Fault Stepover Benchmarks
TPV22 and TPV23

Michael Barall
Invisible Software, Inc.

SCEC Dynamic Rupture Code Validation Workshop

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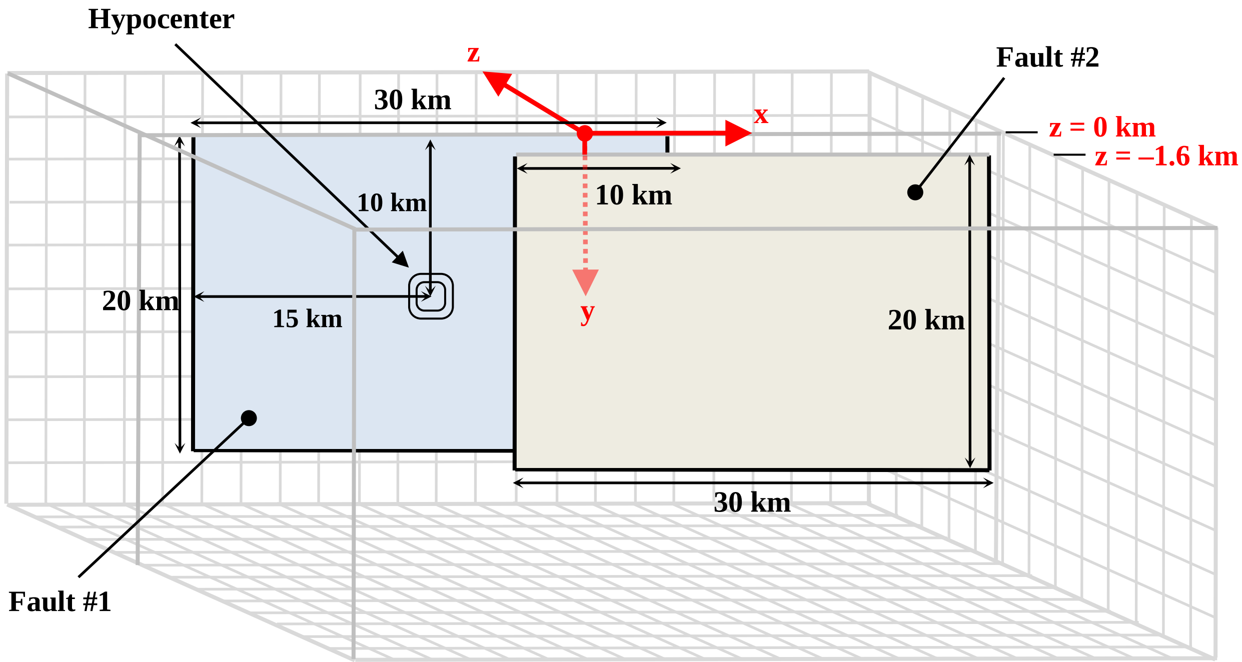
TPV22 — Extensional Stepover (1600 m).



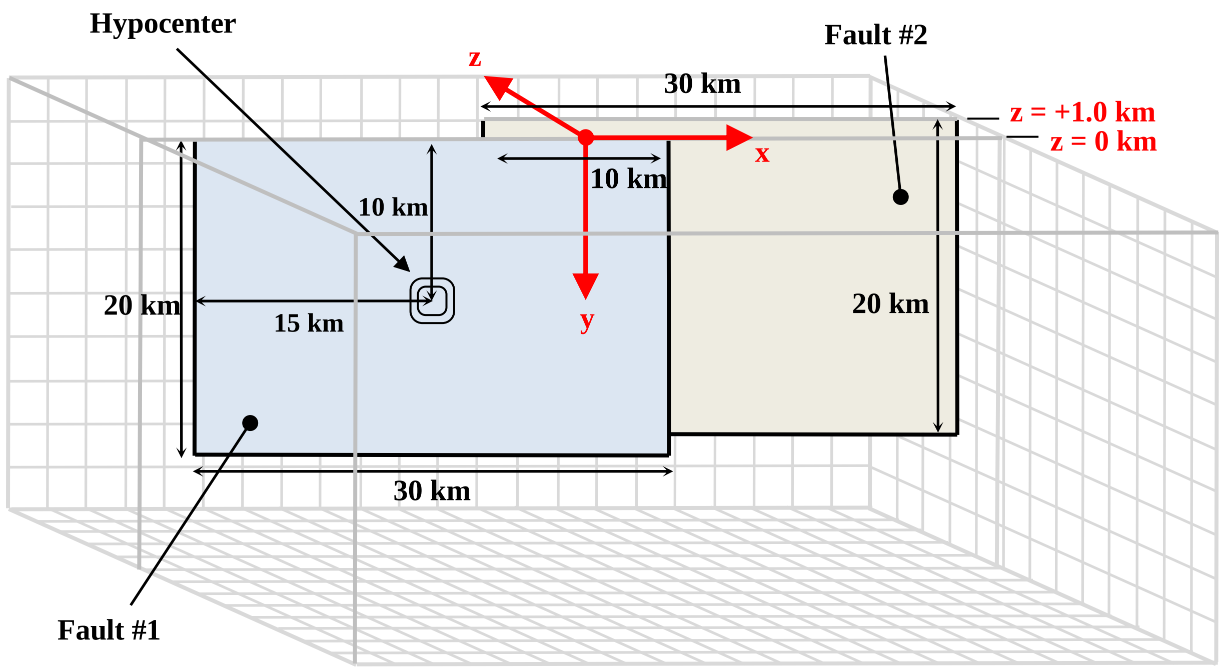
Right-lateral strike-slip faults in a linear elastic half-space:

Density $\rho = 2670\ \mathrm{kg/m^3}$

Shear-wave velocity $V_s = 3464\ \mathrm{m/s}$

Pressure-wave velocity $V_p = 6000\ \mathrm{m/s}$

TPV23 — Compressional Stepover (1000 m).



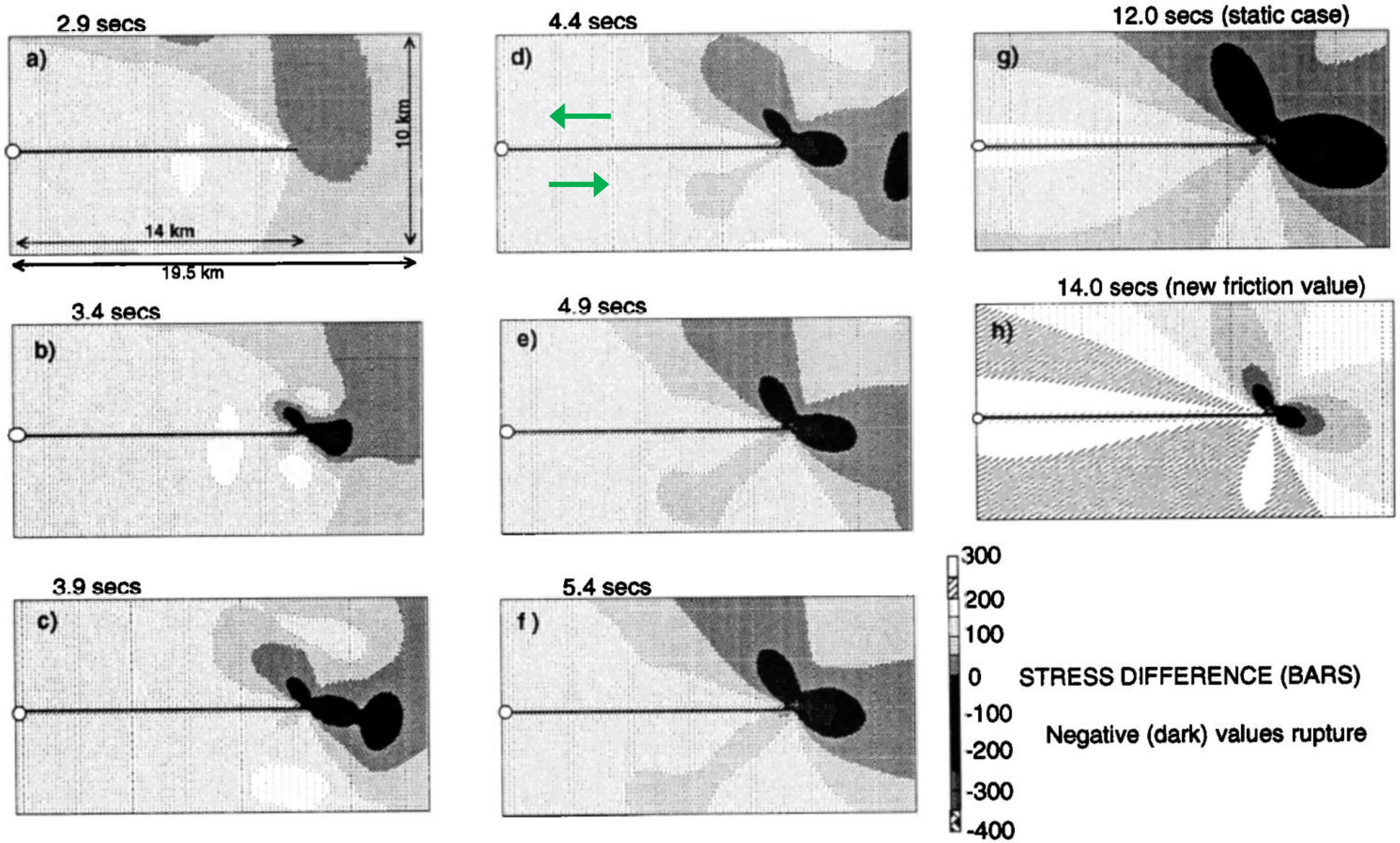
Linear slip-weakening friction.

Right-lateral faults.

Requested resolutions: 100 m and 50 m.

Issues in Dynamic Rupture Simulations of Fault Stepovers

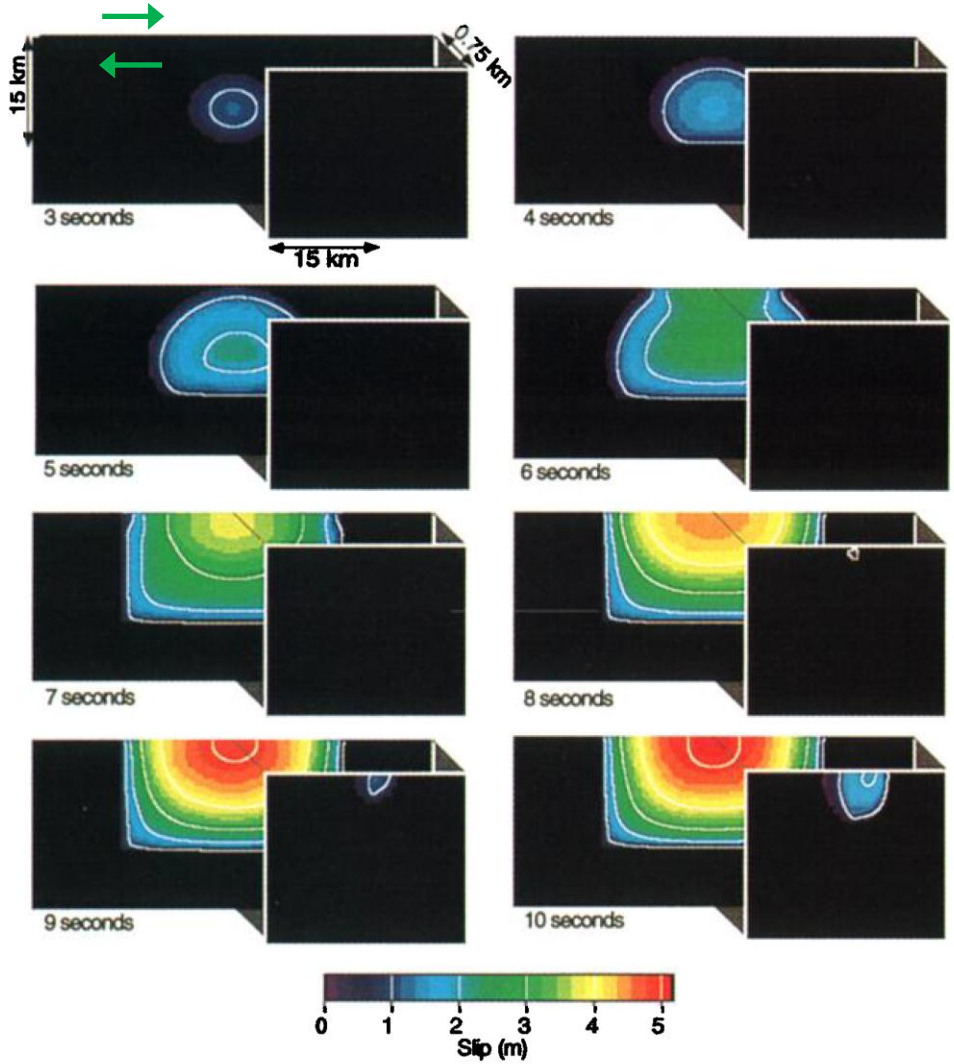
Stepover Distance and Coulomb Stress — 3D is Different than 2D.



Harris, Archuleta, and Day (1991) — 2D simulations.

- Maximum stepover distance ~ 5 km.
- Figure above shows Coulomb stress on a hypothetical parallel fault.
- Fault in the figure is left-lateral, so extensional side is on the top

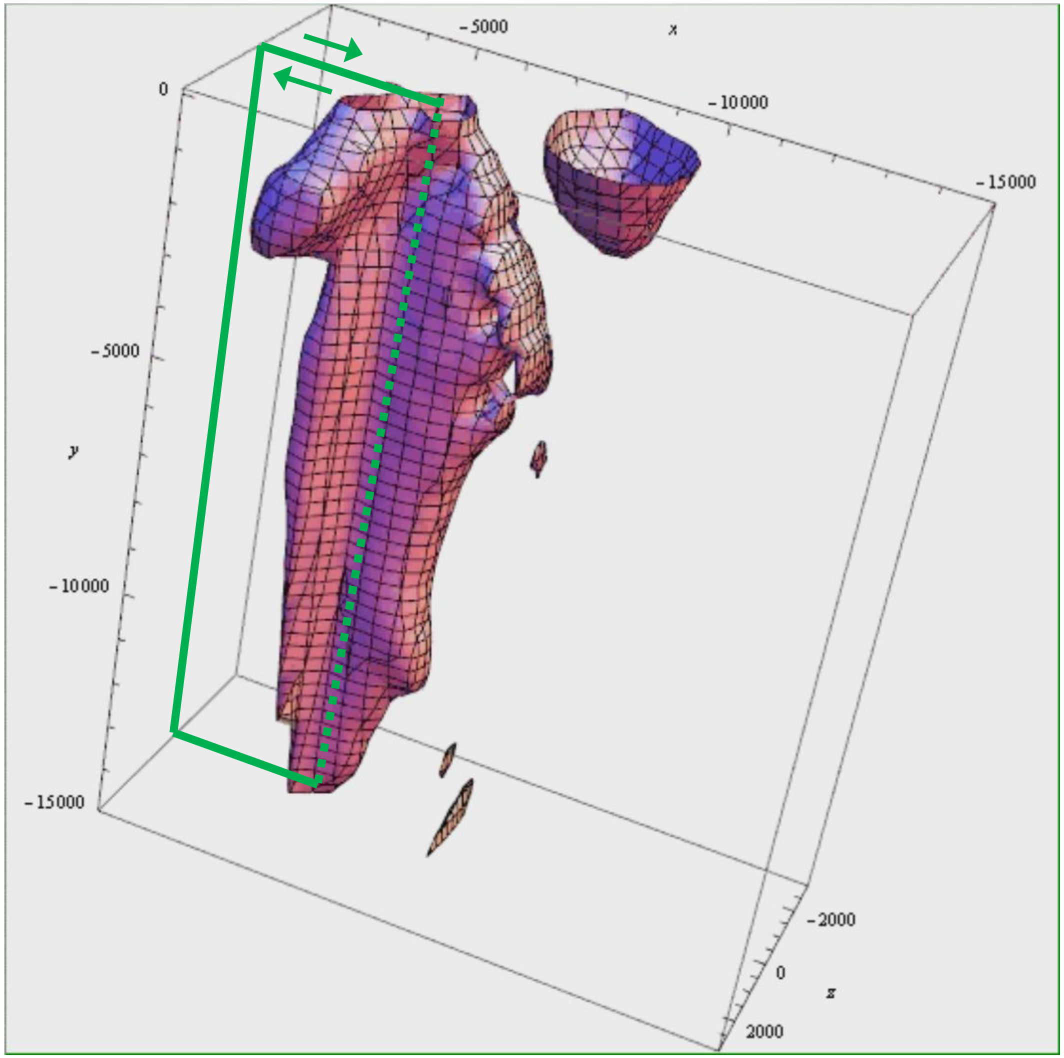
Stepover Distance — 3D is Different than 2D.



Harris and Day (1999) —3D simulations (extensional stepover and subshear rupture).

- Maximum stepover distance ~ 1 km.
- Rupture on fault #2 begins at the earth's surface.

Movie — Coulomb Stress Surrounding the End of a Fault, in 3D.

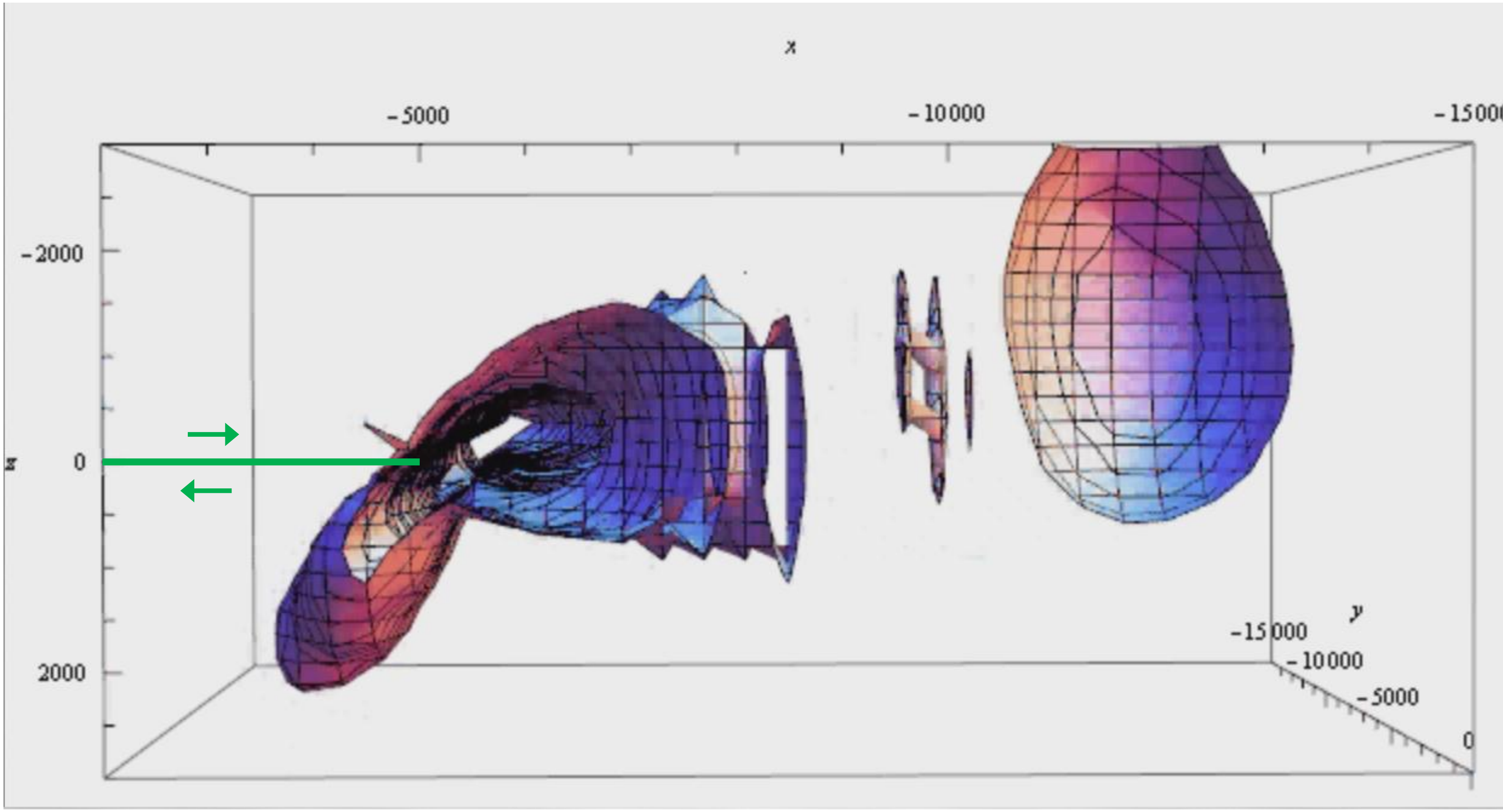


Movie shows where Coulomb stress on a hypothetical second fault would exceed a threshold value.

- The fault extends from the left edge to -5000 m along-strike.
- The compressional side is in back, the extensional side is in front.

(The movie is from a test run, which does not have the same parameters as TPV22-23).

Movie — Coulomb Stress Surrounding the End of a Fault, in 3D.



Movie shows where Coulomb stress on a hypothetical second fault would exceed a threshold value.

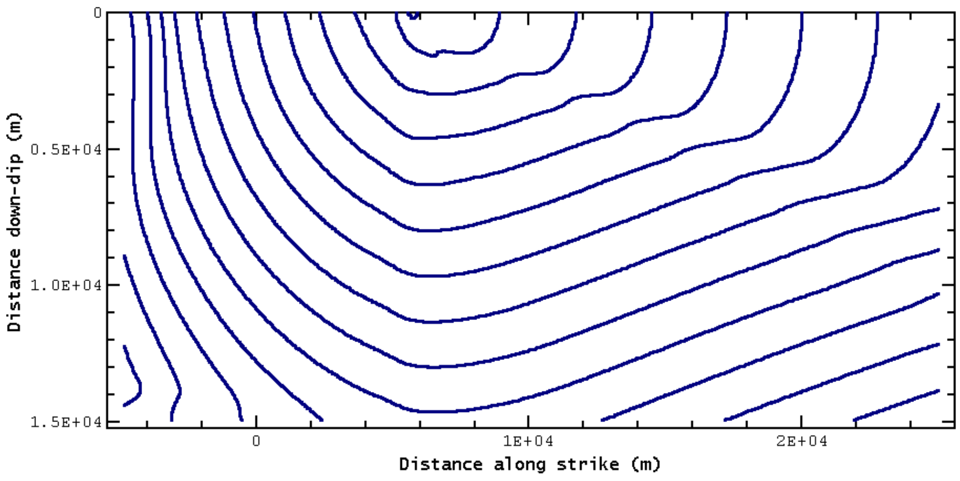
- The fault extends from the left edge to -5000 m along-strike.
- The compressional side is on top, the extensional side is on bottom.

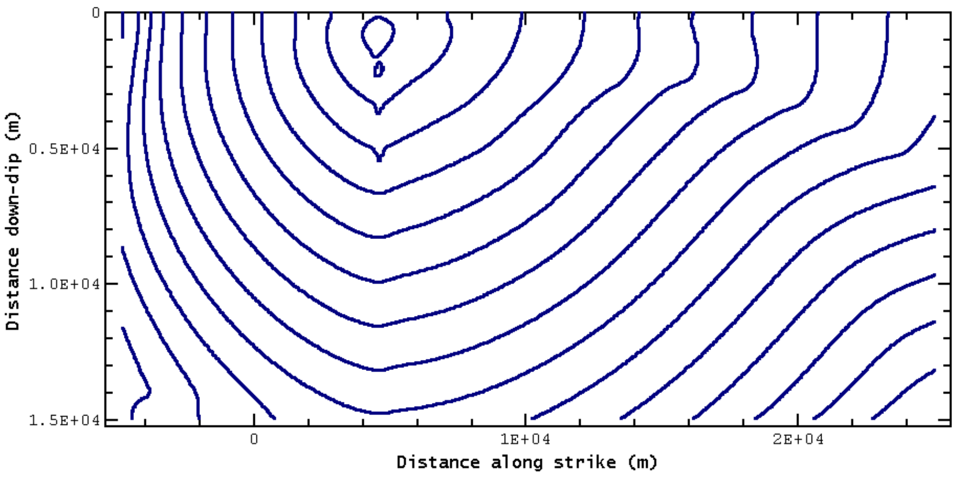
(The movie is from a test run, which does not have the same parameters as TPV22-23).

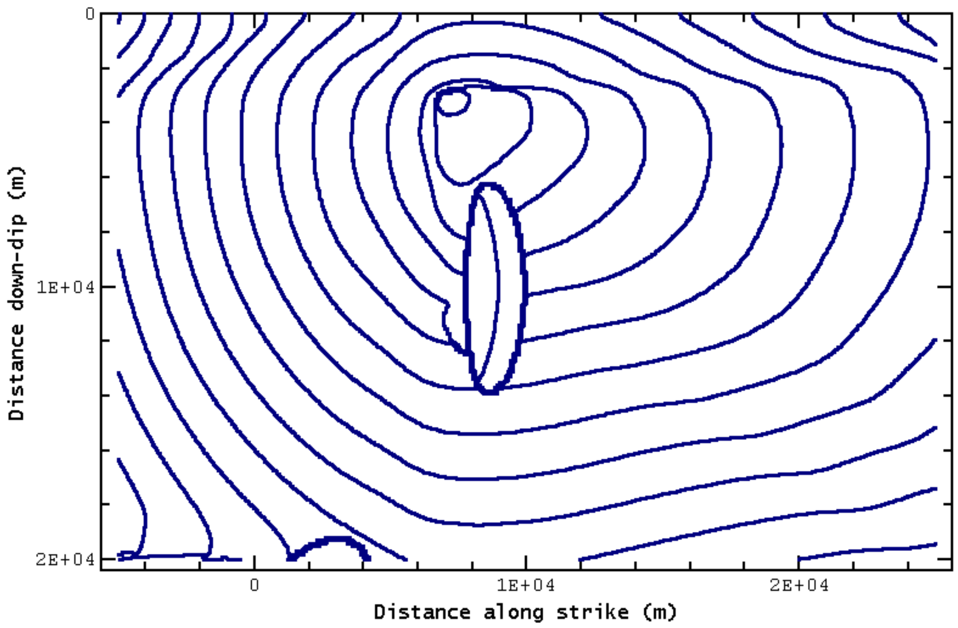
Nucleation Follies on Fault #2.

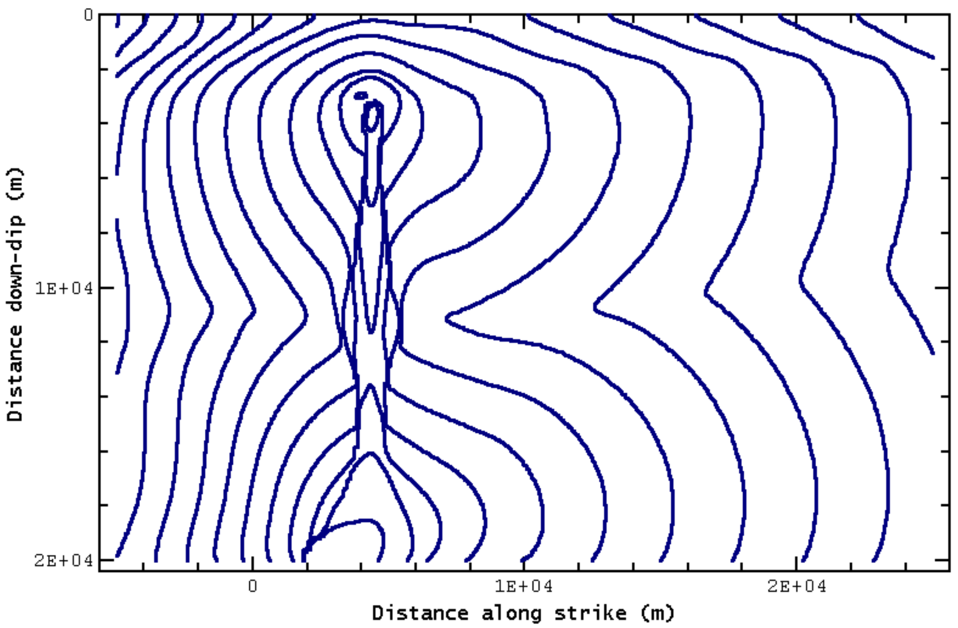
Compressional Examples

Dilational Examples

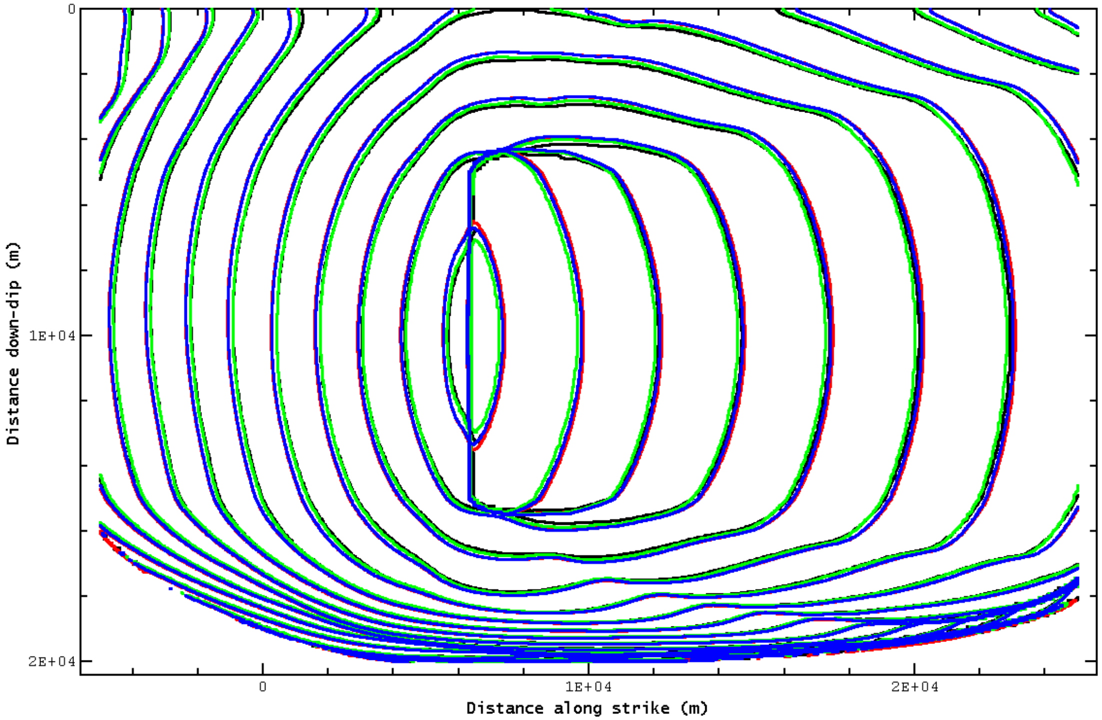




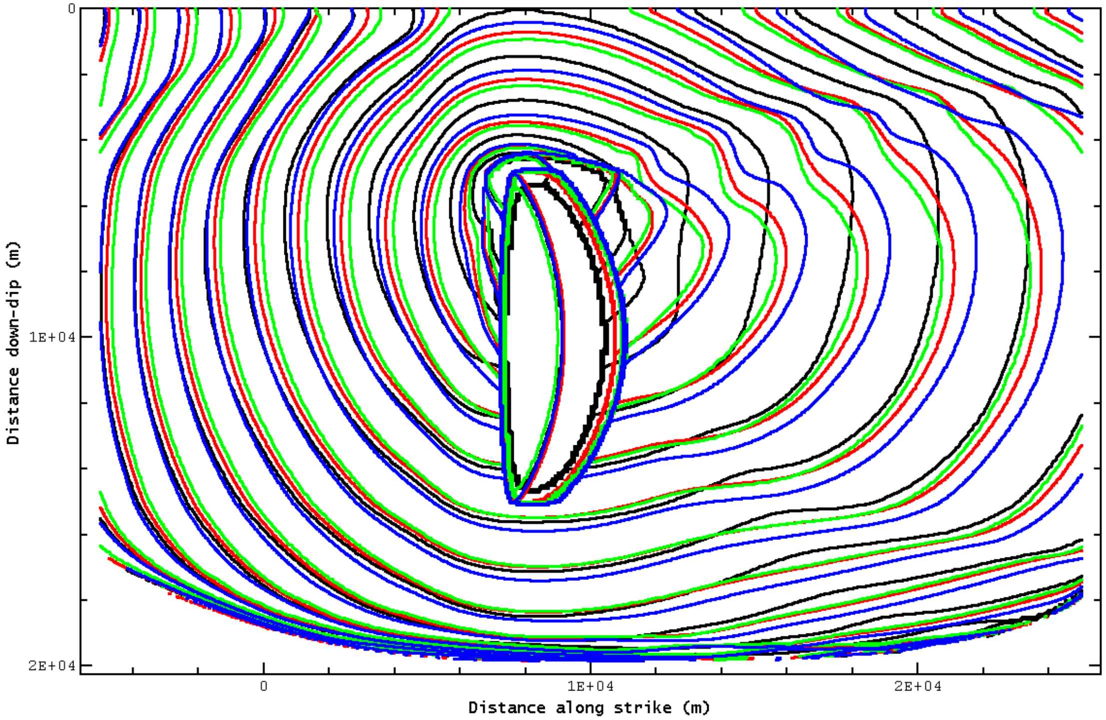




Loss of Numerical Precision.



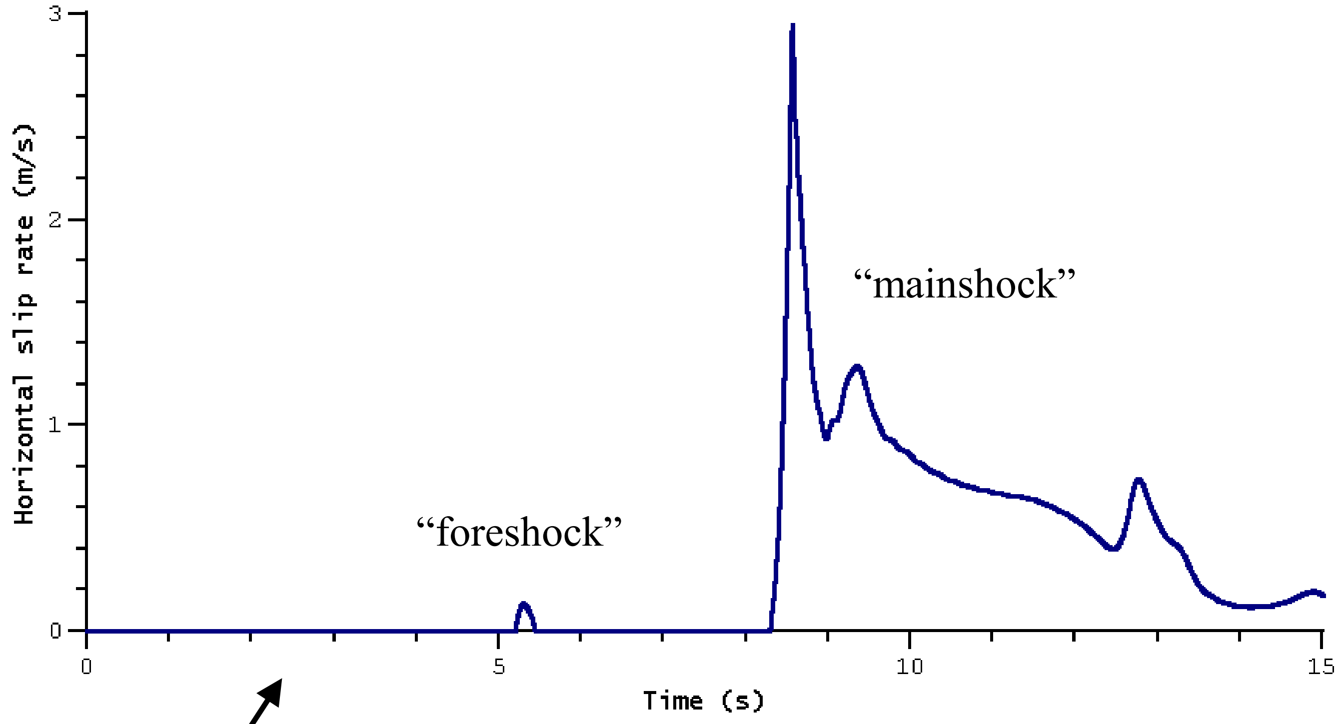
Compressional Stepover 1000 m

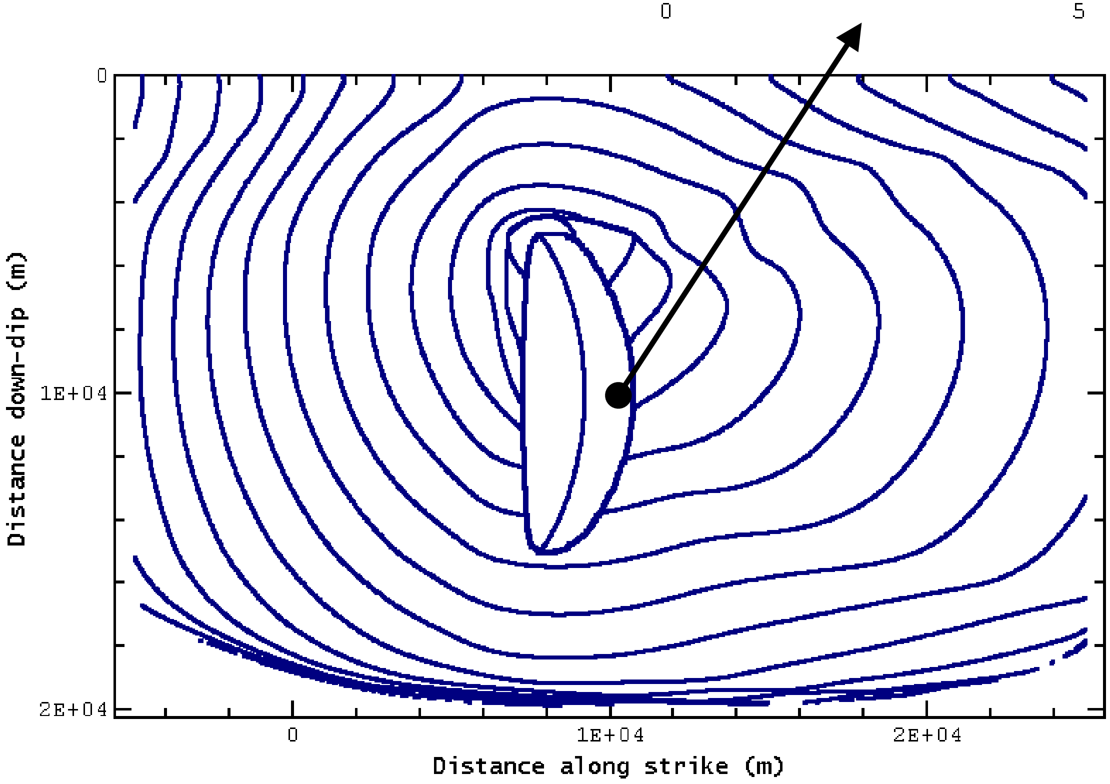


Compressional Stepover 1400 m

Finite Element (FaultMod) 100 m
Finite Element (FaultMod) 50 m
Finite Difference (DayFD) 100 m
Finite Difference (DayFD) 50 m

Complicated Slip-Time History.





TPV22-23 Design

Friction Parameters.

$$\mu_s = 0.548$$

$$\mu_d = 0.373$$

$$d_0 = 0.30\ \mathrm{m}$$

$$C_0 = \begin{cases} (0.0014\ \mathrm{MPa/m})(5000\ \mathrm{m} - \mathrm{depth})\,, & \text{if depth} \leq 5000\ \mathrm{m} \\ 0.0\ \mathrm{MPa}\,, & \text{if depth} \geq 5000\ \mathrm{m} \end{cases}$$

Cohesion tapers from 7.0 MPa at the earth's surface, to 0 at depths of 5000 m or greater.

Cohesion in the upper 5 km suppresses the tendency of the rupture on fault #2 to nucleate at the earth's surface.

Initial Stress.

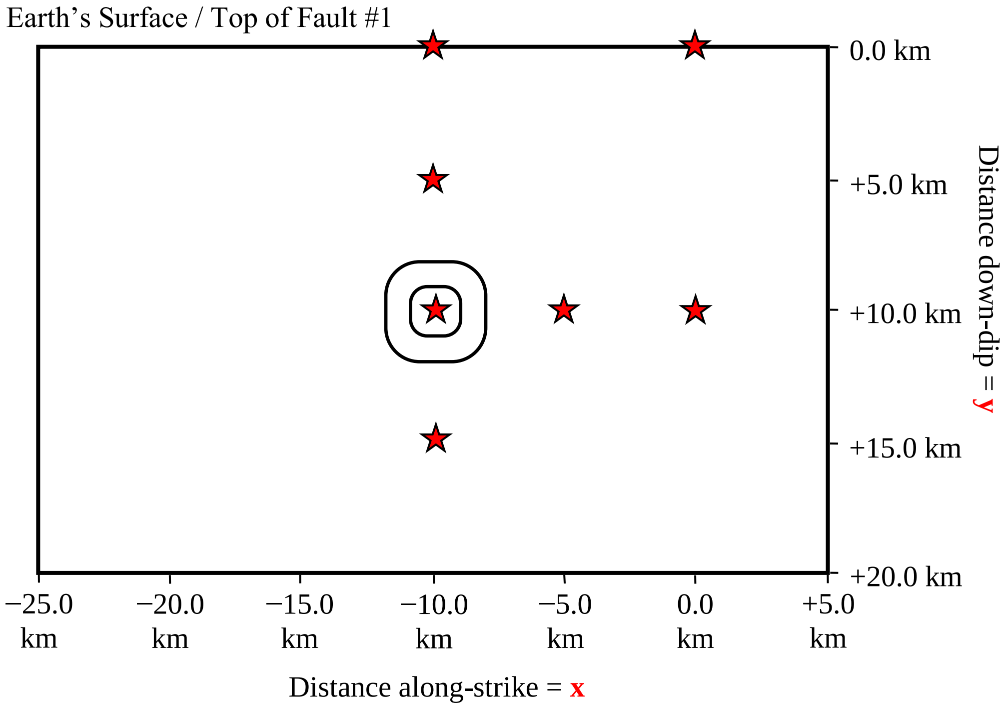
$$\sigma_{\text{ini}} = 60.00 \text{ MPa}$$

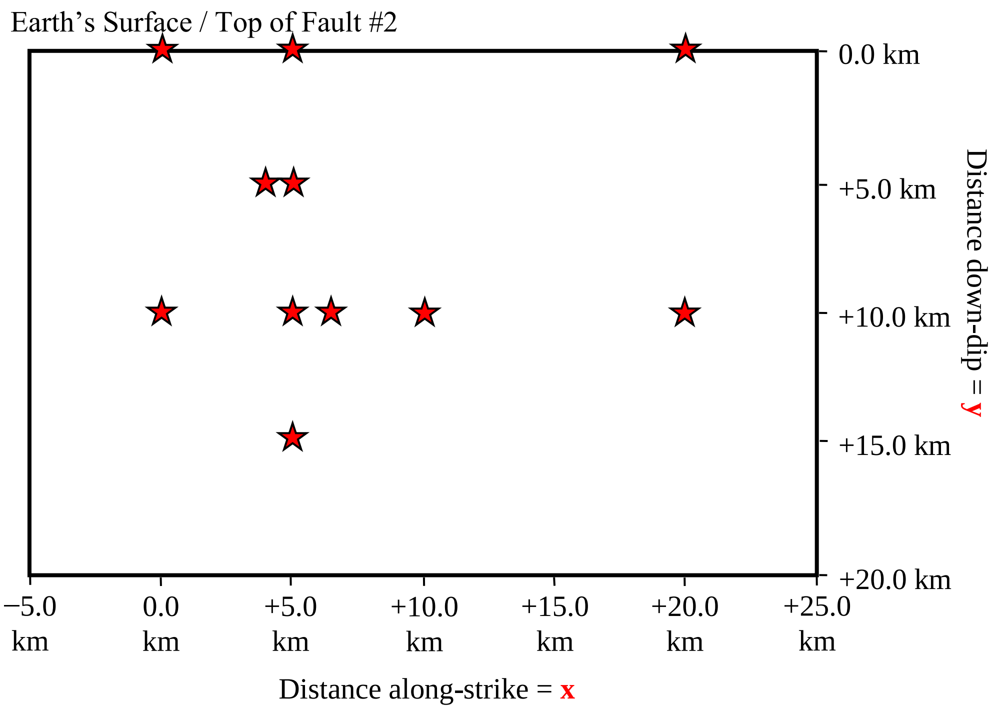
$$\tau_{\text{ini}} = \begin{cases} 29.38 \text{ MPa}, & \text{if depth} \leq 15000 \text{ m} \\ 29.38 \text{ MPa} - (0.002938 \text{ MPa/m})(\text{depth} - 15000 \text{ m}), & \text{if depth} \geq 15000 \text{ m} \end{cases}$$

Stresses are chosen to produce a supershear rupture, so the rupture is energetic enough to make the jump.

Initial shear stress tapers down from 29.38 MPa at a depth of 15000 m, to 14.69 MPa at the bottom of the fault at depth 20000 .

Reducing the initial shear stress in the lower 5 km creates a “soft” barrier at the bottom of the fault, and prevents nucleation on fault #2 from occurring at the bottom of the fault.



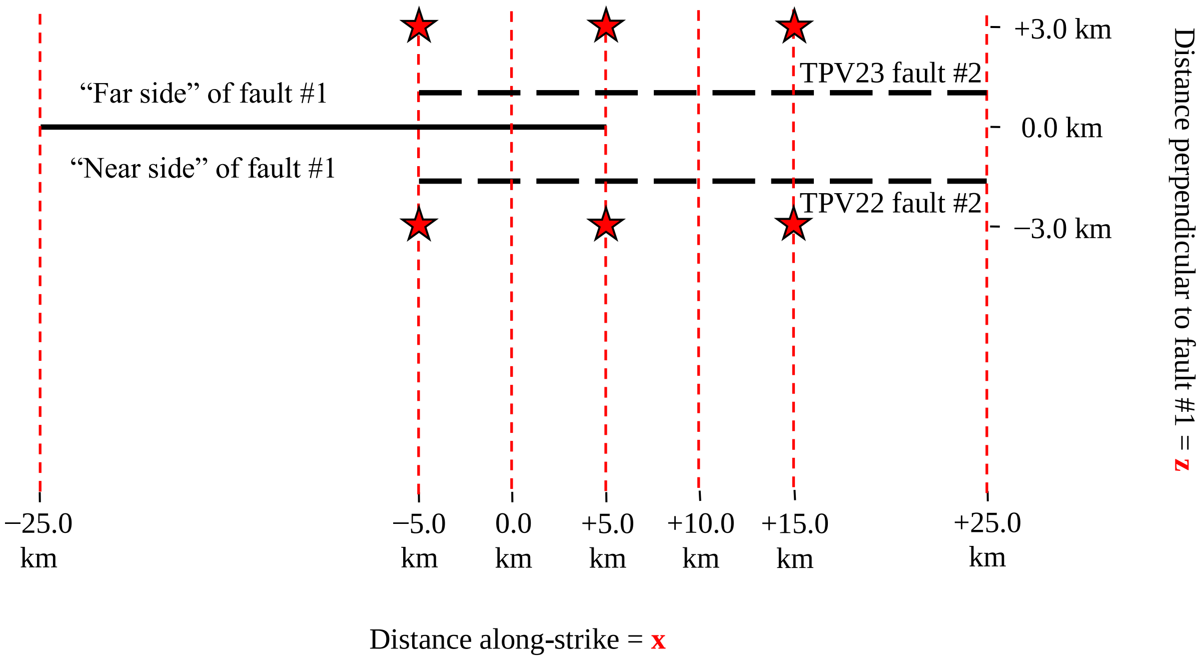


On-Fault Stations.

Modelers are asked to submit slip, slip rate, and stress as a function of time, for 7 stations on fault #1 (top) and 11 stations on fault #2 (bottom).

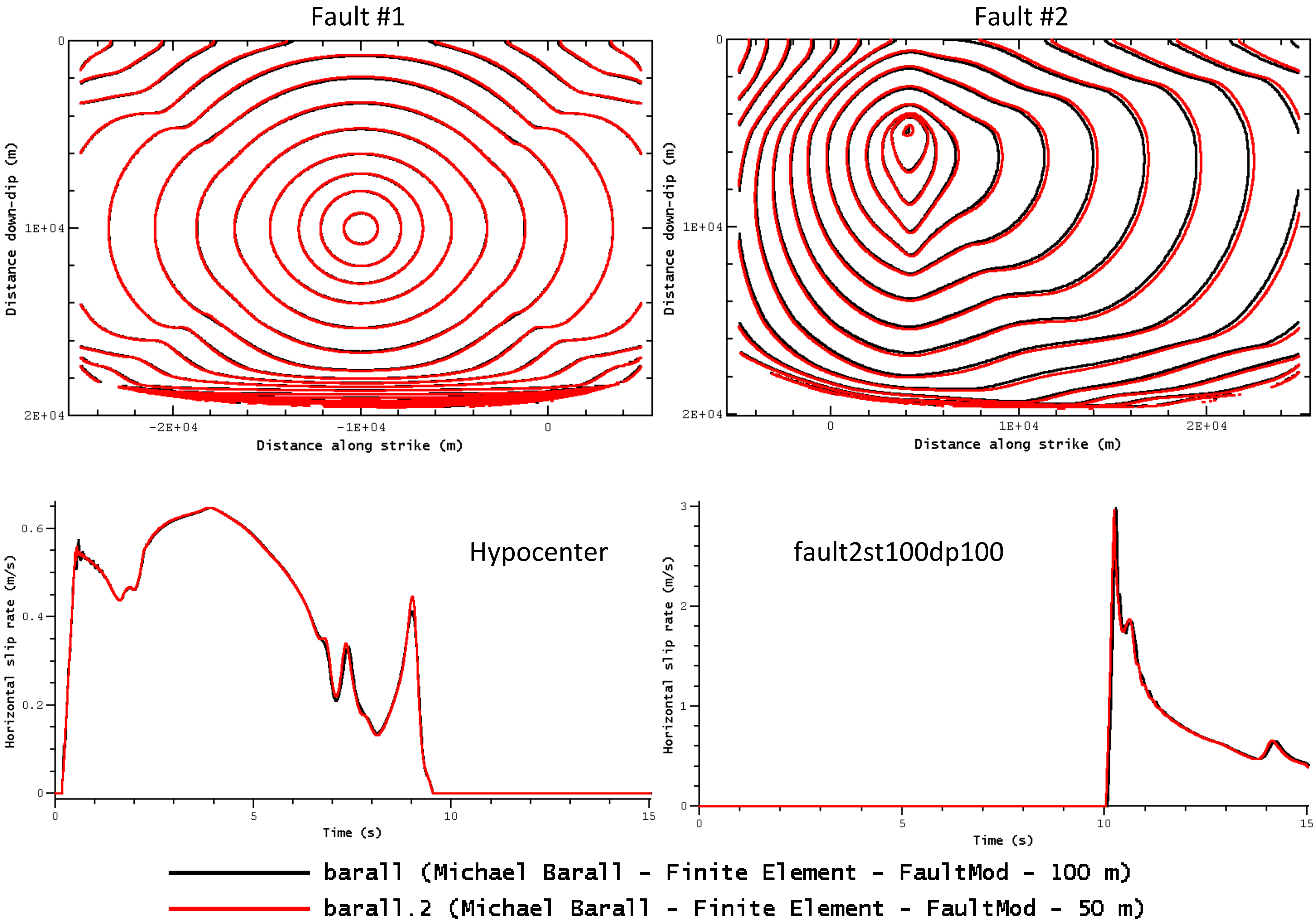
In addition, modelers are asked to submit the time at which each point on the fault begins to slip, from which we construct rupture contour plots.

Off-Fault Stations.



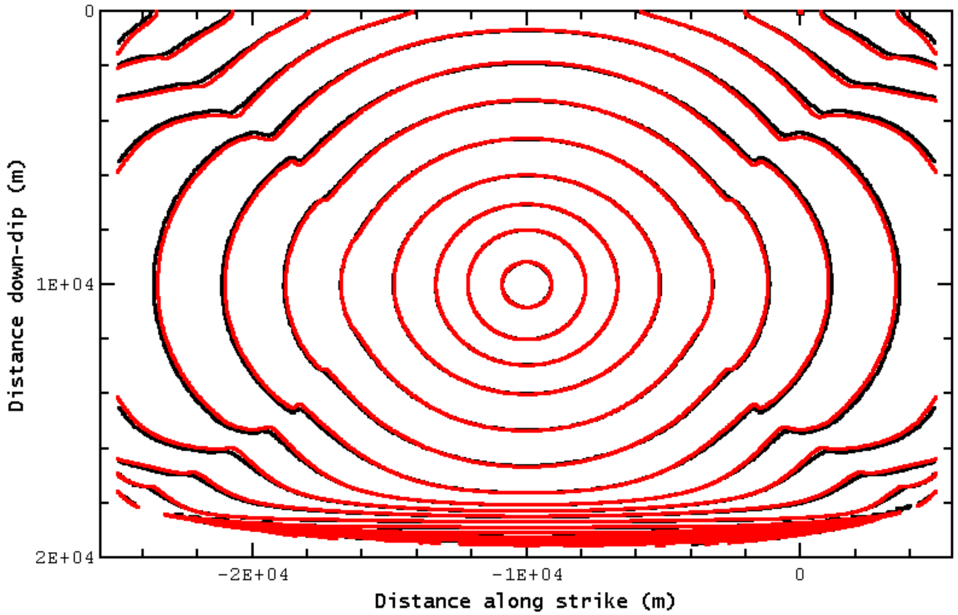
Modelers are asked to submit displacement and velocity as a function of time, for 6 stations on the earth's surface.

TPV22 Results — 50 vs. 100 Meters

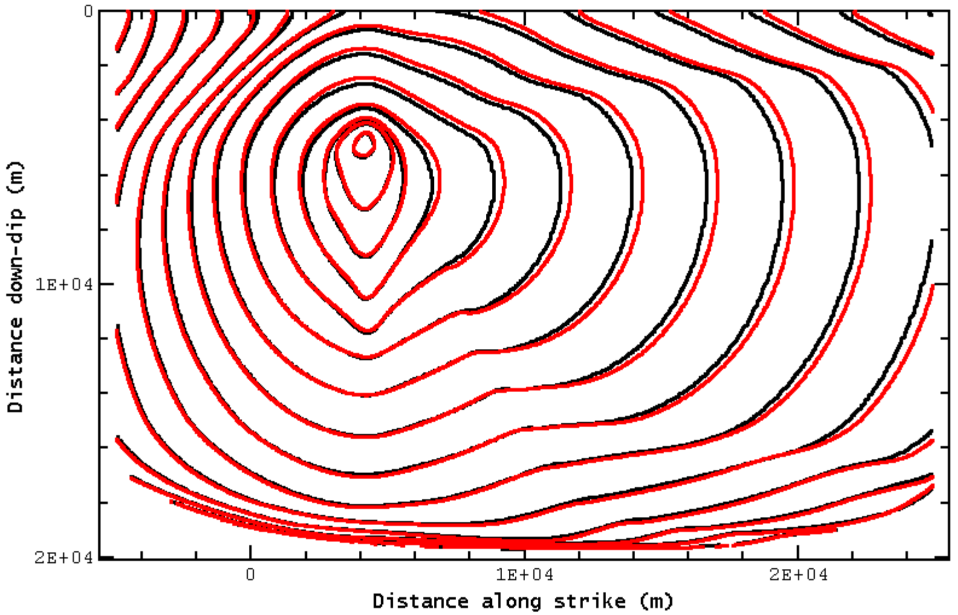


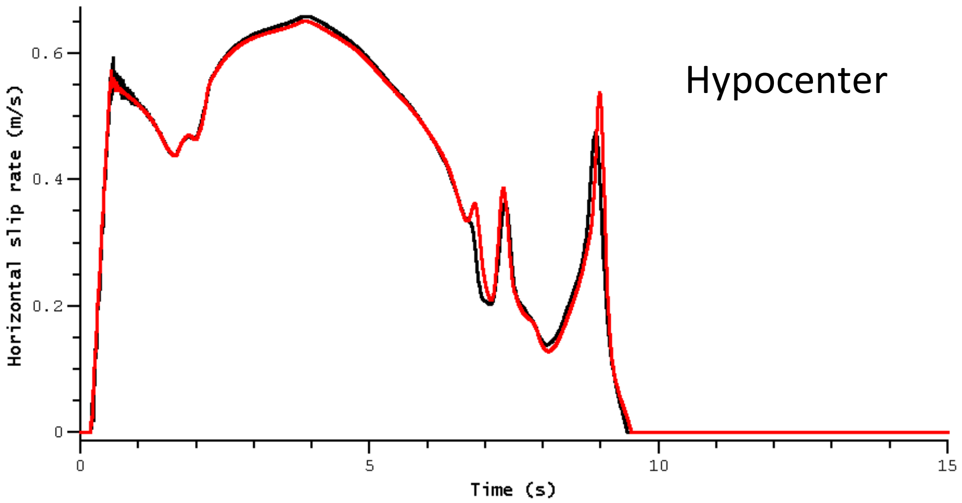
Fault #1
Fault #2
0
1E+04
2E+04
-2E+04
-1E+04
Distance down-dip (m)
Distance along strike (m)
Hypocenter
fault2st100dp100
Horizontal slip rate (m/s)
0.6
0.4
0.2
3
2
1
5
10
15
Time (s)
barall (Michael Barall - Finite Element - FaultMod - 100 m)
barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)

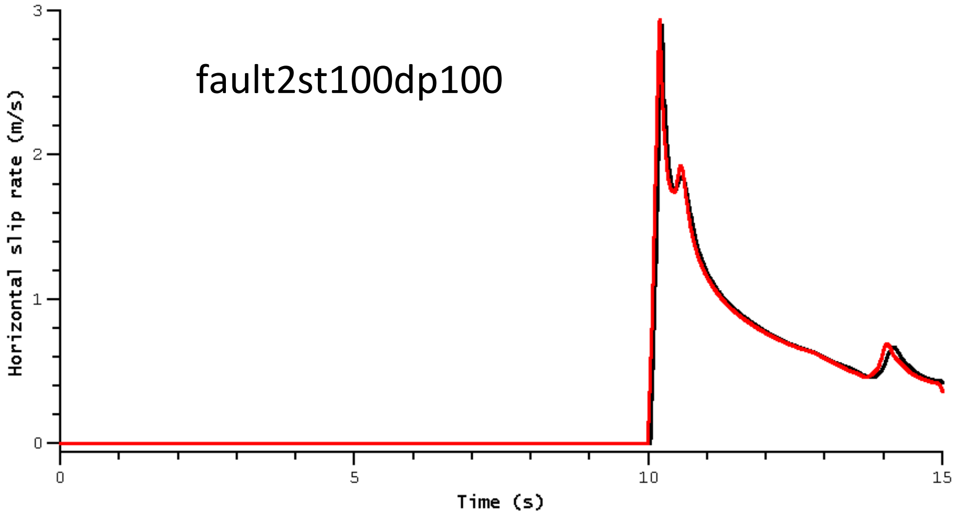
Fault #1



Fault #2

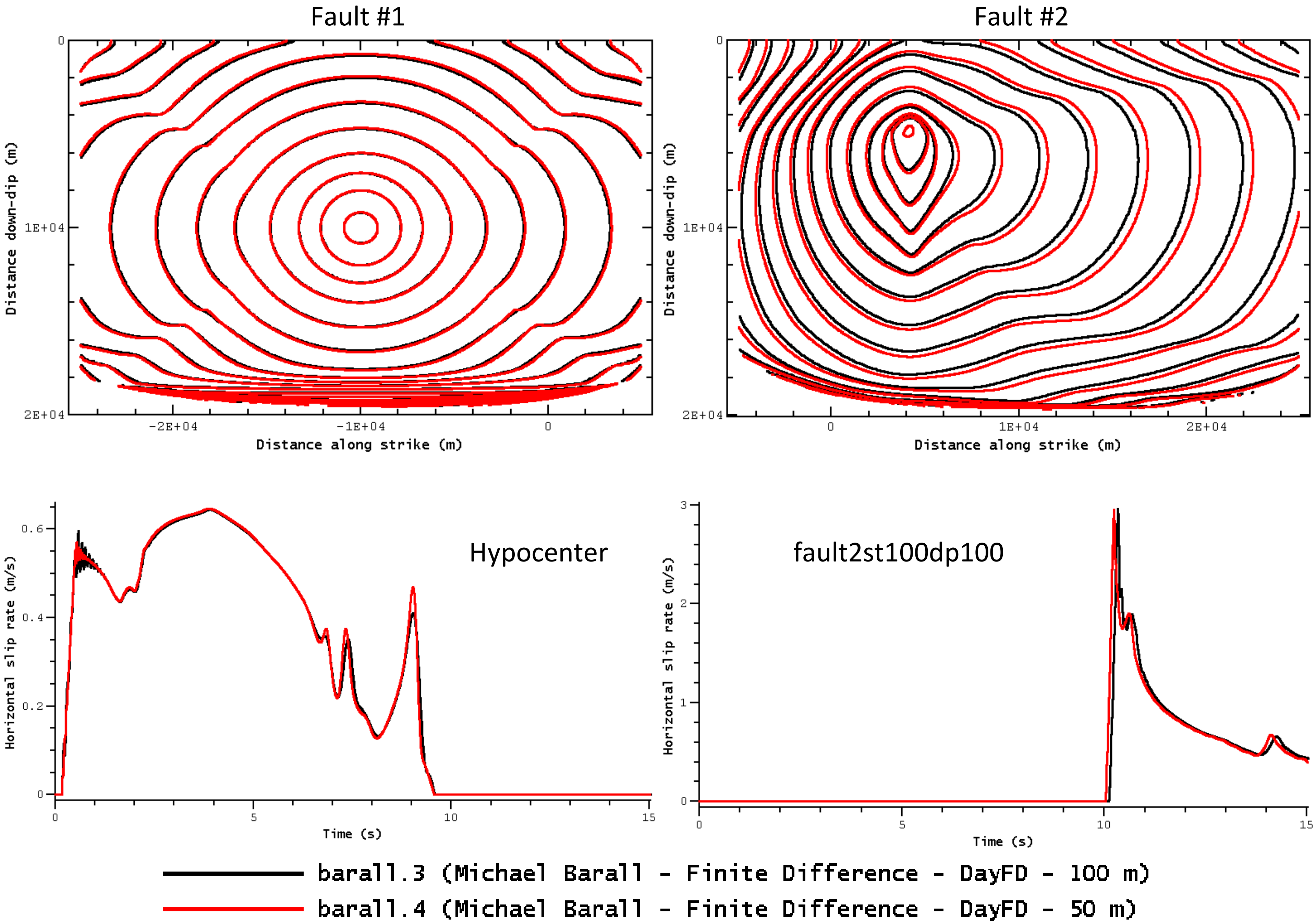


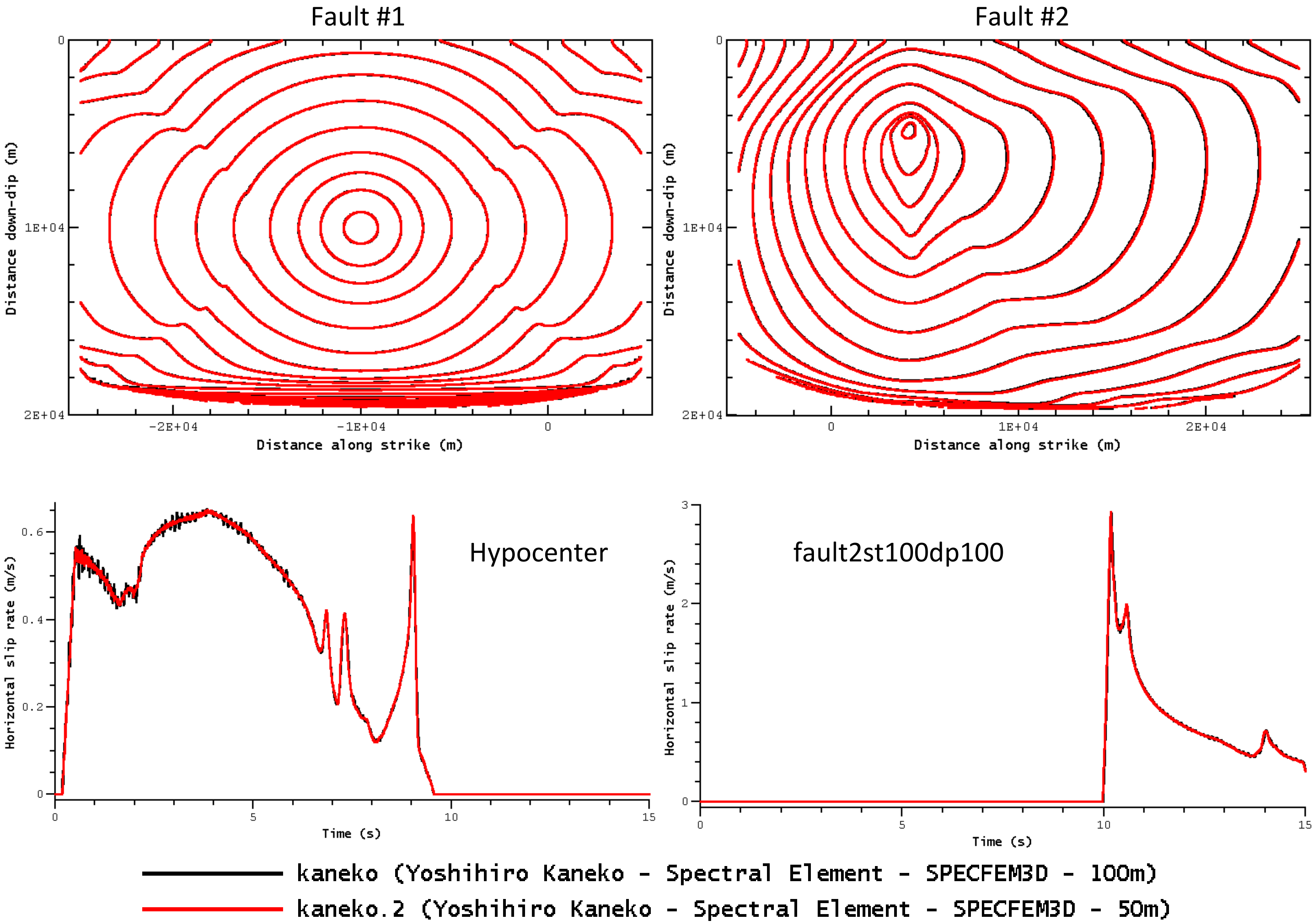




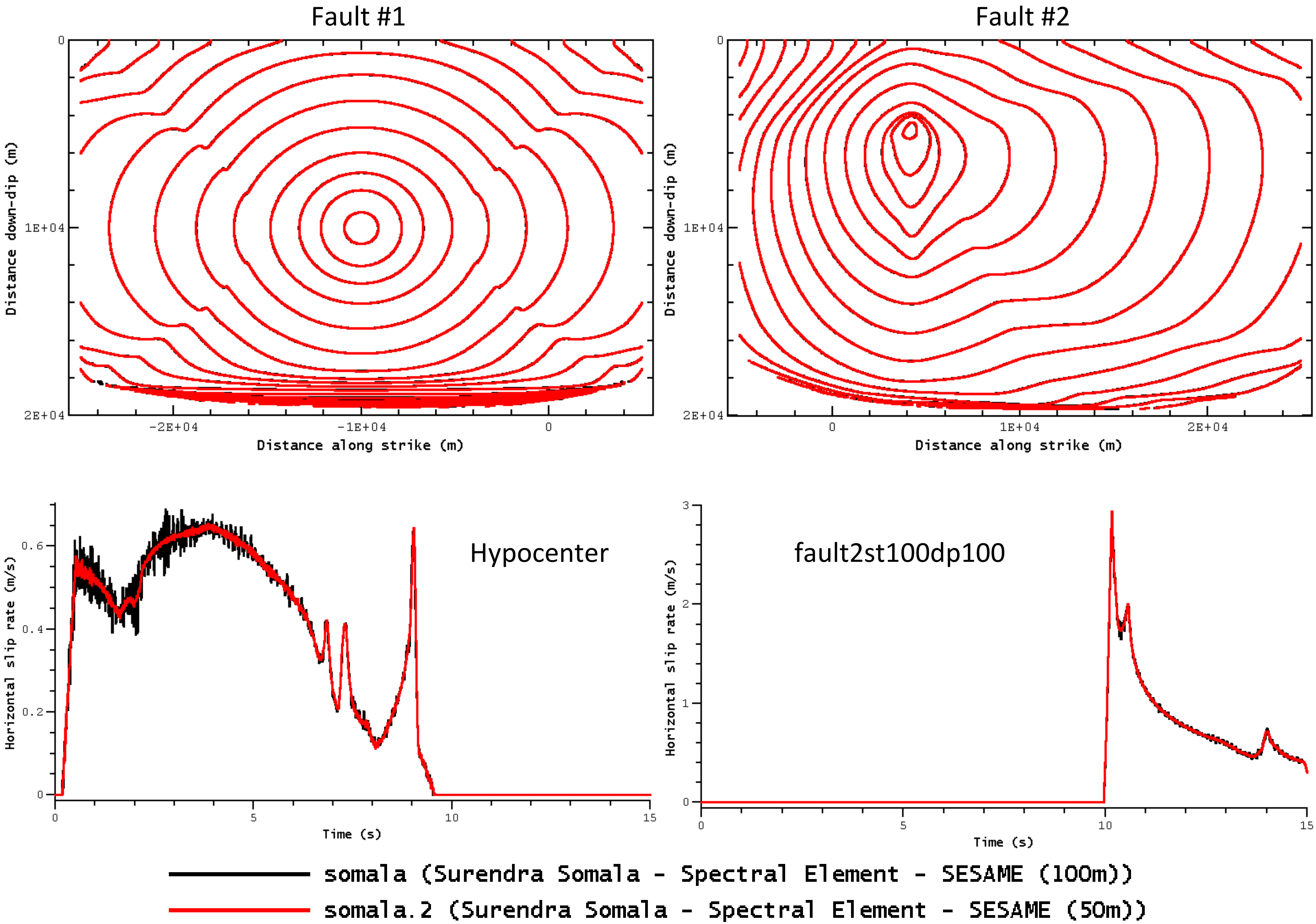
payne (Ryan Payne - Finite Element - EQdyna - 100m)

payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)

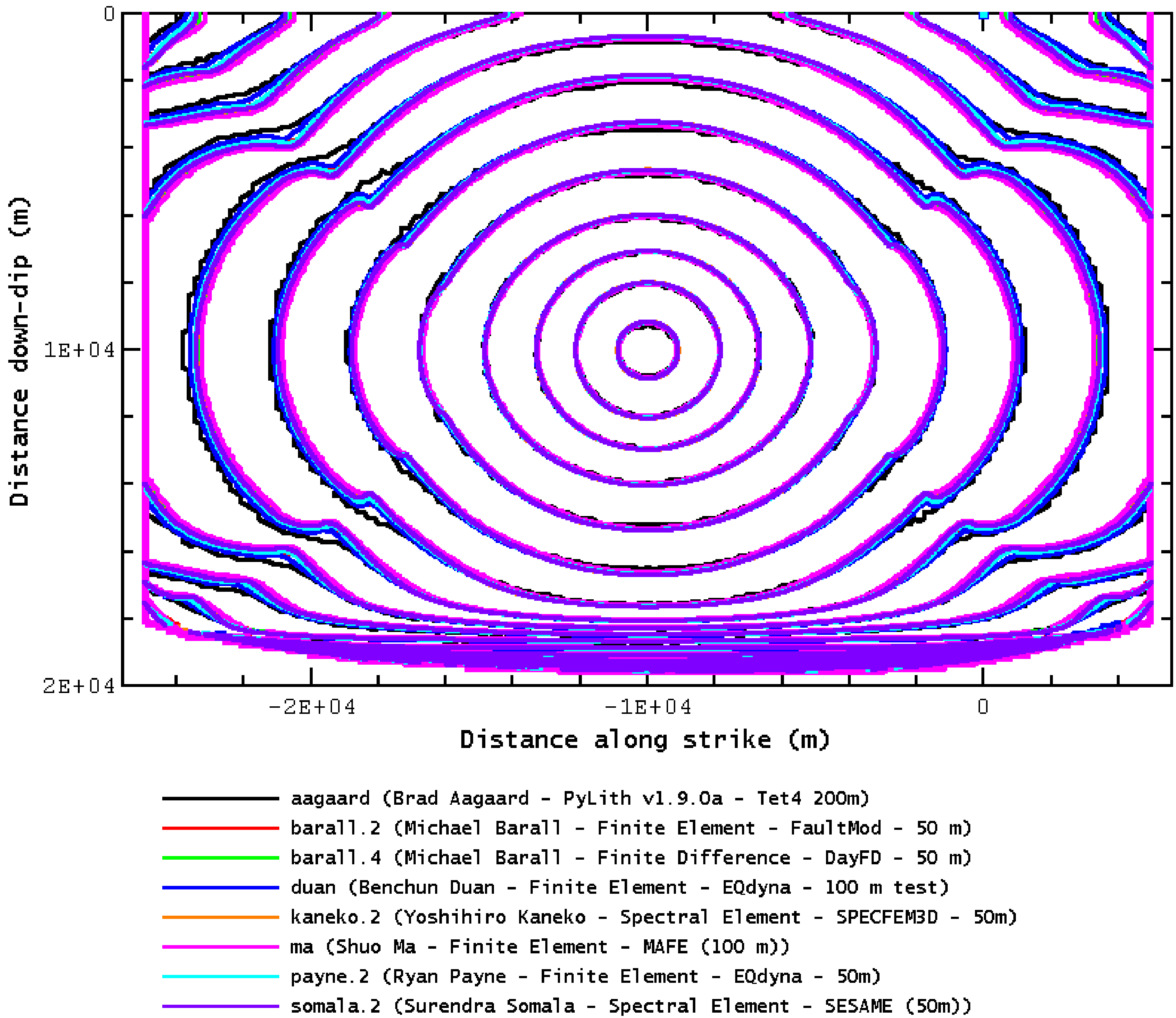

Fault #1
Fault #2
Distance down-dip (m)
Distance along strike (m)
0
1E+04
2E+04
-2E+04
-1E+04
Hypocenter
fault2st100dp100
Horizontal slip rate (m/s)
Time (s)
0.2
0.4
0.6
5
10
15
1
2
3
barall.3 (Michael Barall - Finite Difference - DayFD - 100 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)

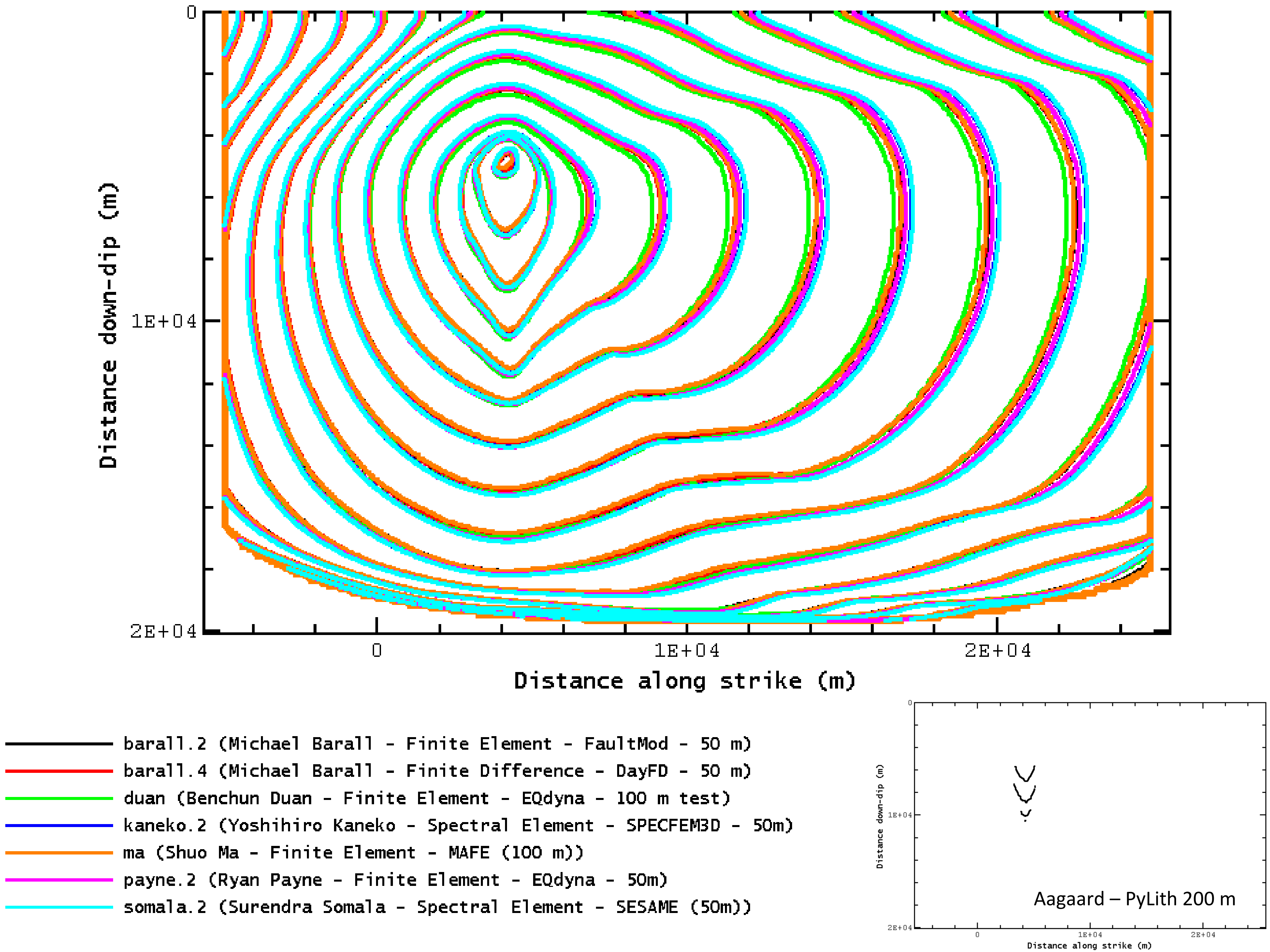


Fault #1
Fault #2
Distance down-dip (m)
Distance along strike (m)
0
1E+04
2E+04
-2E+04
-1E+04
Hypocenter
fault2st100dp100
Horizontal slip rate (m/s)
Time (s)
kaneko (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 100m)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)


Fault #1
Fault #2
Distance down-dip (m)
Distance along strike (m)
0
1E+04
2E+04
-2E+04
-1E+04
0
1E+04
2E+04
Hypocenter
fault2st100dp100
Horizontal slip rate (m/s)
Time (s)
0
0.2
0.4
0.6
1
2
3
5
10
15
somala (Surendra Somala - Spectral Element - SESAME (100m))
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

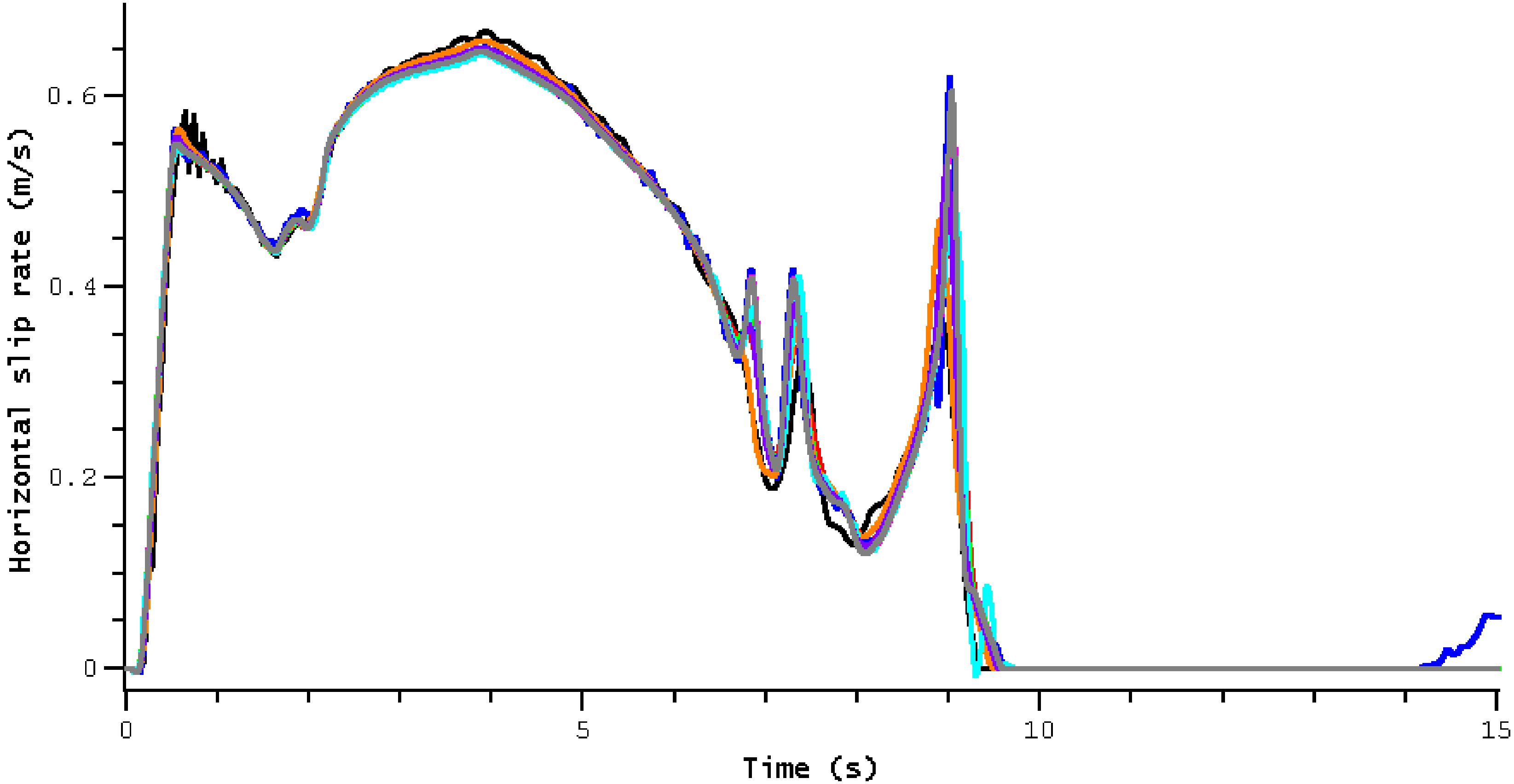
TPV22 Comparisons
(1600 m Extensional Stepover)

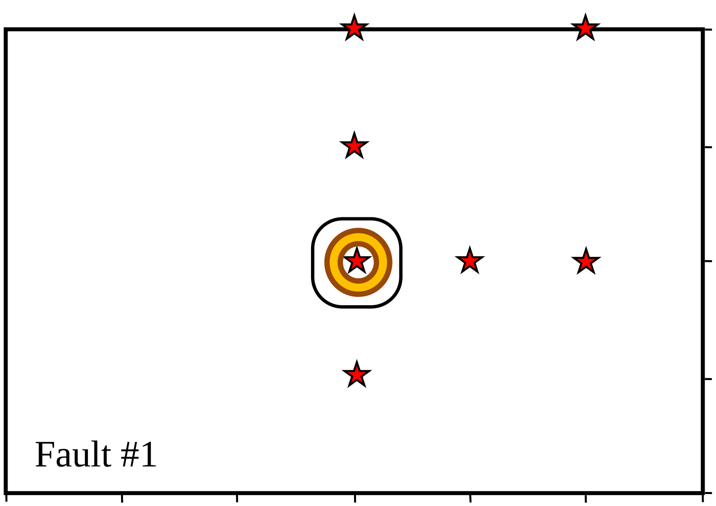

0
1E+04
2E+04
-2E+04
-1E+04
0
Distance down-dip (m)
Distance along strike (m)
aagaard (Brad Aagaard - PyLith v1.9.0a - Tet4 200m)
barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))



0
1E+04
2E+04
Distance down-dip (m)
0
1E+04
2E+04
Distance along strike (m)
barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))
Aagaard – PyLith 200 m
Distance down-dip (m)
Distance along strike (m)

fault1st-100dp100 (hypocenter)

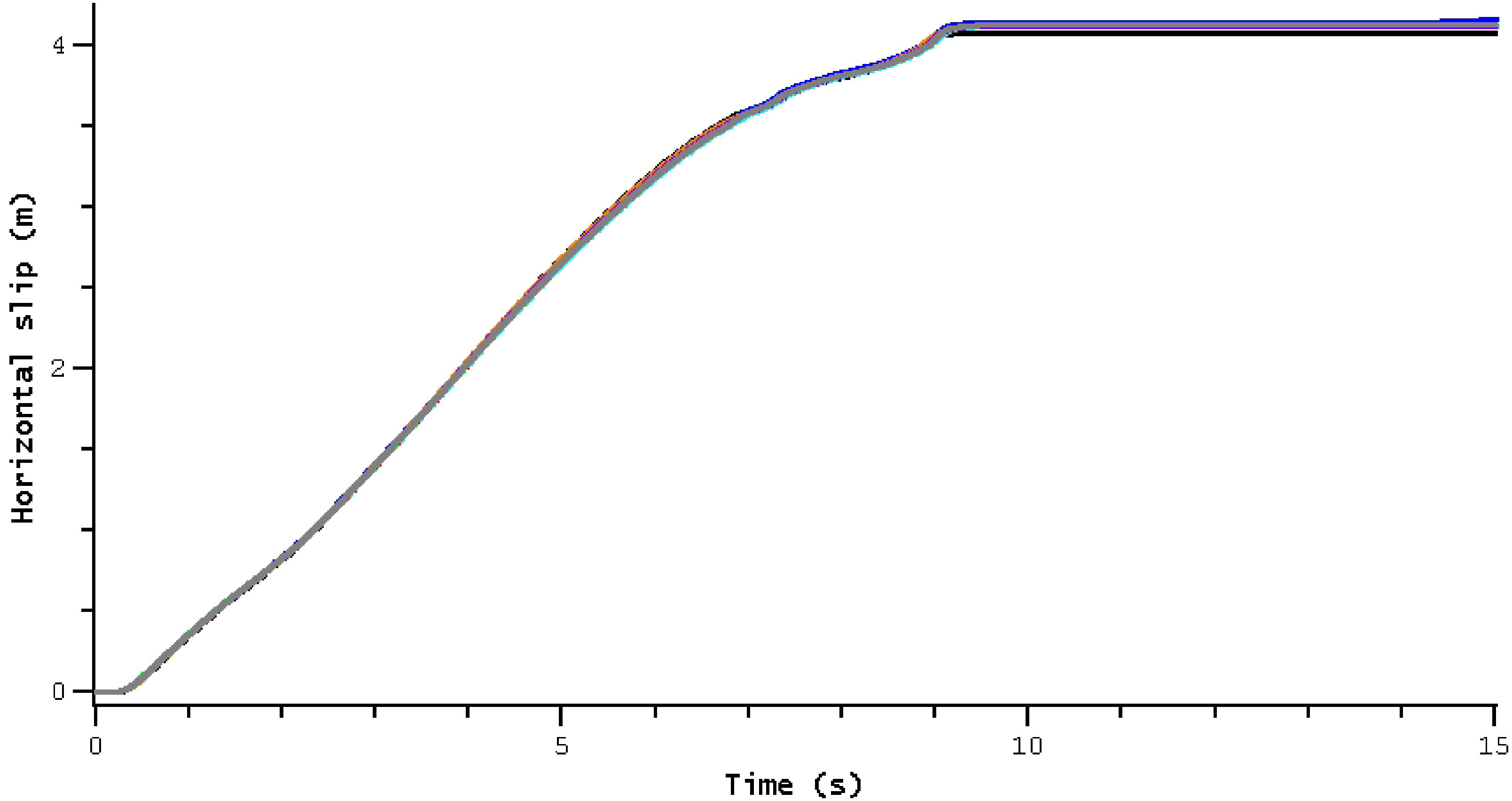


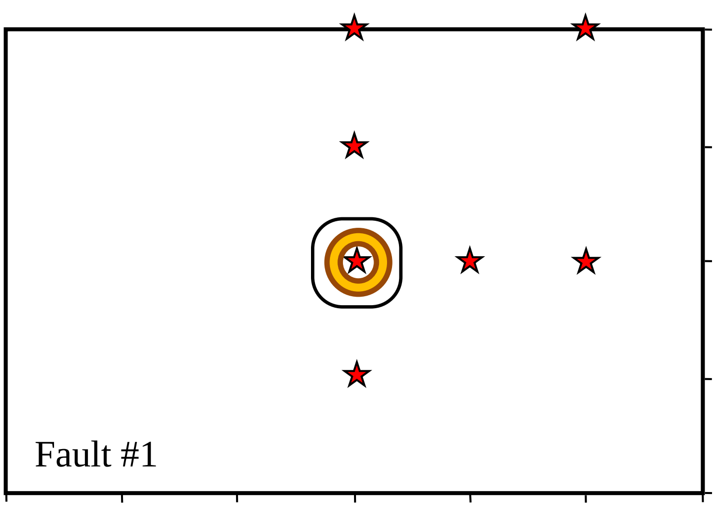


- aagaard (Brad Aagaard - PyLith v1.9.0a - Tet4 200m)
- barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
- barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
- cruz-atienza (Tago/Cruz-Atienza - Discontinuous Galerkin - DGCrack - 200 m)
- duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
- kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
- ma (Shuo Ma - Finite Element - MAFE (100 m))
- payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
- somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

5 Hz low-pass filter applied to all time series.

fault1st-100dp100 (hypocenter)

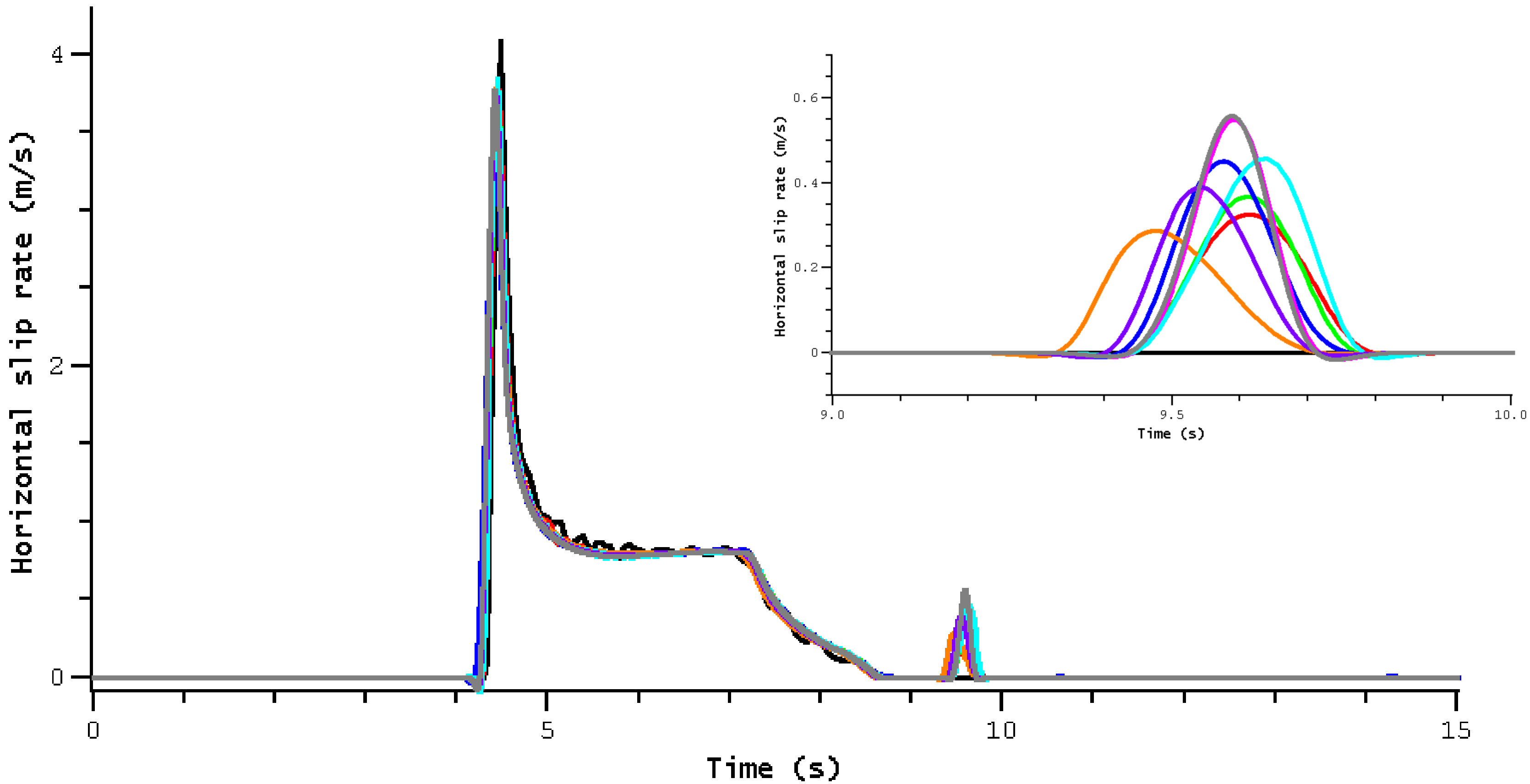


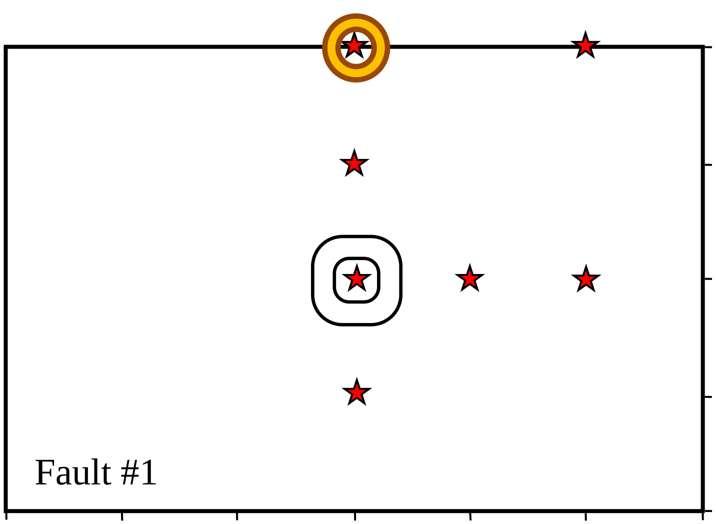


aagaard (Brad Aagaard - PyLith v1.9.0a - Tet4 200m)
barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
cruz-atienza (Tago/Cruz-Atienza - Discontinuous Galerkin - DGCrack - 200 m)
duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

5 Hz low-pass filter applied to all time series.

fault1st-100dp000

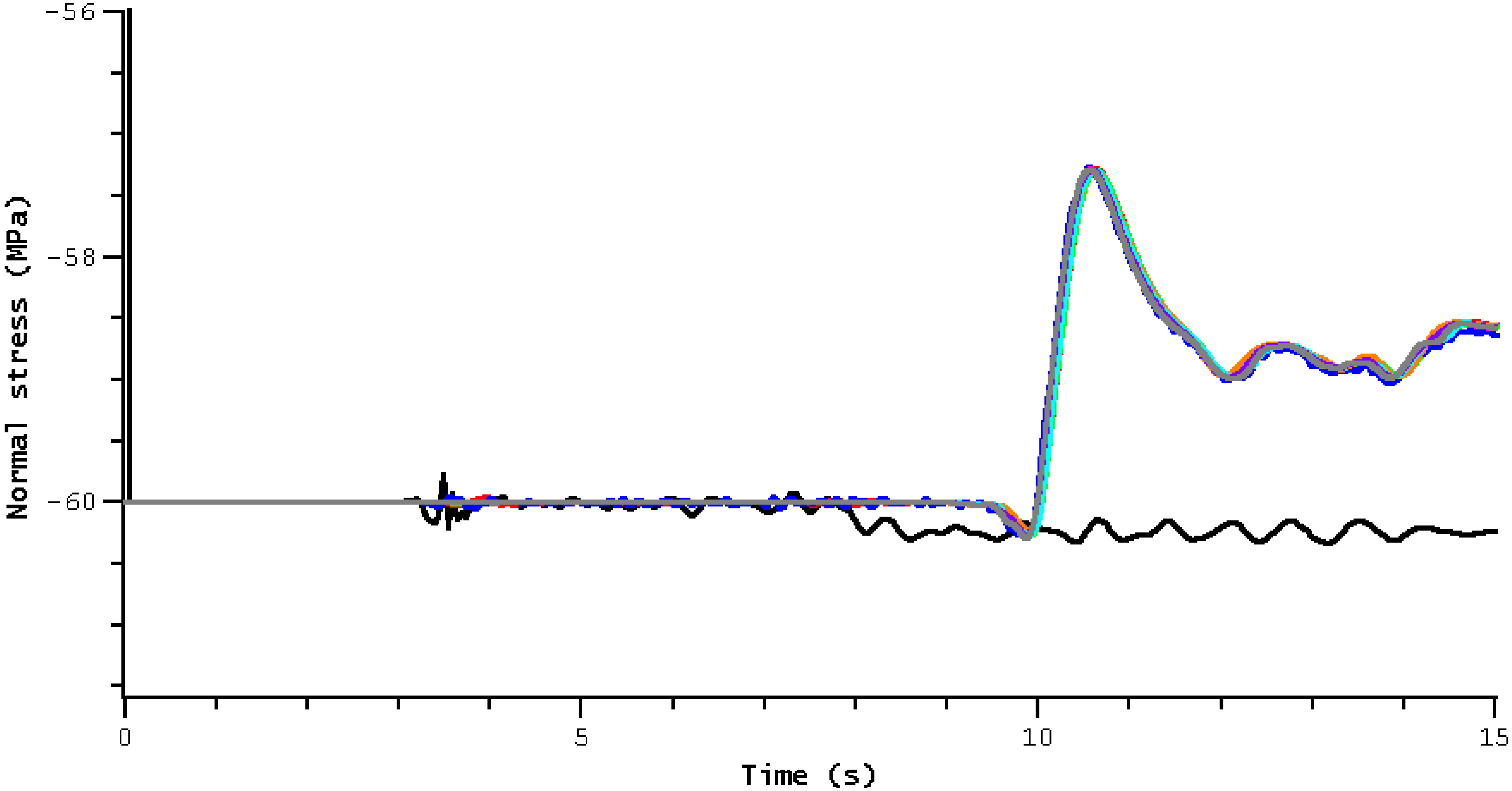


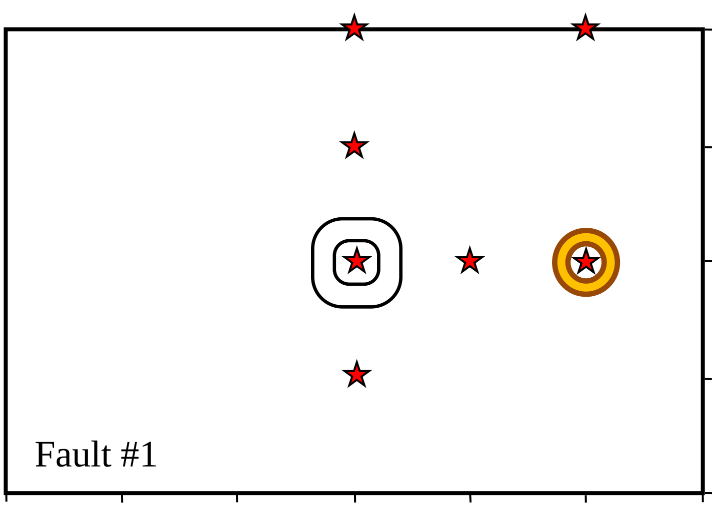


- aagaard (Brad Aagaard - PyLith v1.9.0a - Tet4 200m)
- barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
- barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
- cruz-atienza (Tago/Cruz-Atienza - Discontinuous Galerkin - DGCrack - 200 m)
- duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
- kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
- ma (Shuo Ma - Finite Element - MAFE (100 m))
- payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
- somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

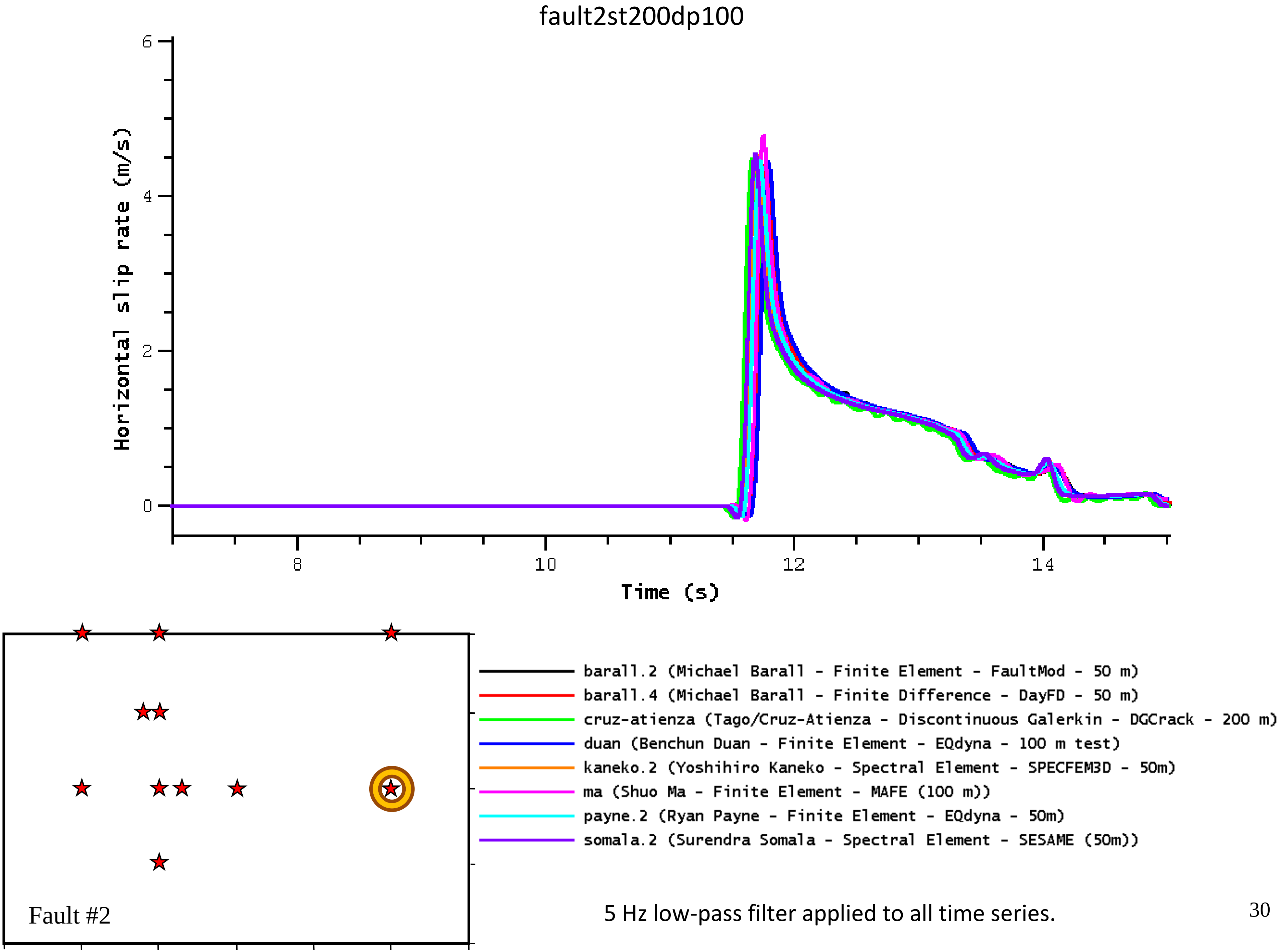
5 Hz low-pass filter applied to all time series.

fault1st-000dp100



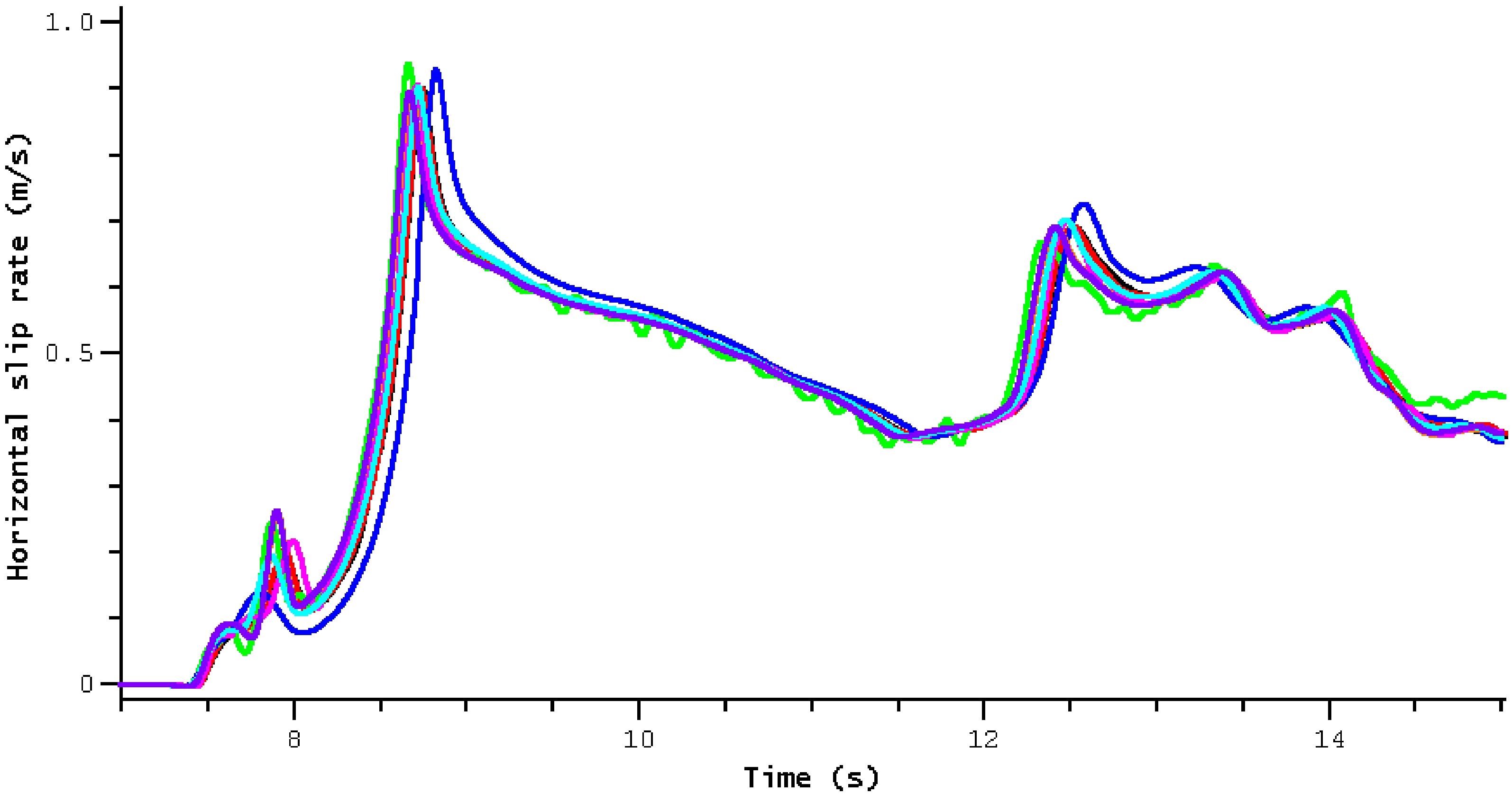


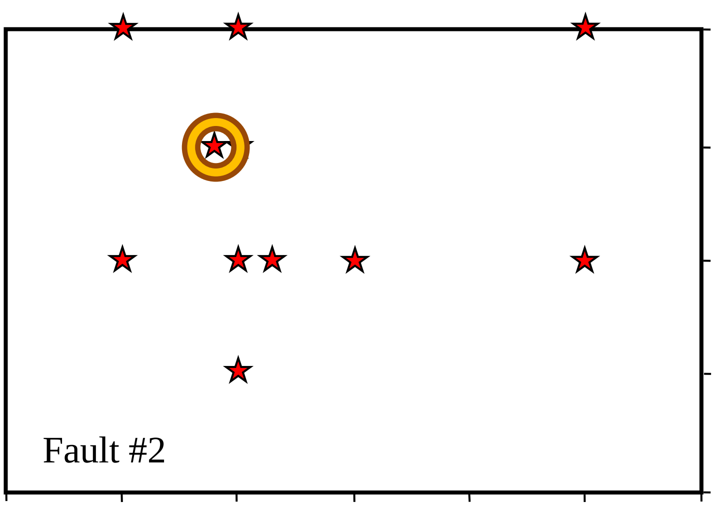
5 Hz low-pass filter applied to all time series.



5 Hz low-pass filter applied to all time series.

fault2st040dp050

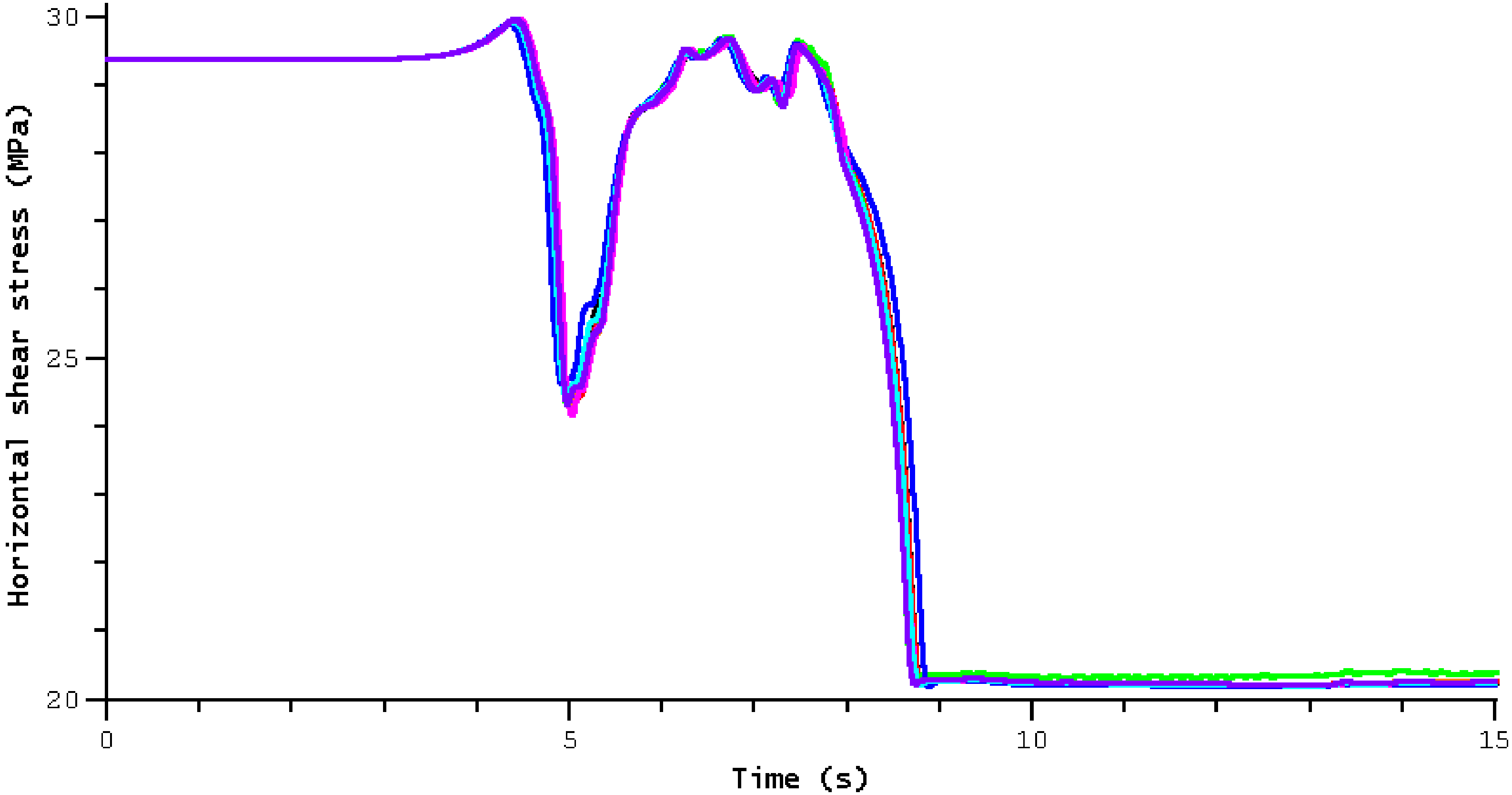


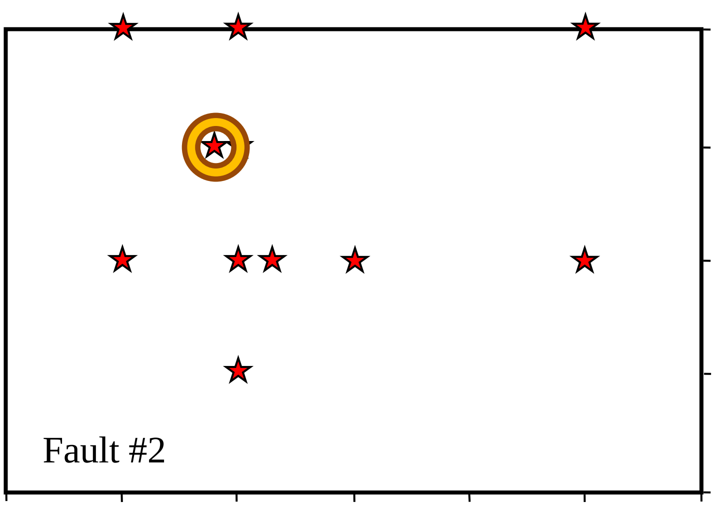


baral1.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
cruz-atienza (Tago/Cruz-Atienza - Discontinuous Galerkin - DGCrack - 200 m)
duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

5 Hz low-pass filter applied to all time series.

fault2st040dp050

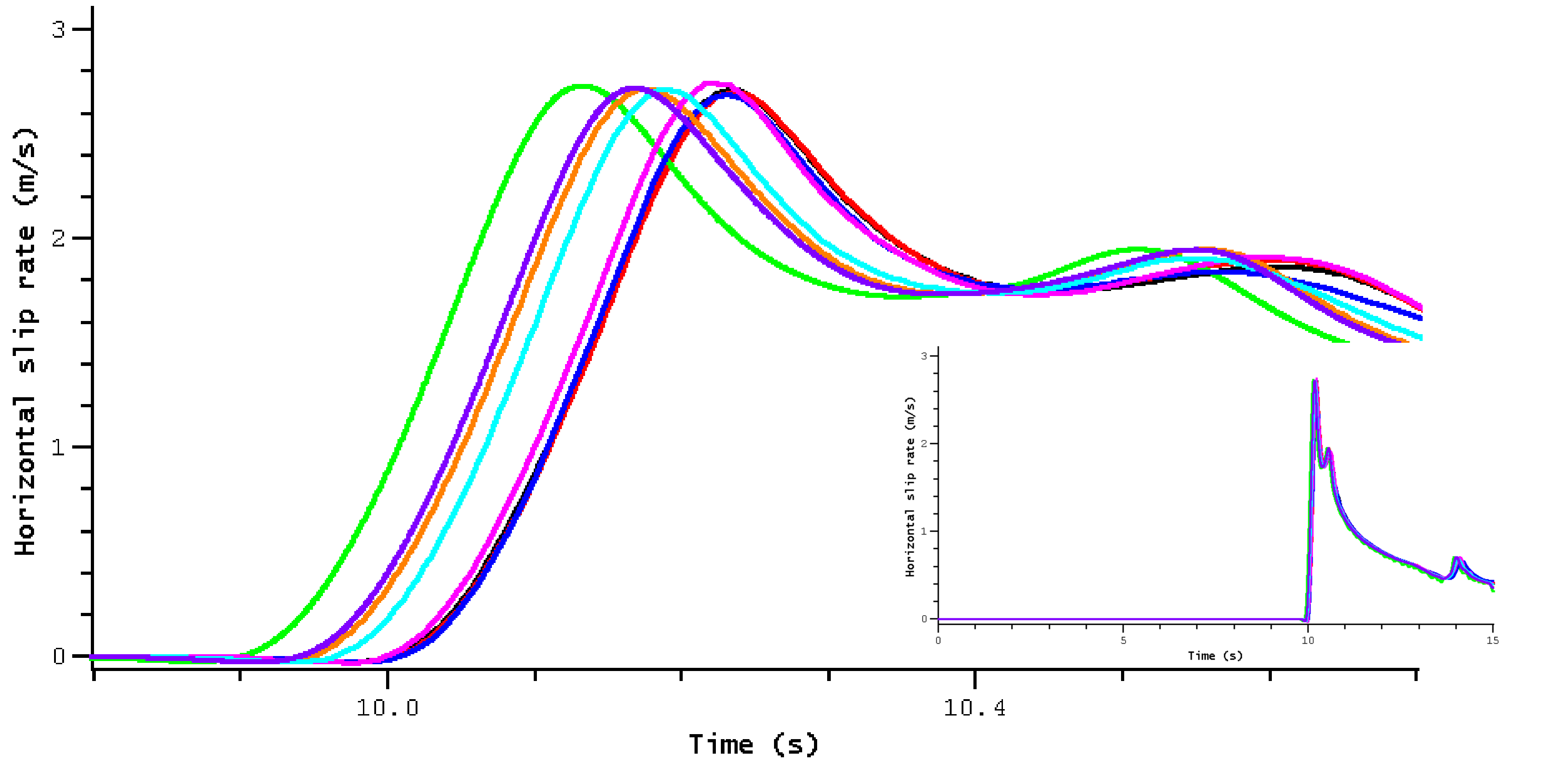


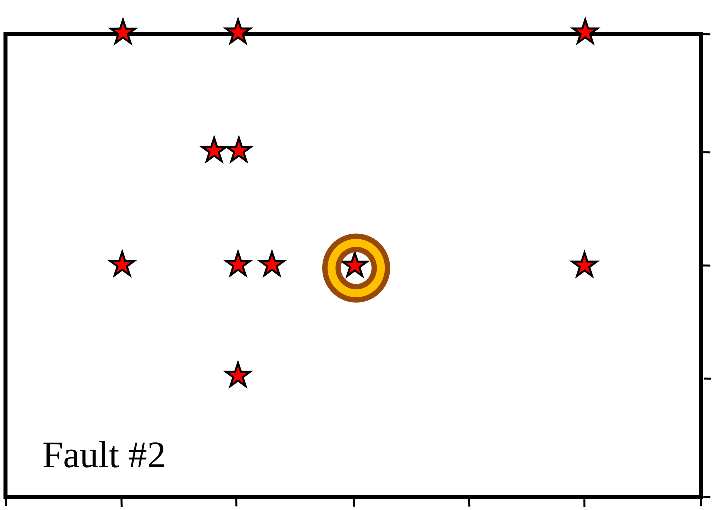


- barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
- barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
- cruz-atienza (Tago/Cruz-Atienza - Discontinuous Galerkin - DGCrack - 200 m)
- duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
- kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
- ma (Shuo Ma - Finite Element - MAFE (100 m))
- payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
- somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

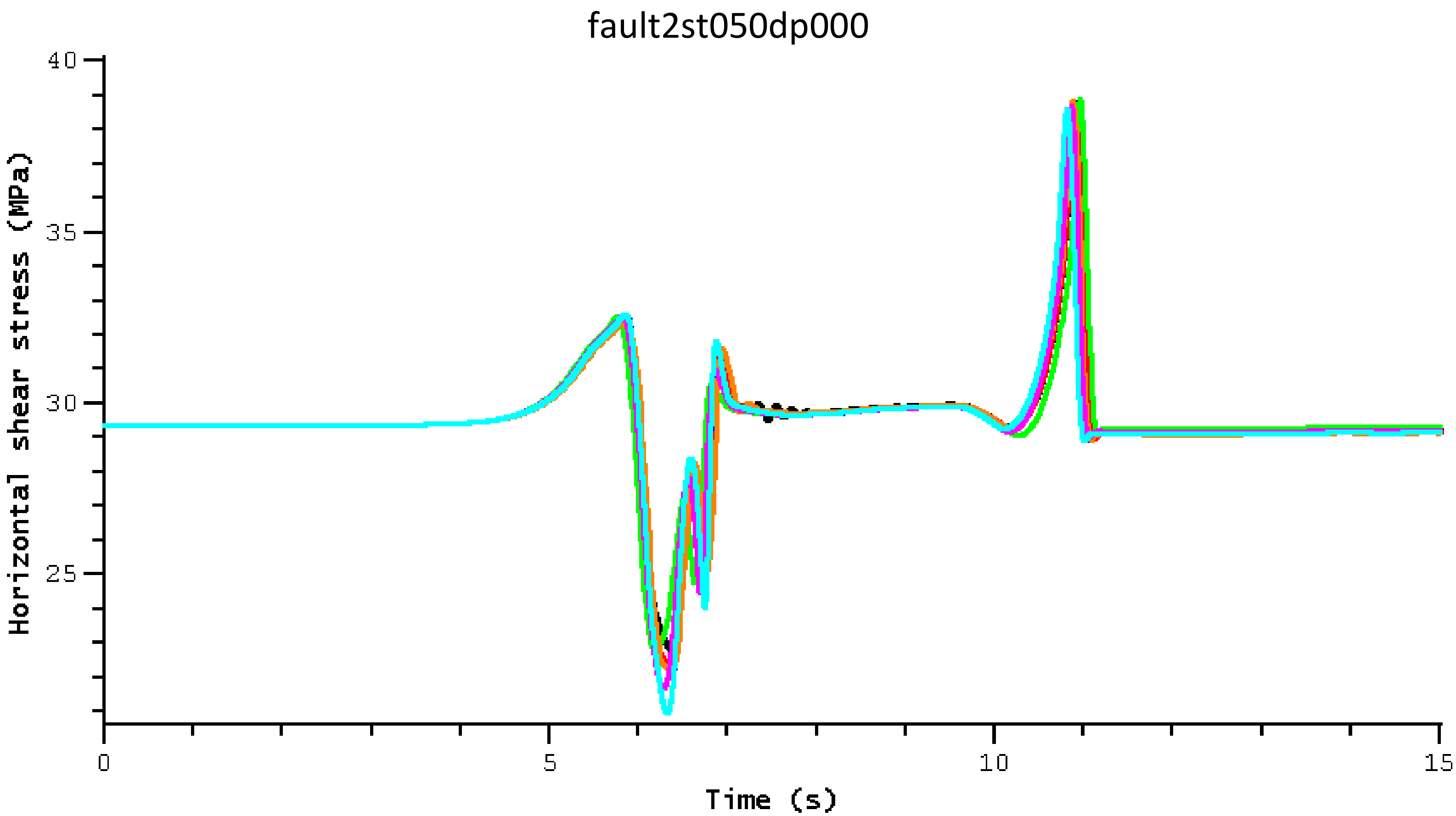
5 Hz low-pass filter applied to all time series.

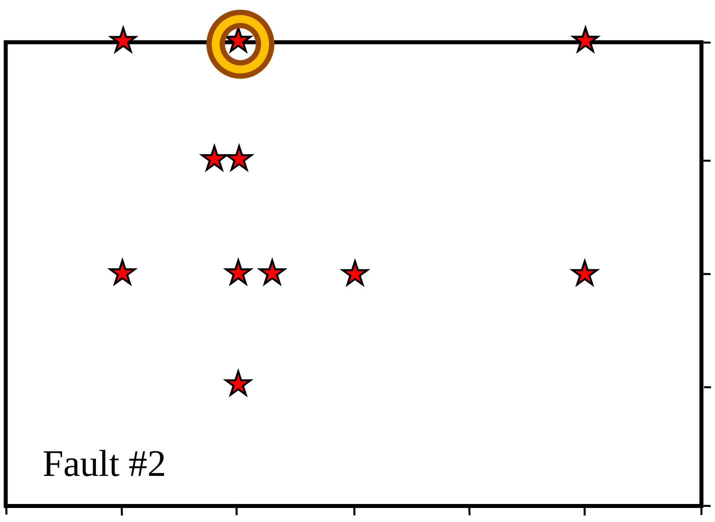
fault2st100dp100

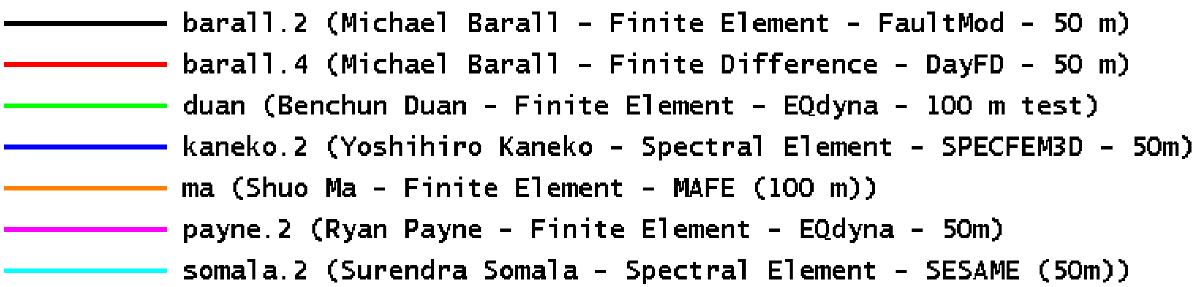




5 Hz low-pass filter applied to all time series.

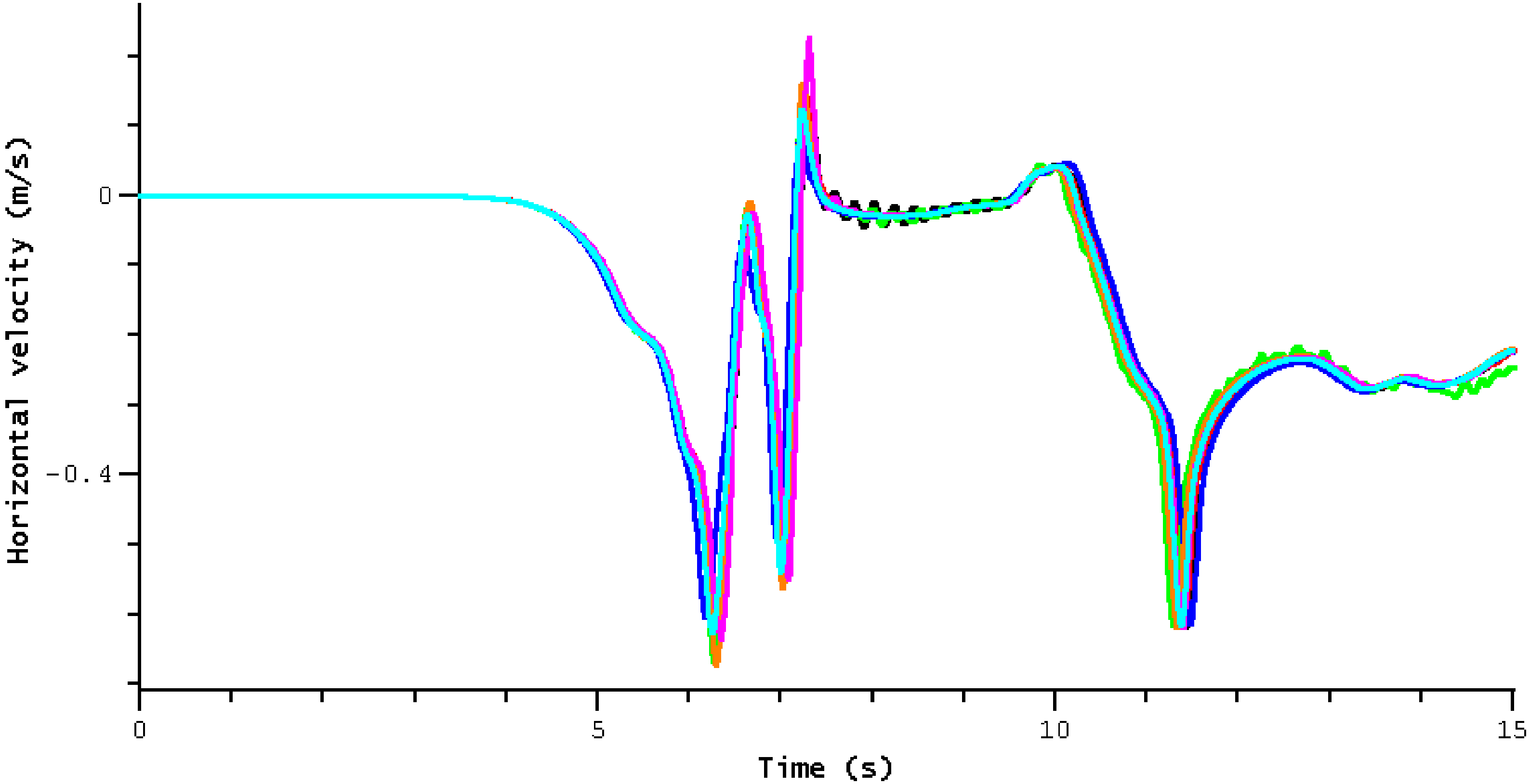


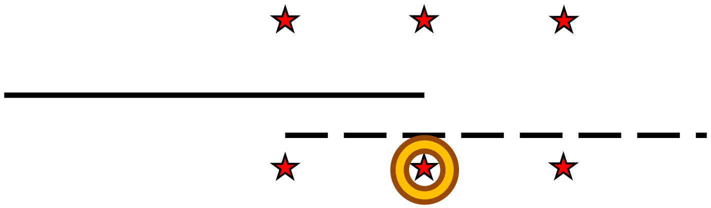




5 Hz low-pass filter applied to all time series.

body-030st050dp000

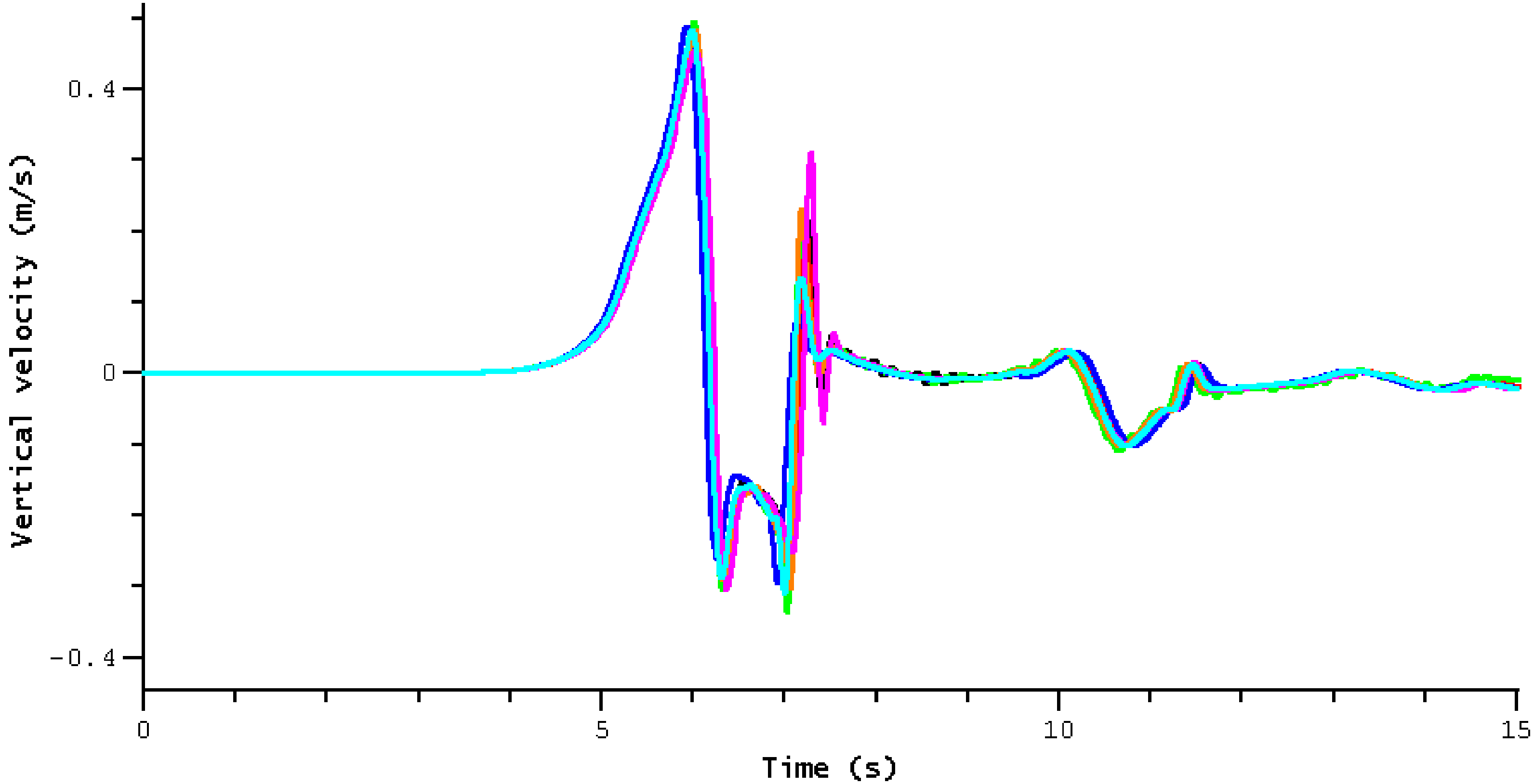


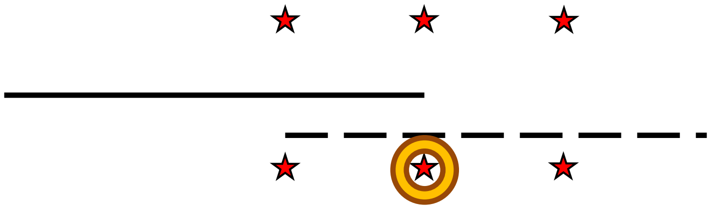


barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
cruz-atienza (Tago/Cruz-Atienza - Discontinuous Galerkin - DGCrack - 200 m)
duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)

5 Hz low-pass filter applied to all time series.

body-030st050dp000

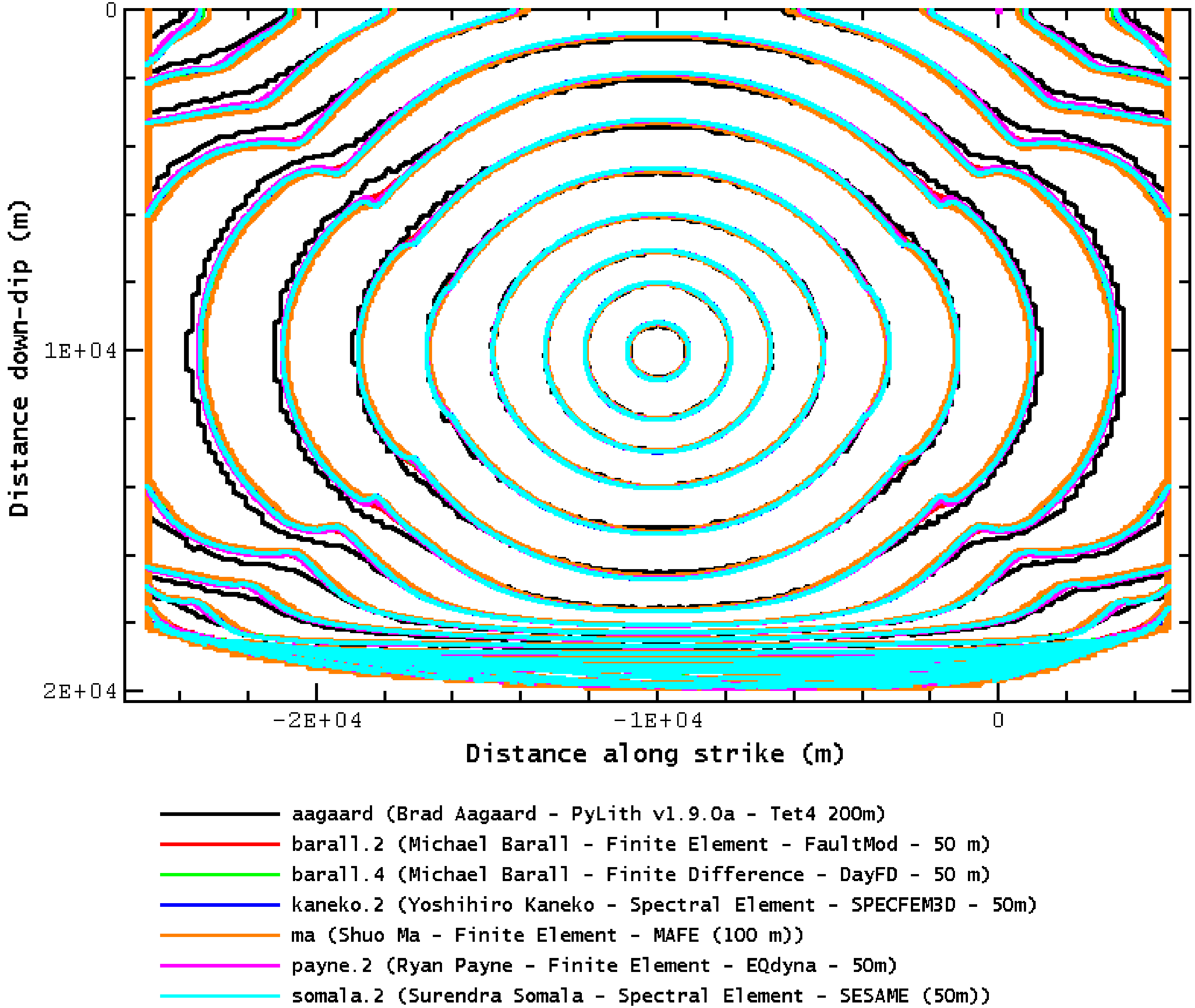


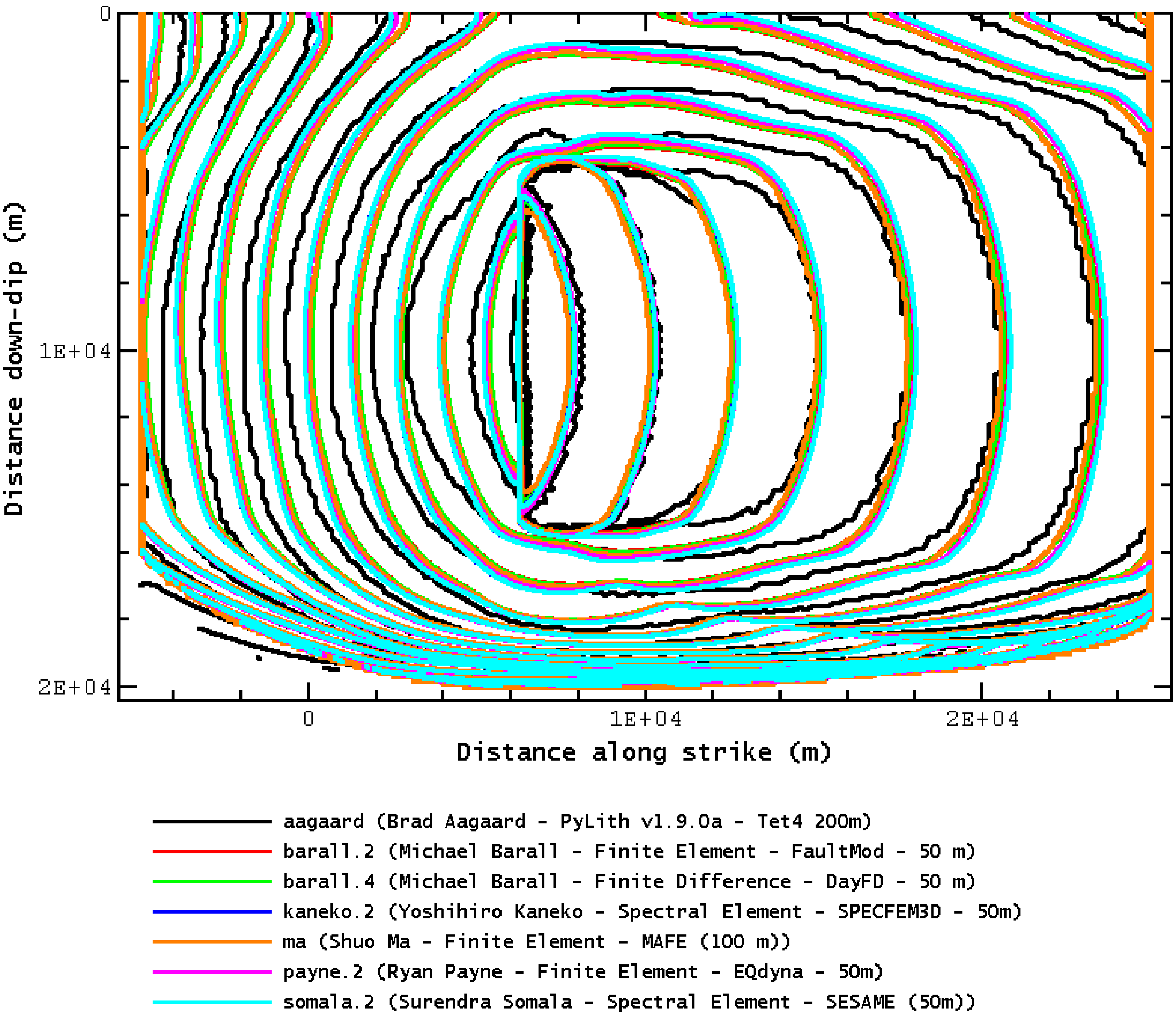


barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
cruz-atienza (Tago/Cruz-Atienza - Discontinuous Galerkin - DGCrack - 200 m)
duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)

5 Hz low-pass filter applied to all time series.

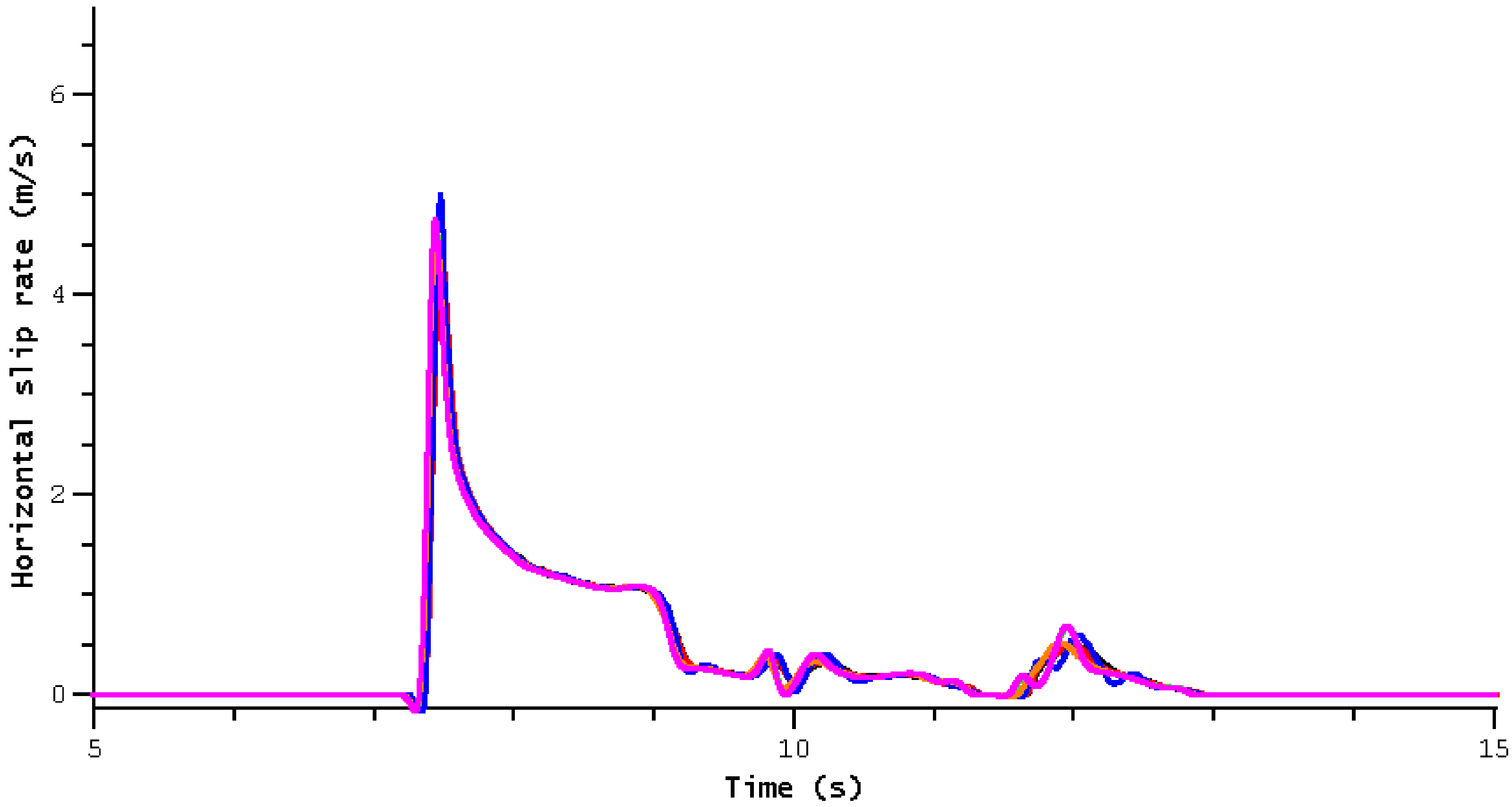
TPV23 Comparisons
(1000 m Compressional Stepover)

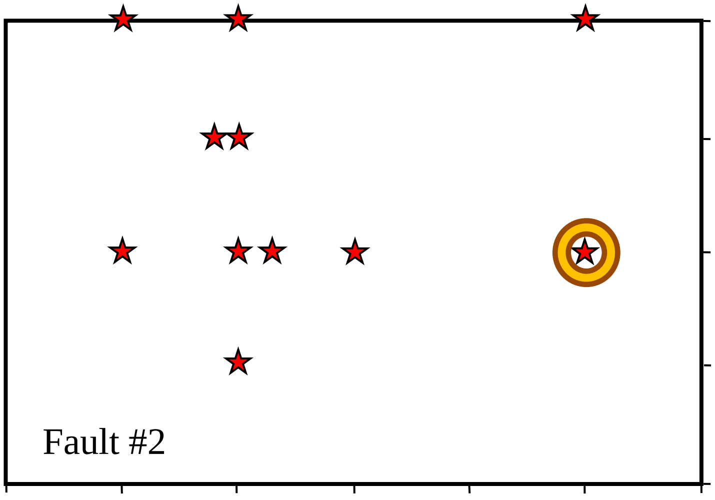

0
1E+04
2E+04
Distance down-dip (m)
-2E+04
-1E+04
0
Distance along strike (m)
aagaard (Brad Aagaard - PyLith v1.9.0a - Tet4 200m)
barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))



0
1E+04
2E+04
Distance down-dip (m)
0
1E+04
2E+04
Distance along strike (m)
aagaard (Brad Aagaard - PyLith v1.9.0a - Tet4 200m)
barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

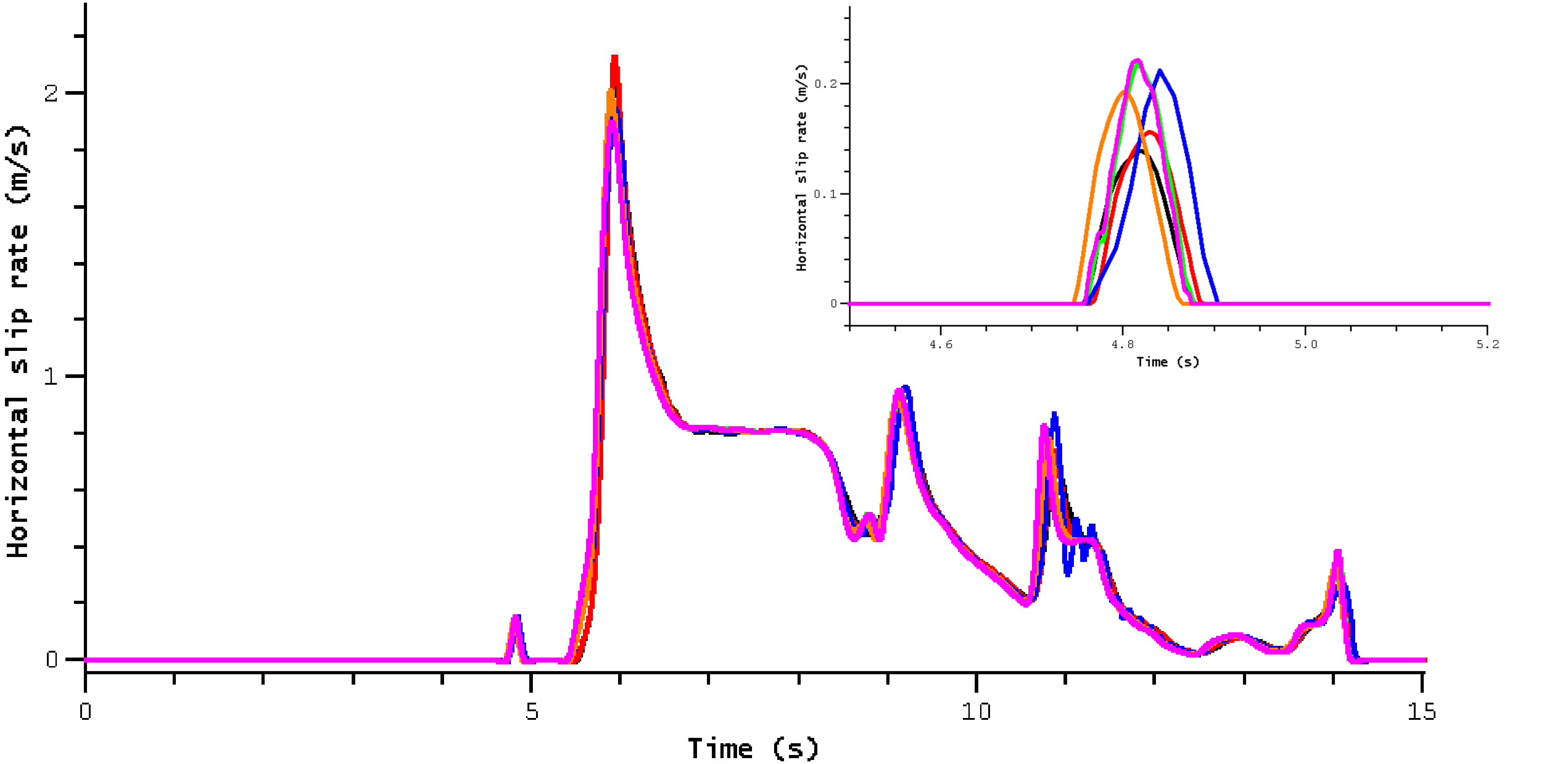
fault2st200dp100

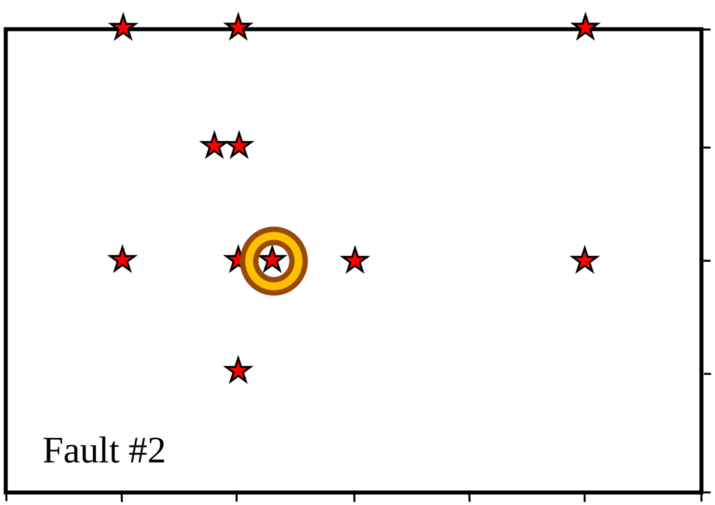




5 Hz low-pass filter applied to all time series.

fault2st065dp100

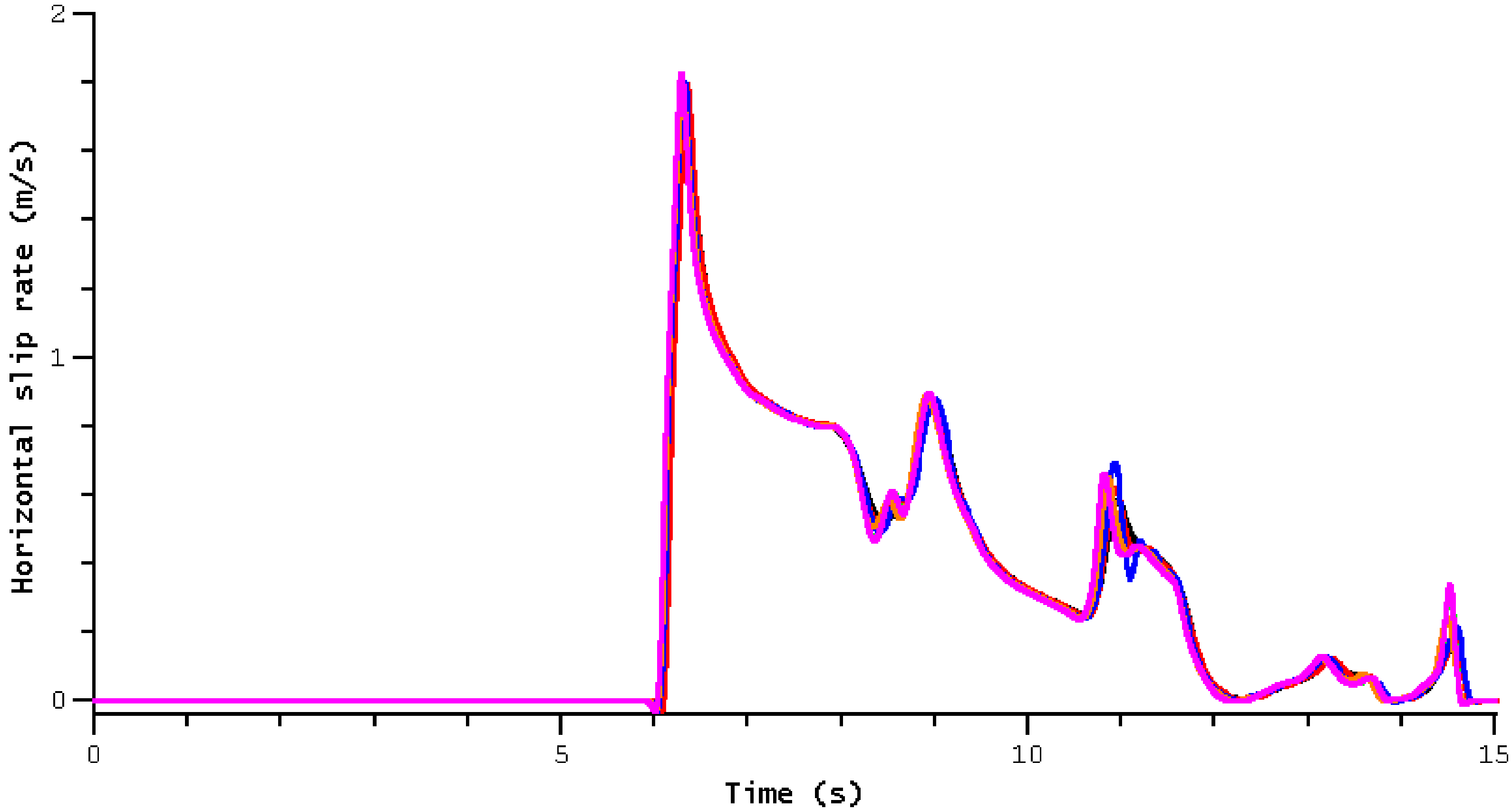


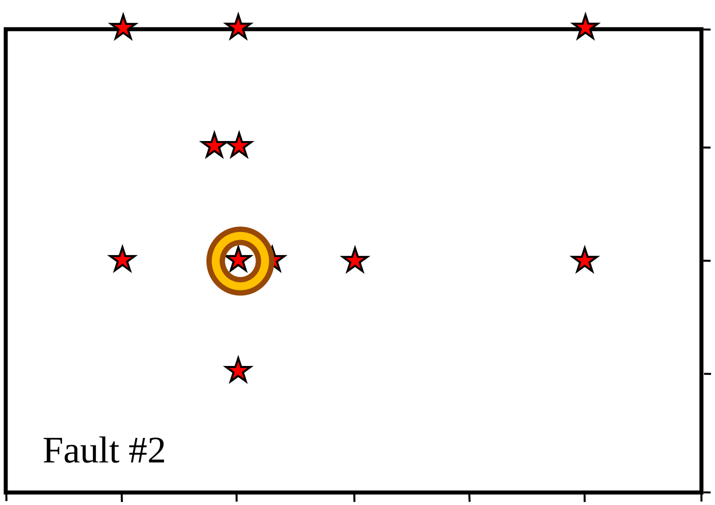


baral1.2 (Michael Barall - Finite Element - FaultMod - 50 m)
baral1.4 (Michael Barall - Finite Difference - DayFD - 50 m)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

5 Hz low-pass filter applied to all time series.

fault2st050dp100

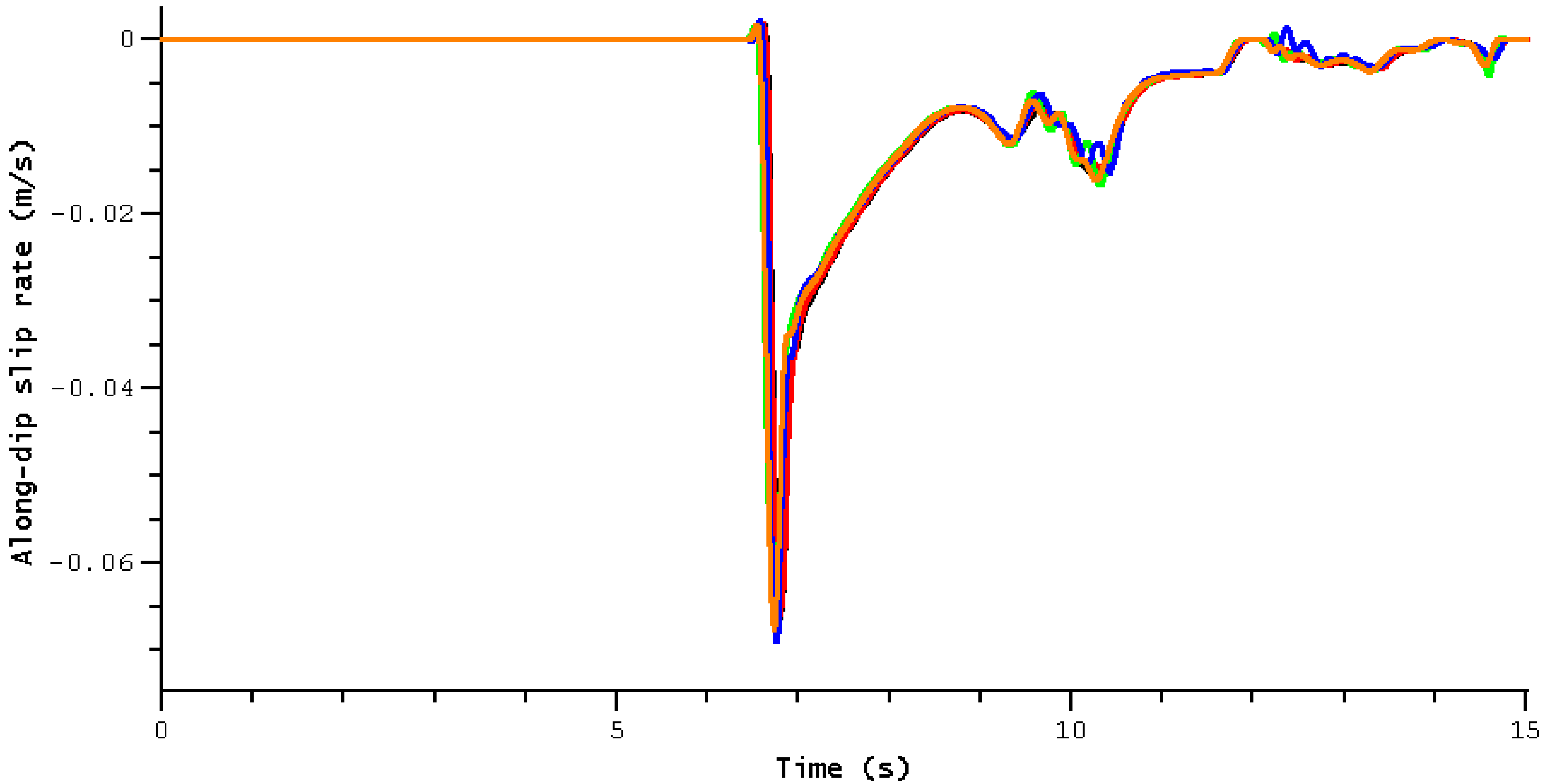


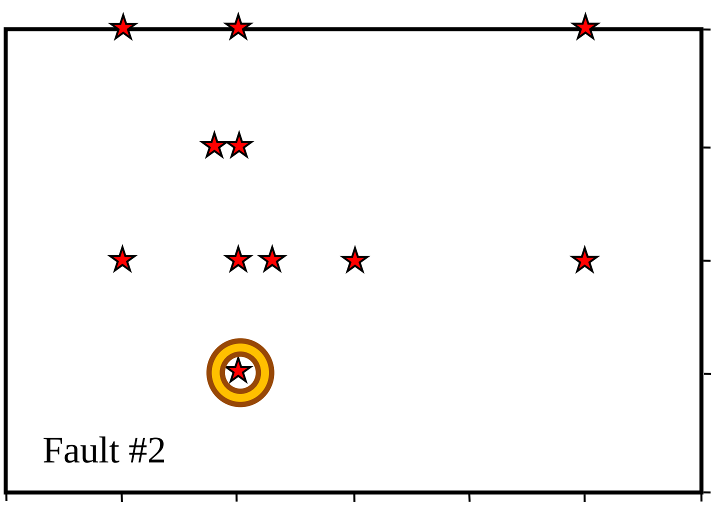


baral1.2 (Michael Barall - Finite Element - FaultMod - 50 m)
baral1.4 (Michael Barall - Finite Difference - DayFD - 50 m)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

5 Hz low-pass filter applied to all time series.

fault2st050dp150

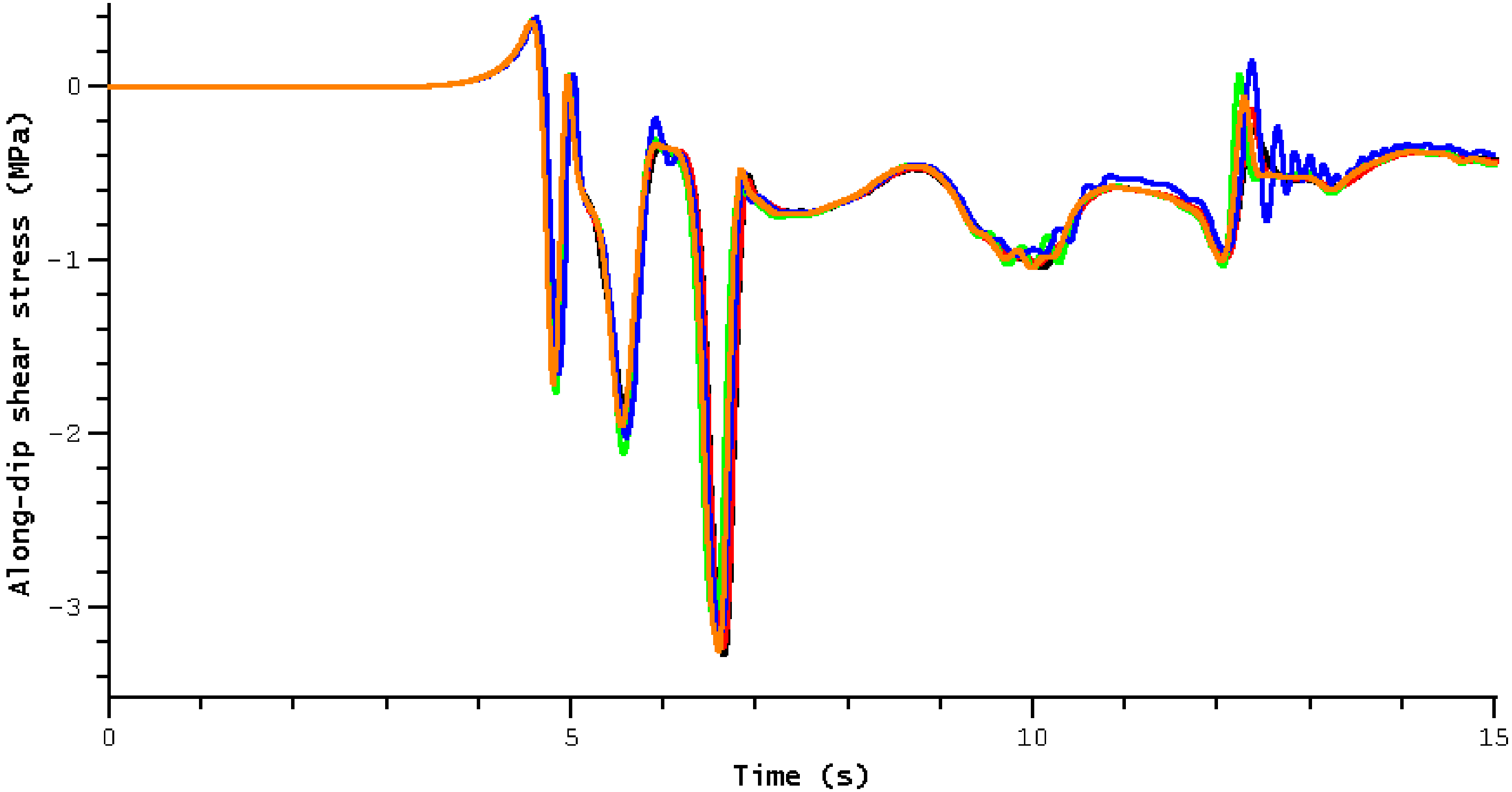


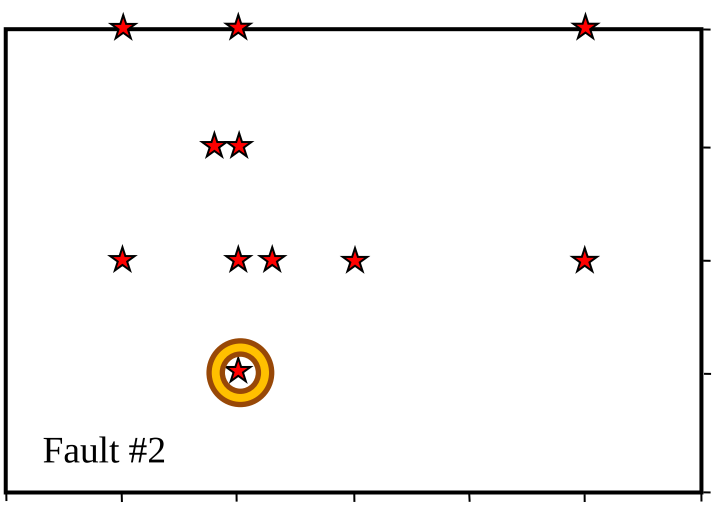


- baral1.2 (Michael Barall - Finite Element - FaultMod - 50 m)
- barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
- kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
- ma (Shuo Ma - Finite Element - MAFE (100 m))
- payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)

5 Hz low-pass filter applied to all time series.

fault2st050dp150

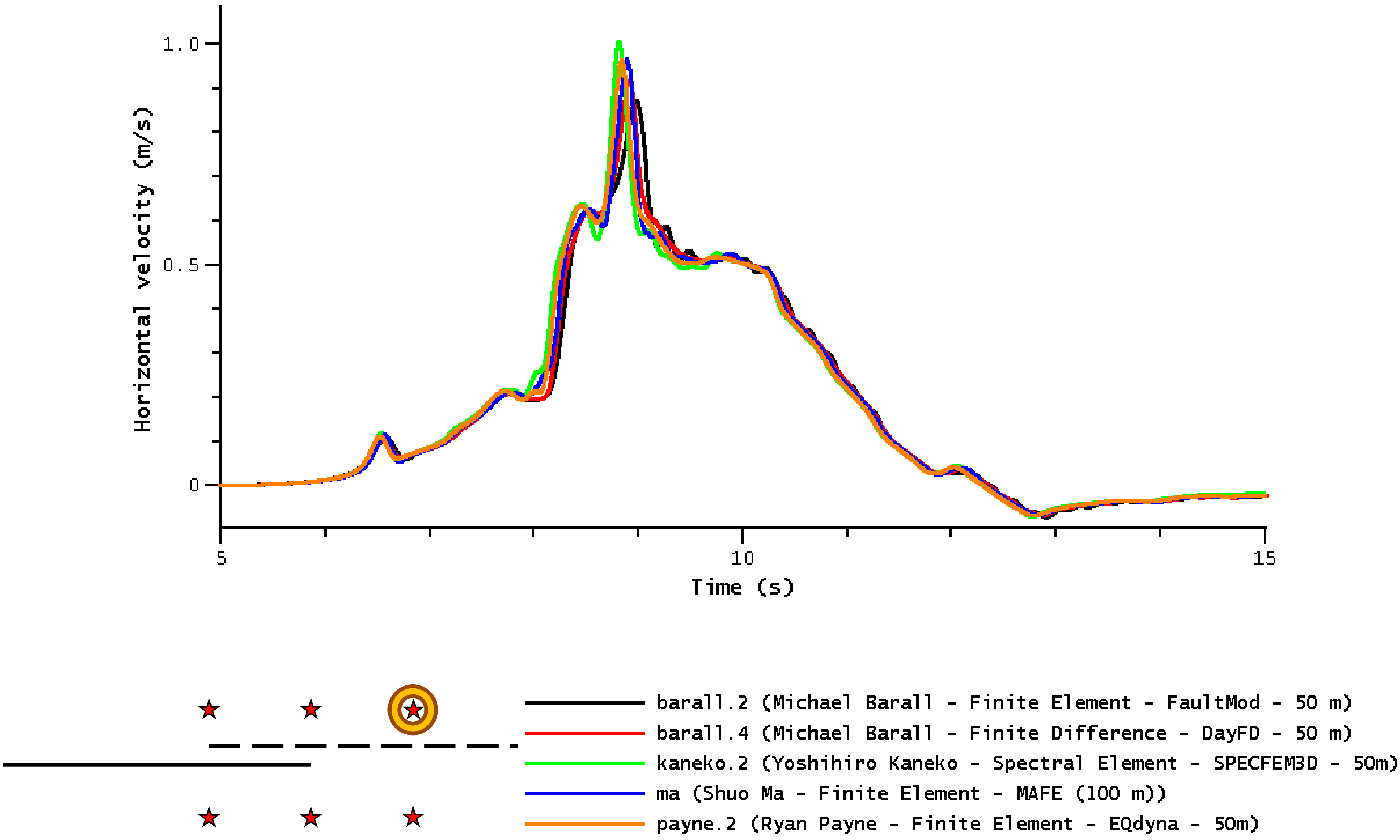




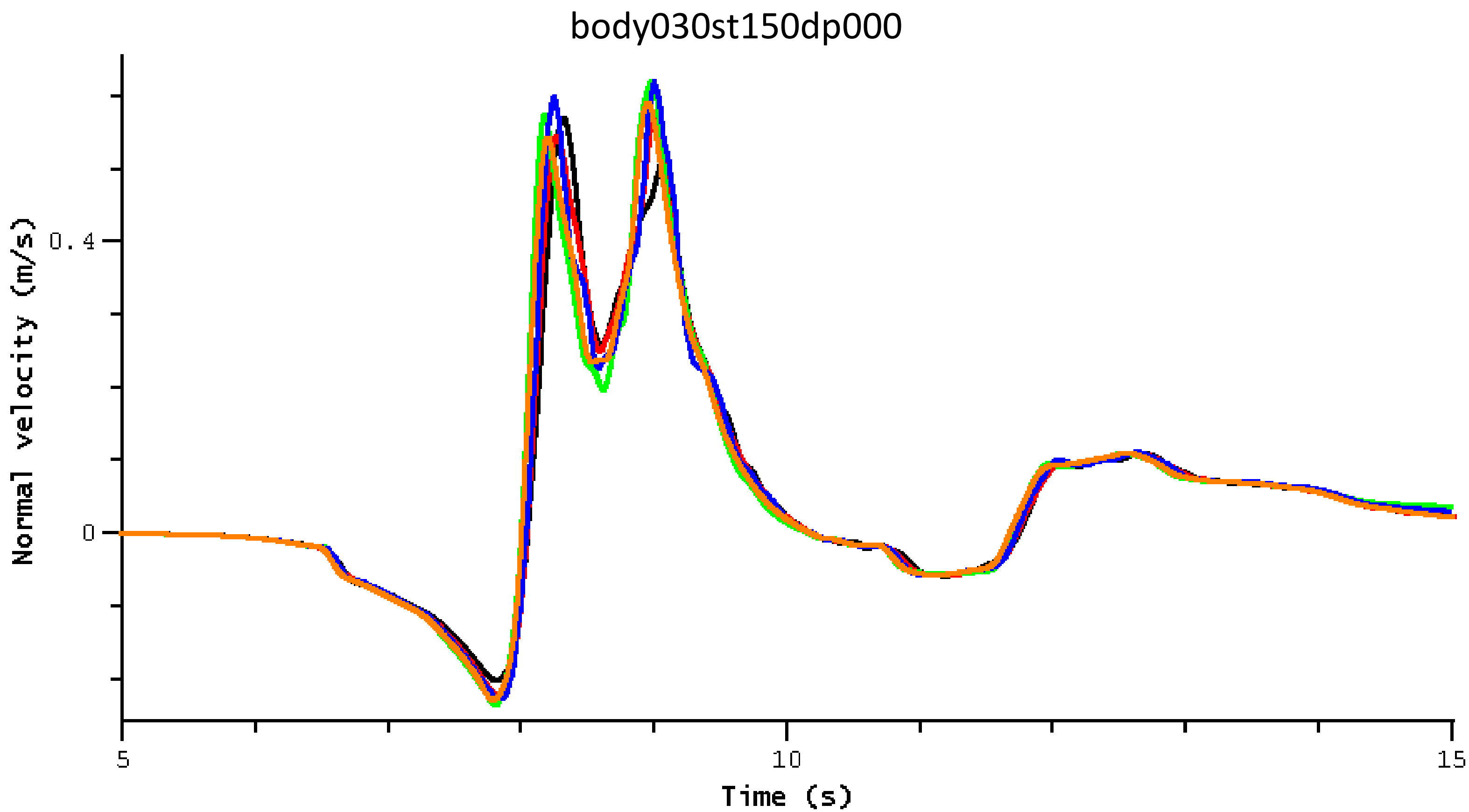
baral1.2 (Michael Barall - Finite Element - FaultMod - 50 m)
baral1.4 (Michael Barall - Finite Difference - DayFD - 50 m)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)

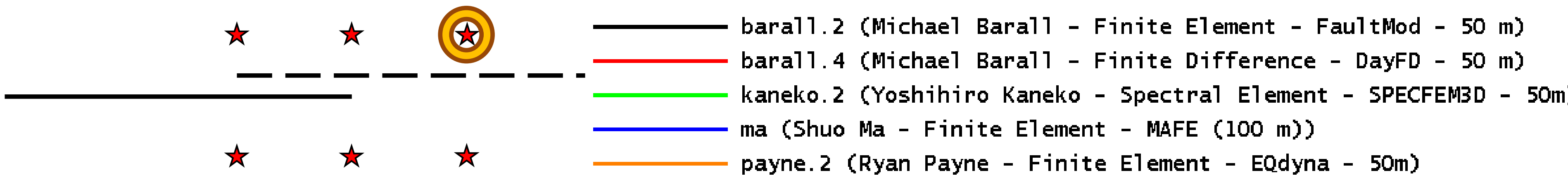
5 Hz low-pass filter applied to all time series.

body030st150dp000



5 Hz low-pass filter applied to all time series.





5 Hz low-pass filter applied to all time series.

Conclusions

Our stepover benchmarks are:

TPV22 = Extensional 1600 m stepover.

TPV23 = Compressional 1000 m stepover.

These multi-fault benchmarks must be carefully designed to avoid:

- Loss of numerical precision, which may occur when shear stress is near the minimum required to sustain a rupture.
- Nucleation at the top or bottom of fault #2, and other bad nucleation patterns.

Our stepover distances are relatively large for 3D dynamic rupture simulations, so we need supershear rupture conditions to get a jump.

Comparison of 50 m and 100 m results shows good agreement, indicating the benchmarks are well resolved at the requested resolutions.

Comparison between different codes shows good agreement.