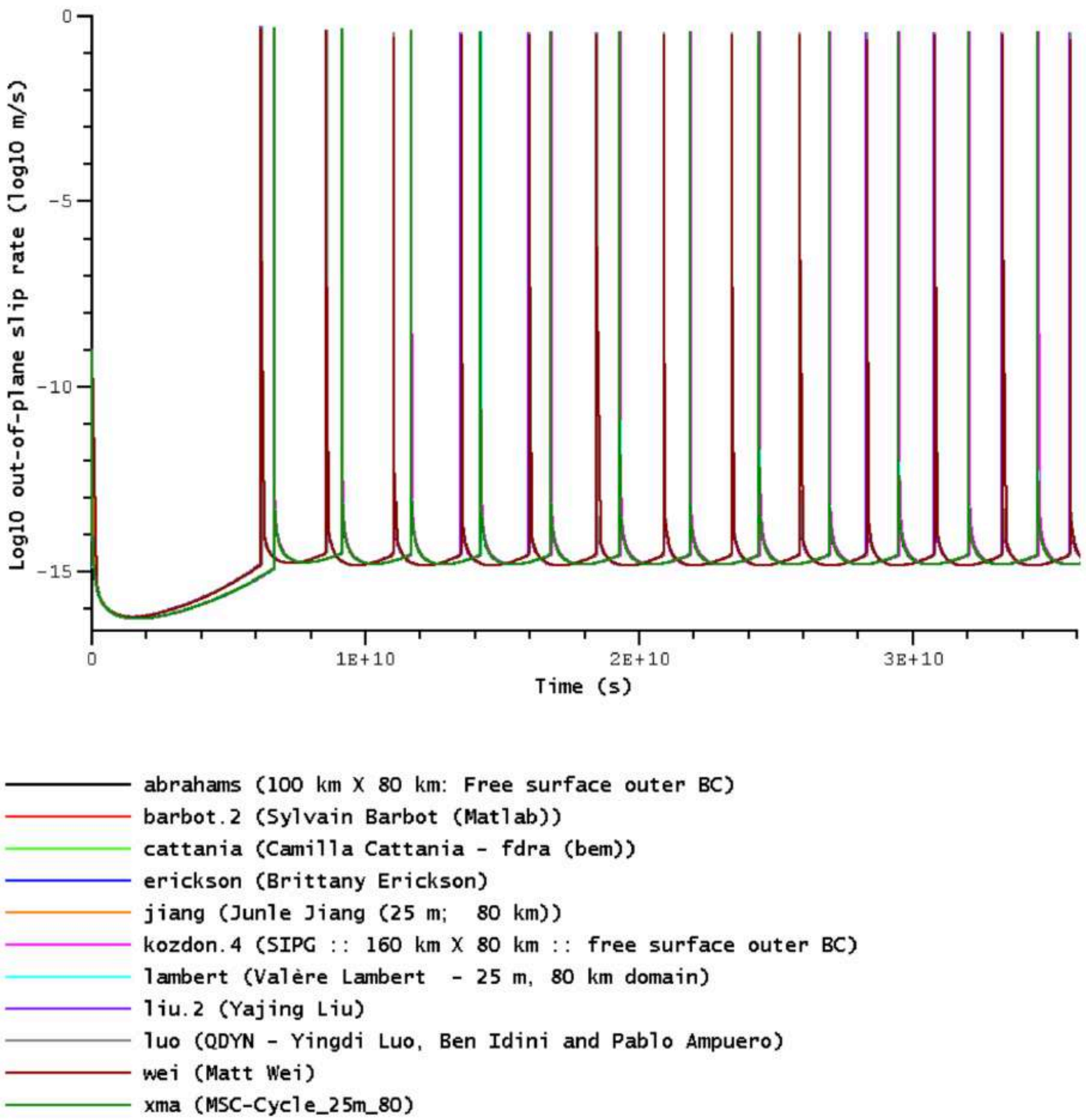


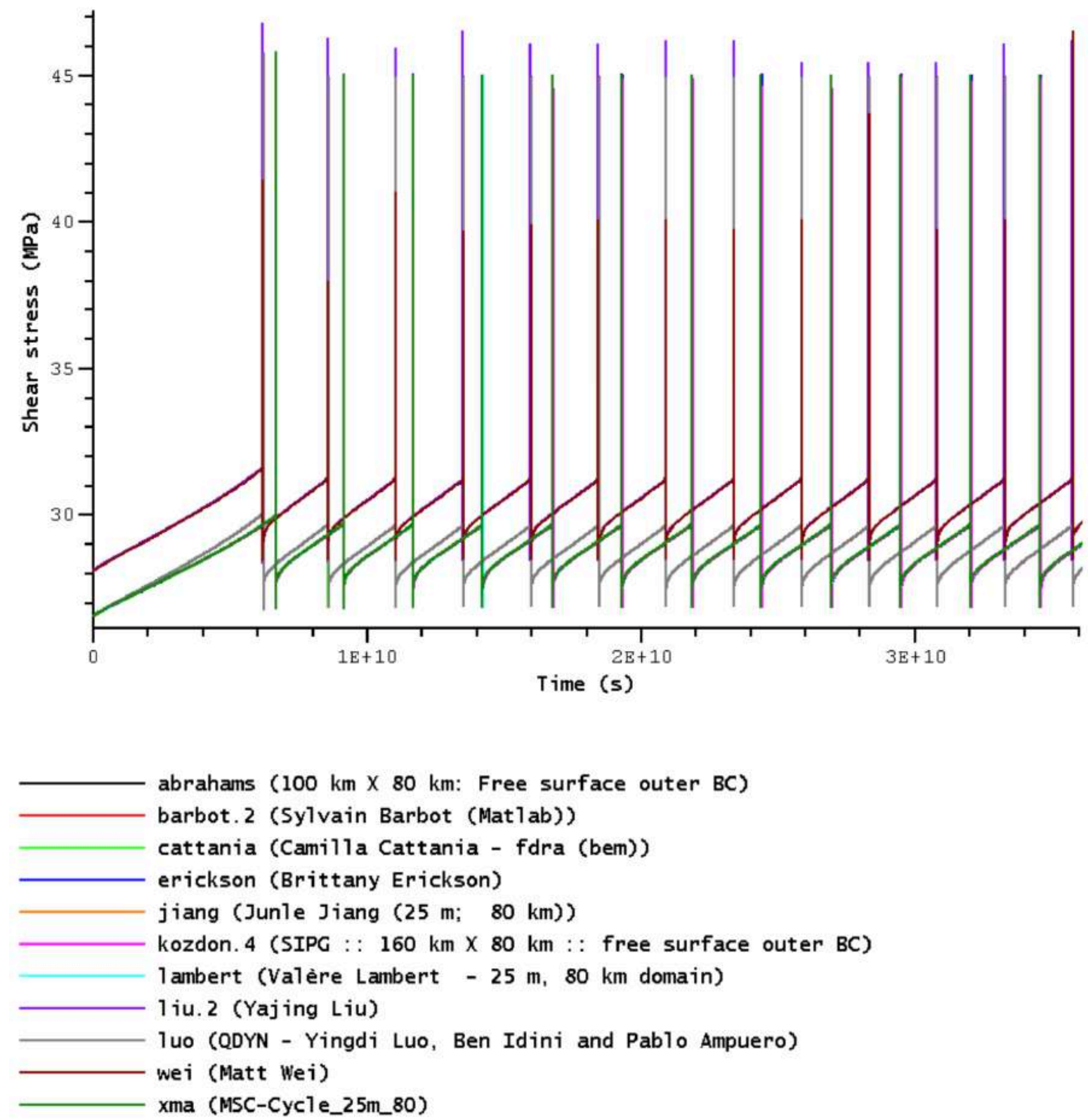
File: fltst_dp250 (z = 25.0 km)



Comparison of all models

Long-term evolution of slip rates/shear stresses at mid-seismogenic depth (z=7.5 km)

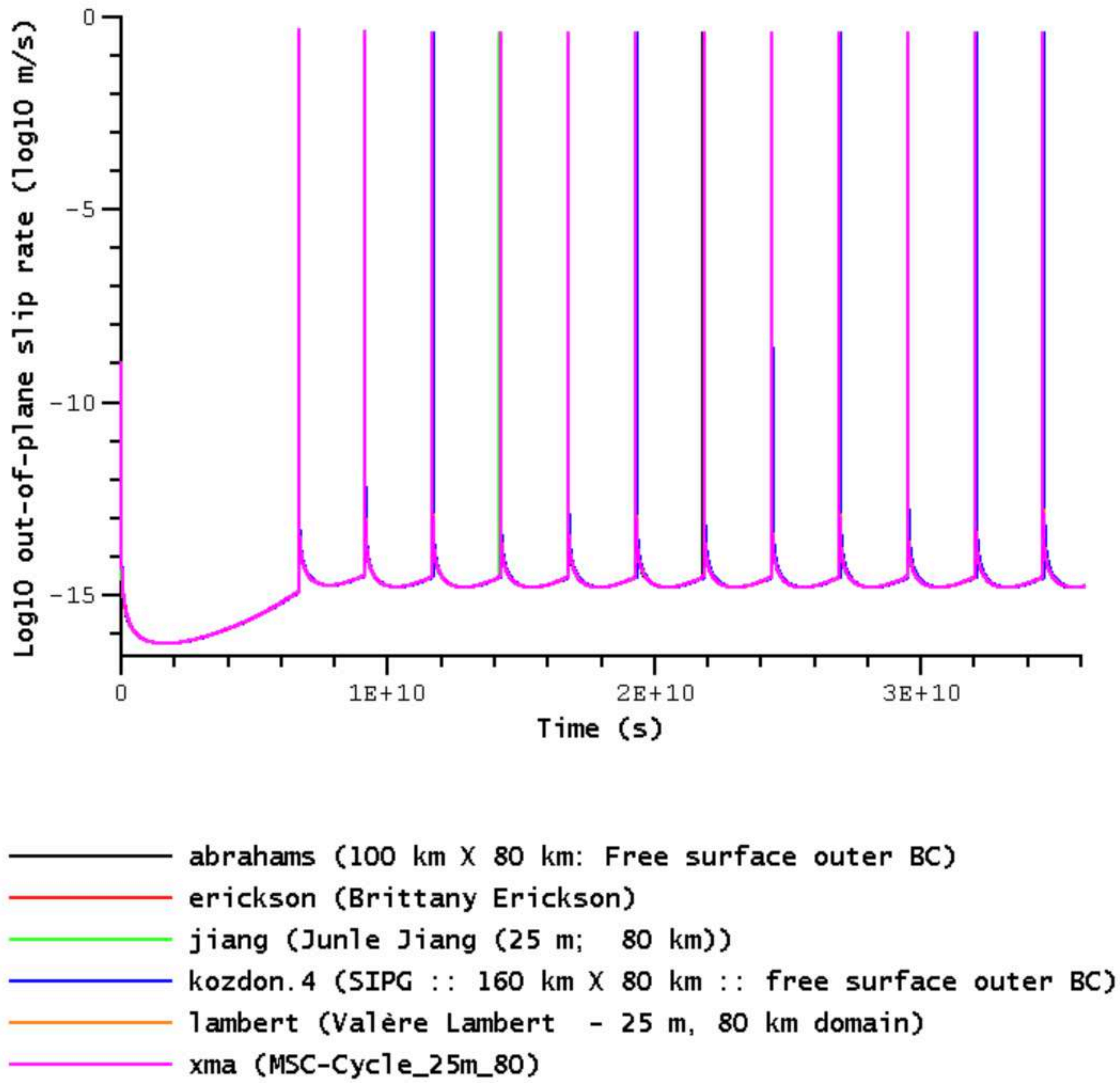


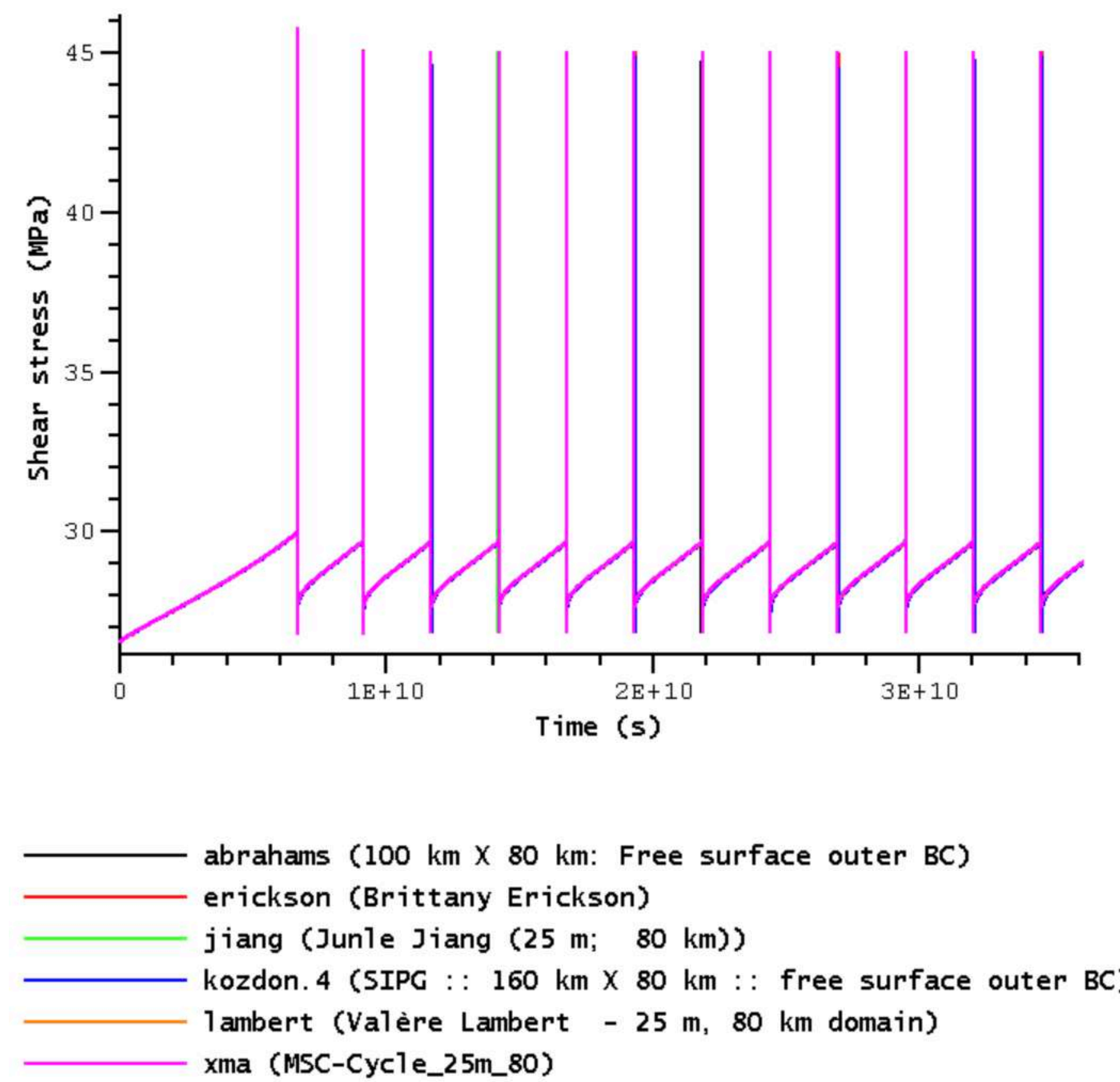


Most models have cell sizes of ~25 m and Lz = 40-80 km

Comparison of subgroups of models

Long-term evolution of slip rates/shear stresses at mid-seismogenic depth (z=7.5 km)





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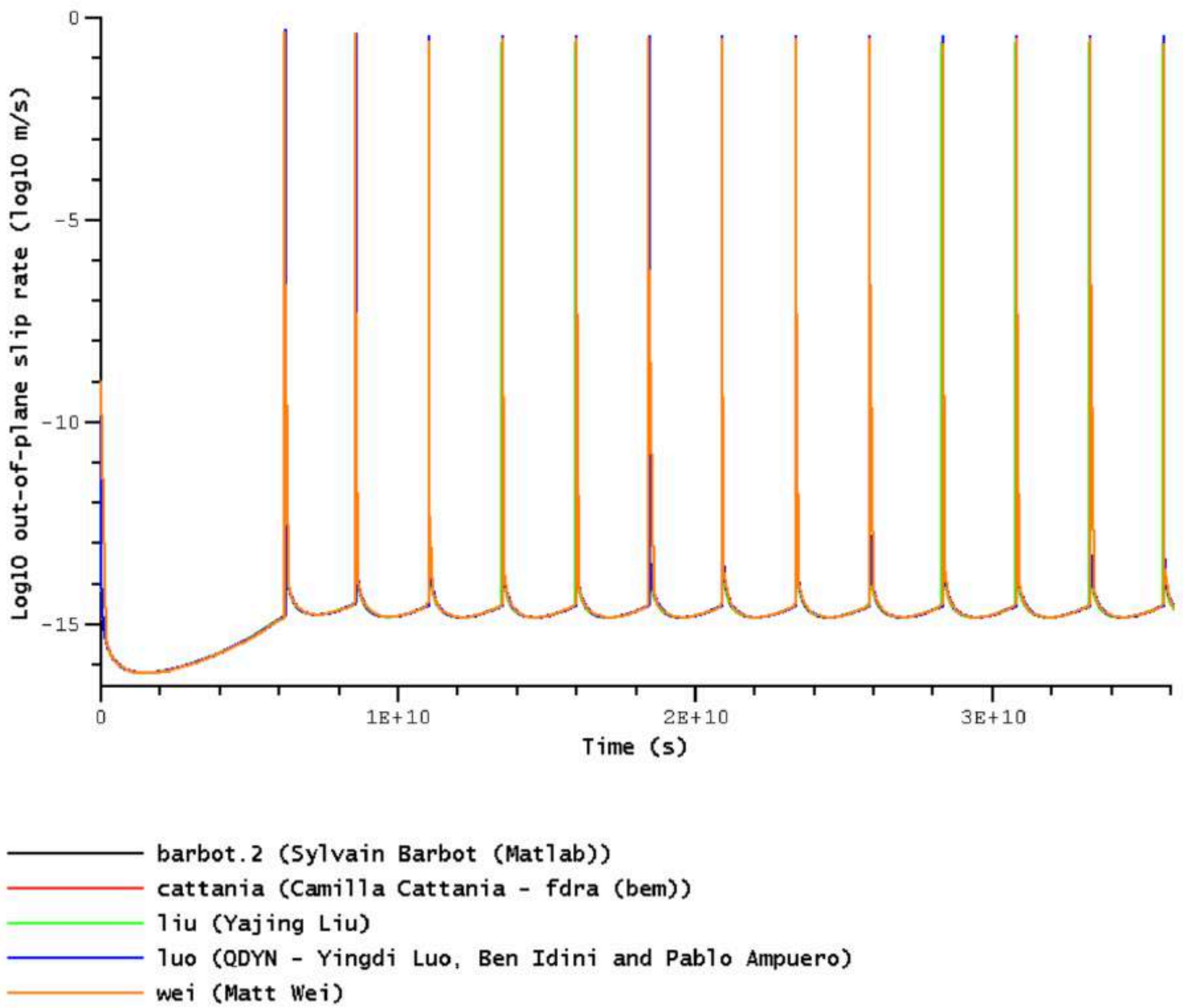
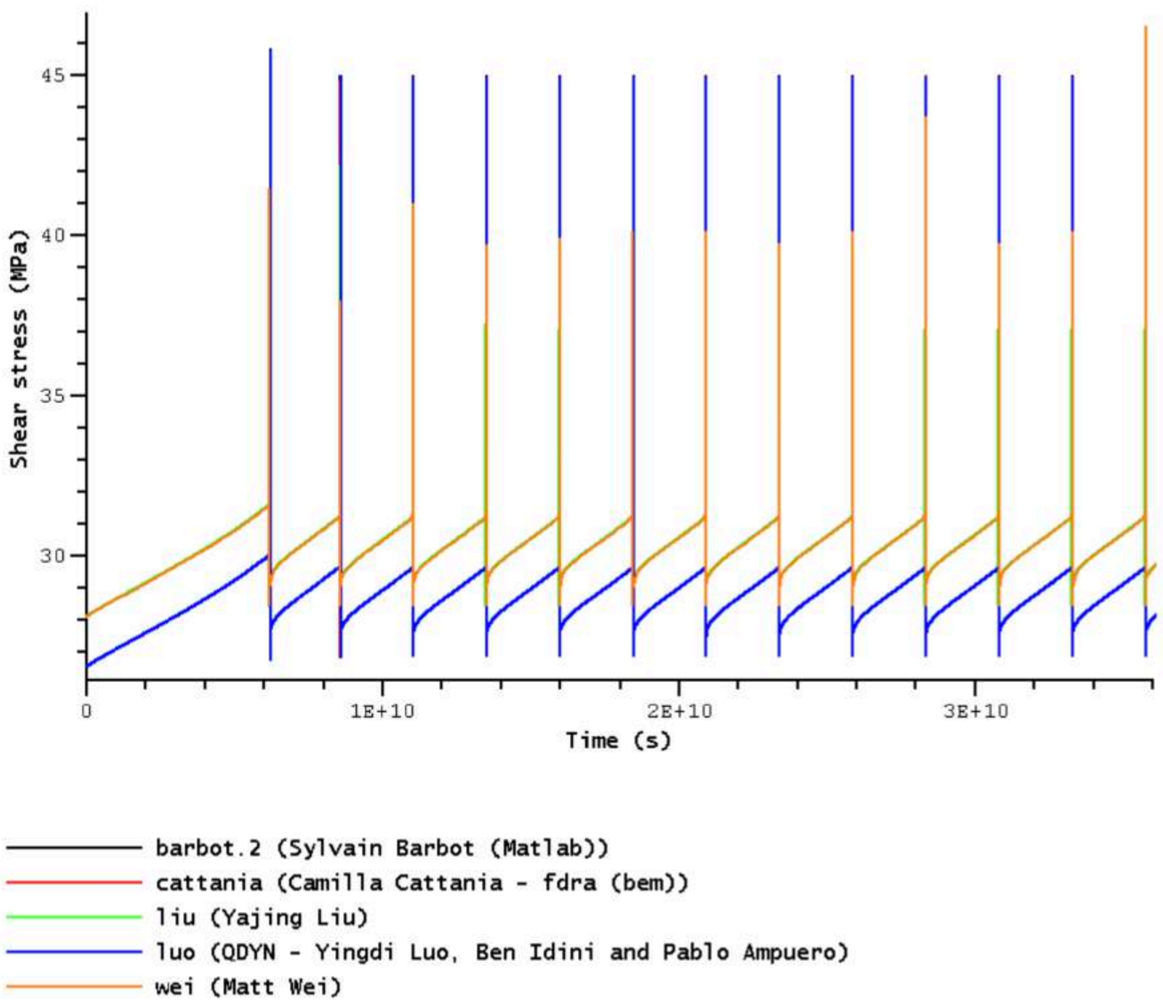
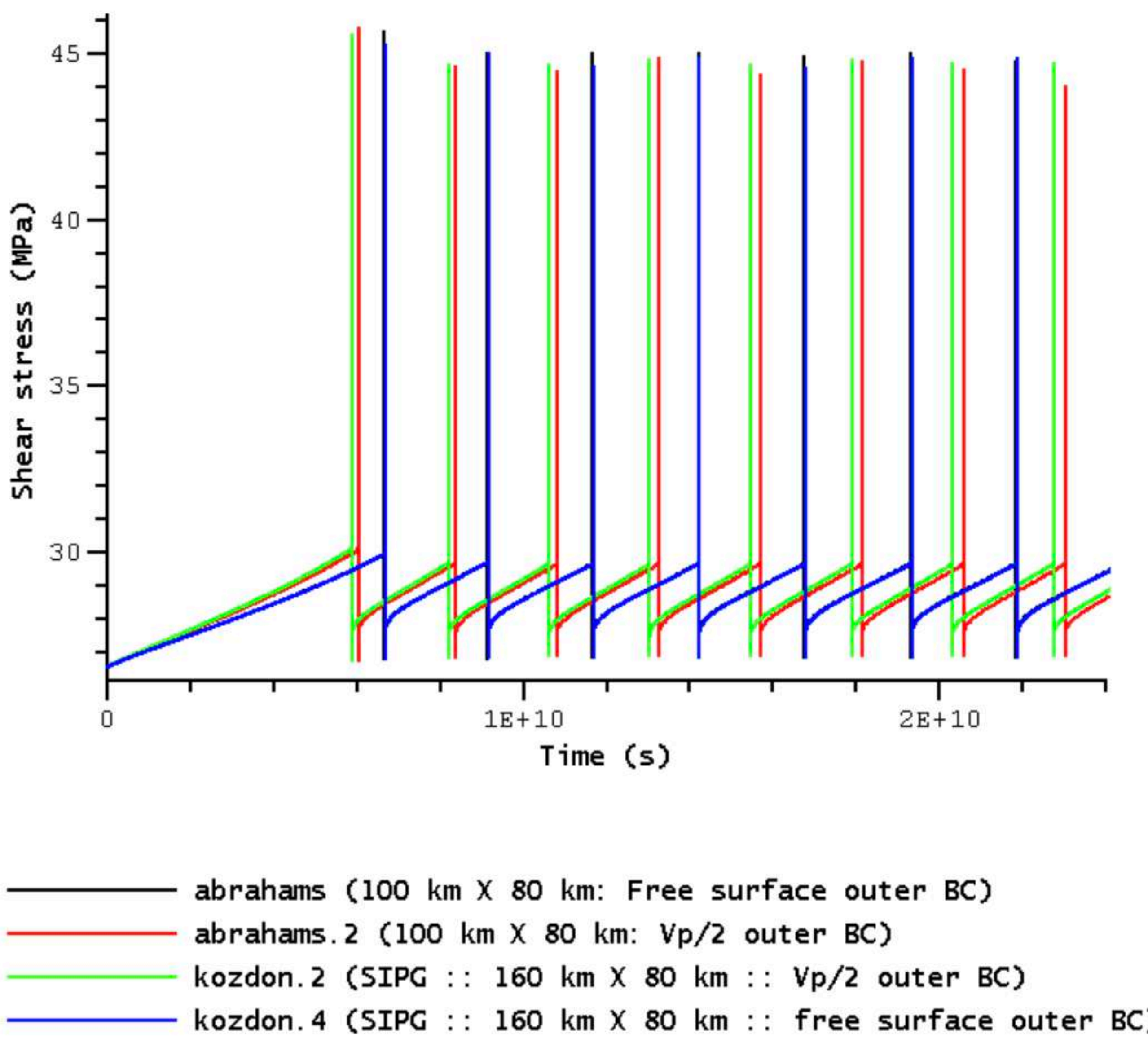


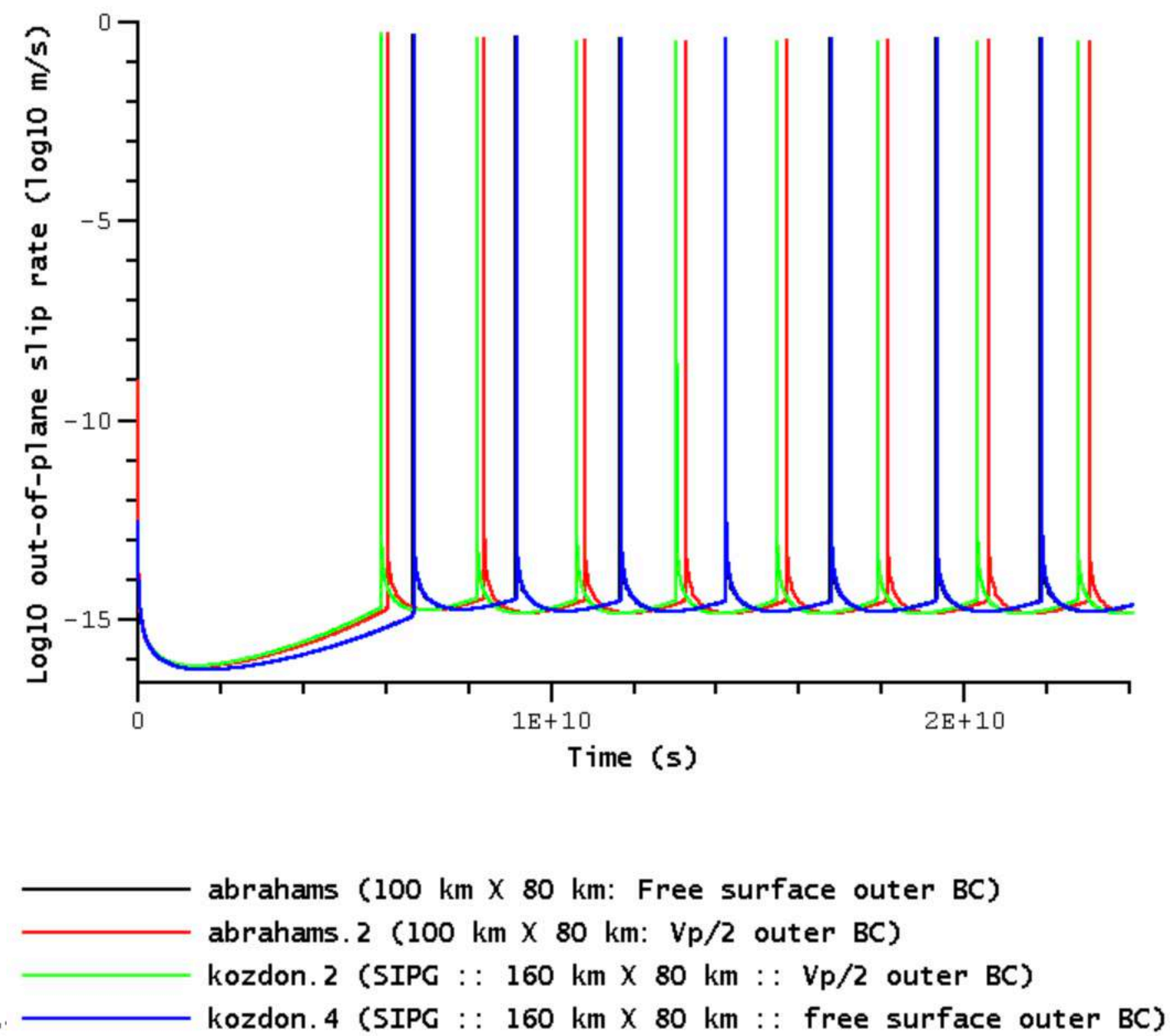


Most models have cell sizes of ~25 m and Lz = 40-80 km

The effect of boundary conditions

Discrepancy due to free surface/displacement outer B.C. in smaller models

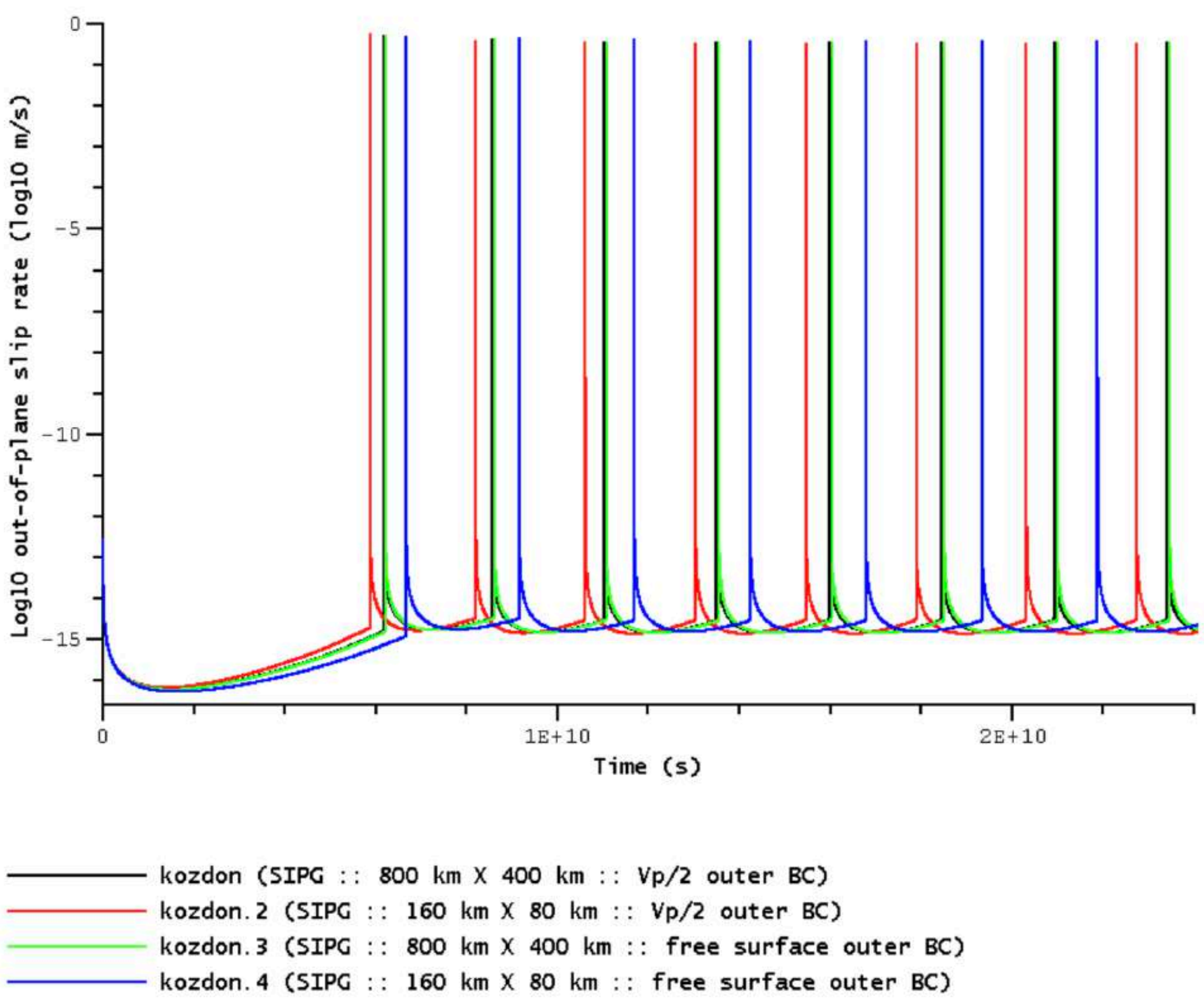


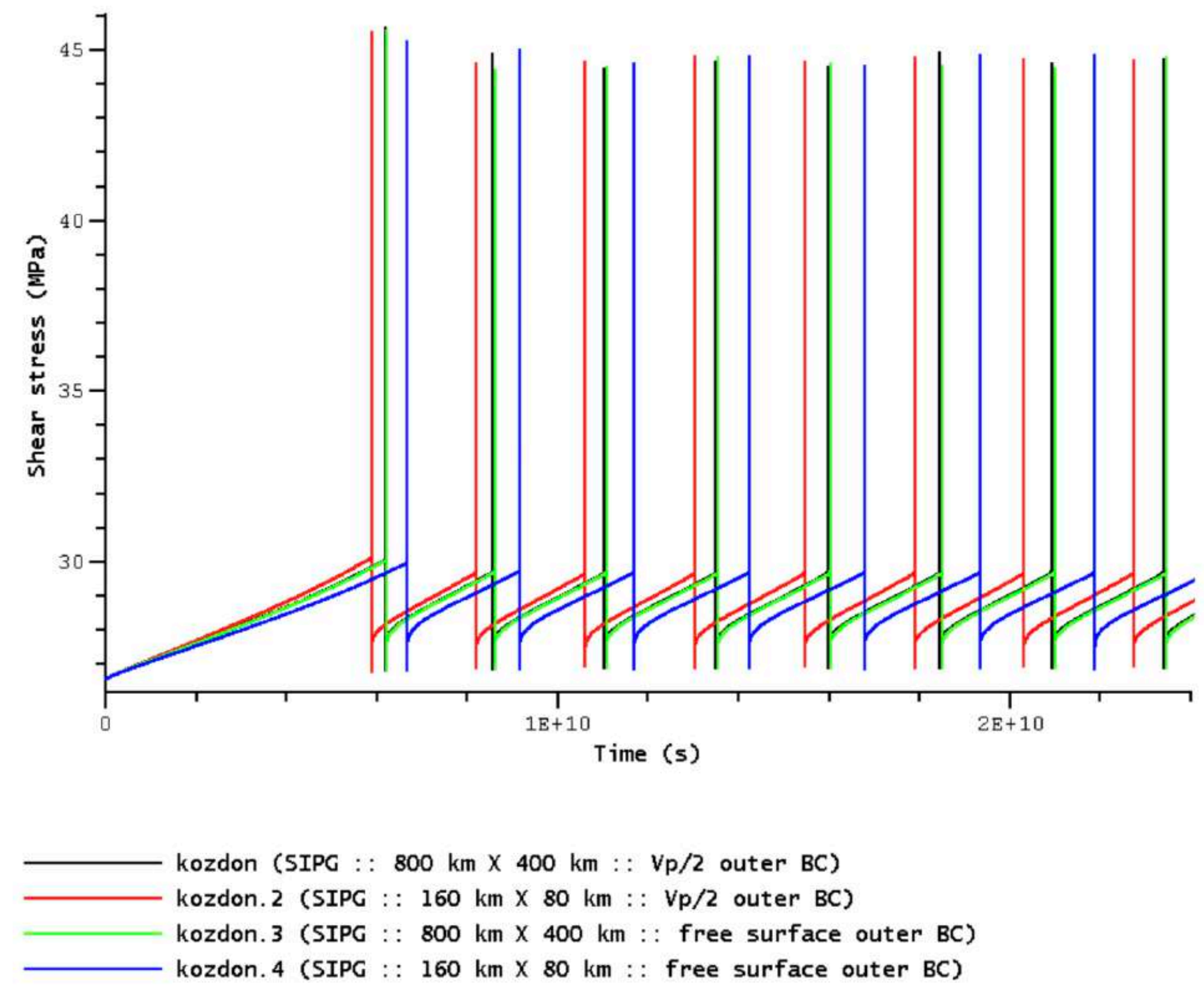


node at mid-seismogenic depth (z=7.5 km)

The effect of boundary conditions

Discrepancy due to outer B.C. is reduced in larger models

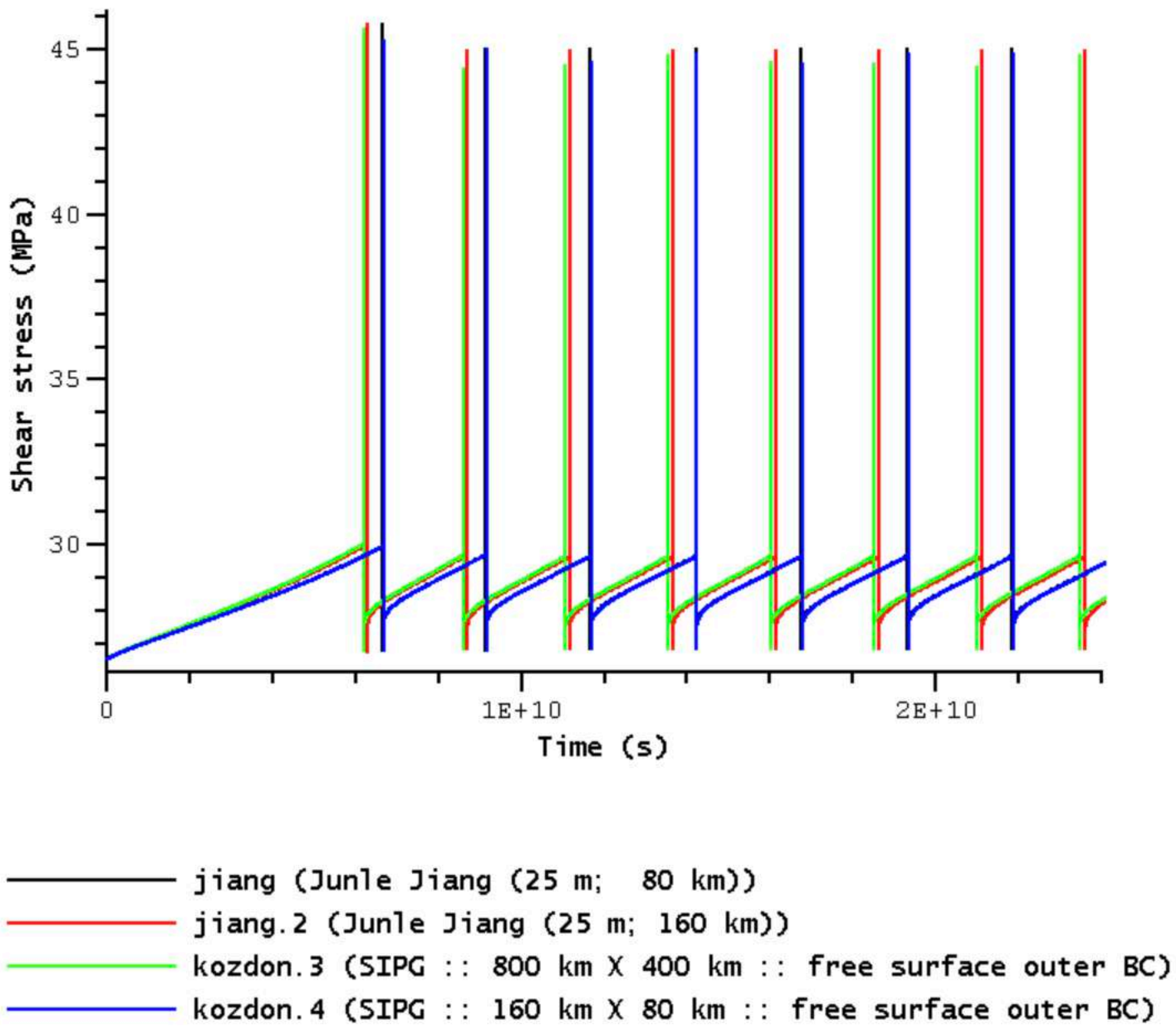




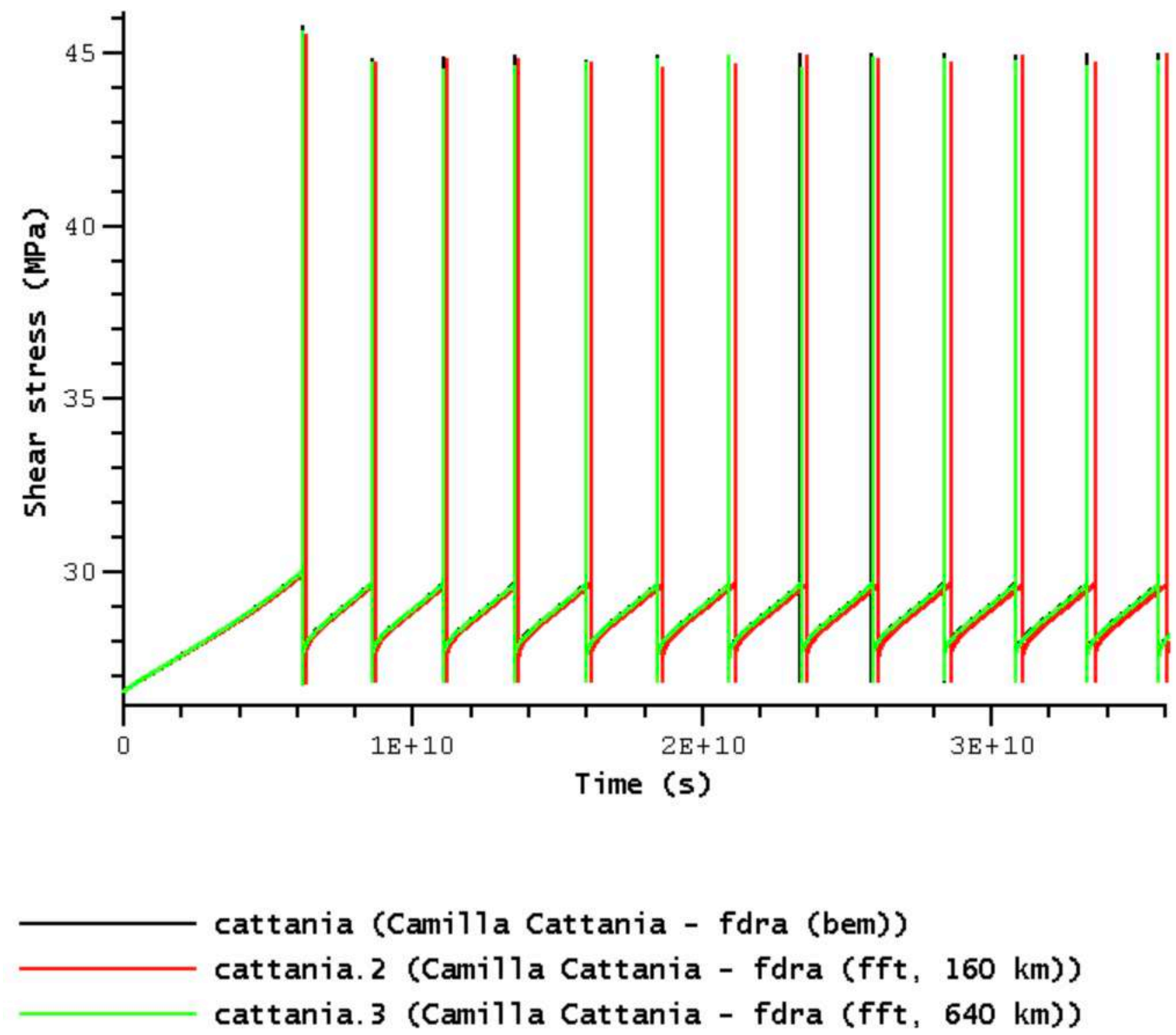
node at mid-seismogenic depth (z=7.5 km)

The effect of computational domain sizes

Discrepancy between 80/160 km models



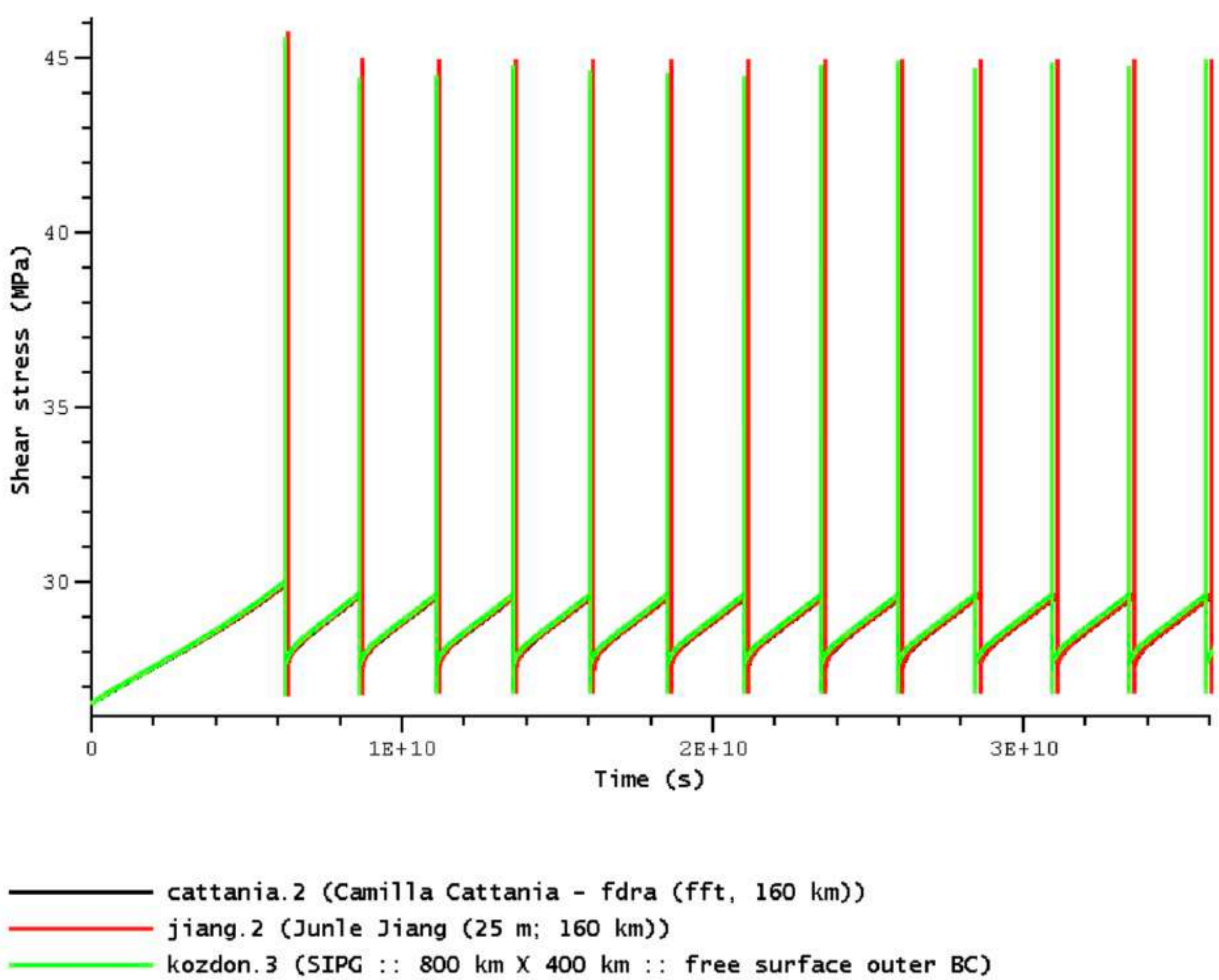
Good match of 160/640 km/HS models



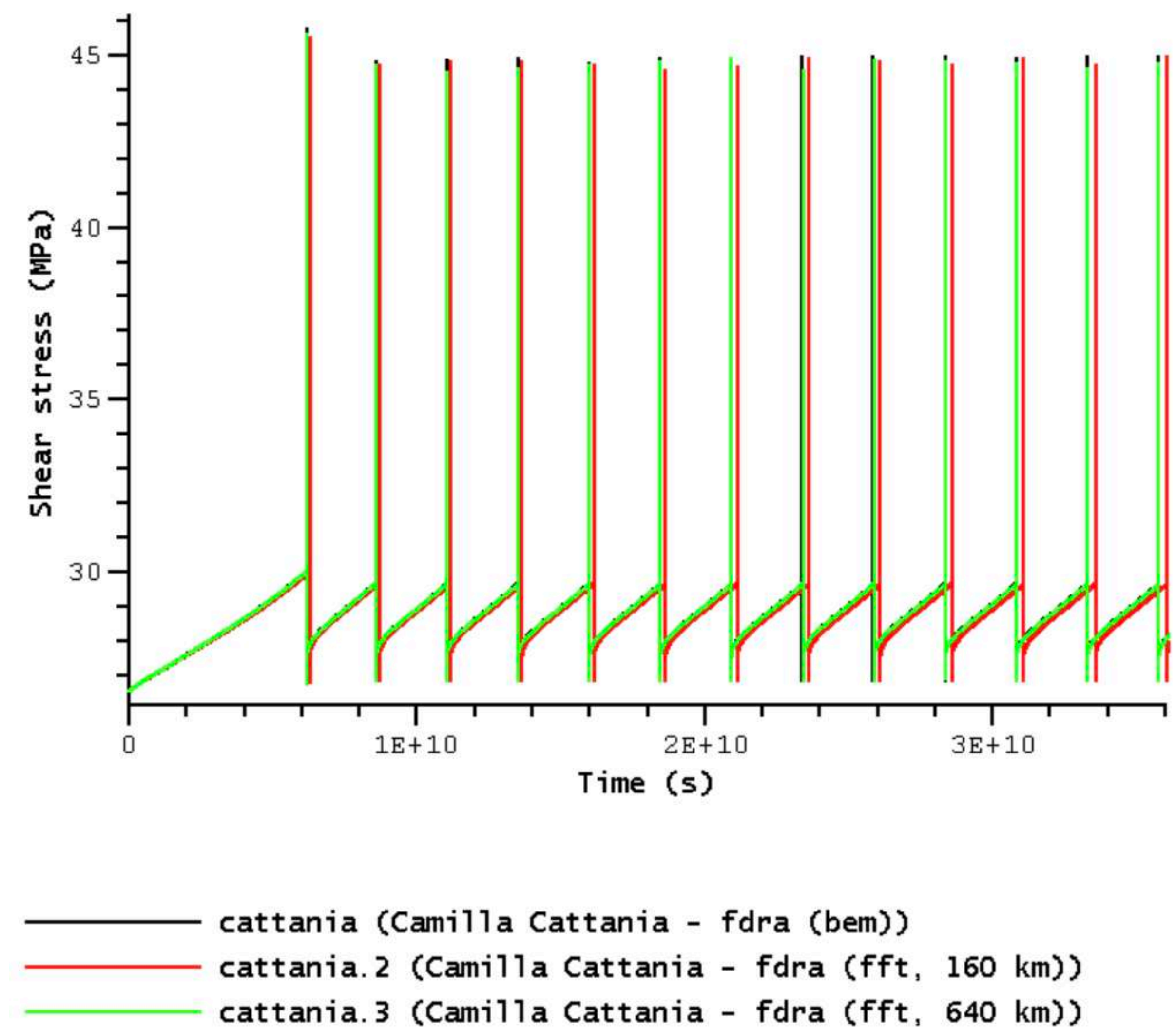
node at mid-seismogenic depth (z=7.5 km)

The effect of computational domain sizes

Excellent matches of similarly large models



Good match of 160/640 km/HS models



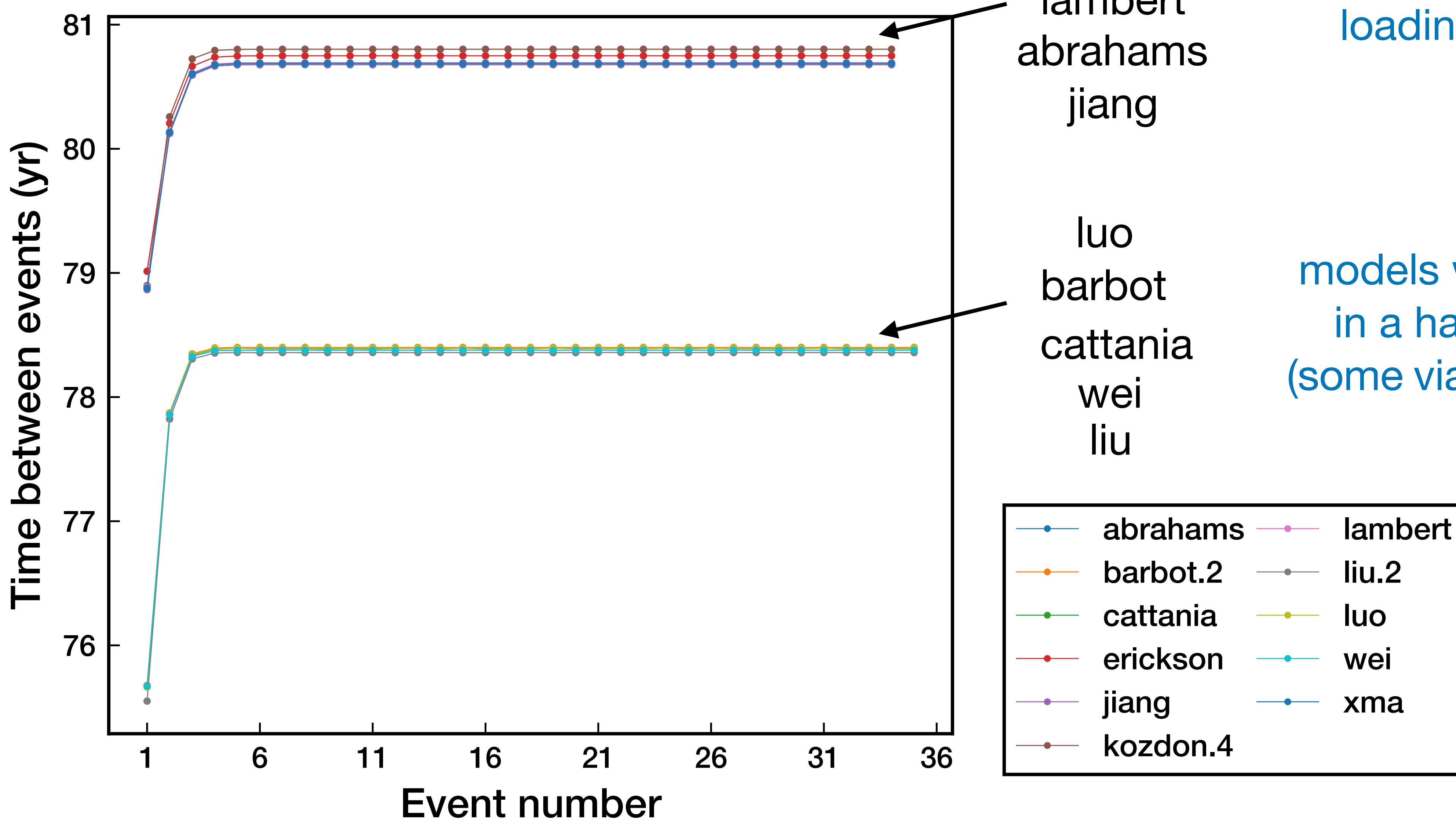
node at mid-seismogenic depth (z=7.5 km)

Time evolution of inter-event period

based on processing of submitted data

seismic phases: V>=0.001 m/s

Models quickly reach an equilibrium
(short spin-up period)



kozdon
erickson
lambert
abrahams
jiang

models w/ a finite loading region

luo
barbot
cattania
wei
liu

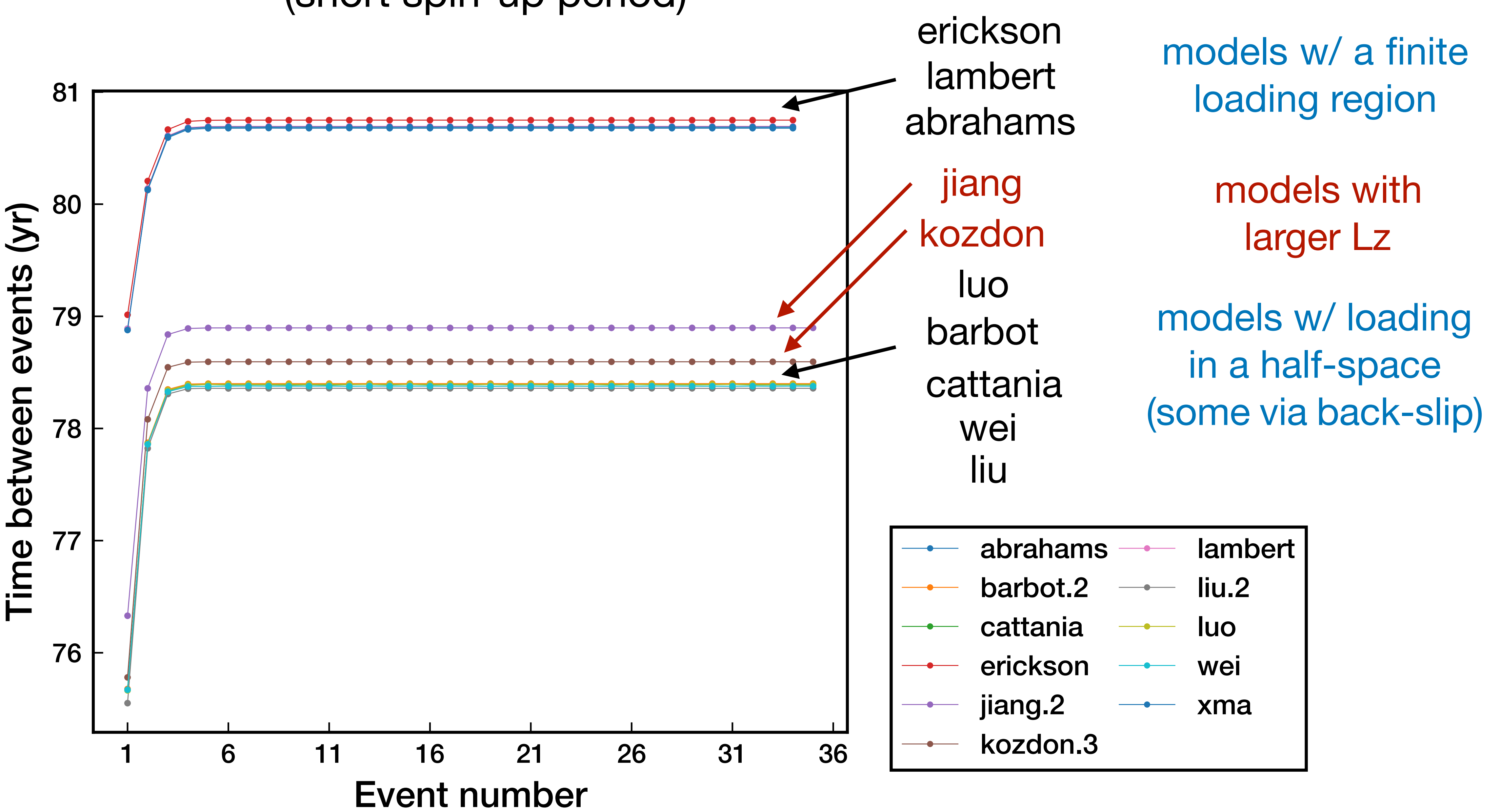
models w/ loading in a half-space (some via back-slip)

Time evolution of inter-event period

based on processing of submitted data

seismic phases: V>=0.001 m/s

Models quickly reach an equilibrium
(short spin-up period)

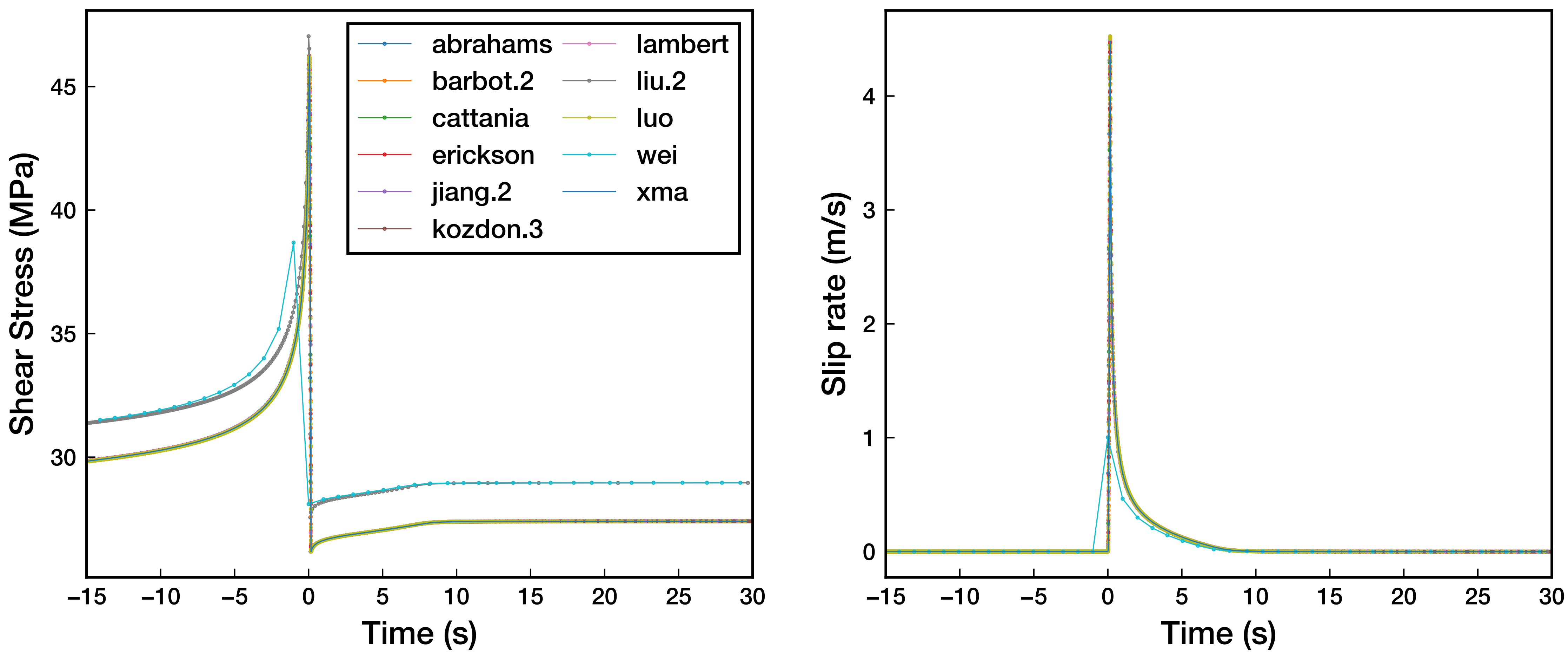


Coseismic period: 1st event in the sequence

z=0 km

Excellent matches between slip rates at the surface

Discrepancy in shear stresses between two models and others



NOTE: waveforms are aligned at the onset of the seismic phase (V>=0.001 m/s)

Coseismic period: 1st event in the sequence

z=0 km

Excellent matches between slip rates at the surface

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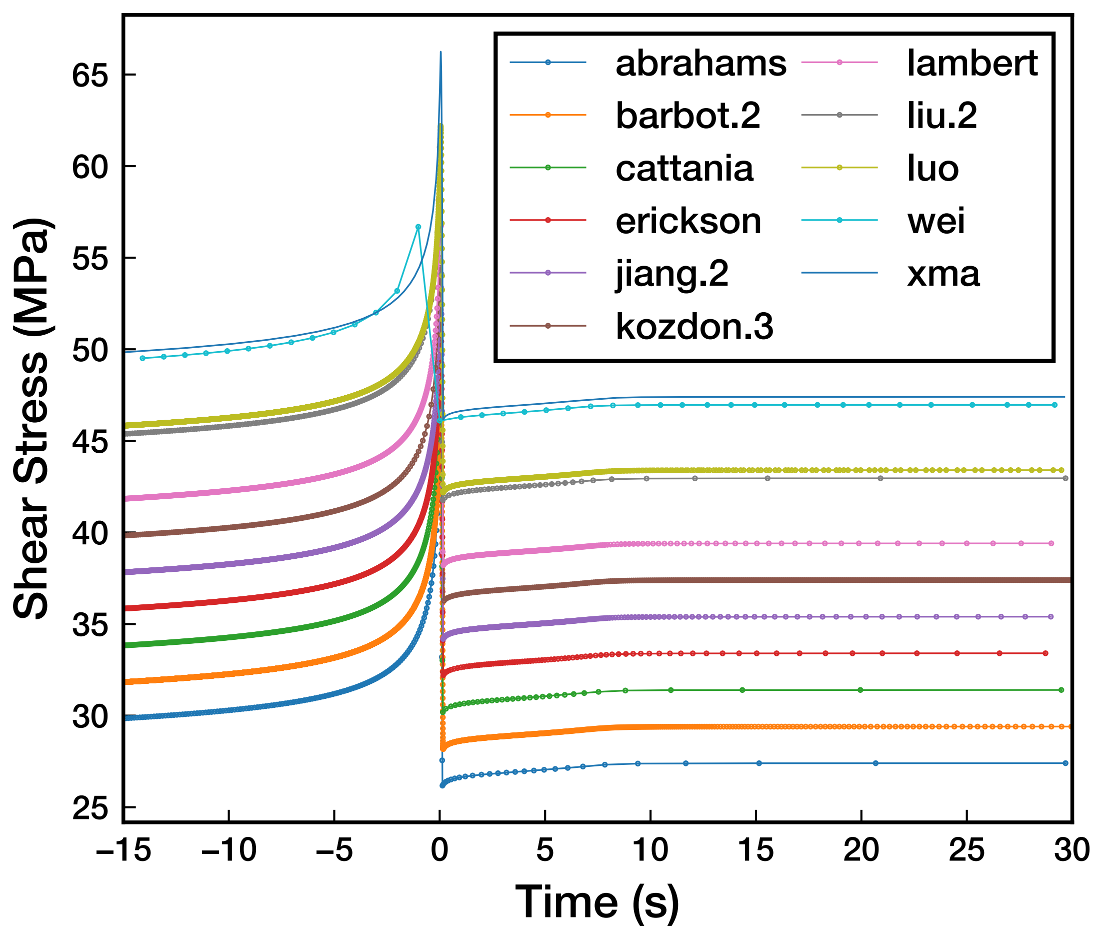
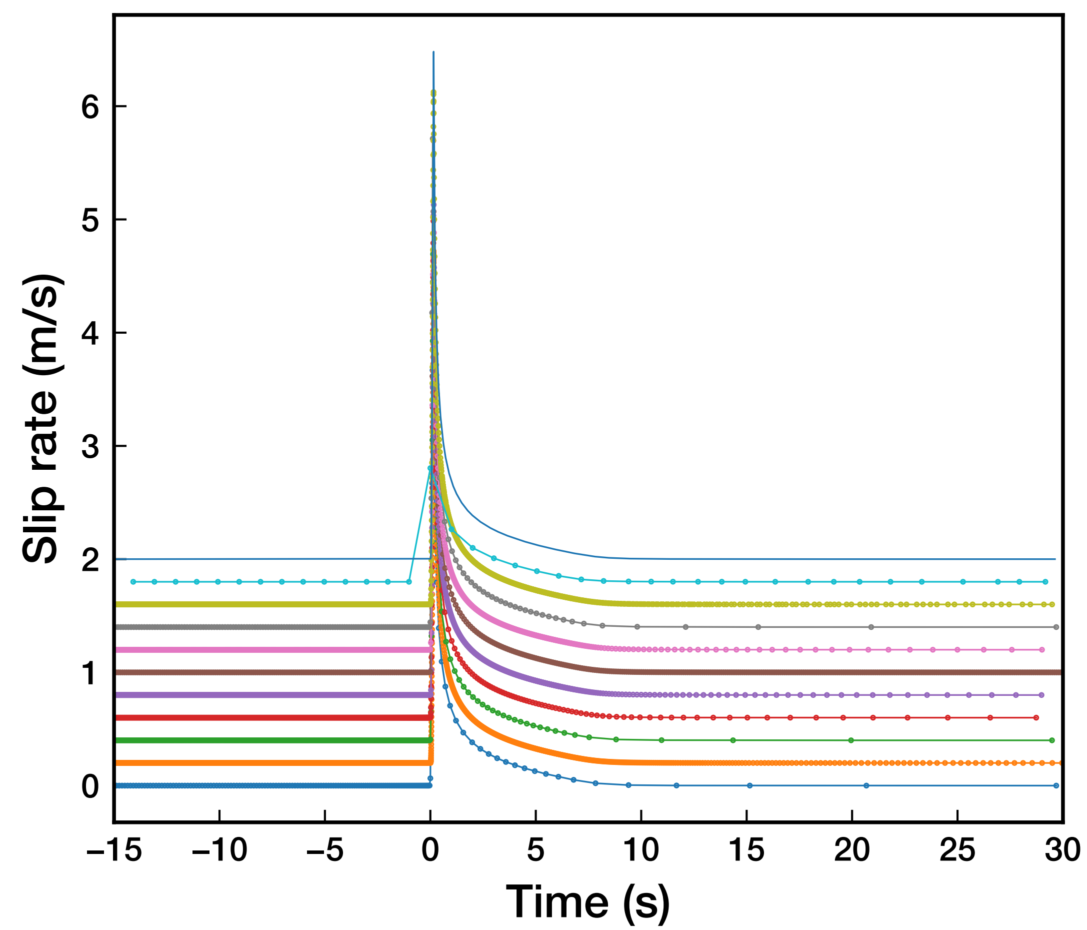


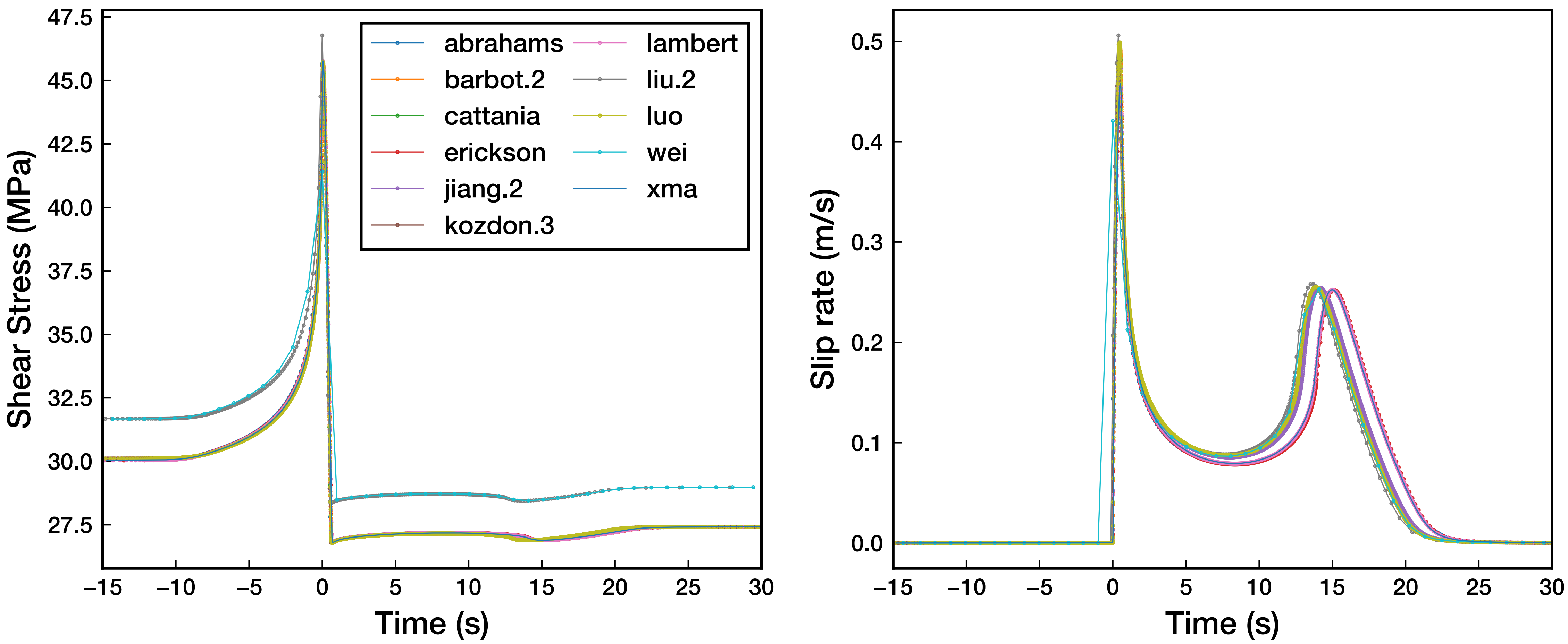


vertically offset

Coseismic period: 1st event in the sequence

z=7.5 km

Discrepancy in slip rates for surface-reflected rupture

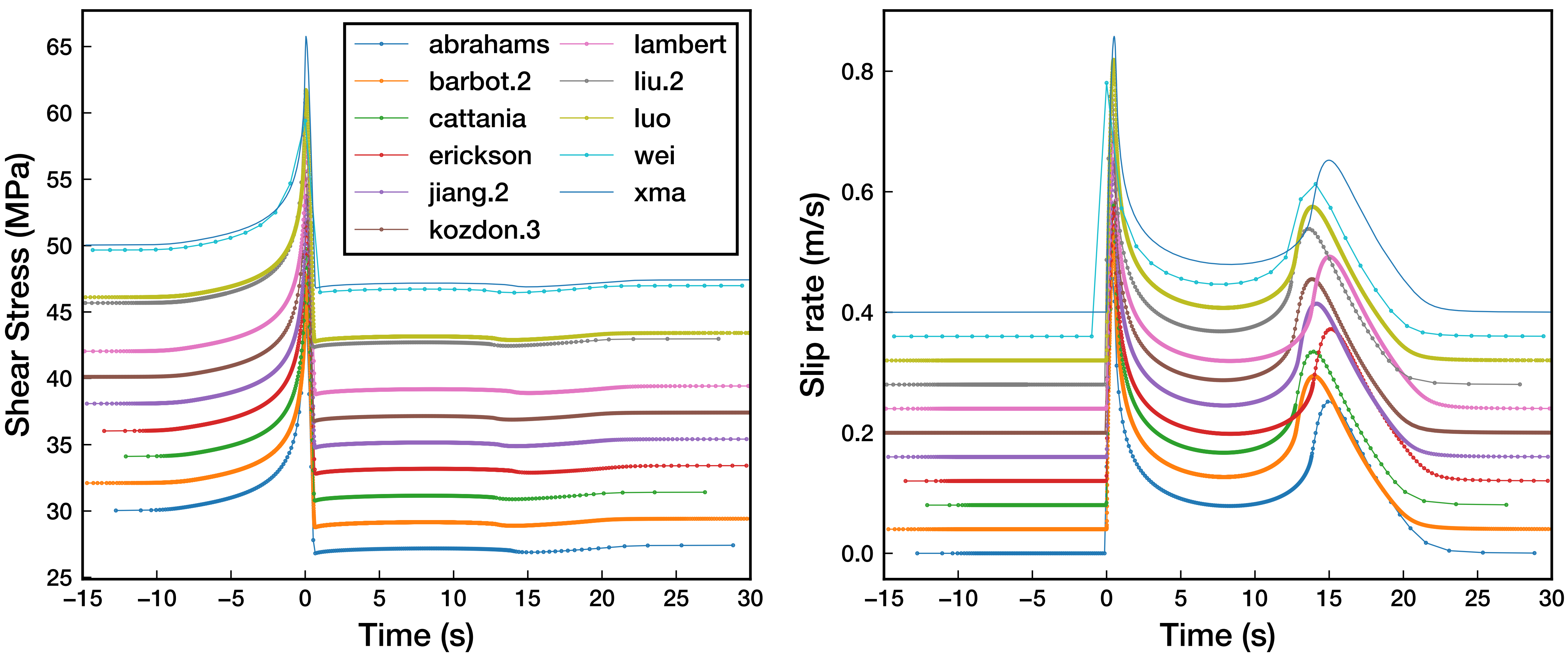


NOTE: waveforms are aligned at the onset of the seismic phase (V>=0.001 m/s)

Coseismic period: 1st event in the sequence

z=7.5 km

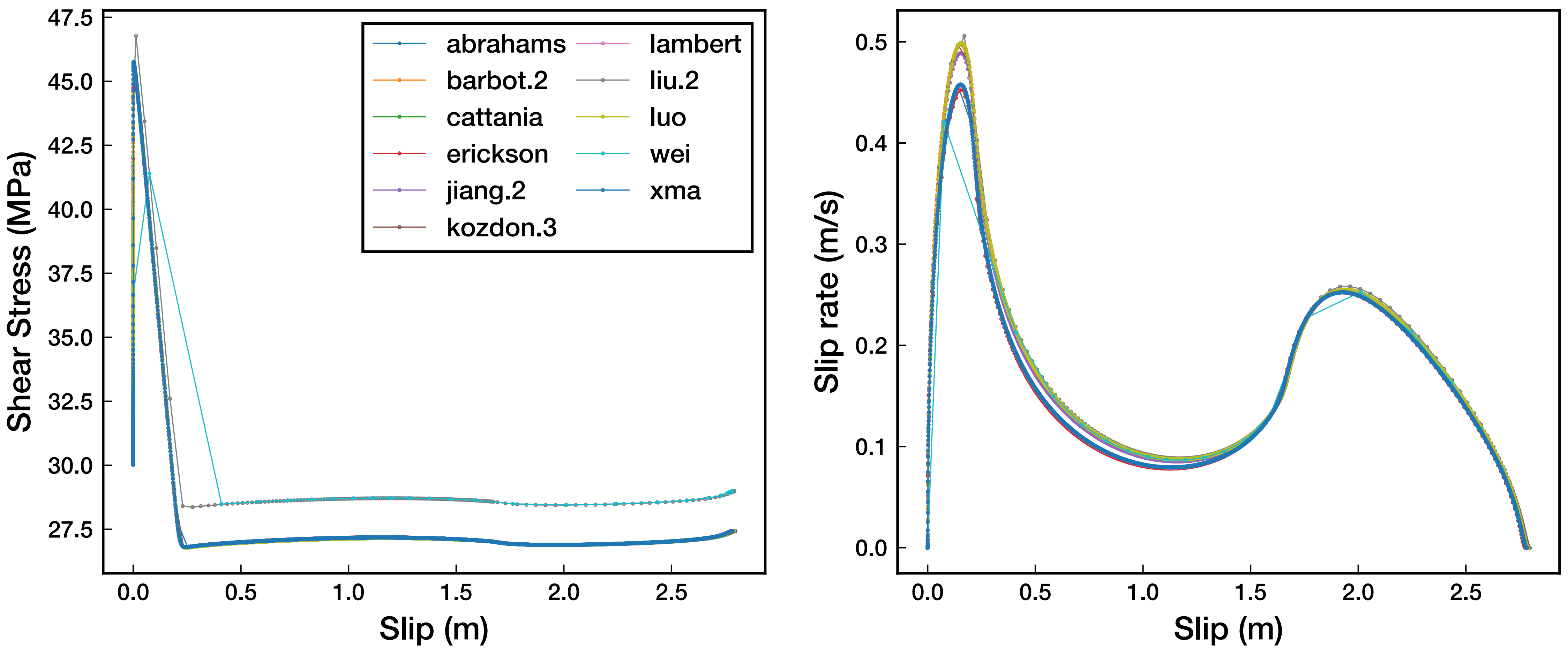
Discrepancy in slip rates for surface-reflected rupture



vertically offset

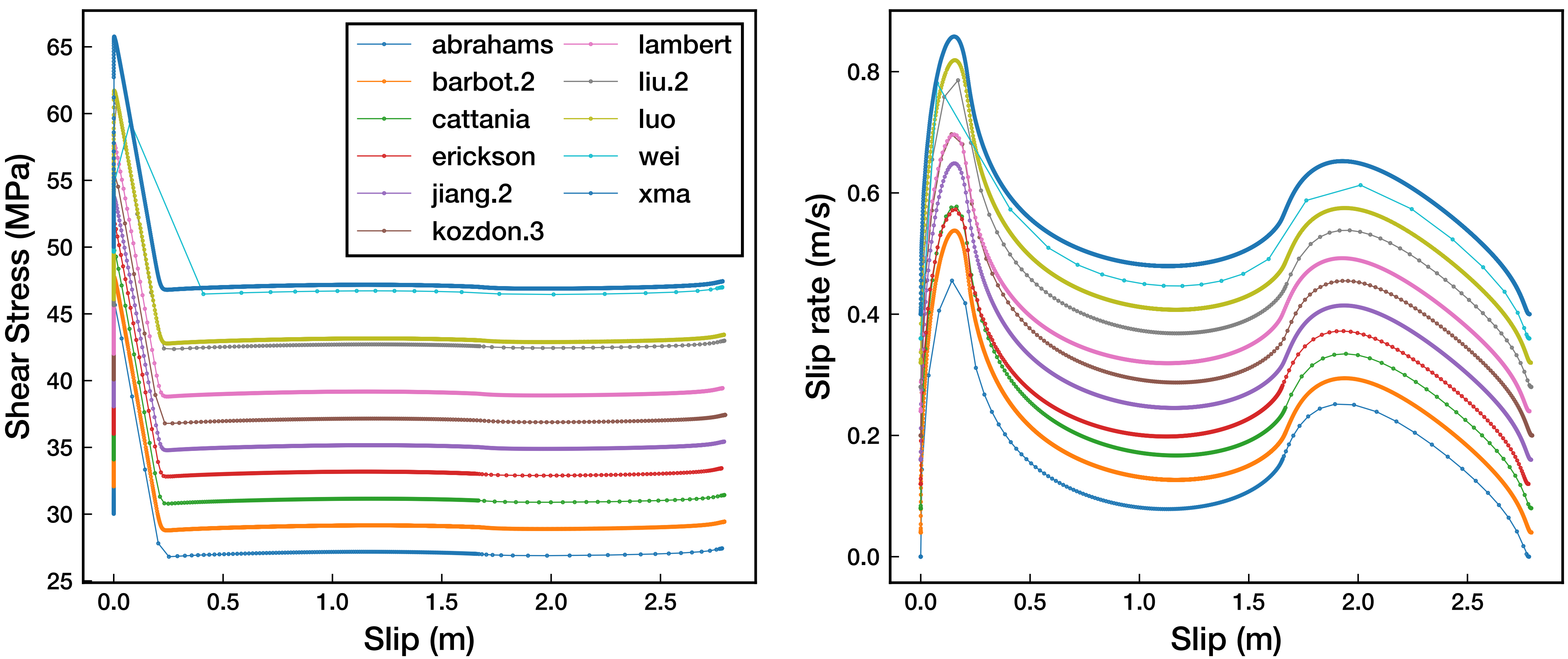
Coseismic period: 1st event in the sequence

z=7.5 km

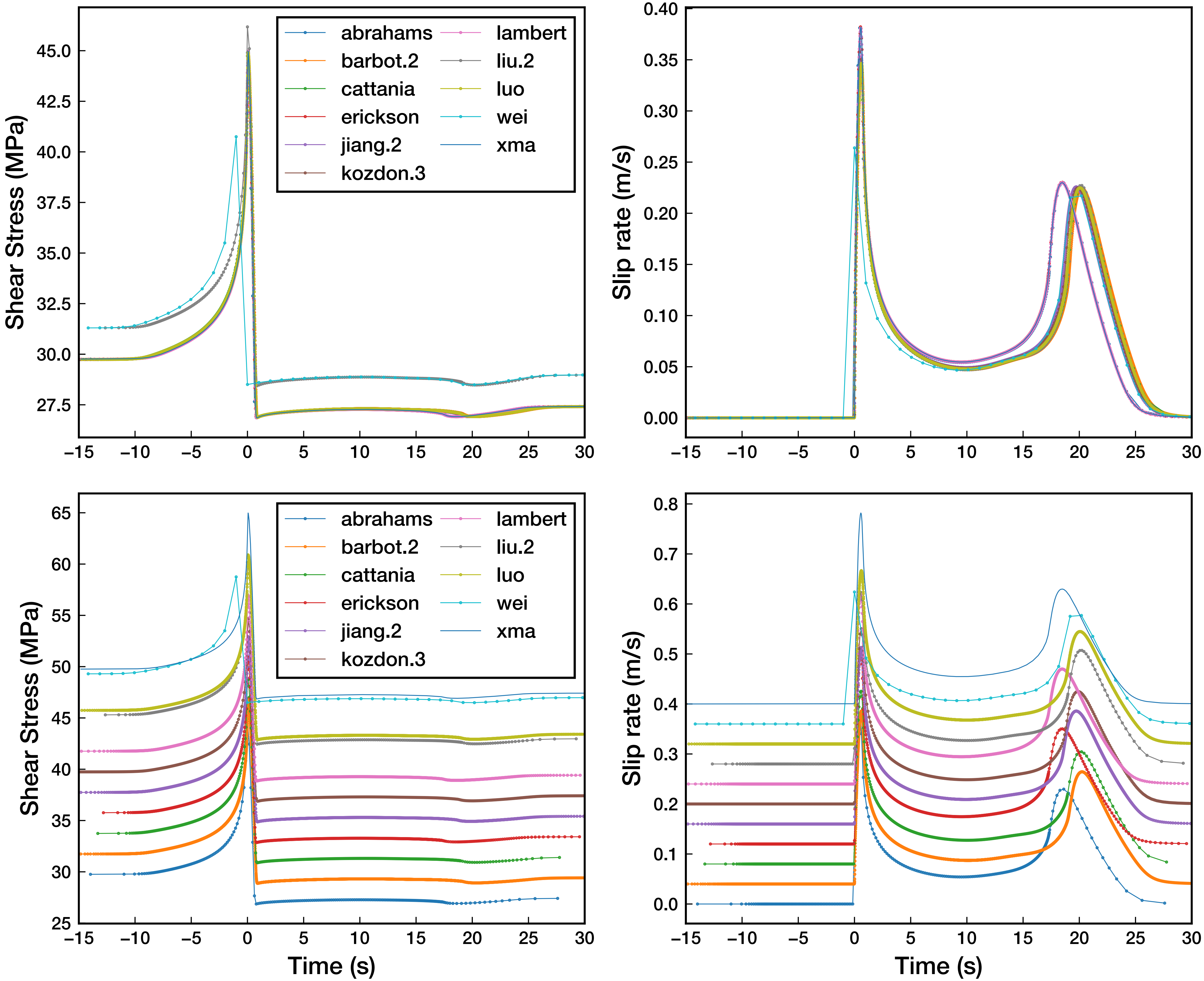


Coseismic period: 1st event in the sequence

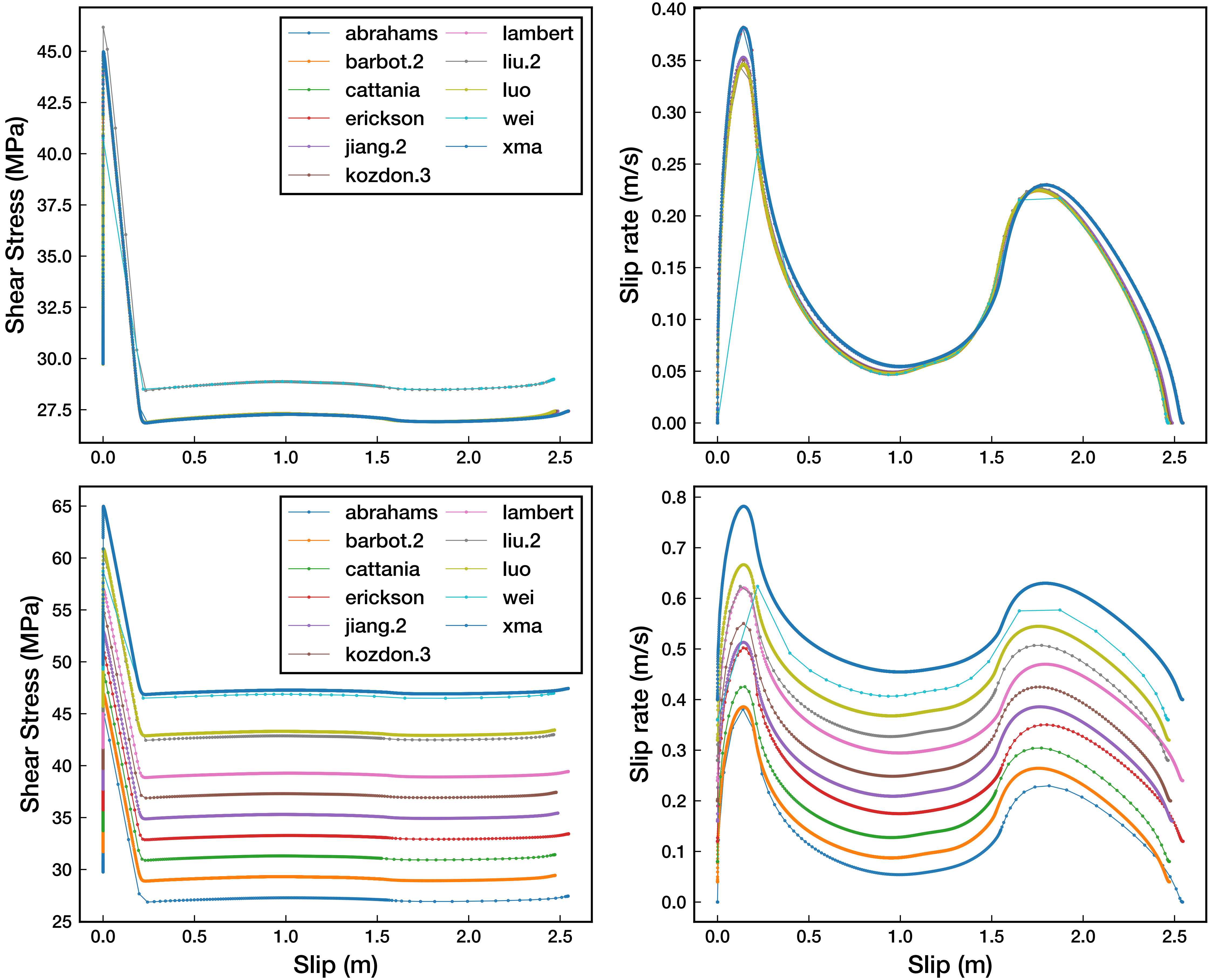
z=7.5 km



Coseismic period: 30th event in the sequence



Coseismic period: 30th event in the sequence



Take-aways from Time Series Comparisons

- Long-term evolution of the slip rate/stress/state/slip on the fault
  - Direct comparisons provided by CVWS
  - Excellent matches between models with similar setup, regardless of methods
  - Discrepancy attributable to differences in outer B.C. or domain sizes
  - Larger domain sizes (>160 km) are needed for all models to match
- Inter-event time quickly stabilizes with time (short spin-up period)
- Coseismic evolution of slip and stress
  - Currently processed manually
  - Excellent agreements in slip rates and stresses for most models at the surface
  - Larger discrepancies in the surface-reflected phase at mid-seismogenic depth, likely due to domain-size-dependent pre-event stress and hence rupture speed

Additional issues:

- Spin-up of models: seems to be qualitatively similar for large enough domains.

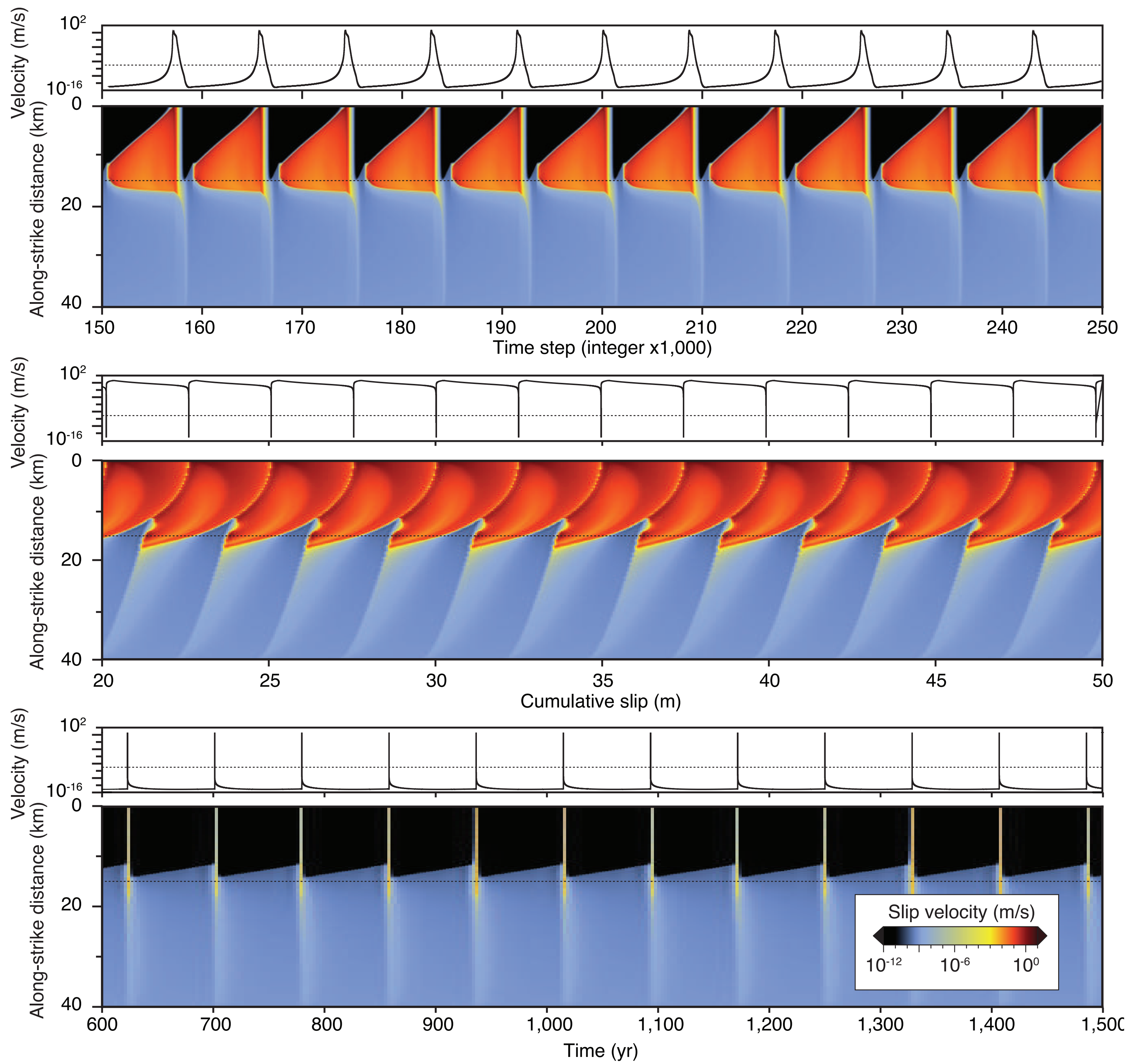
- Efficiency of code? e.g. variable grid spacing, linear solvers?

- Model divergence?

- How should we compare results (verification metrics)?
  - do we only accept results that show independence of domain size?
  - model characteristics, e.g. recurrence periods
  - normed errors in time series/slip profiles

- What constitutes a successful verification exercise? (how much discrepancy/matching do we expect/allow?)
  - define a tolerance on error between model results?
  - convergence as a function of resolution?

Ideas for comparison and visualization



courtesy of S. Barbot

Future SEAS plans

- Future benchmark designs: problems and logistics.
  - smaller h* (have people seen model failure at long times?) and more studies of dependencies on artificial boundary conditions.
  - more 2D problems: different evolution laws, plane strain, viscoelasticity
  - 3D problem

- Development of online platform:
  - plot slip contours
  - compute errors

- Timelines for proposals/workshop/presentation
  - SCEC poster at 2018 annual meeting
  - 2nd benchmark description out for comment in late September, to be submitted in November. Is this a TAG proposal?
  - Next workshop?

- Possible validation exercises

- Relation with different working groups (SDR group, Earthquake Simulators, CRM)