Heterogeneous Initial Stress Benchmarks TPV16 and TPV17

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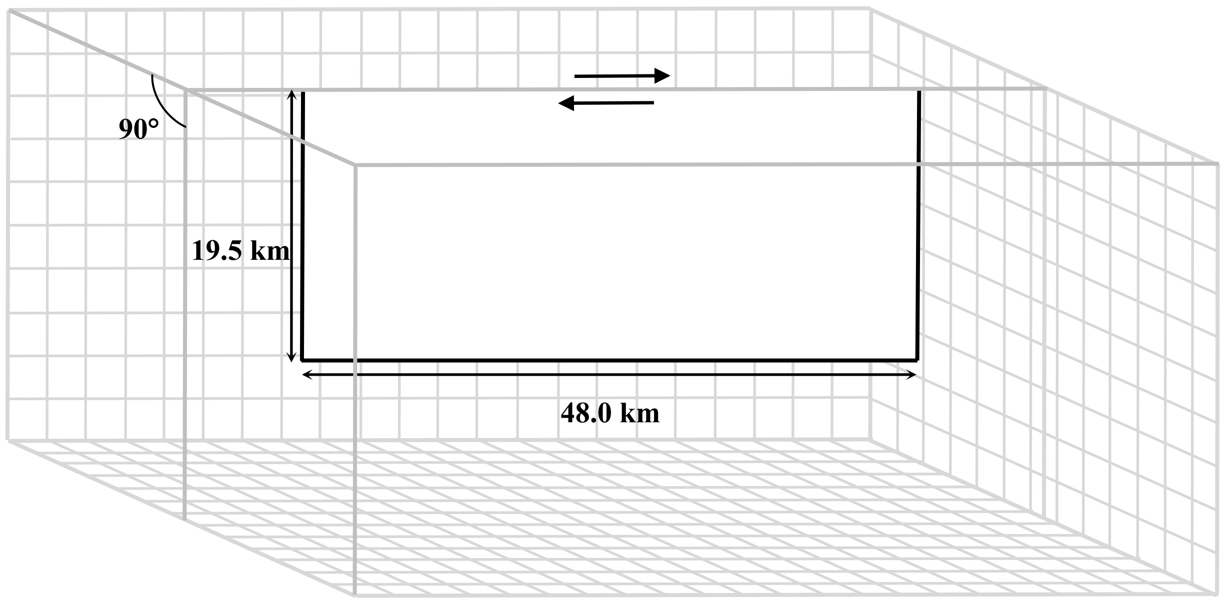
SCEC Dynamic Rupture Code Validation Workshop

February 6, 2012

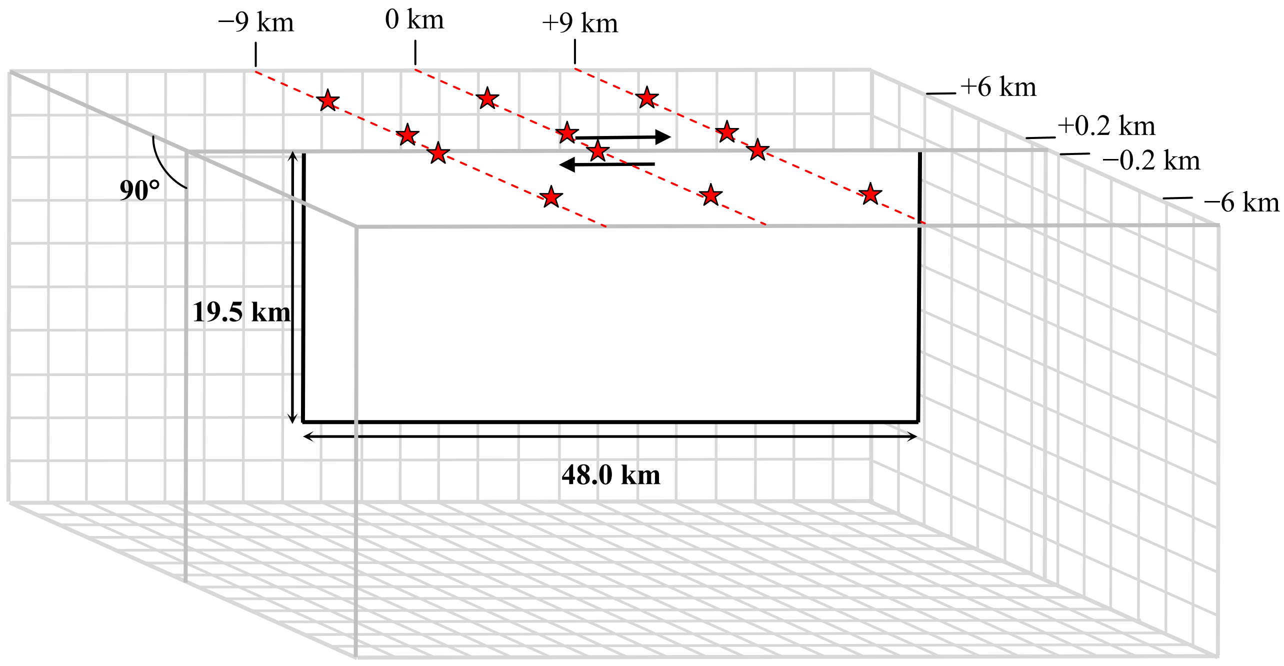
Benchmark Description

TPV16-17 Fault Geometry



TPV16-17 have a vertical, right-lateral, strike-slip fault with heterogeneous initial stress conditions.

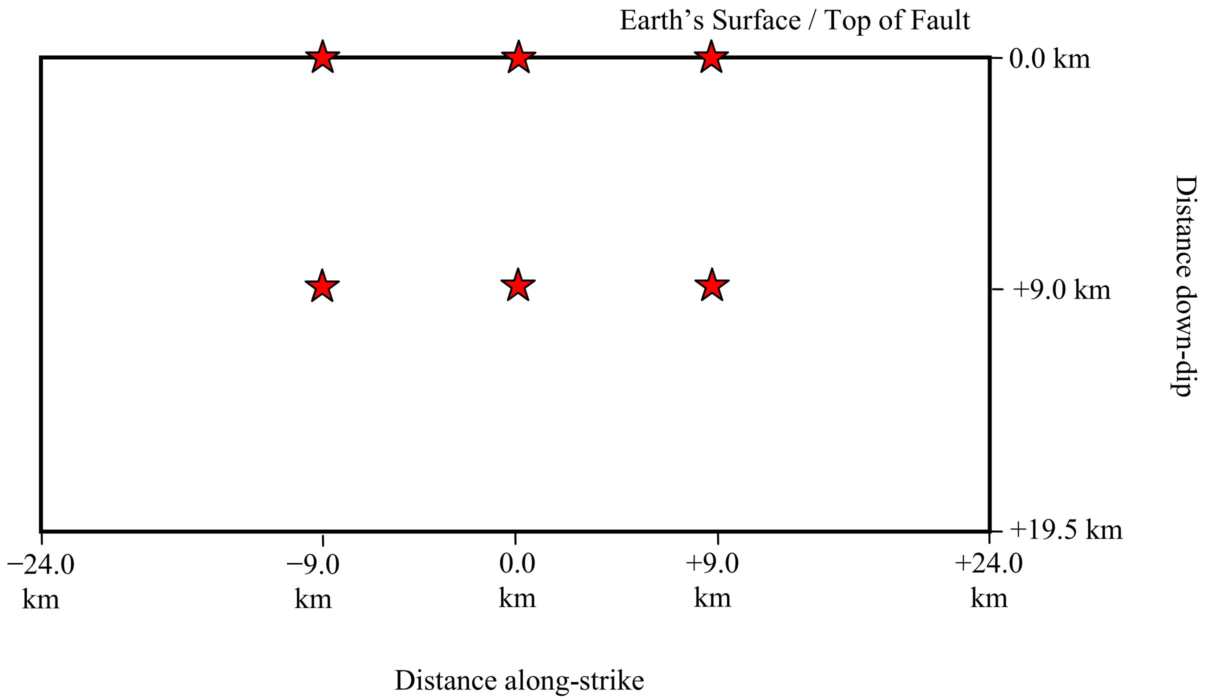
Off-Fault Stations



Modelers are asked to submit displacement and velocity as a function of time, for 12 stations on the earth's surface.

Since the fault is vertical, stations on the far side of the fault should have the same waveforms as the stations on the near side of the fault.

On-Fault Stations



Modelers are asked to submit slip, slip rate, and stress as a function of time, for 6 stations on the fault.

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.

TPV16-17 Parameters

$\text{Density} = 2670.0\ \text{kg/m}^3$

$V_S = 3464.0\ \text{m/s}$

$V_P = 6000.0\ \text{m/s}$

$D_c = 0.40\ \text{m}$

$\mu_s = 0.677$

Same as TPV5

$\mu_d = 0.373$

$\sigma_0 = 60.0\ \text{MPa}$

Equivalent to TPV5 (same difference between yield stress and sliding stress)

Parameter selection follows our practice of reusing material from earlier benchmarks, so we build incrementally on prior work.

Linear Slip-Weakening Friction

When the fault is sliding, the shear stress τ at a given point on the fault is given by:

$$\tau = C + \mu \times \max(0, \sigma)$$

The time-varying coefficient of friction μ is given by:

$$\mu = \begin{cases} \mu_s + (\mu_d - \mu_s) \times D/D_c \,, & \text{if} \;\; D < D_c \;\; \text{and} \;\; t < T \\ \mu_d \,, & \text{if} \;\; D \geq D_c \;\; \text{or} \;\; t \geq T \end{cases}$$

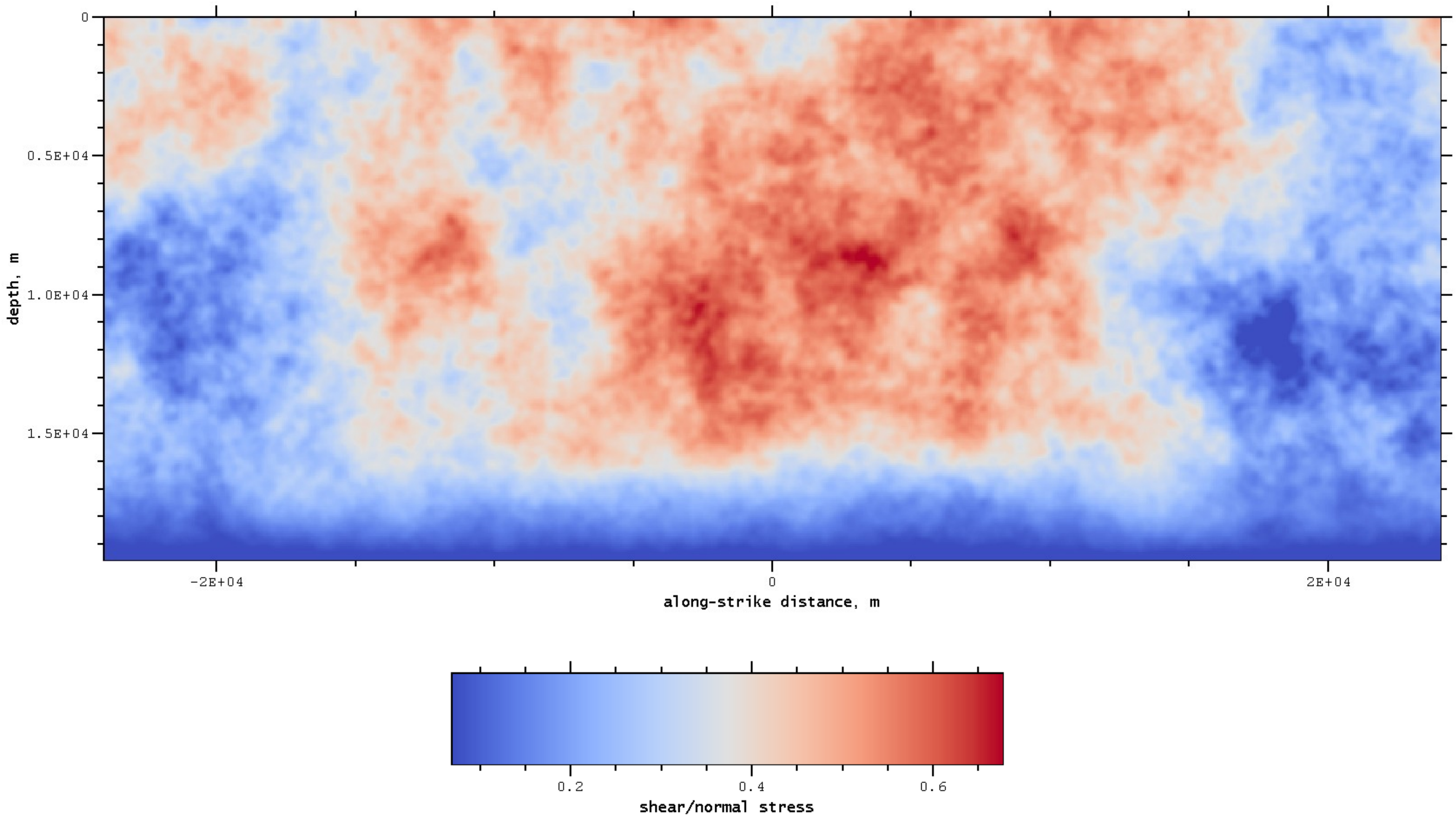
where D is the total distance the node has slipped, and t is the time since the start of the earthquake. The effect is:

- The coefficient of friction declines linear from μ_s to μ_d as the fault slips by distance D_c.

- At time T, the coefficient of friction drops immediately to μ_d (if it is not already μ_d). This only happens within a few hundred meters of the hypocenter.

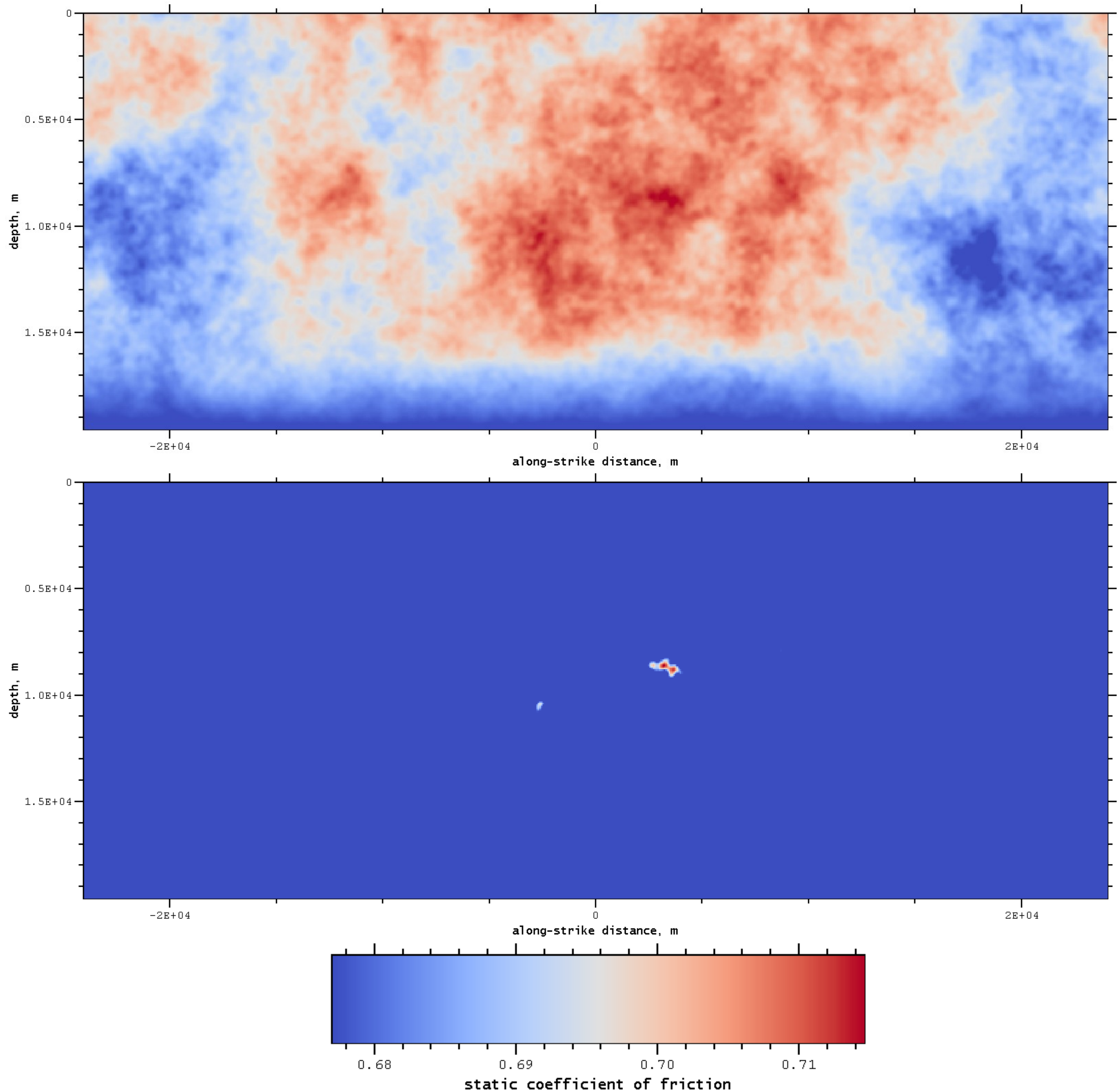
Heterogeneous Initial Conditions

TPV16 Initial Stress



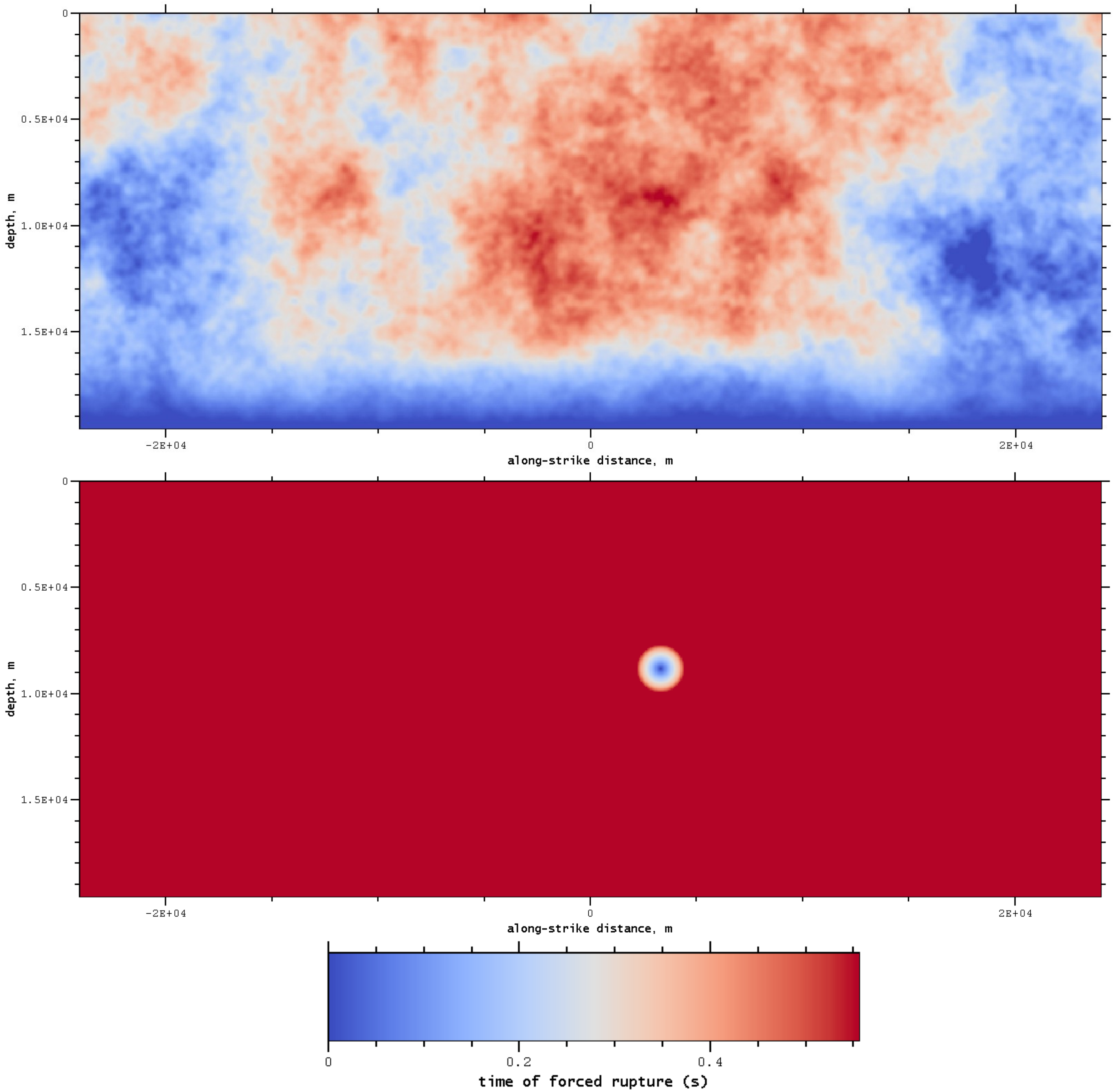
TPV16

Static Coefficient of Friction



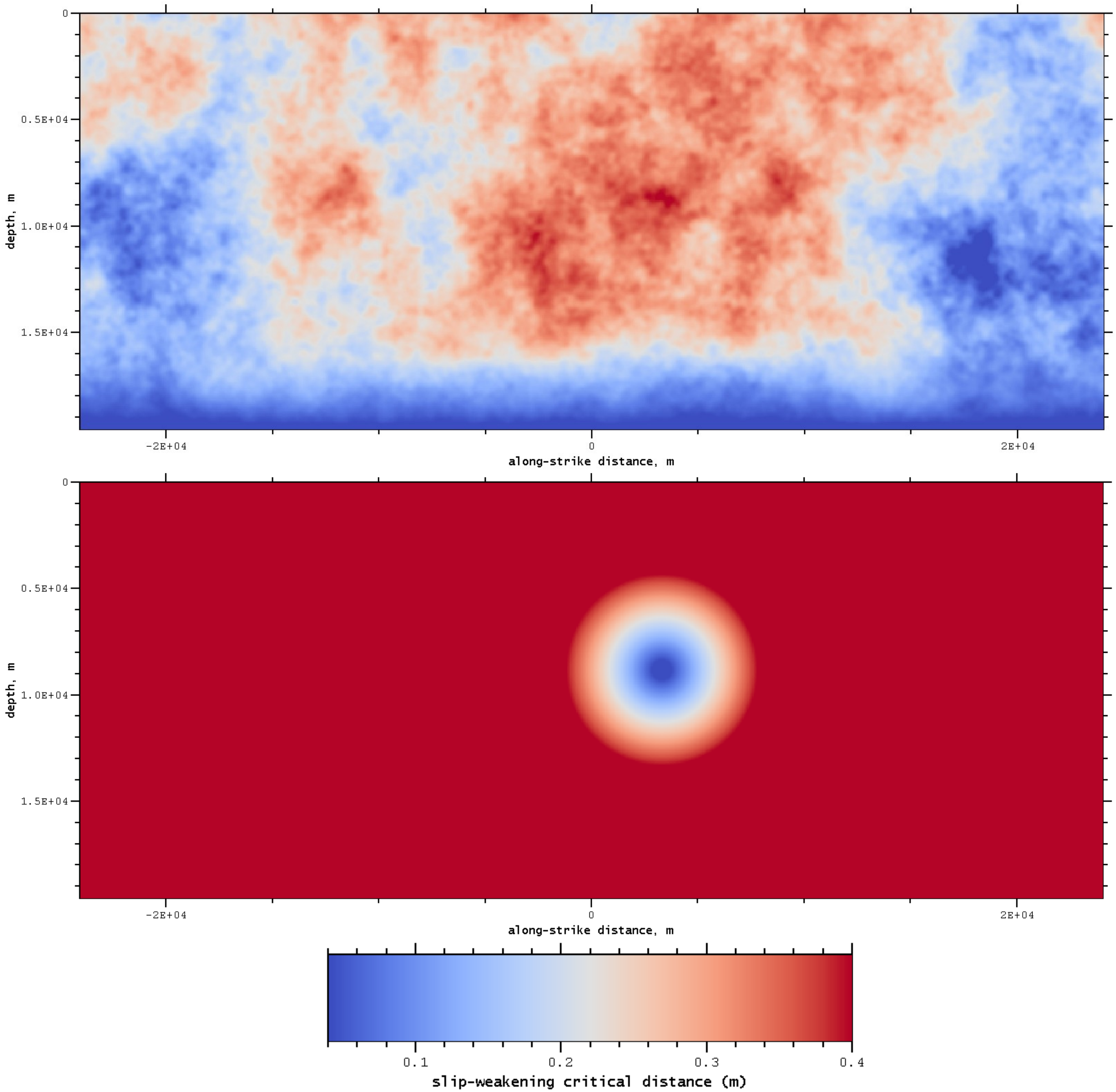
TPV16

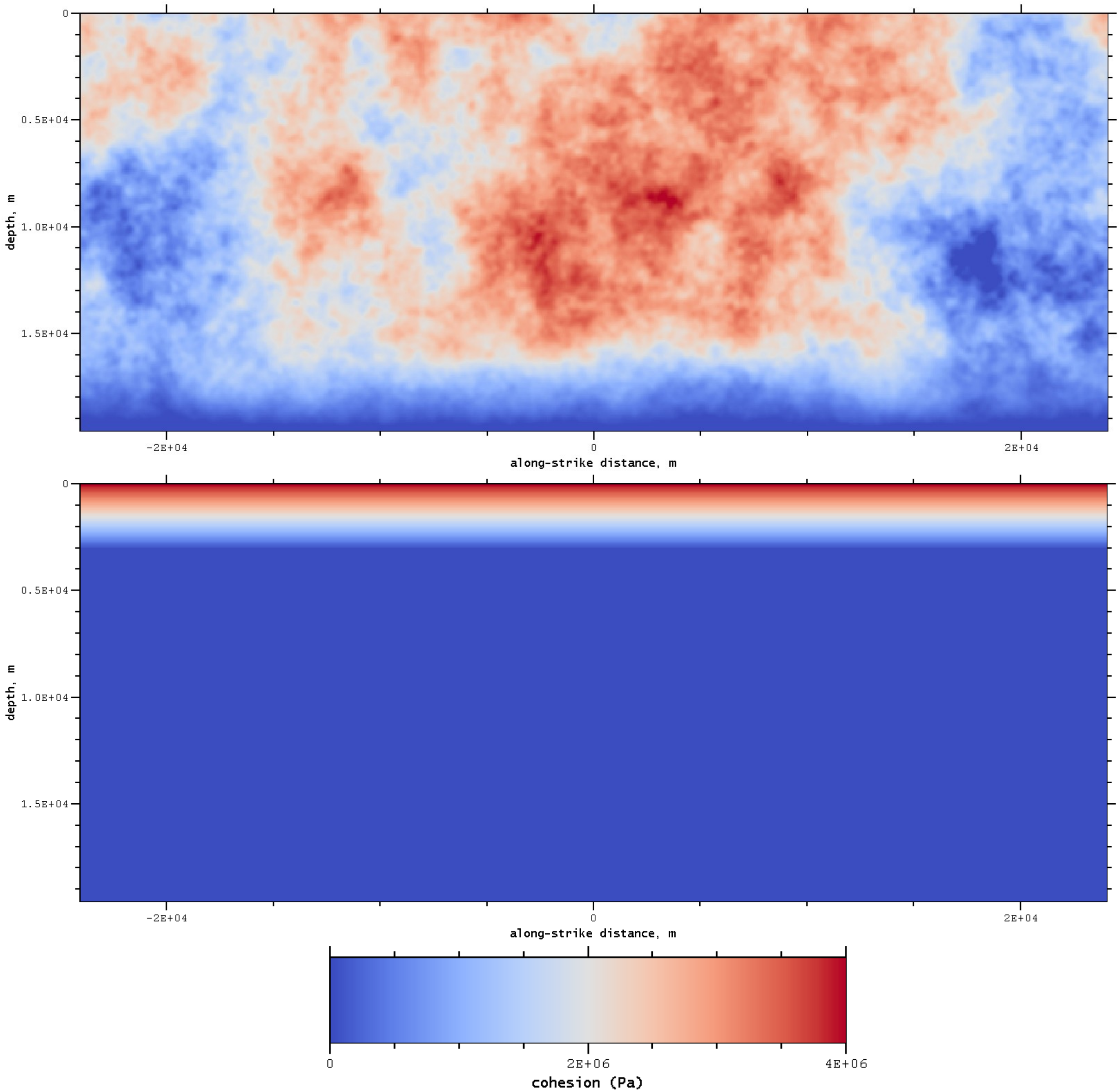
Time of Forced Rupture



TPV16

Slip Weakening Critical Distance

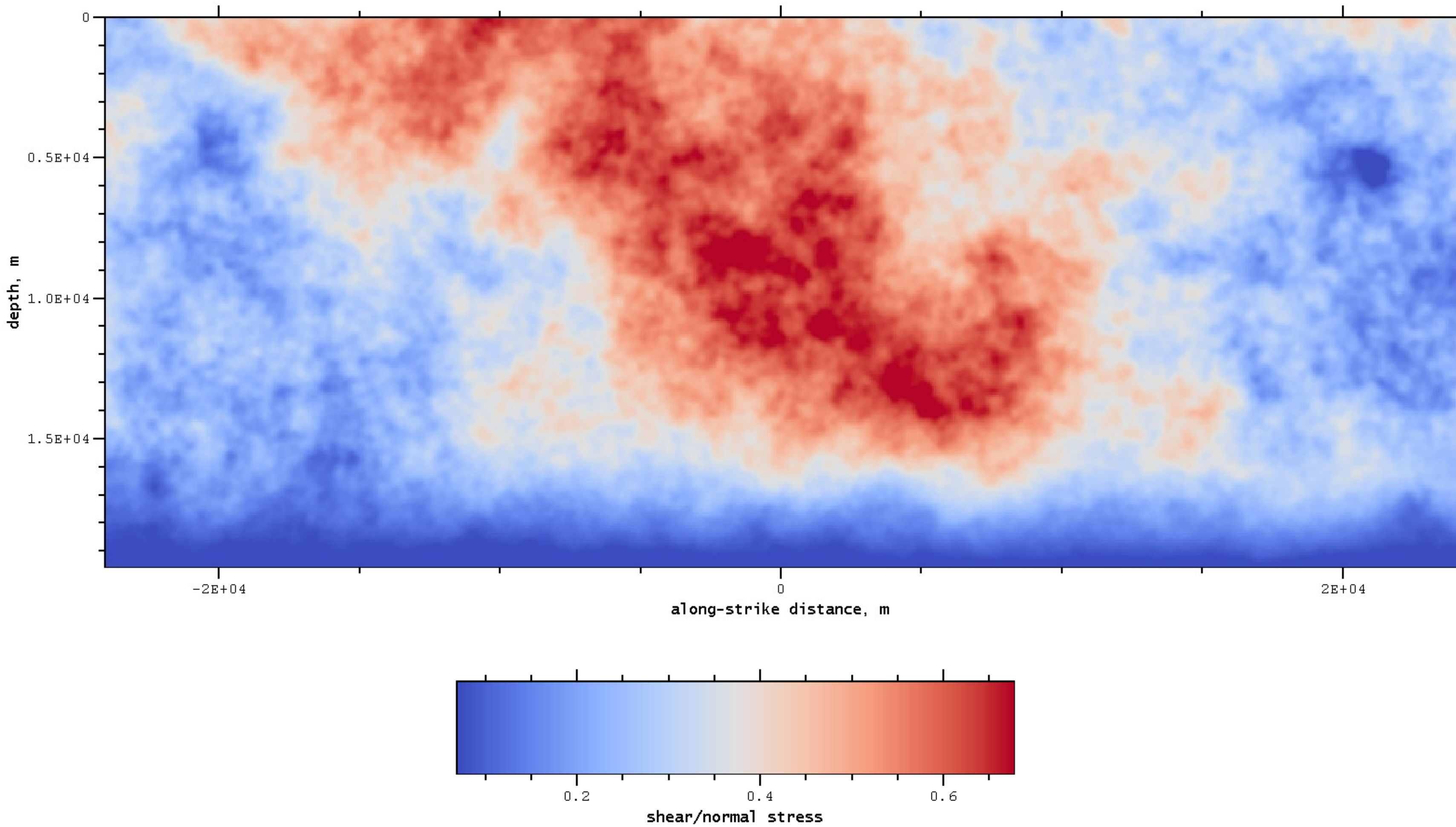




TPV16

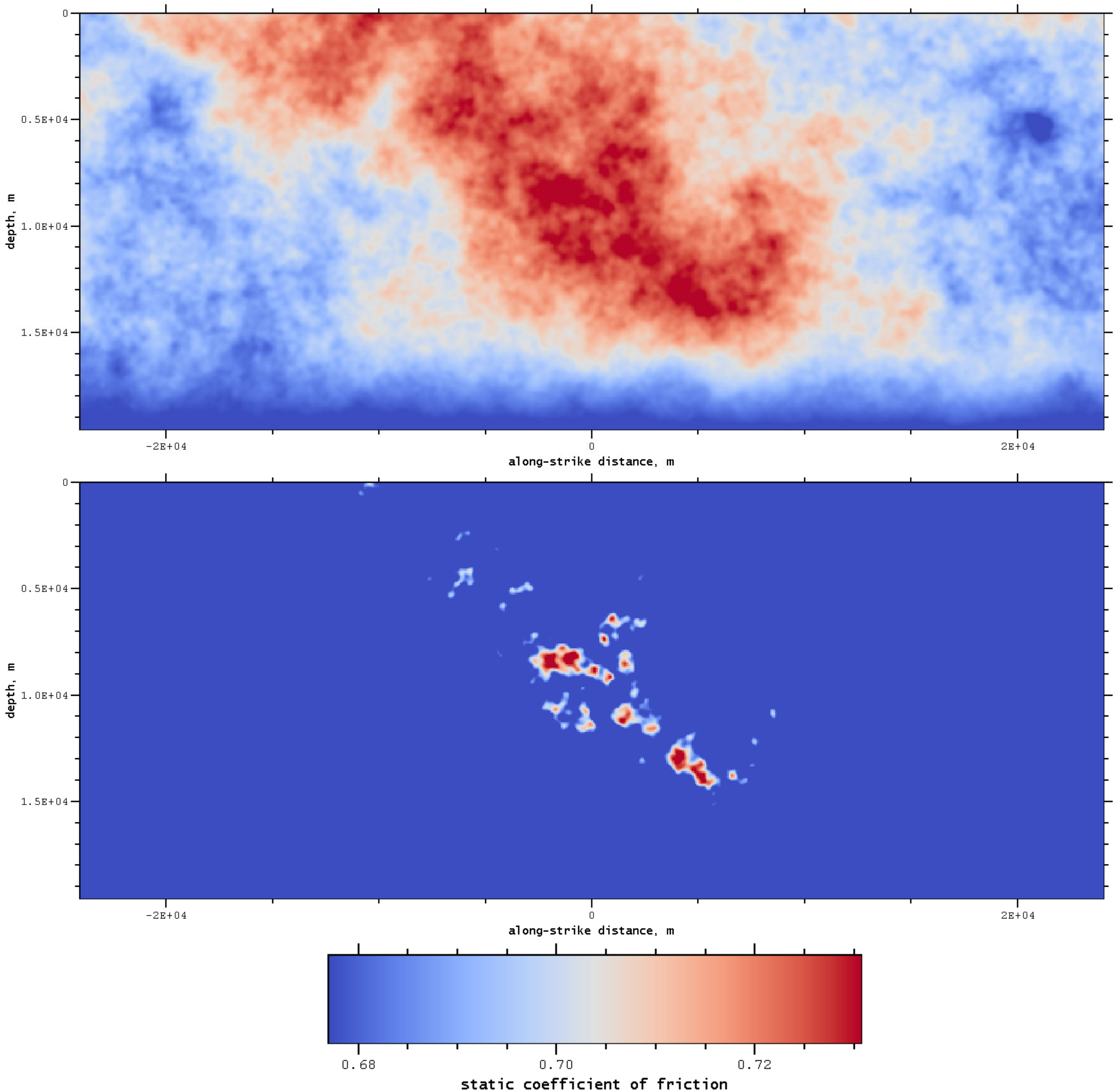
Cohesion

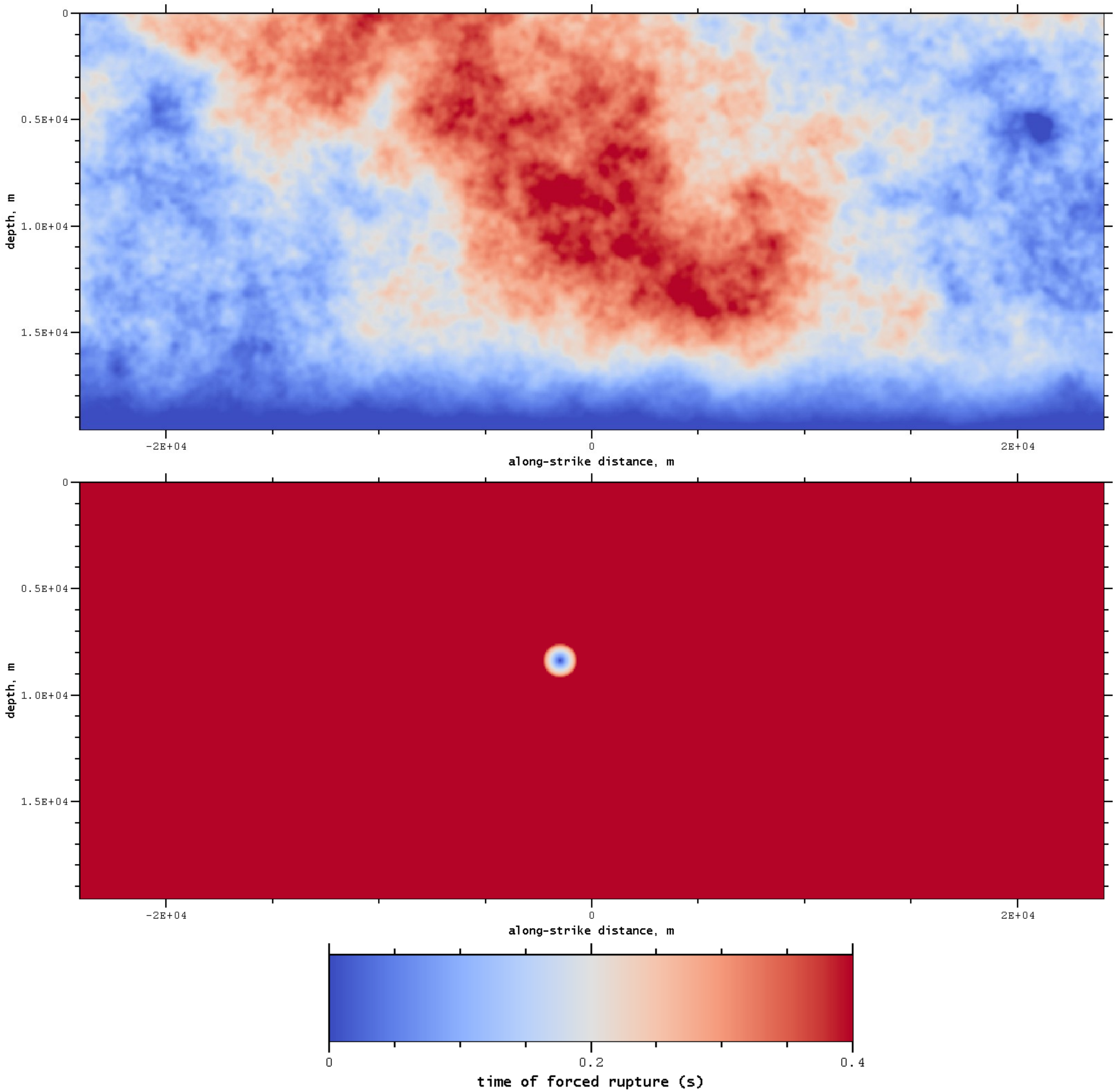
TPV17 Initial Stress



TPV17

Static Coefficient of Friction



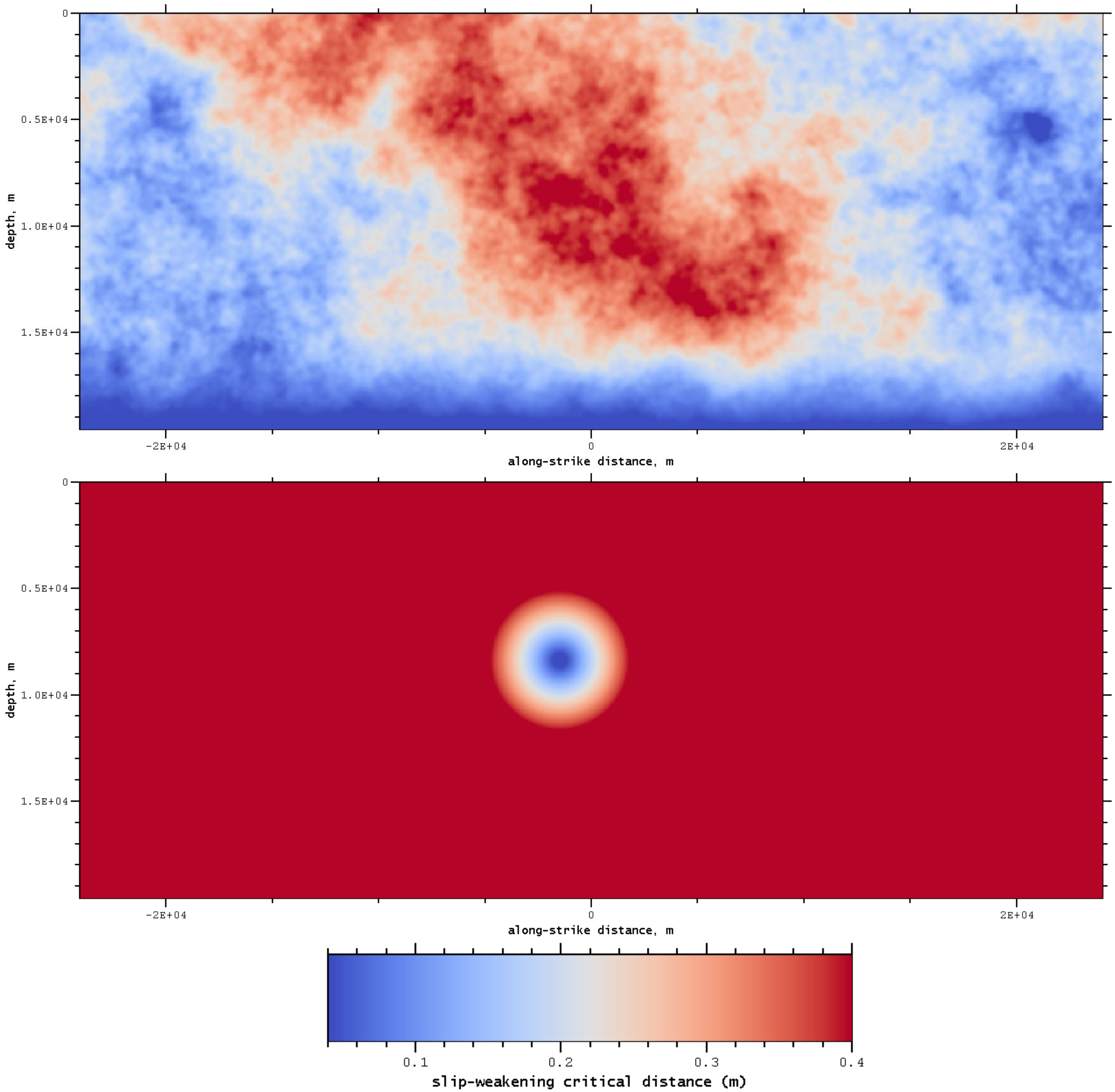


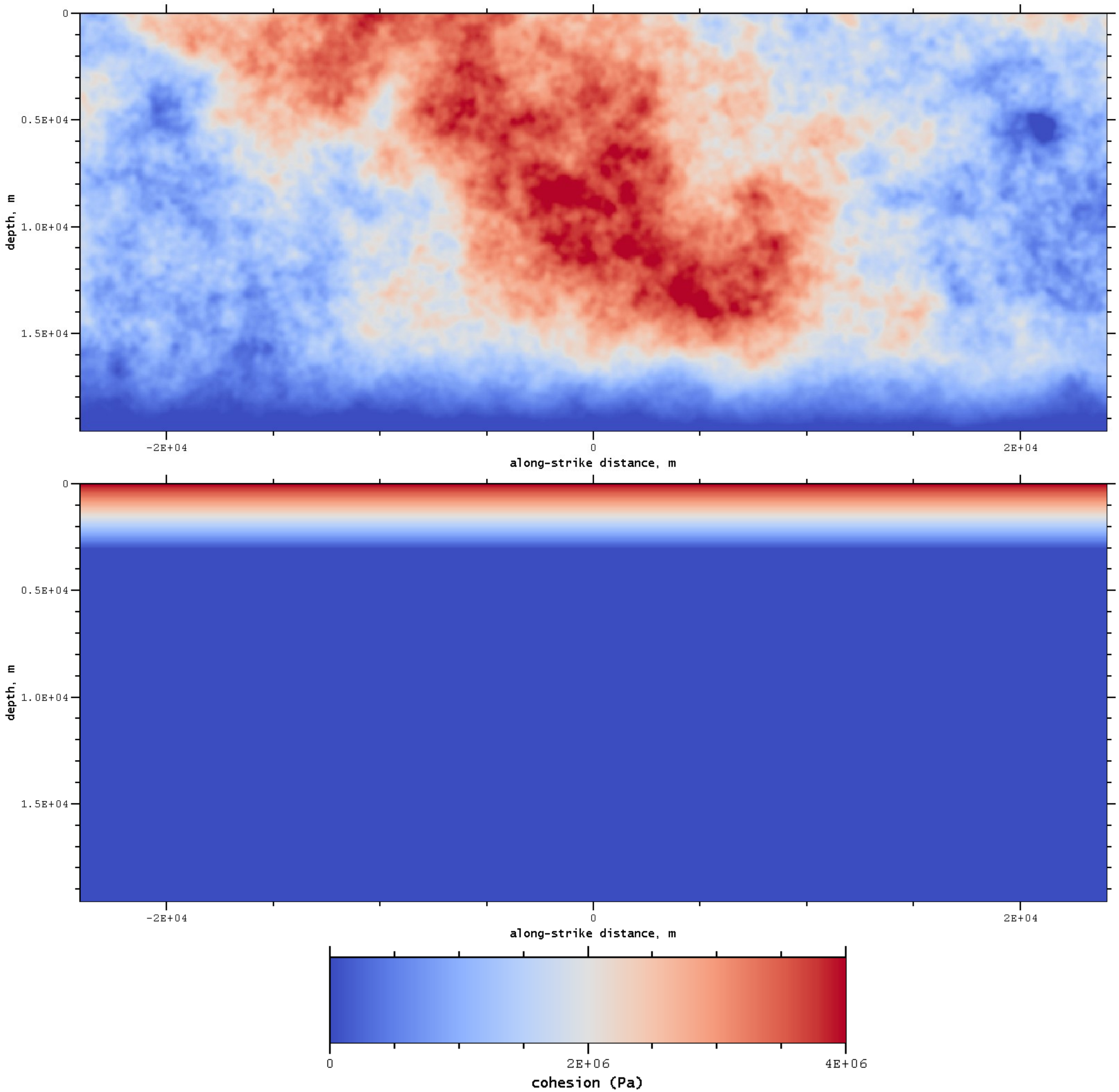
TPV17

Time of Forced Rupture

TPV17

Slip Weakening Critical Distance





TPV17

Cohesion

Nucleation

Day Radius and the Problem of Nucleation

Day (1982) obtained the following formula, which gives the minimum radius R_D that a circular rupture must have, such that it is energetically favorable for the rupture to expand.

Shear modulus μ Static yield stress τ_s Slip-weakening critical distance D_c

$$R_D = \frac{7\pi\mu(\tau_s - \tau_d)D_c}{24(\tau - \tau_d)^2}$$

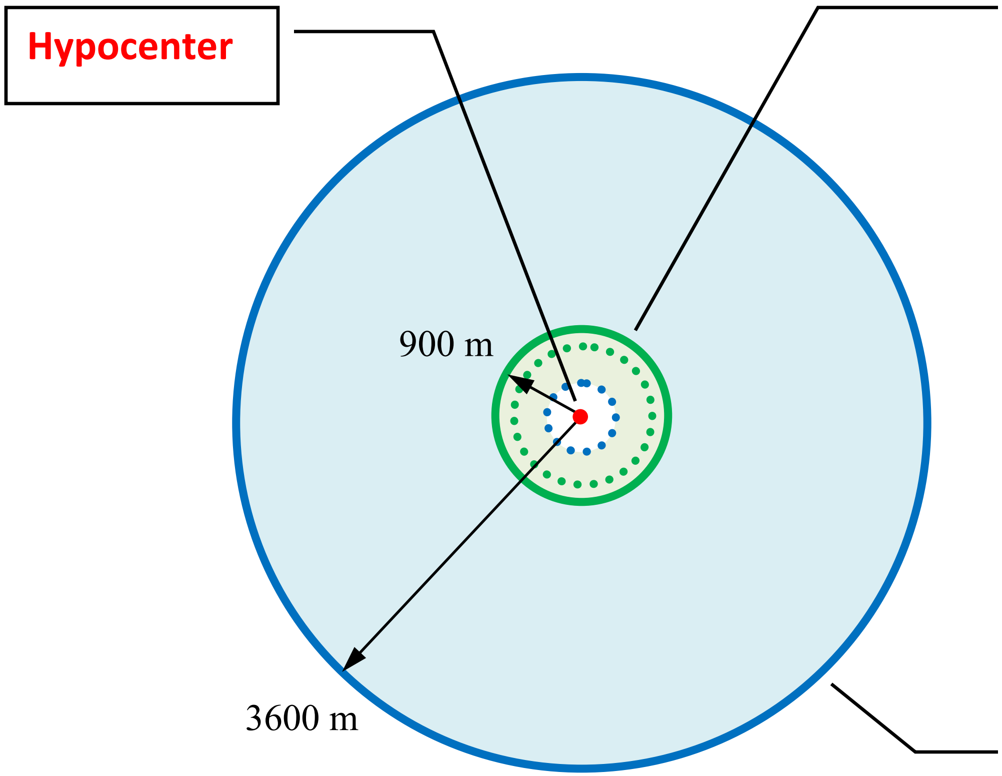
Day radius R_D Initial stress τ Dynamic sliding stress τ_d

For typical parameter values used in spontaneous rupture simulations, the Day radius is about 3 to 4 km.

The nucleation problem is that, somehow, we must impose an artificial mechanism to get the size of the rupture up to the Day radius, at which point the rupture can be self-sustaining.

Two-Stage Nucleation Method

All of today's benchmarks use a new two-stage method of nucleation.



Zone of forced rupture

Forced rupture propagates at $0.7V_S$ to dotted circle (720 m), then $0.35V_S$ to solid circle (900 m). Forced rupture immediately reduces friction coefficient to μ_d.

(Distances shown are for TPV18-21.)

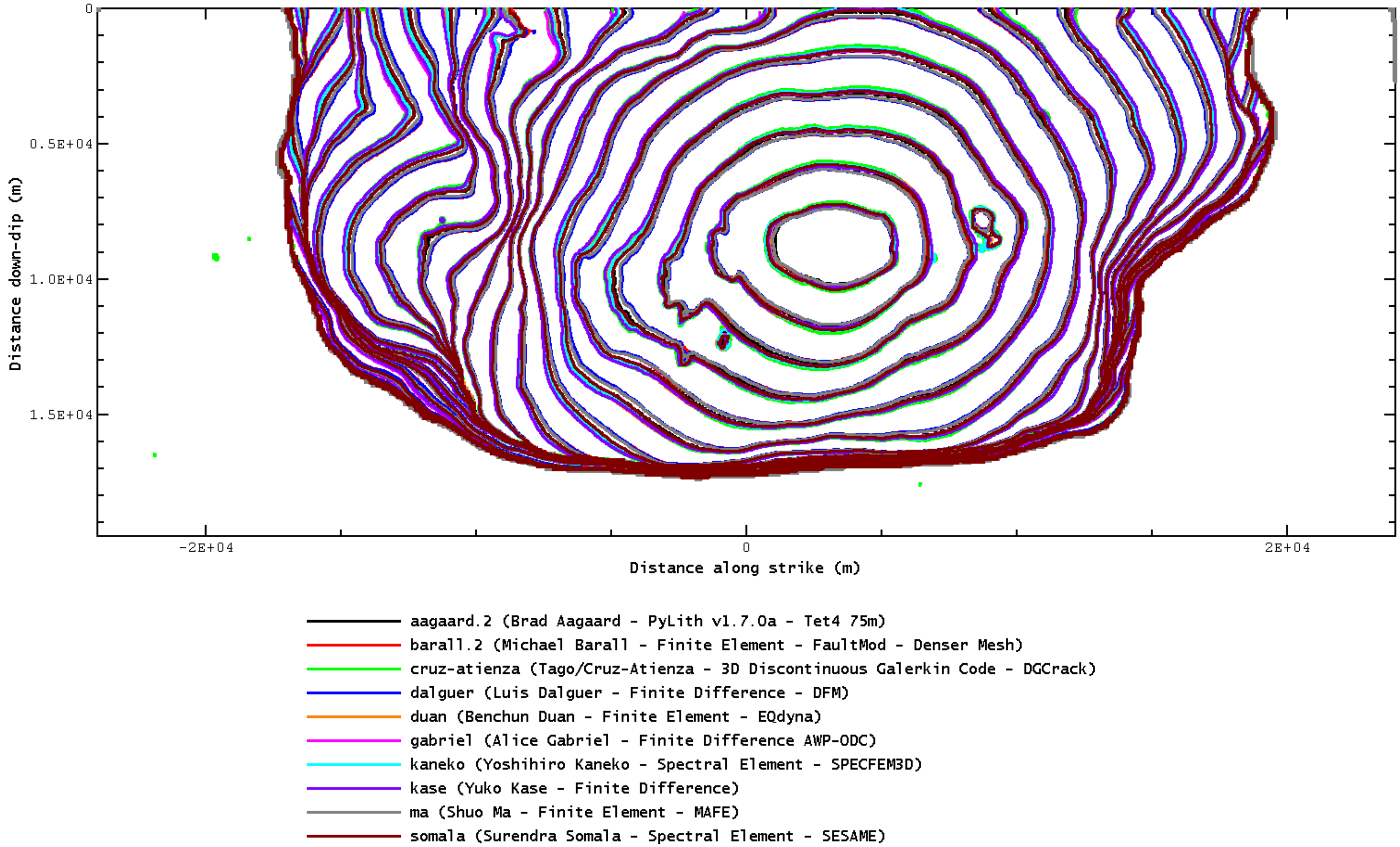
Zone of reduced fracture energy

D_C is linearly tapered from 0.04 m at dotted circle (360 m), to 0.40 m at solid circle (3600 m).

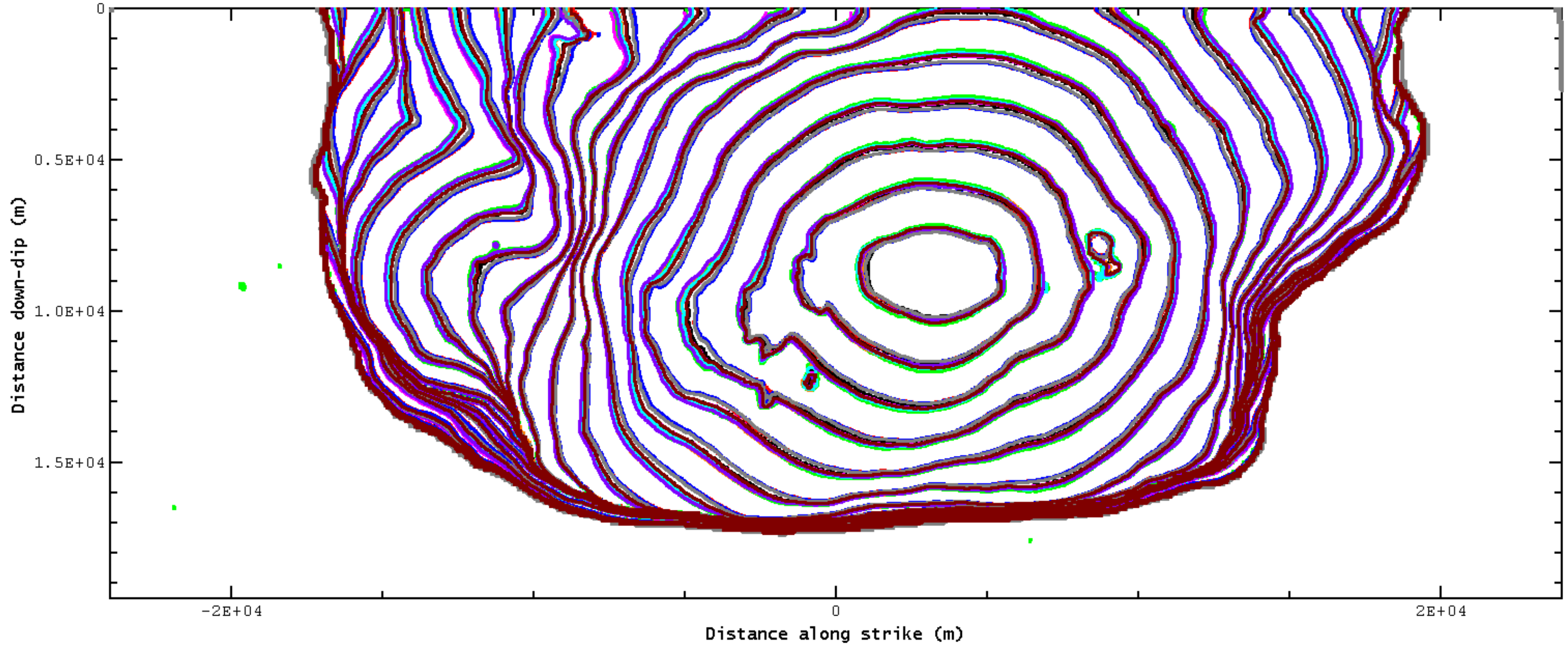
Because the Day radius is proportional to D_C, rupture propagation is energetically favorable once the rupture reaches the dotted blue circle.

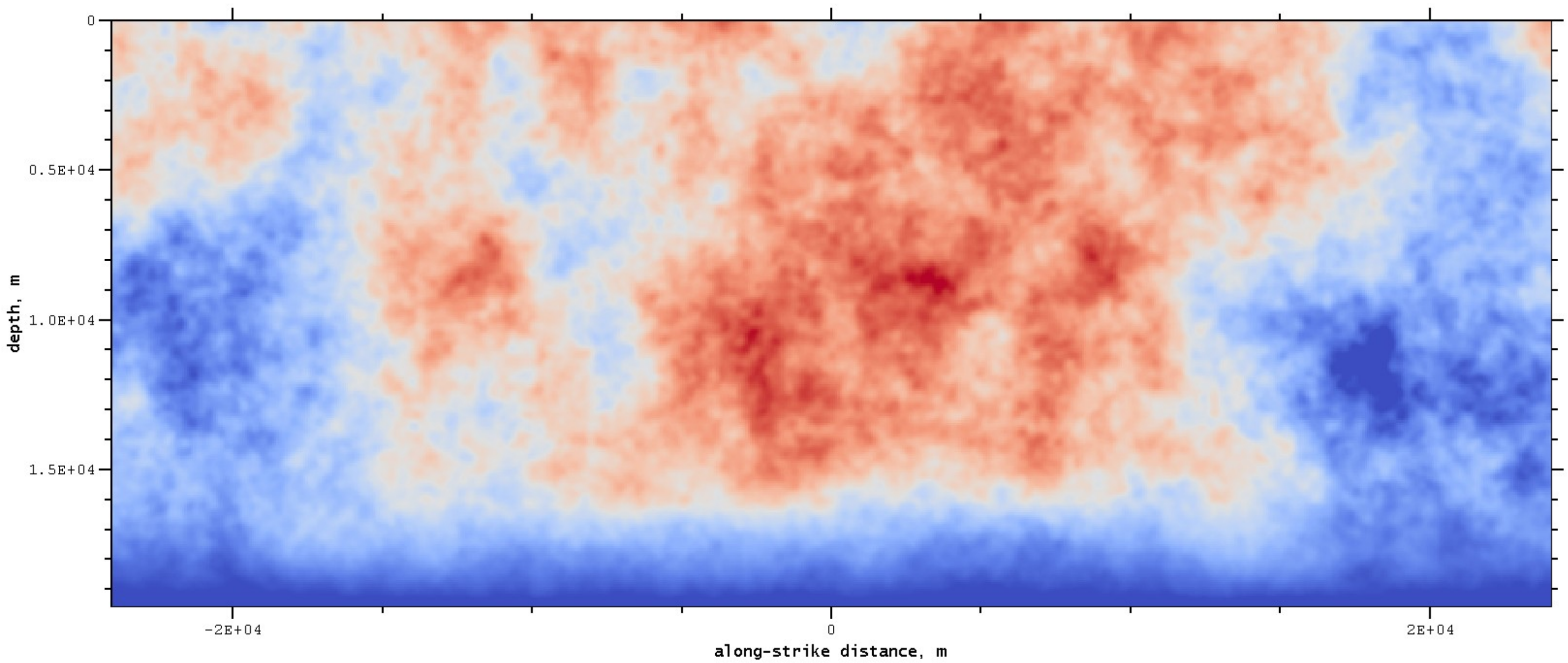
Rupture Contours

TPV16 Rupture Contours

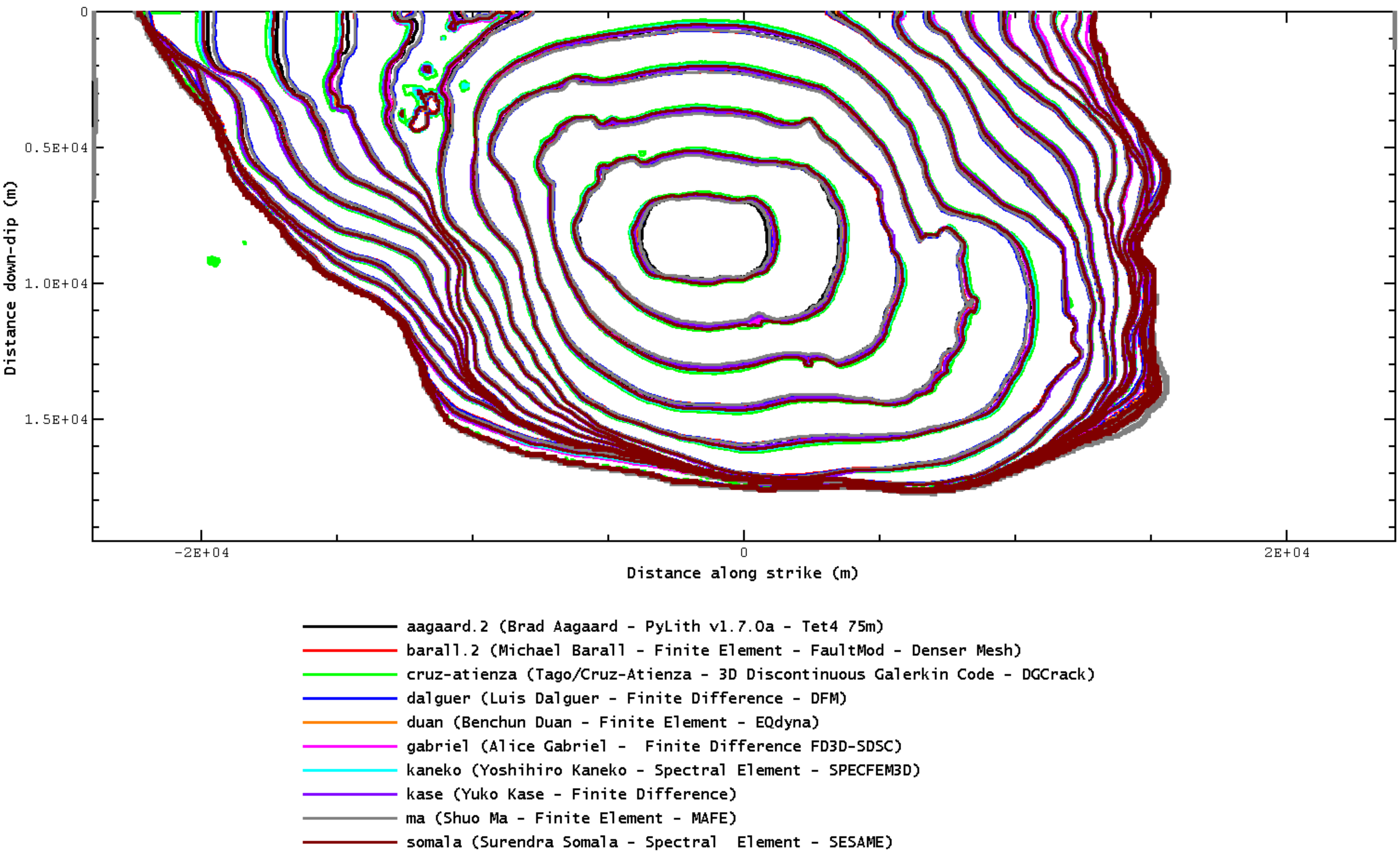


TPV16 Rupture Contours Compared to Initial Stress

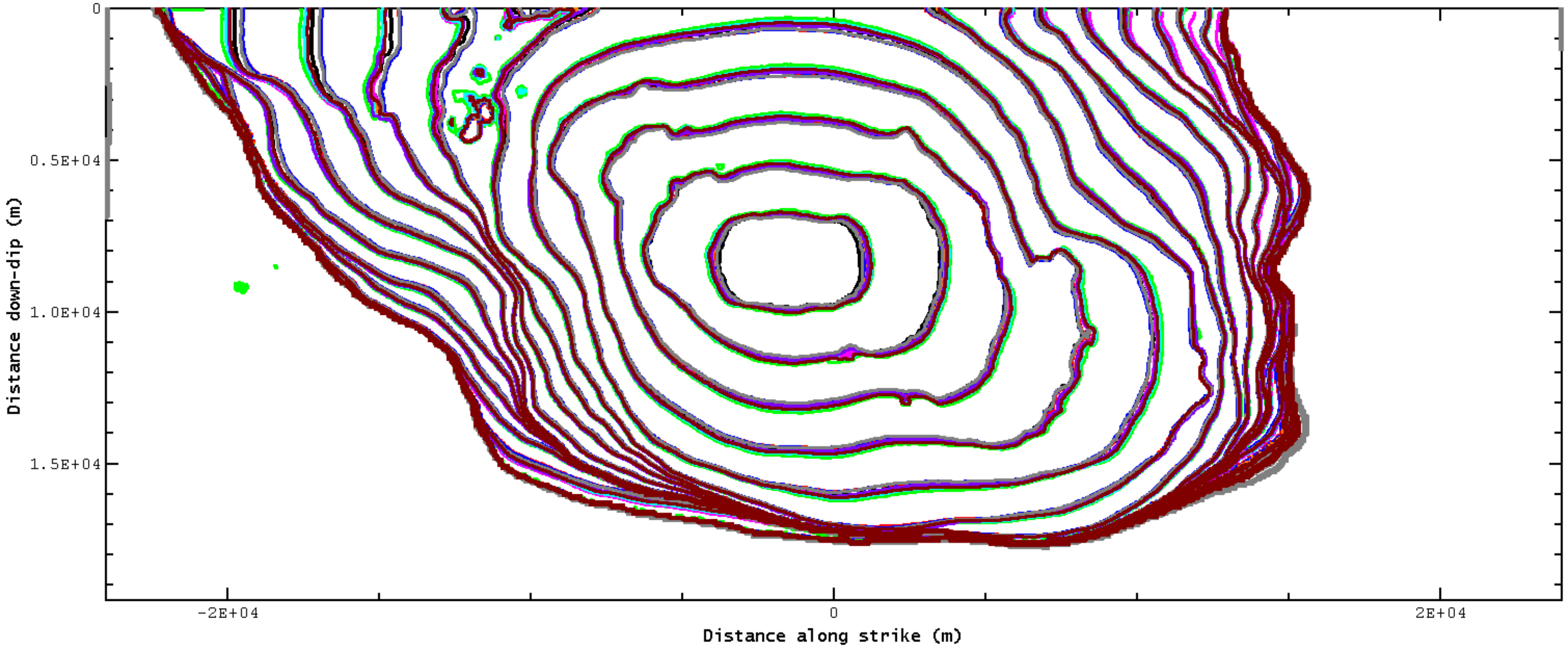


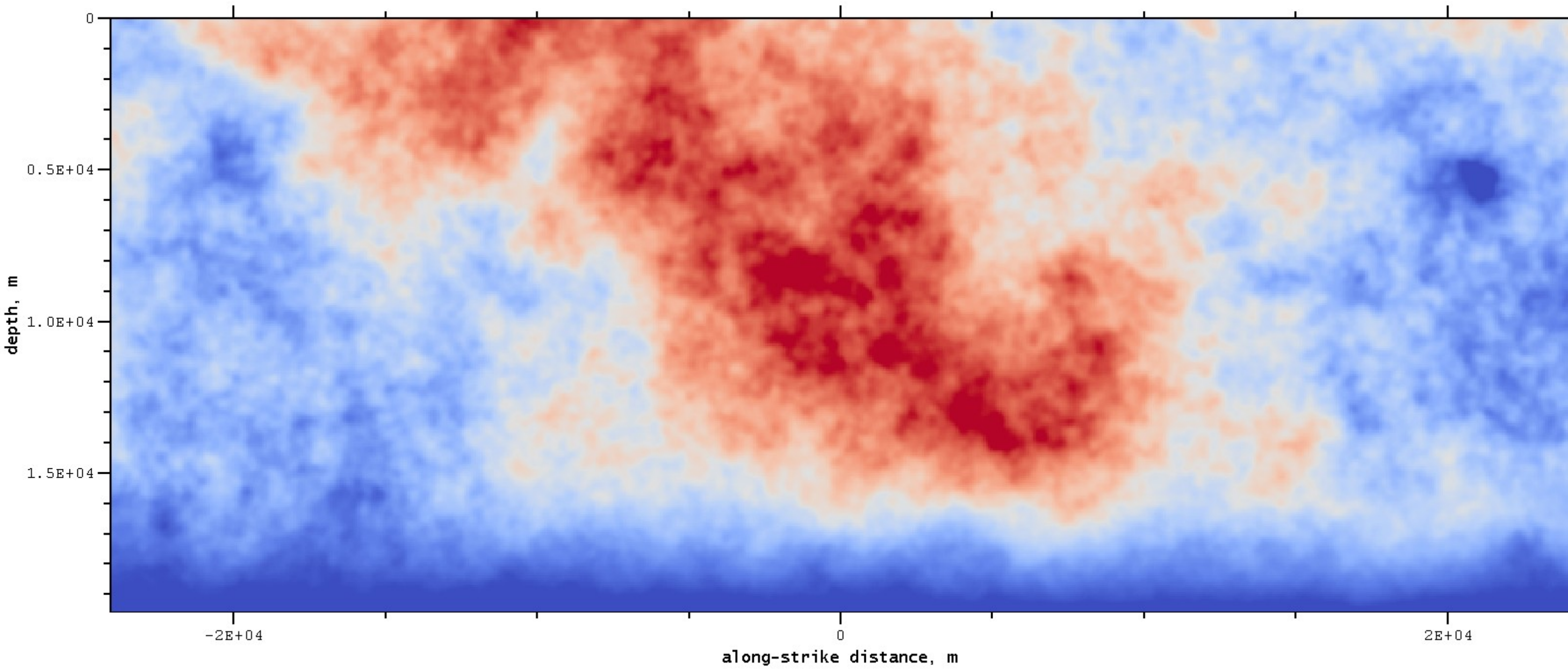


TPV17 Rupture Contours



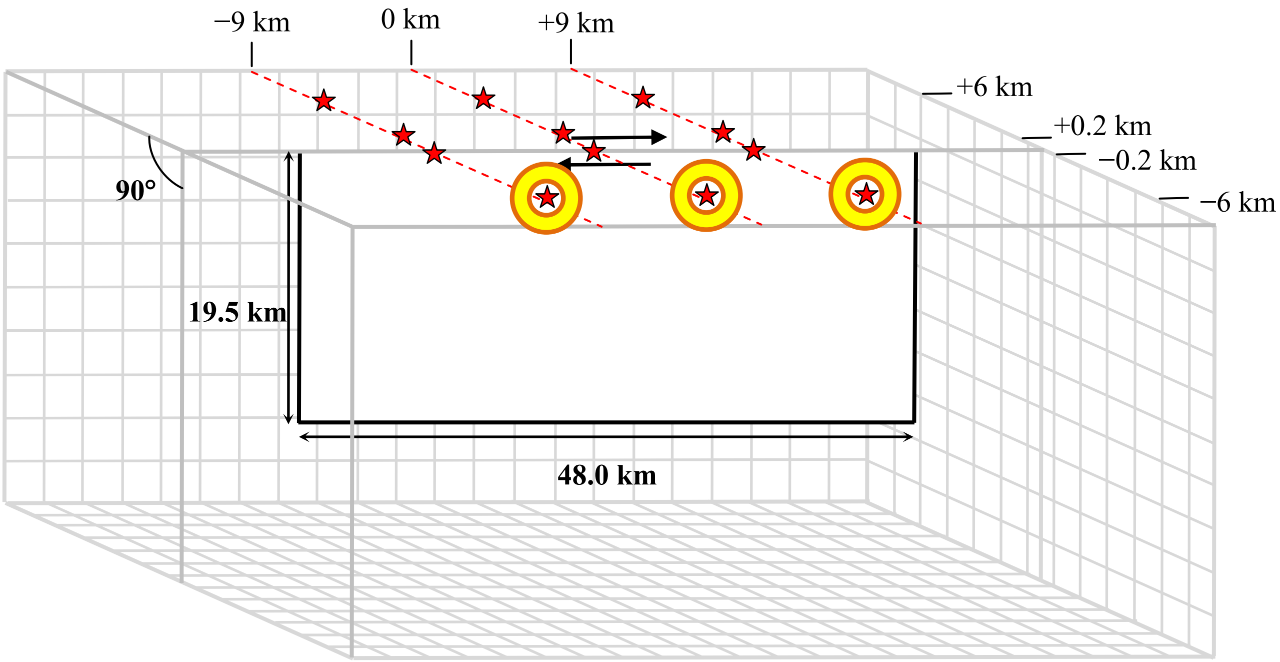
TPV17 Rupture Contours Compared to Initial Stress





Waveform Comparisons for Stations and Realizations

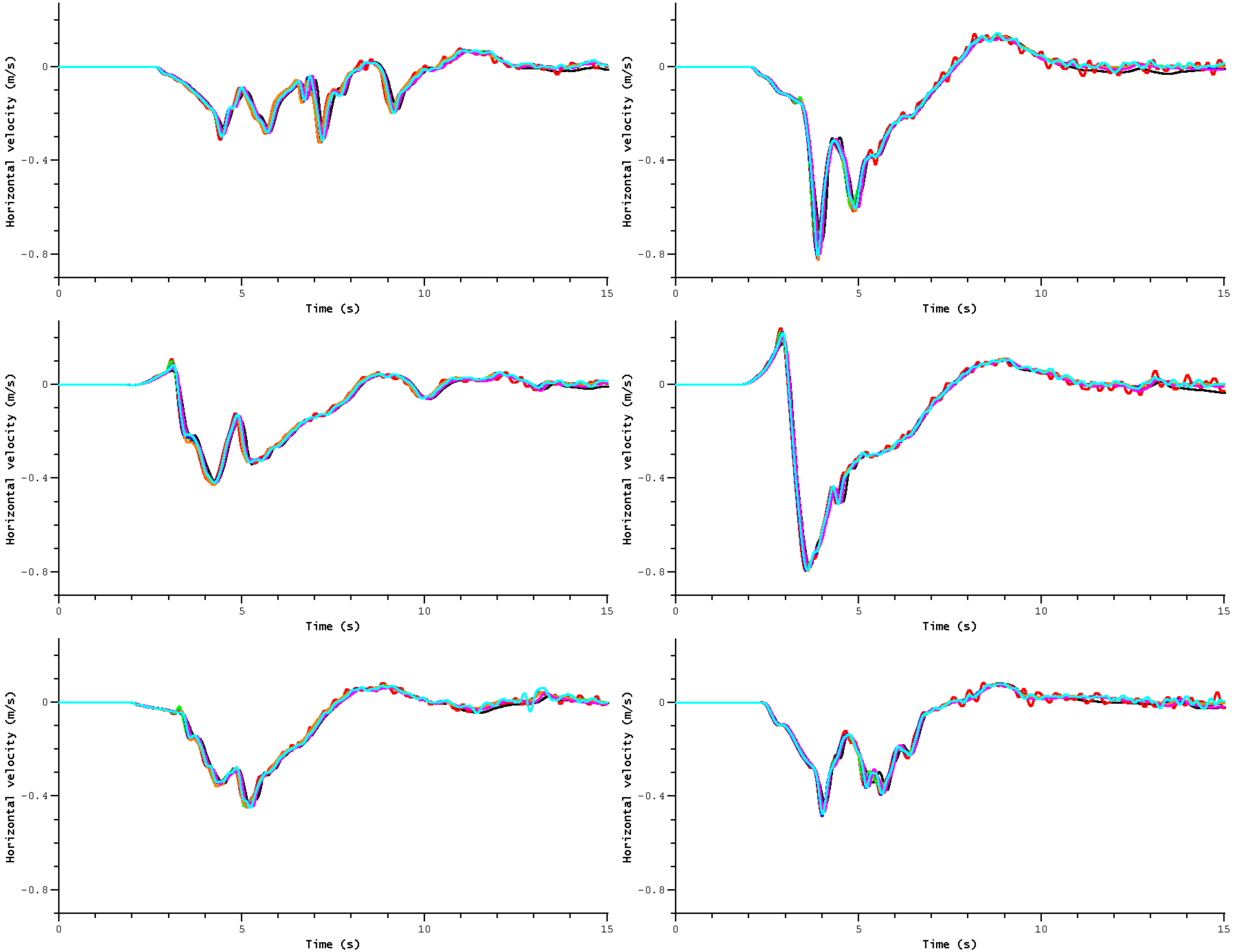
Stations 6 km Off-Fault



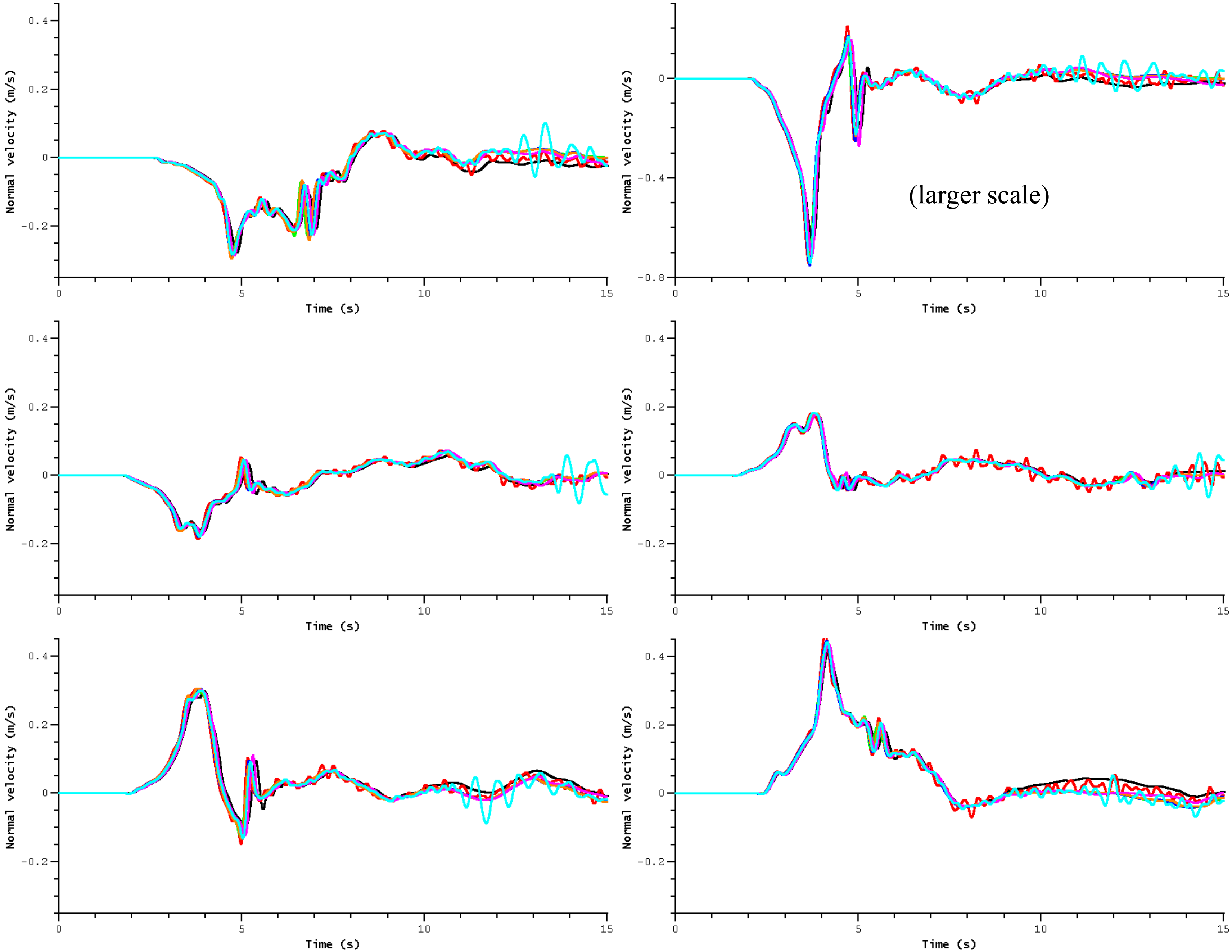
black	barall.2 (Michael Barall - Finite Element - FaultMod - Denser Mesh)
red	cruz-atienza (Tago/Cruz-Atienza - 3D Discontinuous Galerkin Code - DGCrack)
green	duan (Benchun Duan - Finite Element - EQdyna)
blue	kaneko (Yoshihiro Kaneko - Spectral Element - SPECFEM3D)
orange	kase (Yuko Kase - Finite Difference)
magenta	ma (Shuo Ma - Finite Element - MAFE)
cyan	somala (Surendra Somala - Spectral Element - SESAME)

All waveforms are filtered with a 3 Hz low-pass filter.

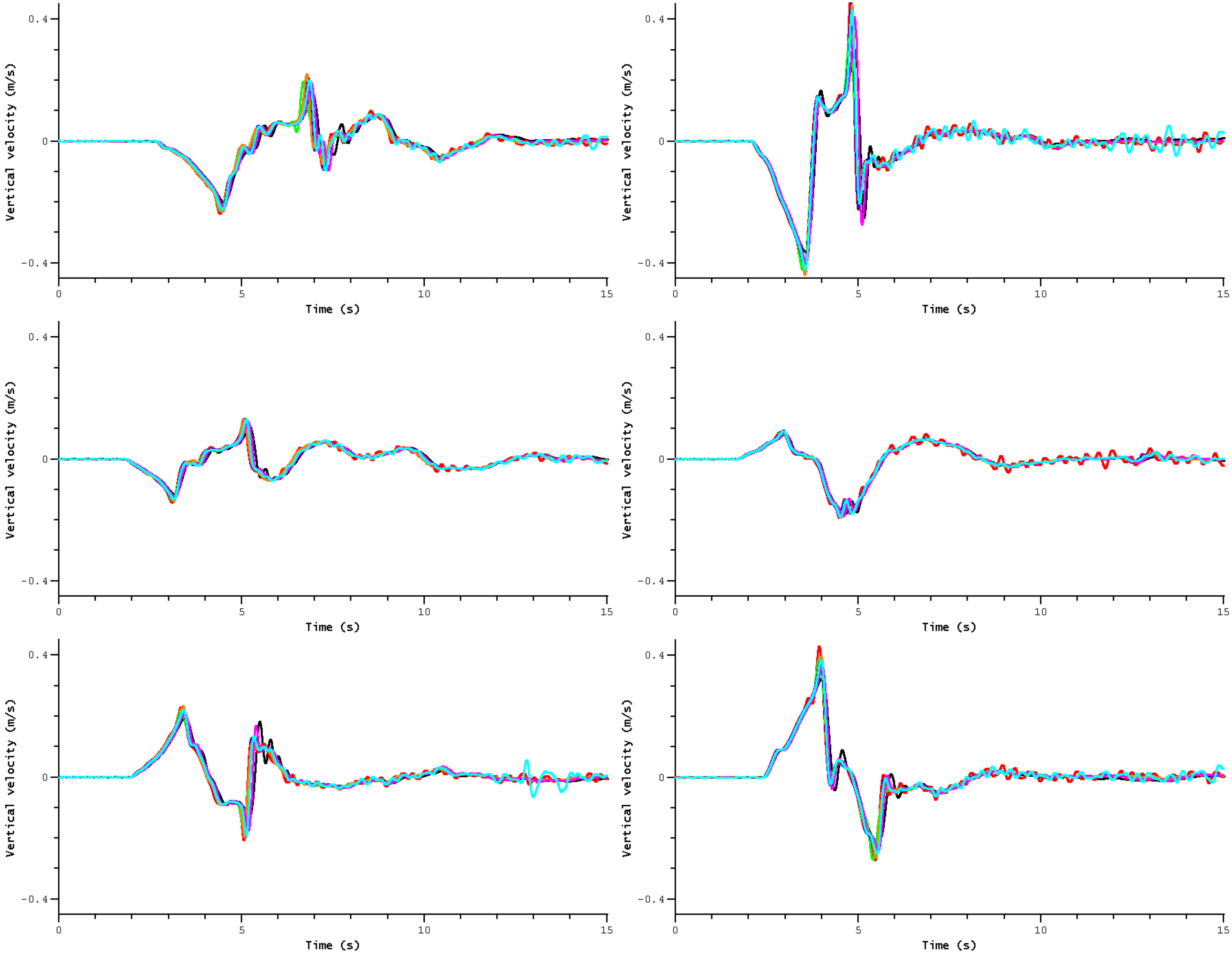
TPV16 Horizontal Velocity TPV17



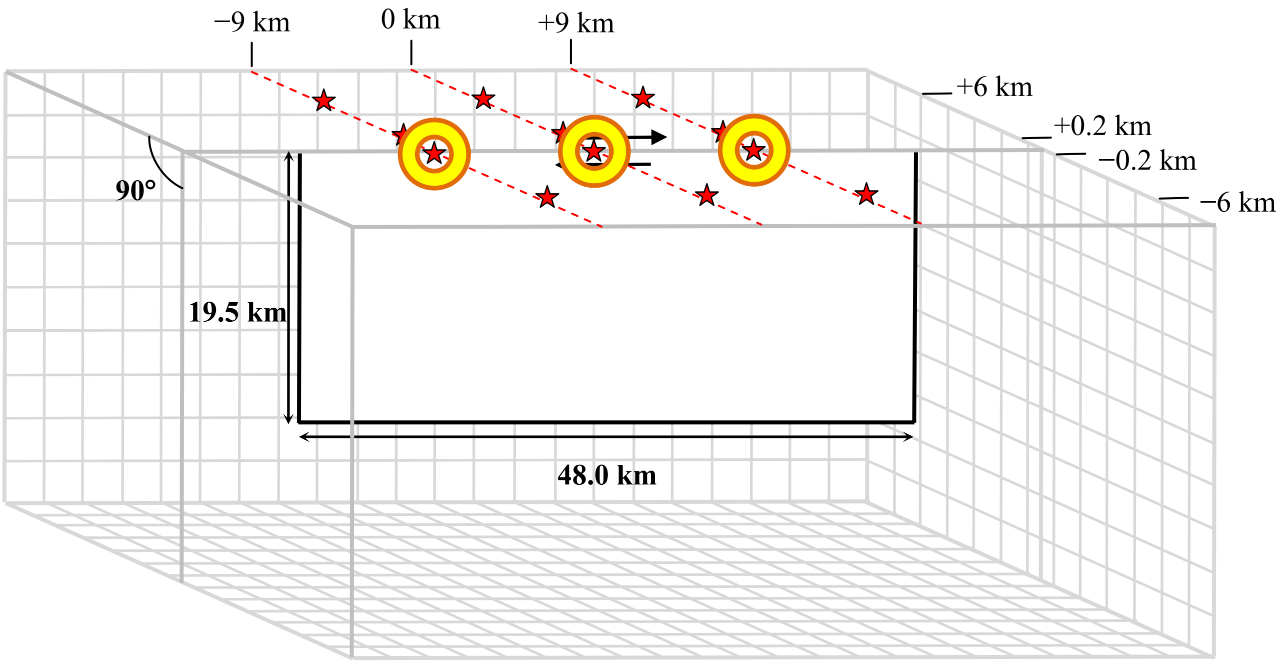
TPV16 Normal Velocity TPV17



TPV16 Vertical Velocity TPV17



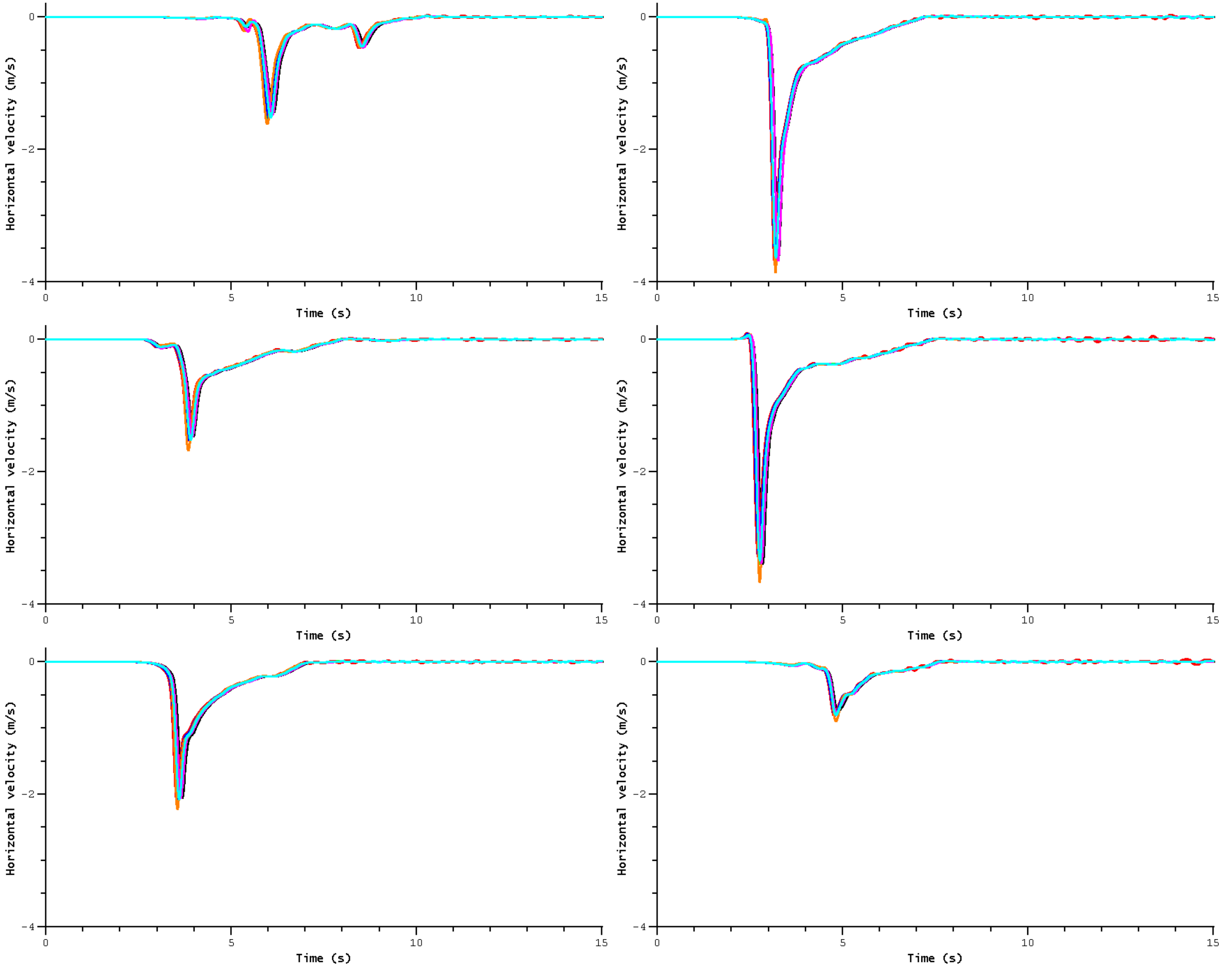
Stations 0.2 km Off-Fault



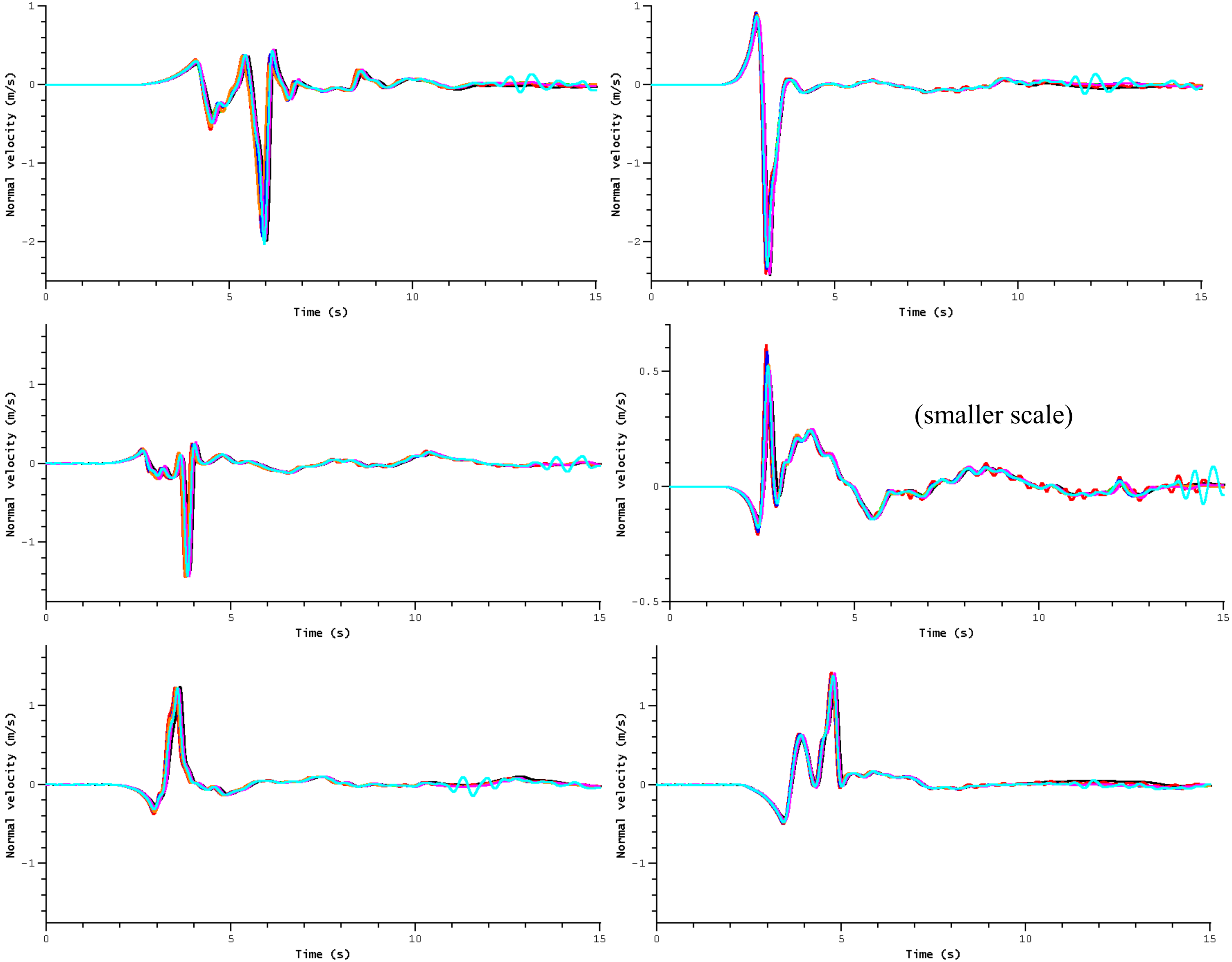
barall.2 (Michael Barall - Finite Element - FaultMod - Denser Mesh)
cruz-atienza (Tago/Cruz-Atienza - 3D Discontinuous Galerkin Code - DGCrack)
duan (Benchun Duan - Finite Element - EQdyna)
kaneko (Yoshihiro Kaneko - Spectral Element - SPECFEM3D)
kase (Yuko Kase - Finite Difference)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Spectral Element - SESAME)

All waveforms are filtered with a 3 Hz low-pass filter.

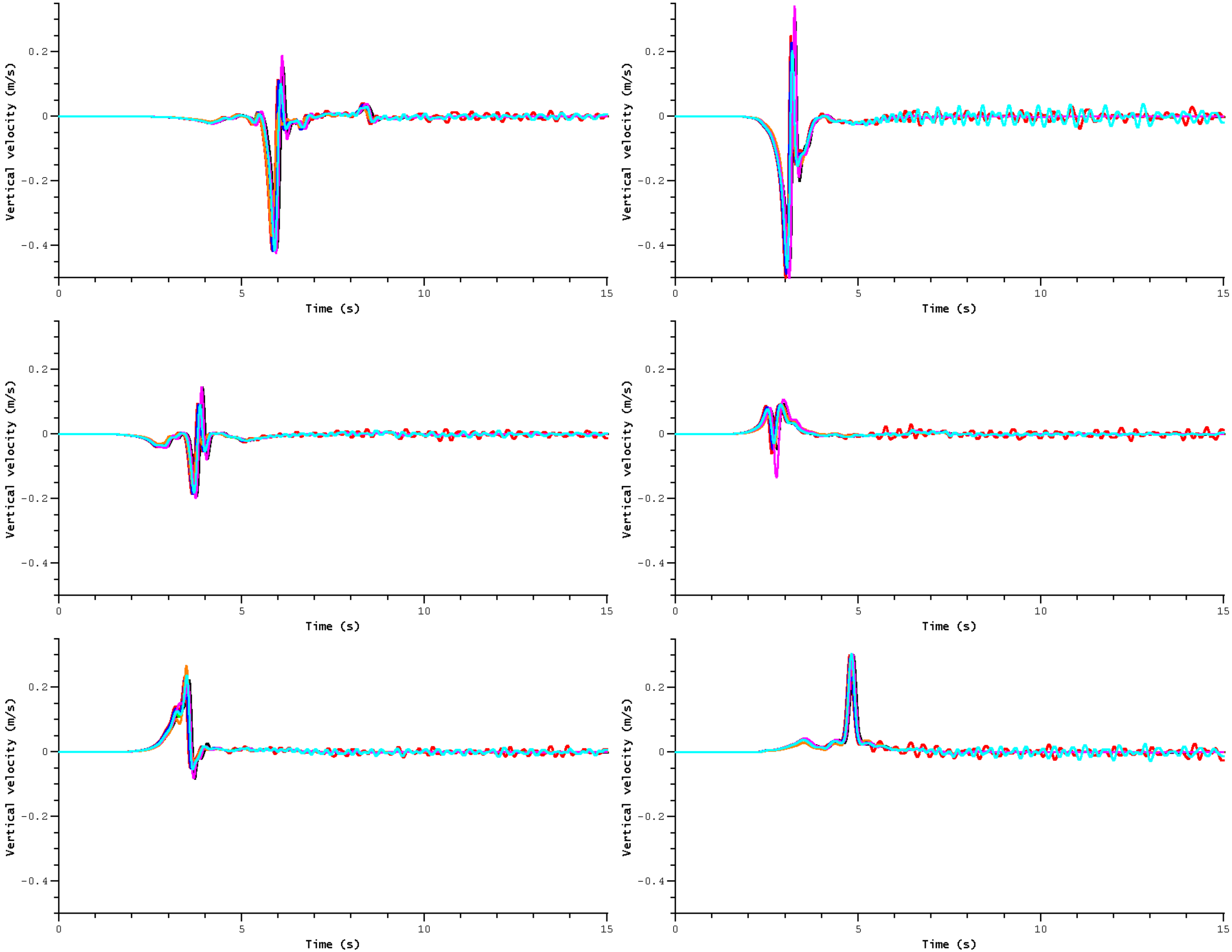
TPV16 **Horizontal Velocity** **TPV17**



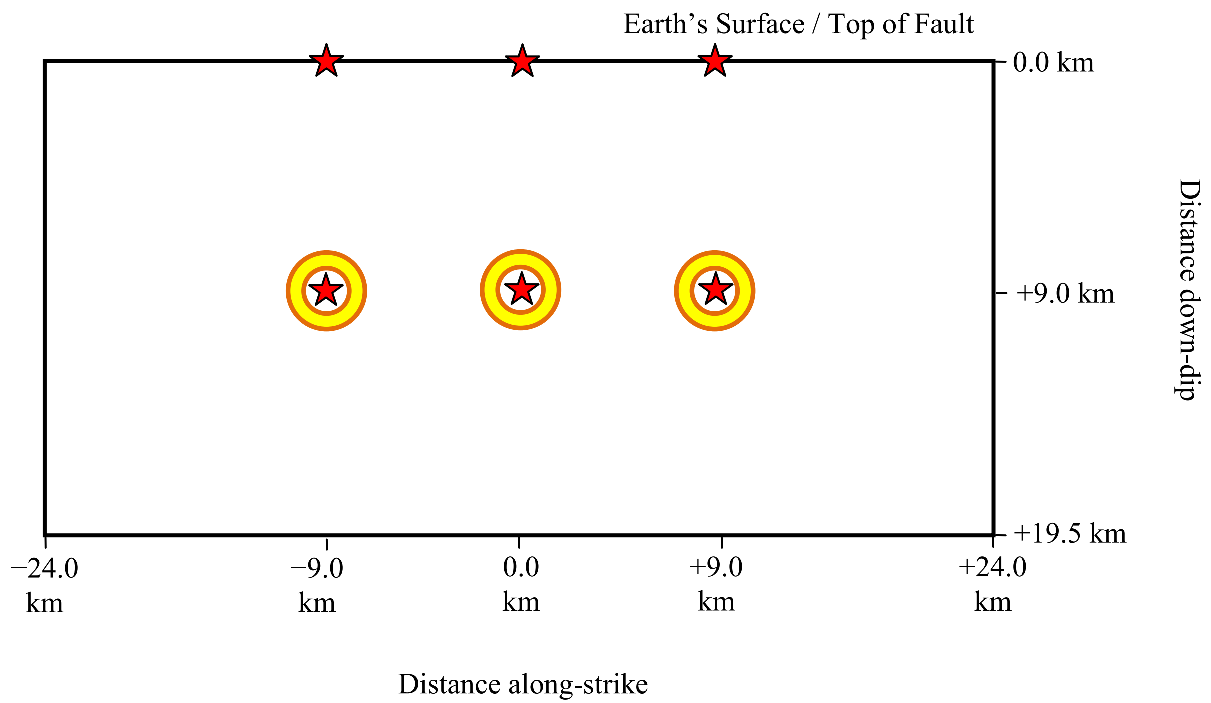
TPV16 Normal Velocity TPV17

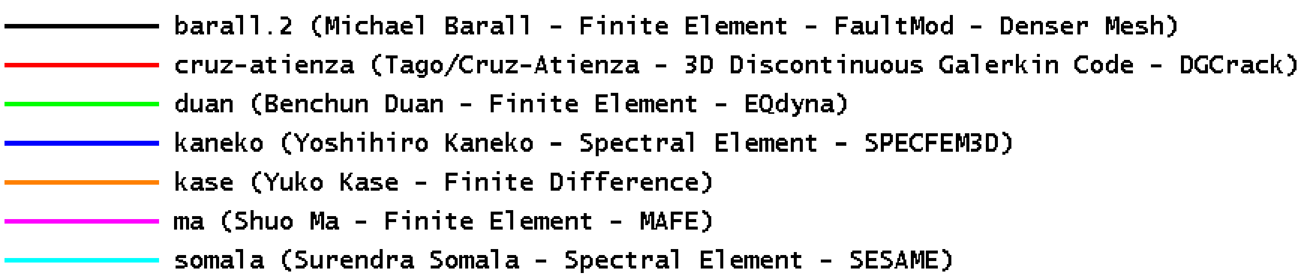


TPV16 Vertical Velocity TPV17



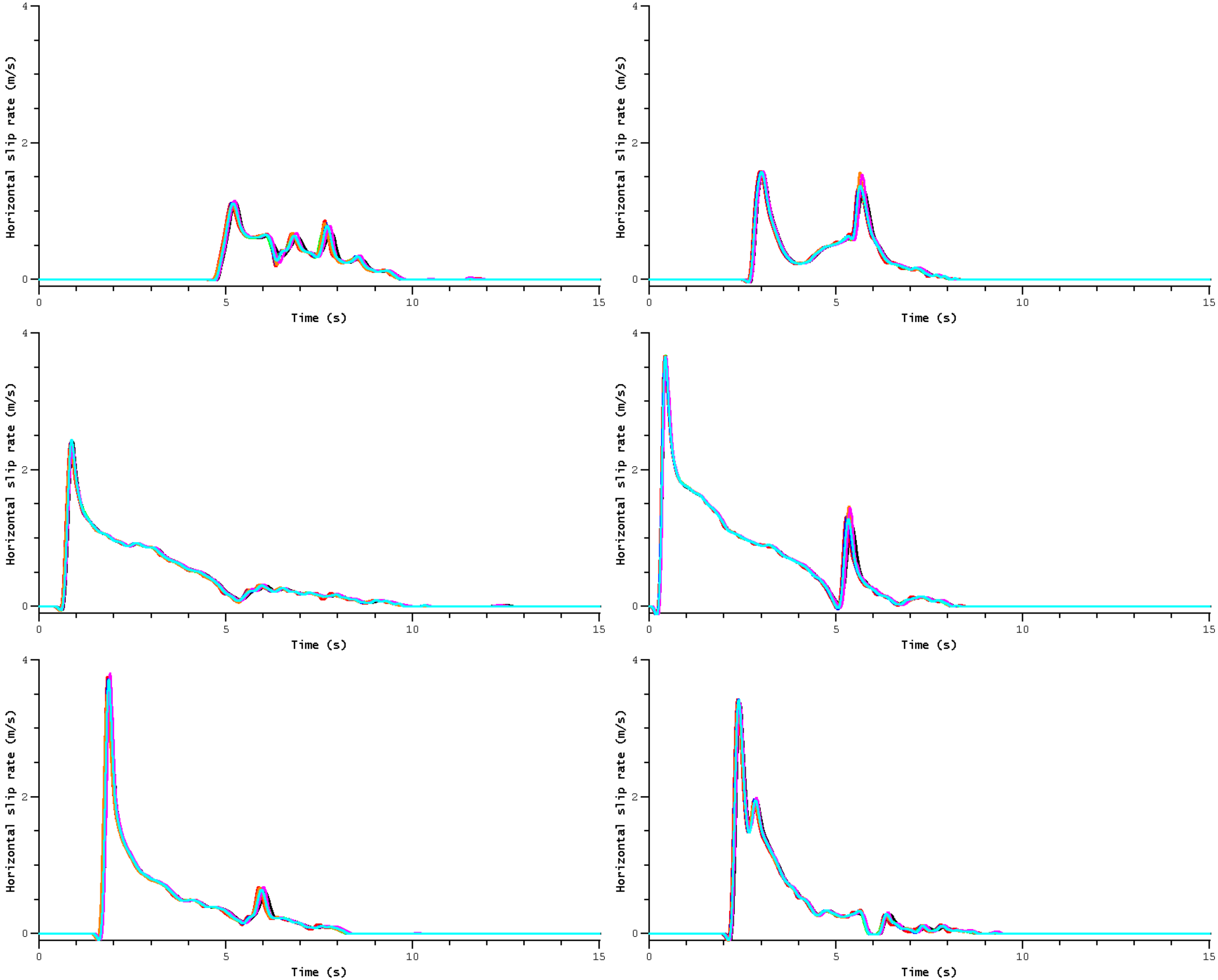
Stations On-Fault at Depth of 9.0 km



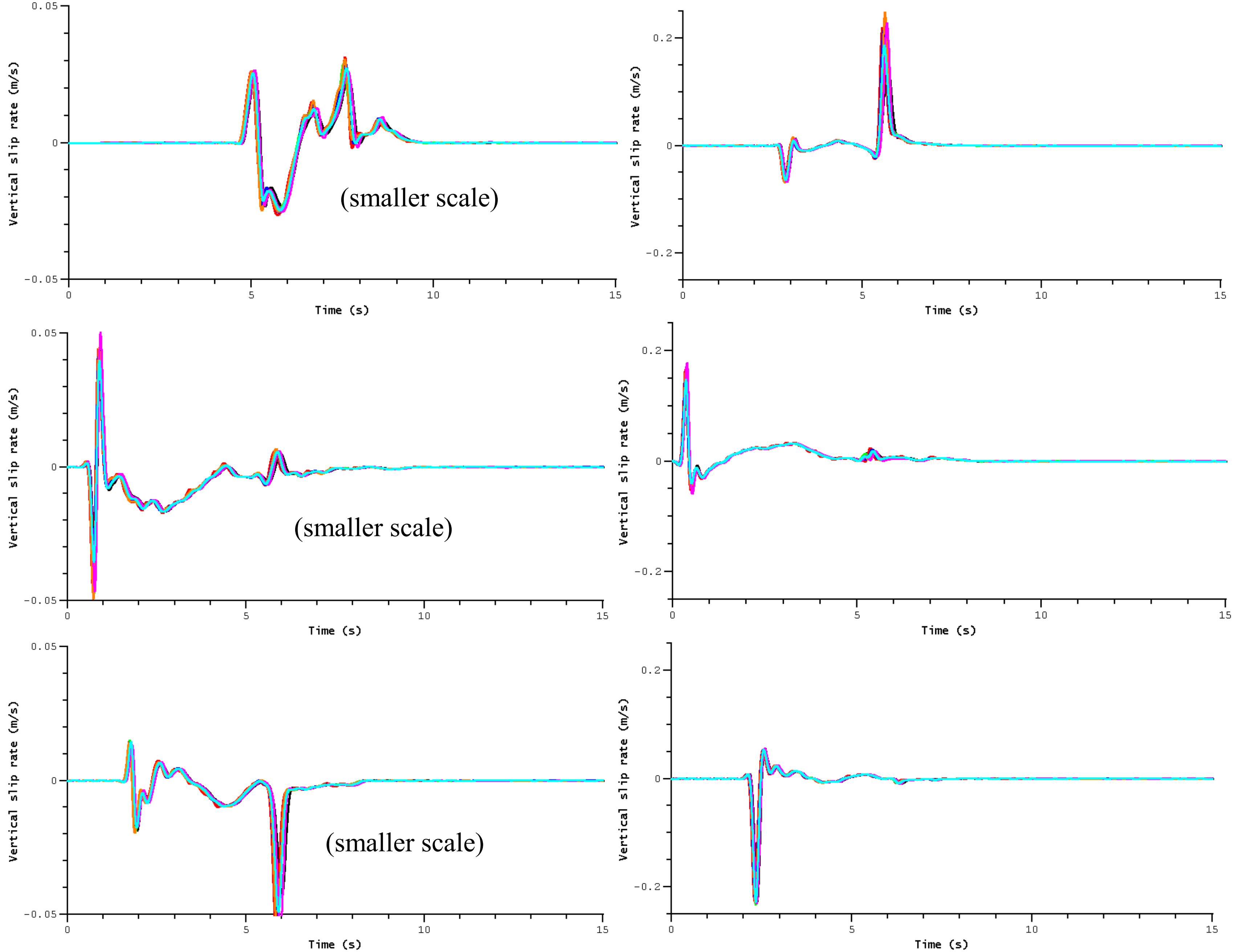


Slip rate waveforms are filtered with a 3 Hz low-pass filter.

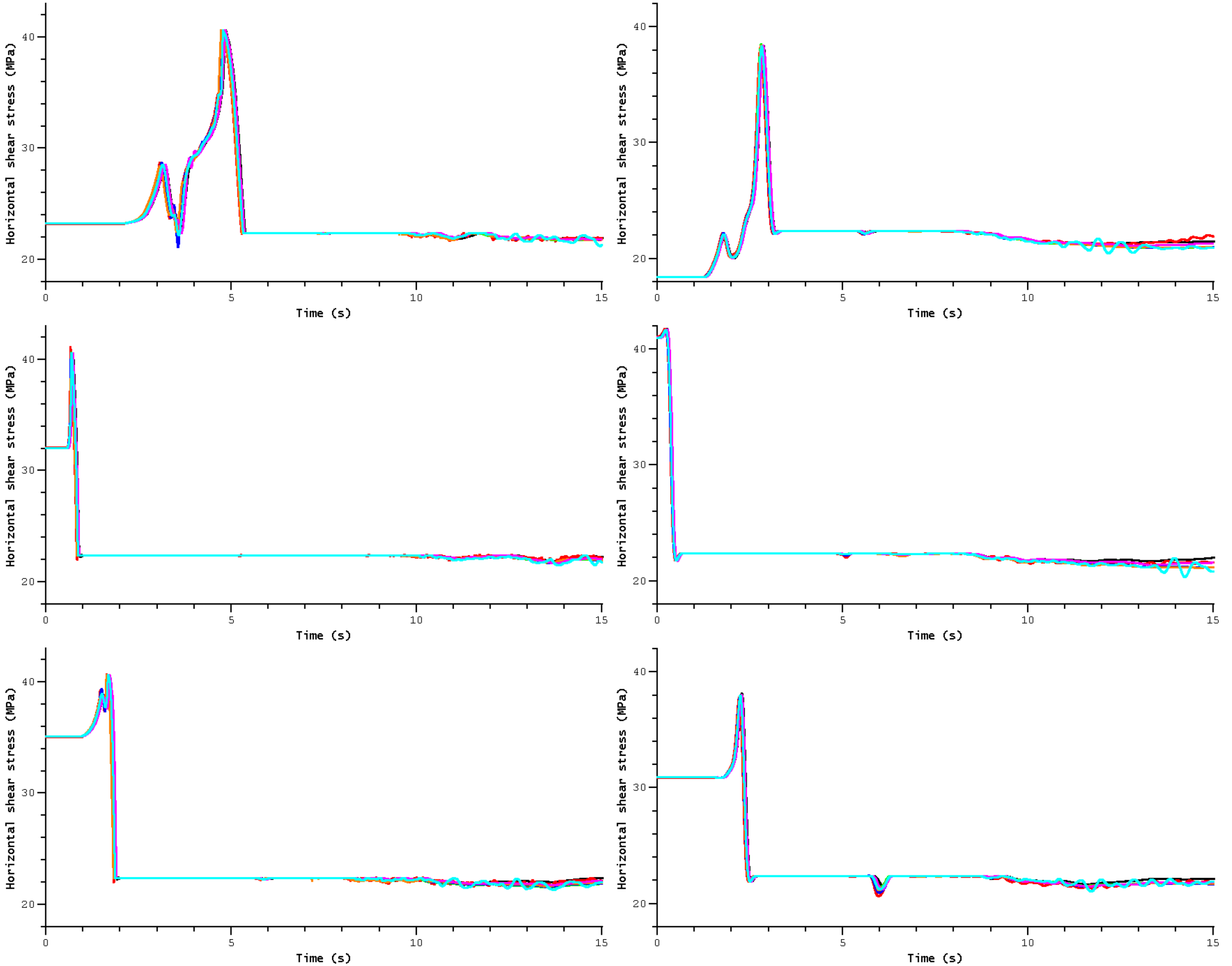
TPV16 **Horizontal Slip Rate** TPV17



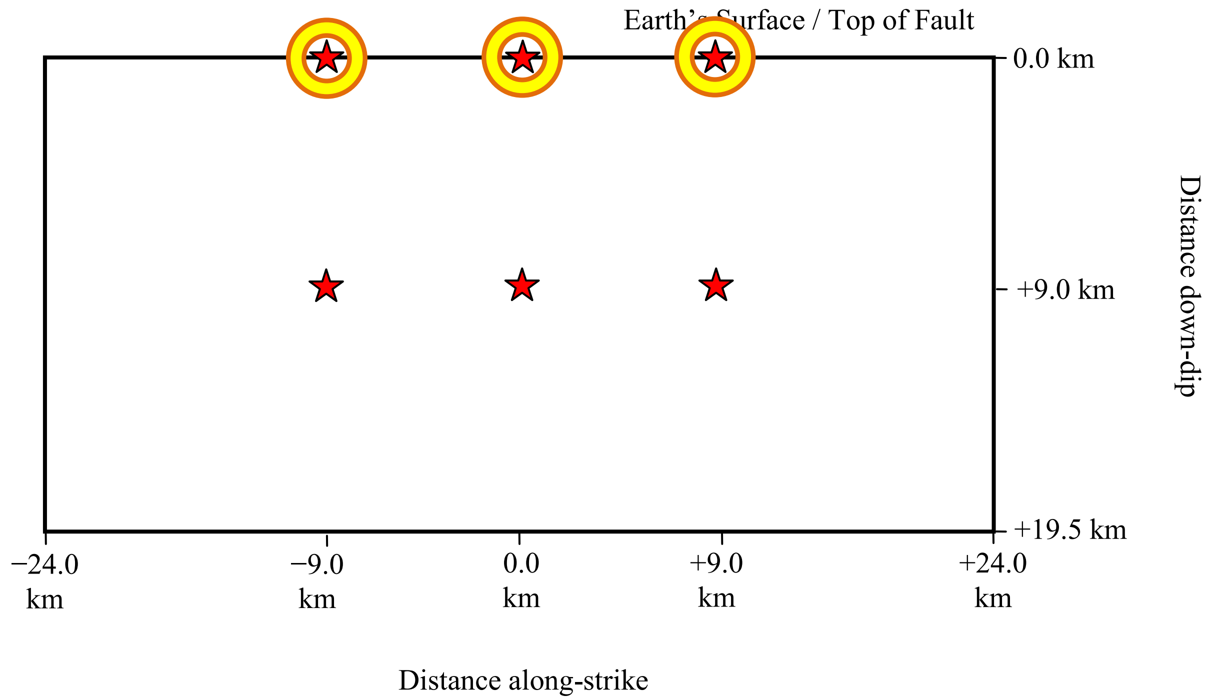
TPV16 Vertical Slip Rate TPV17



TPV16 **Horizontal Shear Stress** **TPV17**



Stations On-Fault at the Earth's Surface



barall.2 (Michael Barall - Finite Element - FaultMod - Denser Mesh)
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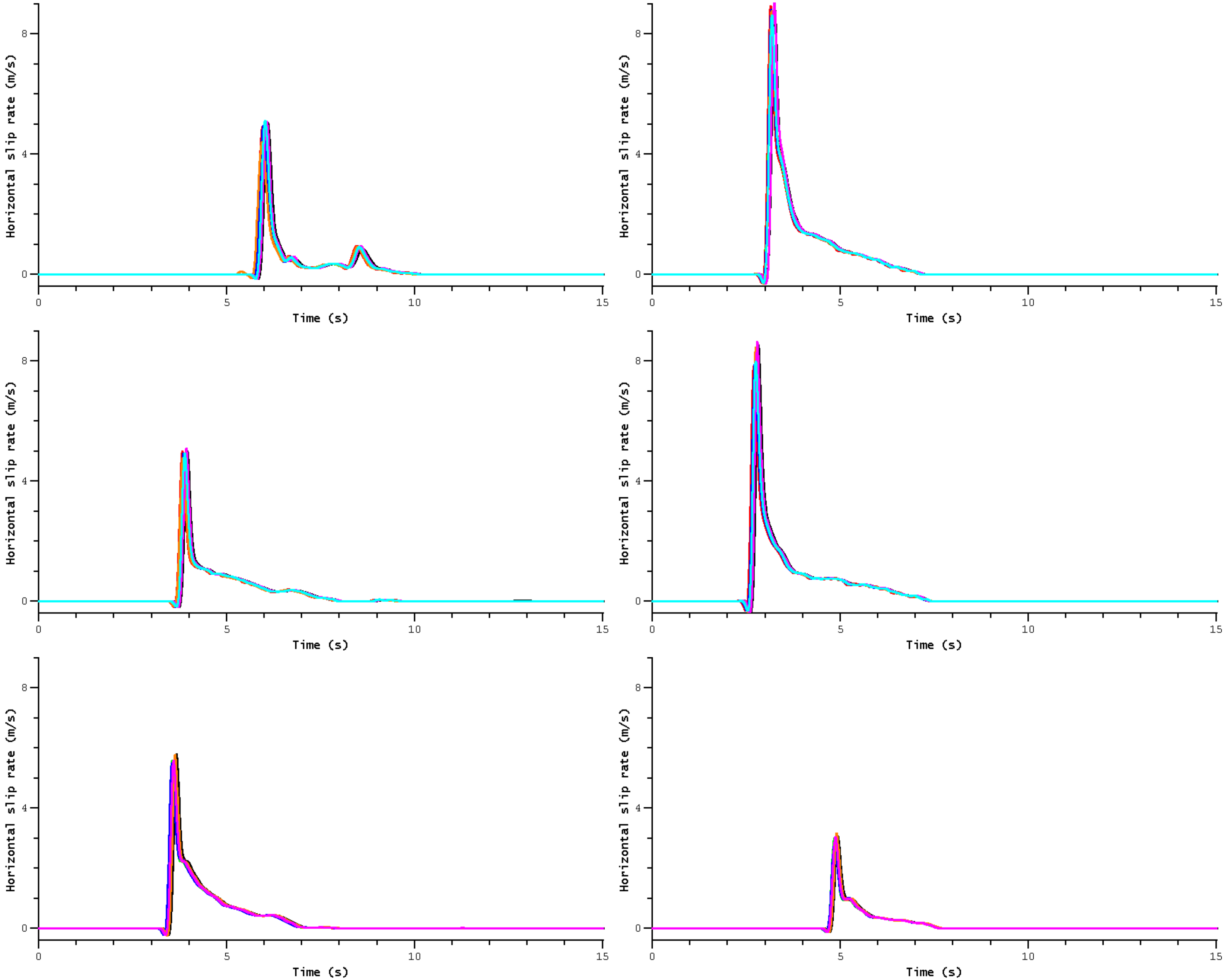
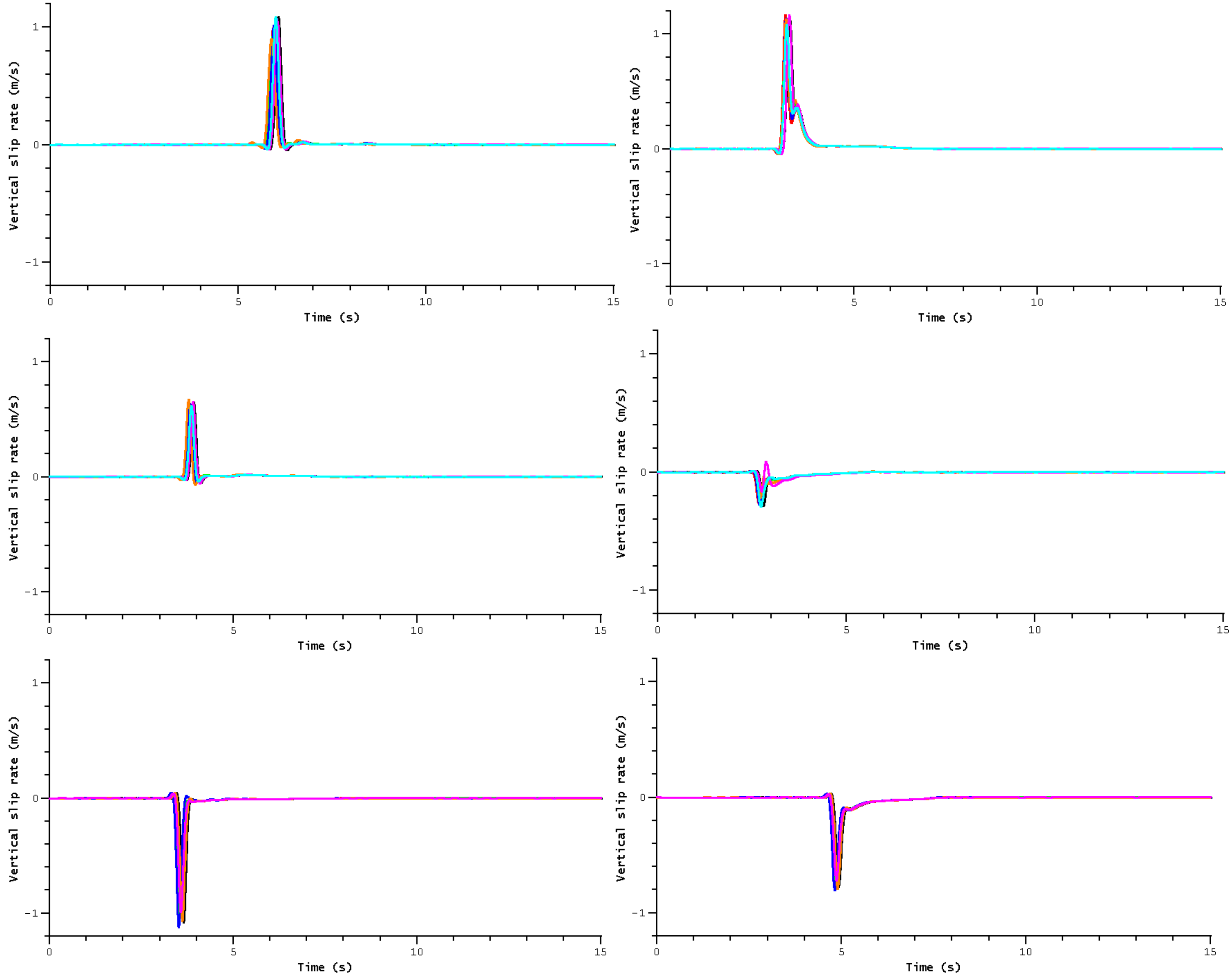
kase (Yuko Kase - Finite Difference)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Spectral Element - SESAME)

Slip rate waveforms are filtered with a 3 Hz low-pass filter.

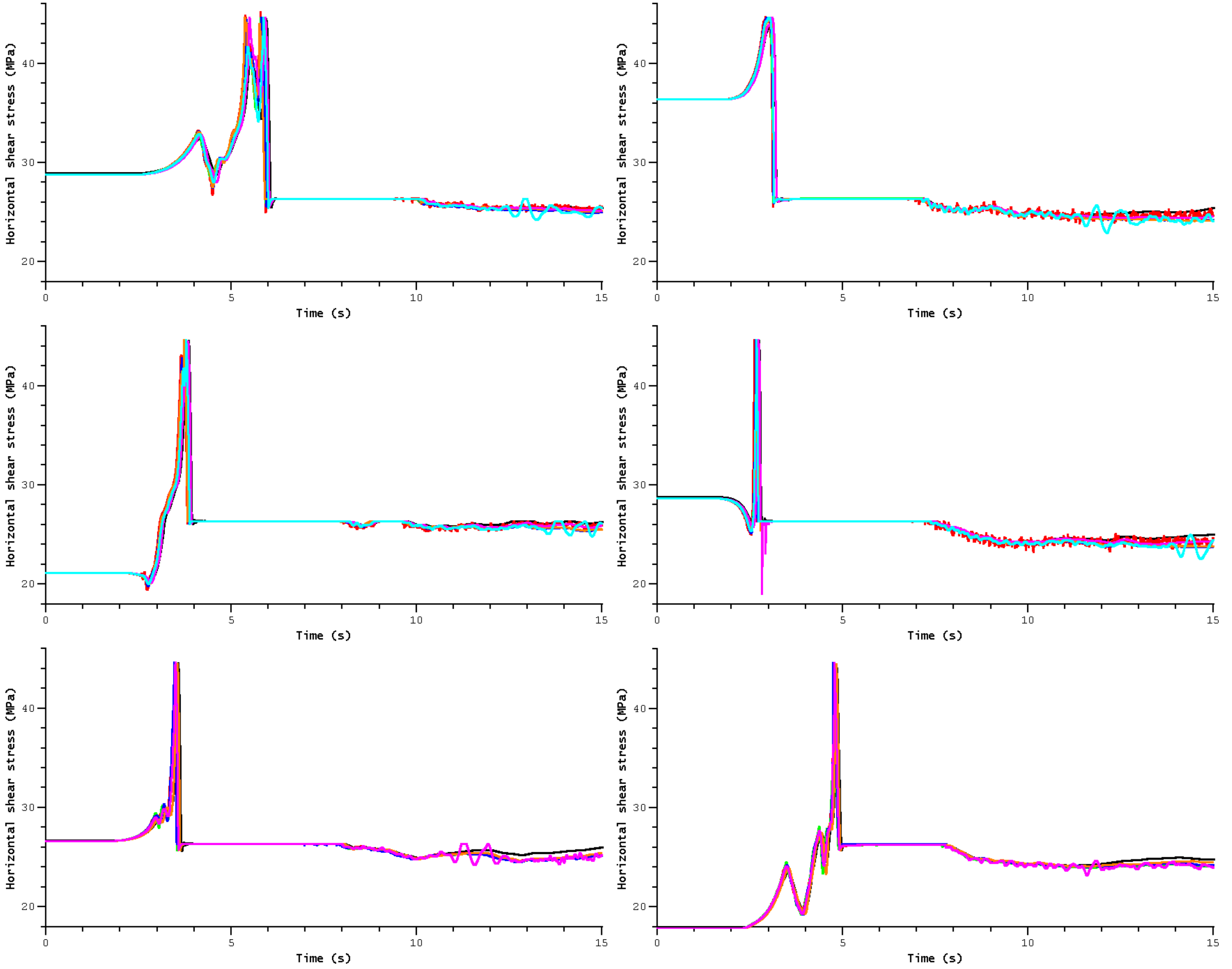
TPV16 **Horizontal Slip Rate** TPV17



TPV16 Vertical Slip Rate TPV17

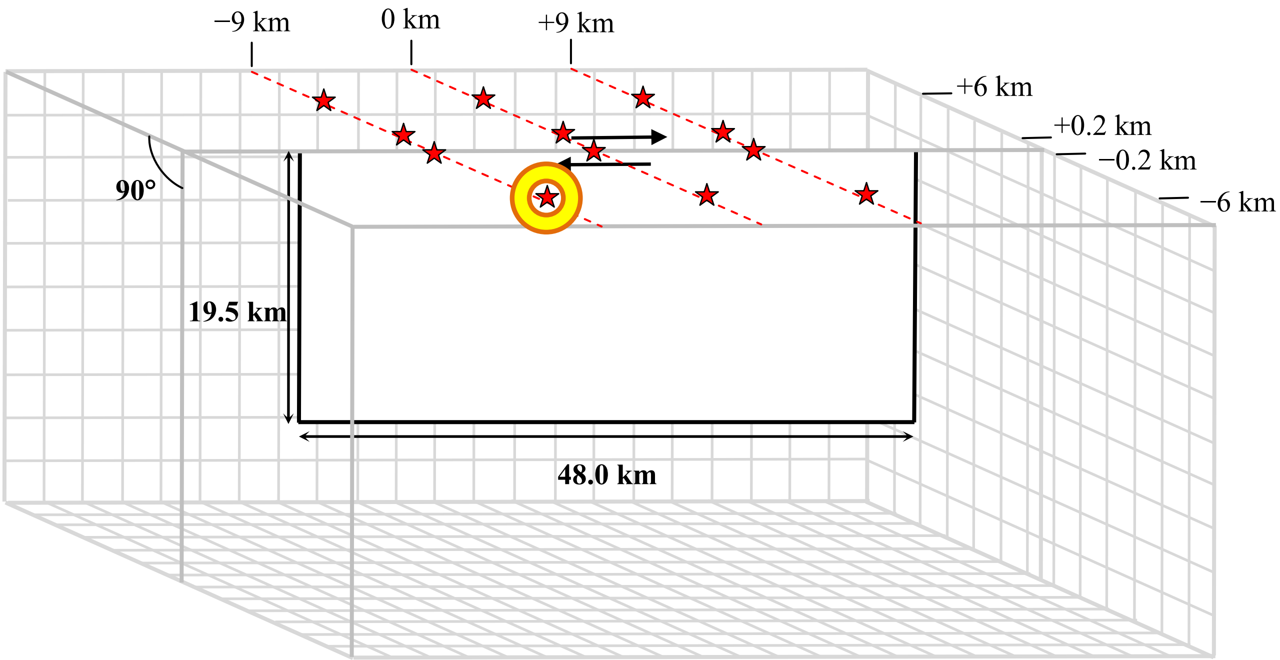


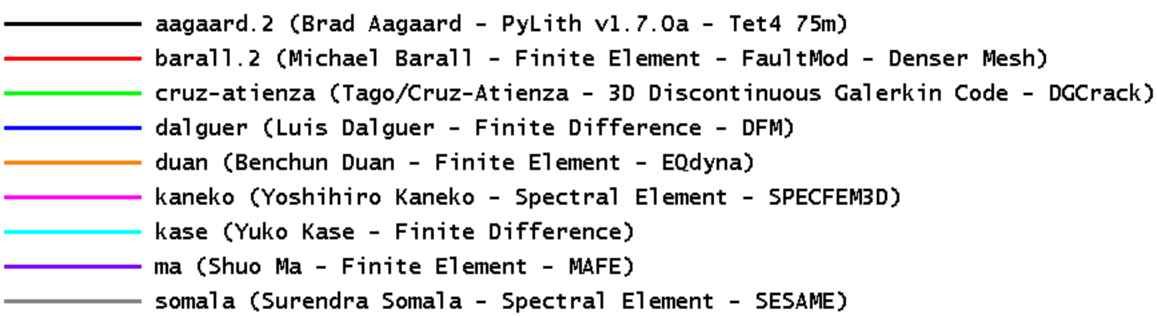
TPV16 Horizontal Shear Stress TPV17



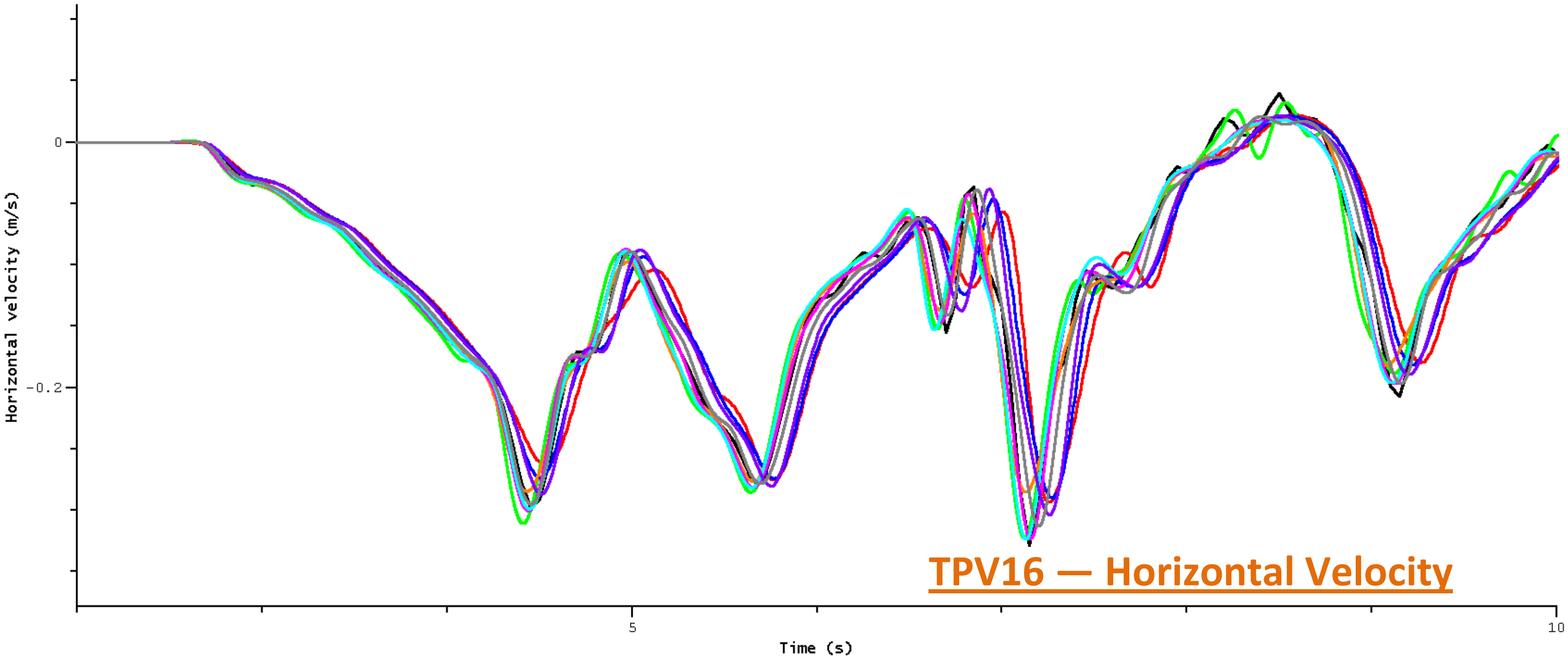
Waveform Comparisons for Codes

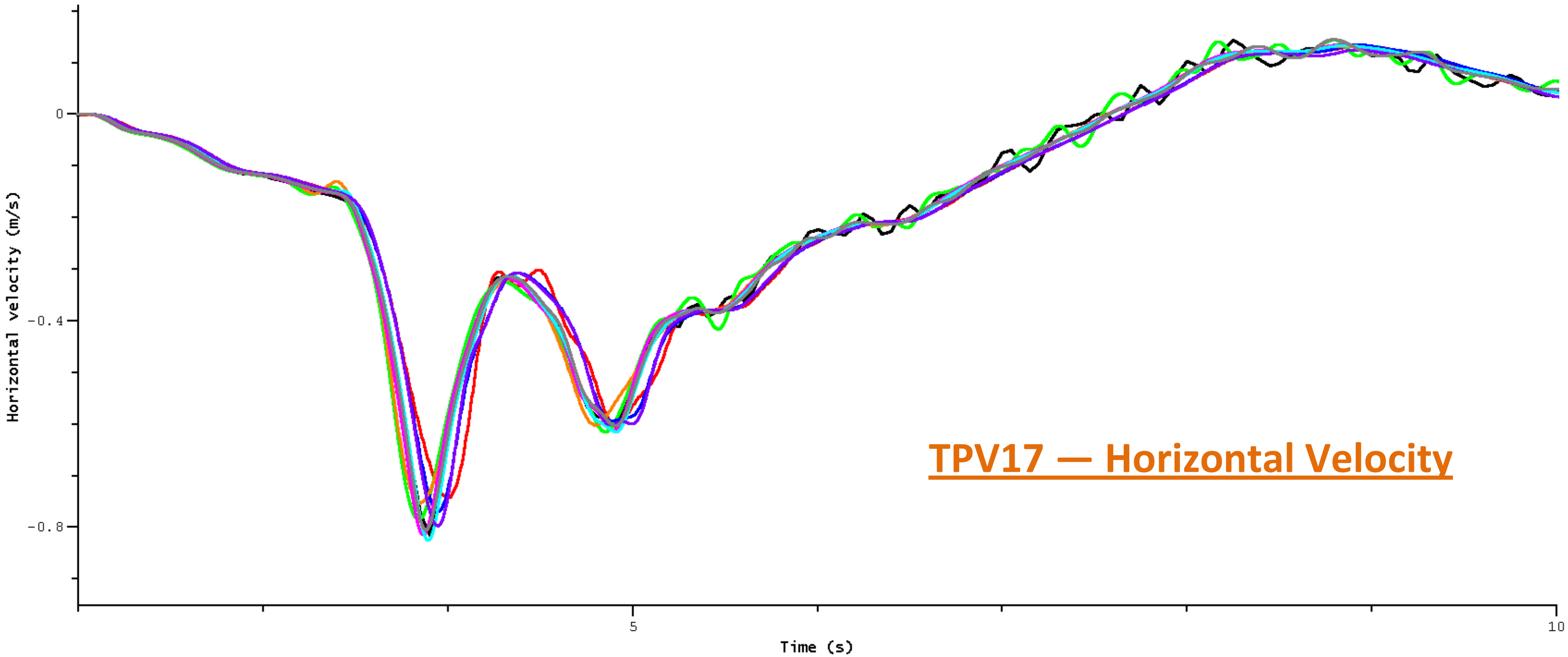
Waveform Comparison for Station 6 km Off-Fault

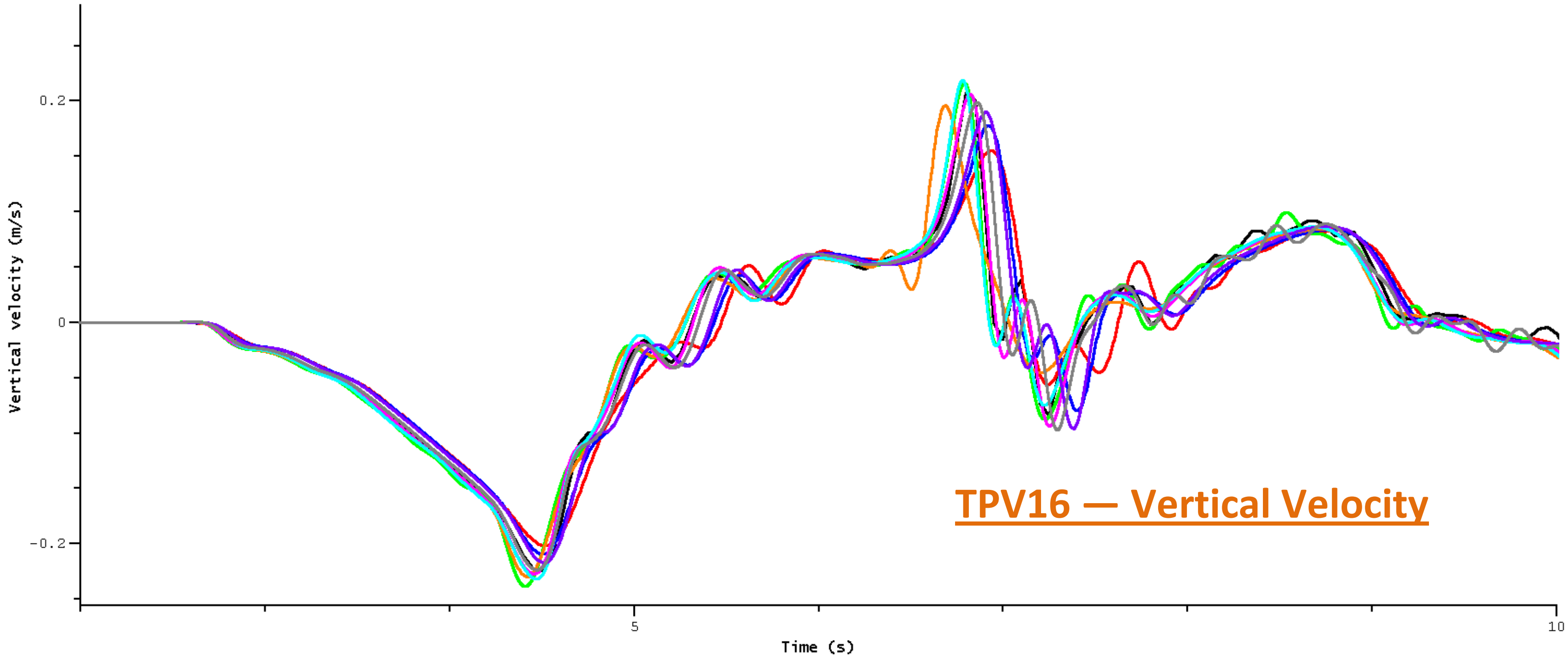


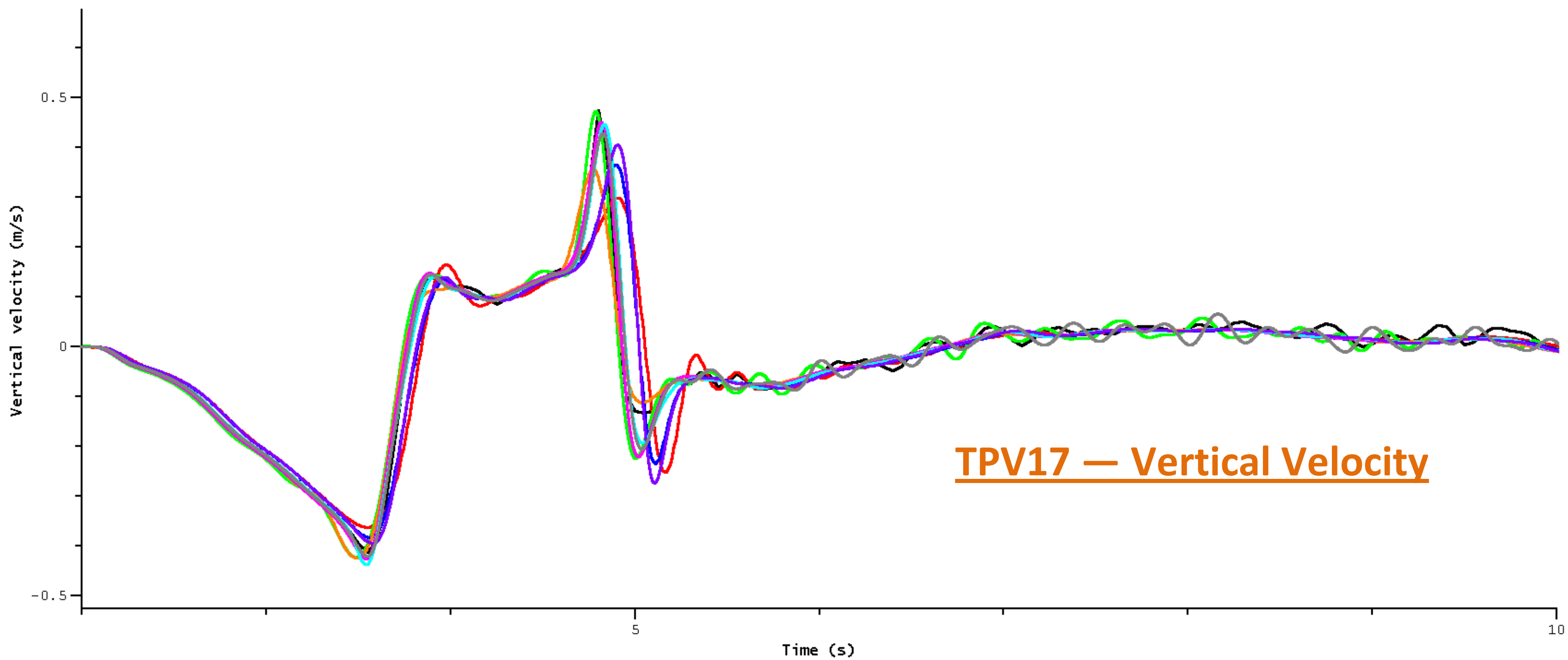


All waveforms are filtered with a 3 Hz low-pass filter.

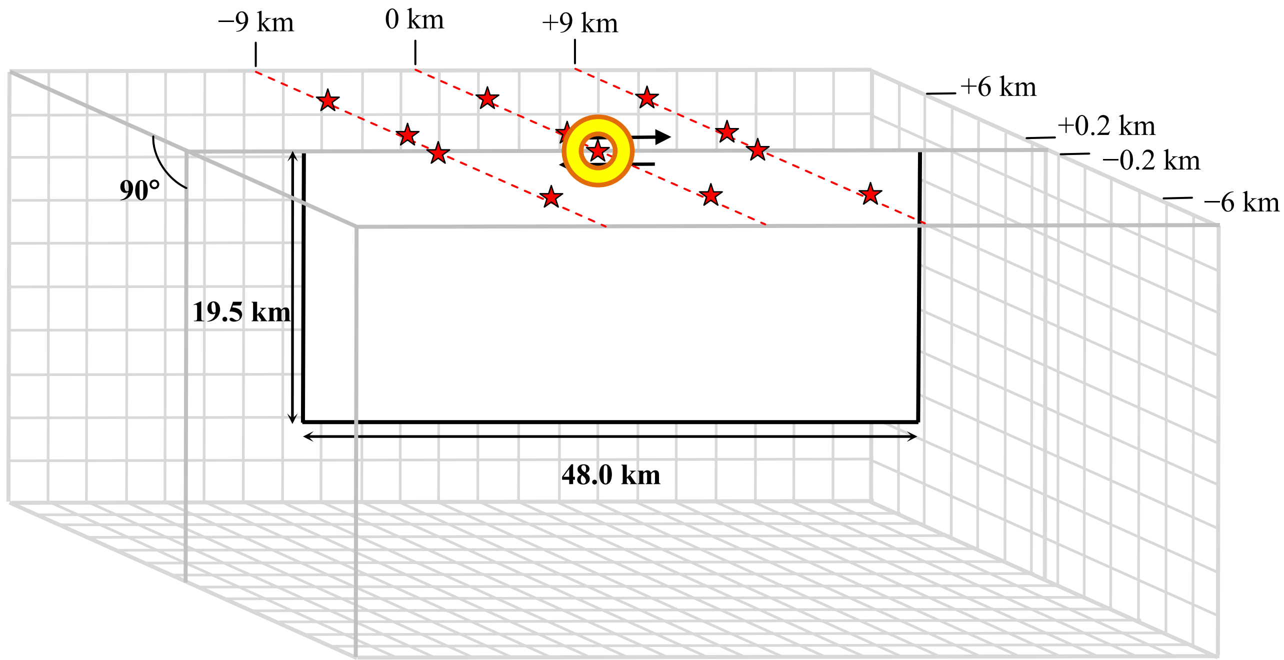

TPV16 — Horizontal Velocity
Horizontal velocity (m/s)
0
-0.2
5
10
Time (s)

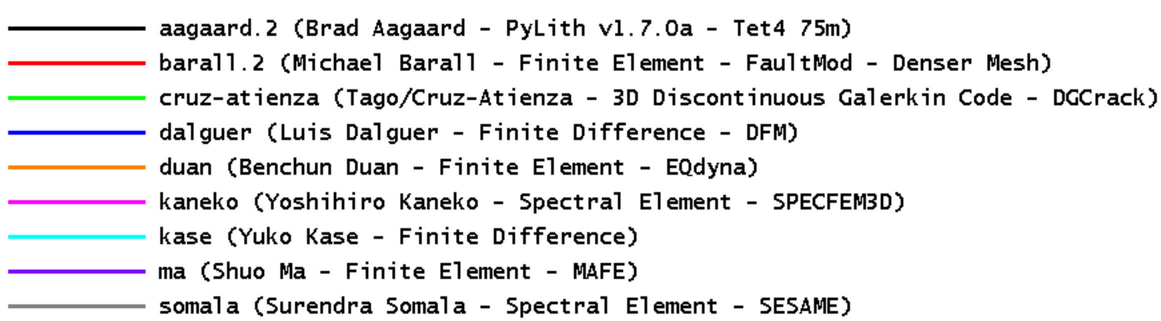

TPV17 — Horizontal Velocity
Horizontal velocity (m/s)
0
-0.4
-0.8
5
10
Time (s)


0.2
0
-0.2
Vertical velocity (m/s)
5
10
Time (s)
TPV16 — Vertical Velocity

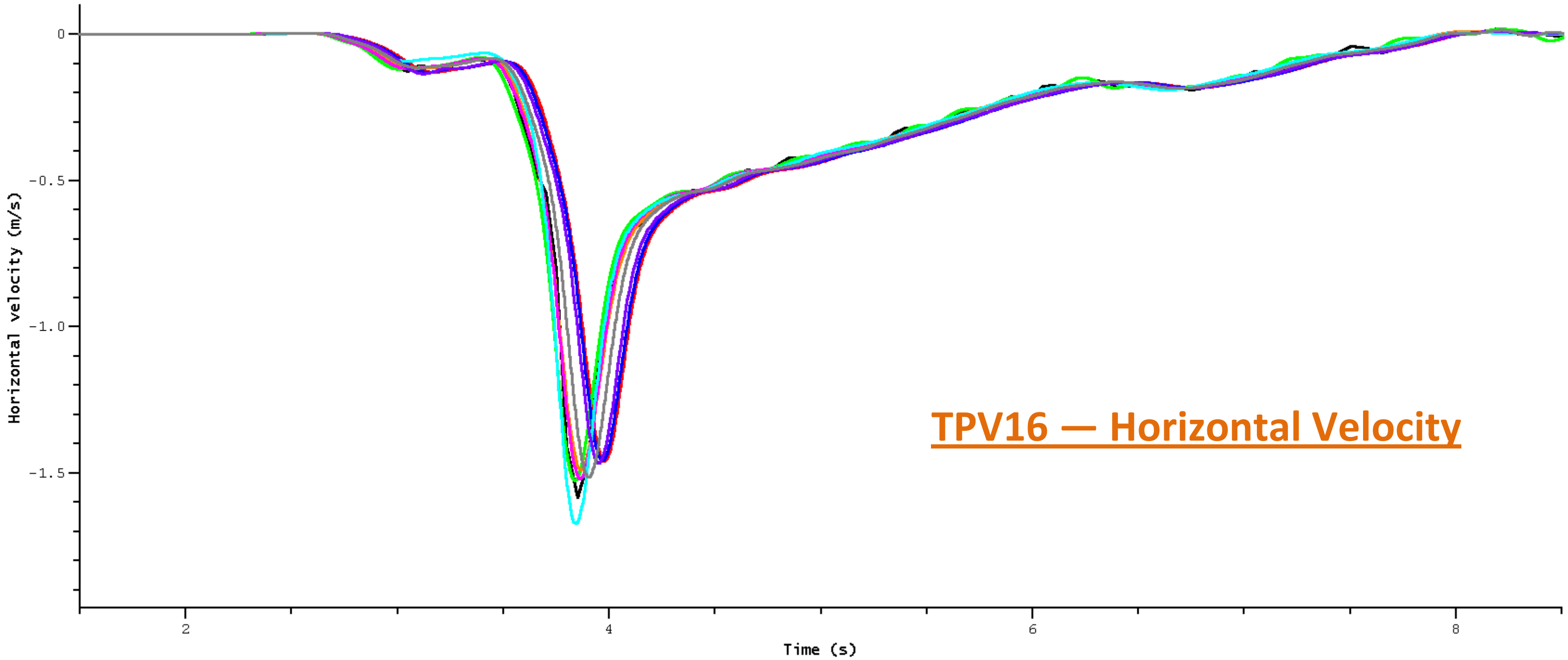

0.5
0
-0.5
Vertical velocity (m/s)
5
10
Time (s)
TPV17 — Vertical Velocity

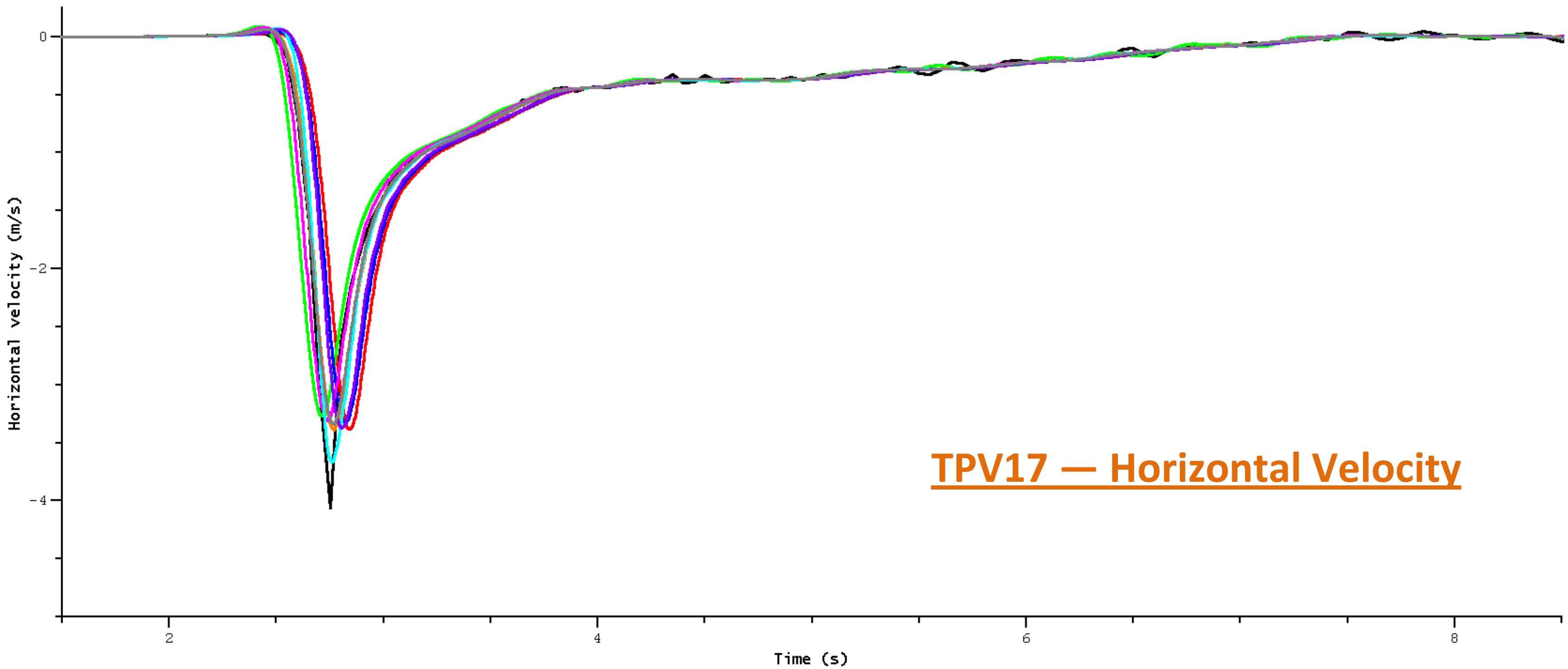
Waveform Comparison for Station 0.2 km Off-Fault

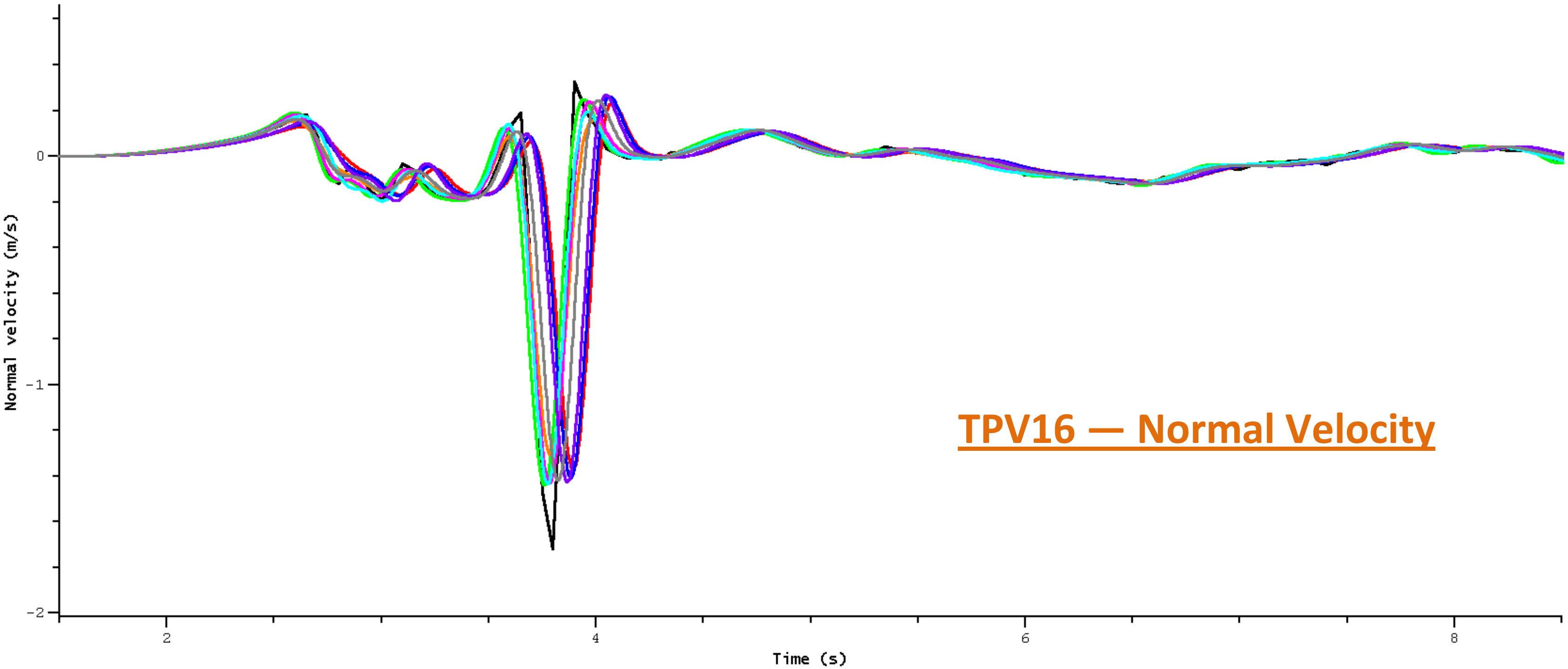


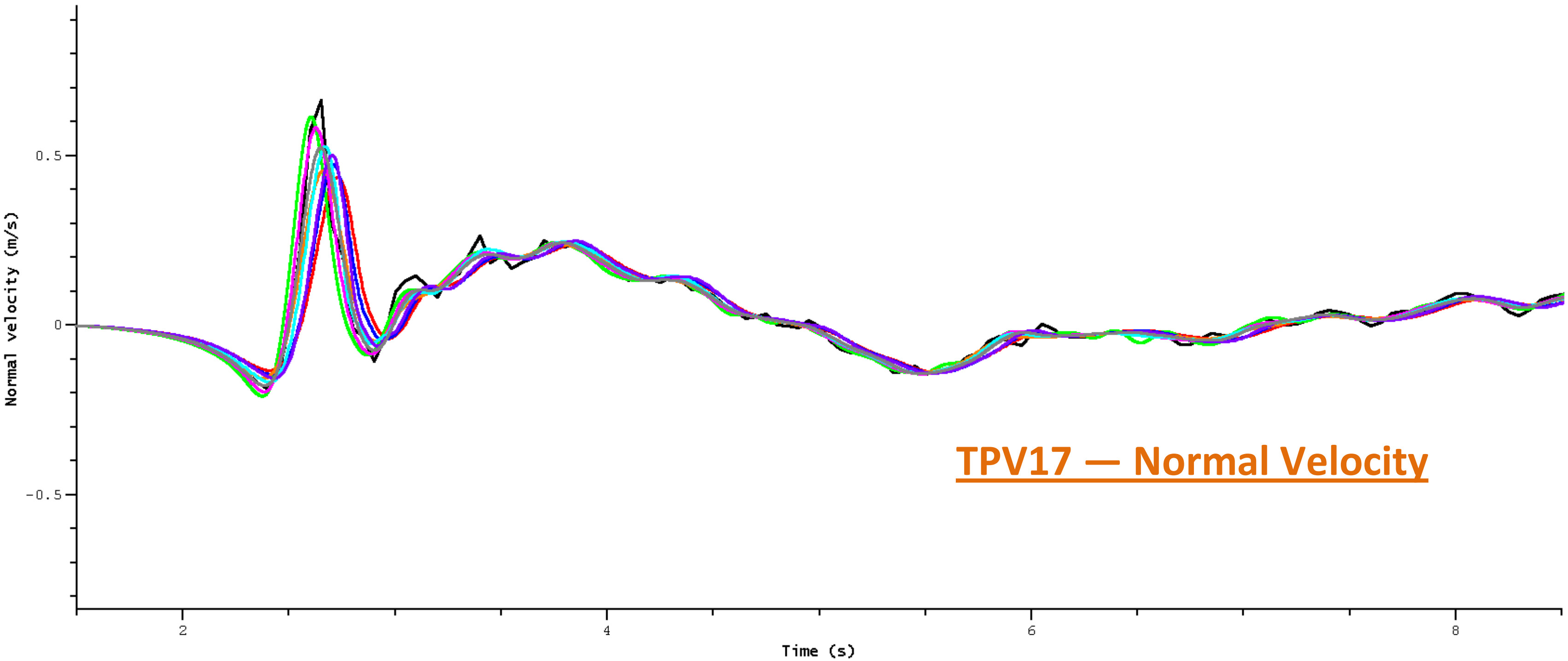


All waveforms are filtered with a 3 Hz low-pass filter.

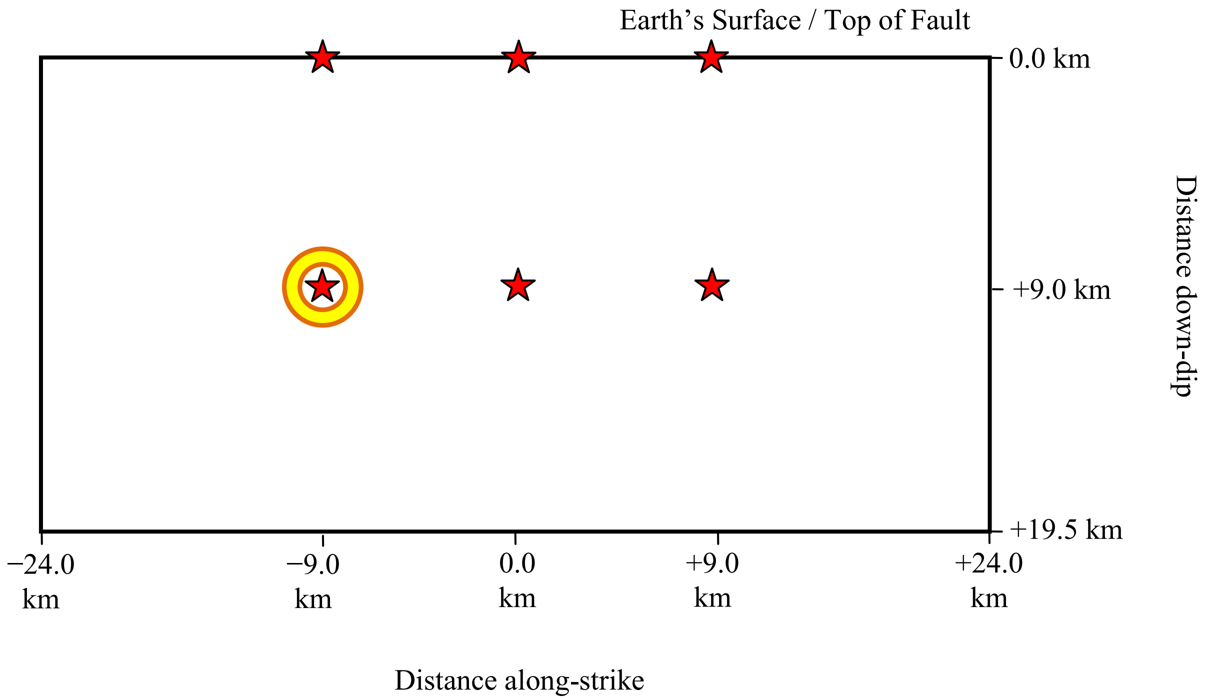

0
-0.5
-1.0
-1.5
Horizontal velocity (m/s)
2
4
6
8
Time (s)
TPV16 — Horizontal Velocity

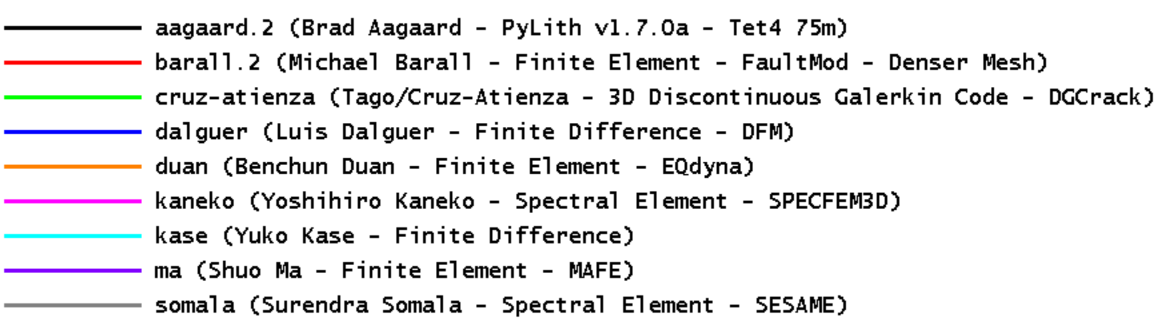

0
-2
-4
Horizontal velocity (m/s)
2
4
6
8
Time (s)
TPV17 — Horizontal Velocity


TPV16 — Normal Velocity
Normal velocity (m/s)
Time (s)
0
-1
-2
2
4
6
8

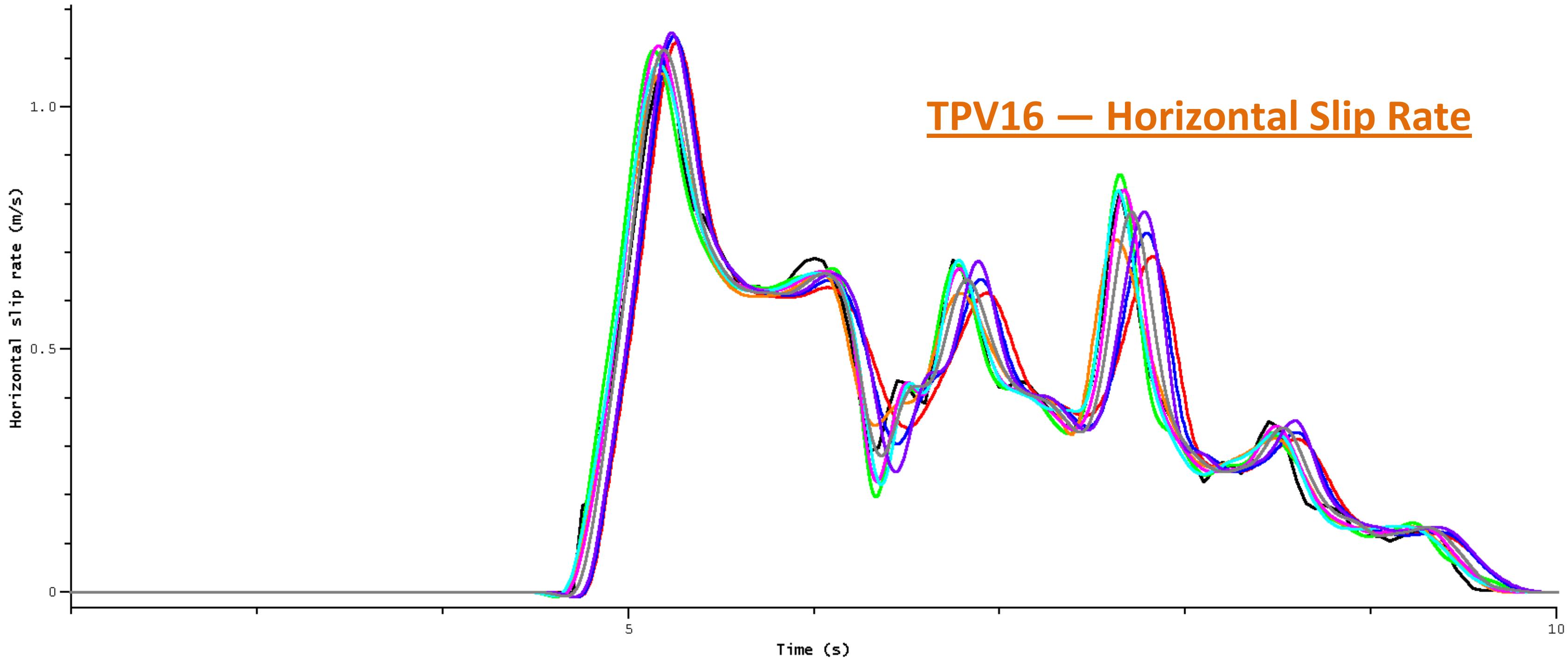

TPV17 — Normal Velocity
Normal velocity (m/s)
Time (s)
0.5
0
-0.5
2
4
6
8

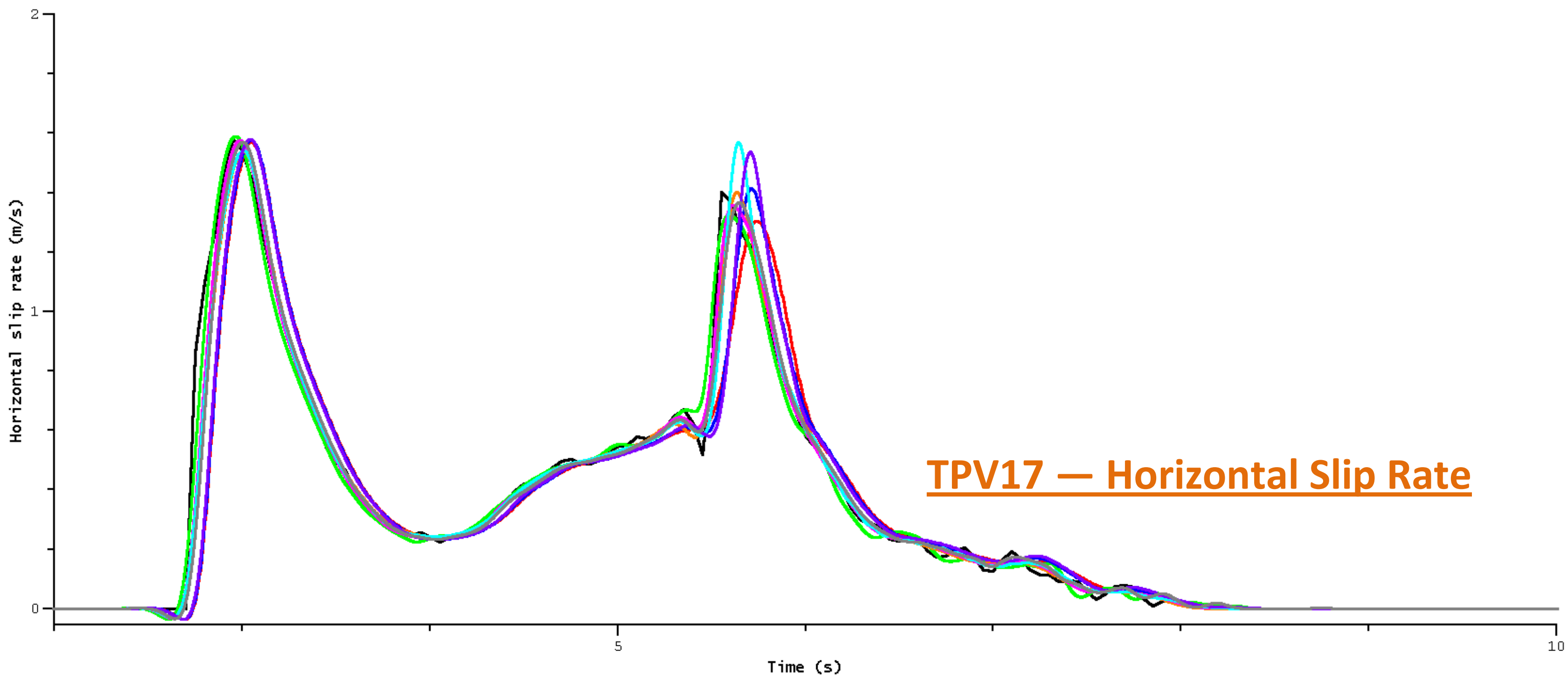
Waveform Comparison for Station On-Fault at Depth of 9.0 km

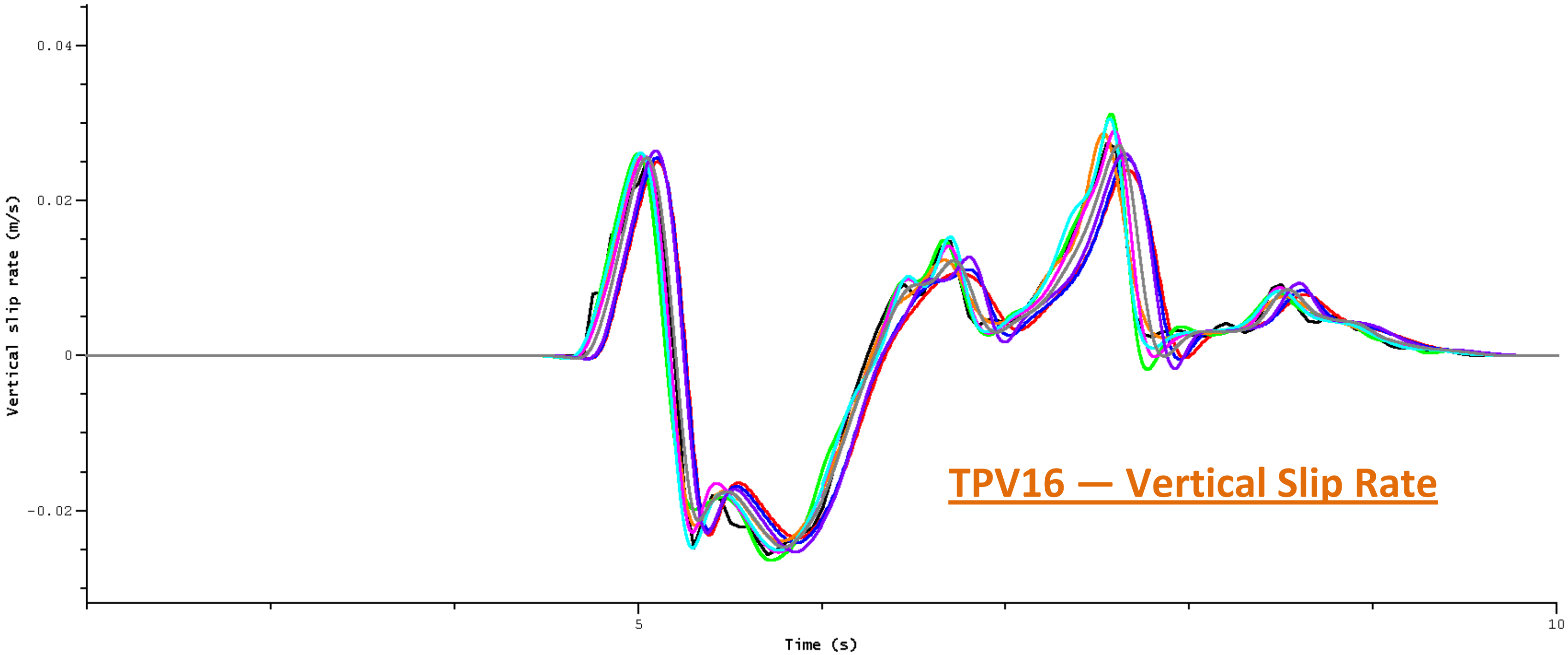


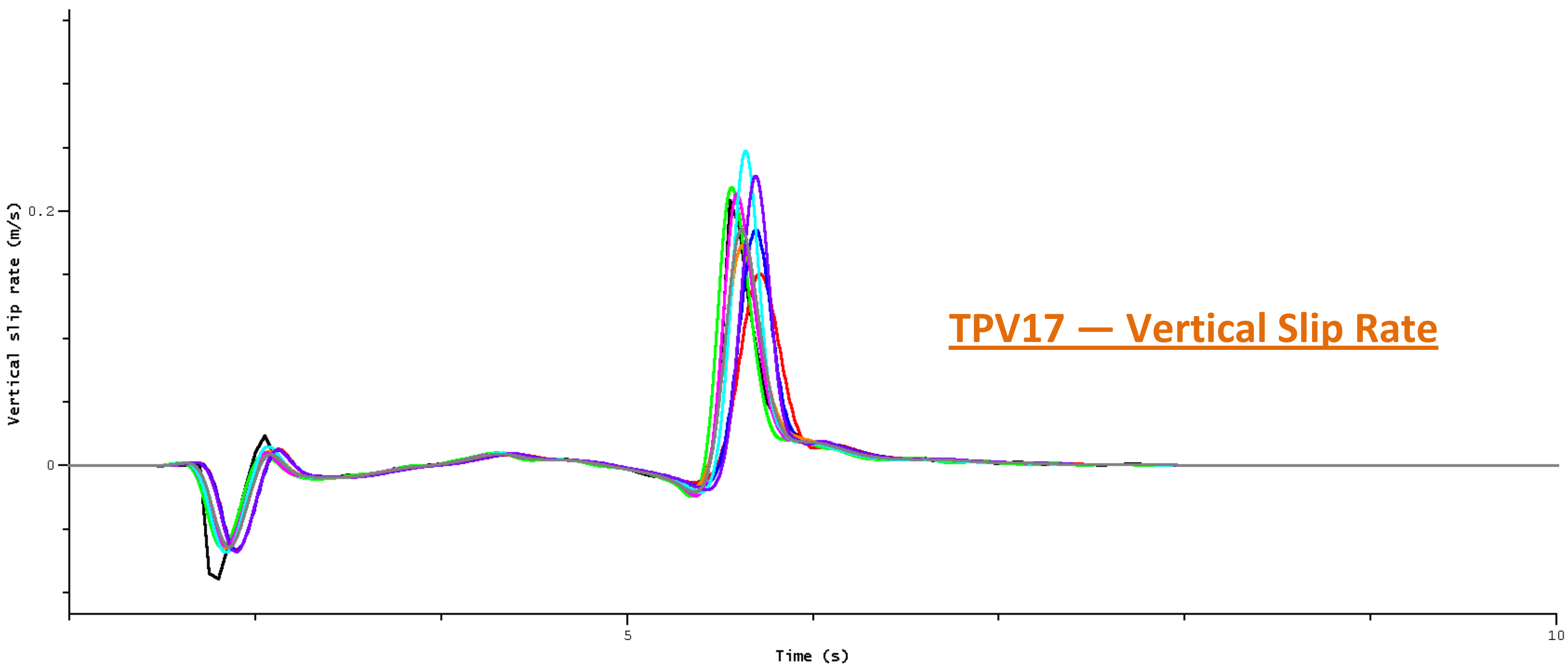


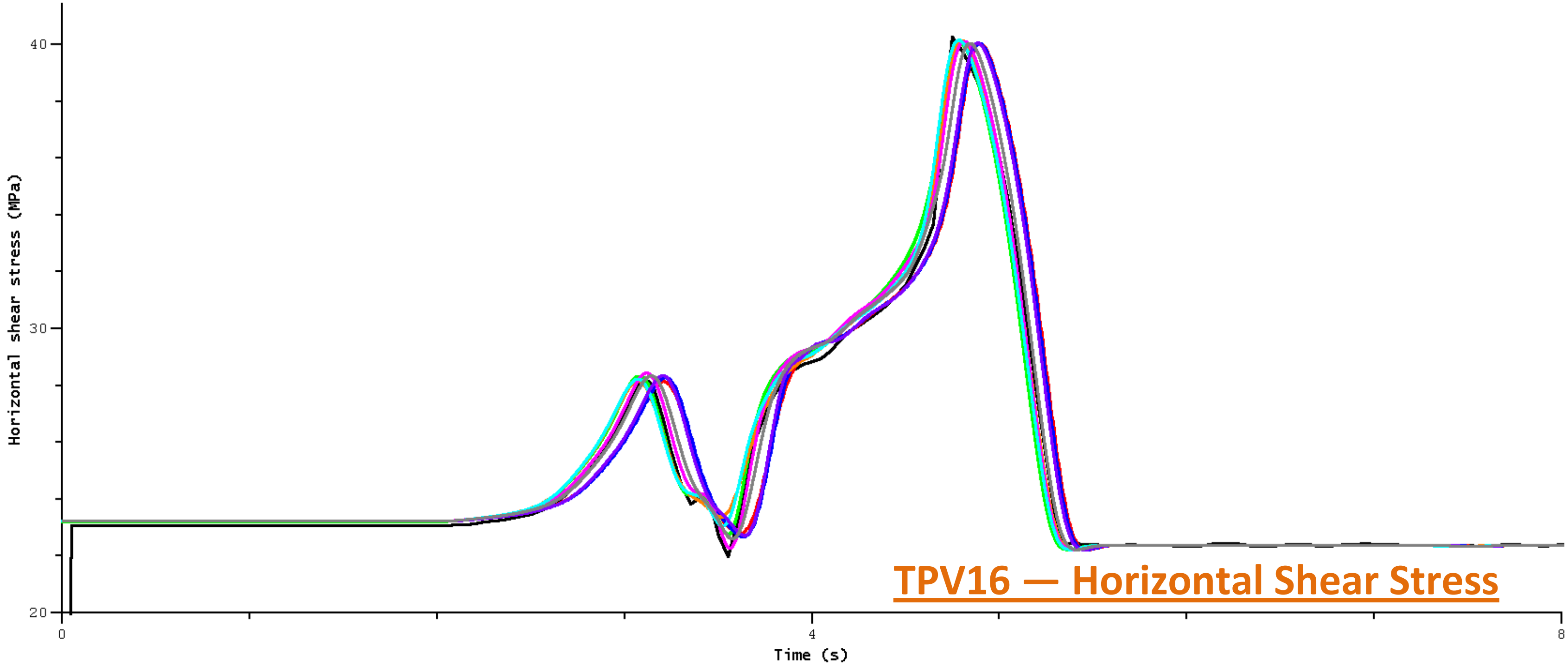
All waveforms are filtered with a 3 Hz low-pass filter.

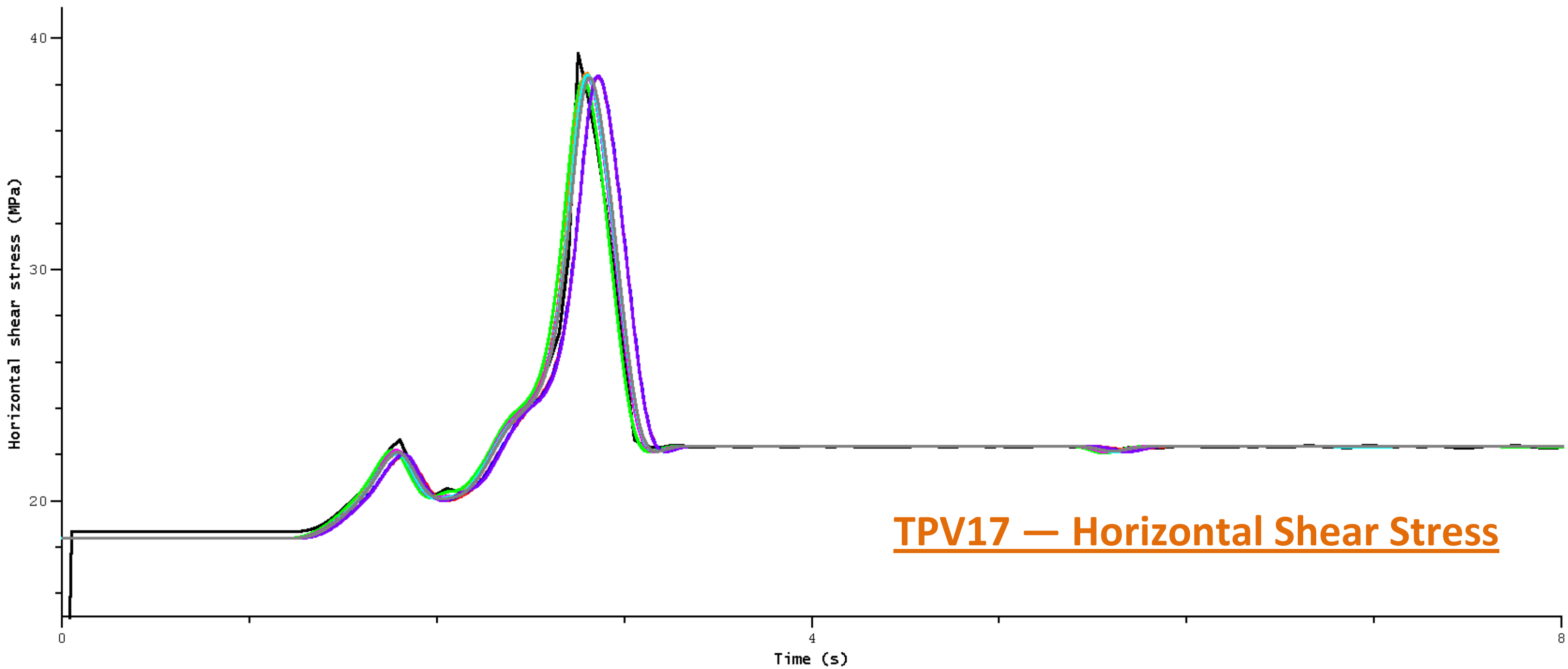

TPV16 — Horizontal Slip Rate
Horizontal slip rate (m/s)
Time (s)
1.0
0.5
0
5
10

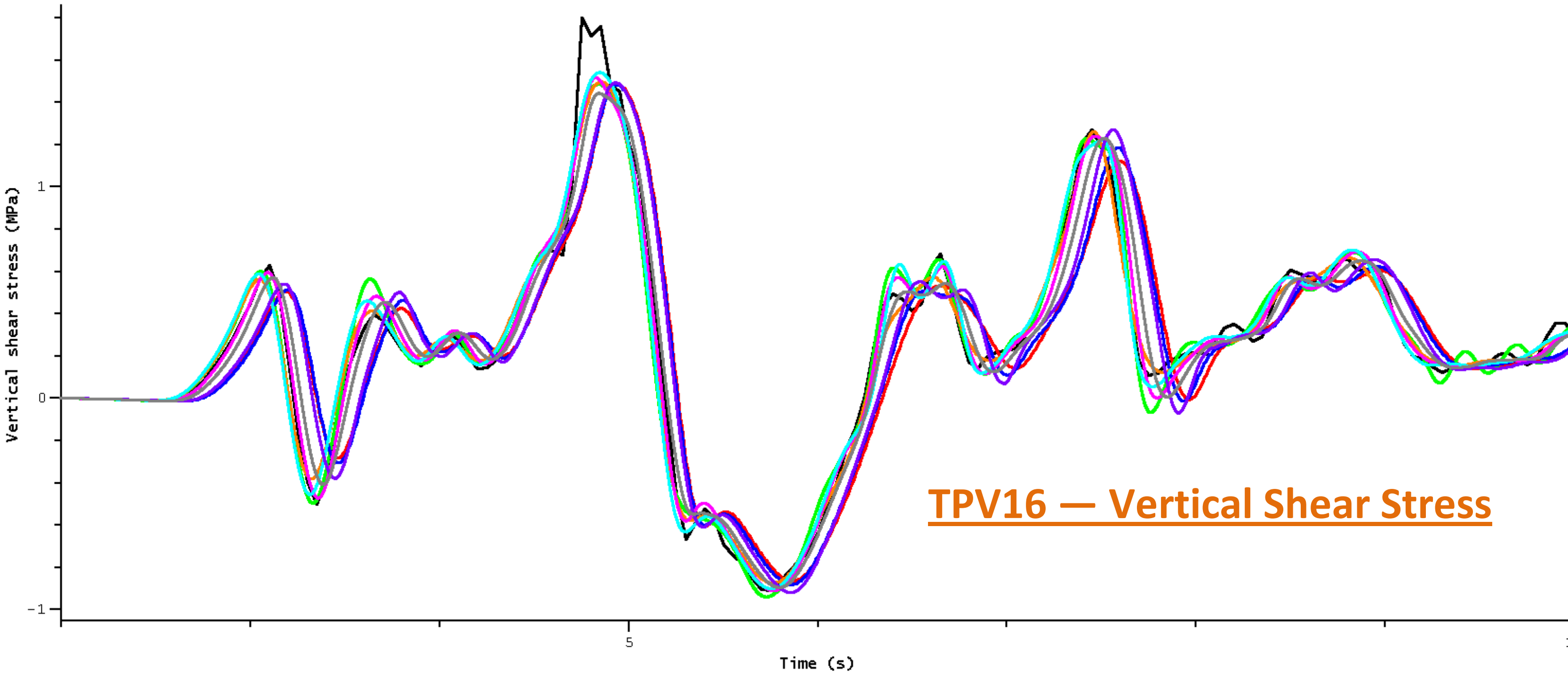

TPV17 — Horizontal Slip Rate
Horizontal slip rate (m/s)
Time (s)
2
1
0
5
10


0.04
0.02
0
-0.02
Vertical slip rate (m/s)
5
10
Time (s)
TPV16 — Vertical Slip Rate

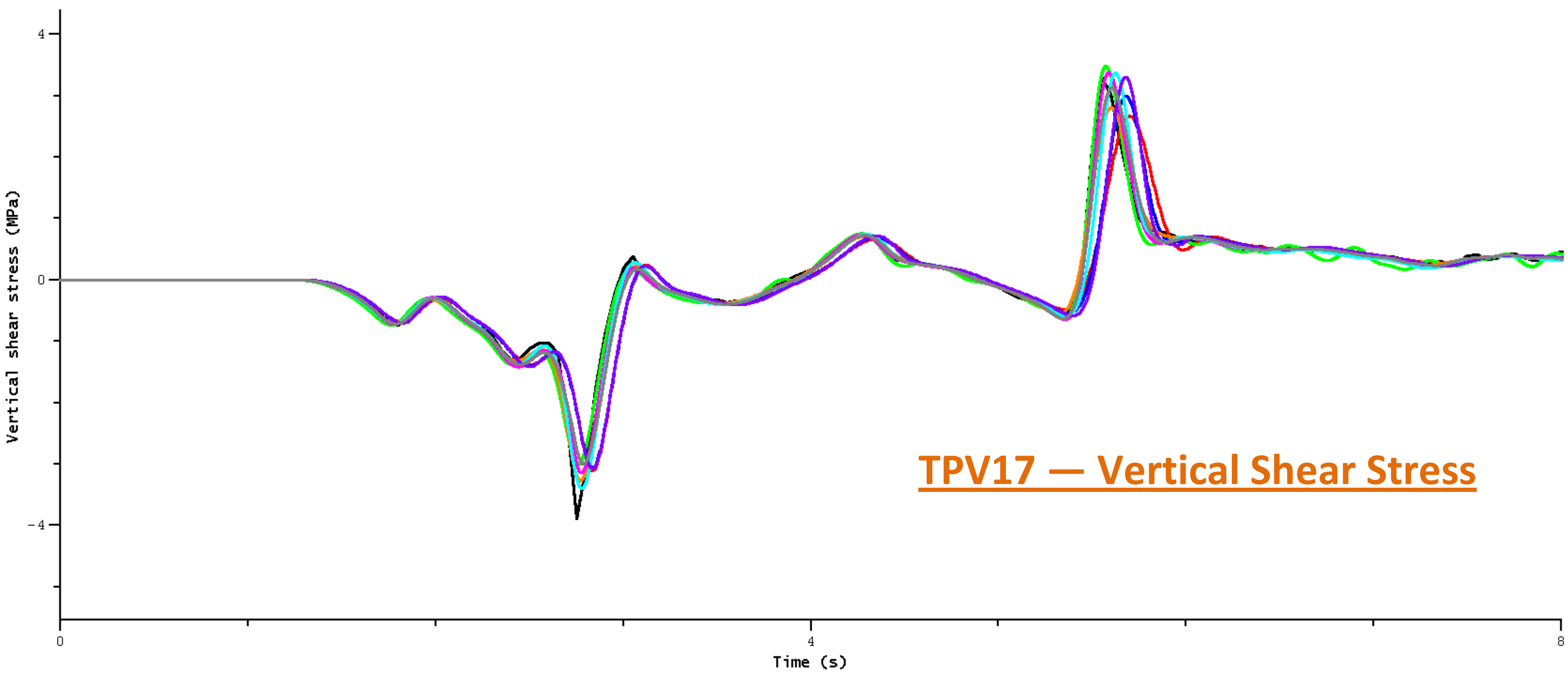

0.2
0
Vertical slip rate (m/s)
5
10
Time (s)
TPV17 — Vertical Slip Rate


TPV16 — Horizontal Shear Stress
Horizontal shear stress (MPa)
Time (s)
40
30
20
0
4
8

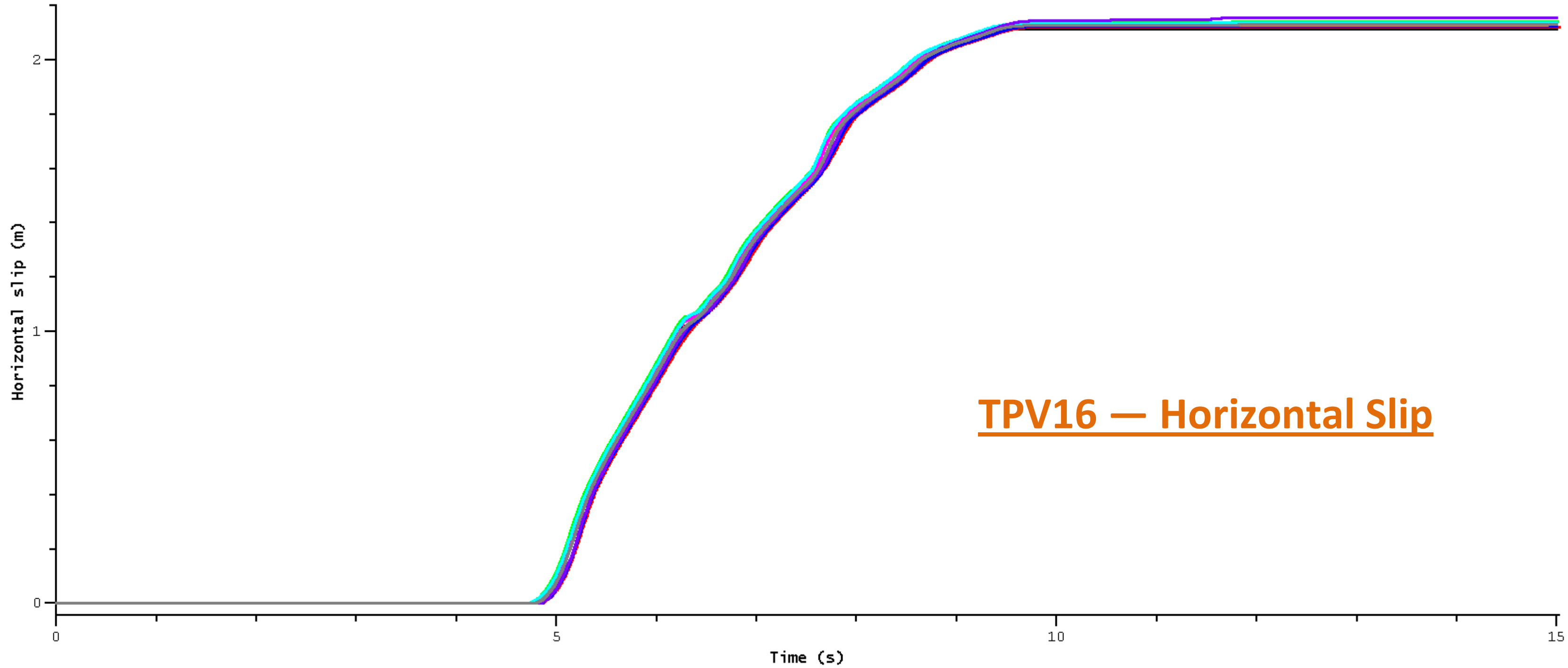

TPV17 — Horizontal Shear Stress
Horizontal shear stress (MPa)
Time (s)
40
30
20
0
4
8

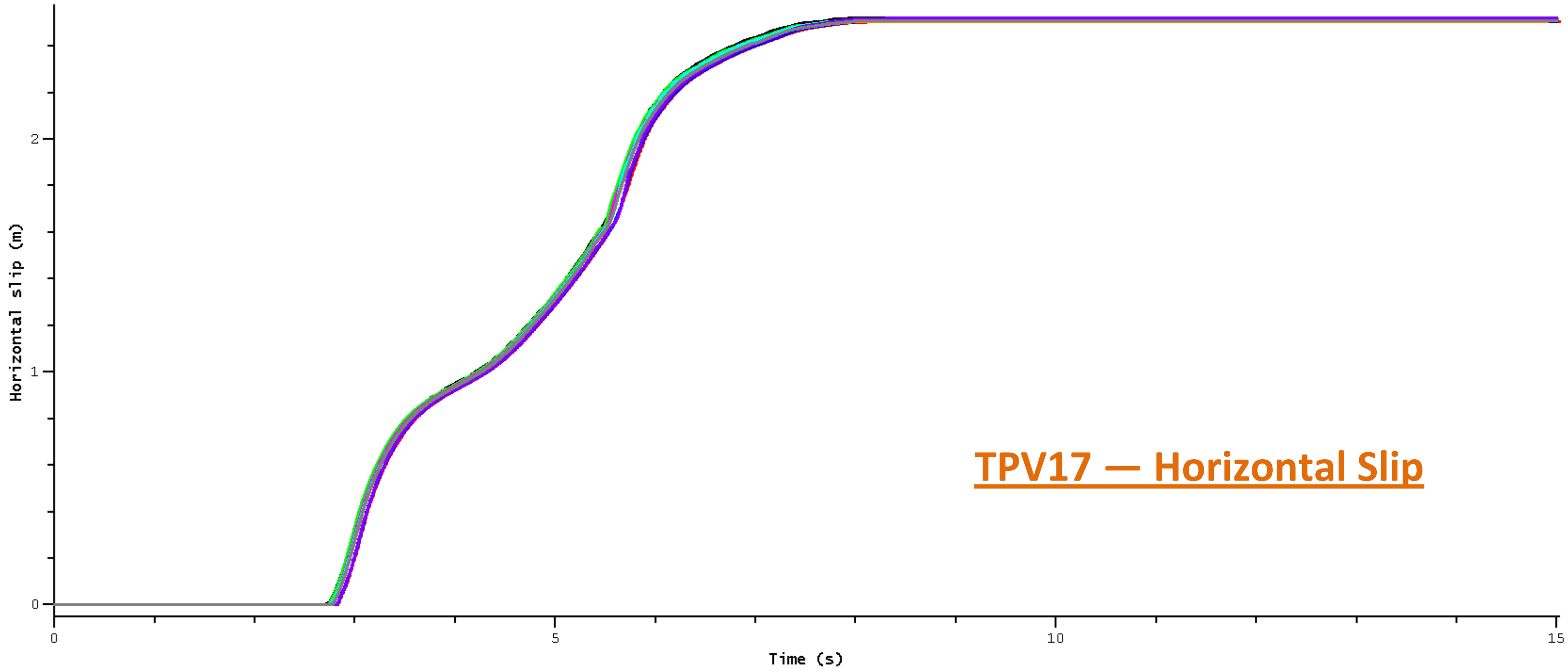


Vertical shear stress (MPa)
1
0
−1
5
10
Time (s)
TPV16 — Vertical Shear Stress

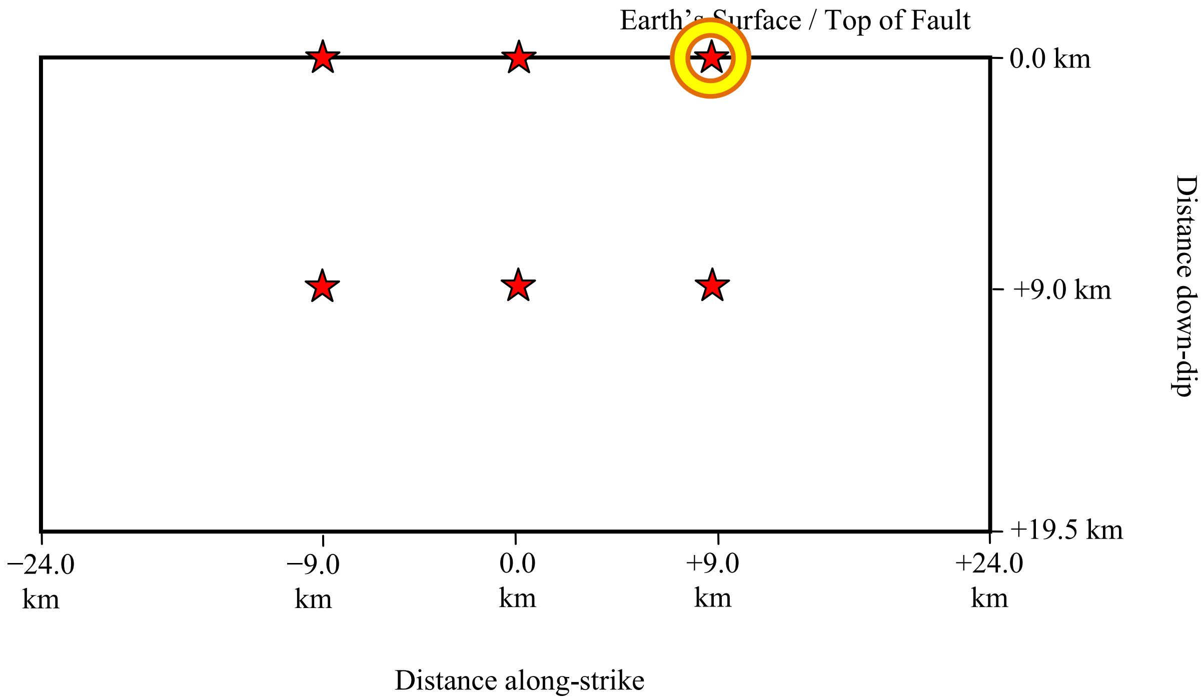


Vertical shear stress (MPa)
4
0
−4
0
4
8
Time (s)
TPV17 — Vertical Shear Stress


TPV16 — Horizontal Slip
Horizontal slip (m)
Time (s)
0
1
2
0
5
10
15

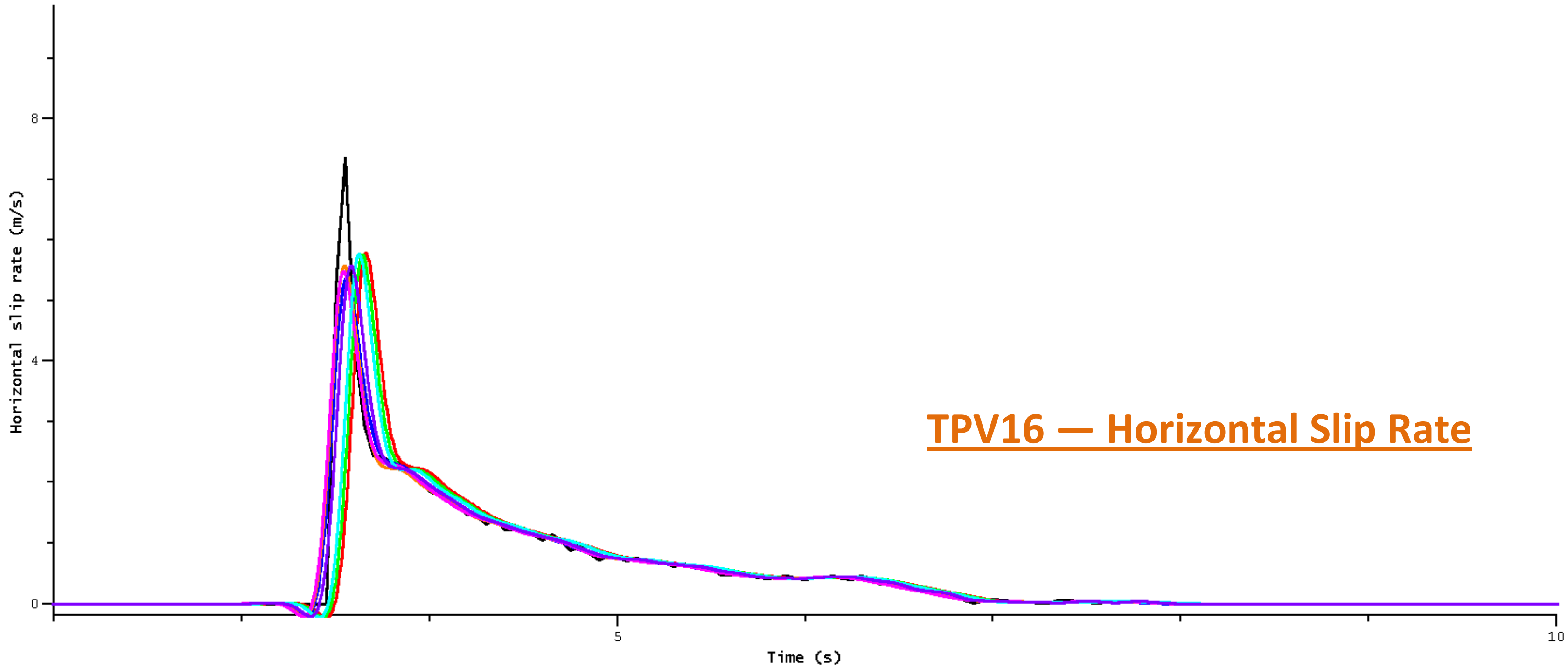

TPV17 — Horizontal Slip
Horizontal slip (m)
Time (s)
0
1
2
0
5
10
15

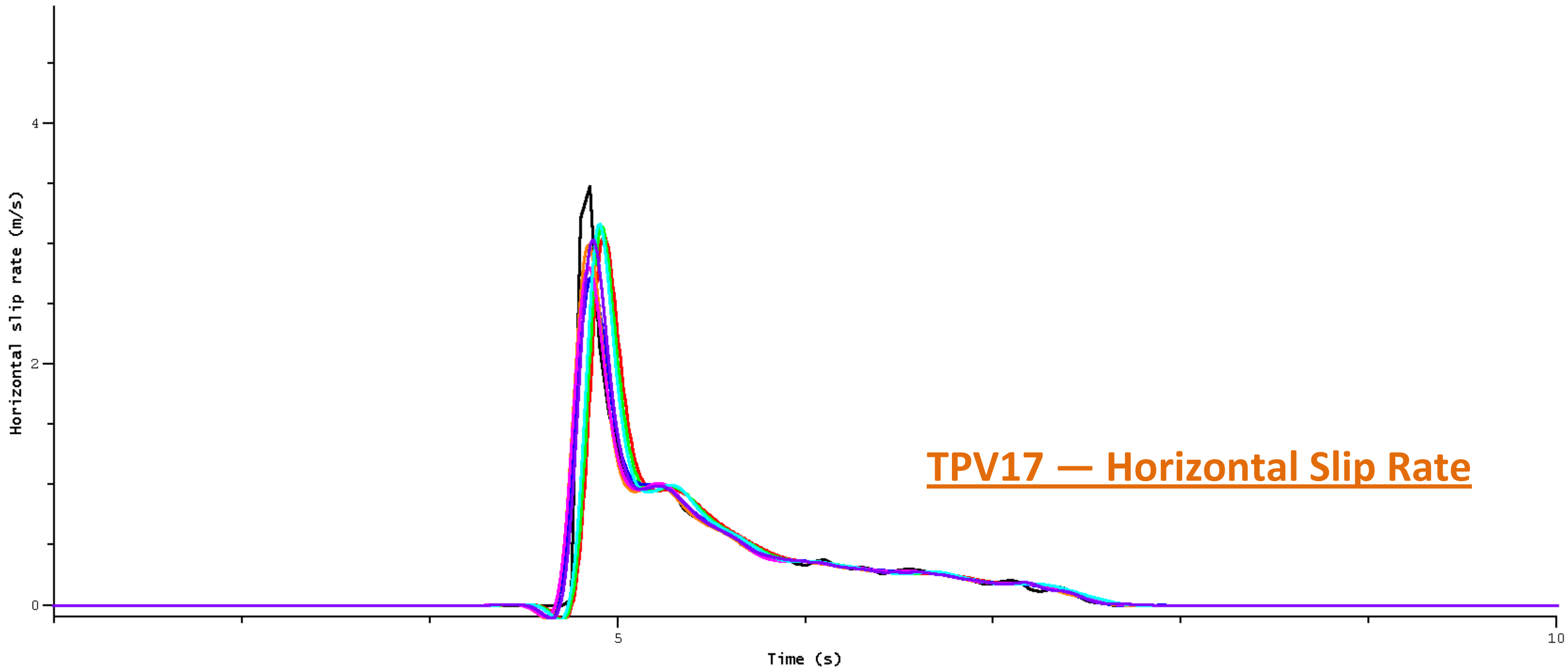
Waveform Comparison for Station On-Fault at the Earth's Surface

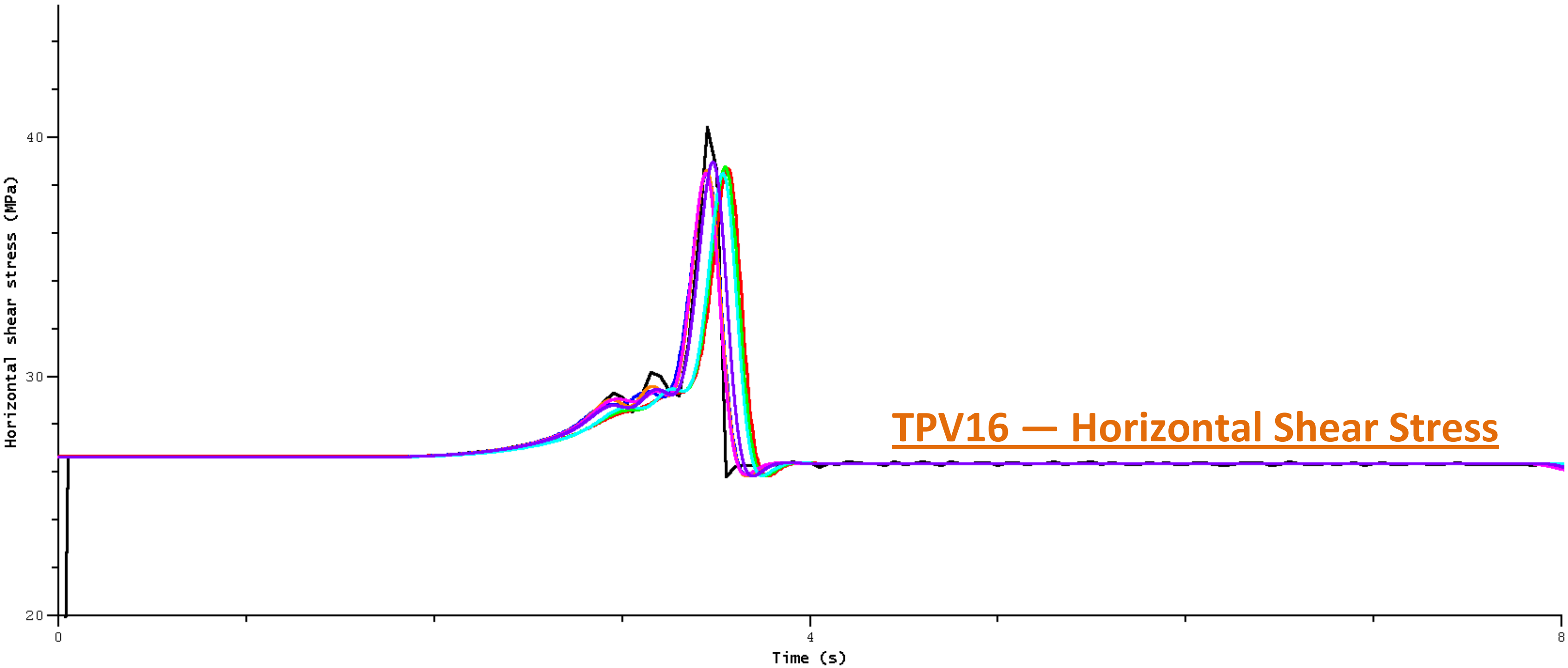


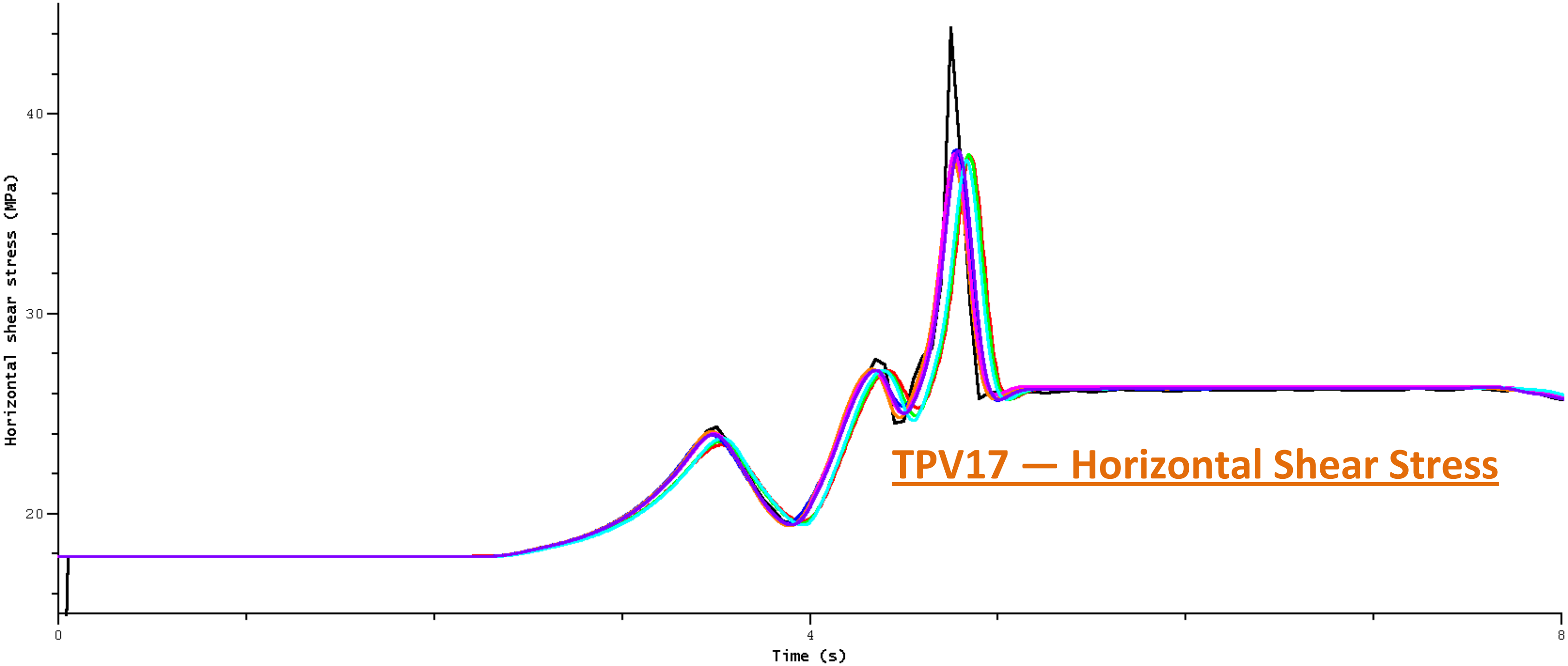
aagaard.2 (Brad Aagaard - PyLith v1.7.0a - Tet4 75m)
barall.2 (Michael Barall - Finite Element - FaultMod - Denser Mesh)
dalguer (Luis Dalguer - Finite Difference - DFM)
duan (Benchun Duan - Finite Element - EQdyna)
kaneko (Yoshihiro Kaneko - Spectral Element - SPECFEM3D)
kase (Yuko Kase - Finite Difference)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Spectral Element - SESAME)

All waveforms are filtered with a 3 Hz low-pass filter.


TPV16 — Horizontal Slip Rate
Horizontal slip rate (m/s)
Time (s)
0
4
8
5
10


TPV17 — Horizontal Slip Rate
Horizontal slip rate (m/s)
Time (s)
0
2
4
5
10


TPV16 — Horizontal Shear Stress
Horizontal shear stress (MPa)
40
30
20
0
4
8
Time (s)


TPV17 — Horizontal Shear Stress
Horizontal shear stress (MPa)
40
30
20
0
4
8
Time (s)

Conclusion

Conclusion

TPV16-17 are designed to be like “TPV5 with random initial stress.”

The codes agree well in contour plots, waveforms, timing, and amplitudes.

The contours show the rupture responding to the random initial stress field.

Thank You