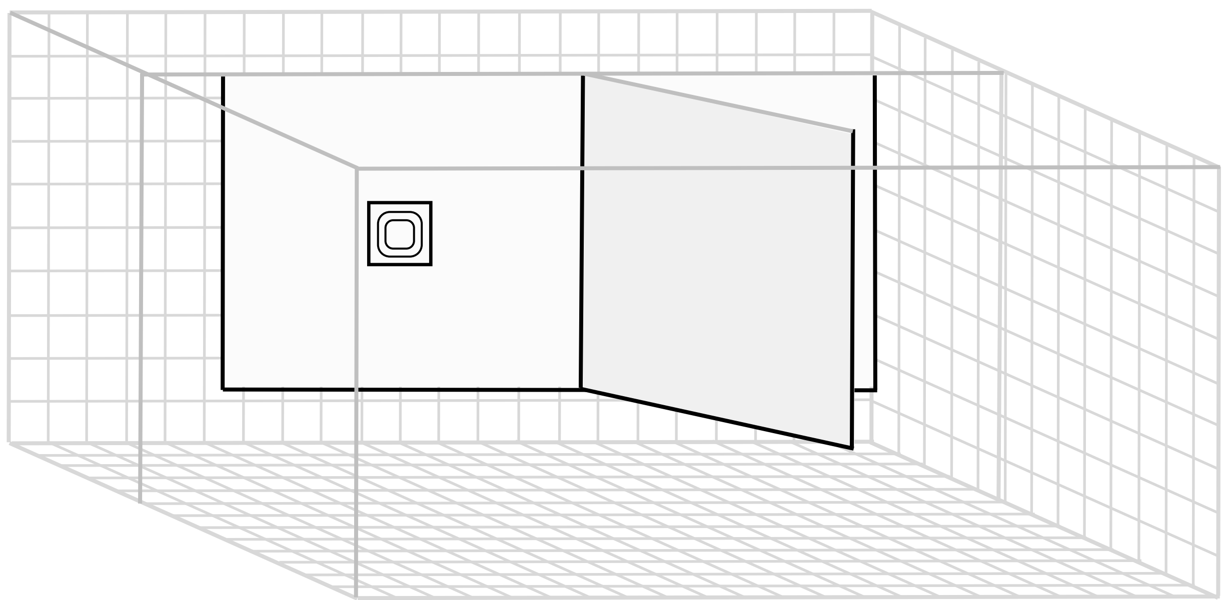
TPV14 & TPV15 — Branched Fault Benchmarks



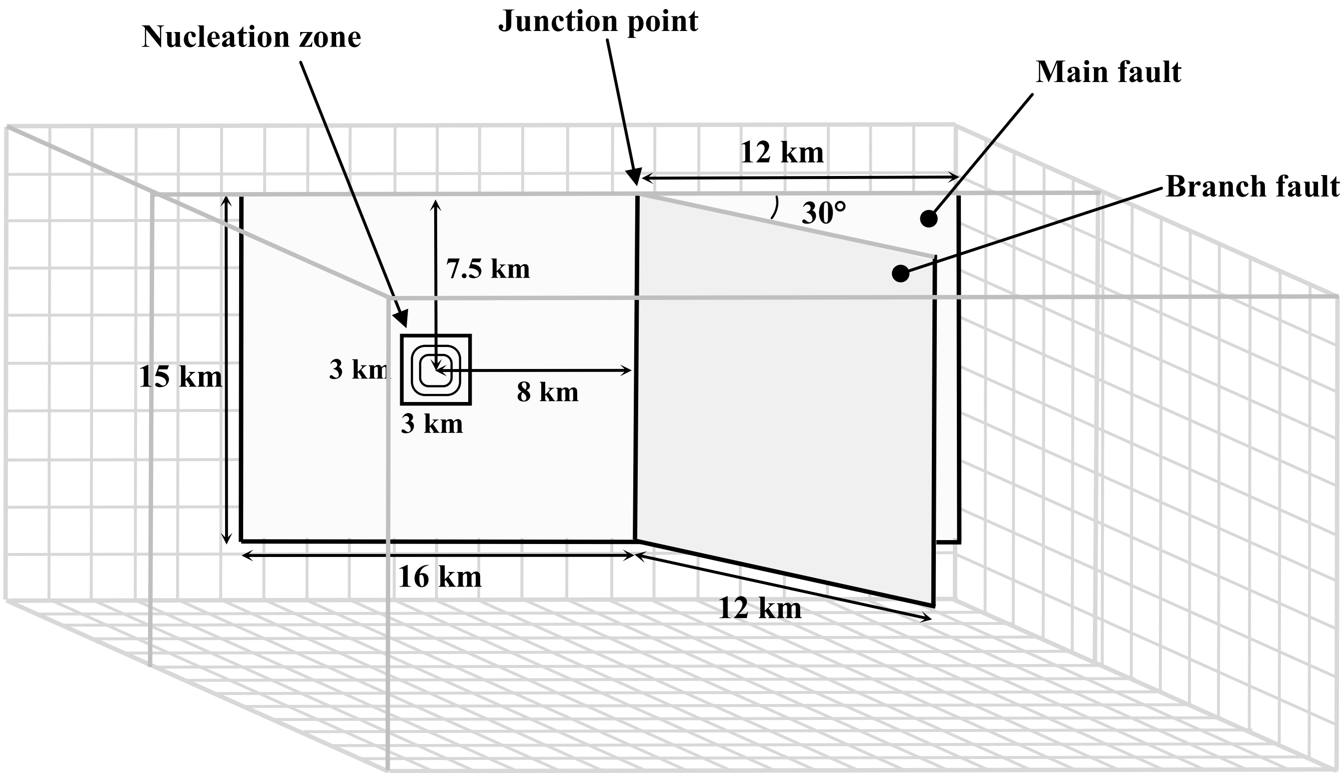
Michael Barall
USGS and Invisible Software, Inc.

SCEC Code Validation Workshop, February 25, 2011

Part 1:

Benchmark Description

TPV14 & TPV15 — Fault Geometry



These are our first benchmarks that do not use a planar fault.

This is a vertical strike-slip main fault, with a vertical strike-slip branch fault at an angle of 30 degrees.

TPV14 & TPV15 — Main Fault

The main fault has the same conditions as TPV5.

Initial Stress	Normal stress = 120 MPa TPV14 shear stress = 70 MPa (right-lateral) TPV15 shear stress = -70 MPa (left-lateral)
Friction Parameters Linear Slip-Weakening	$\mu_s = 0.677$ $\mu_d = 0.525$ $d_0 = 0.40$ m
Rock Properties	$\rho = 2670$ kg/m^3 $V_S = 3464$ m/s $V_P = 6000$ m/s
Nucleation Zone	Size = 3 km × 3 km TPV14 shear stress = 81.6 MPa (right-lateral) TPV15 shear stress = -81.6 MPa (left-lateral)

TPV14 & TPV15 — Branch Fault

The branch fault also has the same conditions as TPV5, except for initial shear stress.

Initial Stress	Normal stress = 120 MPa TPV14 shear stress = 70 MPa (right-lateral) TPV15 shear stress = -78 MPa (left-lateral)
Friction Parameters Linear Slip-Weakening	μ_s = 0.677 μ_d = 0.525 d_0 = 0.40 m

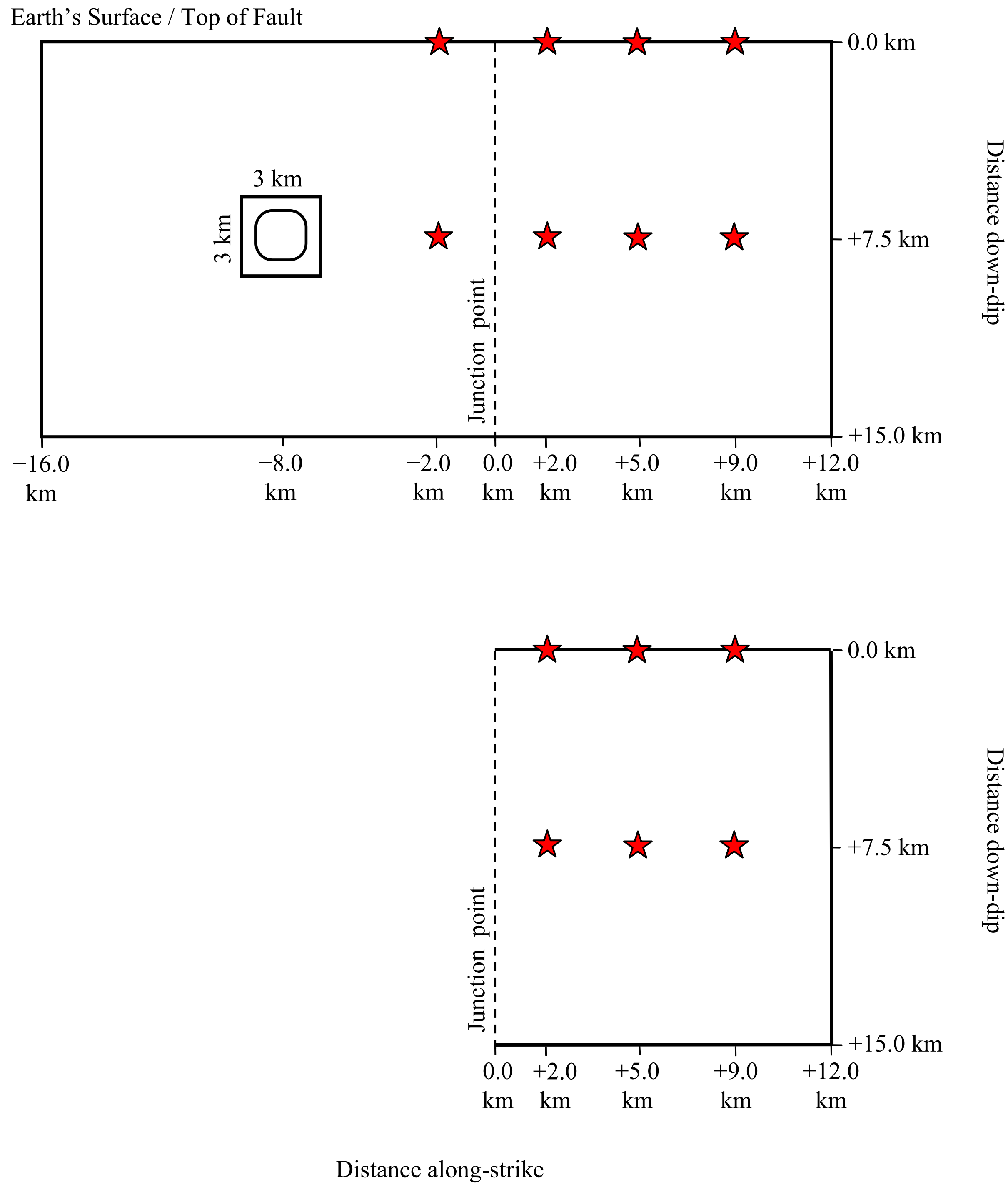
The cases we consider differ *only* in:

- Initial shear stress on the branch fault.
- Right-lateral versus left-lateral (equivalent to switching the branch between the right and left sides of the main fault).

On-Fault Stations

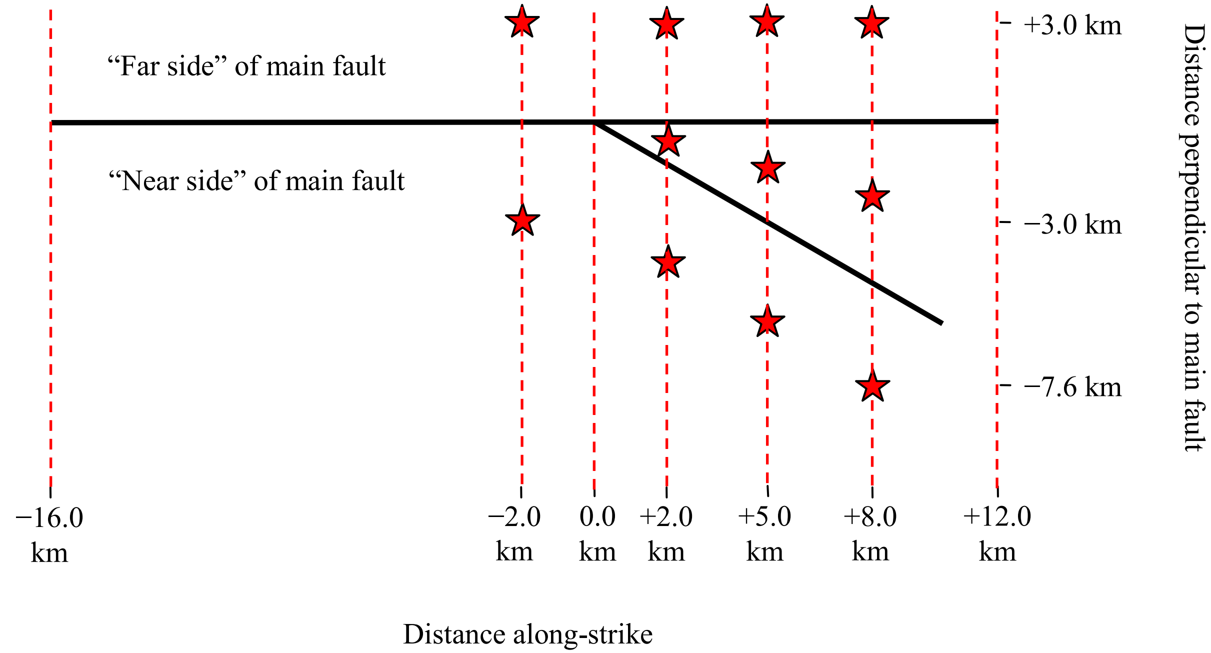
Modelers are asked to submit slip, slip rate, and stress as a function of time, for 8 stations on the main fault (top) and 6 stations on the branch fault (bottom).

In addition, modelers are asked to submit the time at which each point on the fault begins to slip, from which we construct rupture contour plots.

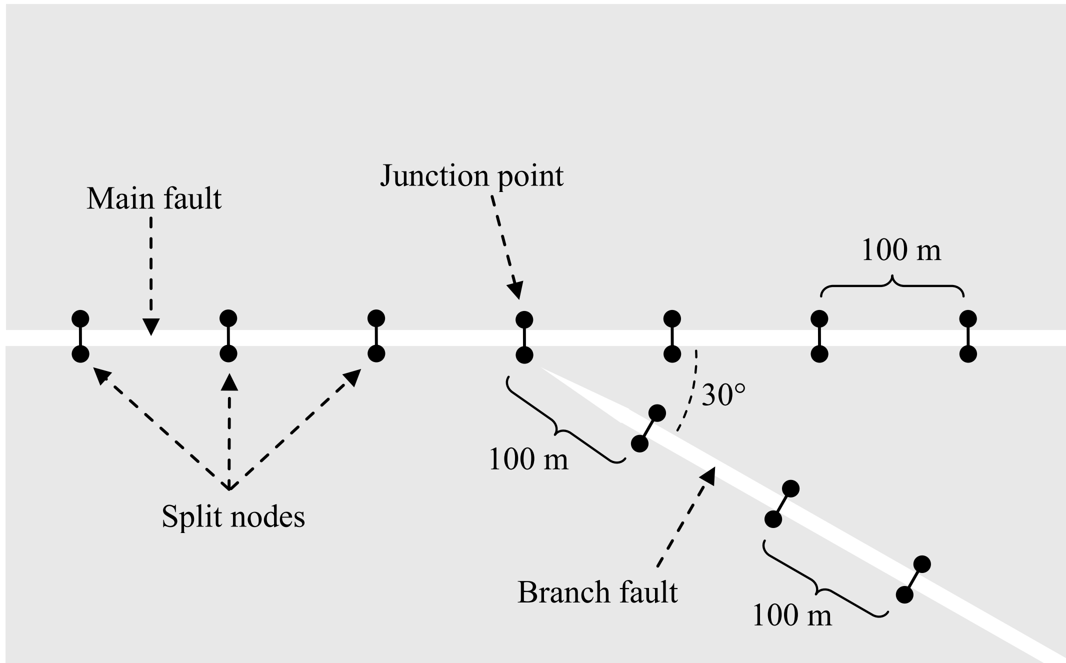


Off-Fault Stations

Modelers are asked to submit displacement and velocity as a function of time, for 11 stations on the earth's surface.



Junction Point Behavior

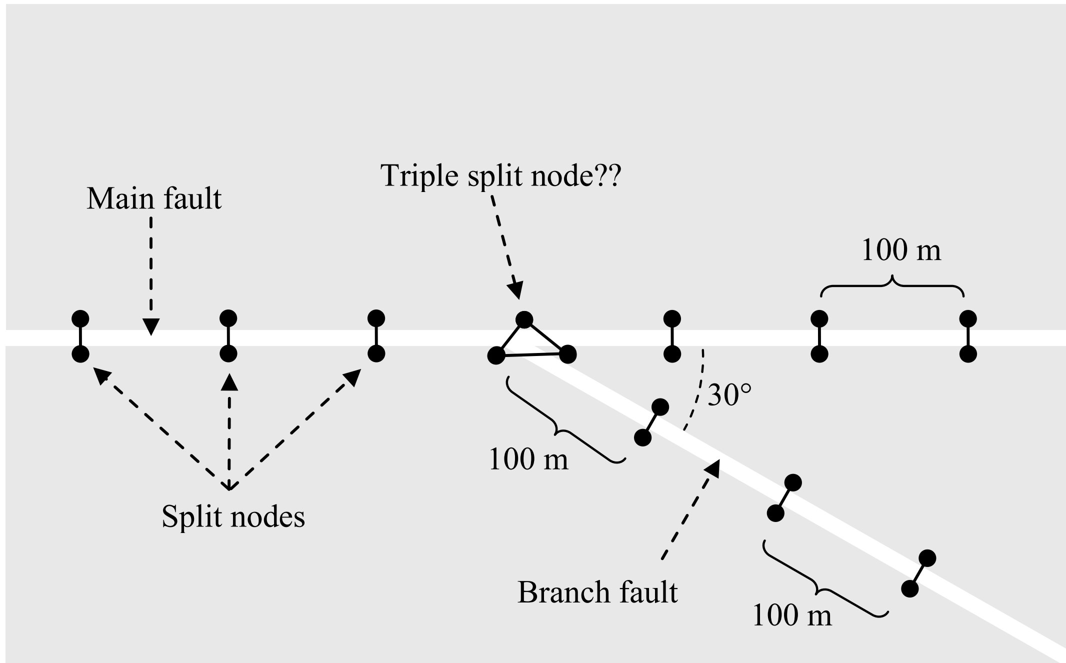


The main fault passes continuously through the junction point.

The branch fault approaches the junction point, to within one element-size, but does not reach the junction point. (Boundary condition is that slip on the branch fault is zero at the junction point.)

The junction point behaves as an ordinary split-node on the main fault.

Could we let the branch fault reach the junction point?

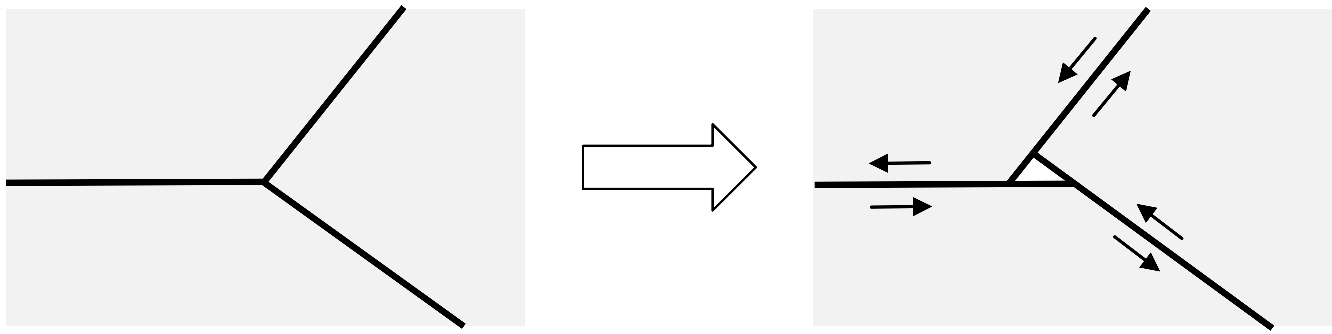


Challenges of defining a friction law for a triple split node:

- What strike-slip motions are permitted?
- Five possible states of dip-slip motion.
- Inability to calculate shear and normal stresses from nodal forces.

Because of these challenges, we did not use a triple split node in TPV14 & TPV15.

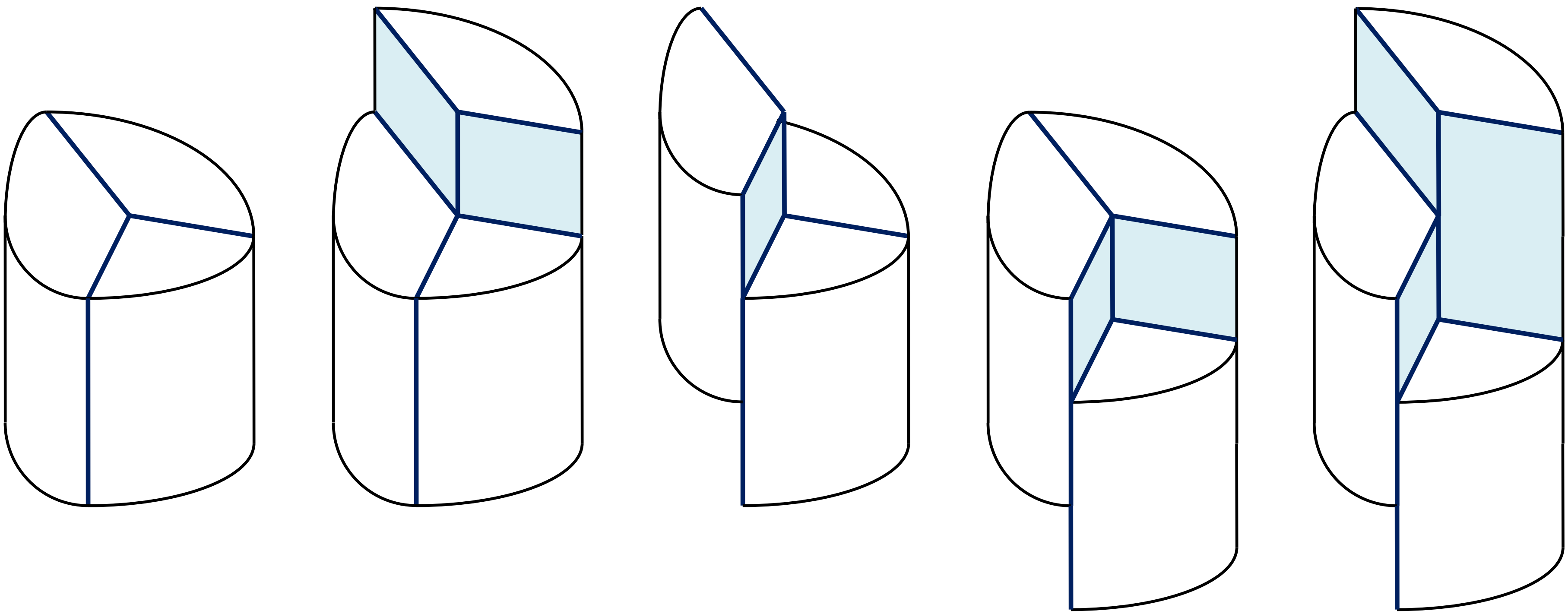
Strike-Slip Motion at a Branch



Joe Andrews proposed that at a branch, slip on all three legs is possible and would open a triangular void. But this requires the three legs to all point in different directions.

In our case, two legs are collinear, so the triangle disappears. We are left with no strike-slip motion on the branch fault at the junction point.

Five States of Dip-Slip Motion at a Branch

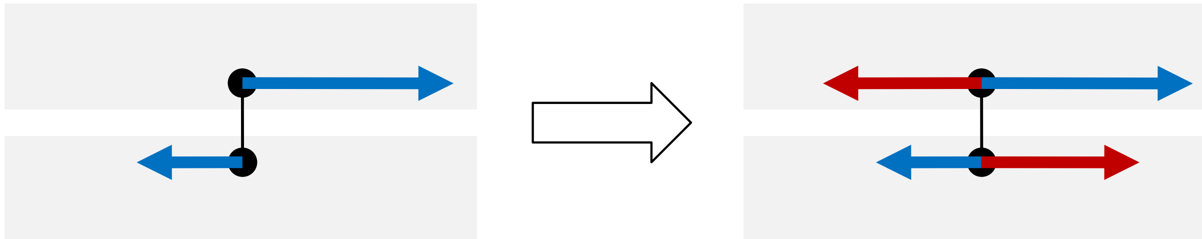


There is no geometric obstacle to dip-slip motion, but there are five possible states:

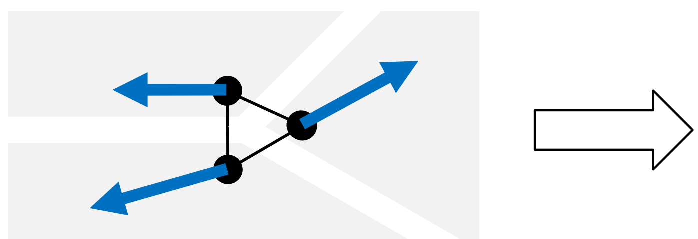
- No sliding, all three blocks are locked.
- One block sliding relative to the other two, which are locked.
- All three blocks sliding relative to each other.

Software would have to implement these states, and state-to-state transitions.

Traction-at-split-nodes does not work for a triple split node



Traction-at-split-nodes (Joe Andrews): Nodal forces (**blue**) are the forces exerted on each node by elastic deformation and acceleration. Given the nodal forces, the shear and normal stress on the fault can be computed by finding the relative force (**red**) that reduces the relative acceleration of the two nodes to zero. (Summing the red and blue vectors on each node produces the same total vector, hence the same acceleration assuming the two nodes have equal mass.)



For a triple split node, given the nodal forces it is not possible to compute shear and normal stress for each of the three legs of the fault. There is only enough information to compute two relative forces, not three.

Part 2:

Possible Outcomes of the Branched Fault

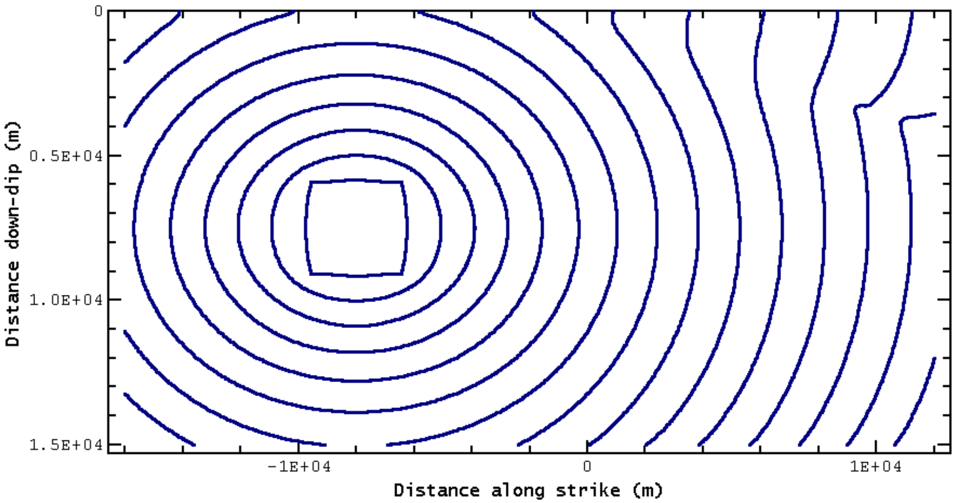
Six Cases to Examine

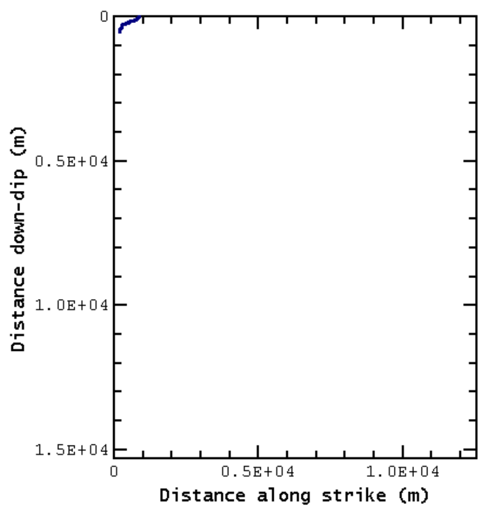
Left-Lateral Cases	Right-Lateral Cases
$\tau_{branch} = -70$ MPa	$\tau_{branch} = +70$ MPa [TPV14]
$\tau_{branch} = -74$ MPa	$\tau_{branch} = +74$ MPa
$\tau_{branch} = -78$ MPa [TPV15]	$\tau_{branch} = +78$ MPa

The cases differ *only* in initial shear stress on the branch fault, and left-lateral versus right-lateral.

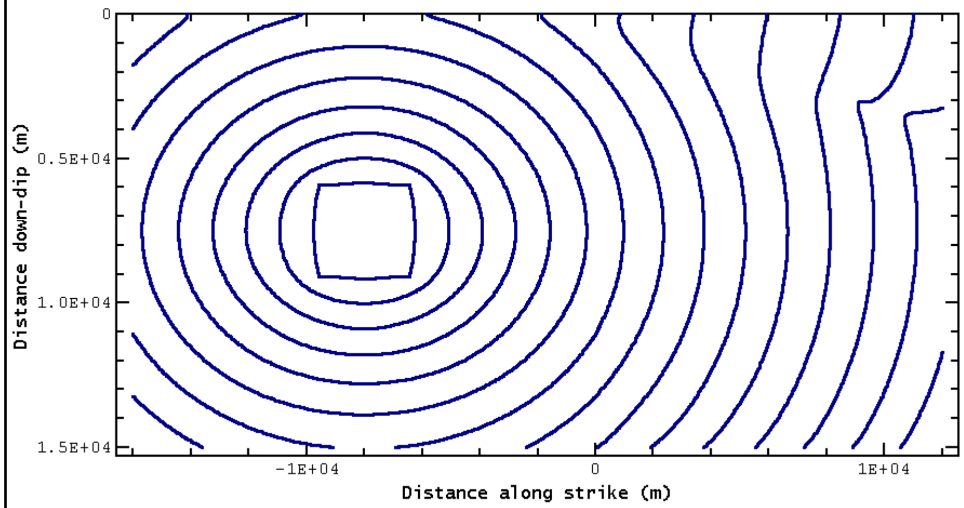
A relatively small change in initial conditions can produce a different outcome.

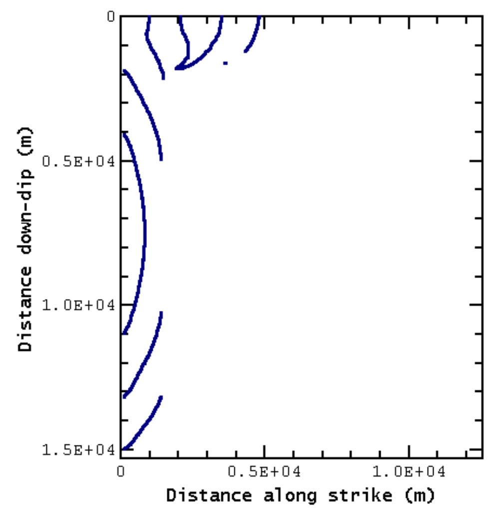
τ_{branch} = −70 MPa (left-lateral)



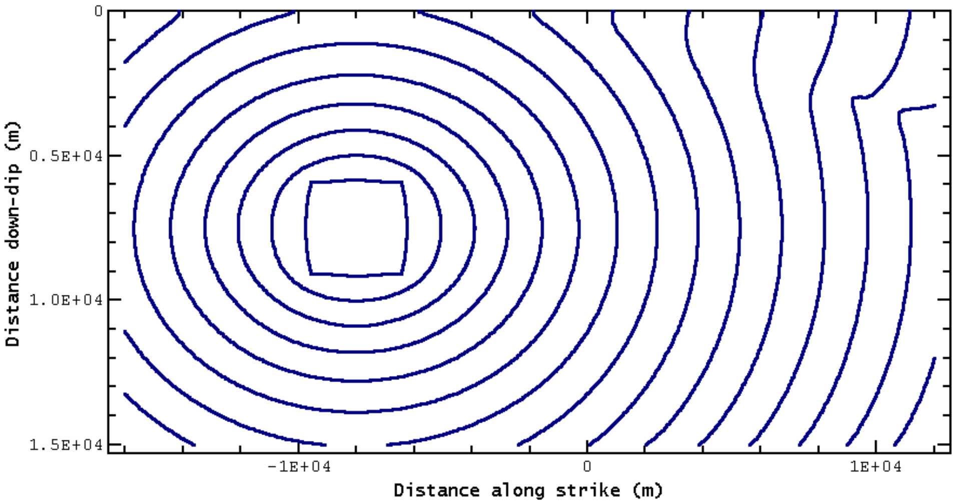


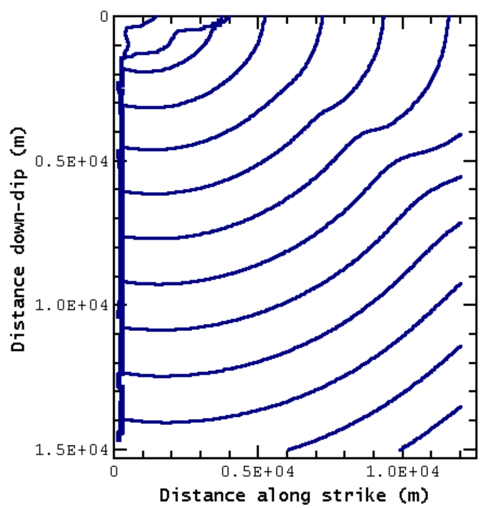
τ_{branch} = +70 MPa (right-lateral)
[TPV14]



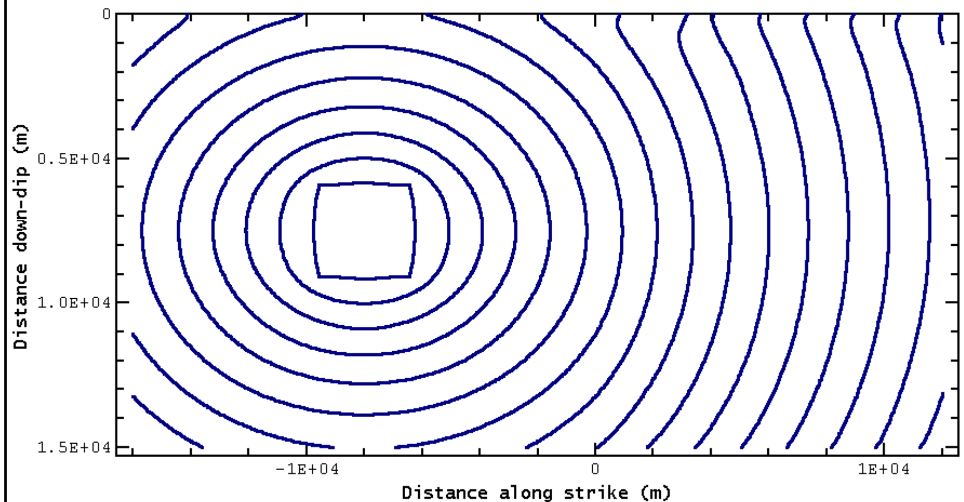


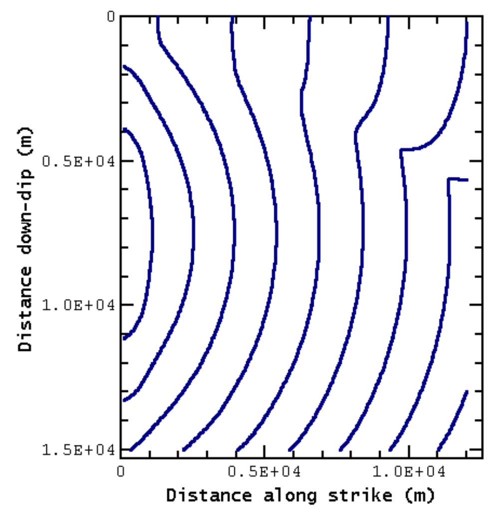
τ_{branch} = −74 MPa (left-lateral)



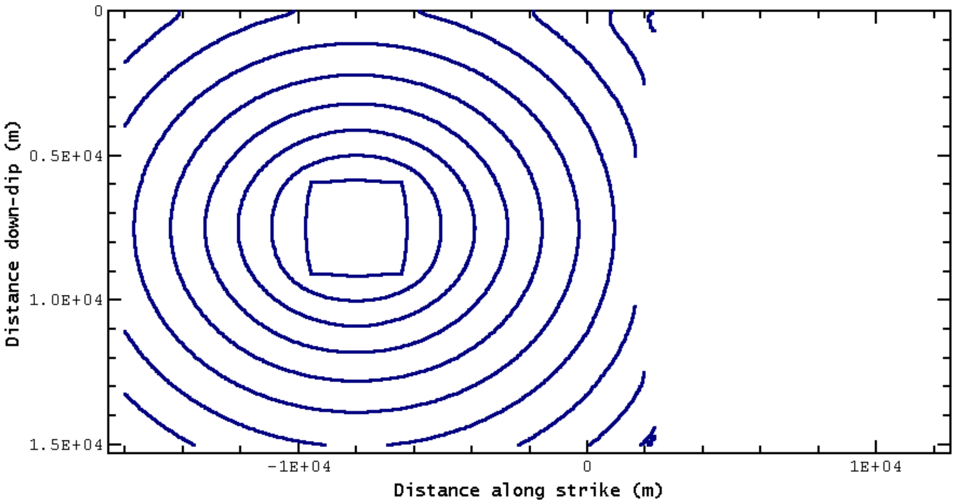


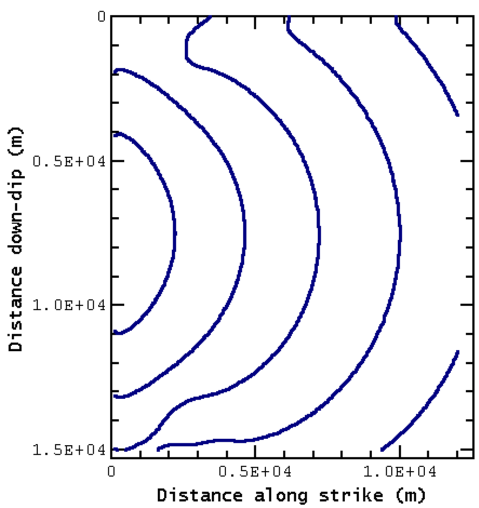
τ_{branch} = +74 MPa (right-lateral)



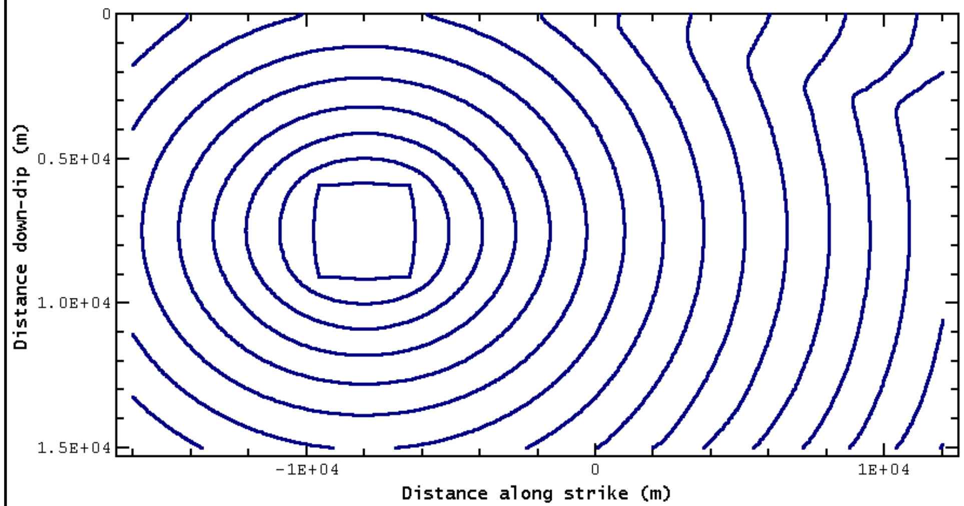


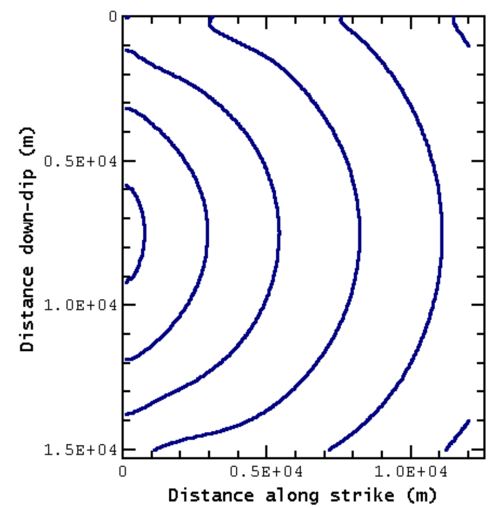
τ_{branch} = −78 MPa (left-lateral)
[TPV15]





τ_{branch} = +78 MPa (right-lateral)

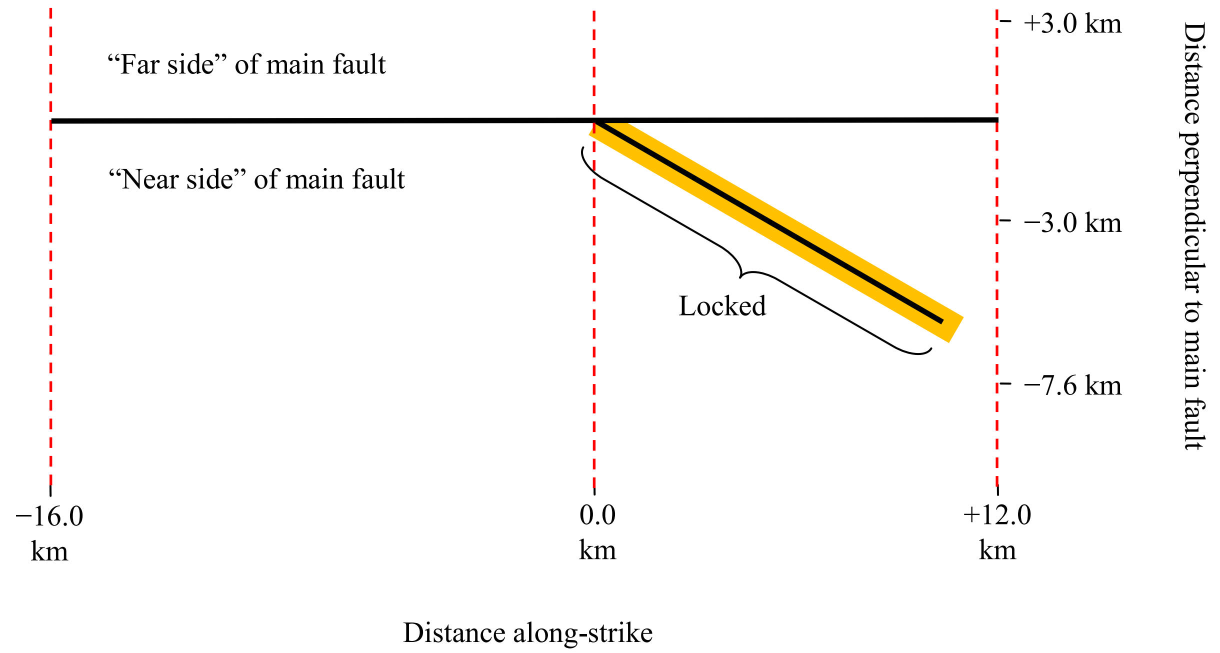


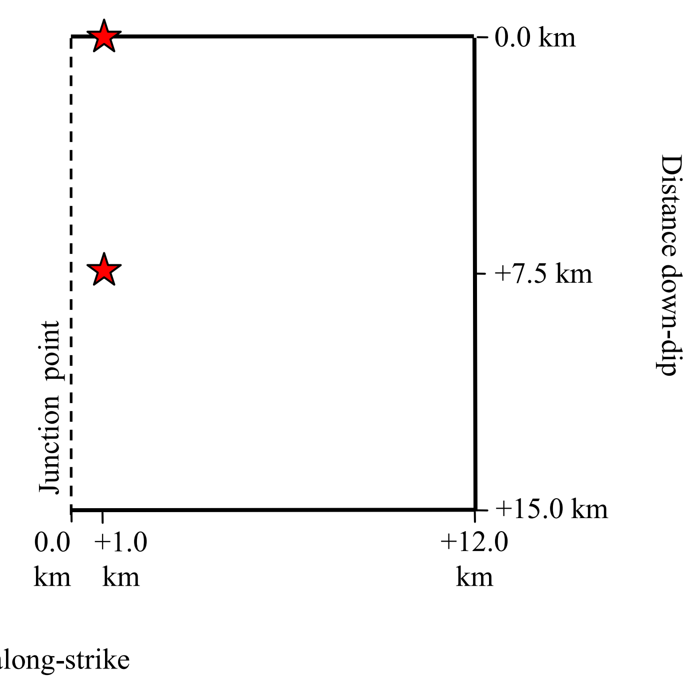


Stress on Branch Fault Due to Rupture on Main Fault

We lock the entire branch fault so it cannot slip, so the rupture remains only on the main fault.

We record the stress at two stations on the branch fault as the main fault rupture passes by.

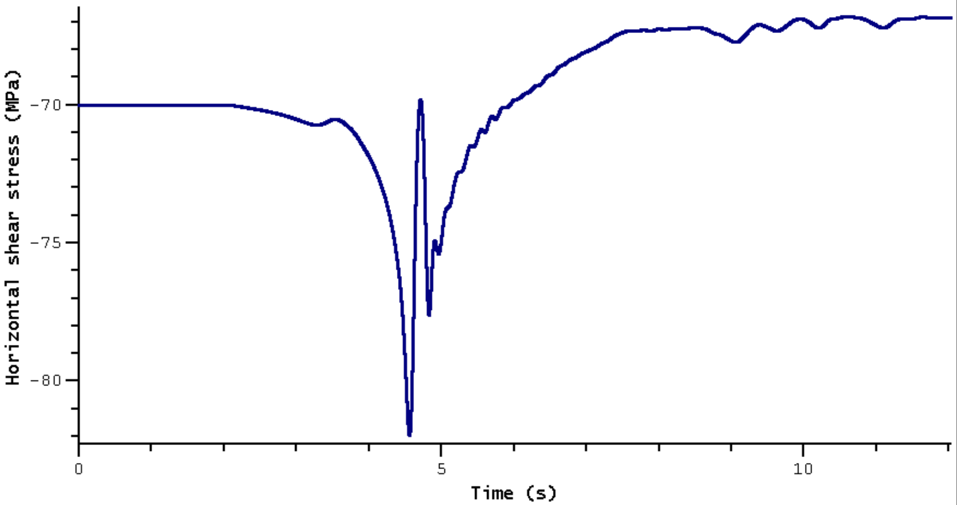




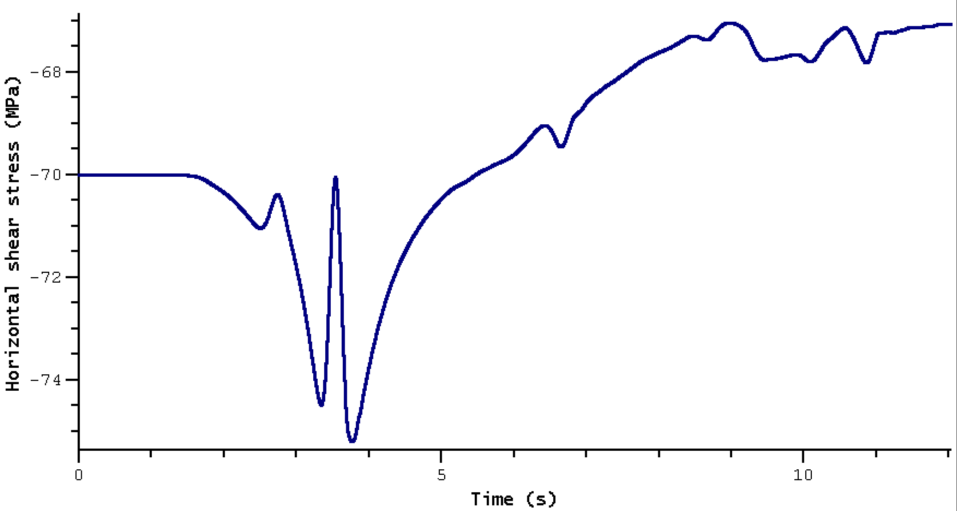
Shear stress on branch fault, due to rupture on main fault

τ_{branch} = −70 MPa (left-lateral)

Depth = 0 km

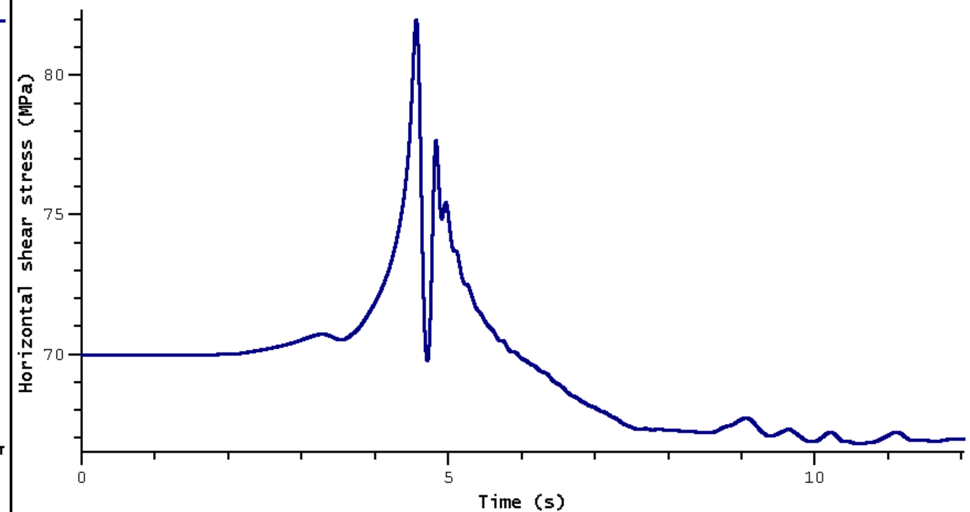


Depth = 7.5 km

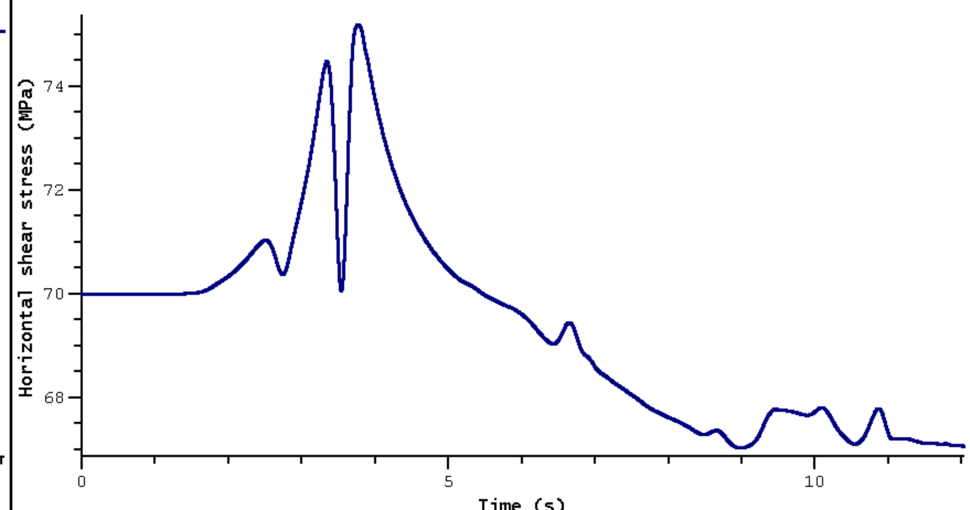


τ_{branch} = +70 MPa (right-lateral) [TPV14]

Depth = 0 km



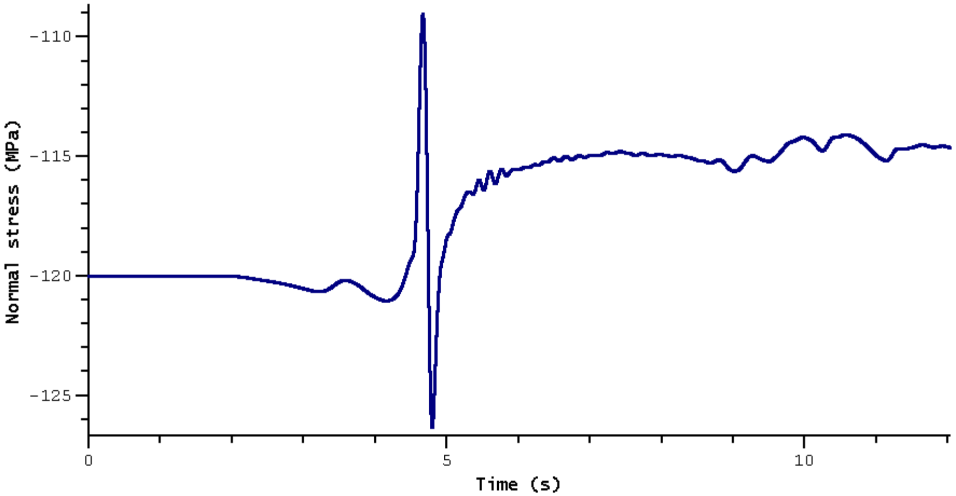
Depth = 7.5 km



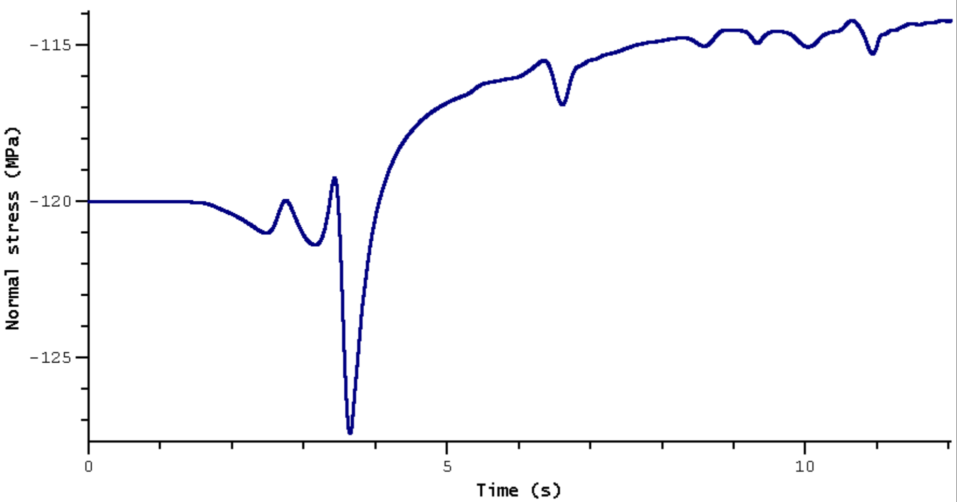
Normal stress on branch fault, due to rupture on main fault

τ_{branch} = −70 MPa (left-lateral)

Depth = 0 km

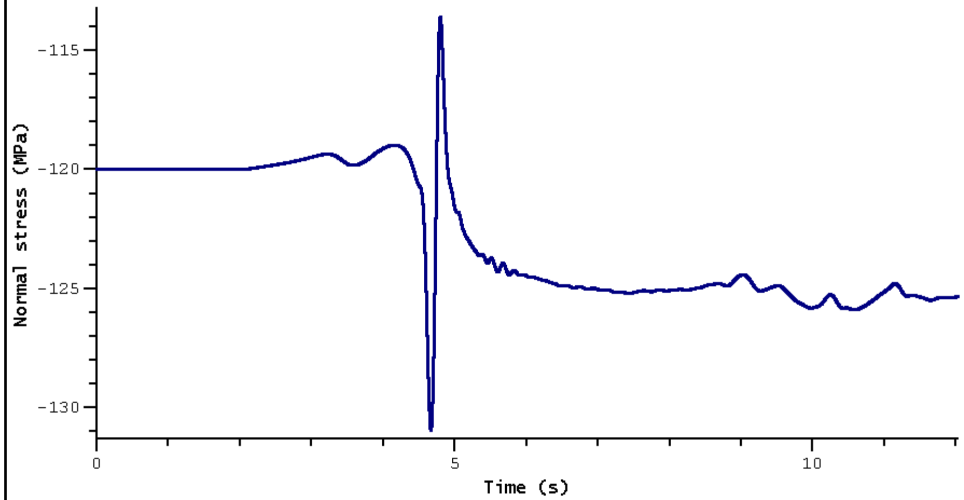


Depth = 7.5 km

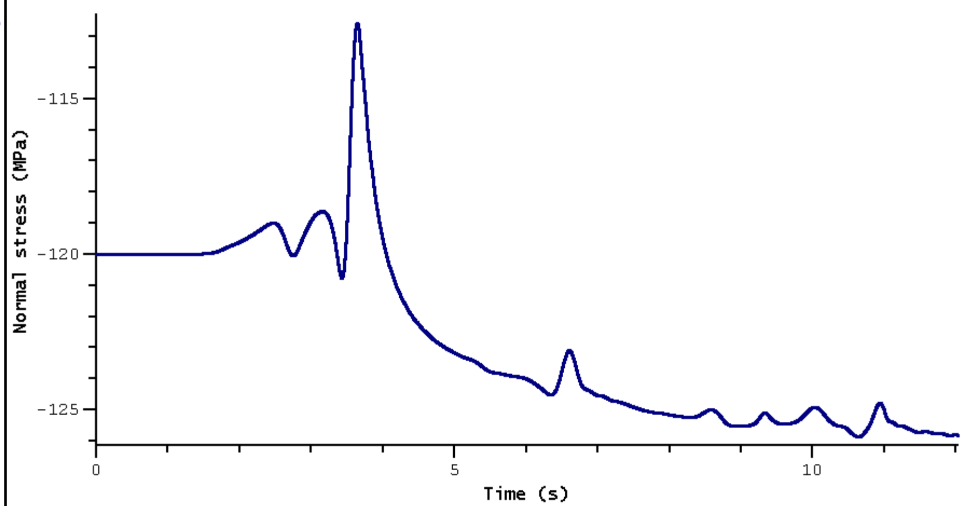


τ_{branch} = +70 MPa (right-lateral) [TPV14]

Depth = 0 km



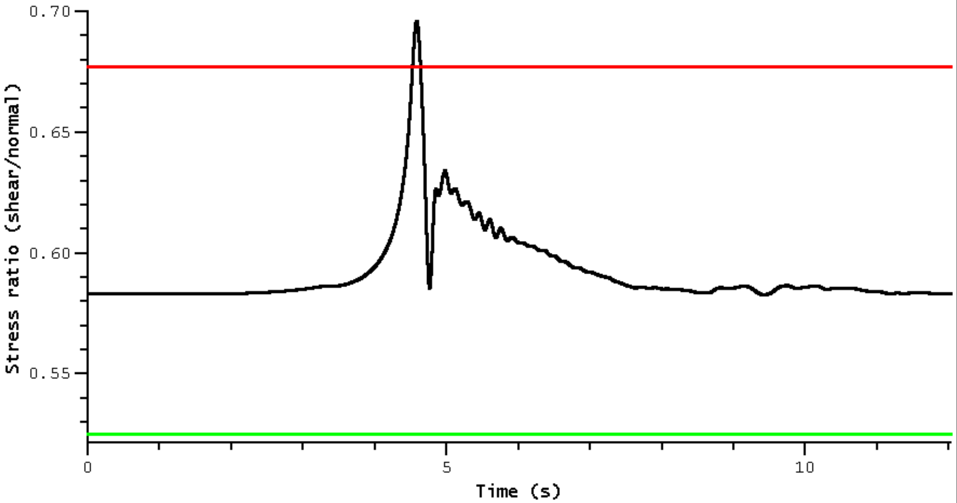
Depth = 7.5 km



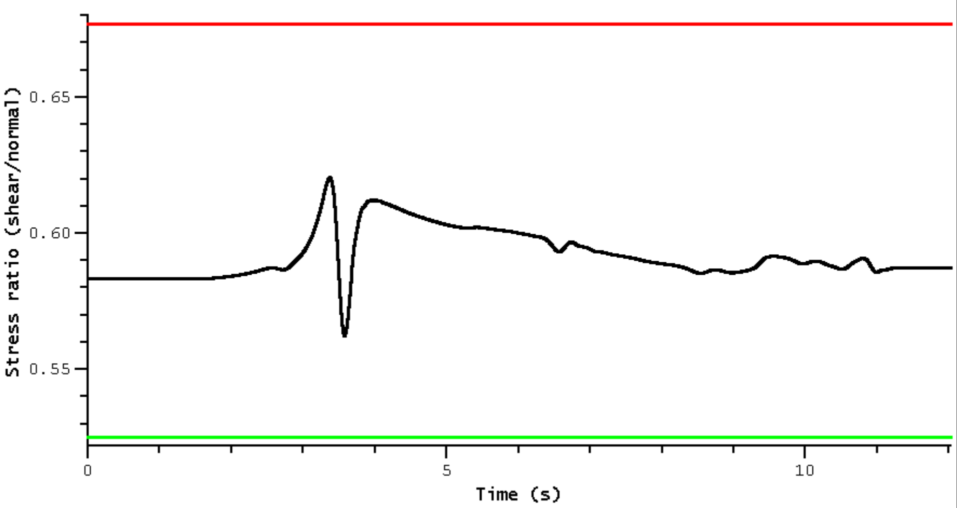
Stress ratio (shear/normal) on branch fault, due to rupture on main fault

τ_{branch} = −70 MPa (left-lateral)

Depth = 0 km

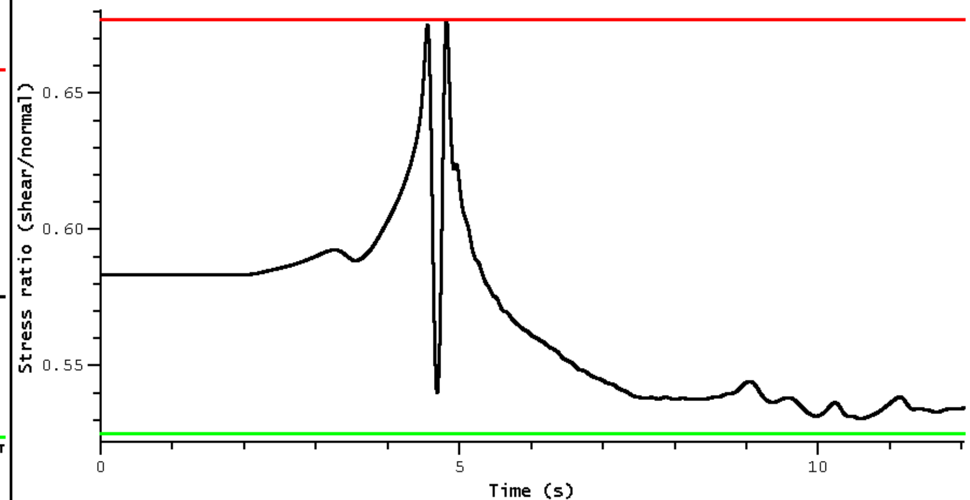


Depth = 7.5 km

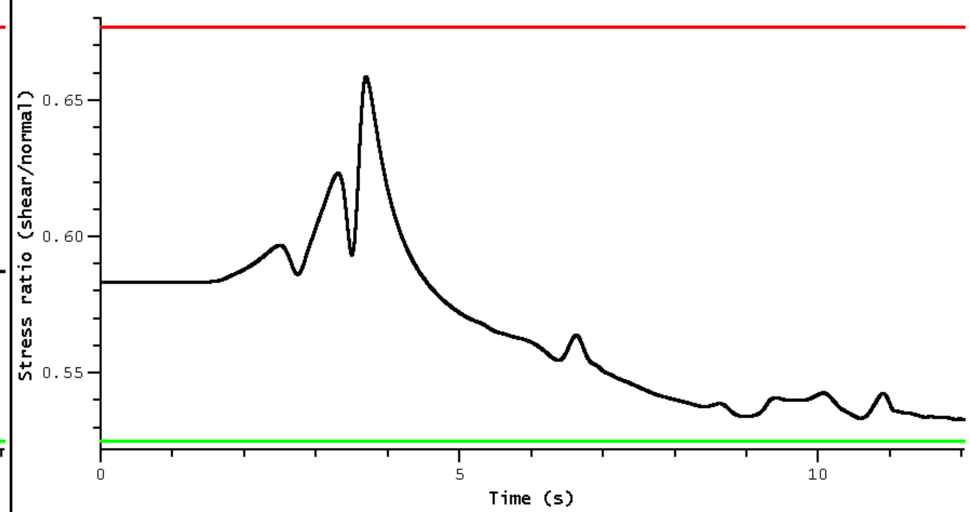


τ_{branch} = +70 MPa (right-lateral) [TPV14]

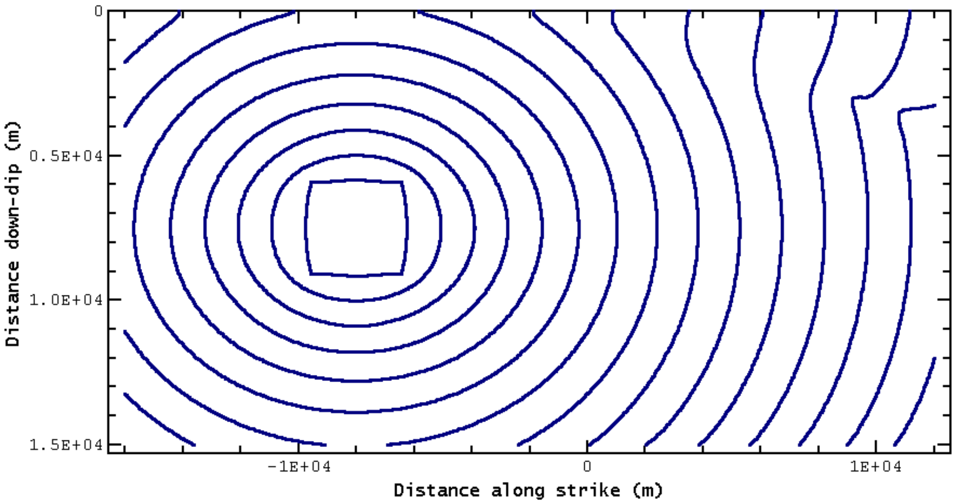
Depth = 0 km

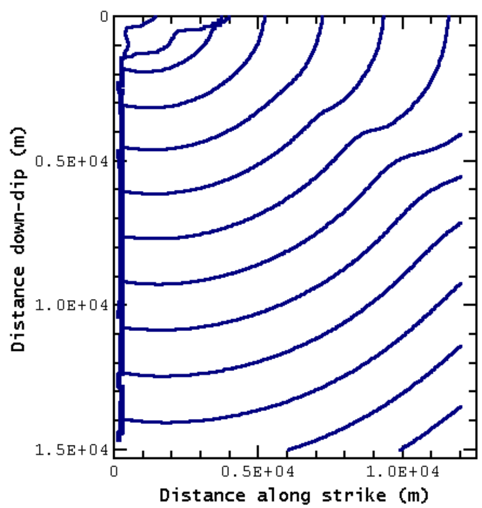


Depth = 7.5 km

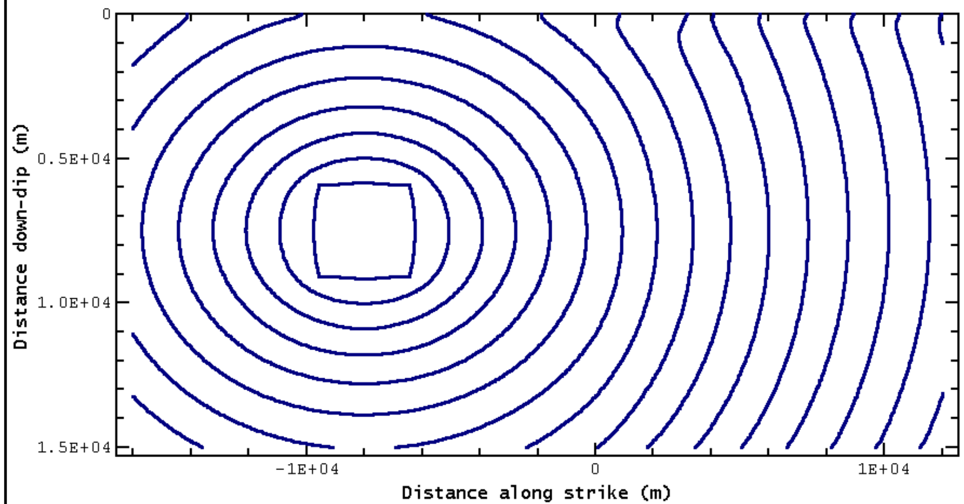


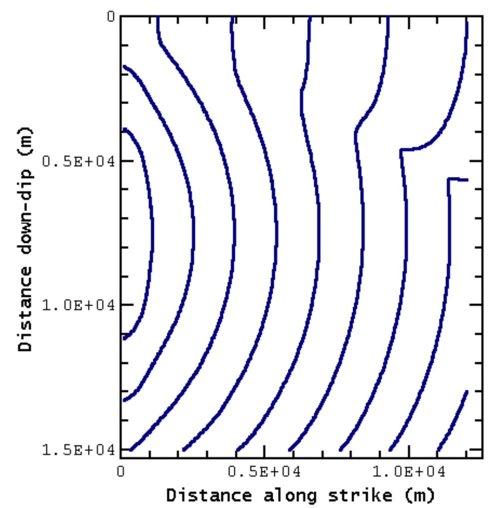
τ_{branch} = −74 MPa (left-lateral)





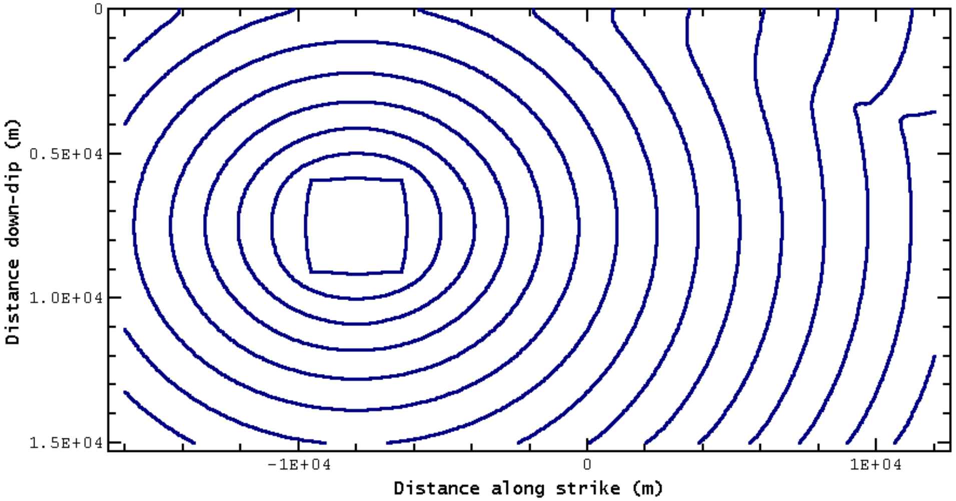
τ_{branch} = +74 MPa (right-lateral)

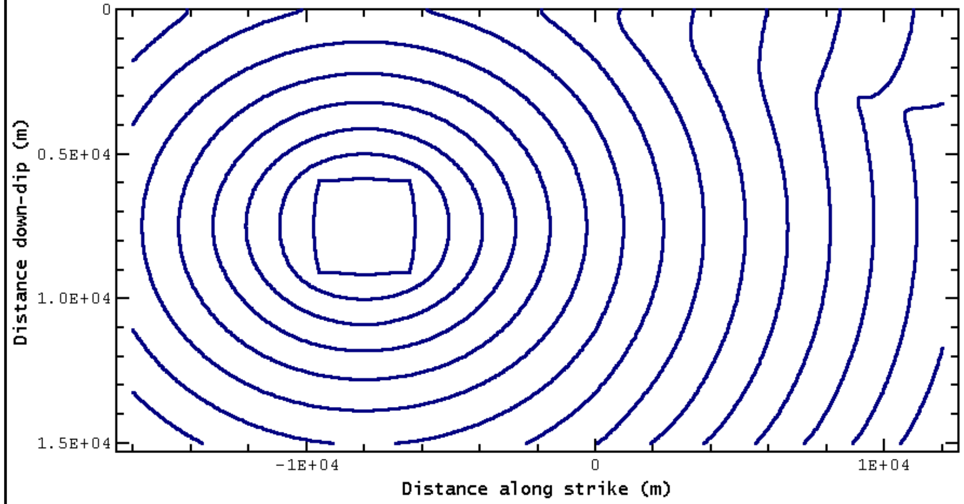


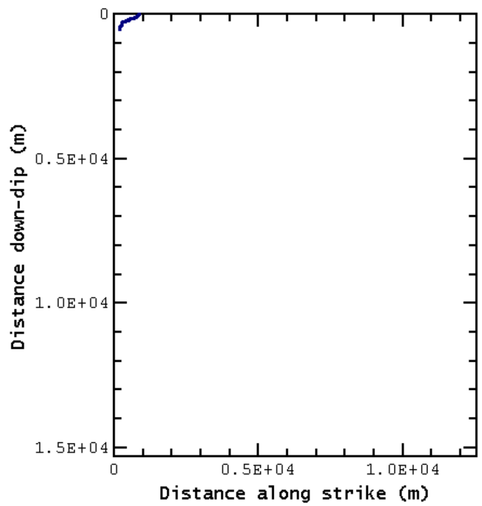


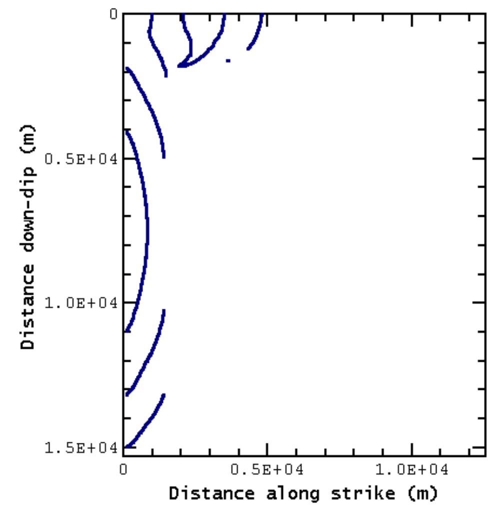
τ_{branch} = −70 MPa (left-lateral)

τ_{branch} = +70 MPa (right-lateral)
[TPV14]





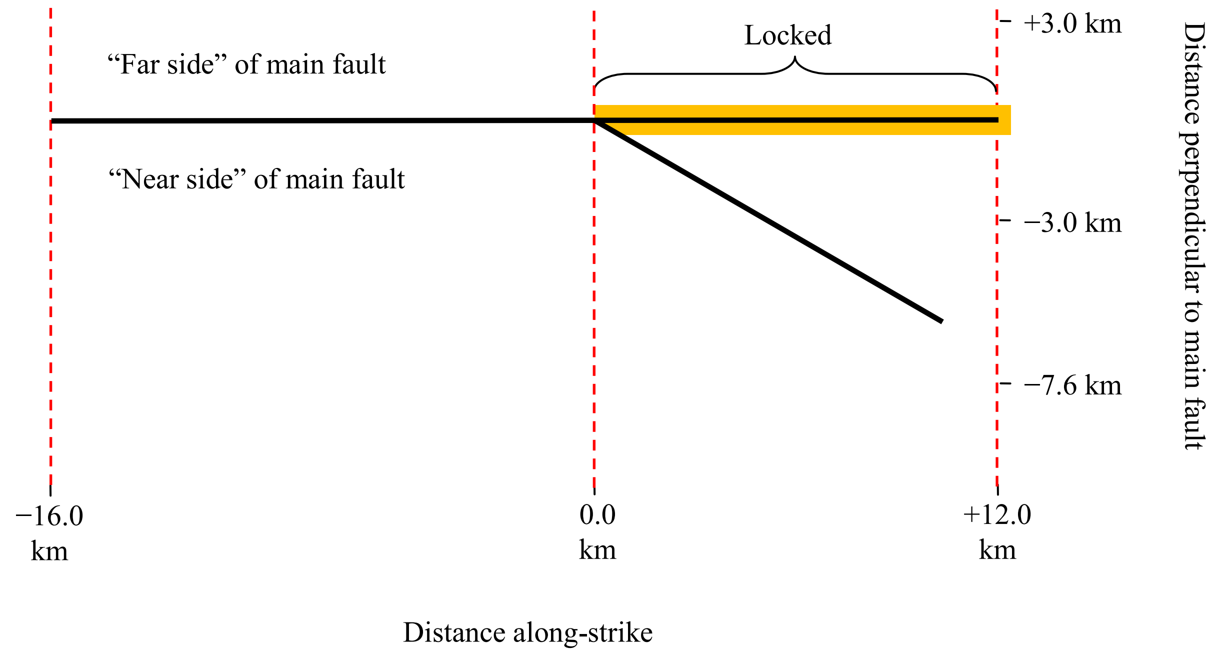


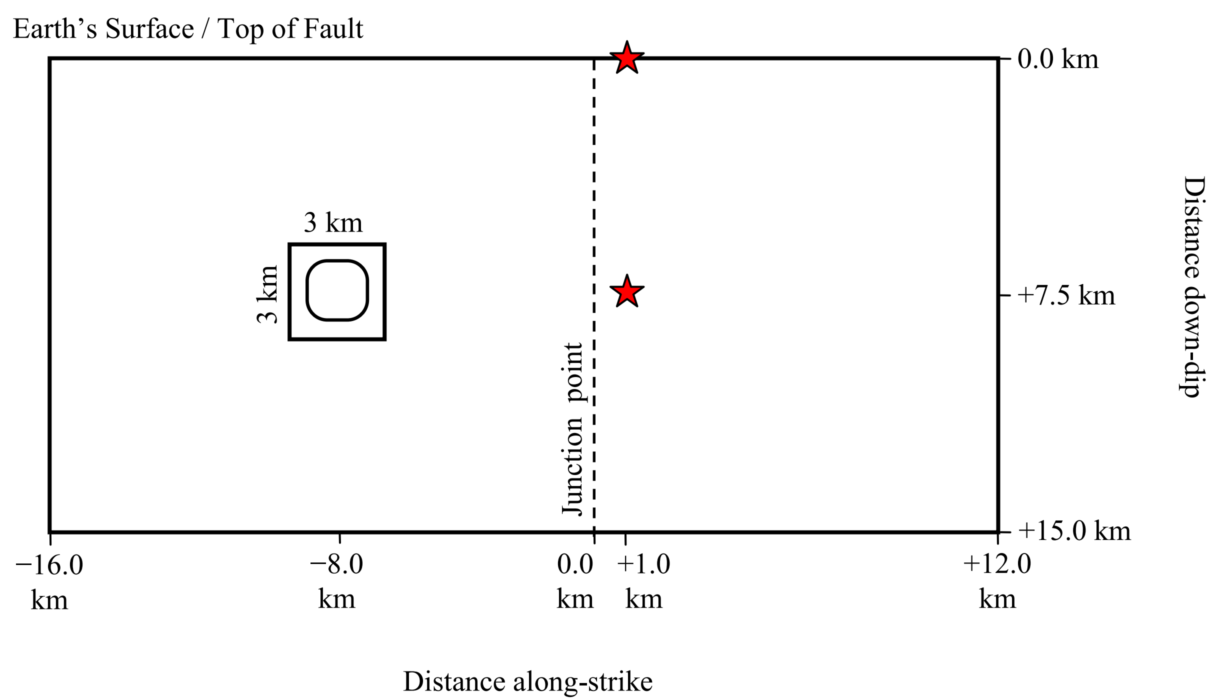


Stress on Main Fault Due to Rupture on Branch Fault

We lock the main fault to the right of the junction point, so the rupture is forced to divert entirely onto the branch fault.

We record the stress at two stations on the main fault as the rupture passes by on the branch fault.

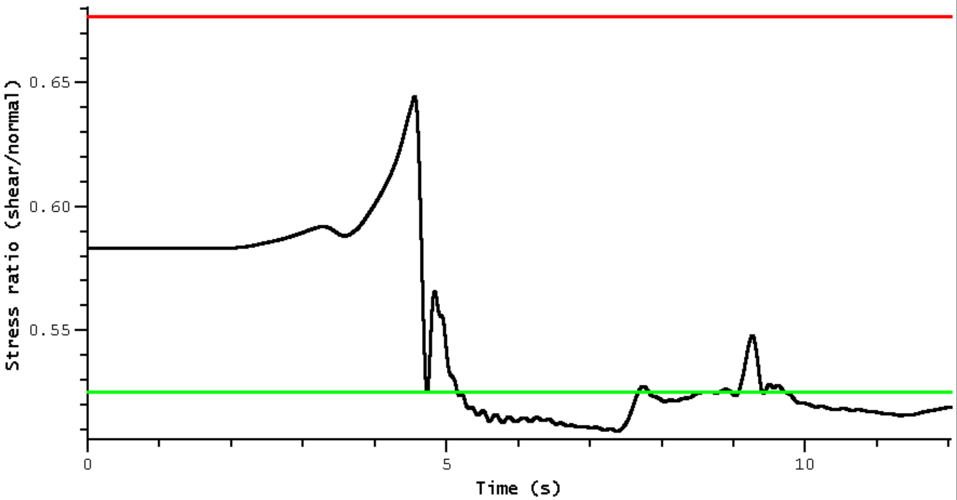




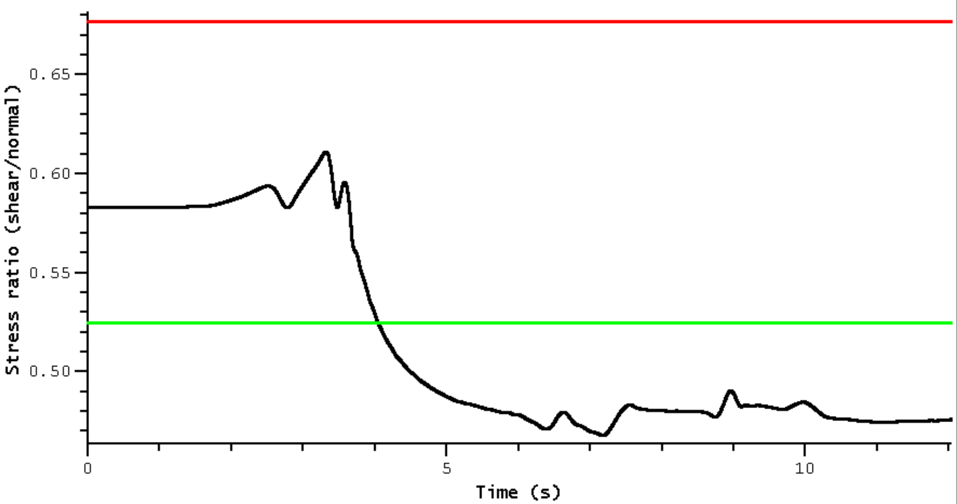
Stress ratio (shear/normal) on main fault, due to rupture on branch fault

τ_{branch} = −78 MPa (left-lateral) [TPV15]

Depth = 0 km

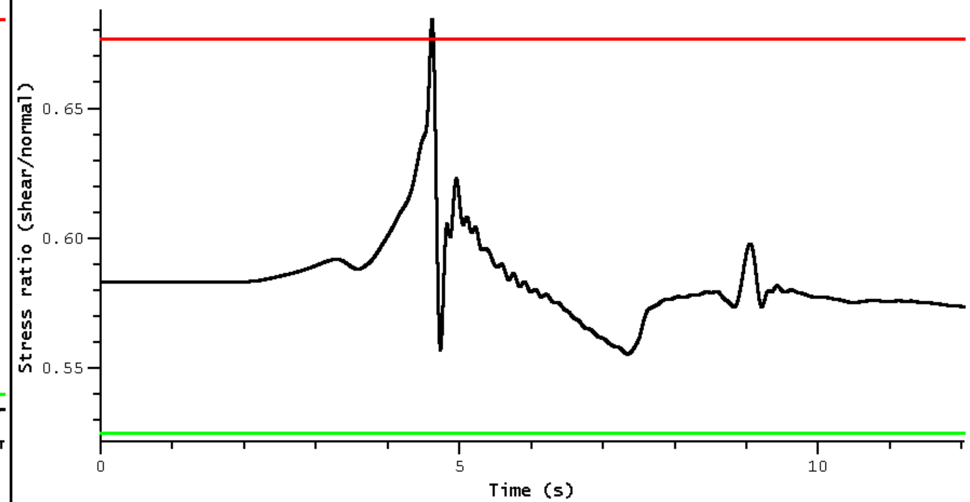


Depth = 7.5 km

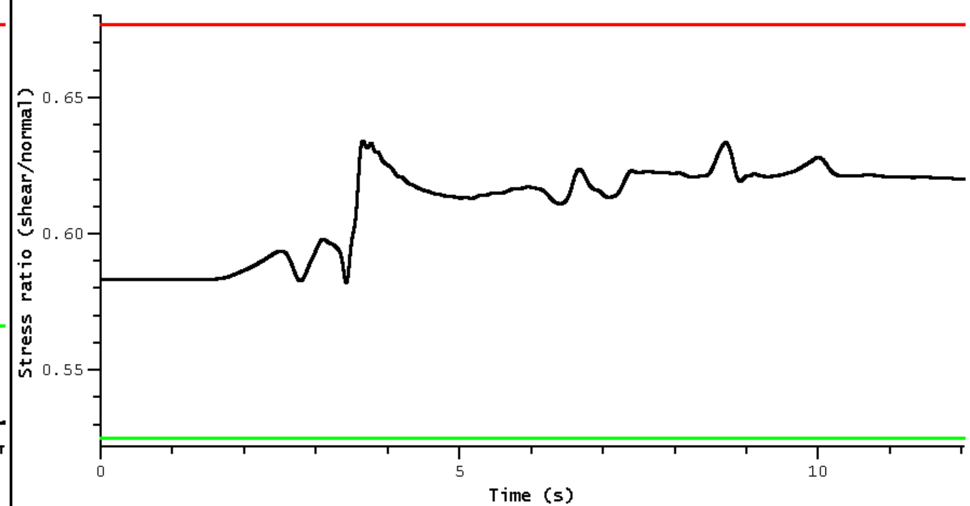


τ_{branch} = +78 MPa (right-lateral)

Depth = 0 km

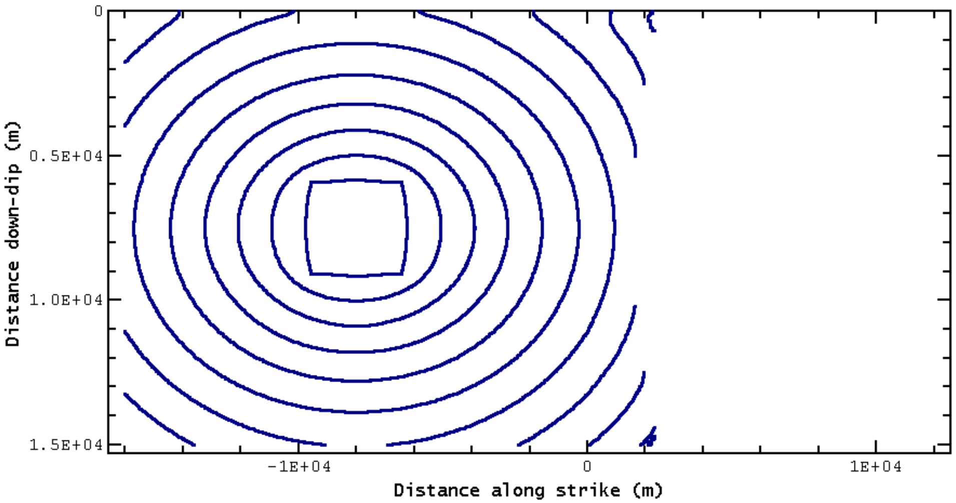


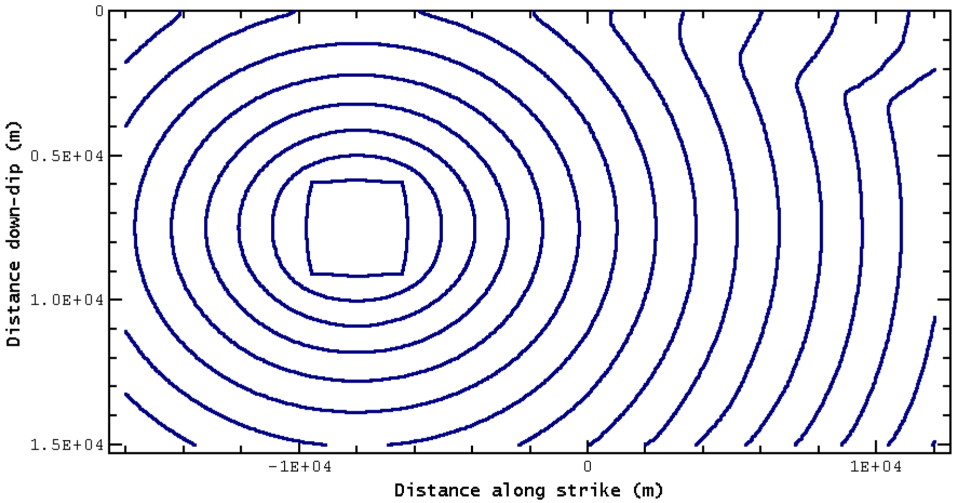
Depth = 7.5 km

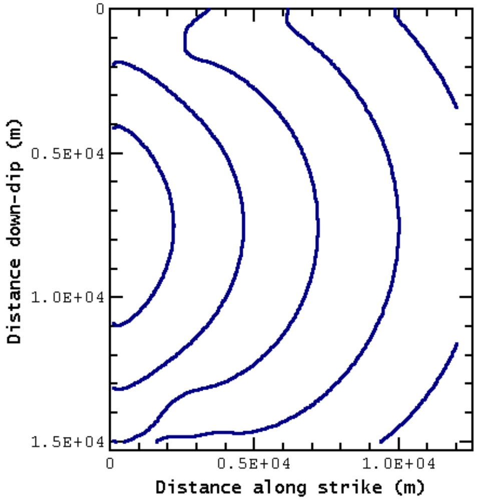


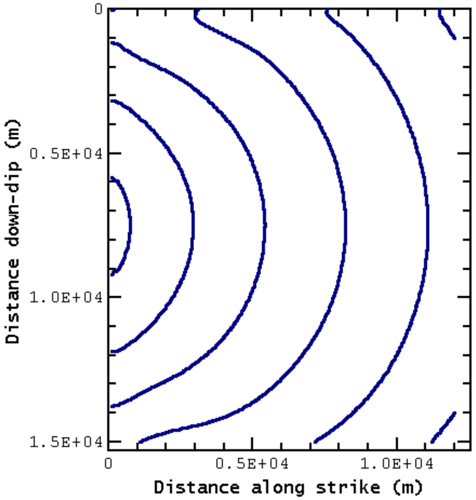
τ_{branch} = −78 MPa (left-lateral)
[TPV15]

τ_{branch} = +78 MPa (right-lateral)









Part 3:

Performance of the Codes

TPV14

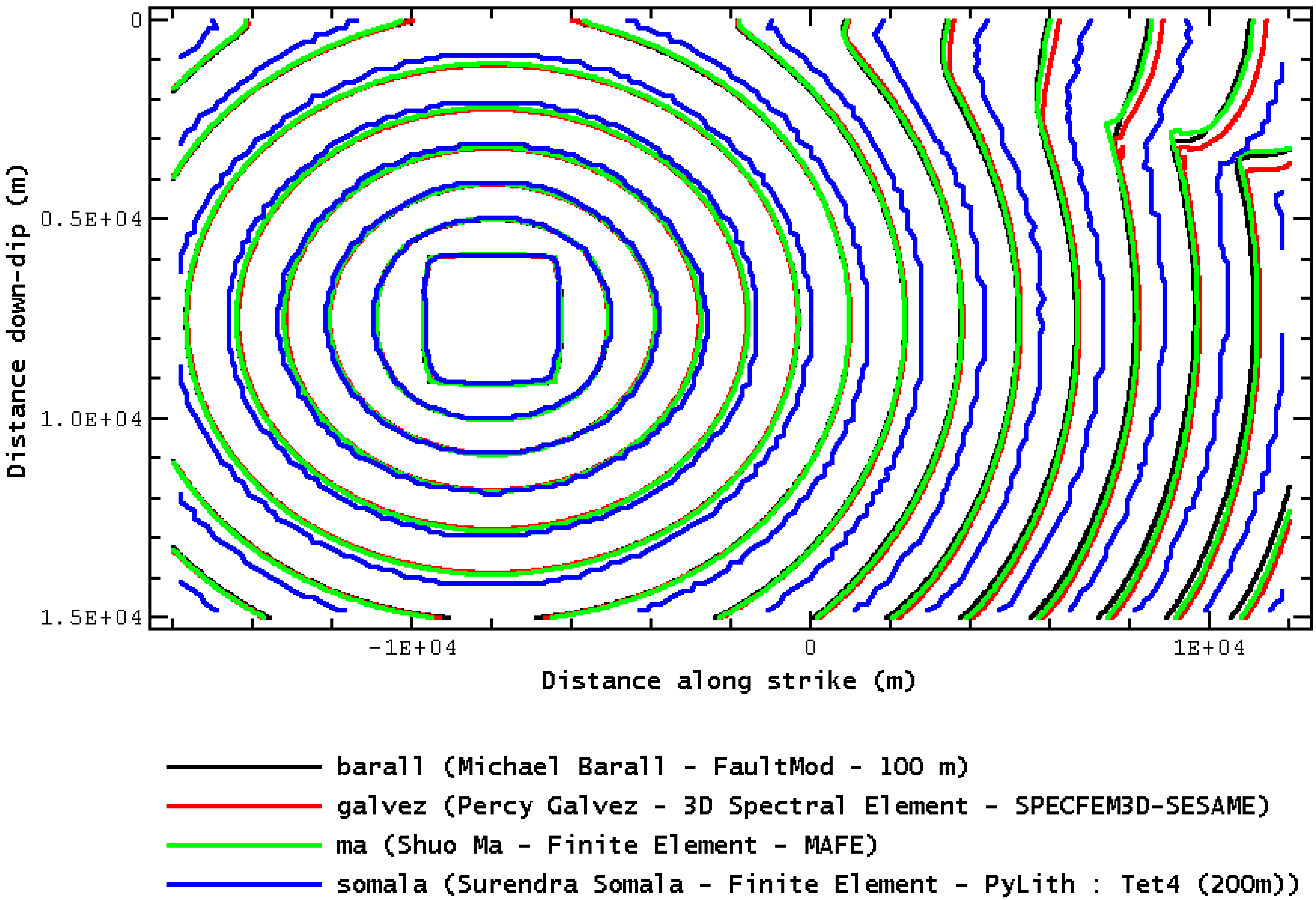
3D Benchmark.

Initial shear stress on branch fault = +70.0 MPa (right-lateral).

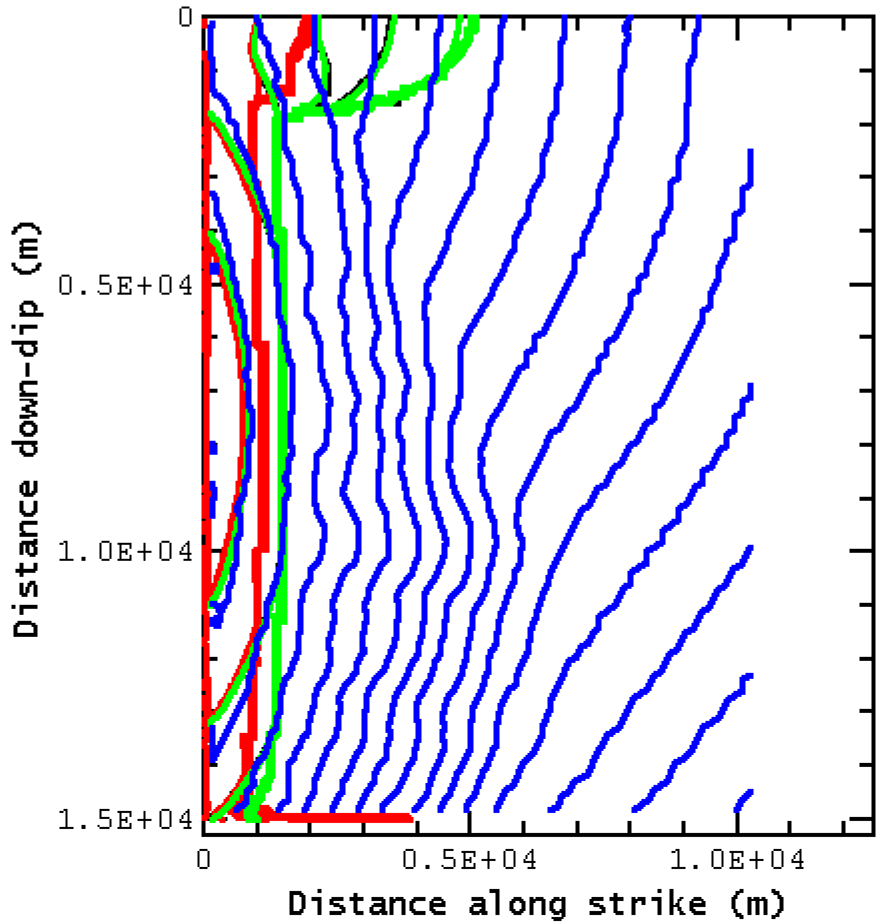
Expected outcome:

- Main fault ruptures completely.
- Branch fault ruptures partially.

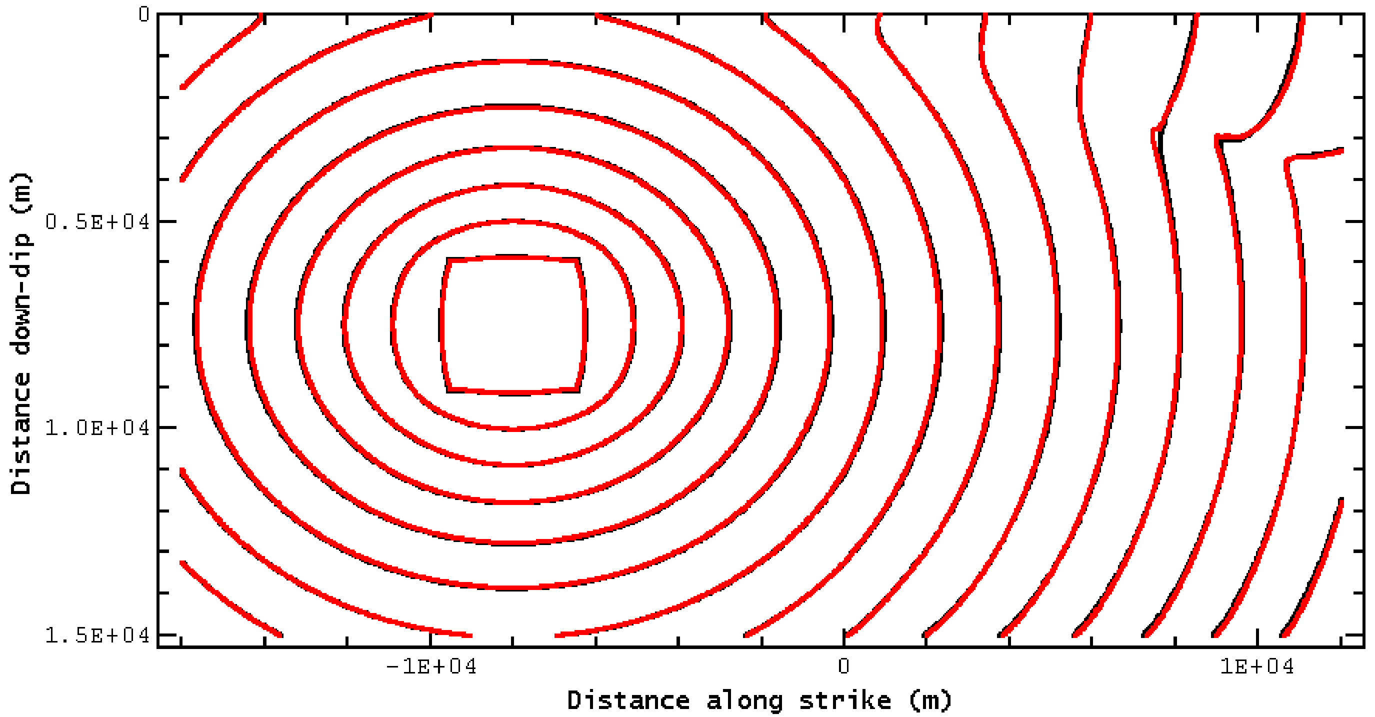
TPV14 — Main Fault Rupture Contours



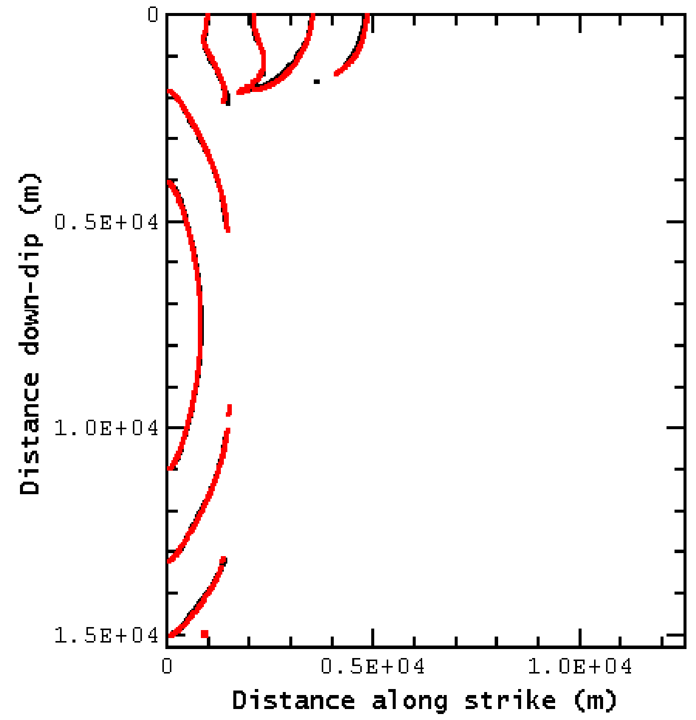
TPV14 — Branch Fault Rupture Contours



barall (Michael Barall - FaultMod - 100 m)
galvez (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Finite Element - PyLith : Tet4 (200m))



TPV14 — 100 m vs. 50 m Resolution

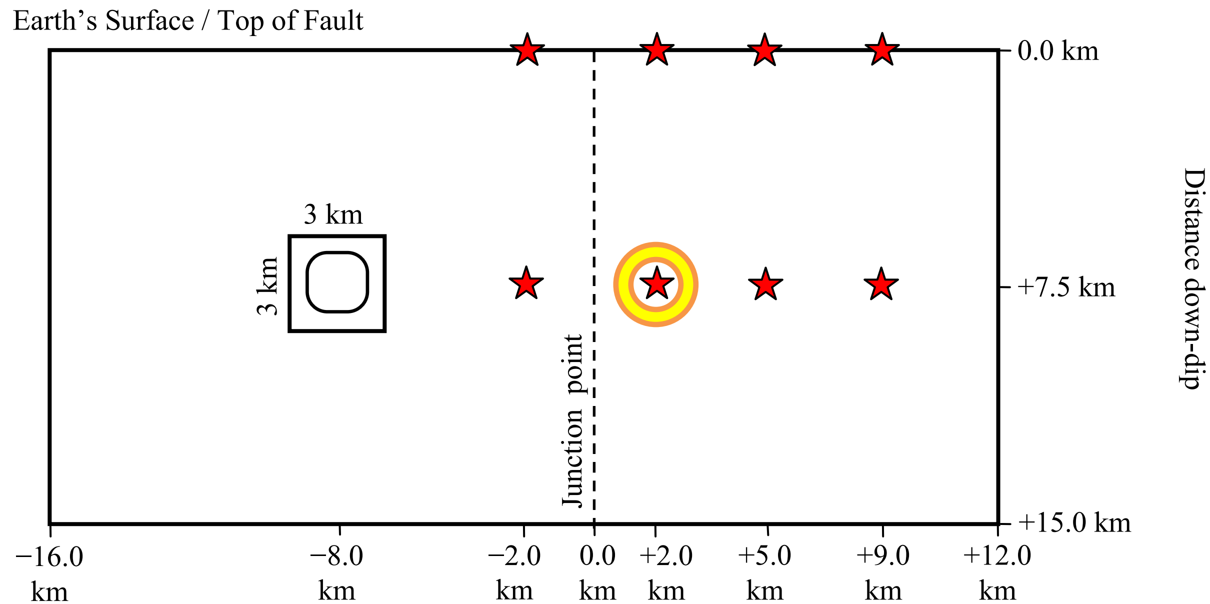


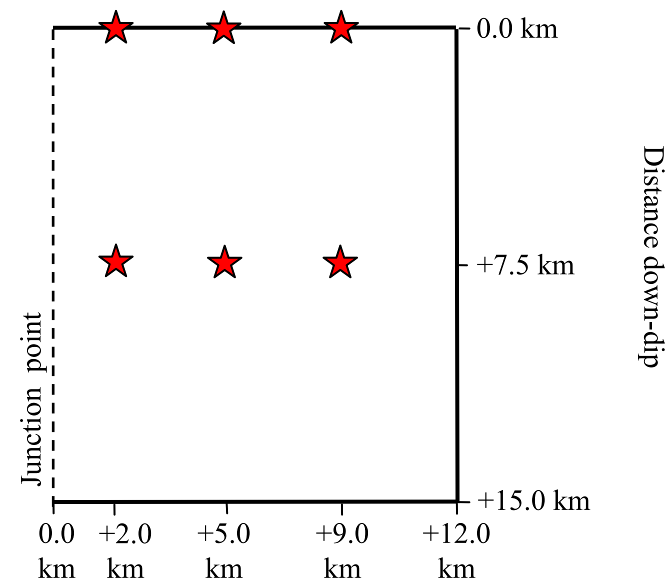
barall (Michael Barall - FaultMod - 100 m)

barall.2 (Michael Barall - FaultMod - 50 m)

TPV14

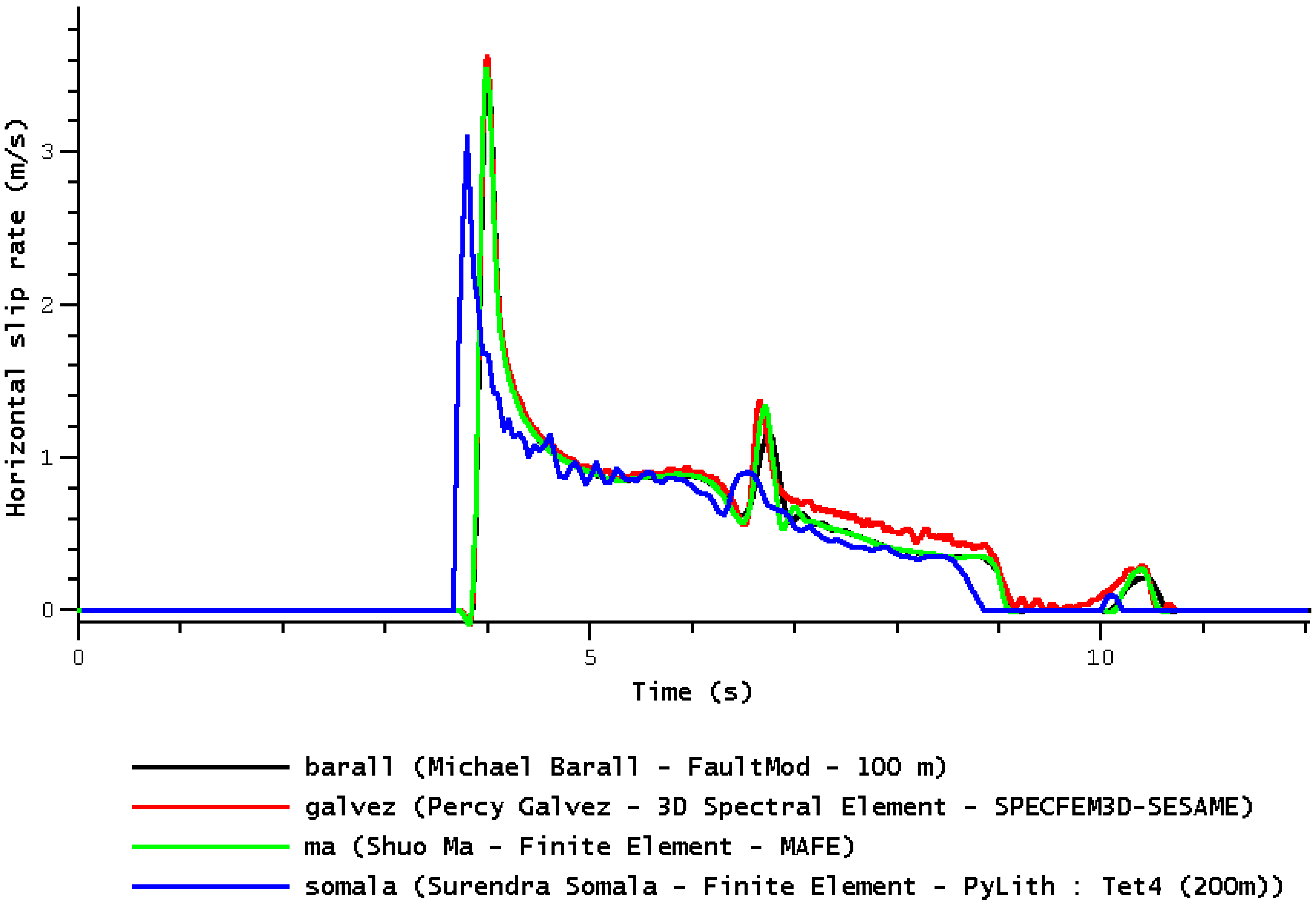
[faultst020dp075]



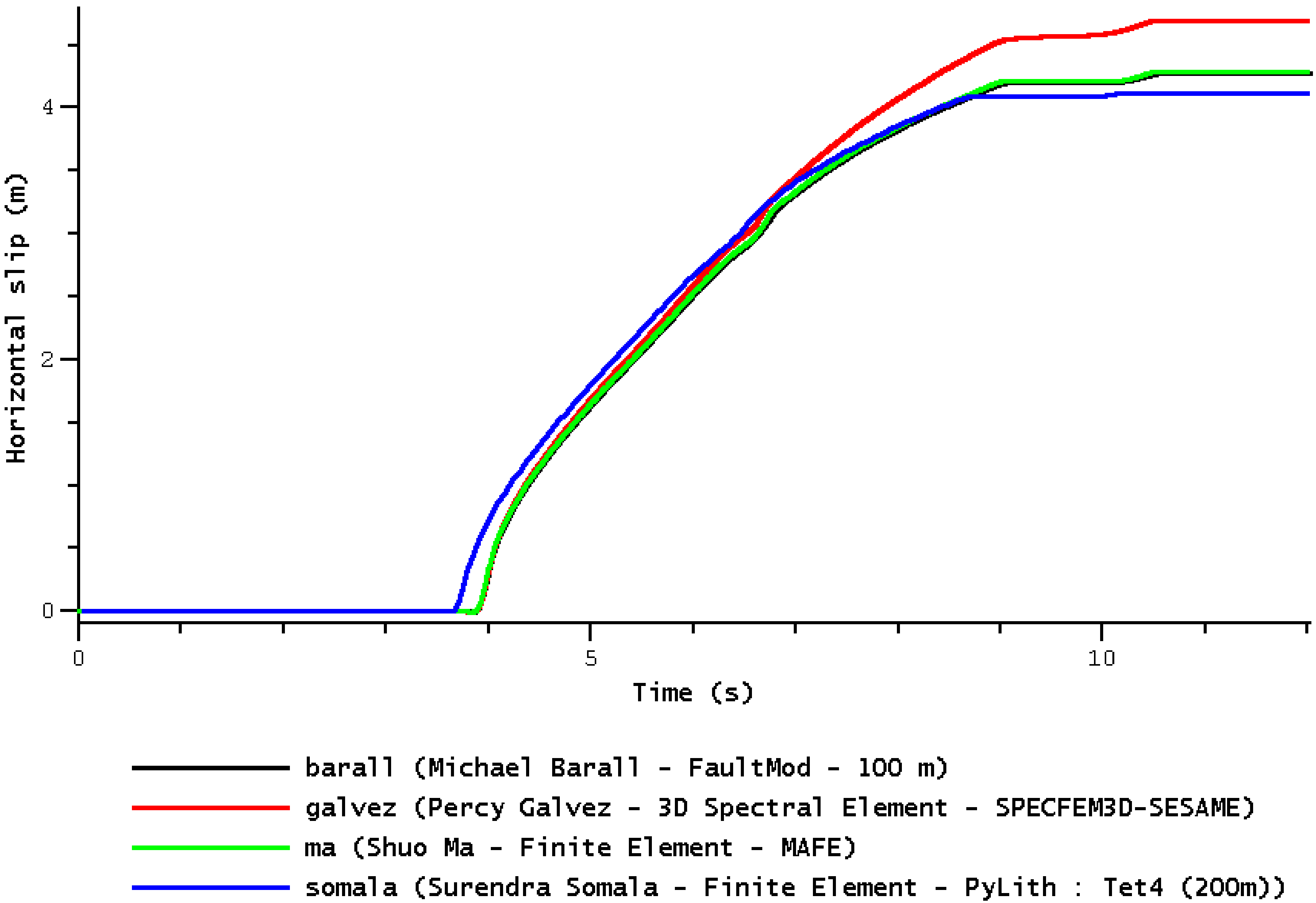


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

TPV14 — Horizontal Slip Rate [faultst020dp075]

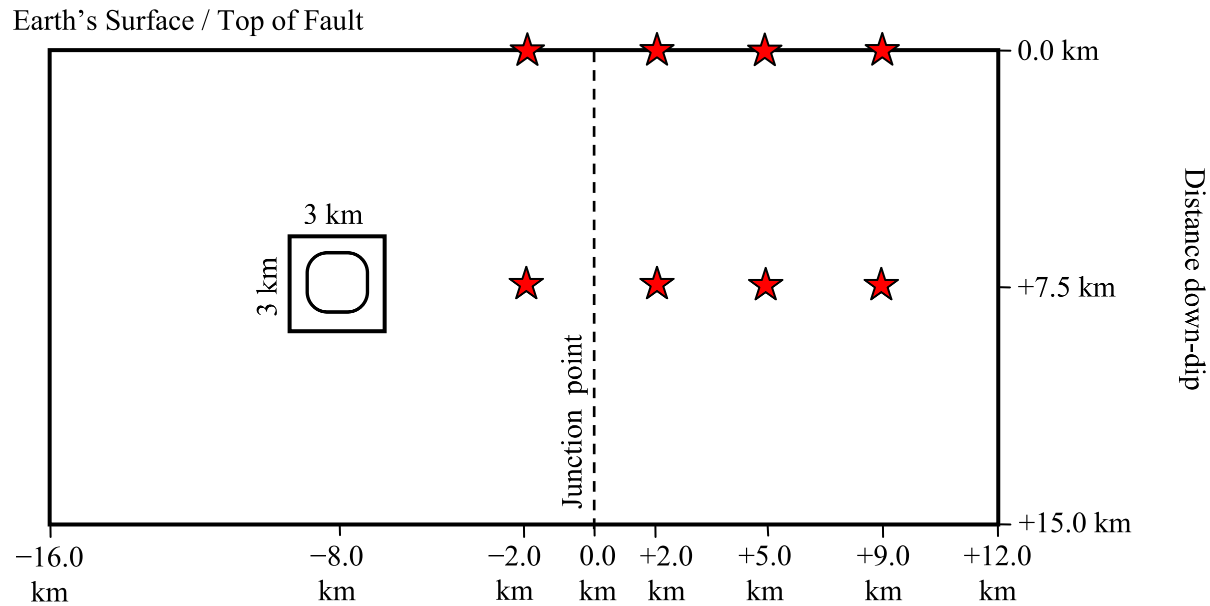


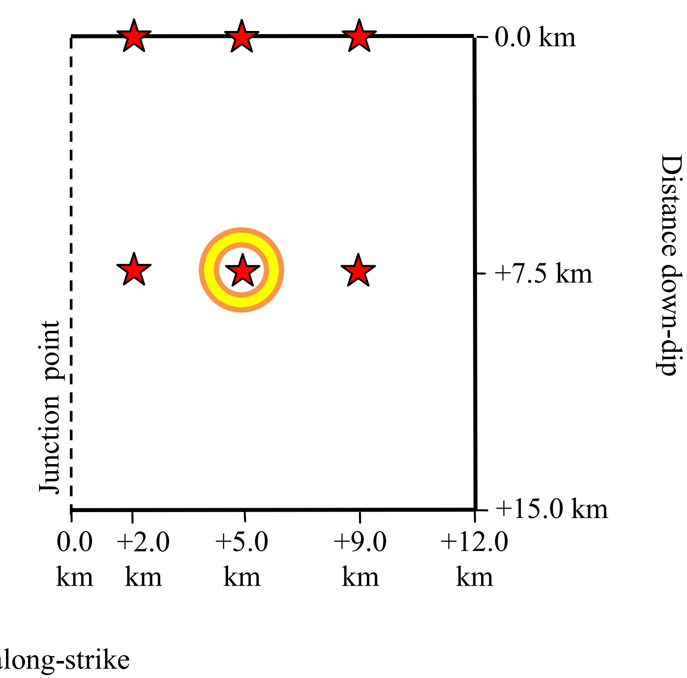
TPV14 — Horizontal Slip [faultst020dp075]



TPV14

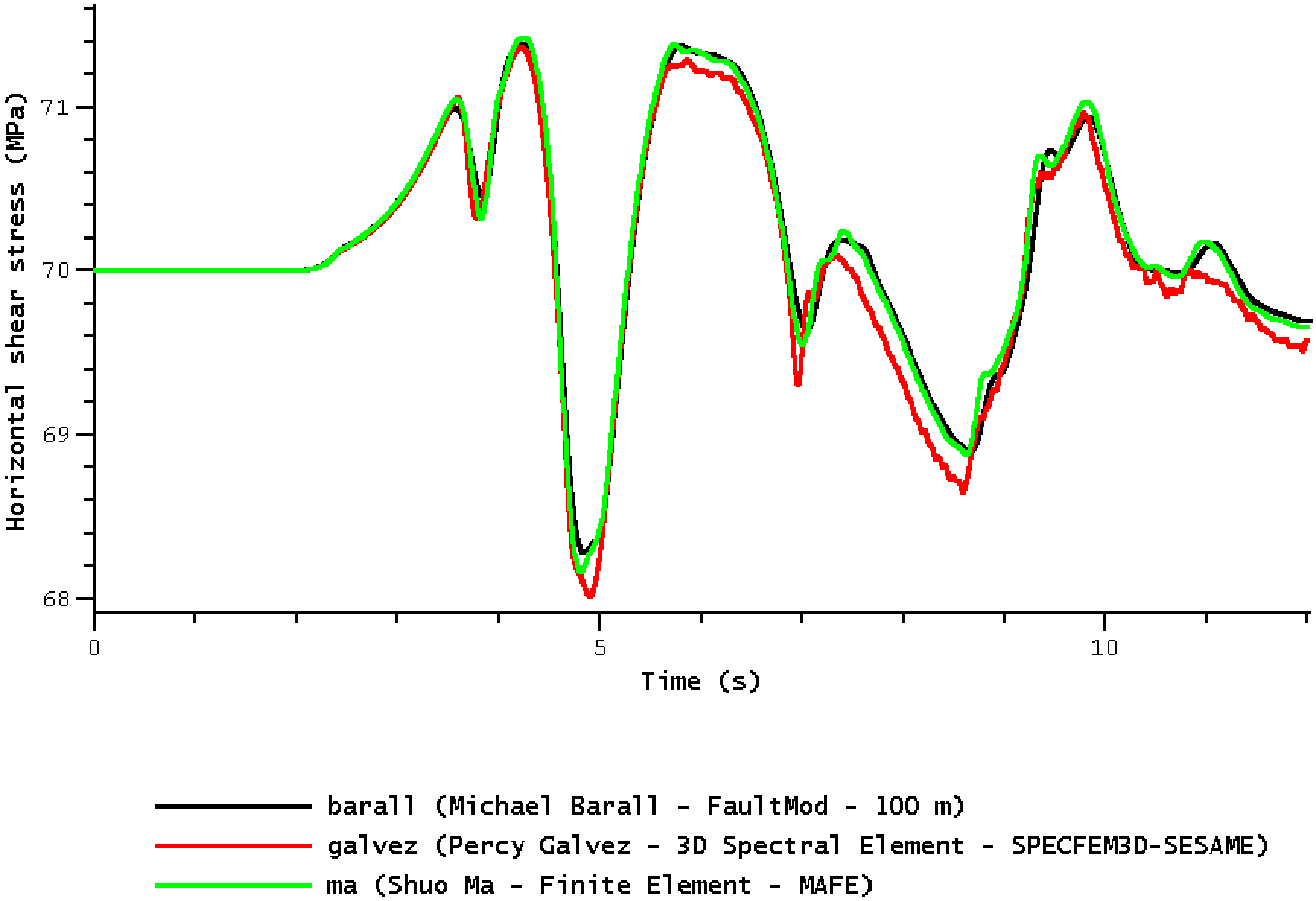
[branchst050dp075]



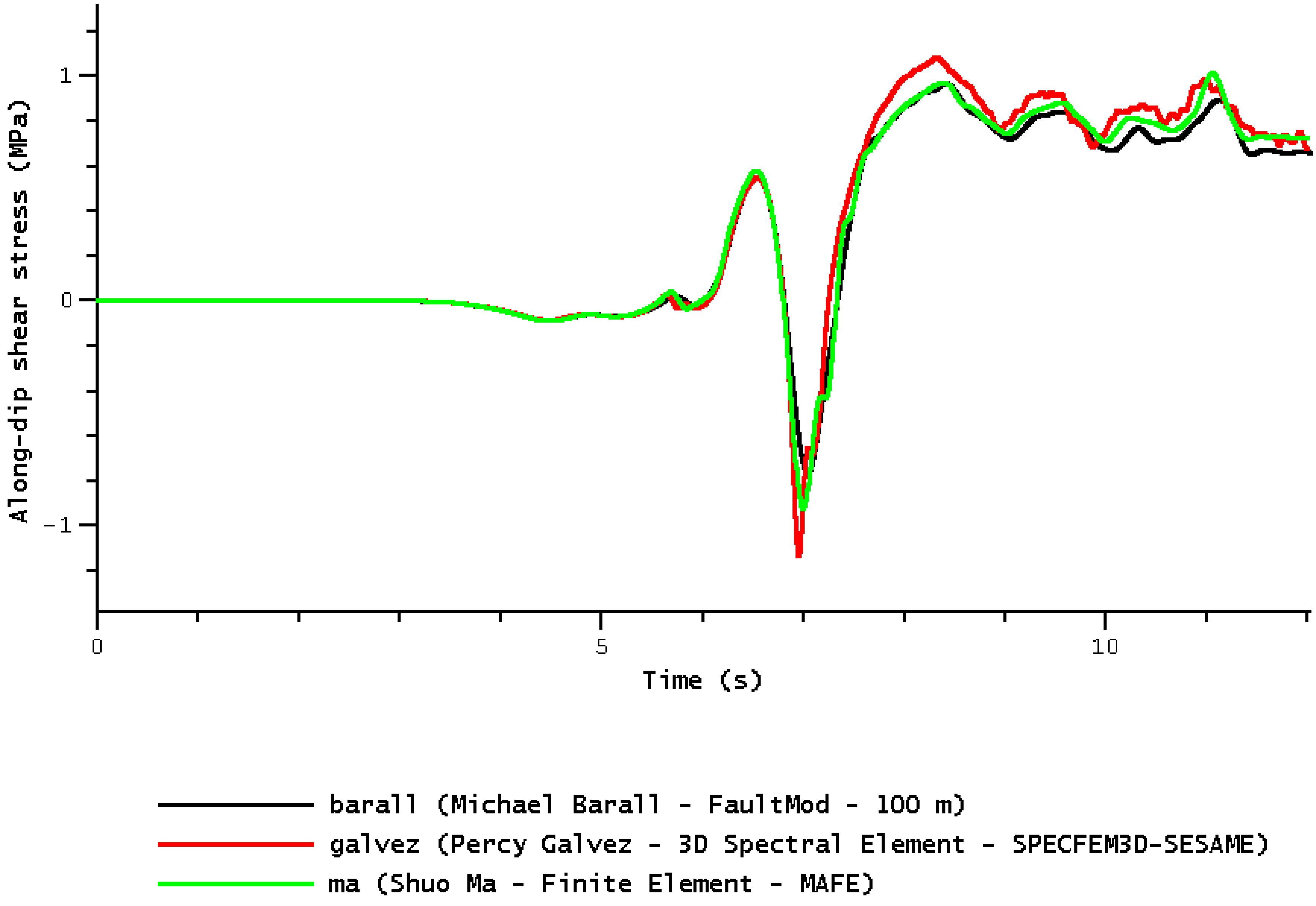


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

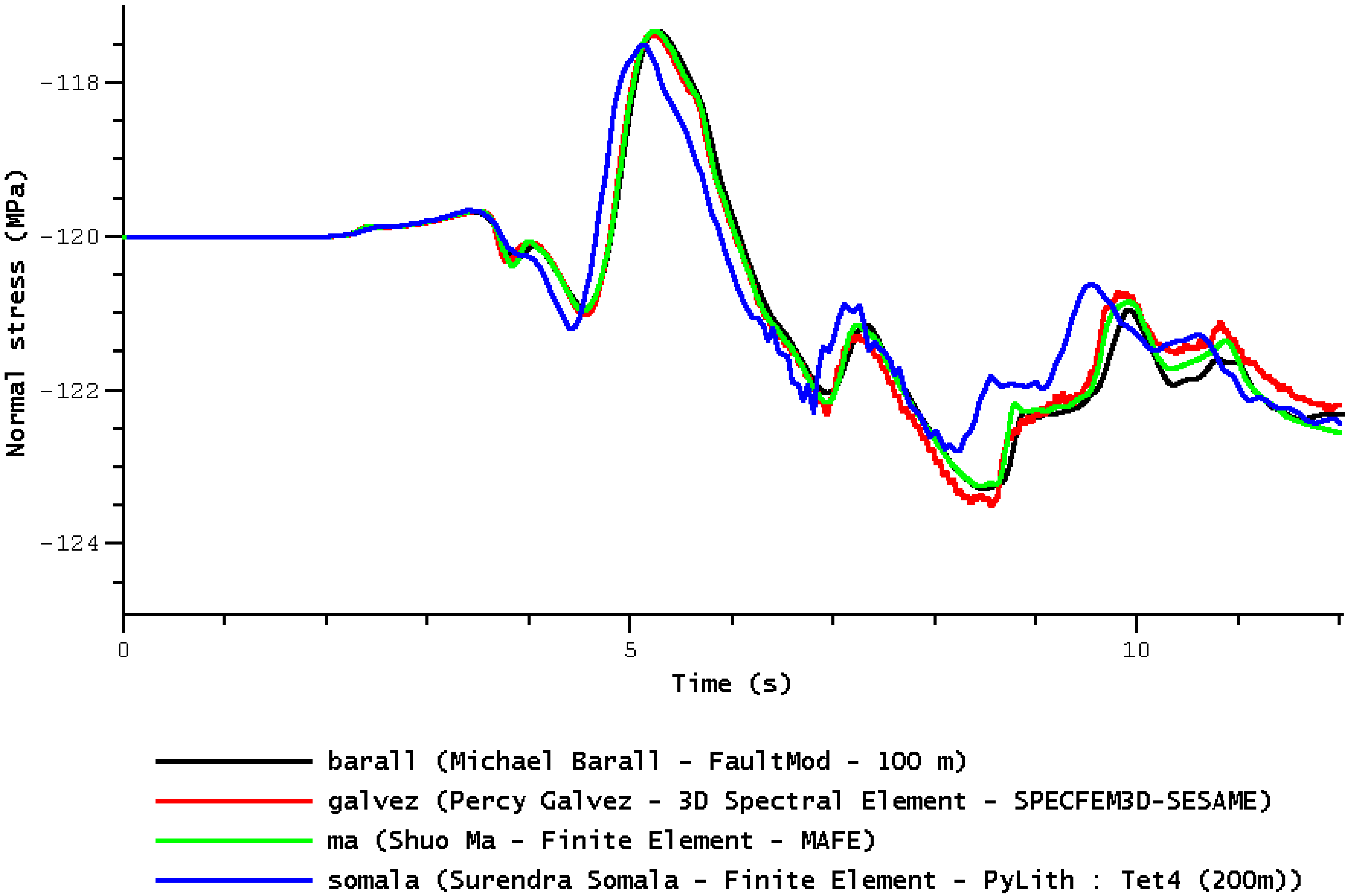
TPV14 — Horizontal Shear Stress [branchst050dp075]



TPV14 — Vertical Shear Stress [branchst050dp075]

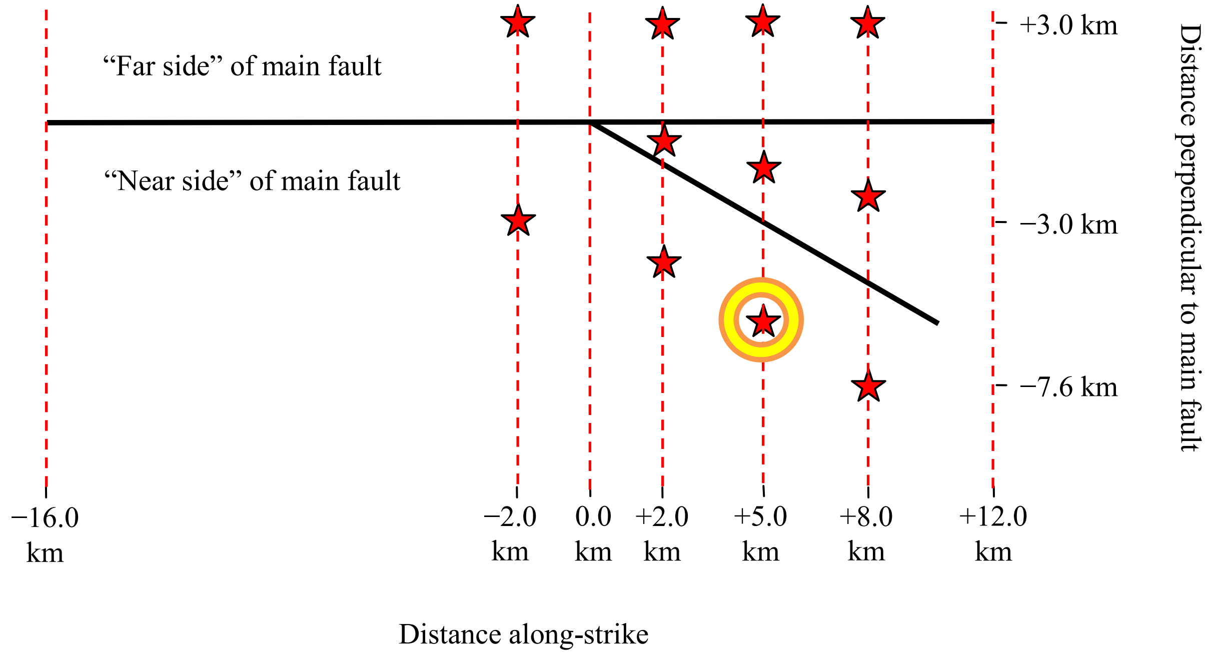


TPV14 — Normal Stress [branchst050dp075]



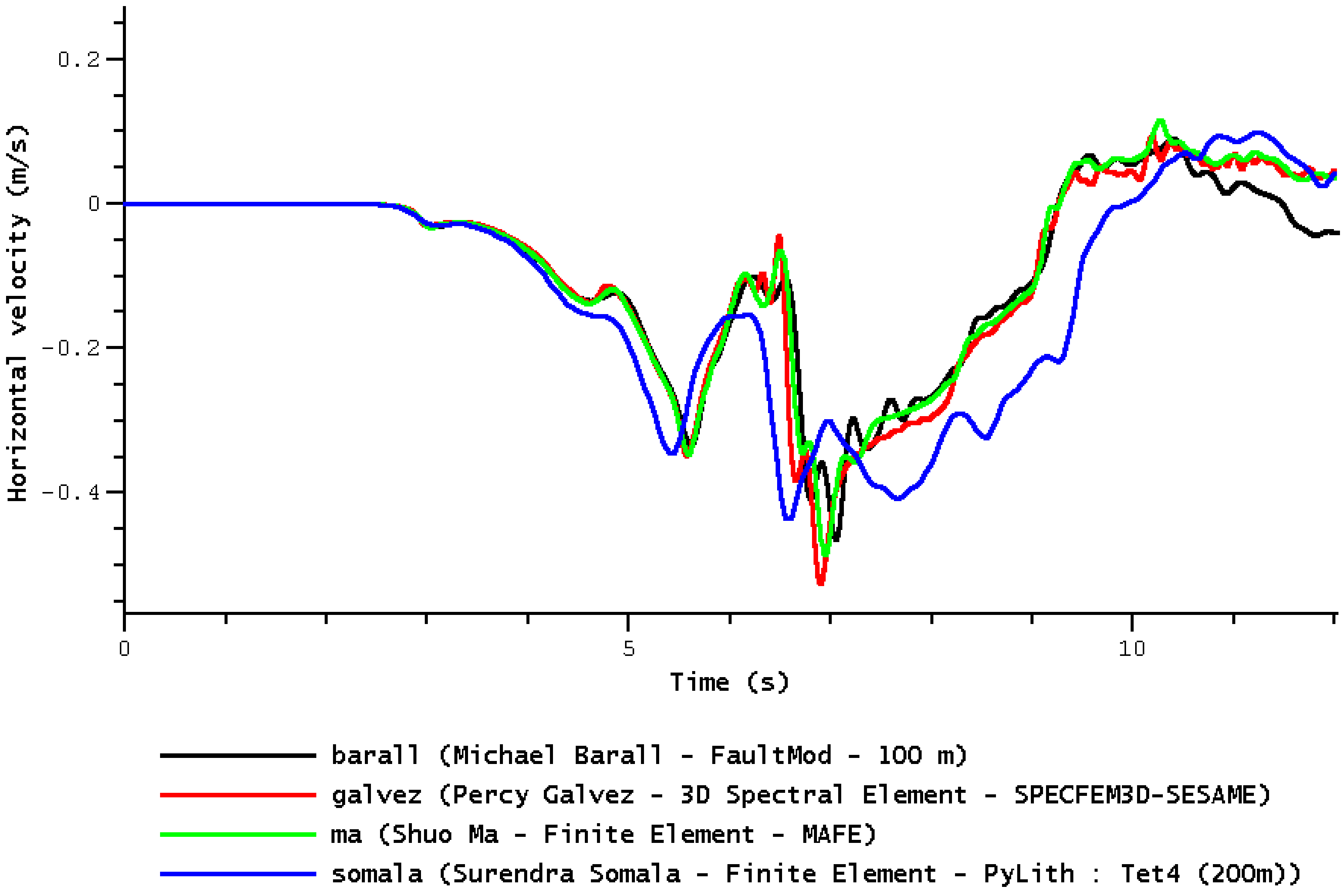
TPV14

[body-059st050dp000]

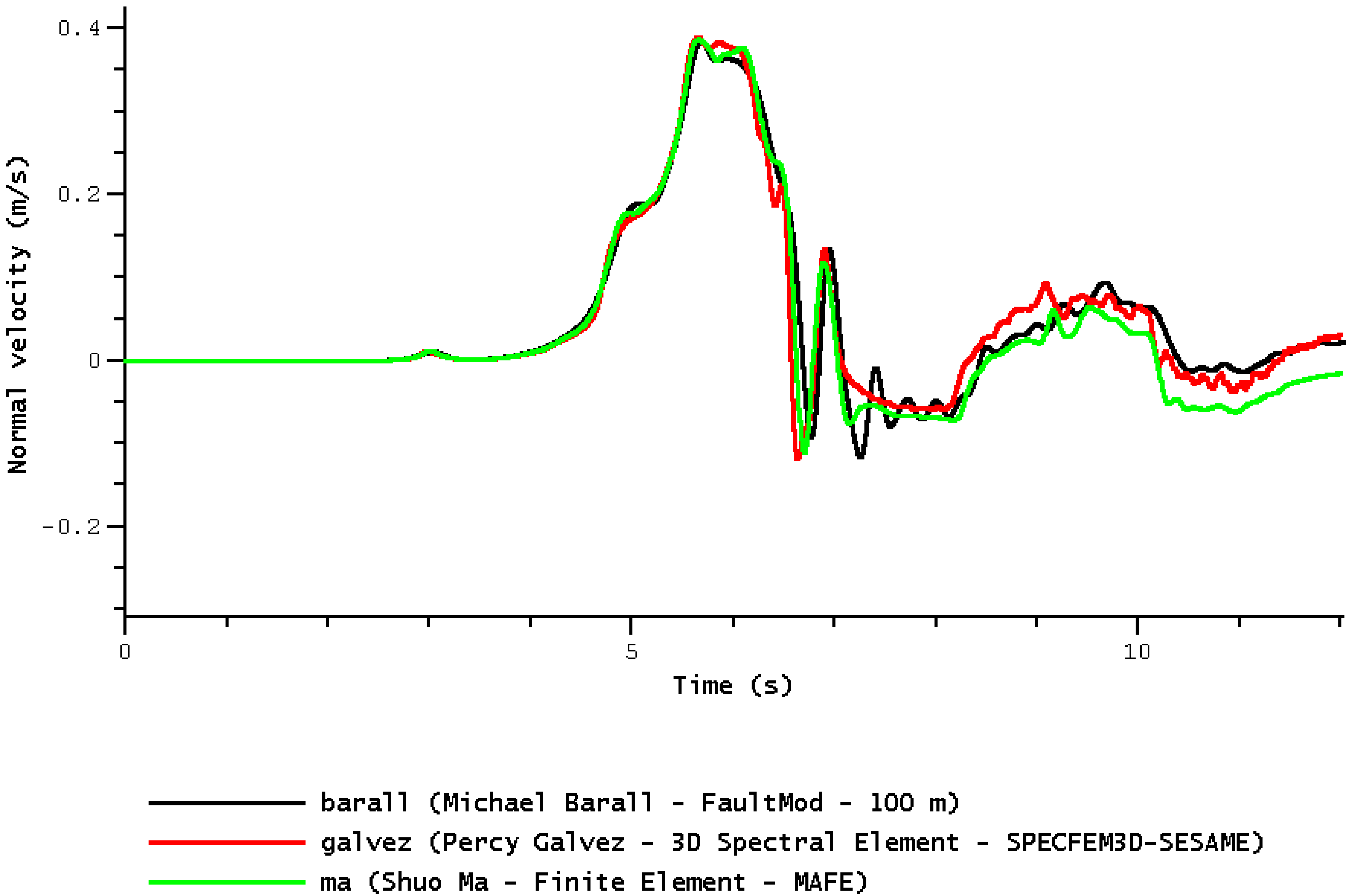


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

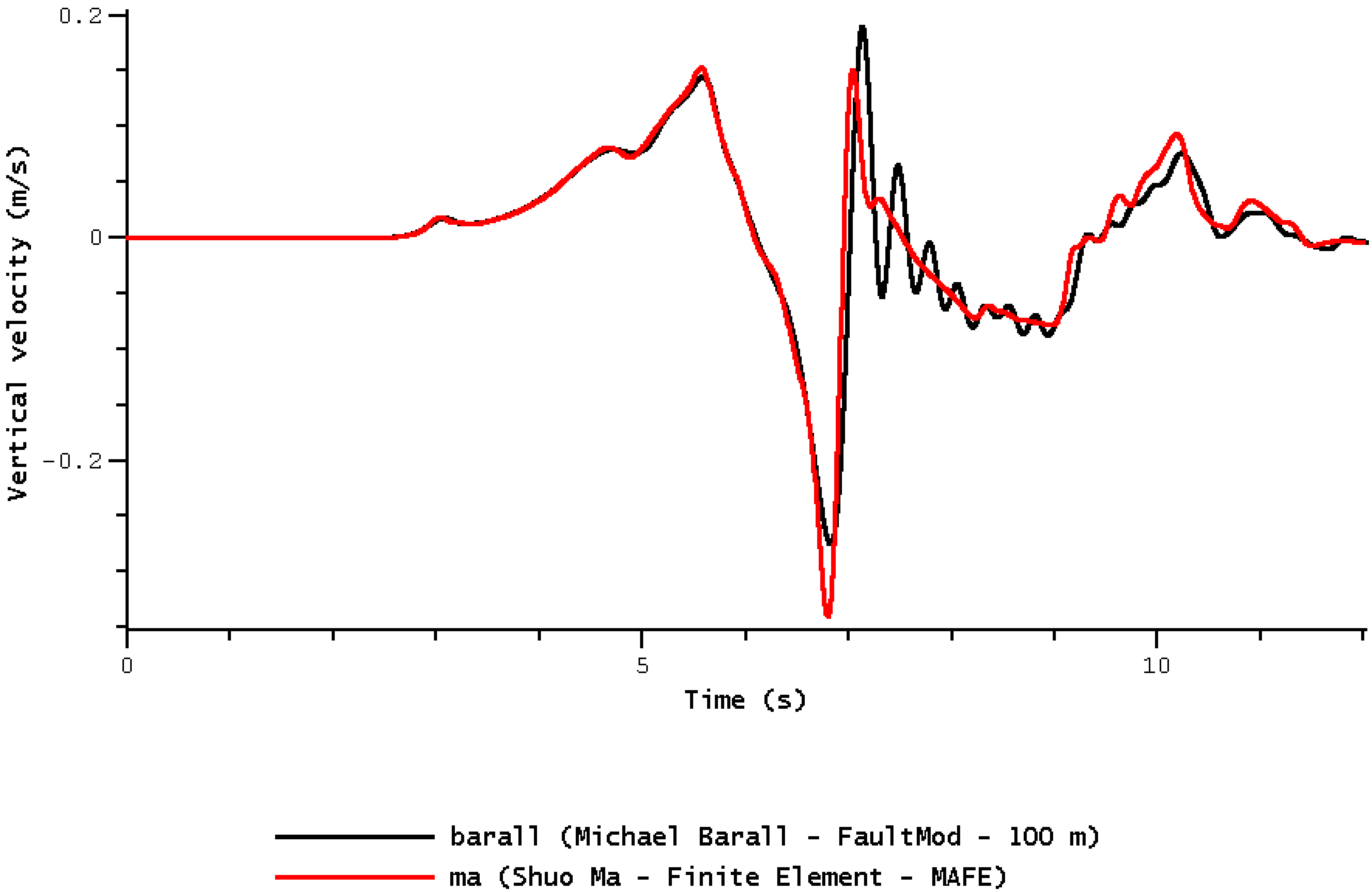
TPV14 — Horizontal Velocity [body-059st050dp000]



TPV14 — Normal Velocity [body-059st050dp000]



TPV14 — Vertical Velocity [body-059st050dp000]



TPV15

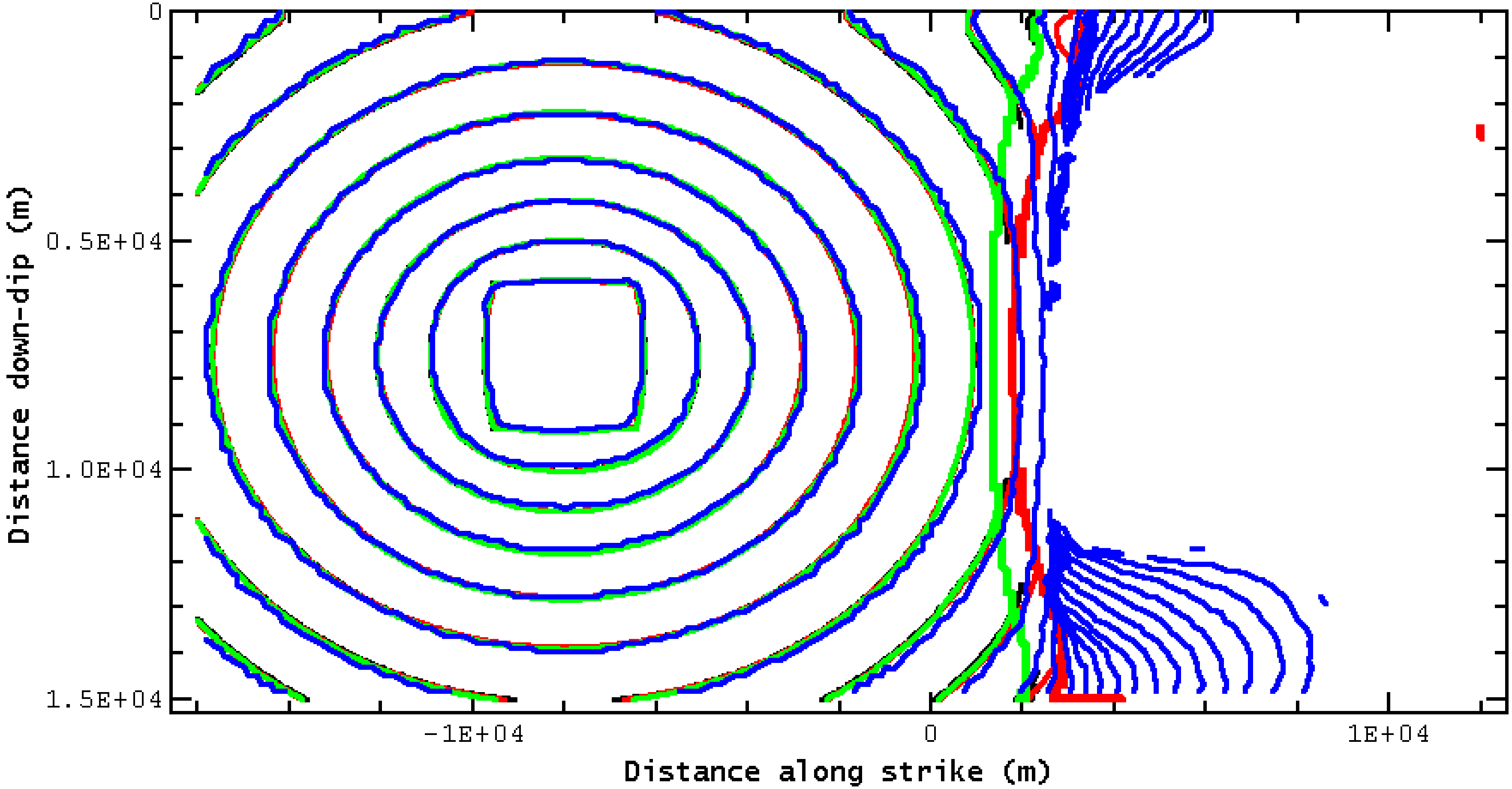
3D Benchmark.

Initial shear stress on branch fault = −78.0 MPa (left-lateral).

Expected outcome:

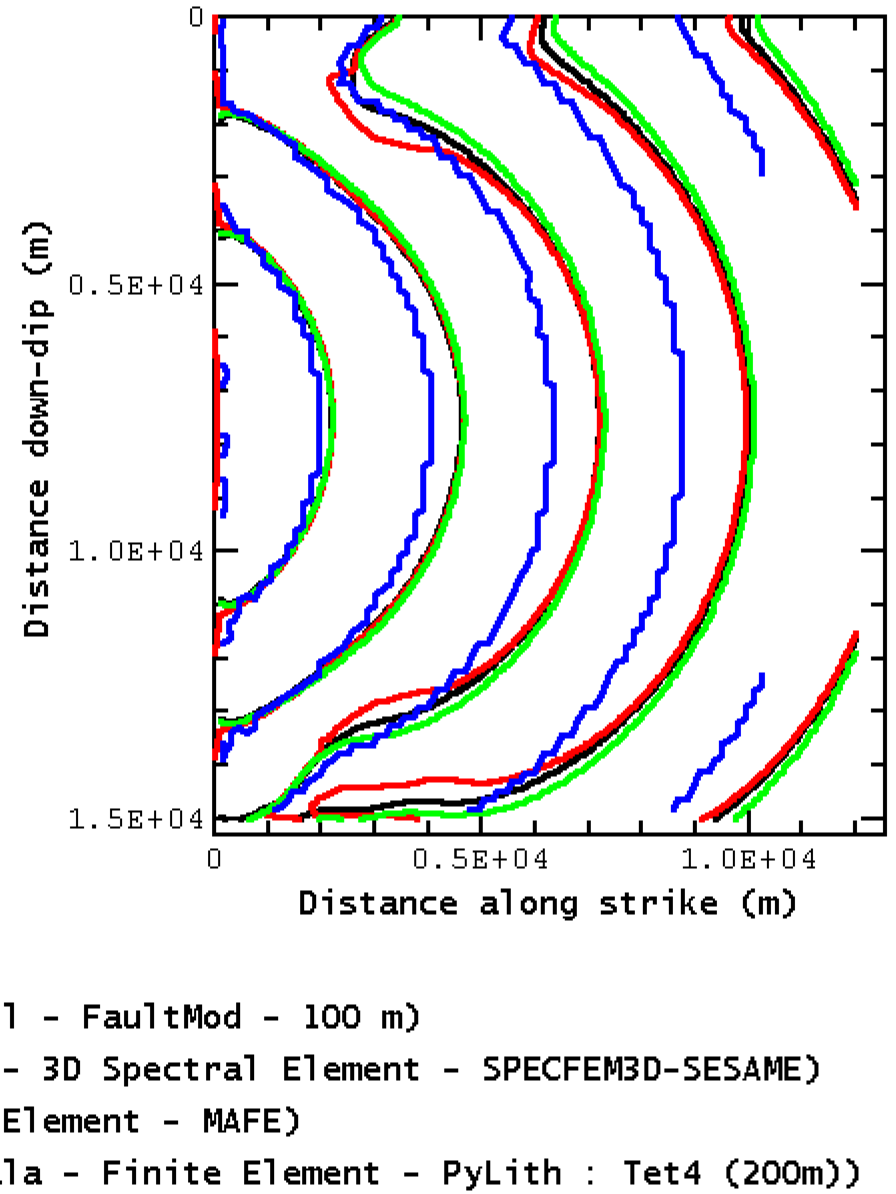
- Main fault rupture stops past the junction point.
- Branch fault ruptures completely.

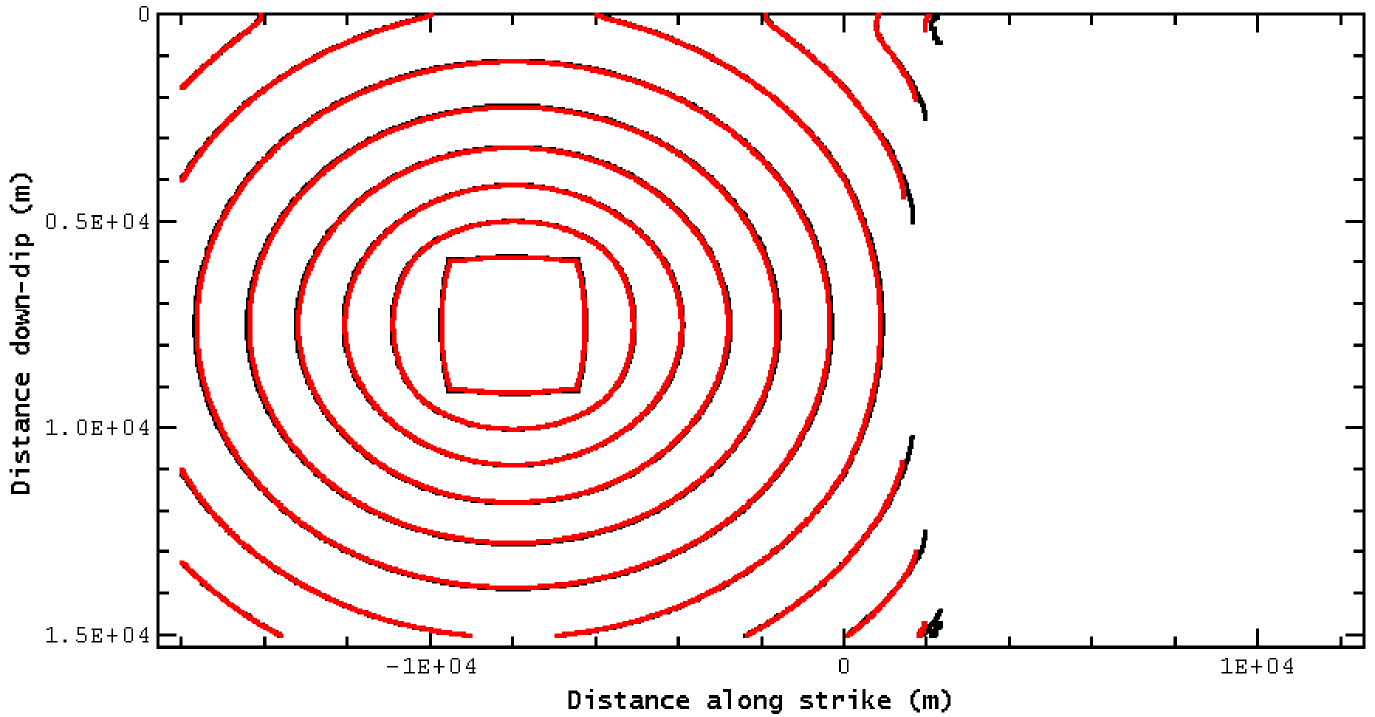
TPV15 — Main Fault Rupture Contours



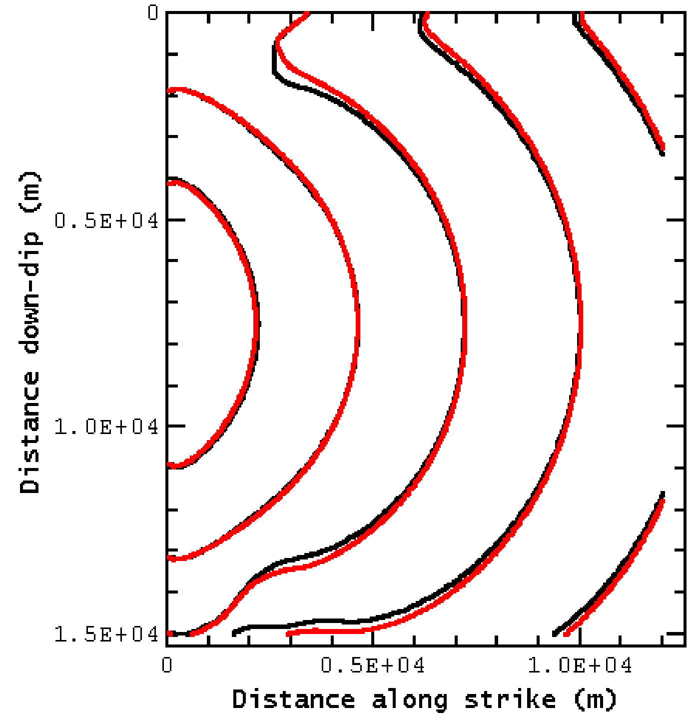
baral1 (Michael Barall - FaultMod - 100 m)
galvez (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Finite Element - PyLith : Tet4 (200m))

TPV15 — Branch Fault Rupture Contours





TPV15 — 100 m vs. 50 m Resolution

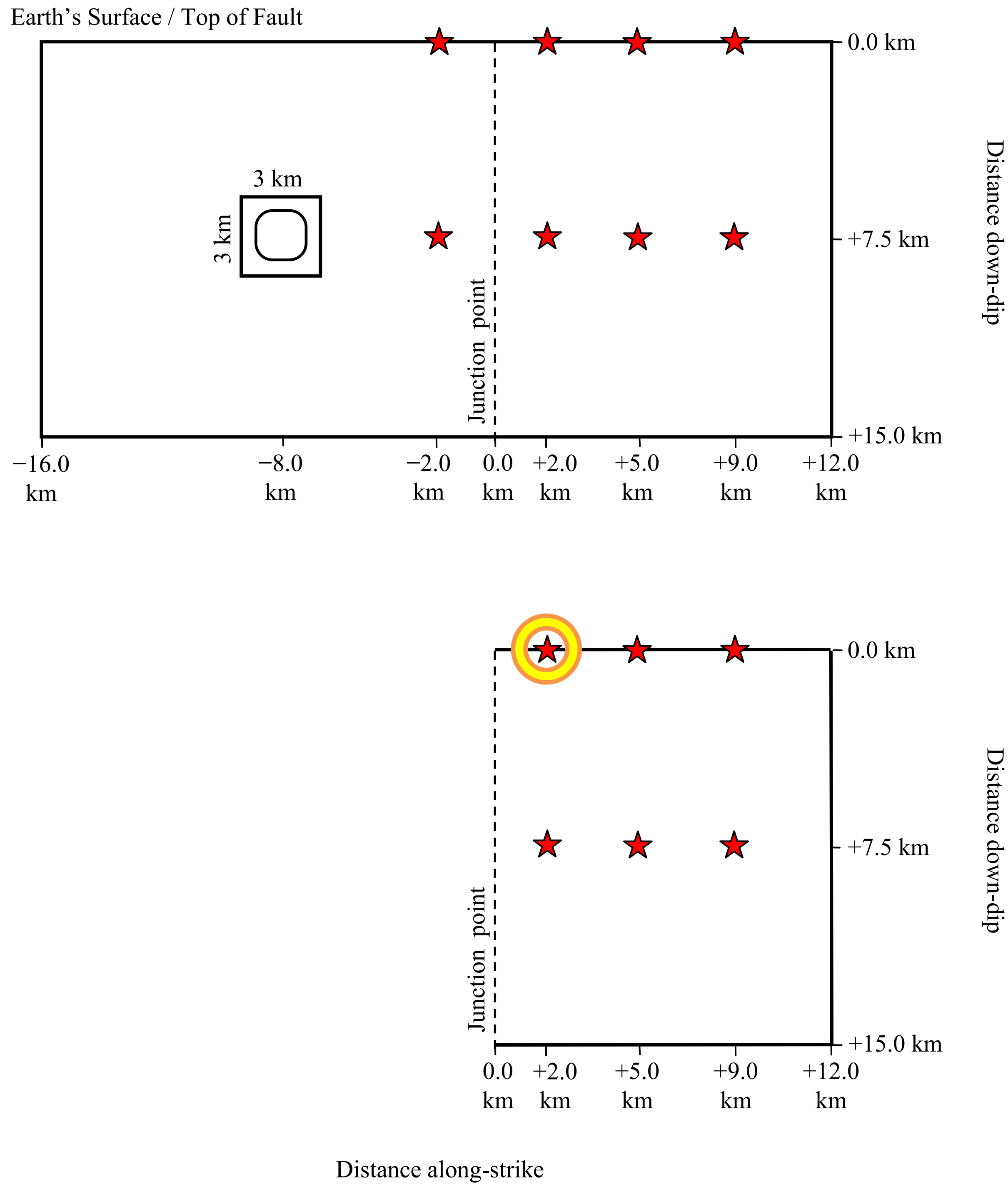


barall (Michael Barall - FaultMod - 100 m)

barall.2 (Michael Barall - FaultMod - 50 m)

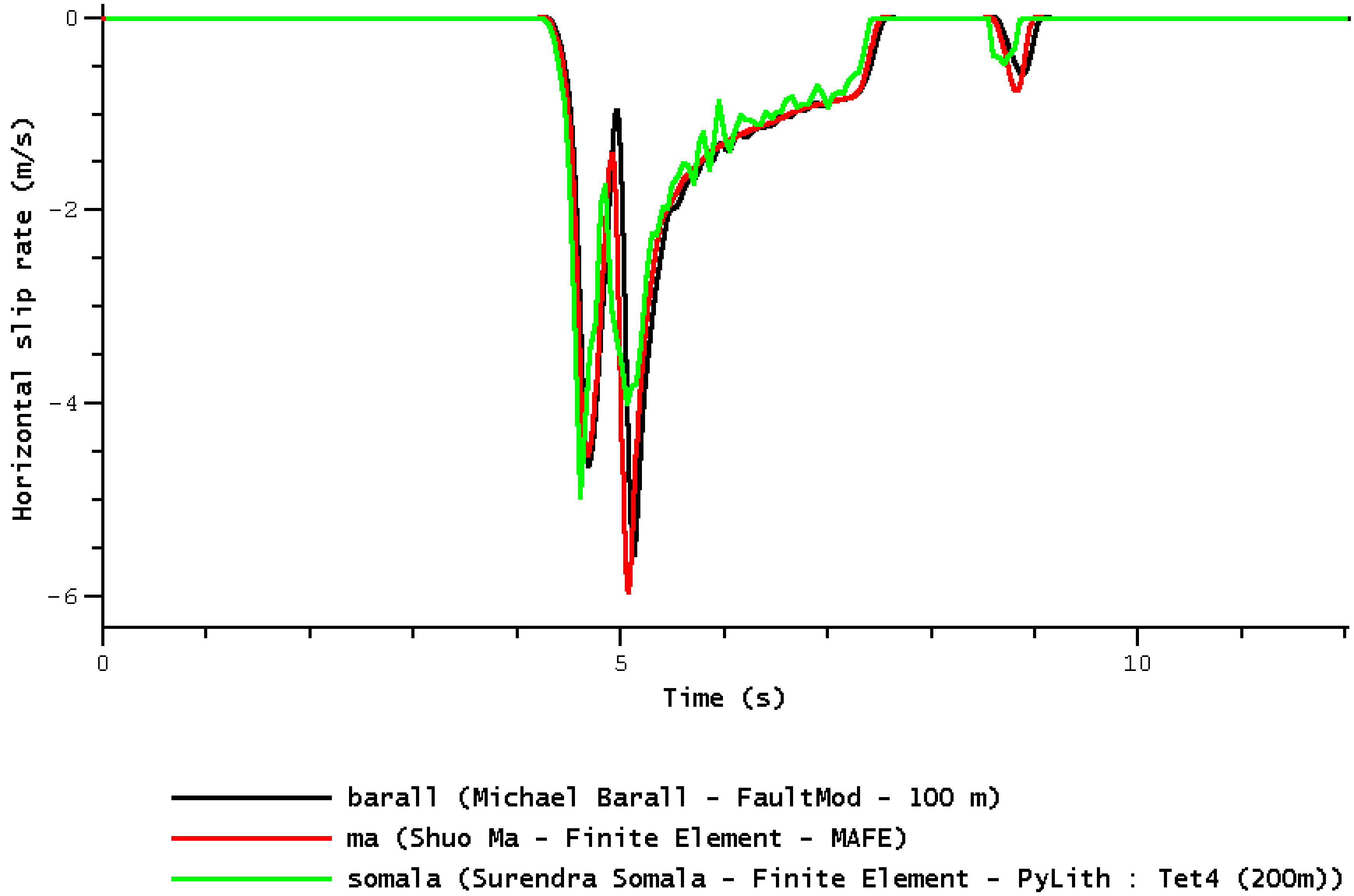
TPV15

[branchst020dp000]

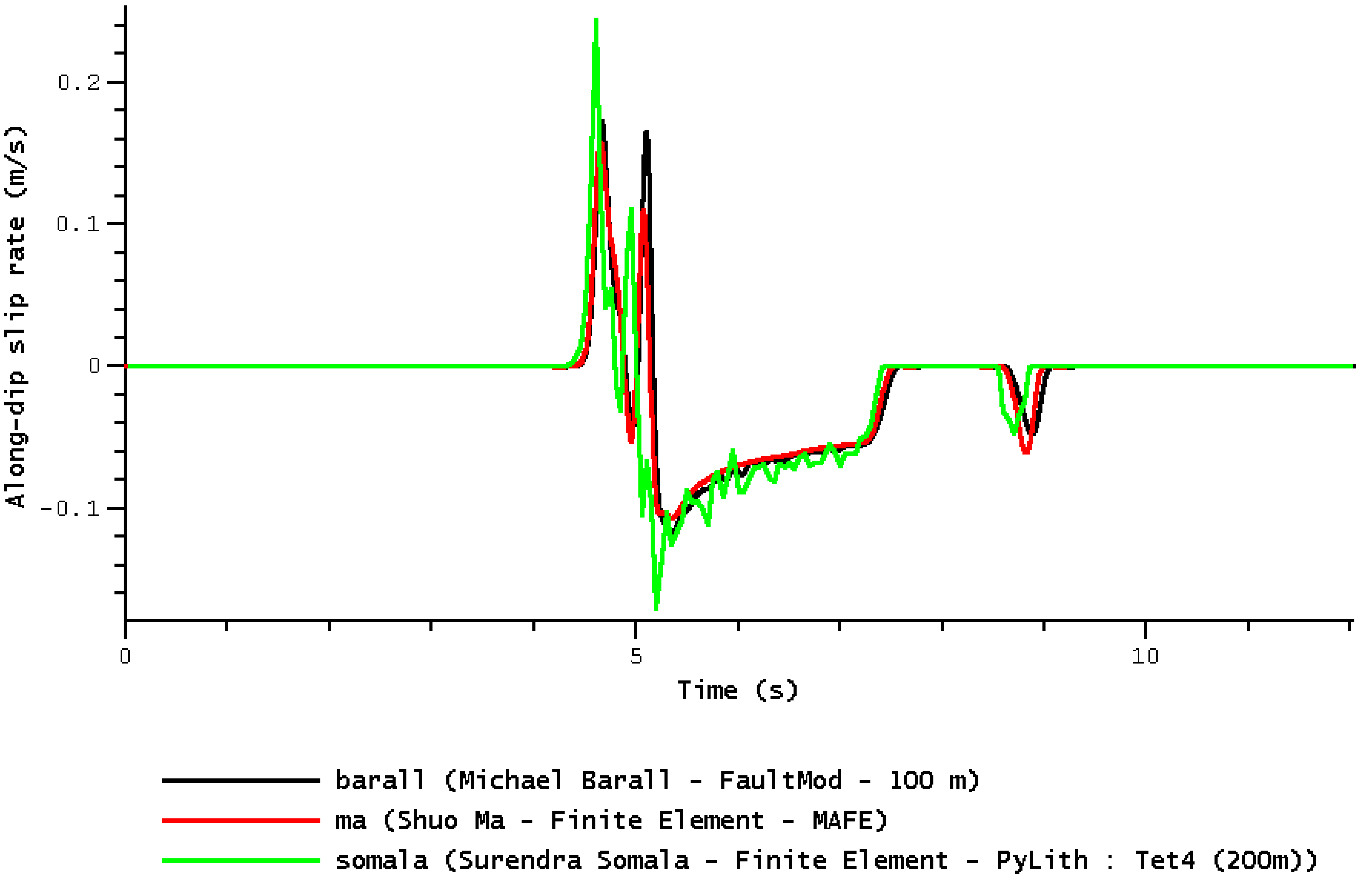


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

TPV15 — Horizontal Slip Rate [branchst020dp000]

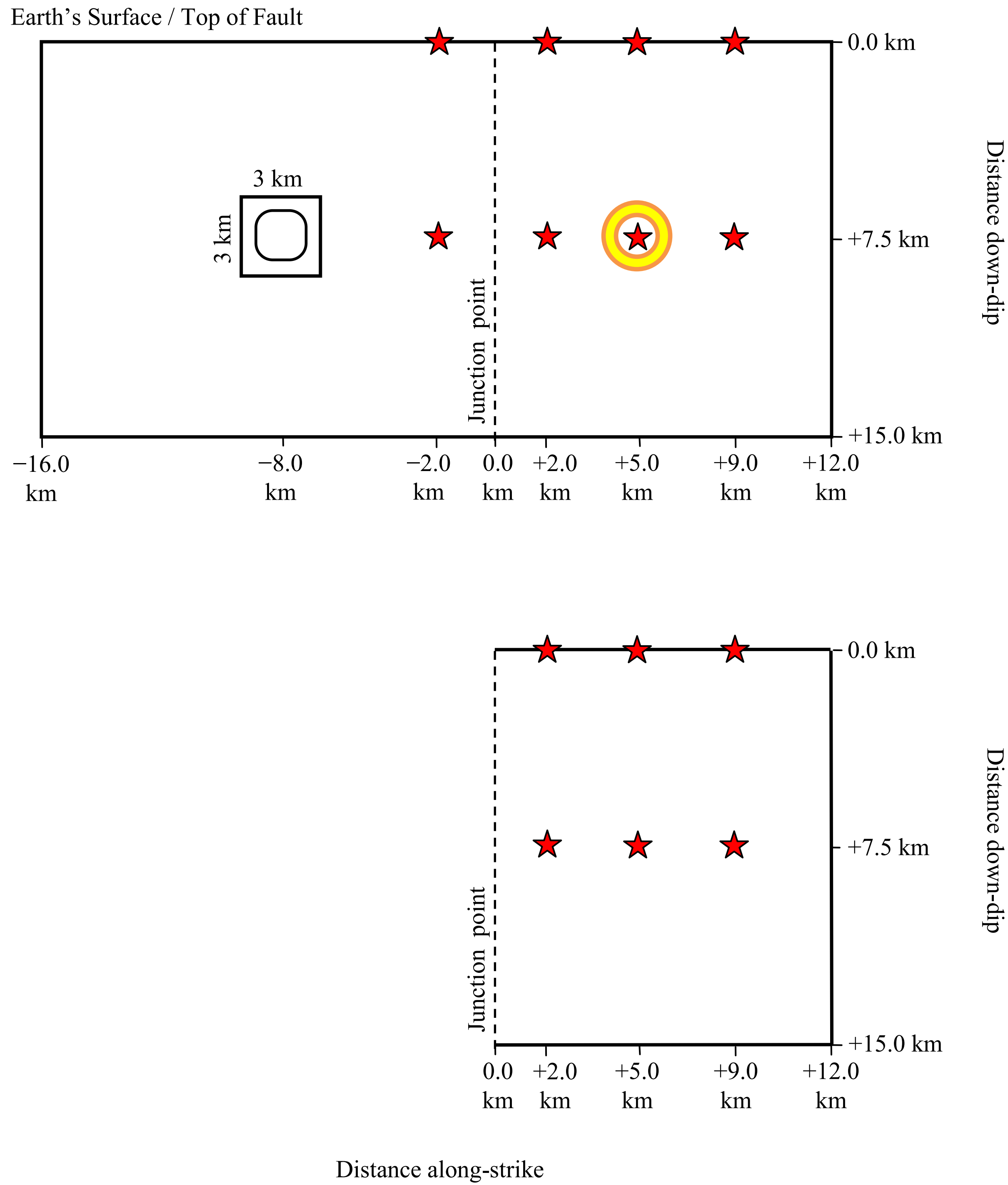


TPV15 — Vertical Slip Rate [branchst020dp000]



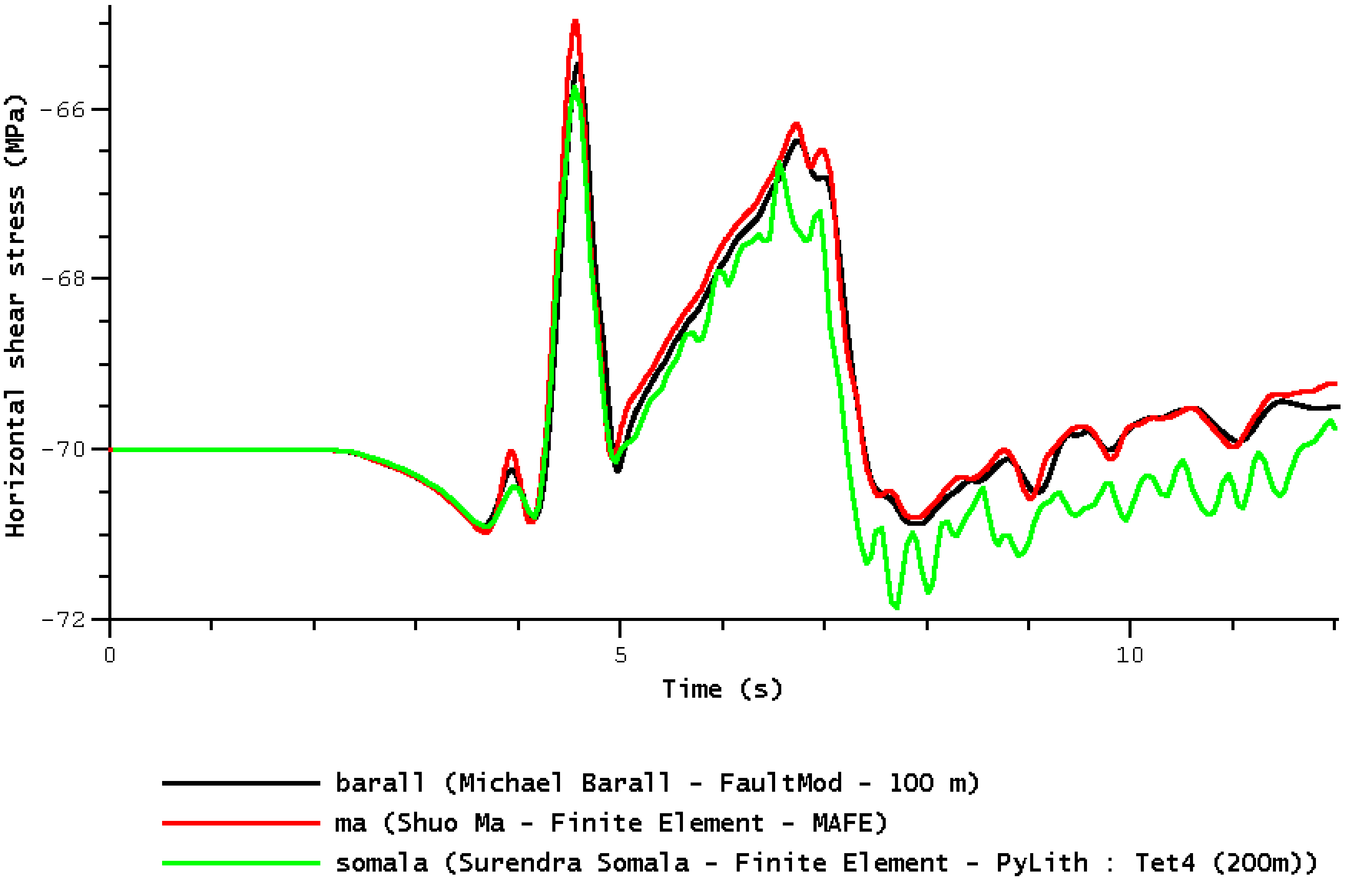
TPV15

[faultst050dp075]

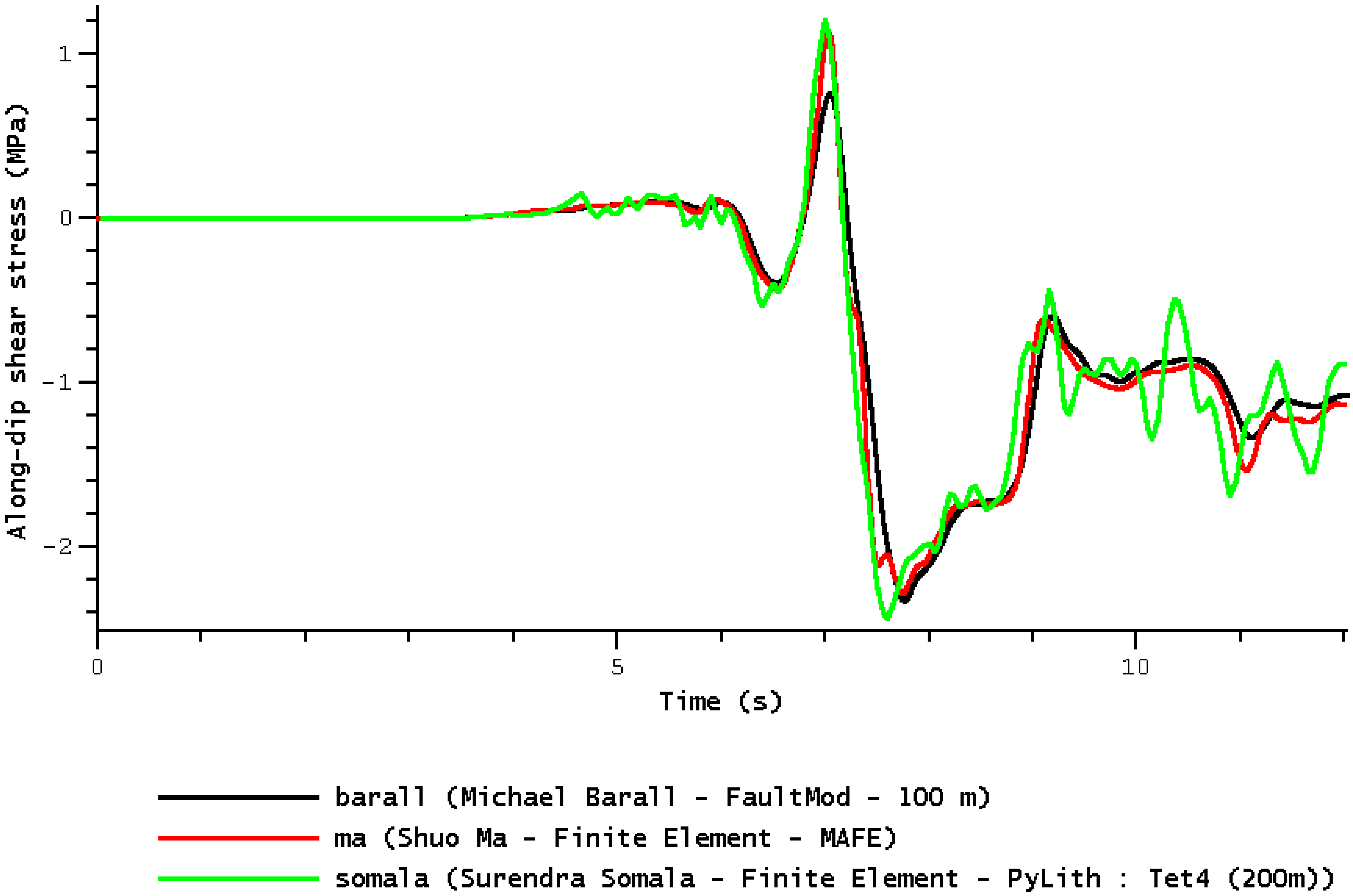


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

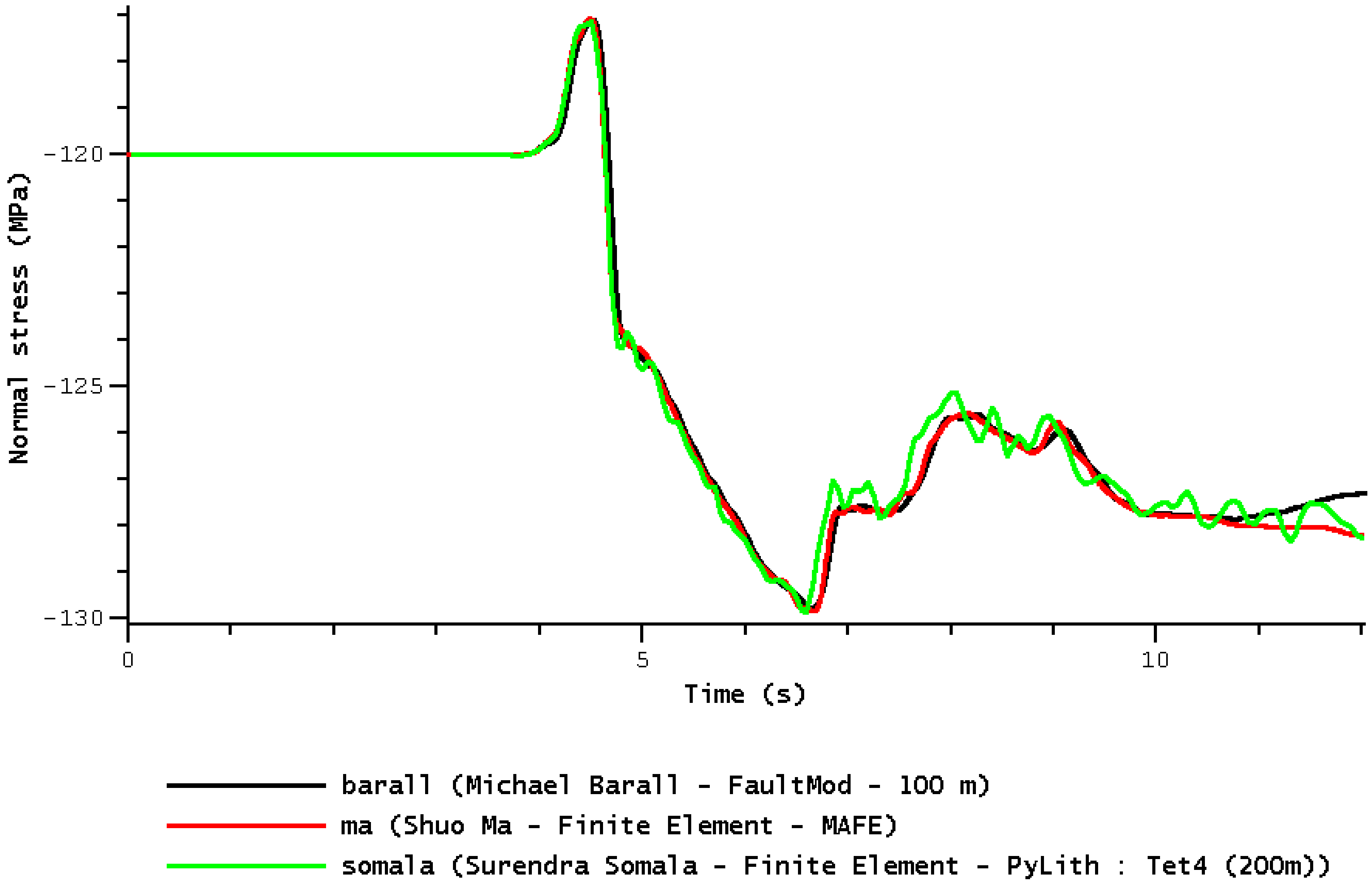
TPV15 — Horizontal Shear Stress [faultst050dp075]



TPV15 — Vertical Shear Stress [faultst050dp075]

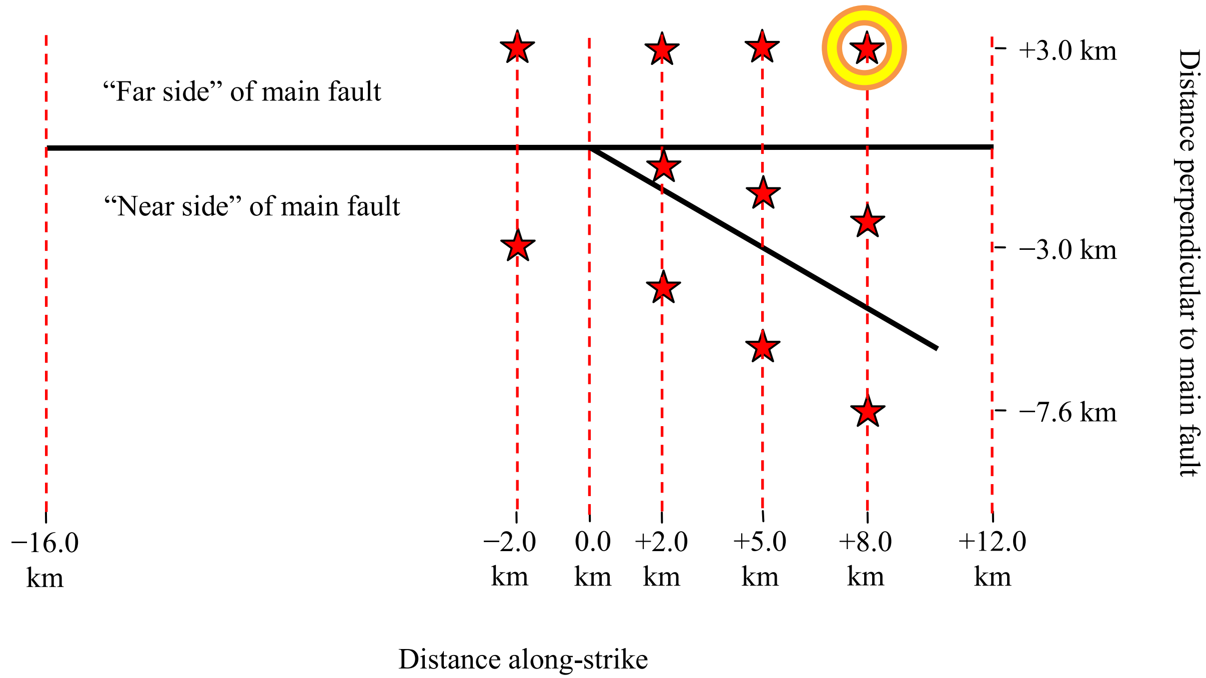


TPV15 — Normal Stress [faultst050dp075]



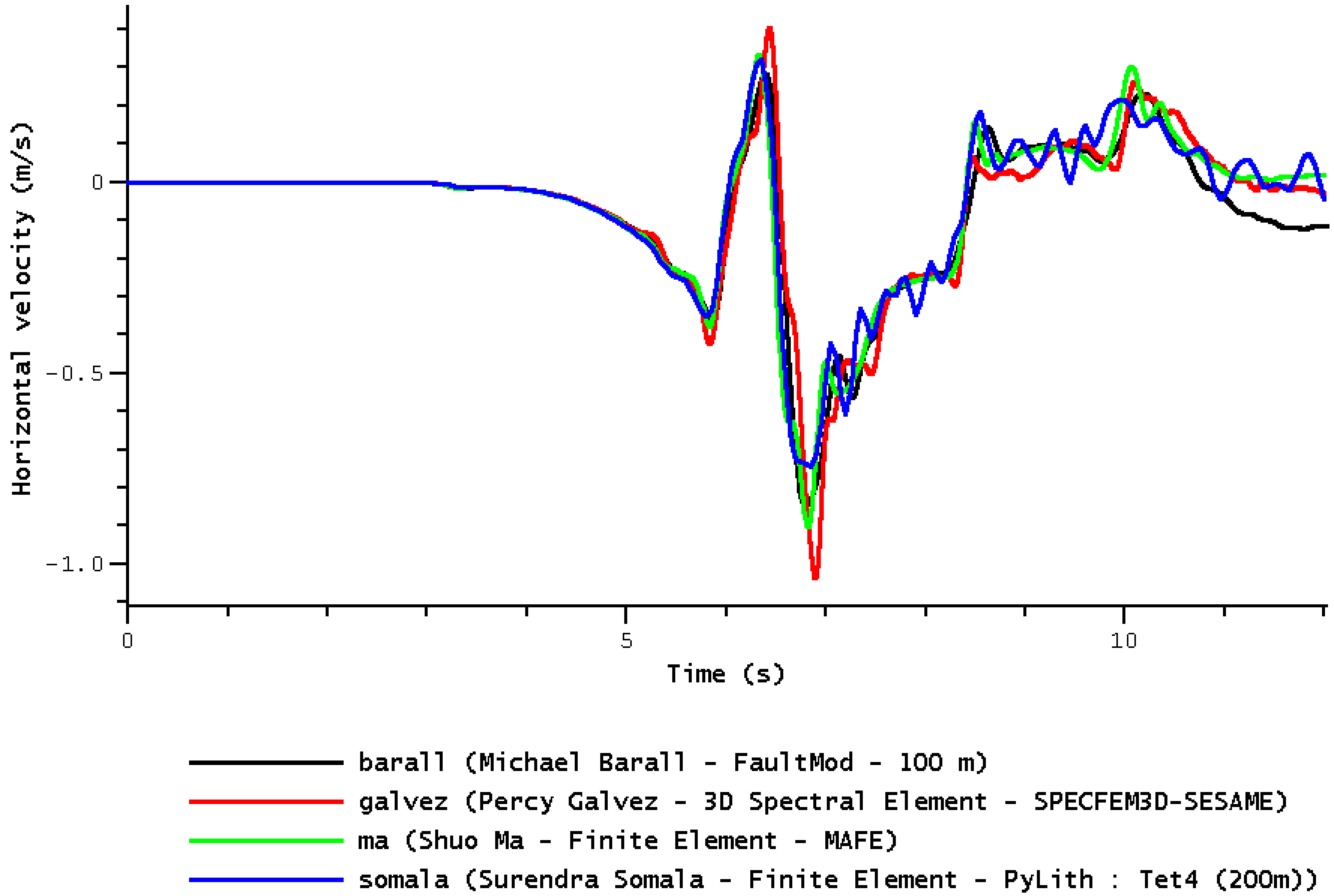
TPV15

[body030st080dp000]

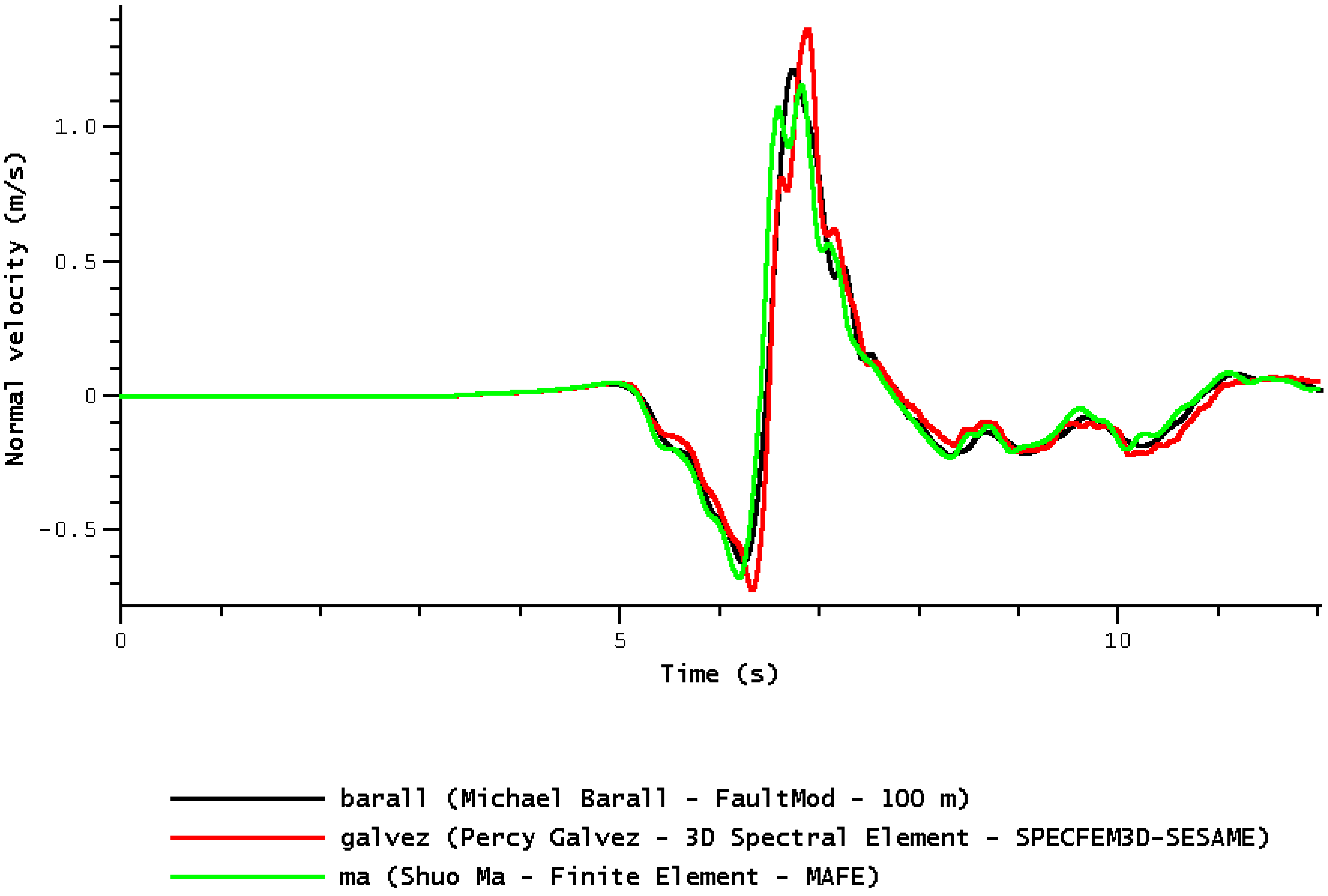


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

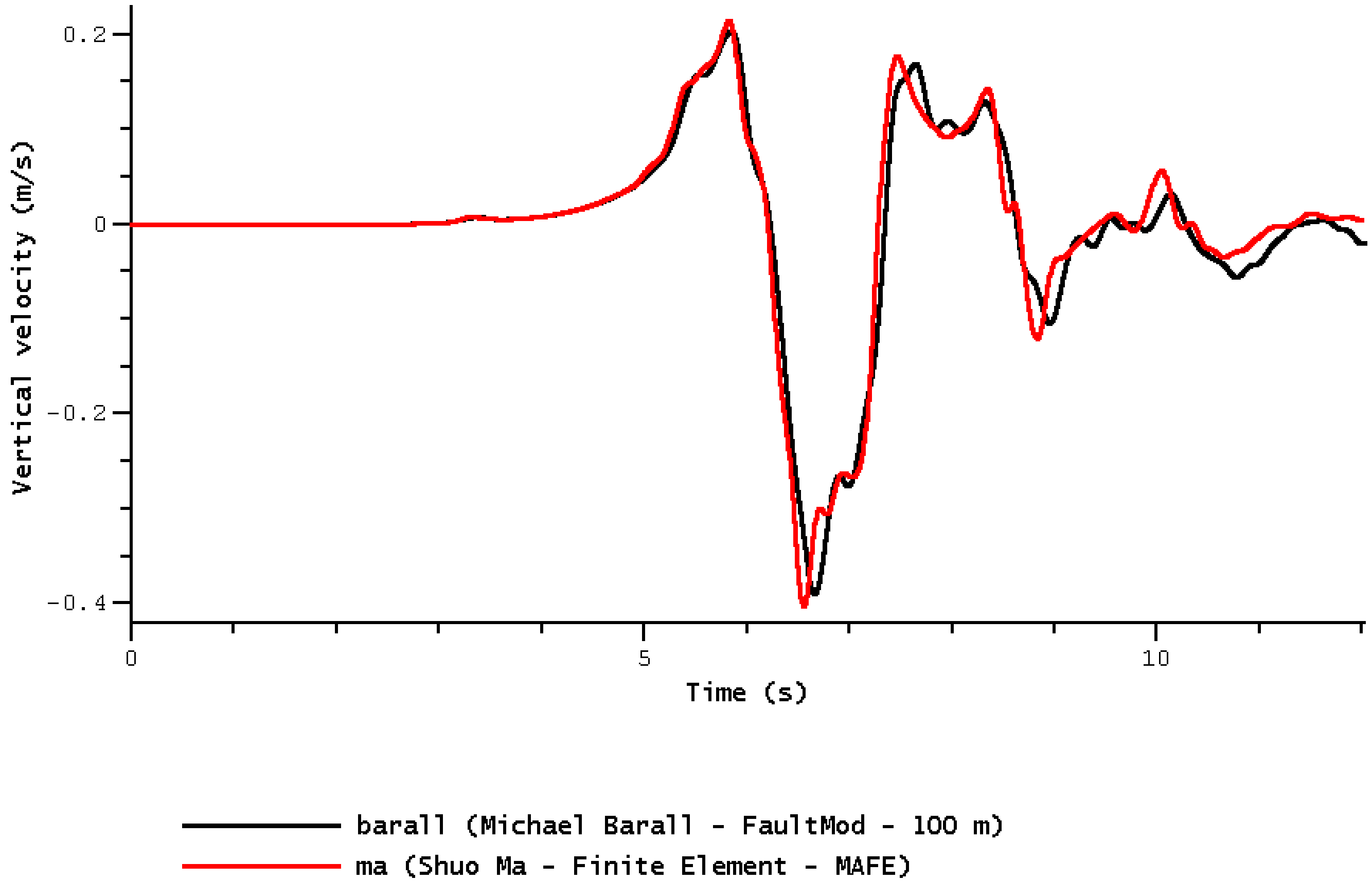
TPV15 — Horizontal Velocity [body030st080dp000]



TPV15 — Normal Velocity [body030st080dp000]



TPV15 — Vertical Velocity [body030st080dp000]



TPV14-2D

2D Benchmark.

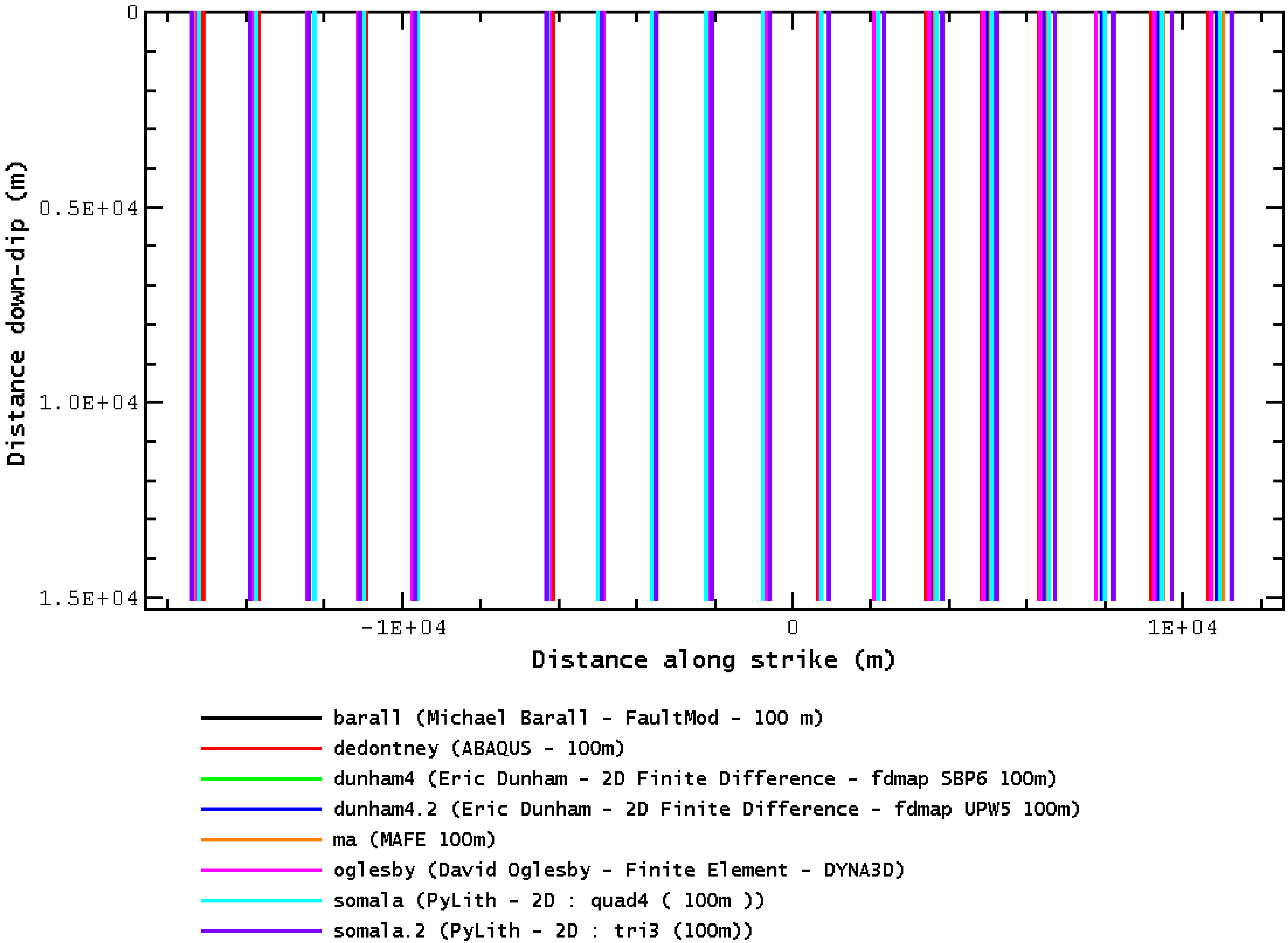
Initial shear stress on branch fault = +70.0 MPa (right-lateral).

Expected outcome:

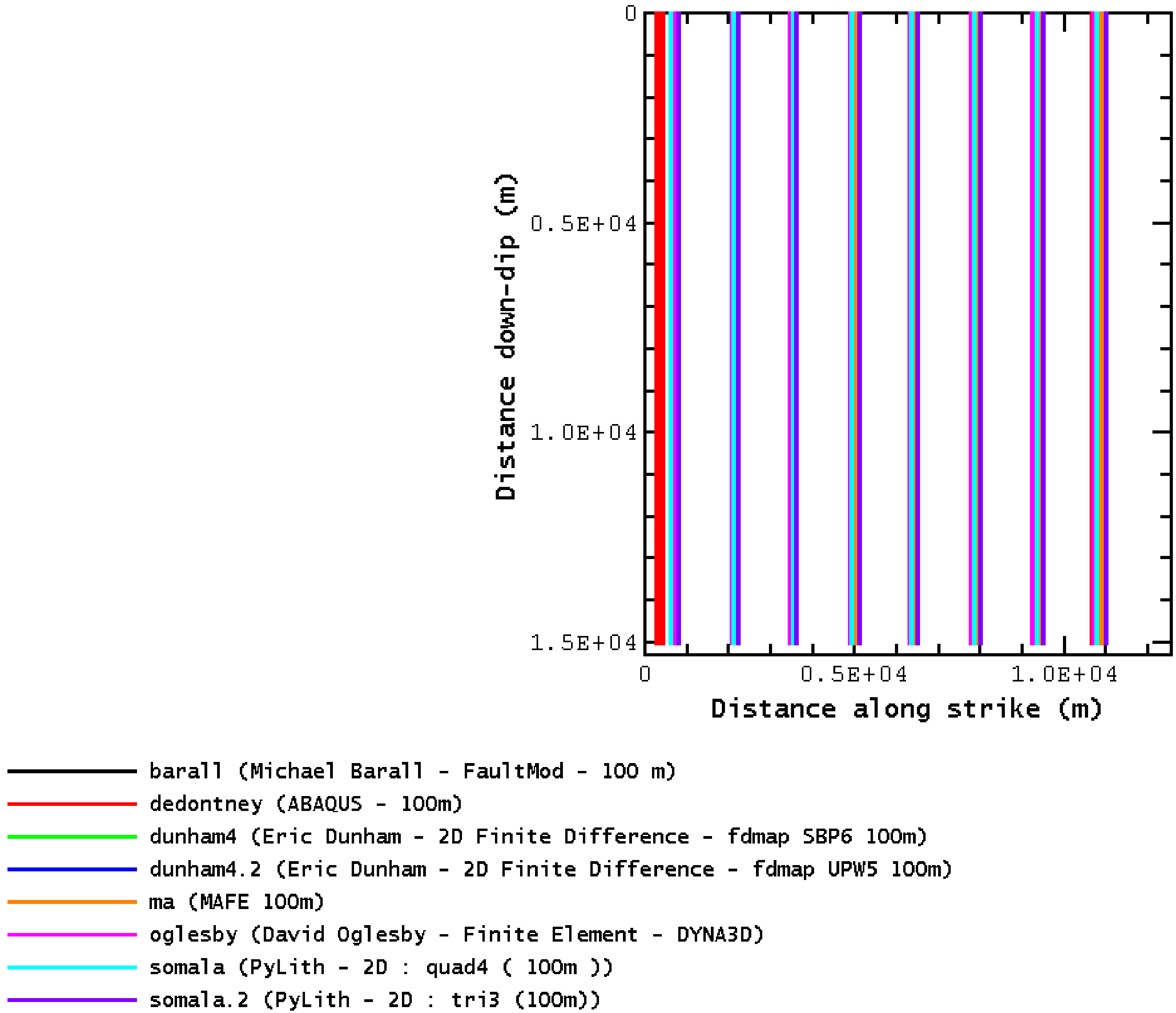
- Main fault ruptures completely.
- Branch fault ruptures completely.

Note: The expected outcome is different than the 3D case.

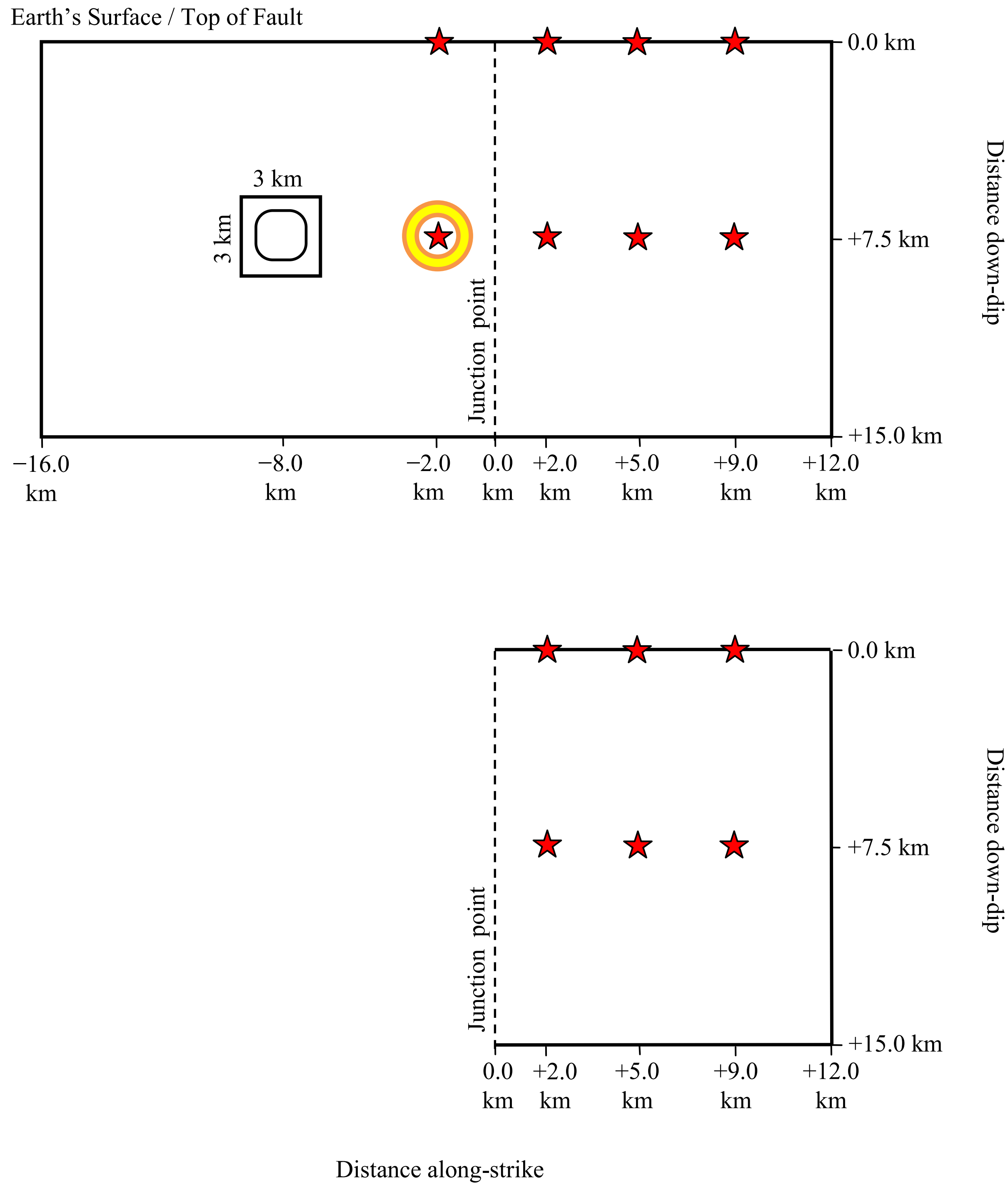
TPV14-2D — Main Fault Rupture Contours



TPV14-2D — Branch Fault Rupture Contours

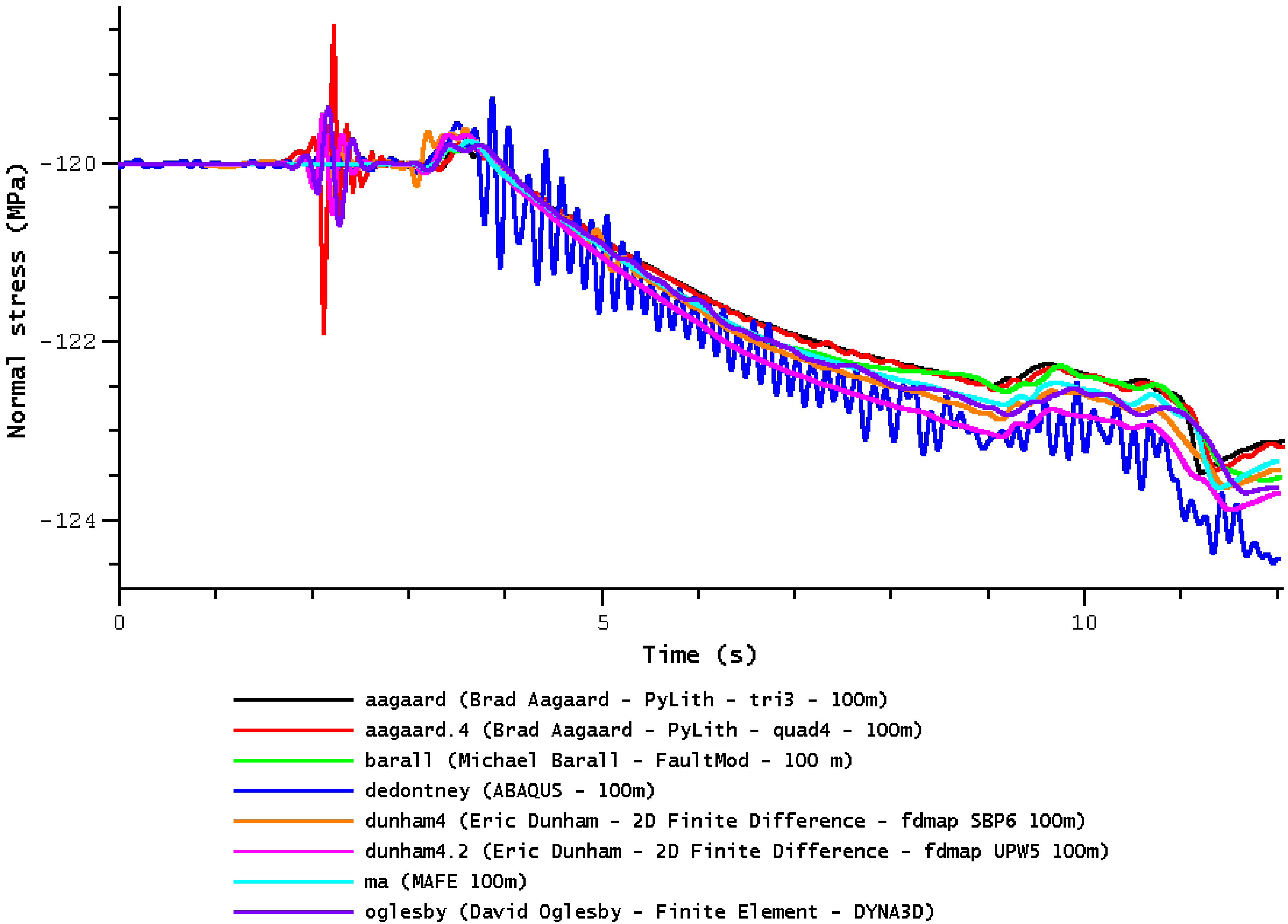


TPV14-2D
[faultst-020dp075]

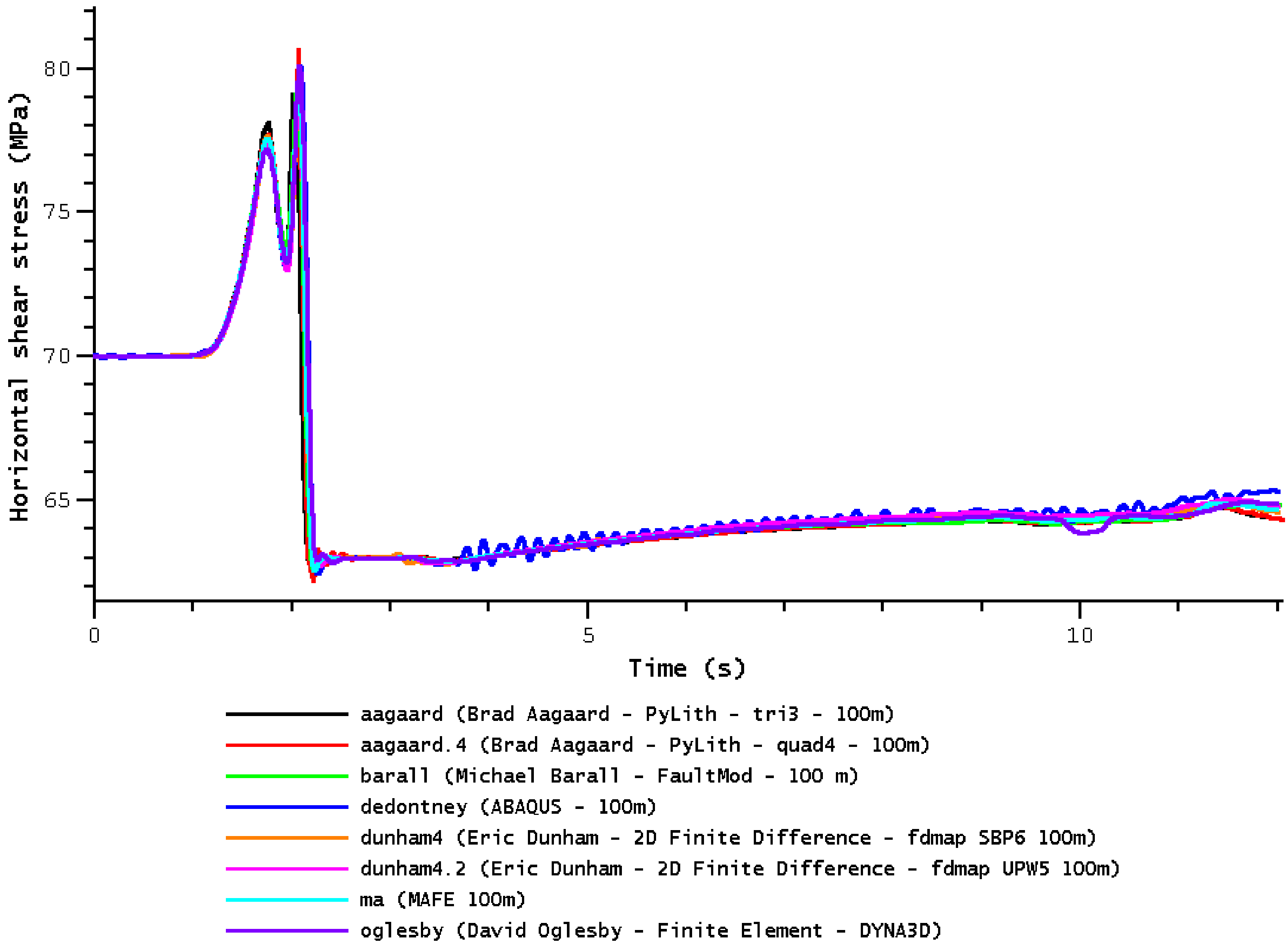


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

TPV14-2D — Normal Stress [faultst-020dp075]

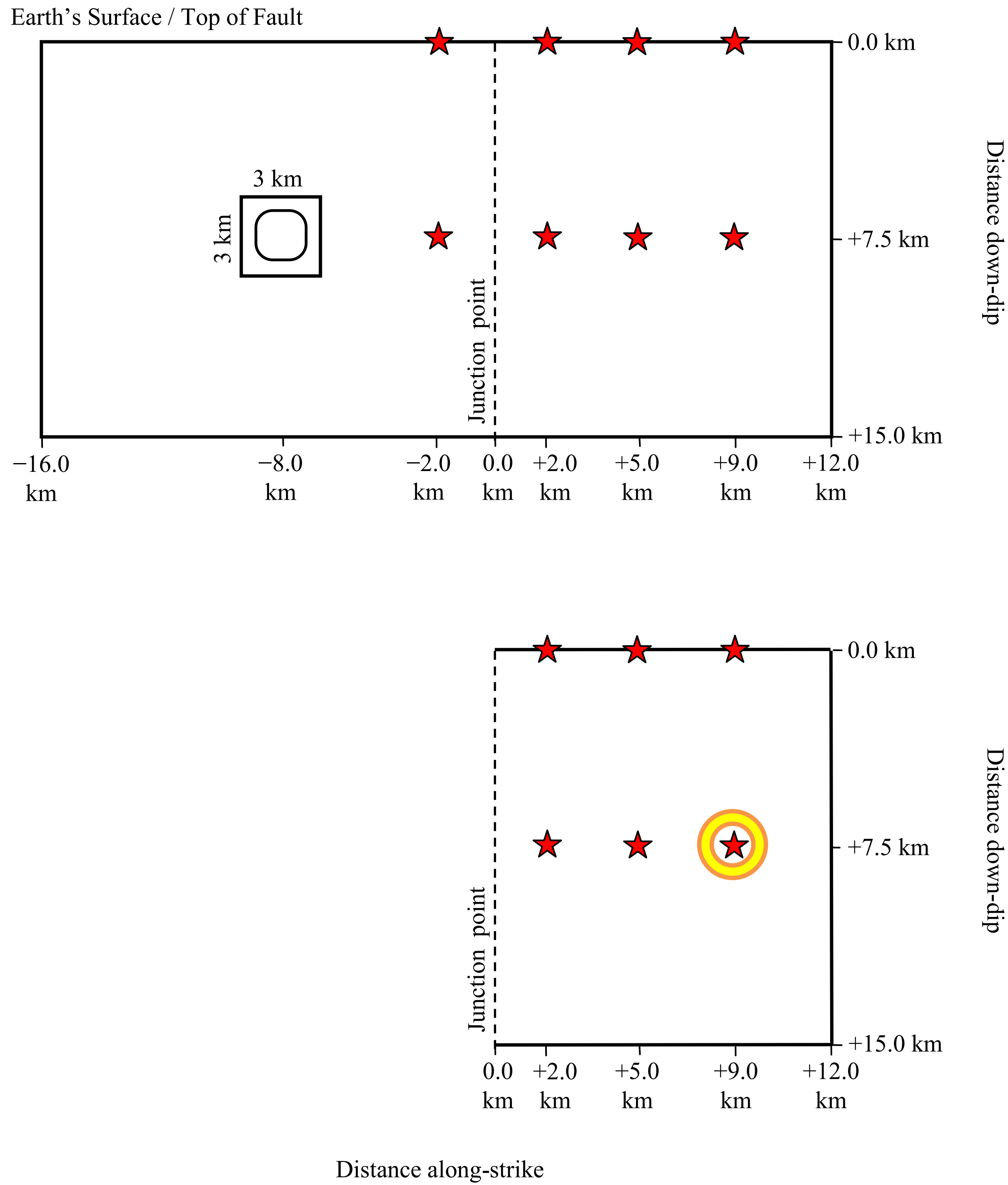


TPV14-2D — Horizontal Shear Stress [faultst-020dp075]



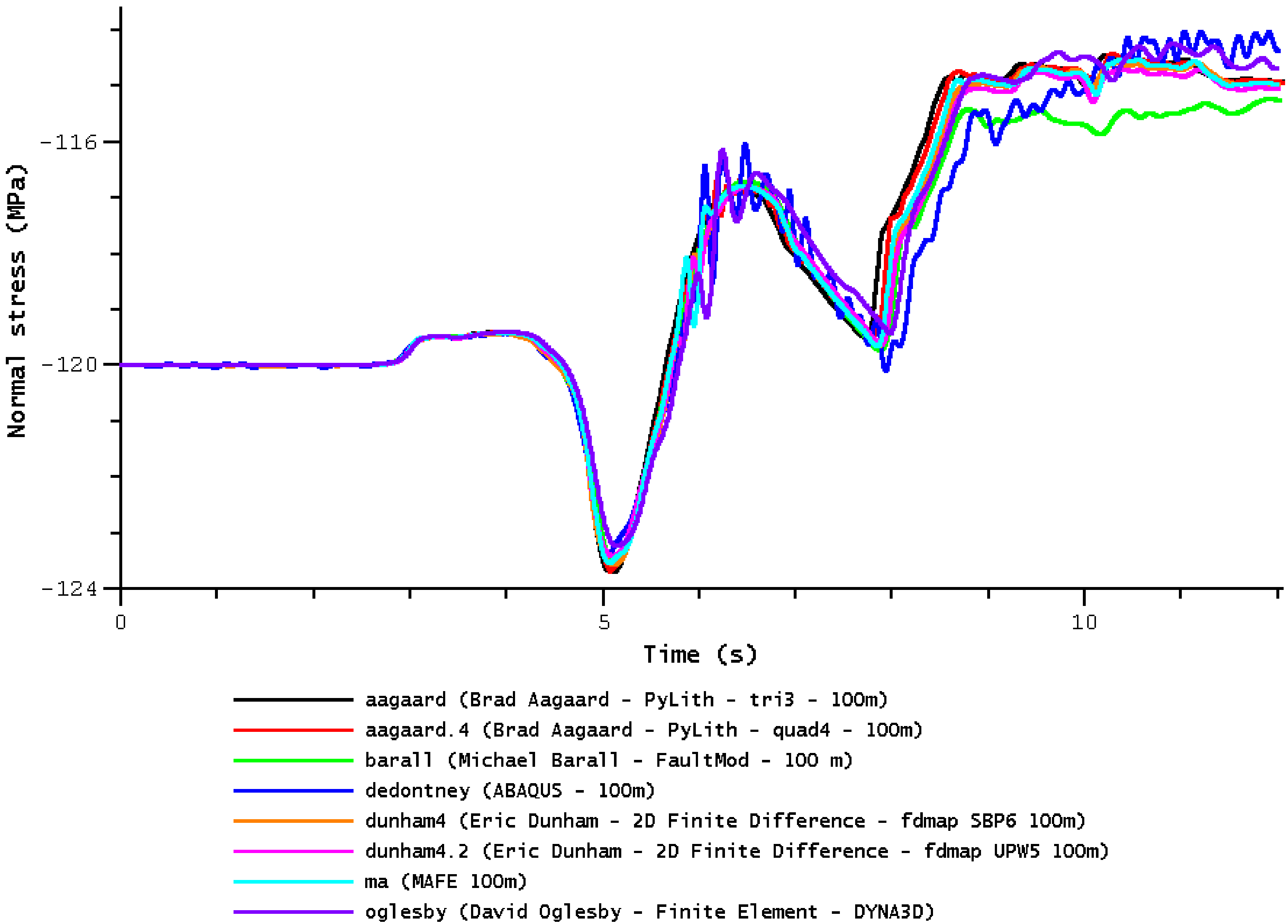
TPV14-2D

[branchst090dp075]

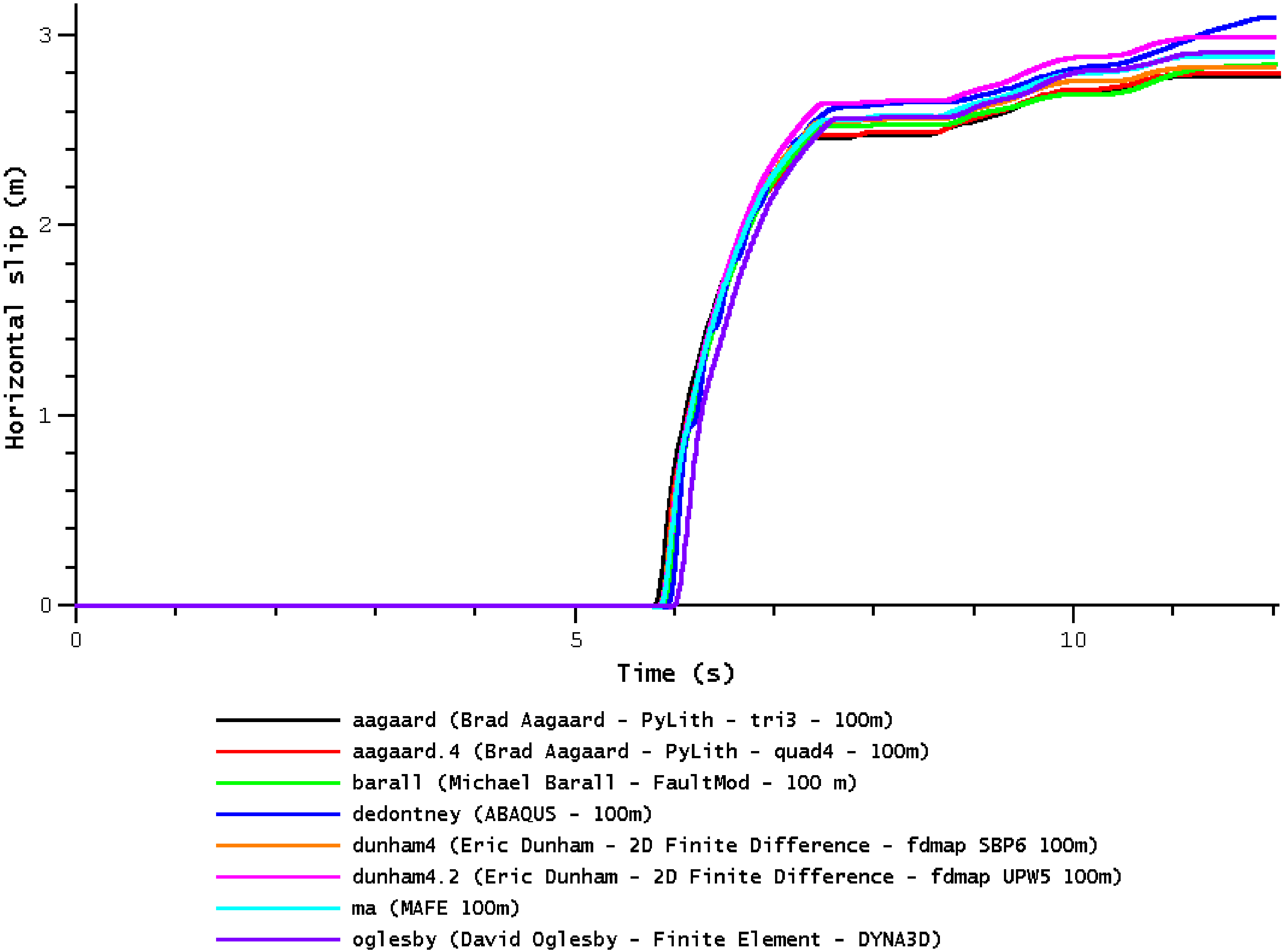


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

TPV14-2D — Normal Stress [branchst090dp075]

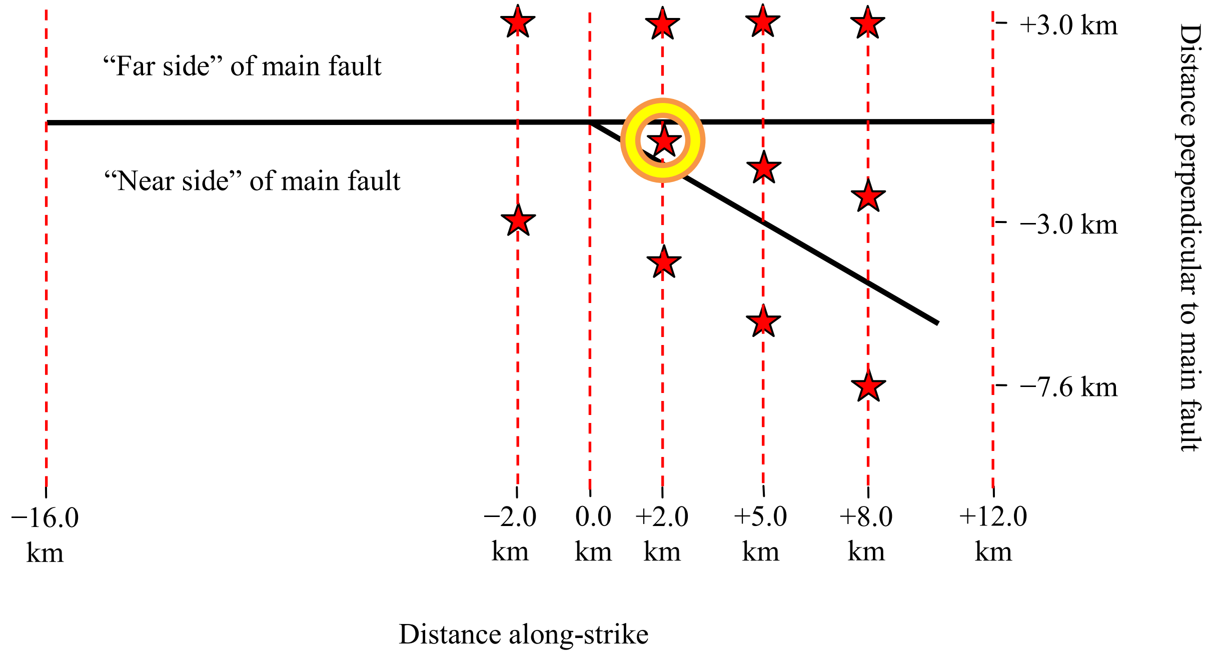


TPV14-2D — Horizontal Slip [branchst090dp075]



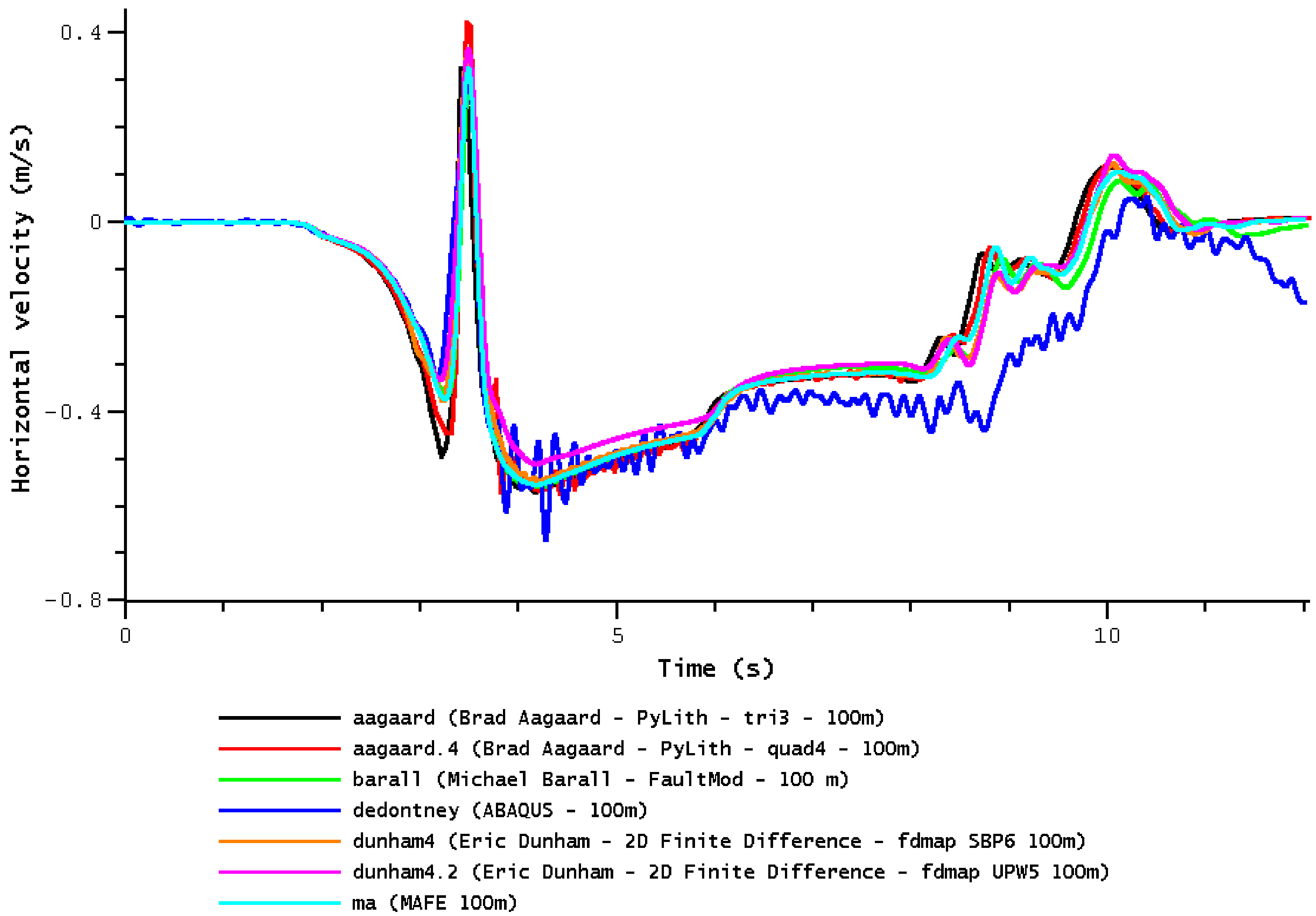
TPV14-2D

[body-006st020dp075]

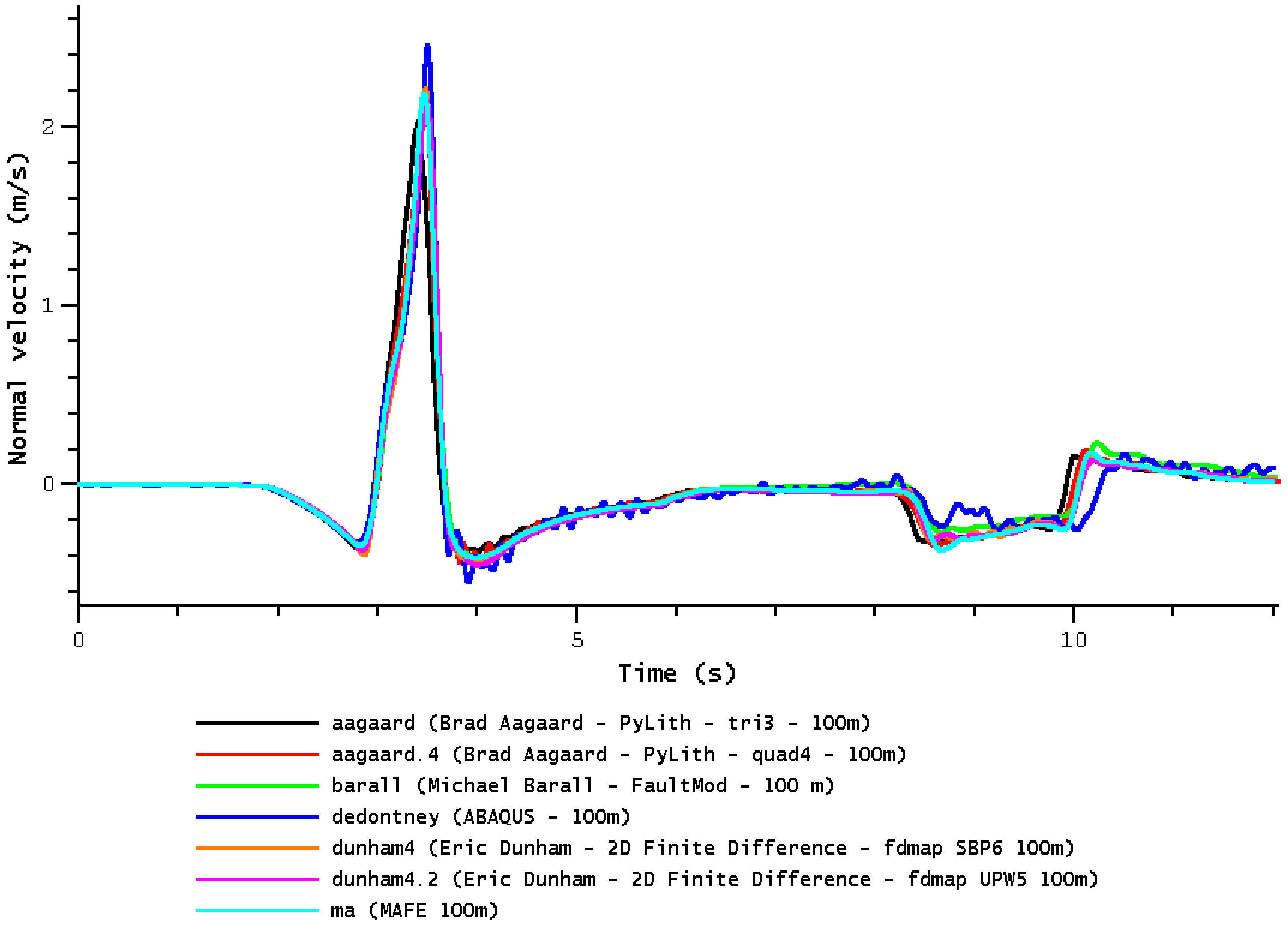


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

TPV14-2D — Horizontal Velocity [body-006st020dp075]



TPV14-2D — Normal Velocity [body-006st020dp075]



TPV15-2D

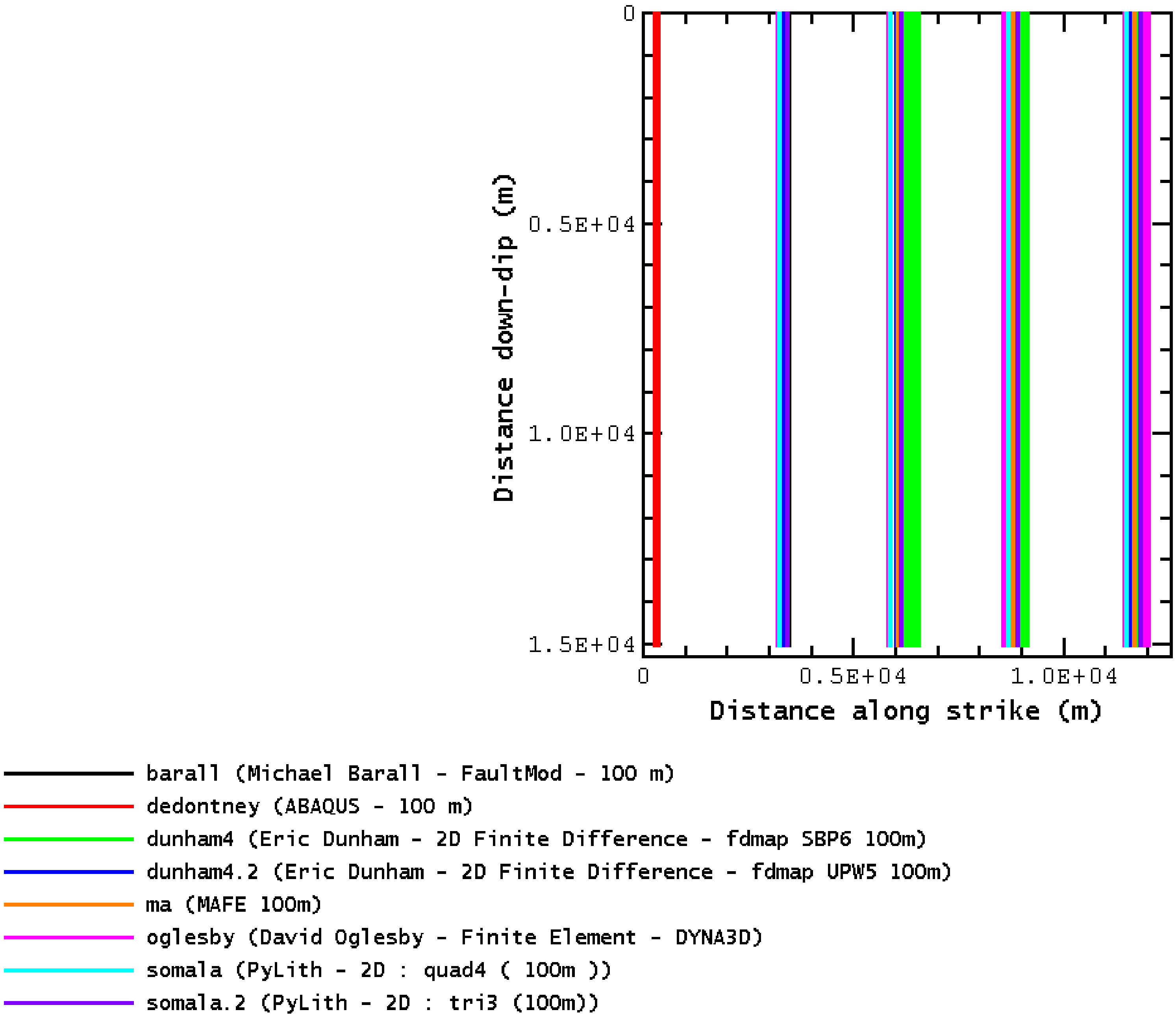
2D Benchmark.

Initial shear stress on branch fault = −78.0 MPa (left-lateral).

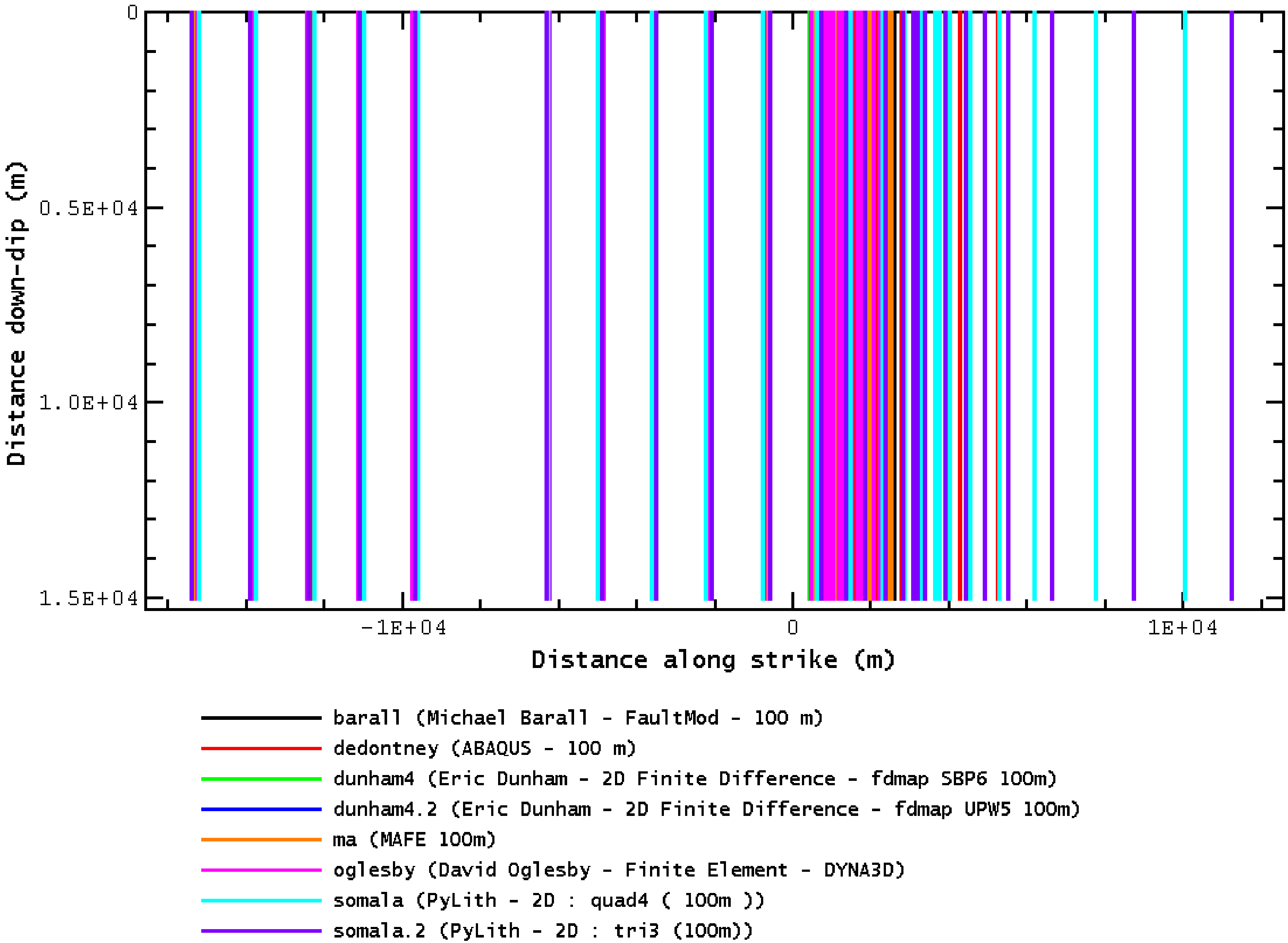
Expected outcome:

- Main fault rupture stops past the junction point.
- Branch fault ruptures completely.

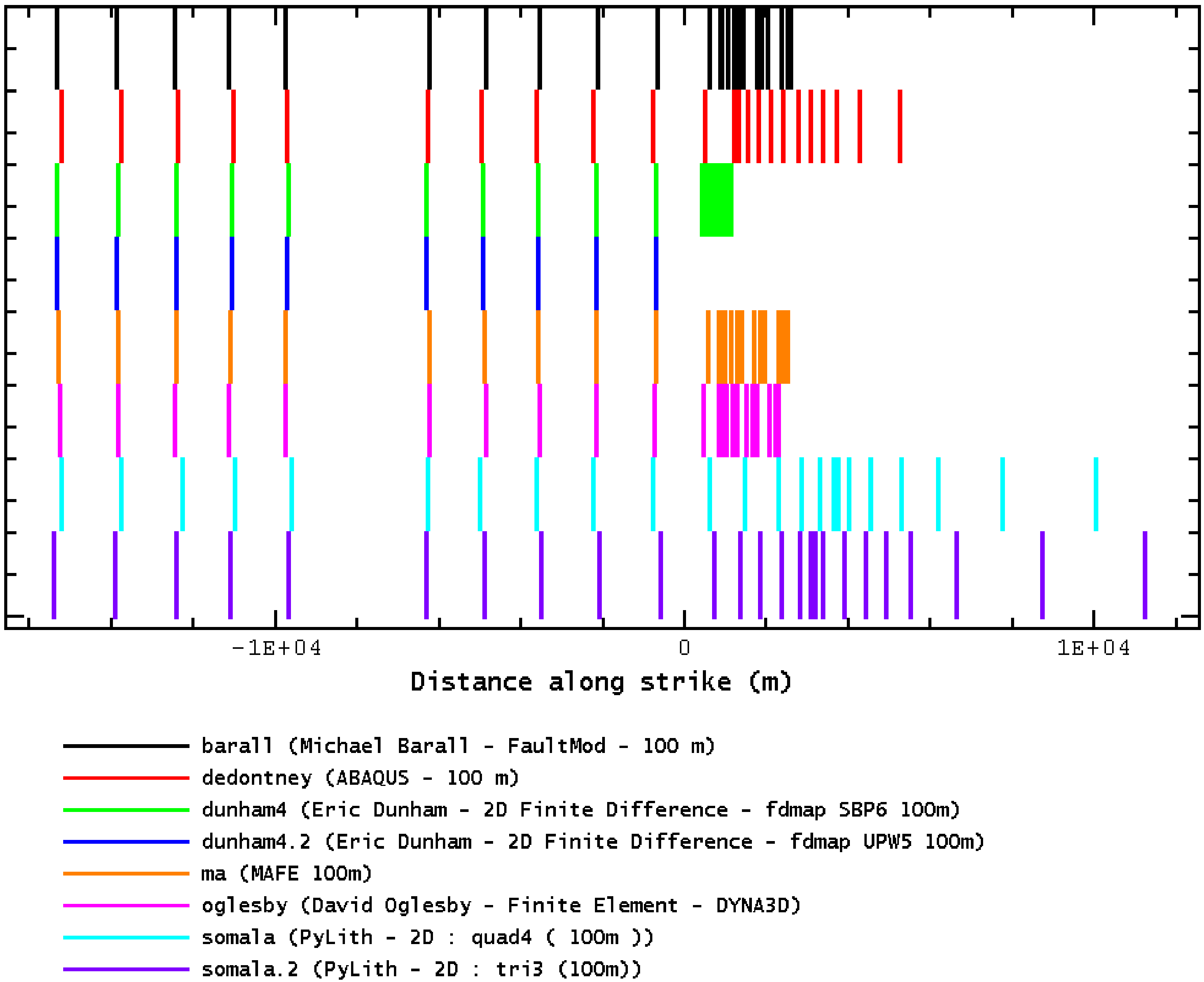
TPV15-2D — Branch Fault Rupture Contours



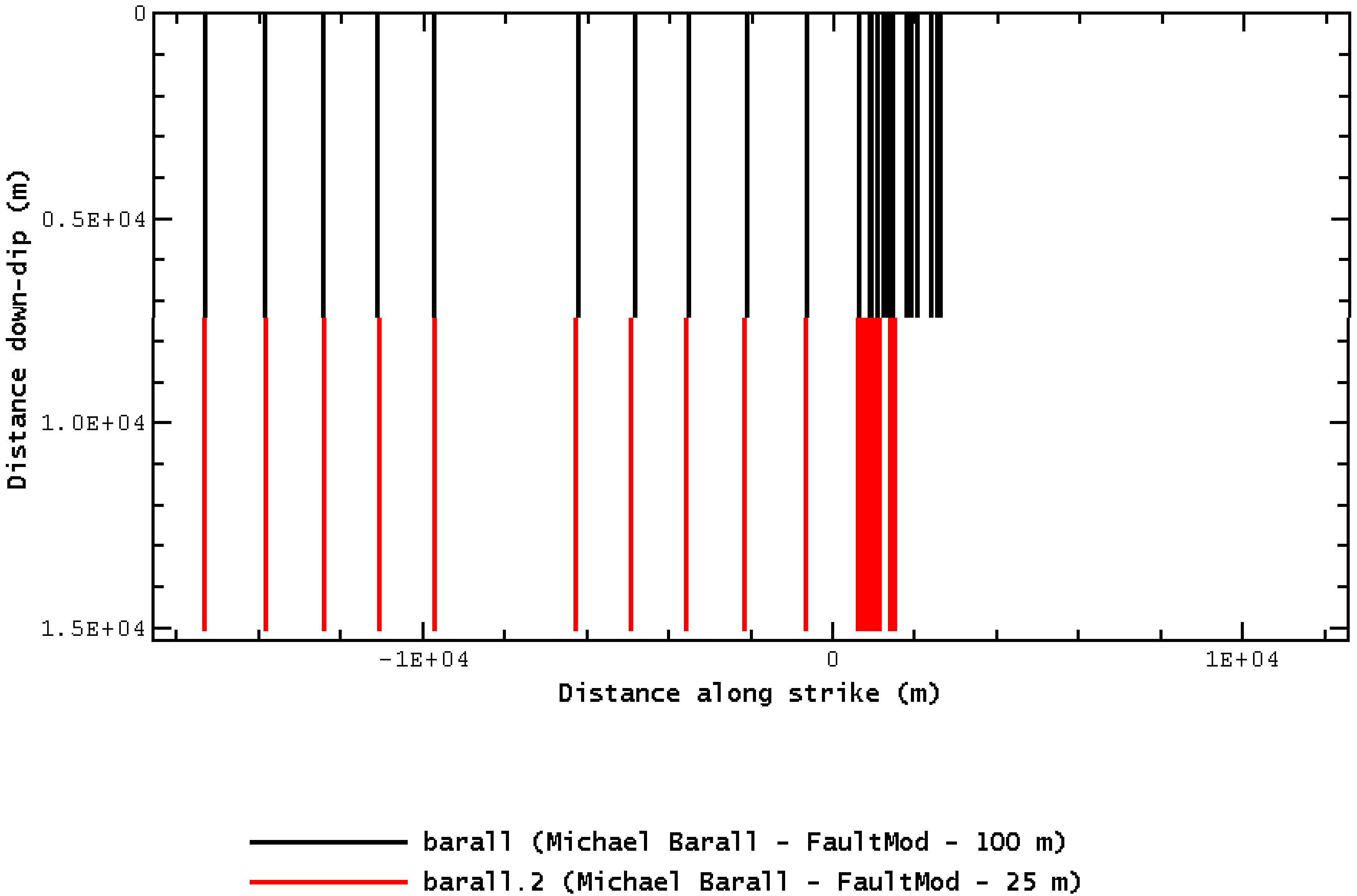
TPV15-2D — Main Fault Rupture Contours



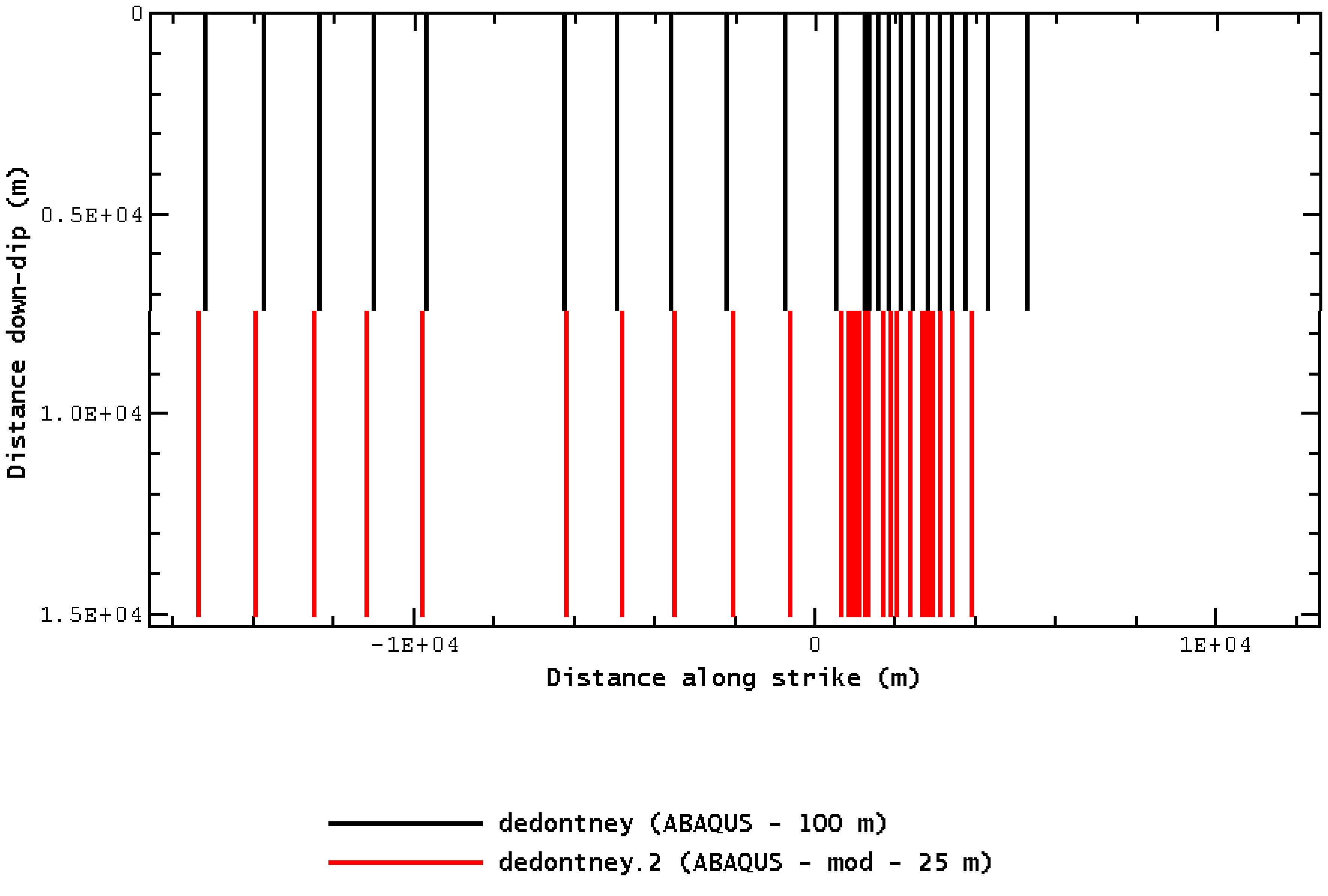
TPV15-2D — Main Fault Rupture Contours



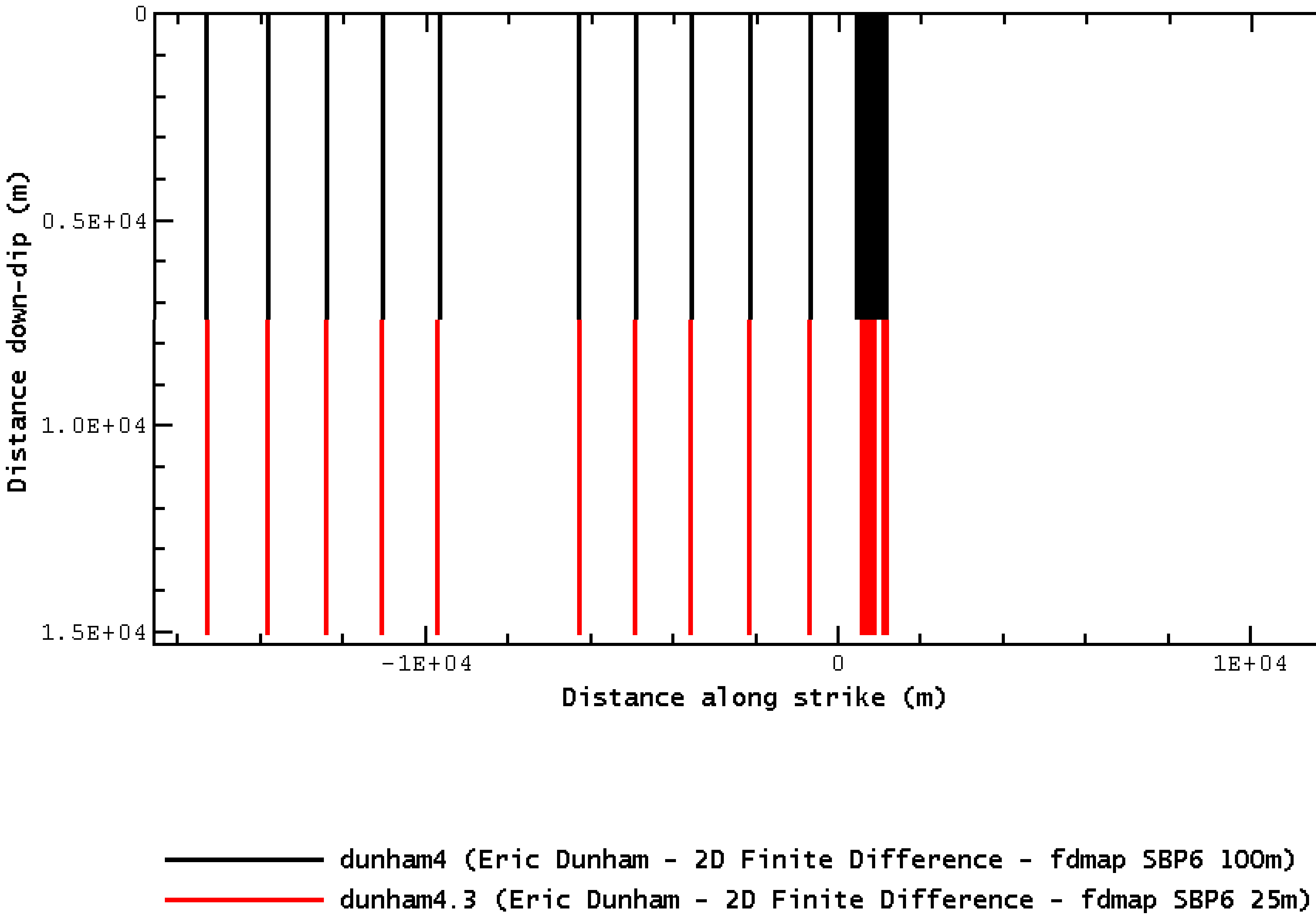
TPV15-2D — Main Fault Rupture Contours, 100 m vs. 25 m



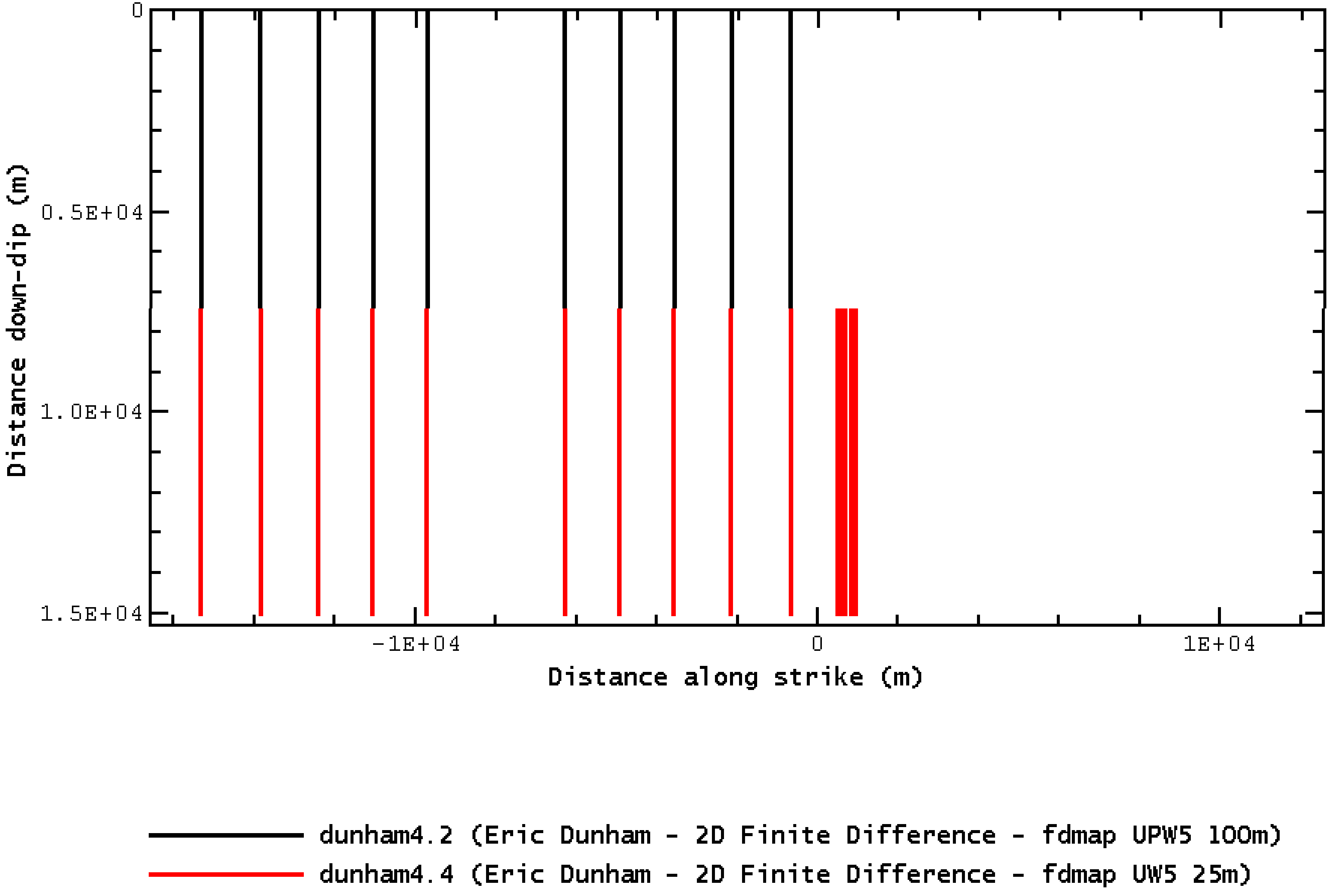
TPV15-2D — Main Fault Rupture Contours, 100 m vs. 25 m



TPV15-2D — Main Fault Rupture Contours, 100 m vs. 25 m

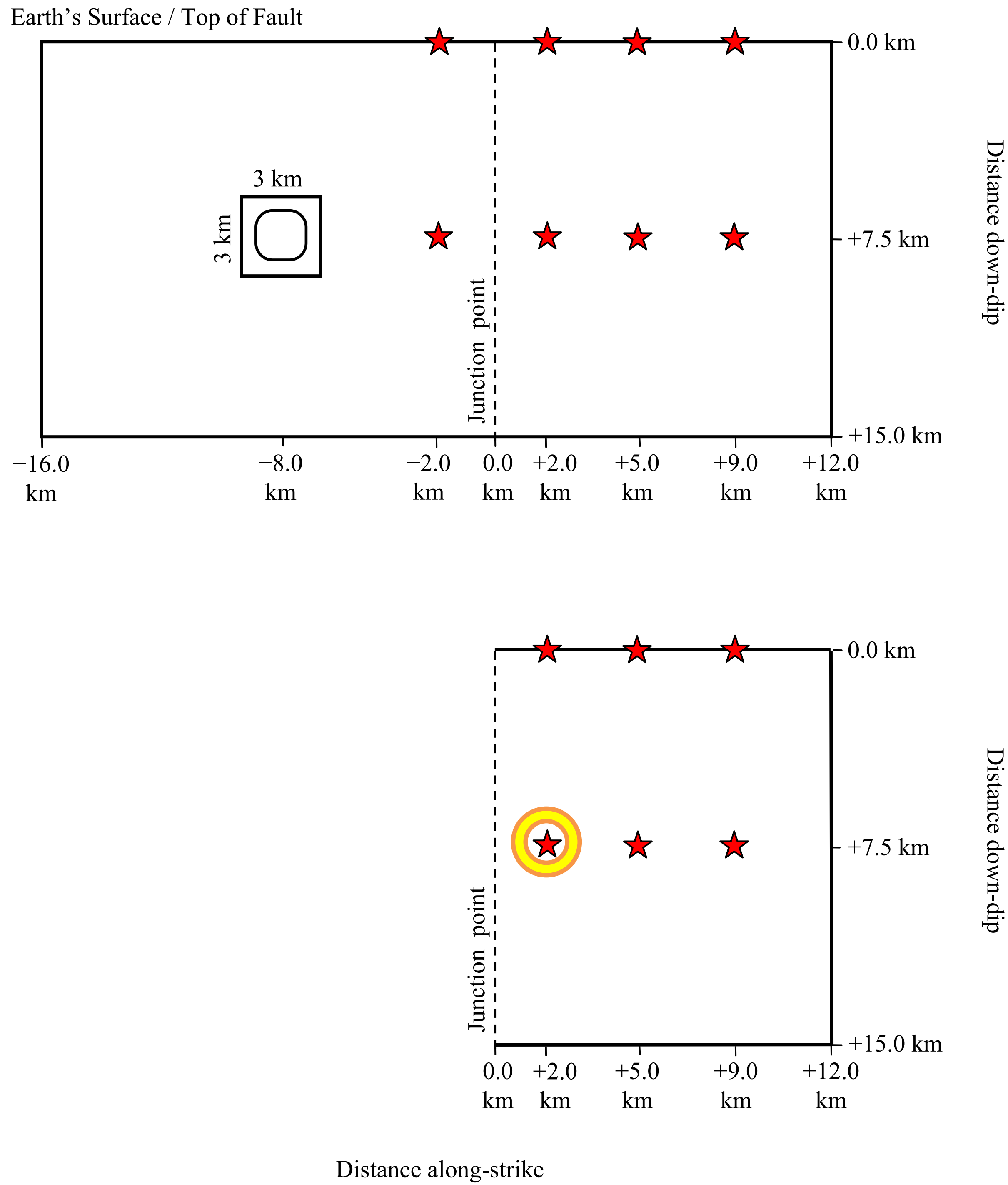


TPV15-2D — Main Fault Rupture Contours, 100 m vs. 25 m



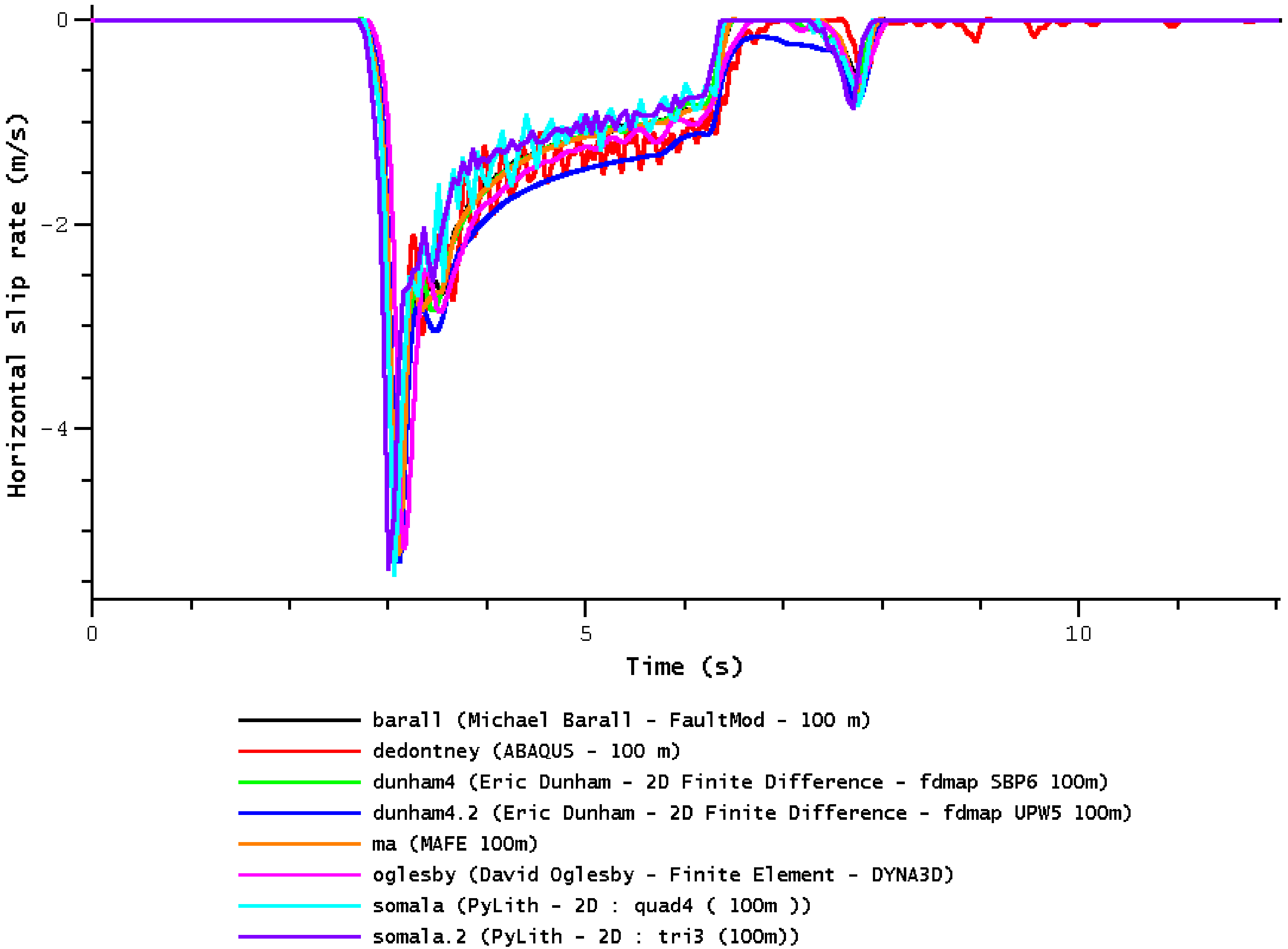
TPV15-2D

[branchst020dp075]

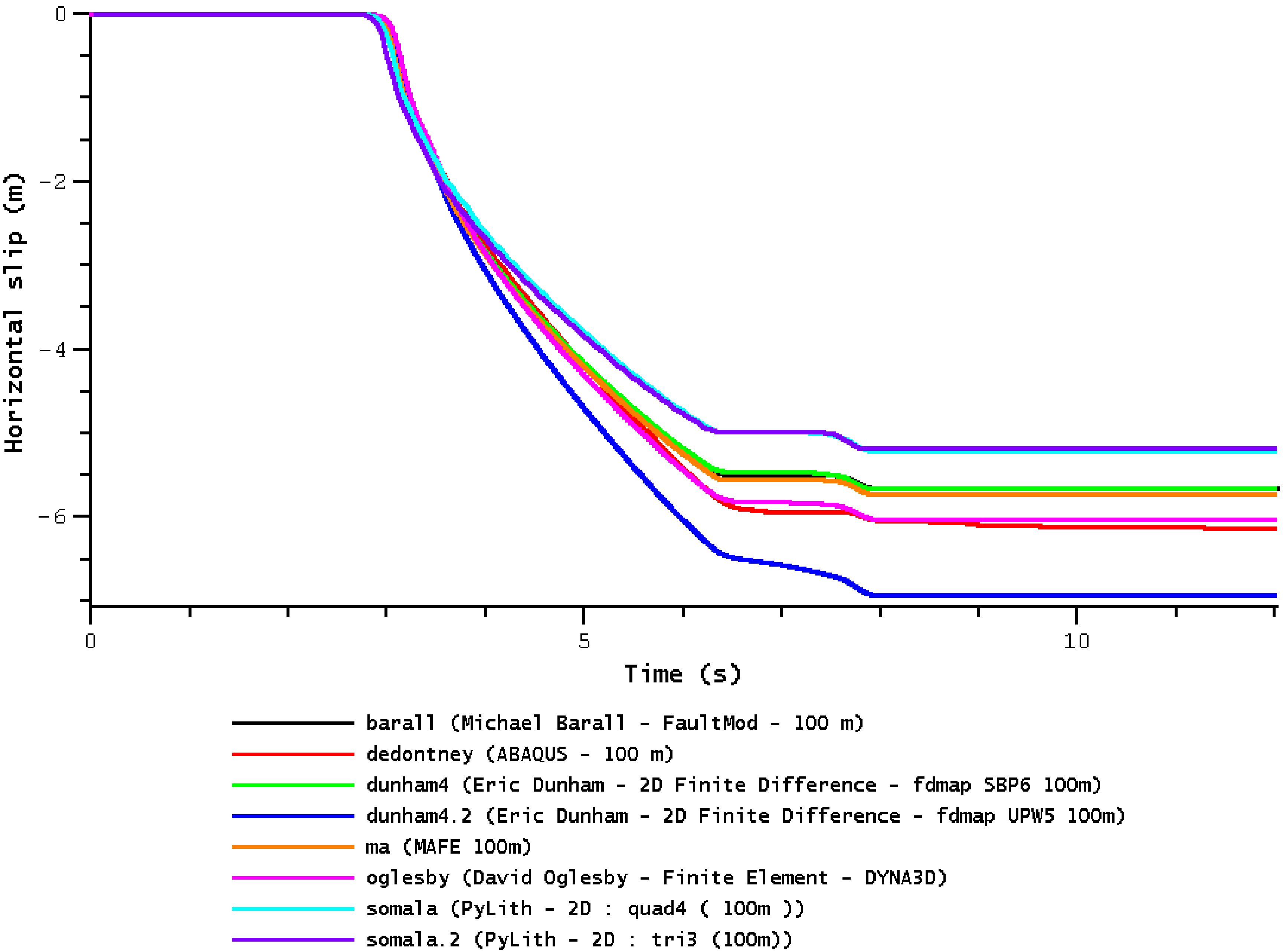


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

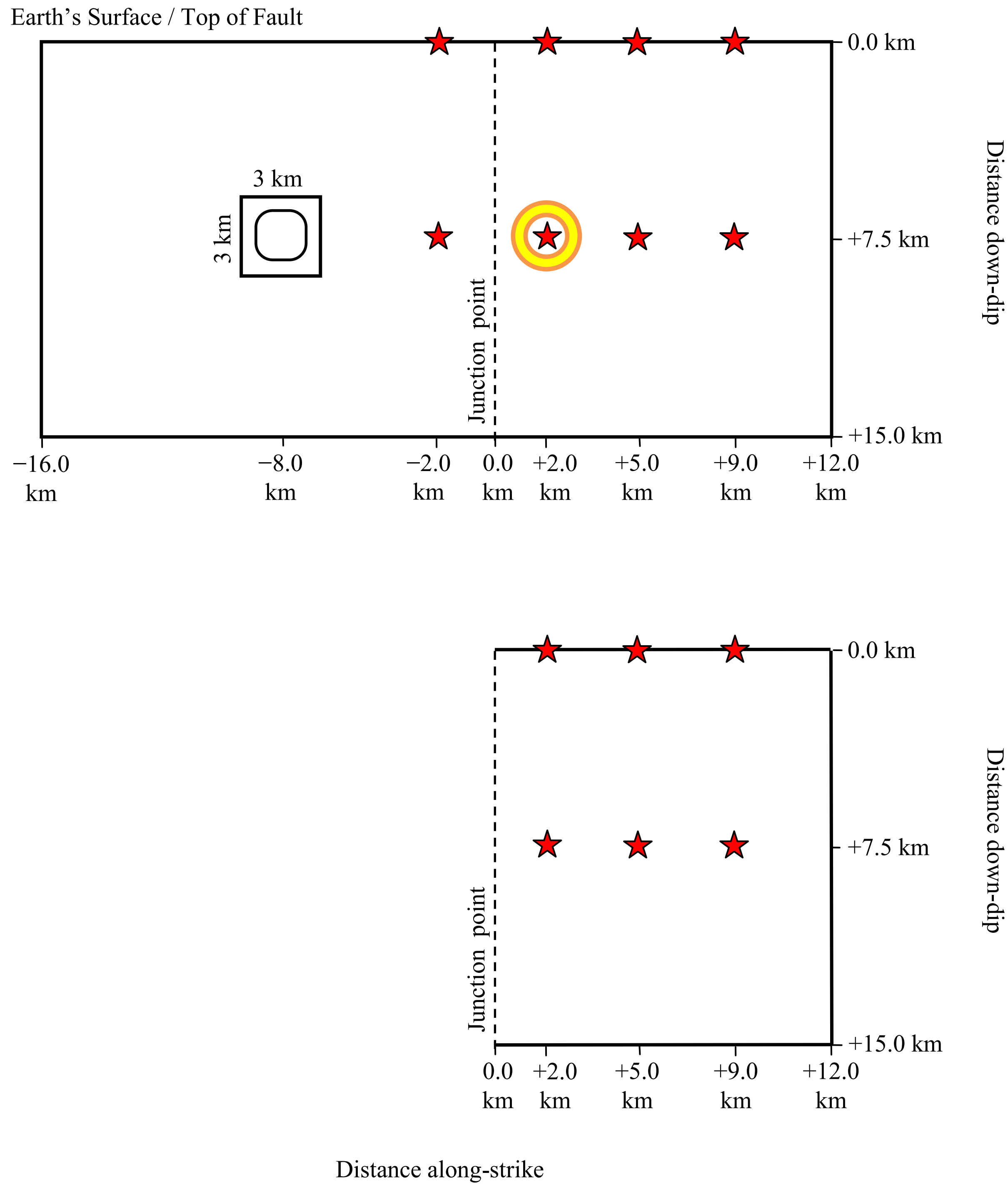
TPV15-2D — Horizontal Slip Rate [branchst020dp075]



TPV15-2D — Horizontal Slip [branchst020dp075]

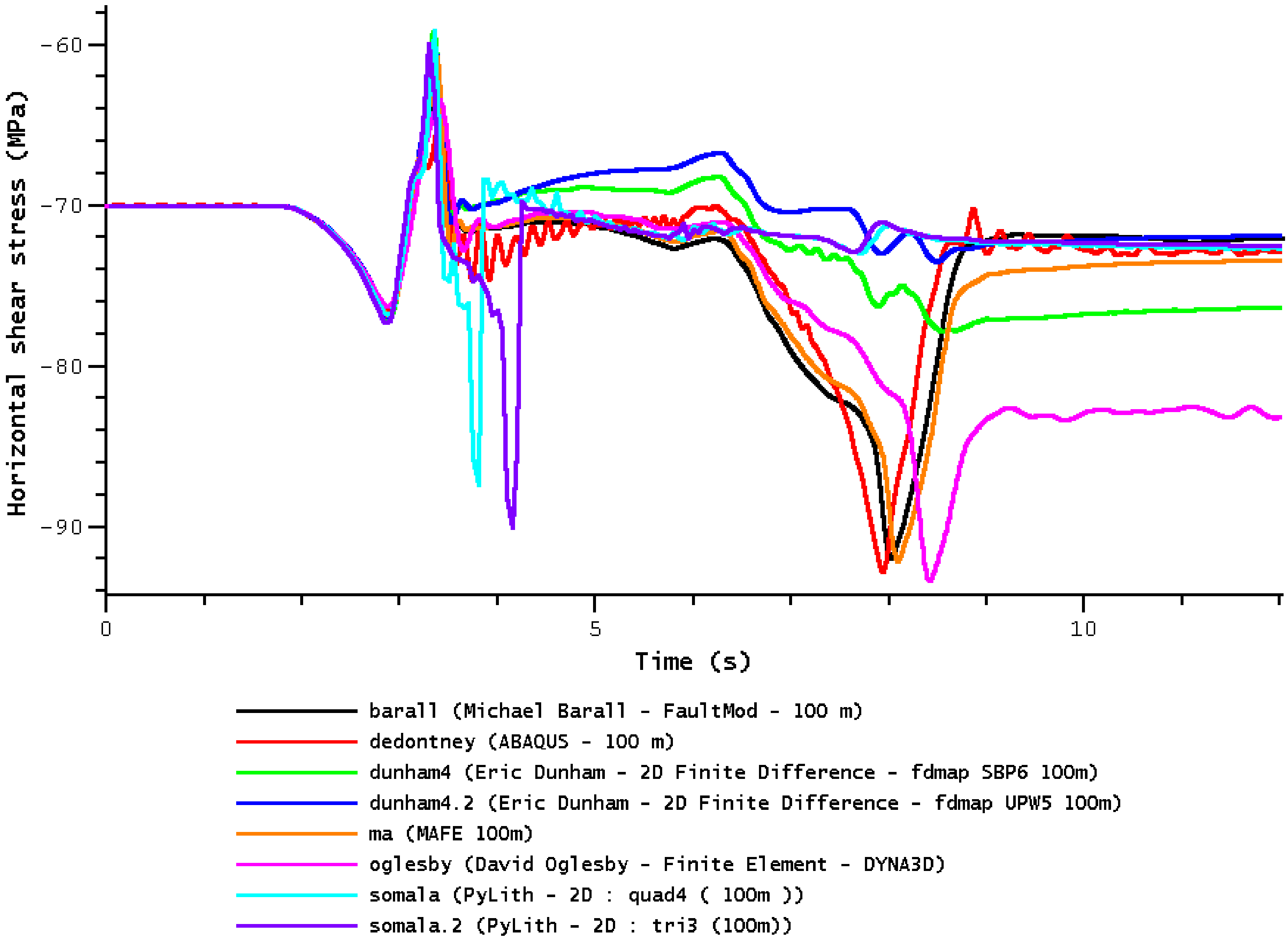


TPV15-2D
[faultst020dp075]

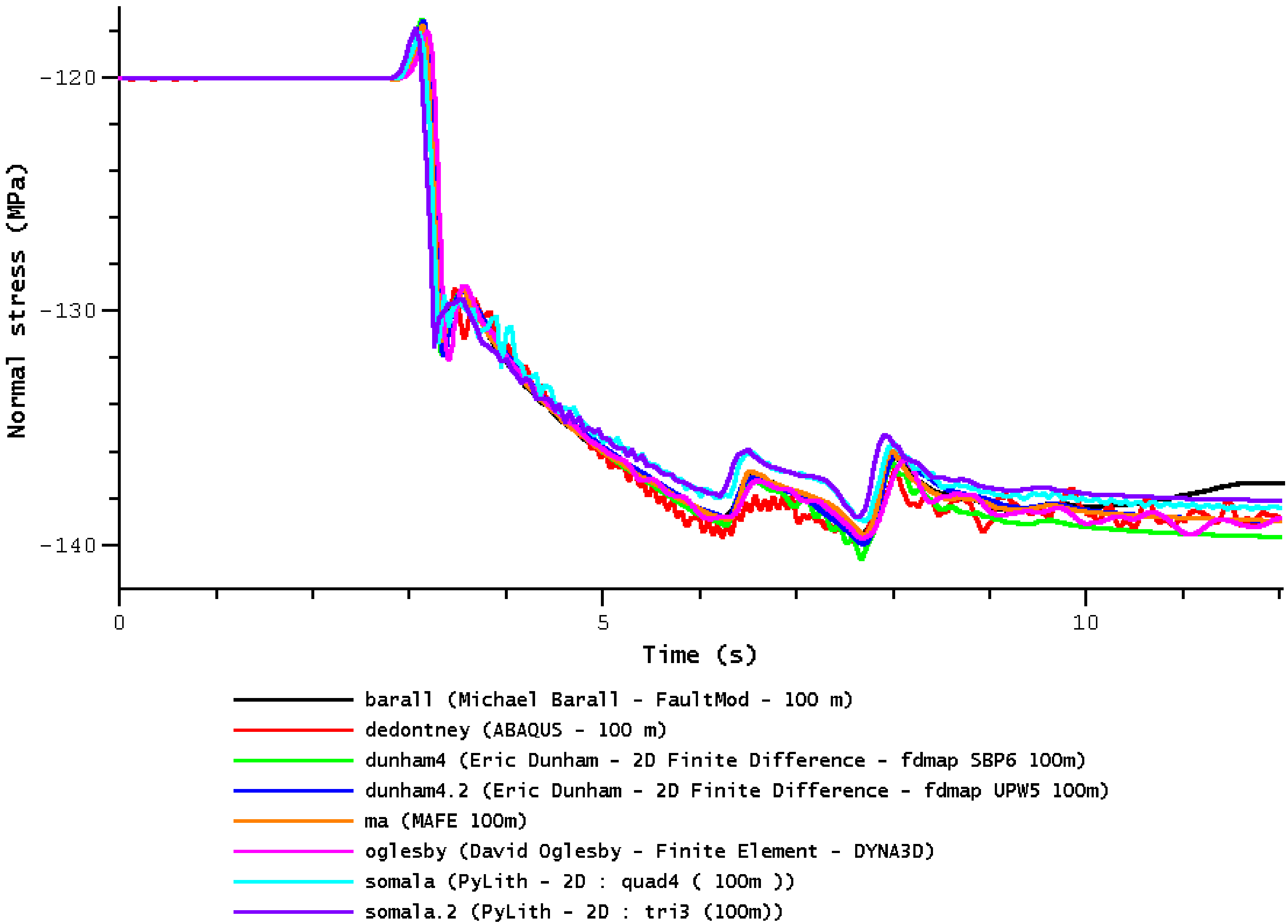


Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

TPV15-2D — Horizontal Shear Stress [faultst020dp075]

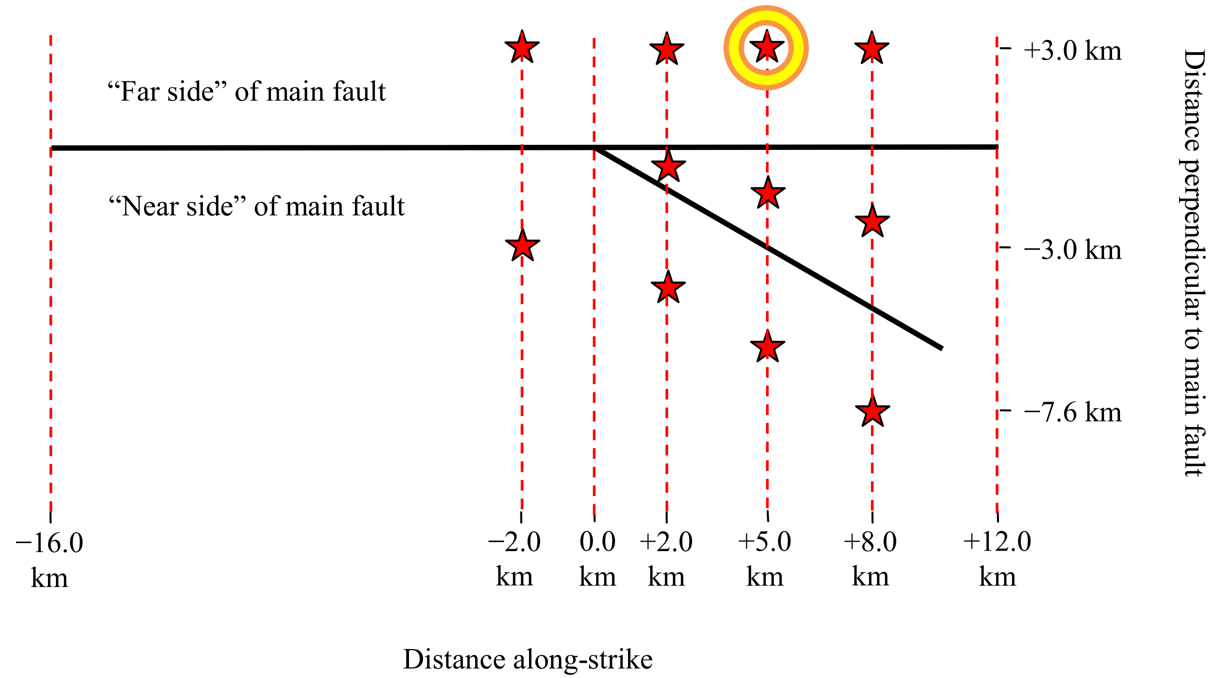


TPV15-2D — Normal Stress [faultst020dp075]



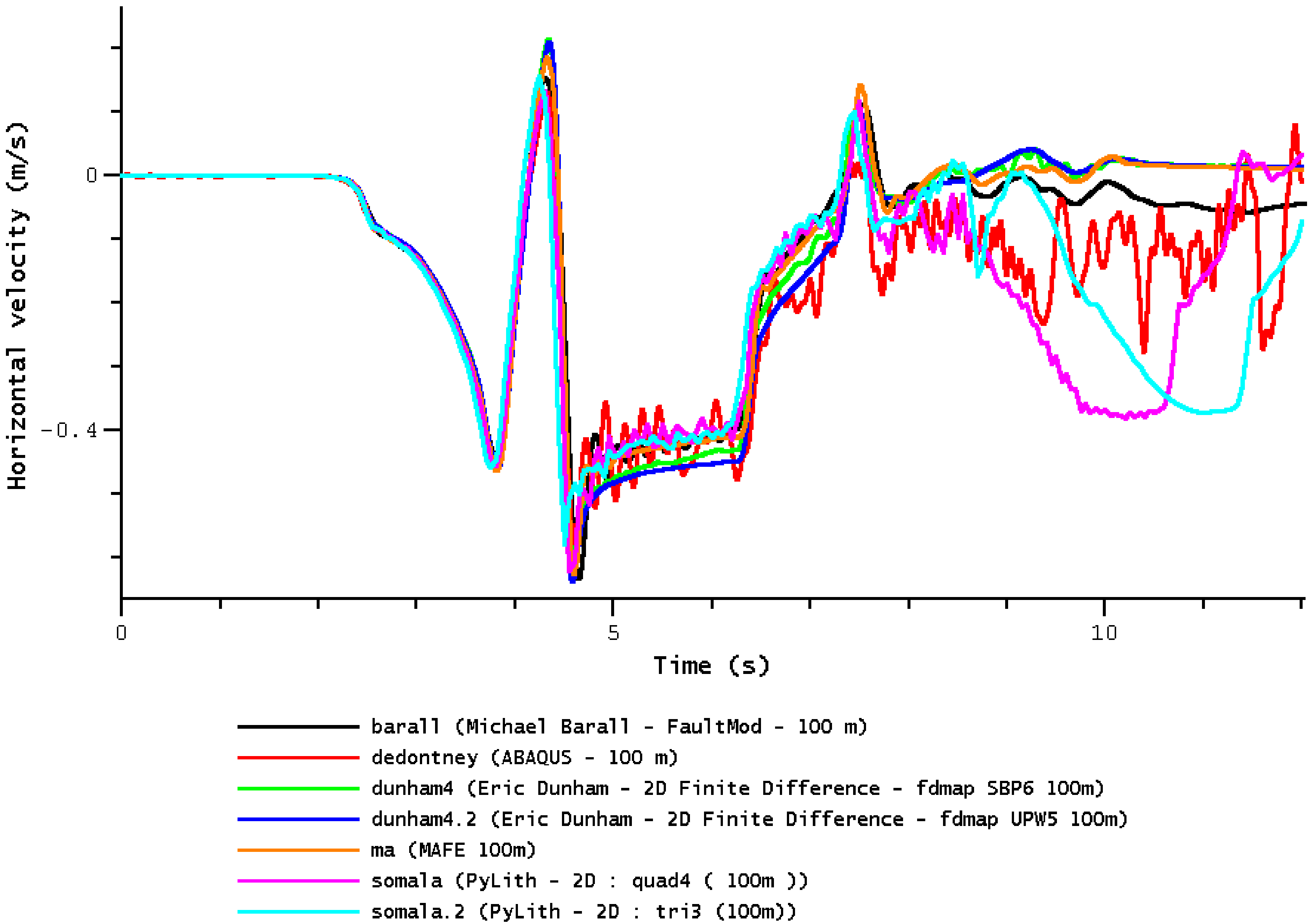
TPV15-2D

[body030st050dp075]



Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).

TPV15-2D — Horizontal Velocity [body030st050dp075]



TPV15-2D — Normal Velocity [body030st050dp075]