Imperial Fault, Model 1
TPV34

Michael Barall
Invisible Software, Inc.

SCEC Rupture Dynamics Code Verification Workshop

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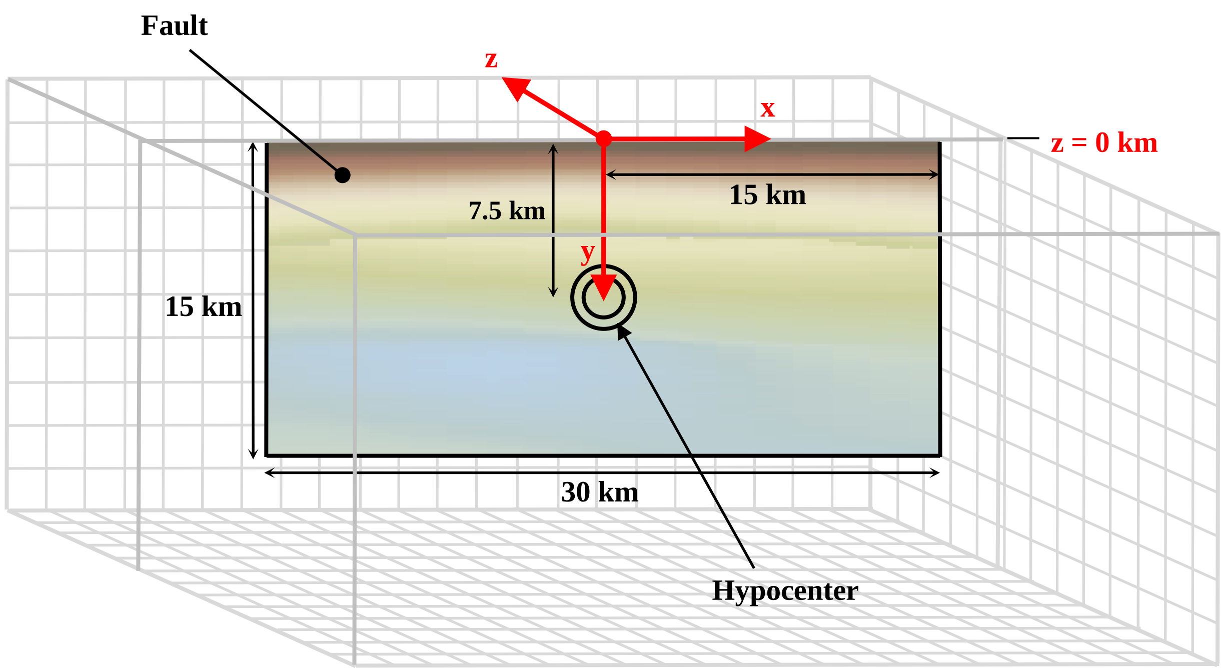
TPV34 Design

TPV34 — Imperial Fault, Model 1



Right-lateral strike-slip fault in an elastic half-space with a 3D velocity structure.

The Imperial Fault

TPV34 is our first benchmark that models a specific fault set in its actual 3D velocity structure.

The Imperial Fault straddles the California-Mexico border, south of the Salton Sea. It is about 45 km long and 15 km deep, with a dip angle varying from 81 to 90 degrees.

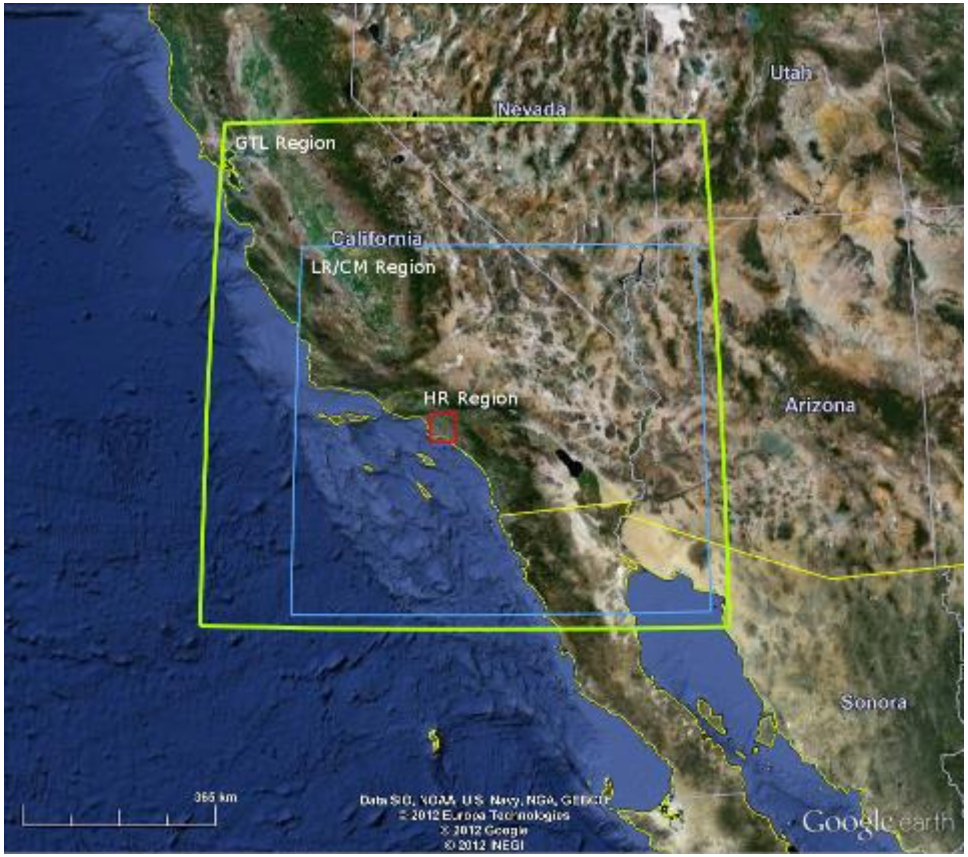
For TPV34, we approximate the fault with a vertical plane 30 km long and 15 km deep.

TPV35 and TPV36 will use a better approximation of the fault geometry.

SCEC Community Velocity Model CVM-H

CVM-H is a velocity model for southern California. It is comprised of five models:

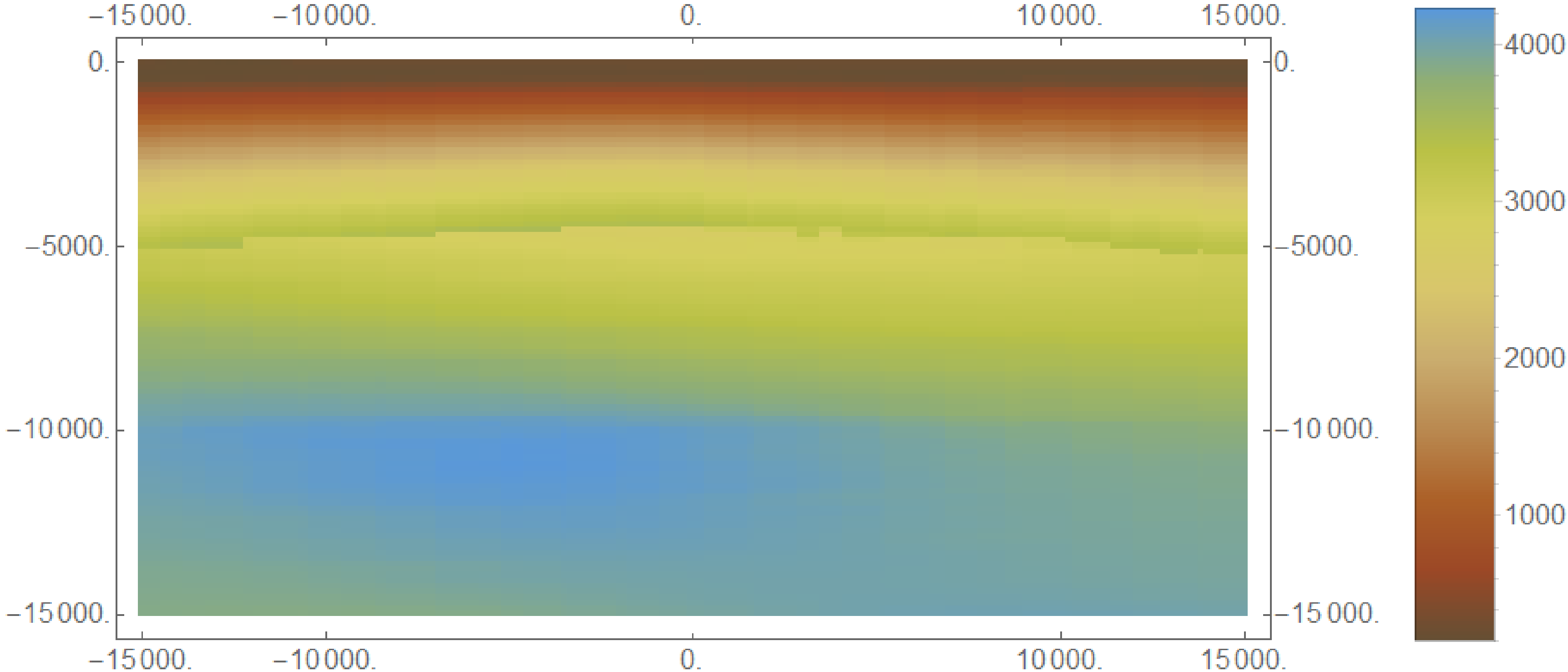
- LR = Low-resolution
  (1 km × 100 m resolution)
- CM = Lower crust/mantle
  (10 km × 1 km resolution)
- HR = High-resolution
  (250 m × 100 m resolution)
- GTL = Geotechnical layer
  (250 m resolution)
- 1D = 1D background



CVM-H applies smoothing at the transitions between different models, and uses the 1D model outside and below the region covered by the other models.

CVM-H gives the value of V_P at each point in the model domain. The values of V_S and ρ are computed from V_P using empirical mathematical formulas (can be different for each model).

SCEC Community Velocity Model CVM-H
Values of V_S on the Fault Surface

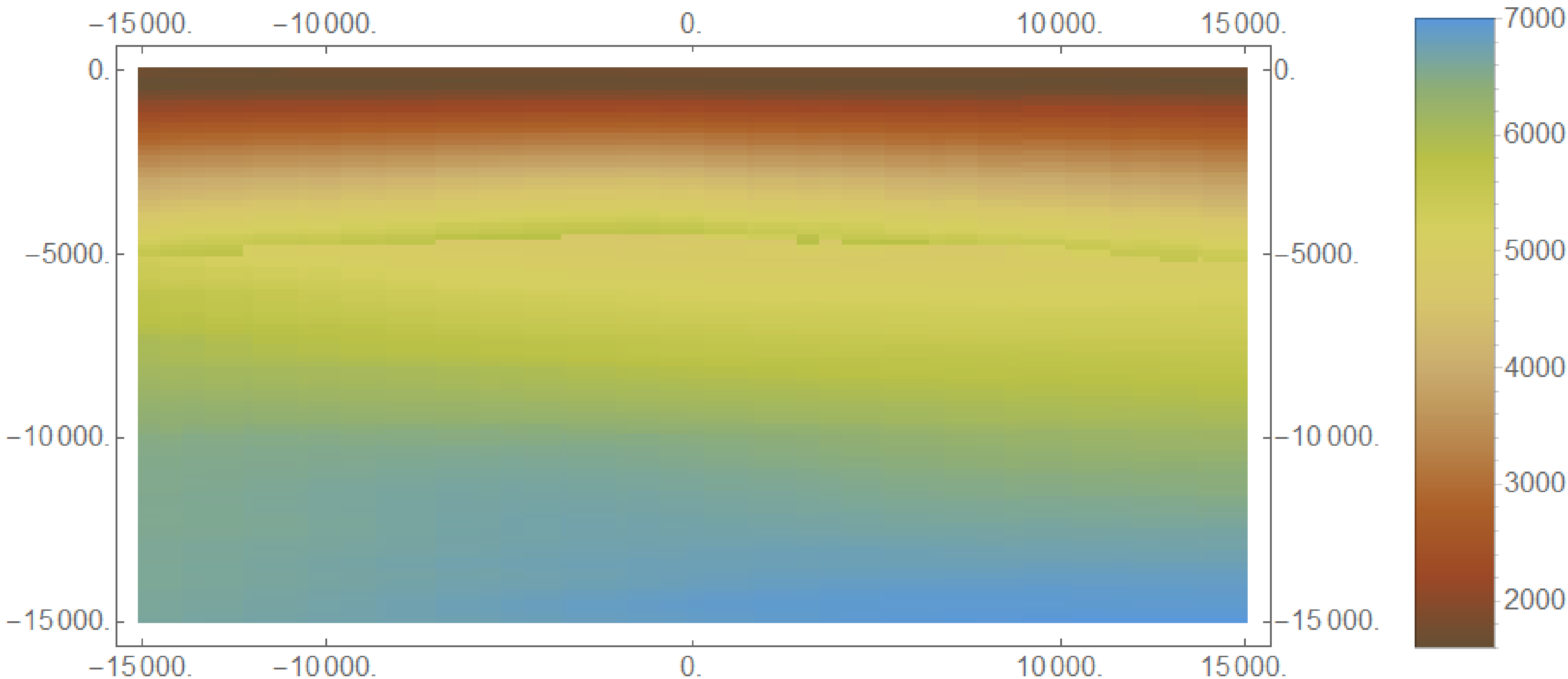


In CVM-H, the minimum V_S on the fault surface is 199 m/s.

We alter the velocity model, to impose a minimum V_S of 1400 m/s.

(If either V_S or V_P is too low, then V_S, V_P, and ρ are all set to their minimum values.)

SCEC Community Velocity Model CVM-H
Values of V_P on the Fault Surface

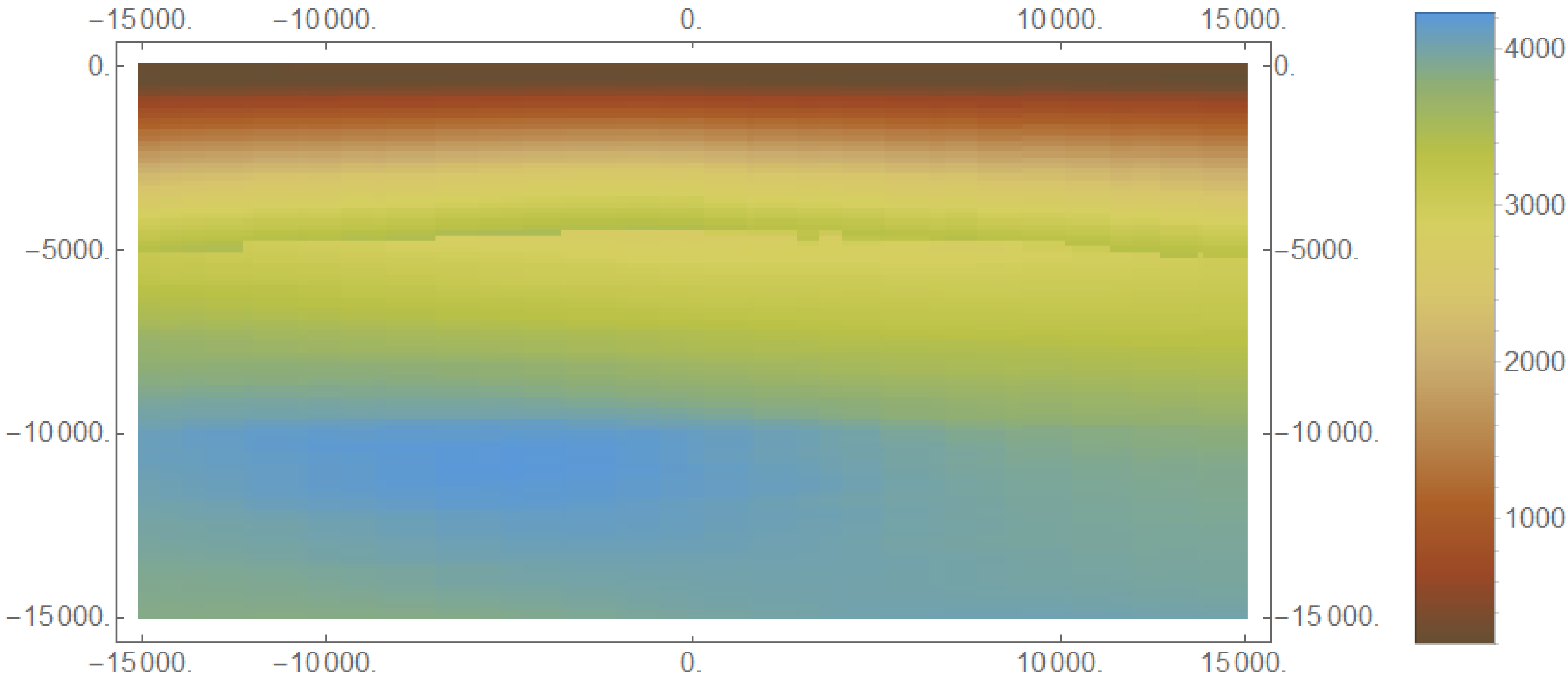


In CVM-H, the minimum V_P on the fault surface is 1590 m/s.

We alter the velocity model, to impose a minimum V_P of 2984 m/s.

(If either V_S or V_P is too low, then V_S, V_P, and ρ are all set to their minimum values.)

SCEC Community Velocity Model CVM-H
Values of ρ on the Fault Surface



In CVM-H, the minimum ρ on the fault surface is 1702 kg/m^3.

We alter the velocity model, to impose a minimum ρ of 2220.34 kg/m^3.

(If either V_S or V_P is too low, then V_S, V_P, and ρ are all set to their minimum values.)

Initial Stress on the Fault – "Constant Strain"

(TPV34 uses the same initial stress as TPV31-32.)

The initial stress is defined to be "**constant strain**", which is proportional to the shear modulus:

Initial normal stress $\sigma_0 = (60\ \mathrm{MPa})(\mu/\mu_0)$

Initial shear stress $\sigma_{13} = (30\ \mathrm{MPa})(\mu/\mu_0)$

Stress proportional to shear modulus μ.

In the above formulas:

μ = shear modulus

μ_0 = TPV5 shear modulus = 32.03812032 GPa

Parameters for Slip-Weakening Friction

(TPV34 uses the same friction parameters as TPV31-32.)

Friction parameters:

Static coefficient of friction $\mu_s = 0.580$

Dynamic coefficient of friction $\mu_d = 0.450$

Slip-weakening critical distance $d_0 = 0.18\ \text{m}$

Cohesion $C_0 = \begin{cases} (0.000425\ \text{MPa/m})(2400\ \text{m} - \text{depth}), & \text{if depth} \leq 2400\ \text{m} \\ 0\ \text{MPa}, & \text{if depth} \geq 2400\ \text{m} \end{cases}$

Cohesion = 1.02 MPa at the earth's surface.

Frictional cohesion C_0 is 1.02 MPa at the earth's surface, tapering to 0 at a depth of 2400 m.

Slip-weakening friction law:

Shear stress $\tau = C_0 + \mu \max(0,\ \sigma_n)$

Coefficient of friction $\mu = \mu_s + (\mu_d - \mu_s) \min(D/d_0, 1)$

D = total slip since the beginning of the simulation

σ_n = normal stress.

Linear slip-weakening.
Starts weakening at slip $D = 0$.
Stops weakening at slip $D = d_0$.

Nucleation — Overstress Method

(TPV34 uses the same nucleation parameters as TPV31-32.)

- The nucleation zone is a circle of radius 2000 m, centered at the hypocenter.
- Within the nucleation zone, we impose an additional initial shear stress.
- Within 1400 m of the hypocenter, the initial shear stress is raised to just above the yield stress.
- Between 1400 m and 2000 m from the hypocenter, there is a cosine taper so that the initial stress is smooth (has a continuous first derivative).

Stress proportional to shear modulus μ.

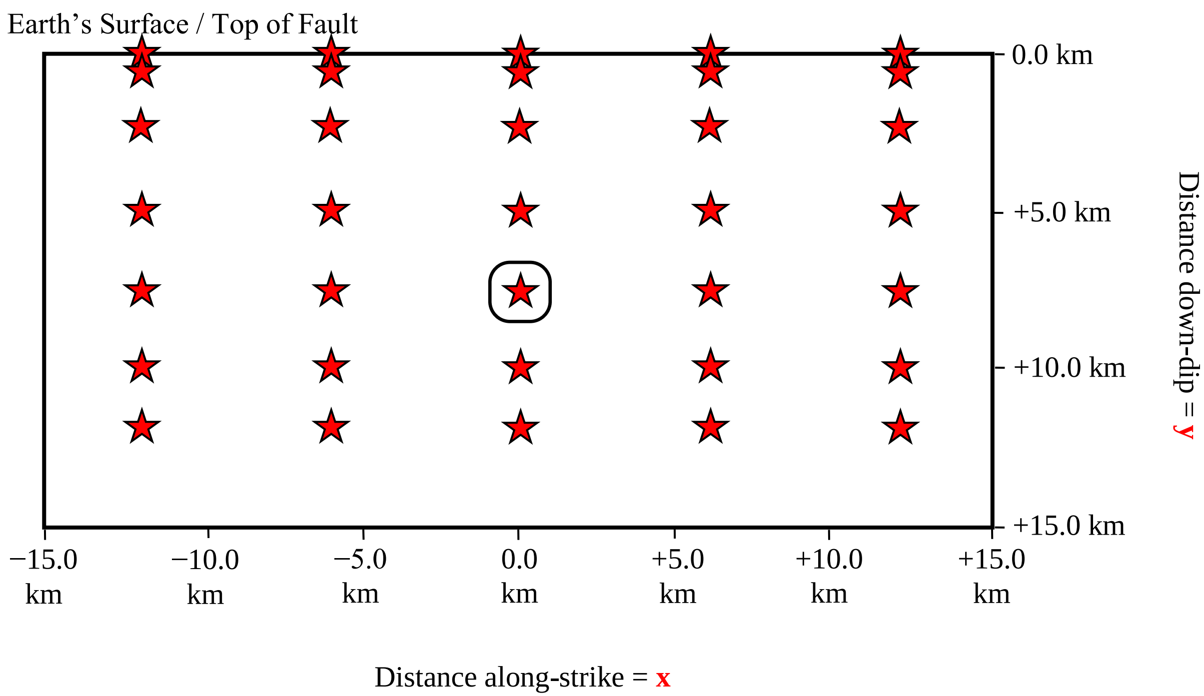
The additional shear stress for nucleation is:

$$\tau_{\text{nuke}}(x,y) = \begin{cases} (4.95\ \text{MPa})(\mu/\mu_0), & \text{if } r \le 1400\ \text{m} \\ (2.475\ \text{MPa})\big(1+\cos\big(\pi(r-1400\ \text{m})/(600\ \text{m})\big)\big)(\mu/\mu_0), & \text{if } 1400\ \text{m} \le r \le 2000\ \text{m} \\ 0, & \text{otherwise} \end{cases}$$

Where r is distance to the hypocenter:

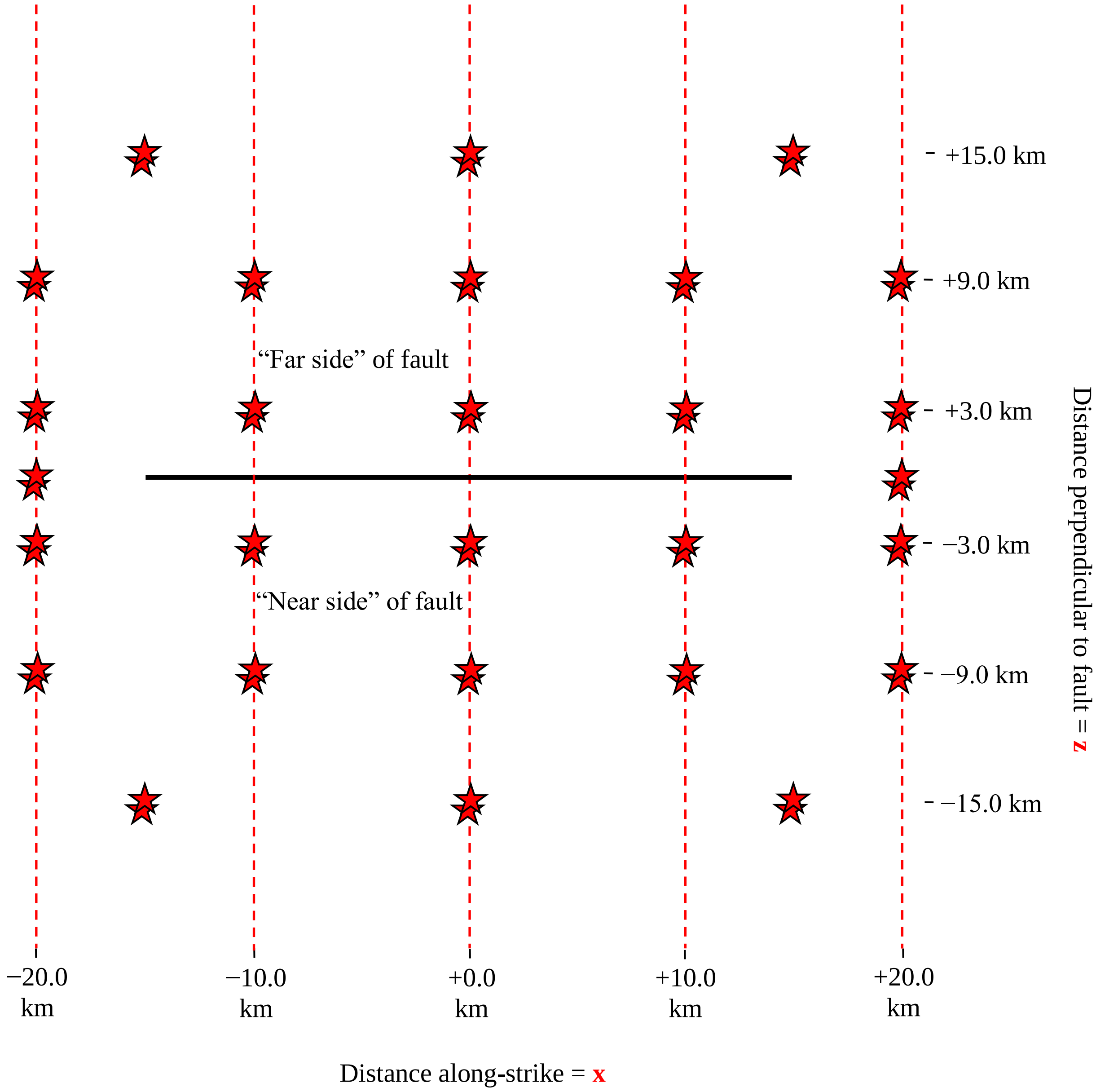
$$r = \sqrt{x^2 + (y - 7500\ \text{m})^2}$$

On-Fault Stations.



Modelers are asked to submit slip, slip rate, and stress as a function of time, for 35 stations on the fault.

In addition, modelers are asked to submit the time at which each point on the fault begins to slip (defined as the time when the slip rate first exceeds 1 mm/s), from which we construct rupture contour plots.



Off-Fault Stations.

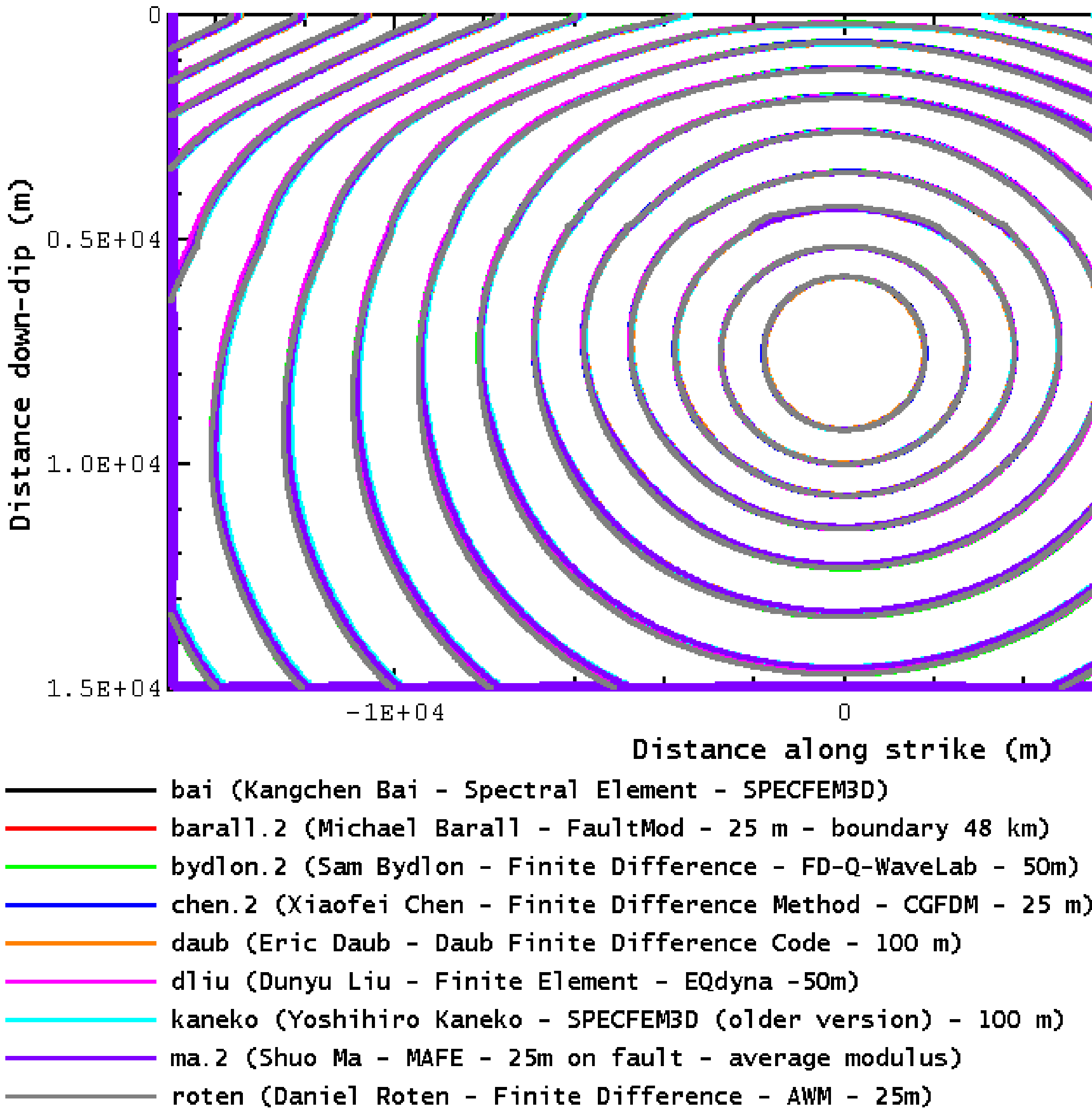
Modelers are asked to submit displacement and velocity as a function of time, for 56 stations.

Stations are organized into 28 "boreholes" with stations at depths of 0 km and 2.4 km.

Stations are placed all around the fault, as we will need to do in our validation exercises.

TPV34 Rupture Contours

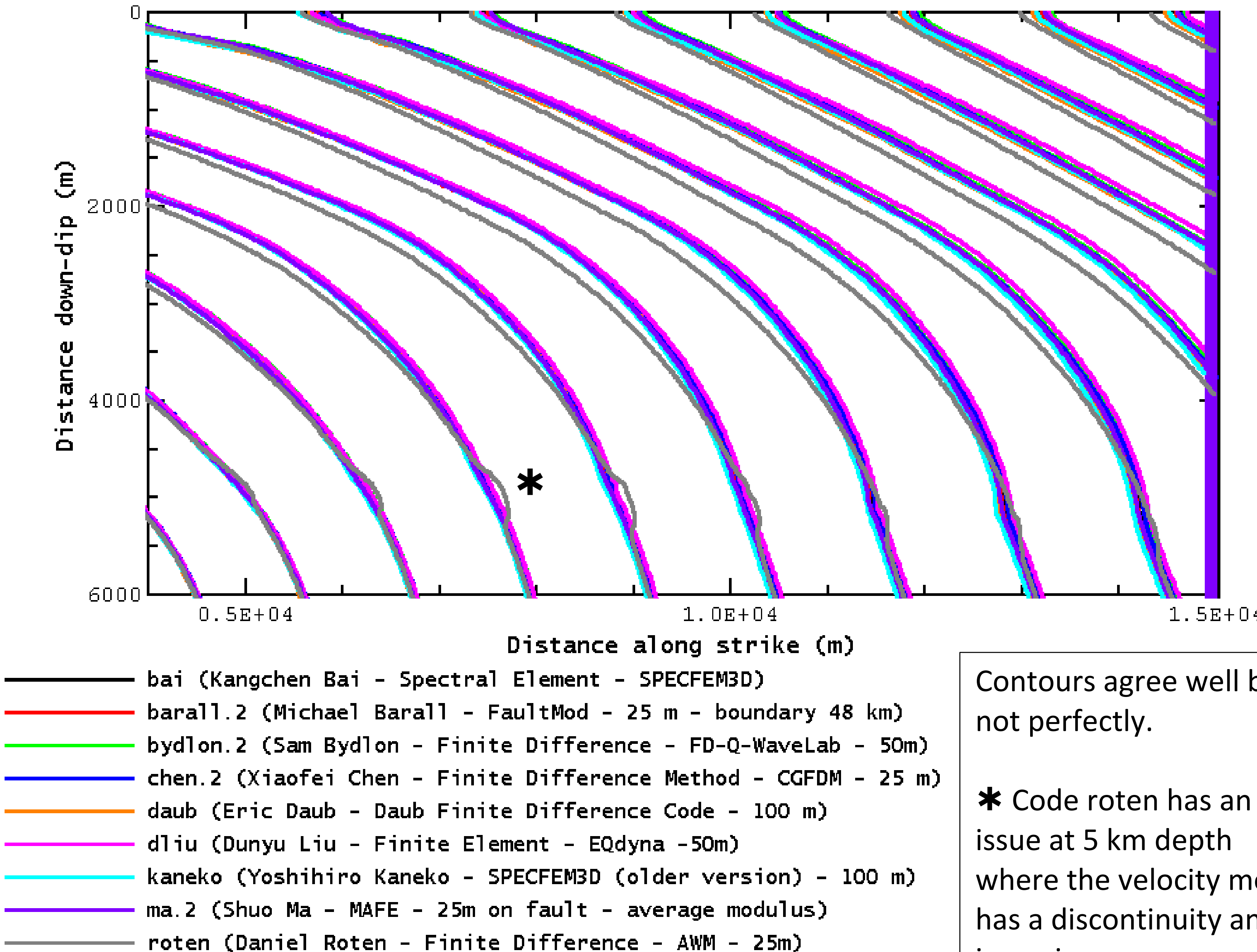
TPV34 Rupture Contours — Highest Resolution from Each of 9 Modelers



Contours agree well but not perfectly.

Note issue at 5 km depth where the velocity model has a discontinuity.

TPV34 Rupture Contours — Enlarged View



Contours agree well but not perfectly.

* Code roten has an issue at 5 km depth where the velocity model has a discontinuity and inversion.

TPV34 Rupture Contours — Metrics (RMS Difference in Rupture Time, Milliseconds)

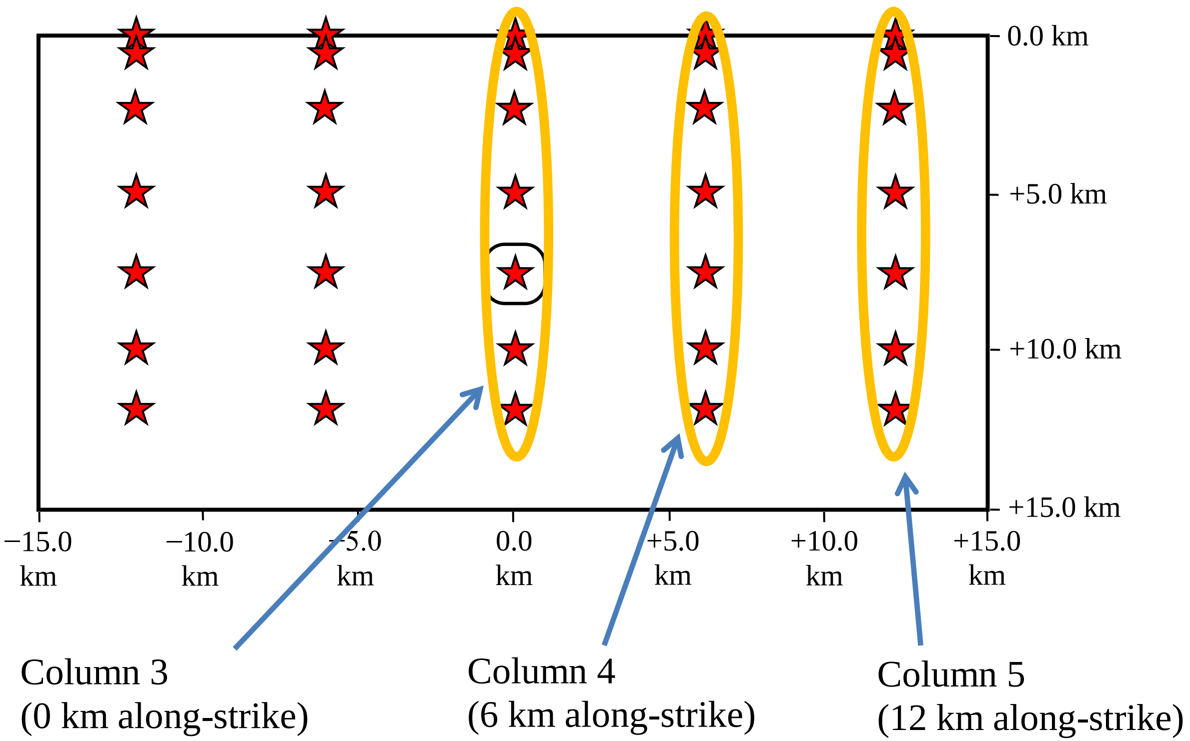
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) bai		5.8	16.7	11.8	21.0	19.8	24.6	15.9	35.8
(2) barall.2	5.8		19.8	13.9	18.0	23.6	22.2	14.0	34.1
(3) bydlon.2	16.7	19.8		7.5	36.6	12.2	40.9	31.4	39.2
(4) chen.2	11.8	13.9	7.5		31.1	15.4	35.3	25.9	36.1
(5) daub	21.0	18.0	36.6	31.1		38.2	8.2	11.4	41.3
(6) dliu	19.8	23.6	12.2	15.4	38.2		42.3	32.5	44.6
(7) kaneko	24.6	22.2	40.9	35.3	8.2	42.3		13.4	44.0
(8) ma.2	15.9	14.0	31.4	25.9	11.4	32.5	13.4		40.9
(9) roten	35.8	34.1	39.2	36.1	41.3	44.6	44.0	40.9	

These are good numbers.

But the values are about twice as large as we saw in TPV31-32.

Process Zone Width

Process Zone Width for TPV34



The metrics can calculate process zone width at the locations of on-fault stations.

We have 35 stations, organized in 5 columns of 7 stations each, so we can check how process zone width varies with depth, and along-strike.

Each slide will show process zone widths for a single column. Columns 1 and 2 (on the left) have similar values to columns 4 and 5, so we won't show them.

TPV34 (Min V_S = 1400) Process Zone Width – Column 3 (at 0 km Along-Strike)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst000dp000	266	250	285	250	203	222	249	286	245
faultst000dp010	239	233	240	237	197	229	221	234	227
faultst000dp024	227	222	226	223	219	227	227	227	182
faultst000dp050	386	382	376	382	370	393	374	389	457
faultst000dp075	---	---	---	---	---	---	---	---	---
faultst000dp100	502	507	503	508	492	512	511	519	488
faultst000dp120	424	422	424	424	411	429	430	427	409

(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D
(2) barall.2	Michael Barall - FaultMod - 25 m - boundary 48 km
(3) bydlon.2	Sam Bydlon - Finite Difference - FD-Q-WaveLab - 50m
(4) chen.2	Xiaofei Chen - Finite Difference Method - CGFDM - 25 m
(5) daub	Eric Daub - Daub Finite Difference Code
(6) dliu	Dunyu Liu - Finite Element - EQdyna -50m
(7) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 100 m
(8) ma.2	Shuo Ma - MAFE - 25m on fault - average modulus
(9) roten	Daniel Roten - Finite Difference - AWM - 25m

Good agreement between codes, as shown by horizontal bands of color. (The roten code is a bit of an outlier.)

TPV34 (Min V_S = 1400) Process Zone Width – Column 4 (at 6 km Along-Strike)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst060dp000	253	257	246	248	295	238	267	283	227
faultst060dp010	222	212	222	214	192	247	219	212	194
faultst060dp024	202	200	197	201	213	223	209	203	144
faultst060dp050	455	455	451	459	442	476	455	470	606
faultst060dp075	493	494	490	498	483	504	492	507	500
faultst060dp100	459	457	457	462	446	473	458	465	480
faultst060dp120	419	415	413	420	402	430	417	421	418

(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D
(2) barall.2	Michael Barall - FaultMod - 25 m - boundary 48 km
(3) bydlon.2	Sam Bydlon - Finite Difference - FD-Q-WaveLab - 50m
(4) chen.2	Xiaofei Chen - Finite Difference Method - CGFDM - 25 m
(5) daub	Eric Daub - Daub Finite Difference Code
(6) dliu	Dunyu Liu - Finite Element - EQdyna -50m
(7) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 100 m
(8) ma.2	Shuo Ma - MAFE - 25m on fault - average modulus
(9) roten	Daniel Roten - Finite Difference - AWM - 25m

Good agreement between codes, as shown by horizontal bands of color.

Only a slight change in values from column 3.

TPV34 (Min V_S = 1400) Process Zone Width – Column 5 (at 12 km Along-Strike)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst120dp000	155	137	157	148	155	155	165	135	134
faultst120dp010	188	167	177	172	176	230	189	170	164
faultst120dp024	155	151	143	150	170	191	166	151	110
faultst120dp050	287	289	279	296	283	322	302	287	291
faultst120dp075	299	301	287	303	295	333	320	301	320
faultst120dp100	317	319	308	322	311	350	338	319	351
faultst120dp120	316	317	309	321	309	352	333	316	329

(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D
(2) barall.2	Michael Barall - FaultMod - 25 m - boundary 48 km
(3) bydlon.2	Sam Bydlon - Finite Difference - FD-Q-WaveLab - 50m
(4) chen.2	Xiaofei Chen - Finite Difference Method - CGFDM - 25 m
(5) daub	Eric Daub - Daub Finite Difference Code
(6) dliu	Dunyu Liu - Finite Element - EQdyna -50m
(7) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 100 m
(8) ma.2	Shuo Ma - MAFE - 25m on fault - average modulus
(9) roten	Daniel Roten - Finite Difference - AWM - 25m

There is still good agreement between codes, as shown by horizontal bands of color.

Values have dropped significantly.

TPV32 had much lower values (60 m) at the earth's surface.

TPV34 Results — On-Fault Stations

TPV34 (Min V_S = 1400) – Summary Metrics for All On-Fault Stations

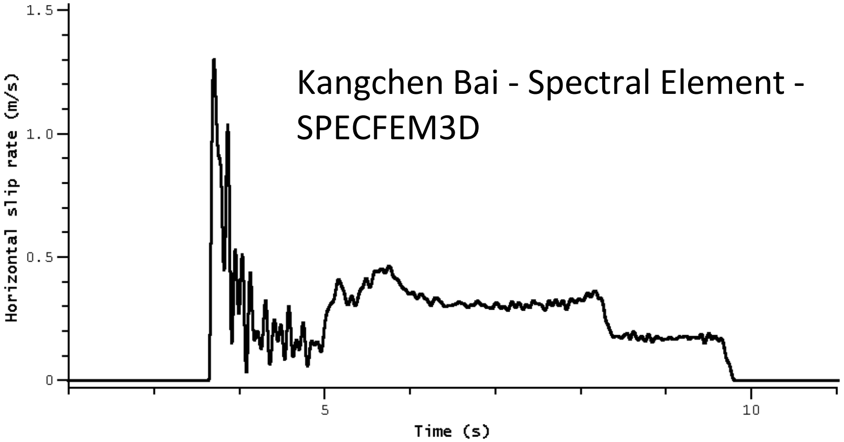
	2d-stress	2d-rate
faultst000dp000	10.2	6.0
faultst000dp010	12.2	12.4
faultst000dp024	7.7	7.2
faultst000dp050	8.5	5.8
faultst000dp075	7.4	3.2
faultst000dp100	5.1	3.7
faultst000dp120	3.5	3.6

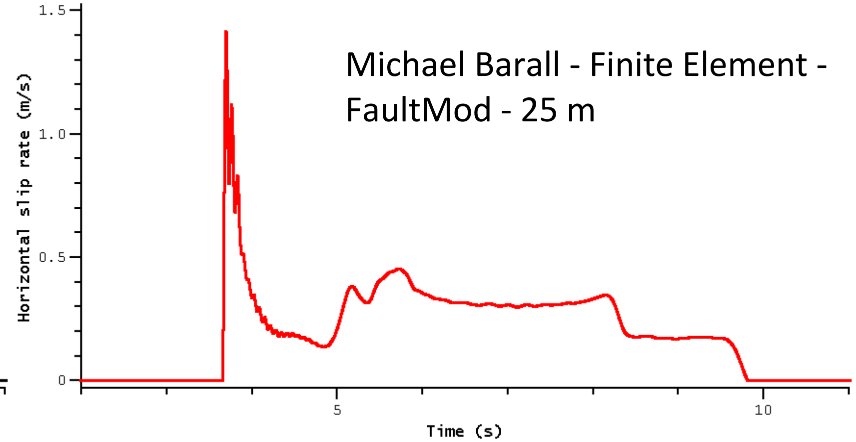
	2d-stress	2d-rate
faultst-060dp000	15.2	4.7
faultst-060dp010	13.9	10.7
faultst-060dp024	6.5	6.4
faultst-060dp050	6.0	4.7
faultst-060dp075	5.3	4.0
faultst-060dp100	4.0	3.3
faultst-060dp120	3.6	3.8
faultst060dp000	17.9	5.5
faultst060dp010	18.5	10.5
faultst060dp024	7.8	7.8
faultst060dp050	8.2	5.6
faultst060dp075	5.4	4.0
faultst060dp100	4.1	3.3
faultst060dp120	3.5	3.2

	2d-stress	2d-rate
faultst-120dp000	19.0	11.3
faultst-120dp010	11.4	12.7
faultst-120dp024	7.7	8.1
faultst-120dp050	6.9	6.5
faultst-120dp075	4.3	5.1
faultst-120dp100	4.4	4.6
faultst-120dp120	4.1	4.9
faultst120dp000	21.4	11.3
faultst120dp010	12.9	12.6
faultst120dp024	9.2	10.1
faultst120dp050	5.3	5.2
faultst120dp075	5.0	4.9
faultst120dp100	4.5	4.5
faultst120dp120	3.8	4.3

These are the waveform comparison metrics, averaged over all pairs of codes, using the best version from each of 9 codes. Agreement is good, with most values under 10%. In the 2d-rate column, the highest numbers are 1 km below the earth's surface.

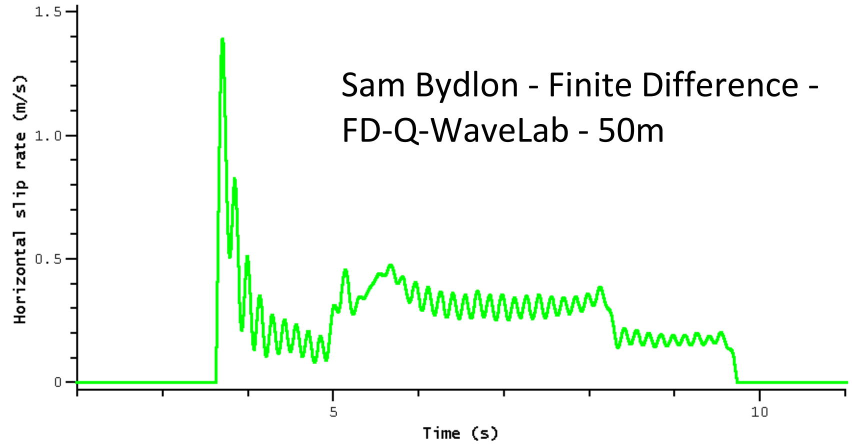
Oscillation Comparison – TPV34 Station faultst000dp010 (Slide 1 of 2)

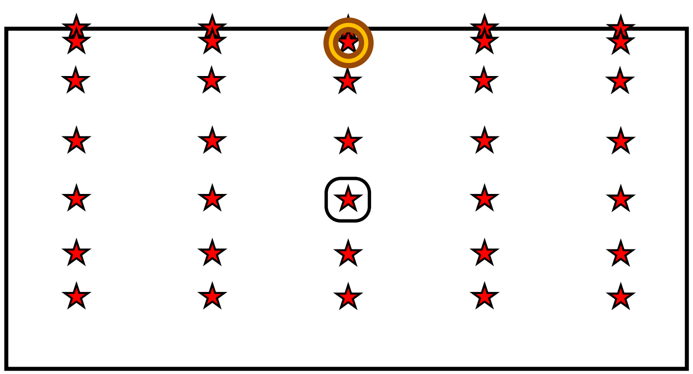


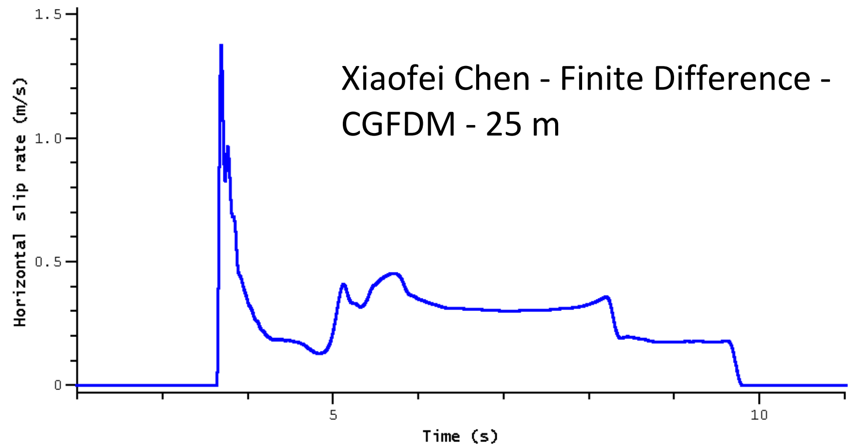


These unfiltered plots of slip rate 1 km below the epicenter show the sorts of oscillations produced by the different codes.

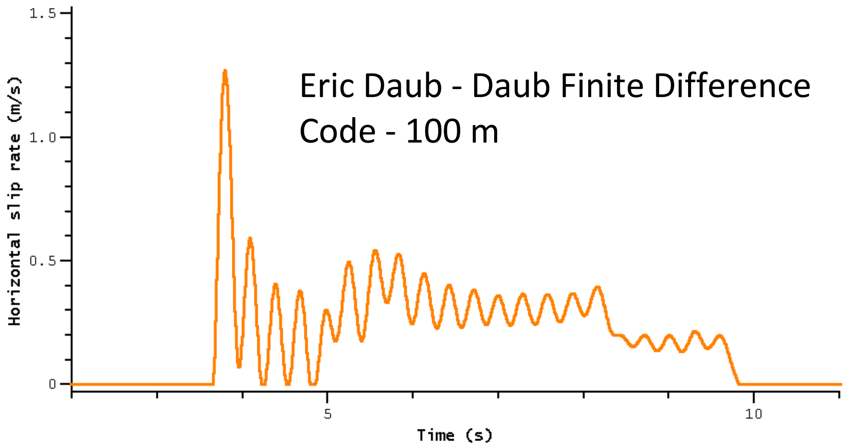
Mode III propagation through low-velocity material seems prone to producing oscillations.

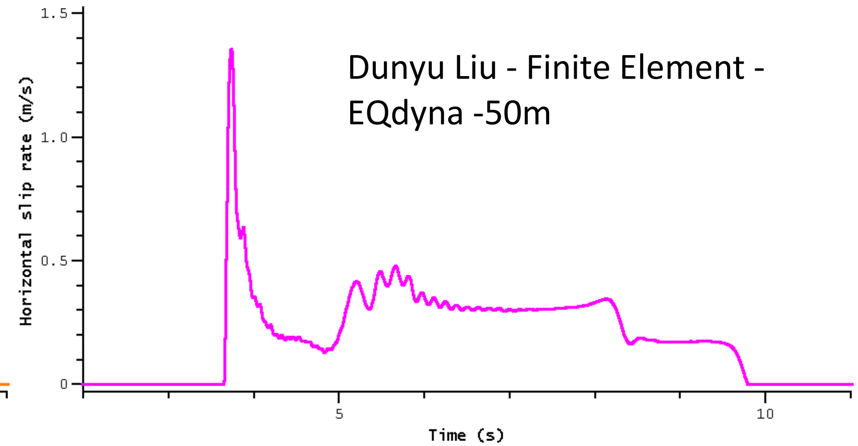


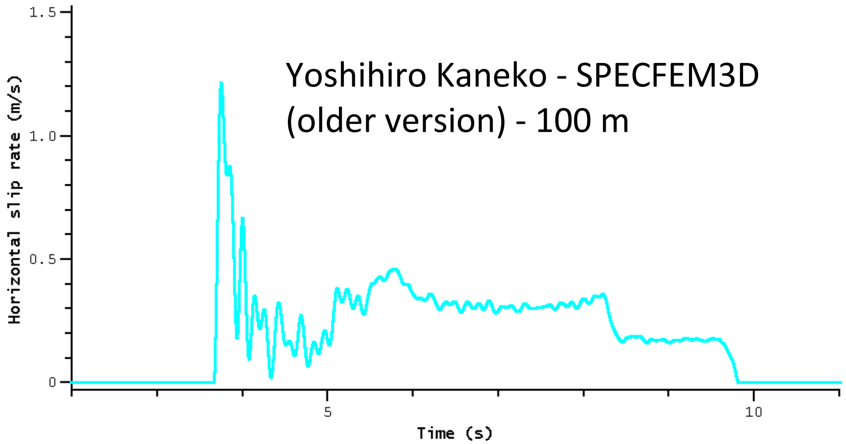


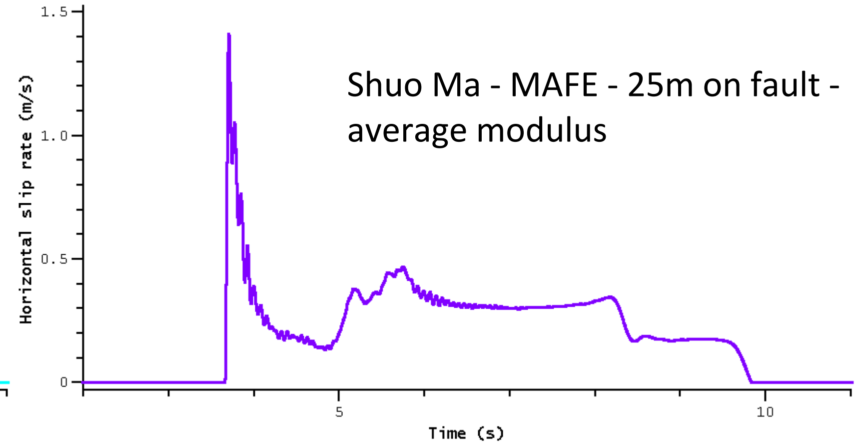


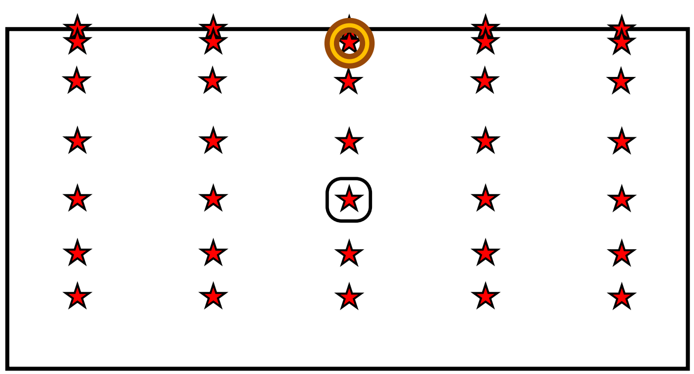
Oscillation Comparison – TPV34 Station faultst000dp010 (Slide 2 of 2)

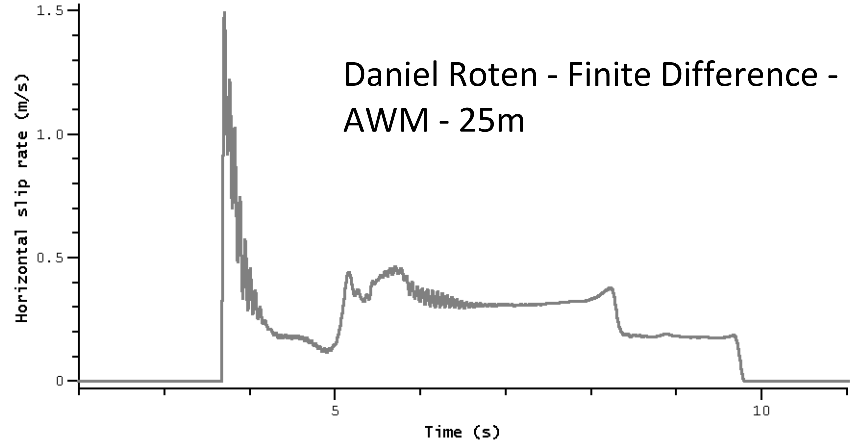




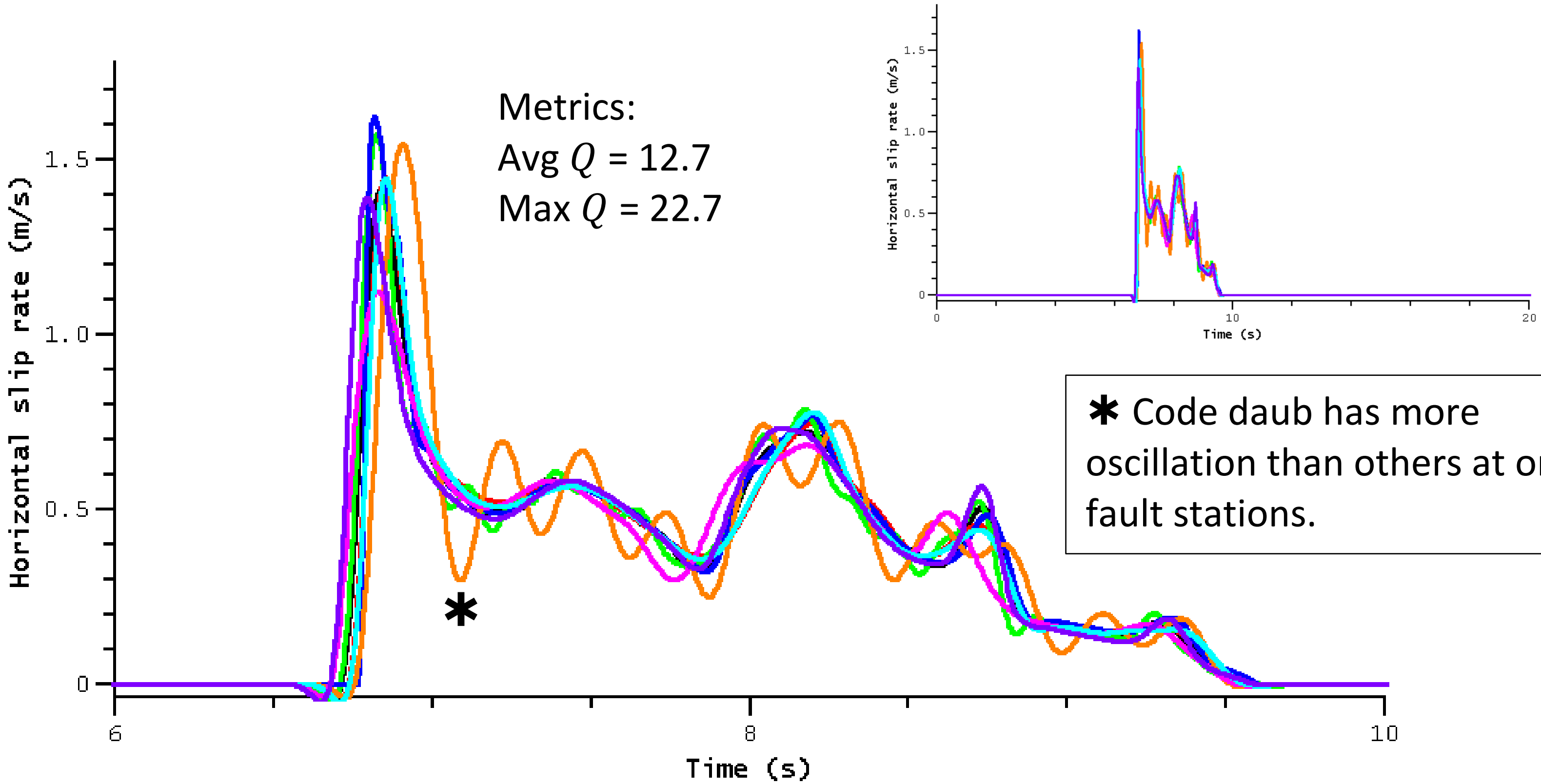






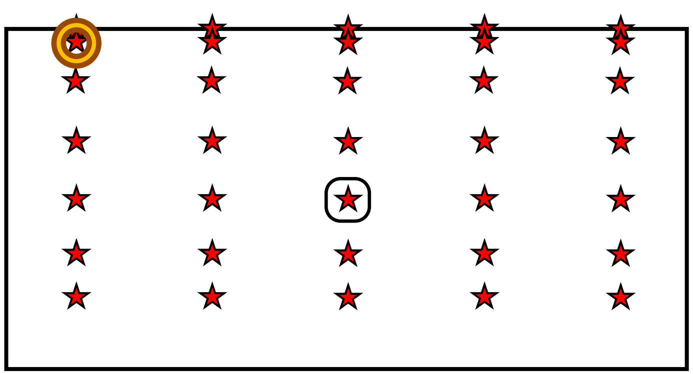


TPV34 – faultst-120dp010 – Horizontal Slip Rate



Metrics:
Avg Q = 12.7
Max Q = 22.7

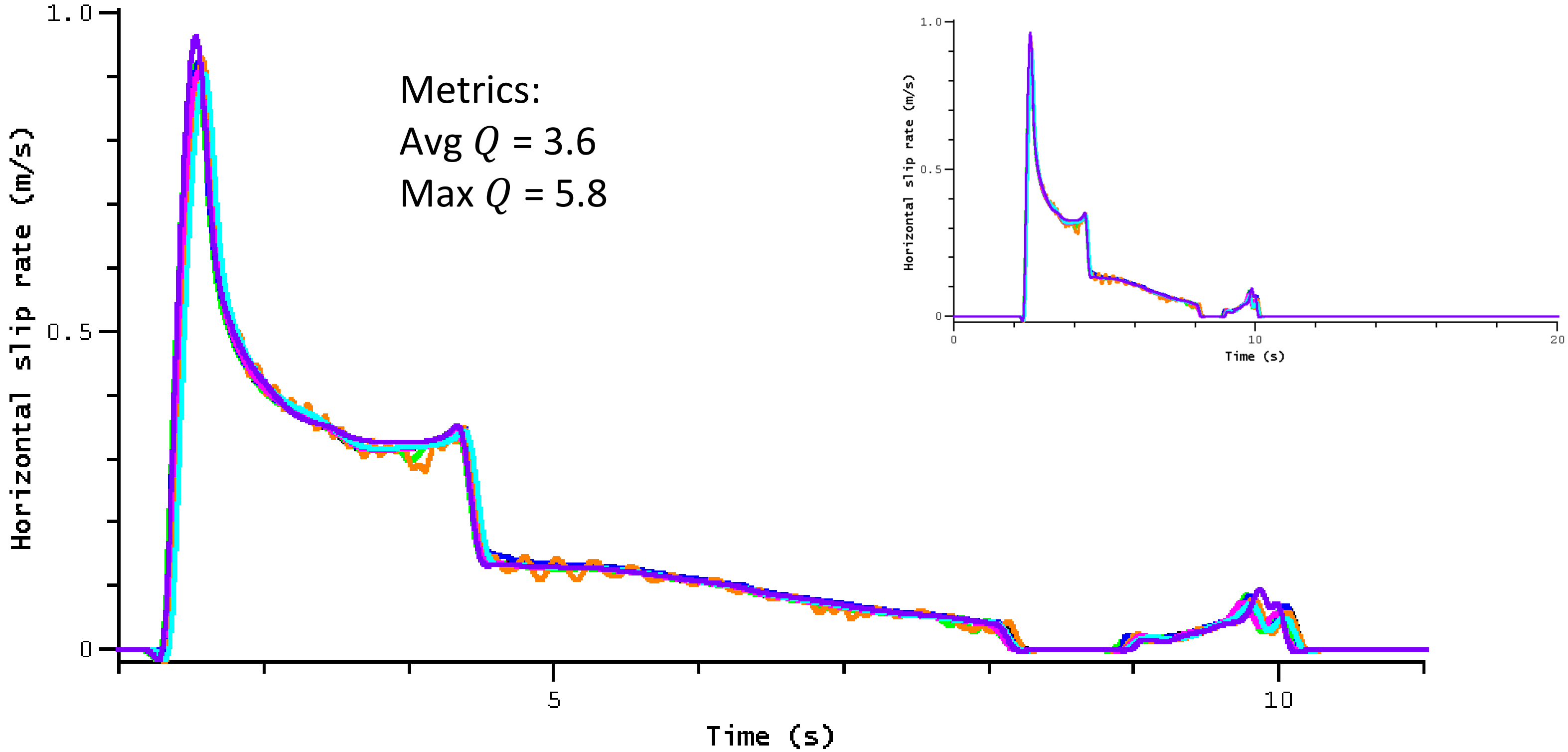
* Code daub has more oscillation than others at on-fault stations.

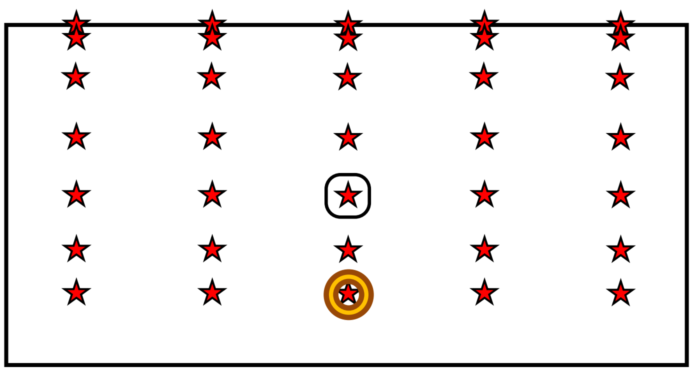


bai (Kangchen Bai - Spectral Element - SPECFEM3D)
barall.2 (Michael Barall - FaultMod - 25 m - boundary 48 km)
bydlon.2 (Sam Bydlon - Finite Difference - FD-Q-WaveLab - 50m)
chen.2 (Xiaofei Chen - Finite Difference Method - CGFDM - 25 m)
daub (Eric Daub - Daub Finite Difference Code - 100 m)
dliu (Dunyu Liu - Finite Element - EQdyna -50m)
ma.2 (Shuo Ma - MAFE - 25m on fault - average modulus)
roten (Daniel Roten - Finite Difference - AWM - 25m)

Filtered at 5 Hz.

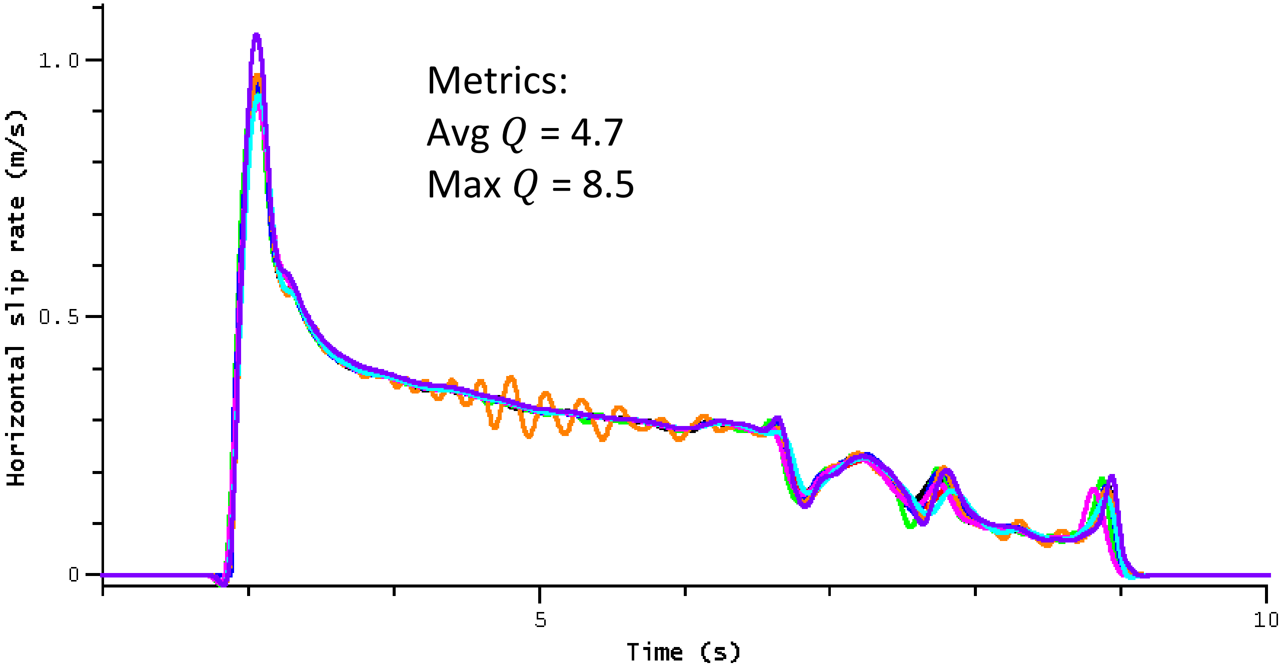
TPV34 – faultst000dp120 – Horizontal Slip Rate





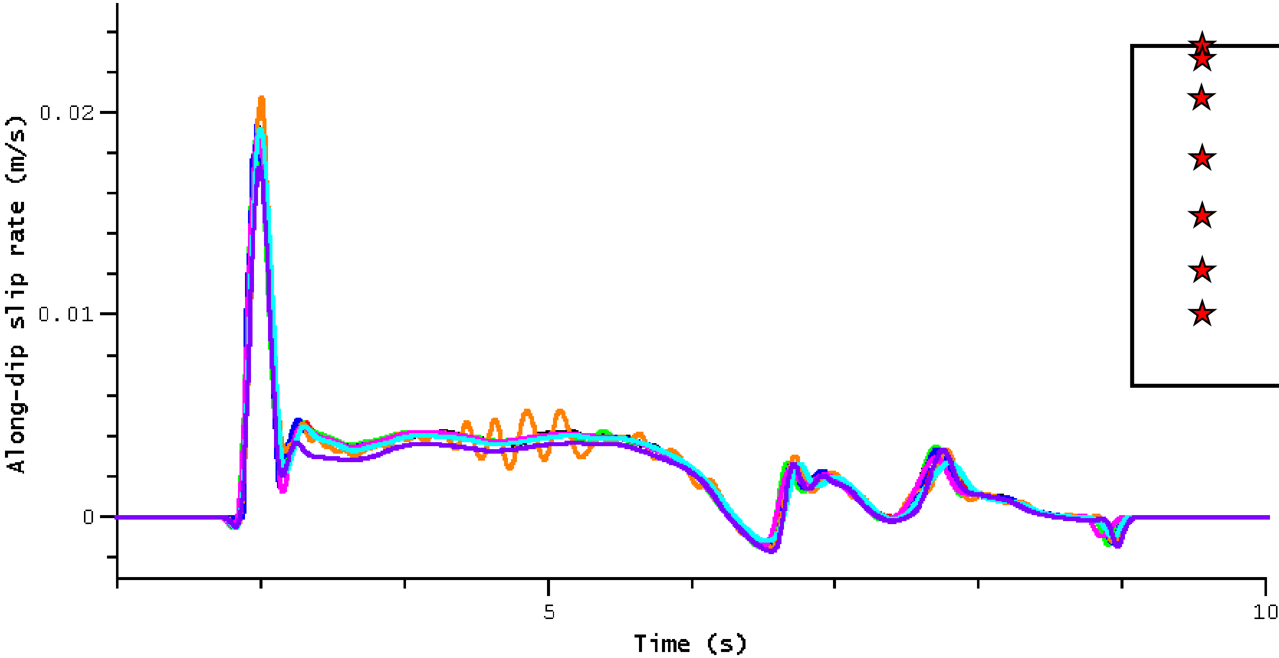
- bai (Kangchen Bai - Spectral Element - SPECFEM3D)
- barall.2 (Michael Barall - FaultMod - 25 m - boundary 48 km)
- bydlon.2 (Sam Bydlon - Finite Difference - FD-Q-WaveLab - 50m)
- chen.2 (Xiaofei Chen - Finite Difference Method - CGFDM - 25 m)
- daub (Eric Daub - Daub Finite Difference Code - 100 m)
- dliu (Dunyu Liu - Finite Element - EQdyna -50m)
- ma.2 (Shuo Ma - MAFE - 25m on fault - average modulus)
- roten (Daniel Roten - Finite Difference - AWM - 25m)

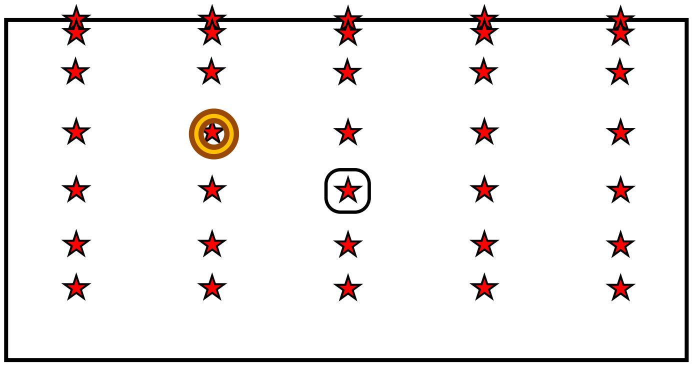
Filtered at 5 Hz.



TPV34 – faultst-060dp050 – Horizontal and Vertical Slip Rates

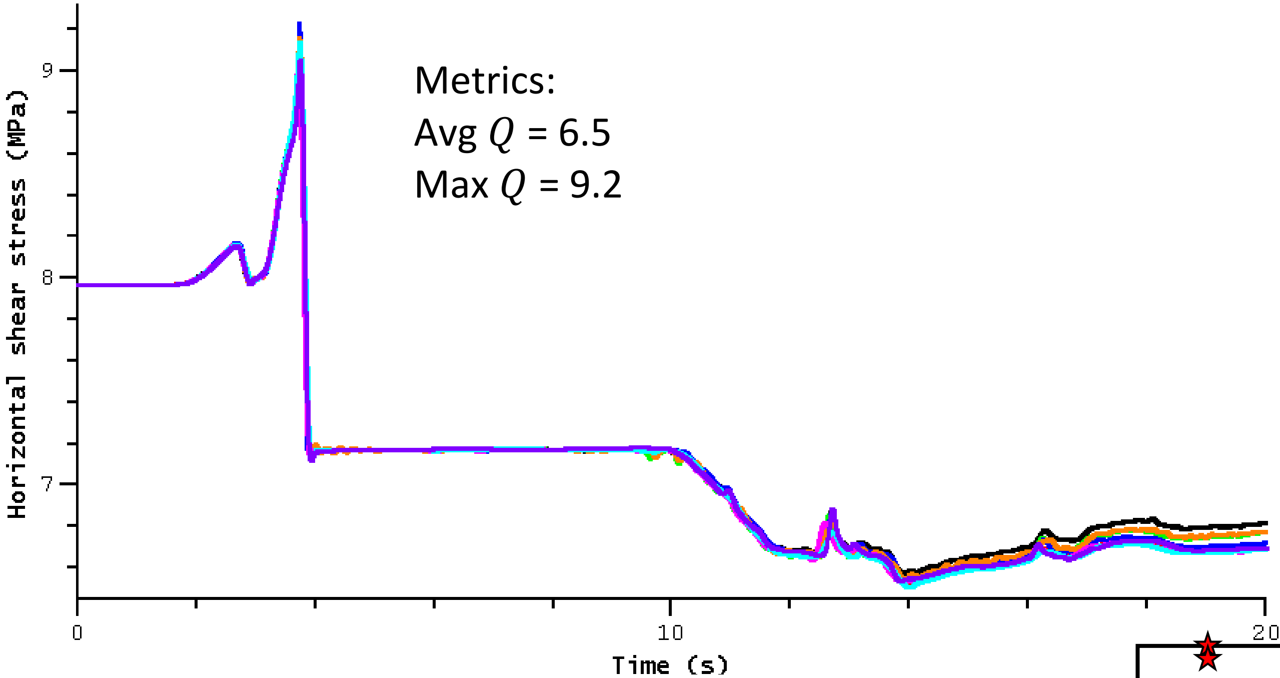
Note excellent agreement in vertical slip rate, despite it being 50 times smaller than the horizontal slip rate.



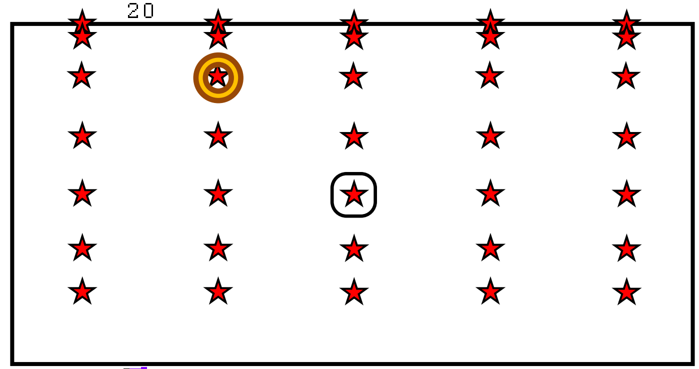


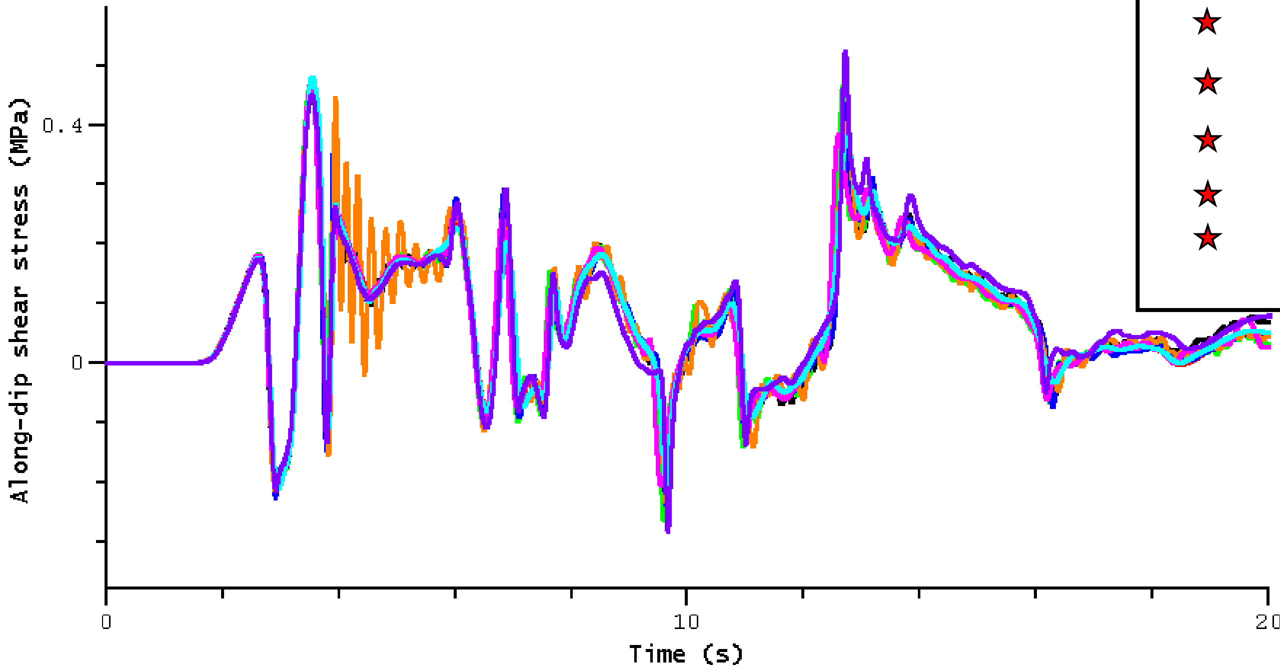
Filtered at 5 Hz.

TPV34 – faultst-060dp024 – Horizontal and Vertical Shear Stress



Horizontal shear stress agrees very well until about 13 seconds, when the values start to fan out. This may be a boundary effect.

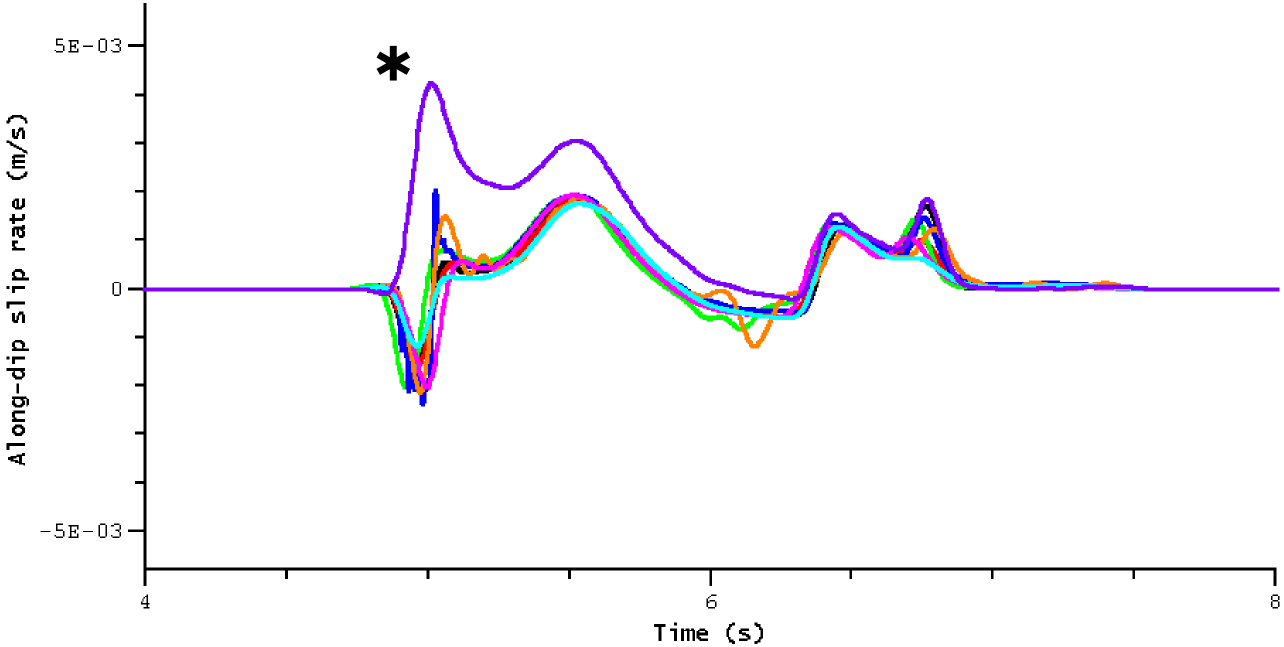




Vertical shear stress is a complicated waveform that all the codes agree on.

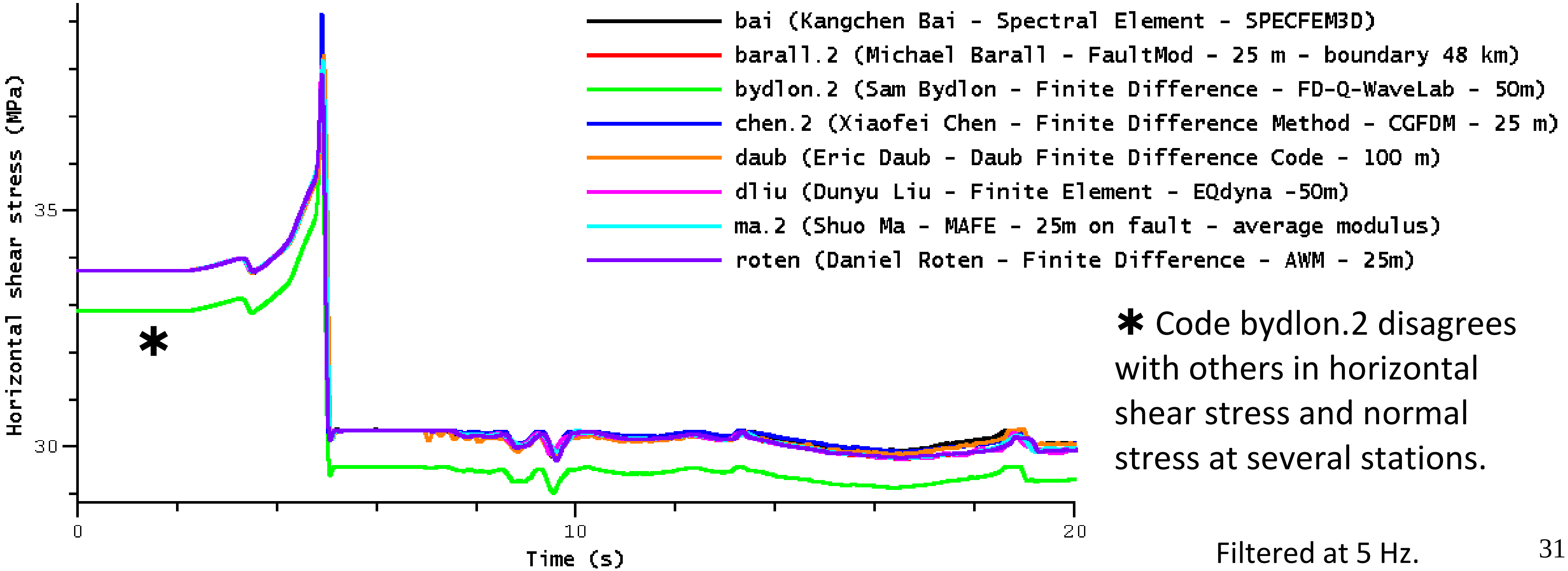
Filtered at 5 Hz.

TPV34 – faultst-120dp075 – Vertical Slip Rate and Horizontal Shear Stress



Vertical slip rate here is very small.

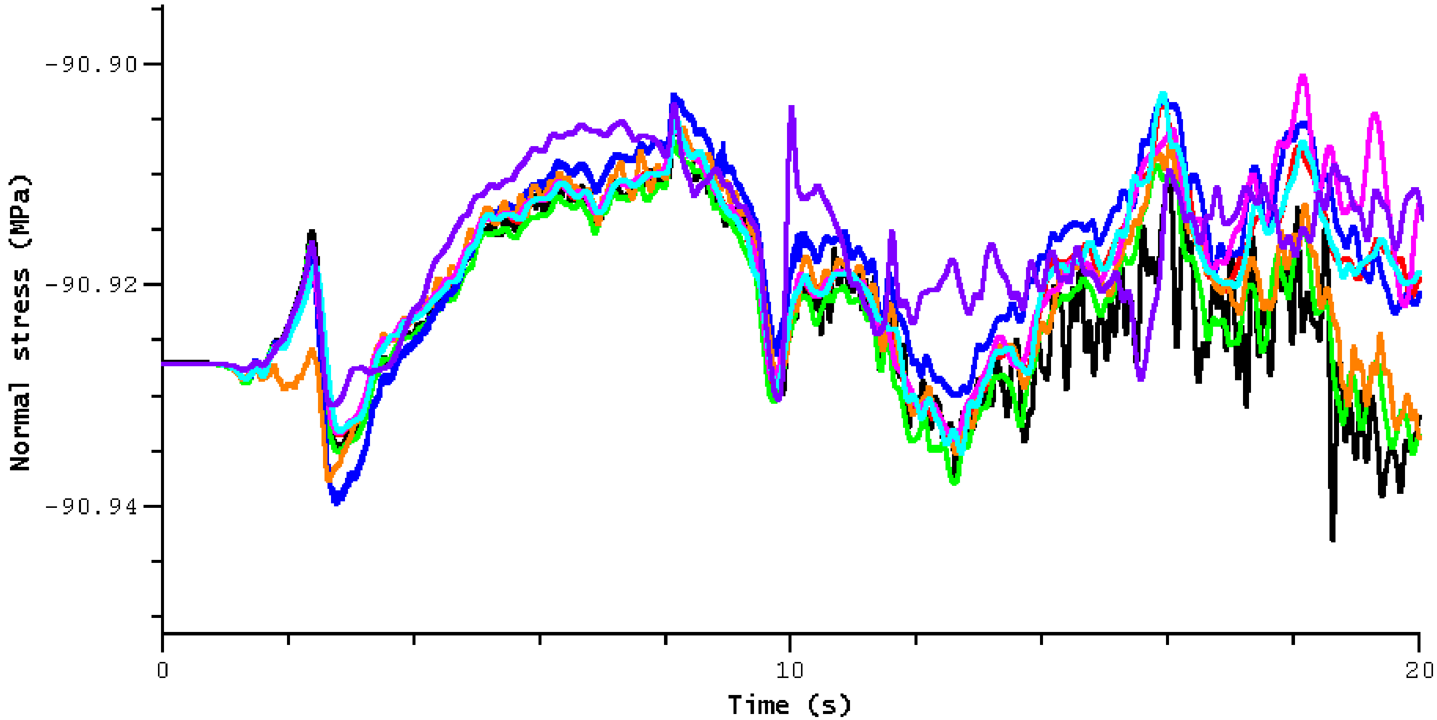
* Code roten disagrees with others in vertical slip rate and vertical shear stress at several stations.



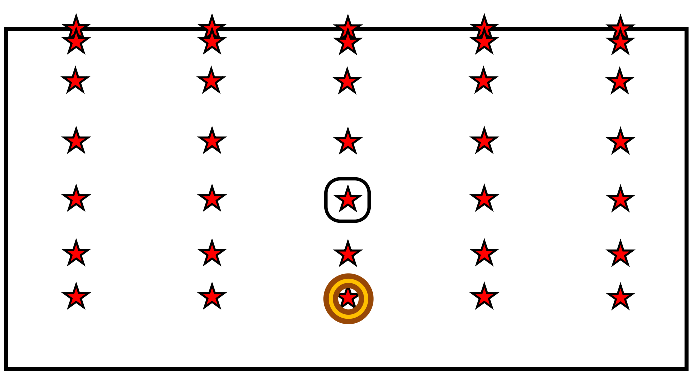
* Code bydlon.2 disagrees with others in horizontal shear stress and normal stress at several stations.

Filtered at 5 Hz.

TPV34 – faultst000dp120 – Normal Stress



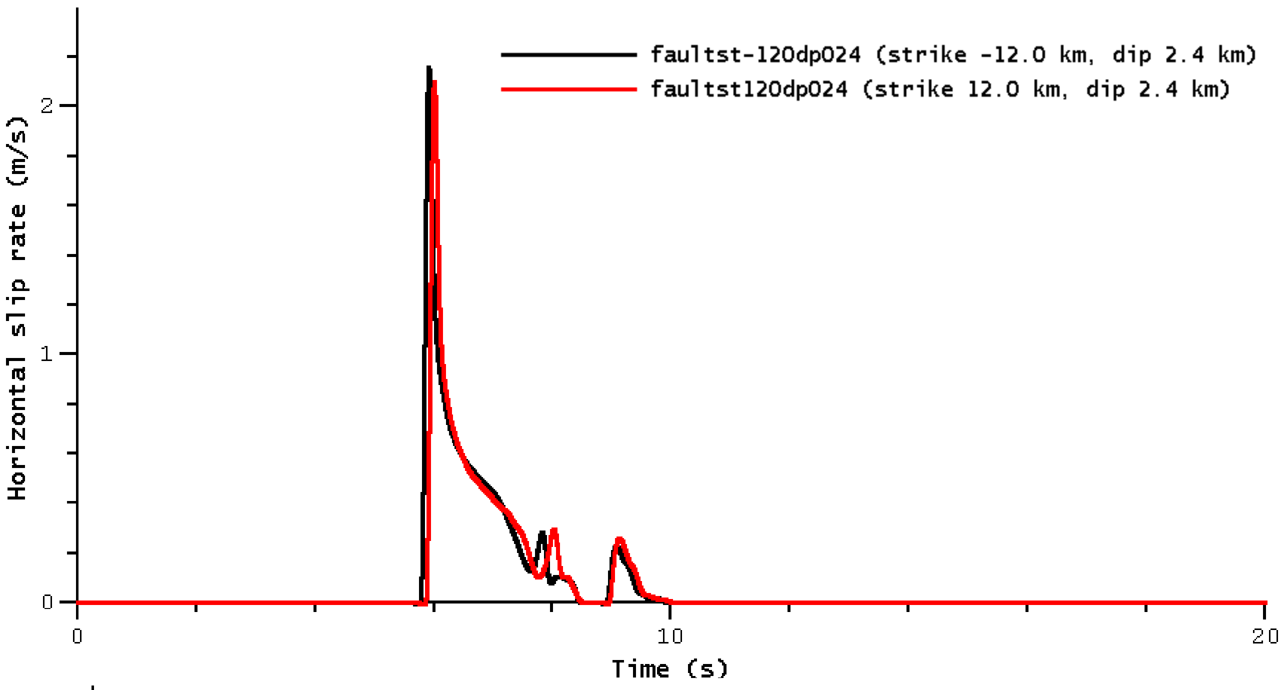
In a 1D model, the normal stress would be constant.
The variation is only 0.05%, yet the codes agree.



- bai (Kangchen Bai - Spectral Element - SPECFEM3D)
- barall.2 (Michael Barall - FaultMod - 25 m - boundary 48 km)
- bydlon.2 (Sam Bydlon - Finite Difference - FD-Q-WaveLab - 50m)
- chen.2 (Xiaofei Chen - Finite Difference Method - CGFDM - 25 m)
- daub (Eric Daub - Daub Finite Difference Code - 100 m)
- dliu (Dunyu Liu - Finite Element - EQdyna -50m)
- ma.2 (Shuo Ma - MAFE - 25m on fault - average modulus)
- roten (Daniel Roten - Finite Difference - AWM - 25m)

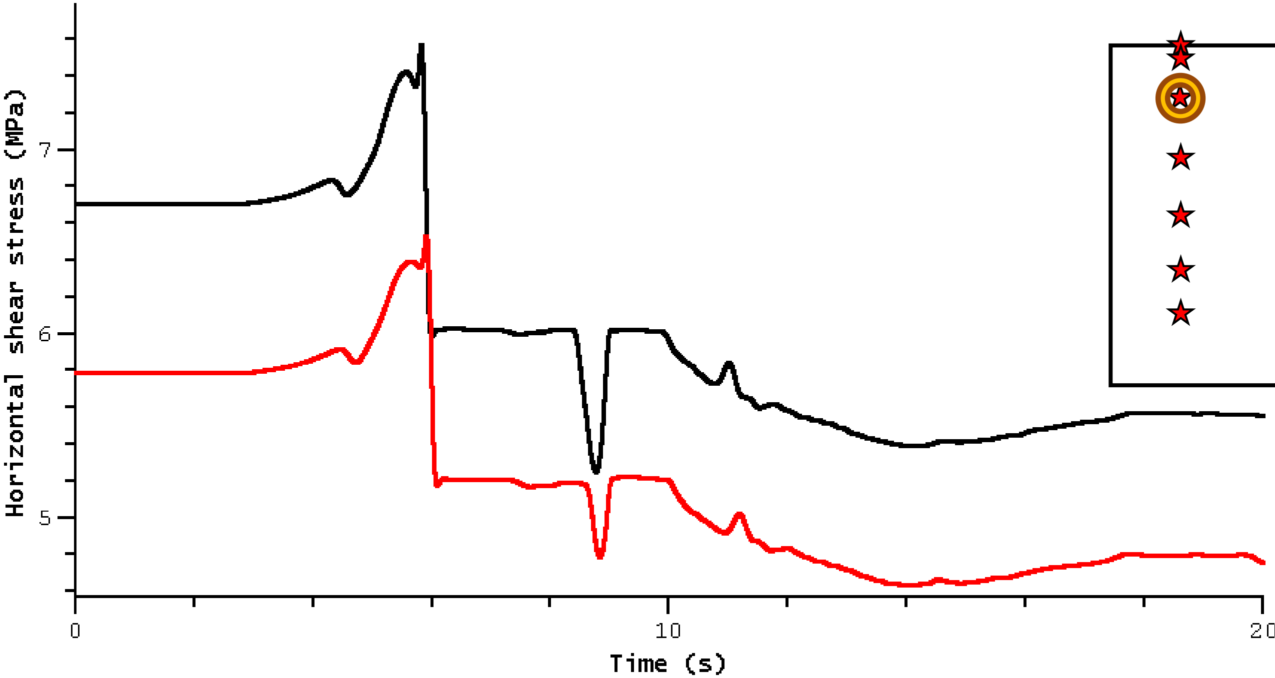
Filtered at 5 Hz.

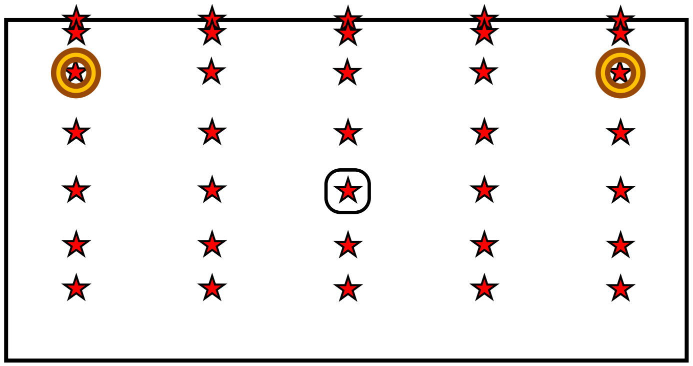
faultst-120dp024 and faultst120dp024 – Horizontal Slip Rate and Shear Stress



In a 1D velocity model, these two stations would have the same results.

Slip rate is almost the same, illustrating that there is not much effect from lateral variation.

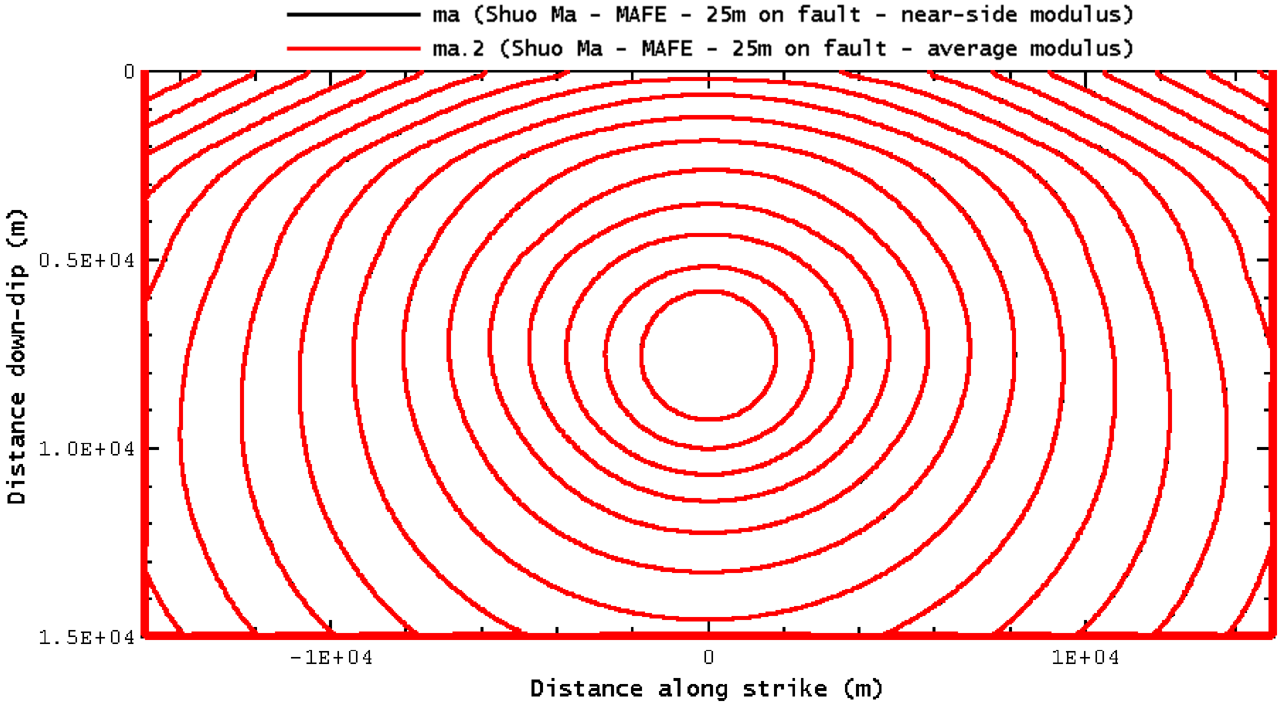




Shear stress is offset because initial stress is proportional to shear modulus.

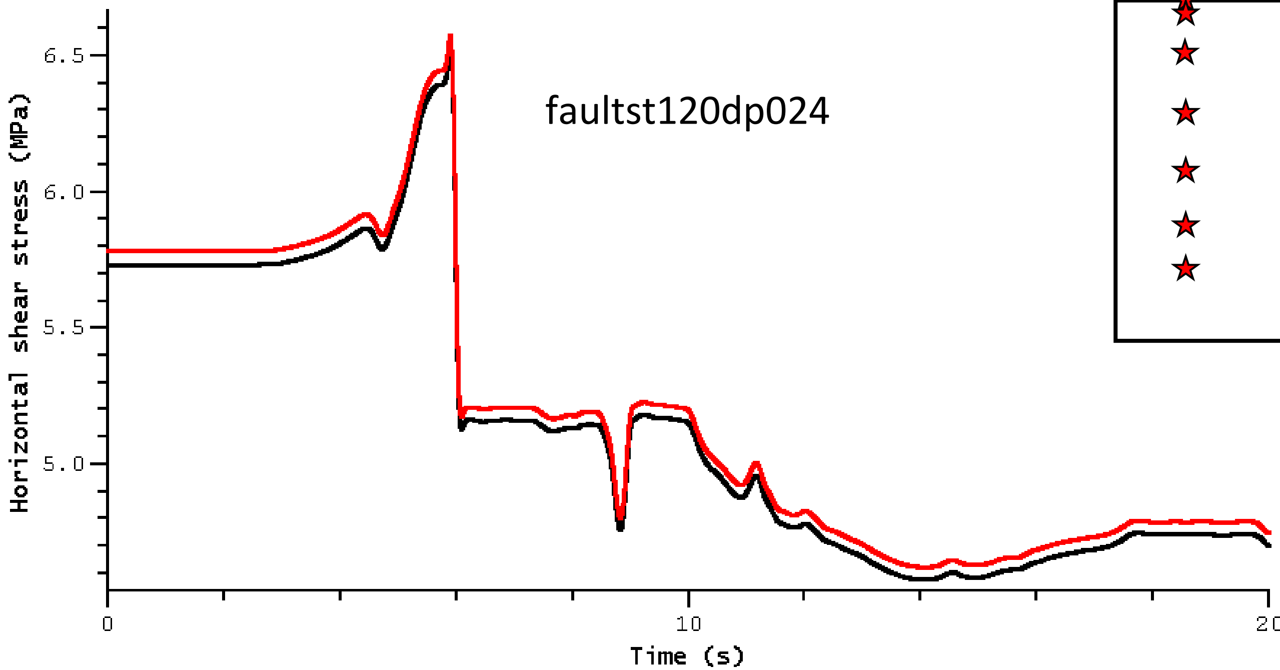
Filtered at 5 Hz. Code: barall.2

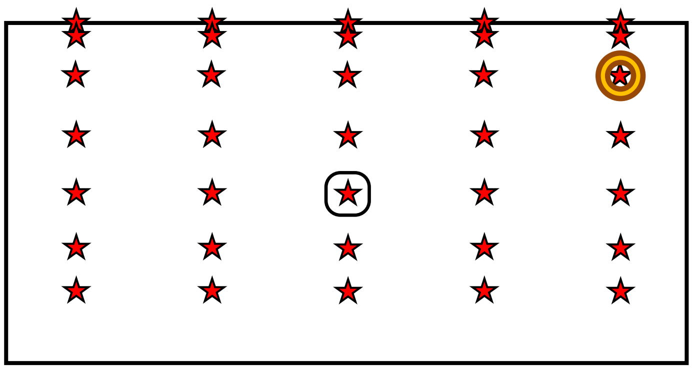
On-Fault Shear Modulus



This test compares two ways to calculate on-fault shear modulus: use the modulus on one side of the fault, or the average modulus on both sides.

Contour plots and almost all waveforms are exactly the same either way.

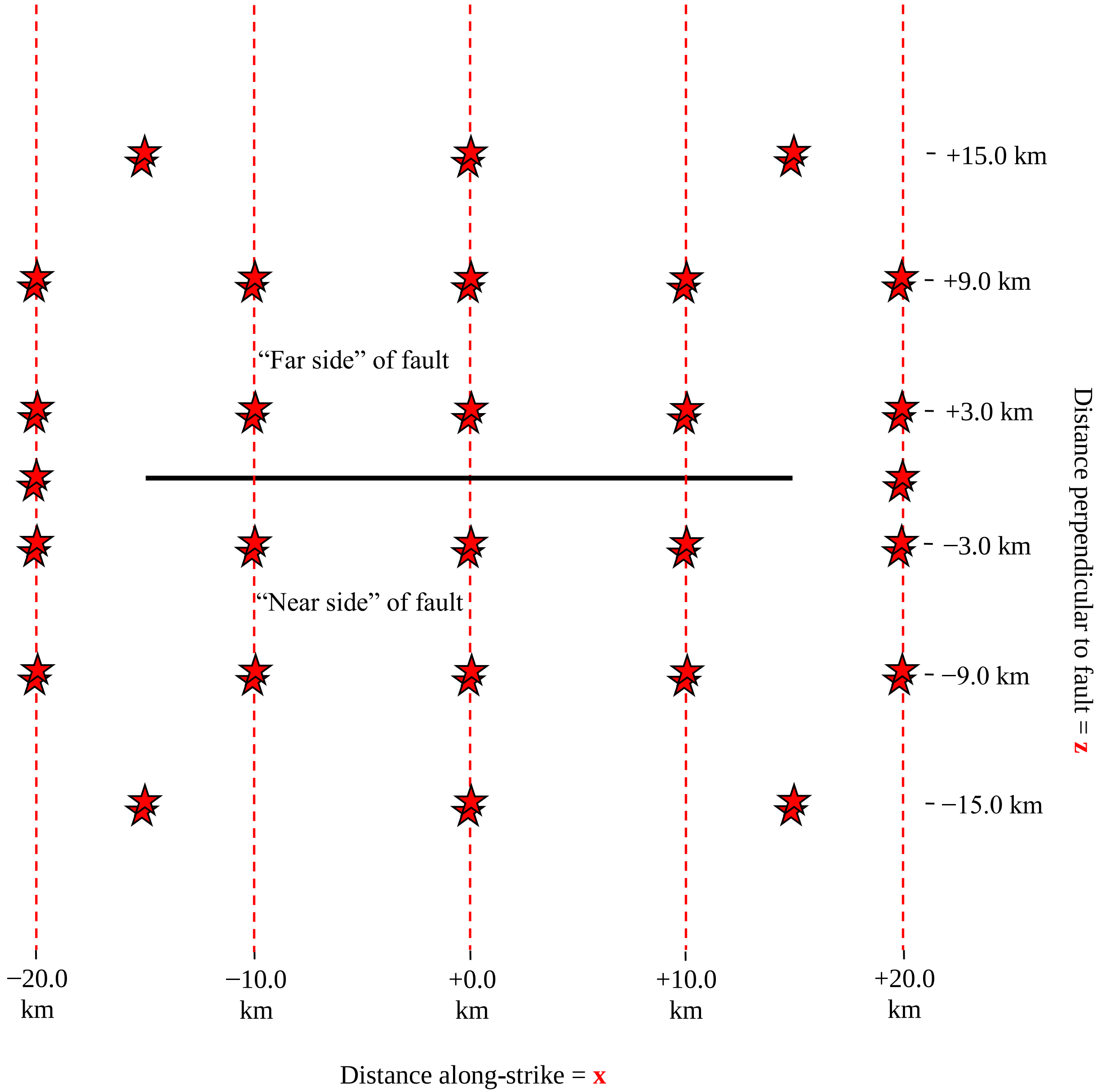




At a few stations on the right, there is a small difference in shear modulus, shown by the offset in shear stress.

Filtered at 5 Hz.

TPV34 Results — Off-Fault Stations



Off-Fault Stations.

Modelers are asked to submit displacement and velocity as a function of time, for 56 stations.

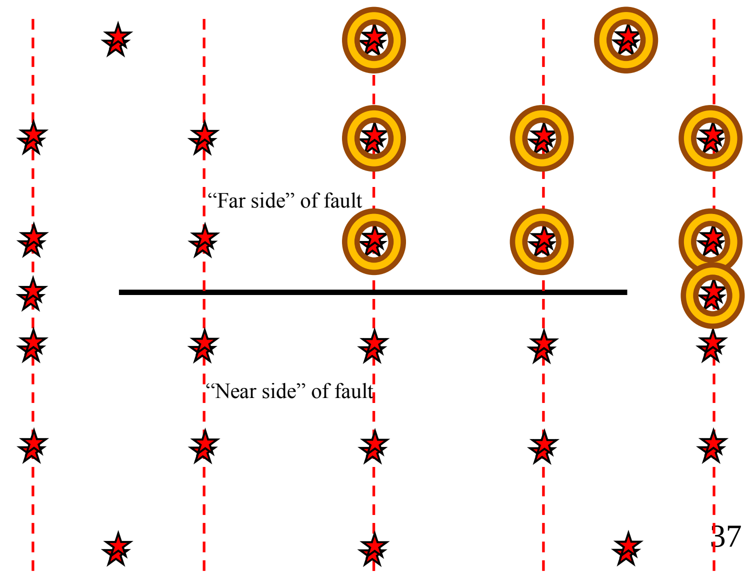
Stations are organized into 28 "boreholes" with stations at depths of 0 km and 2.4 km.

Metrics for Off-Fault Stations (Summary Across 8 Codes)

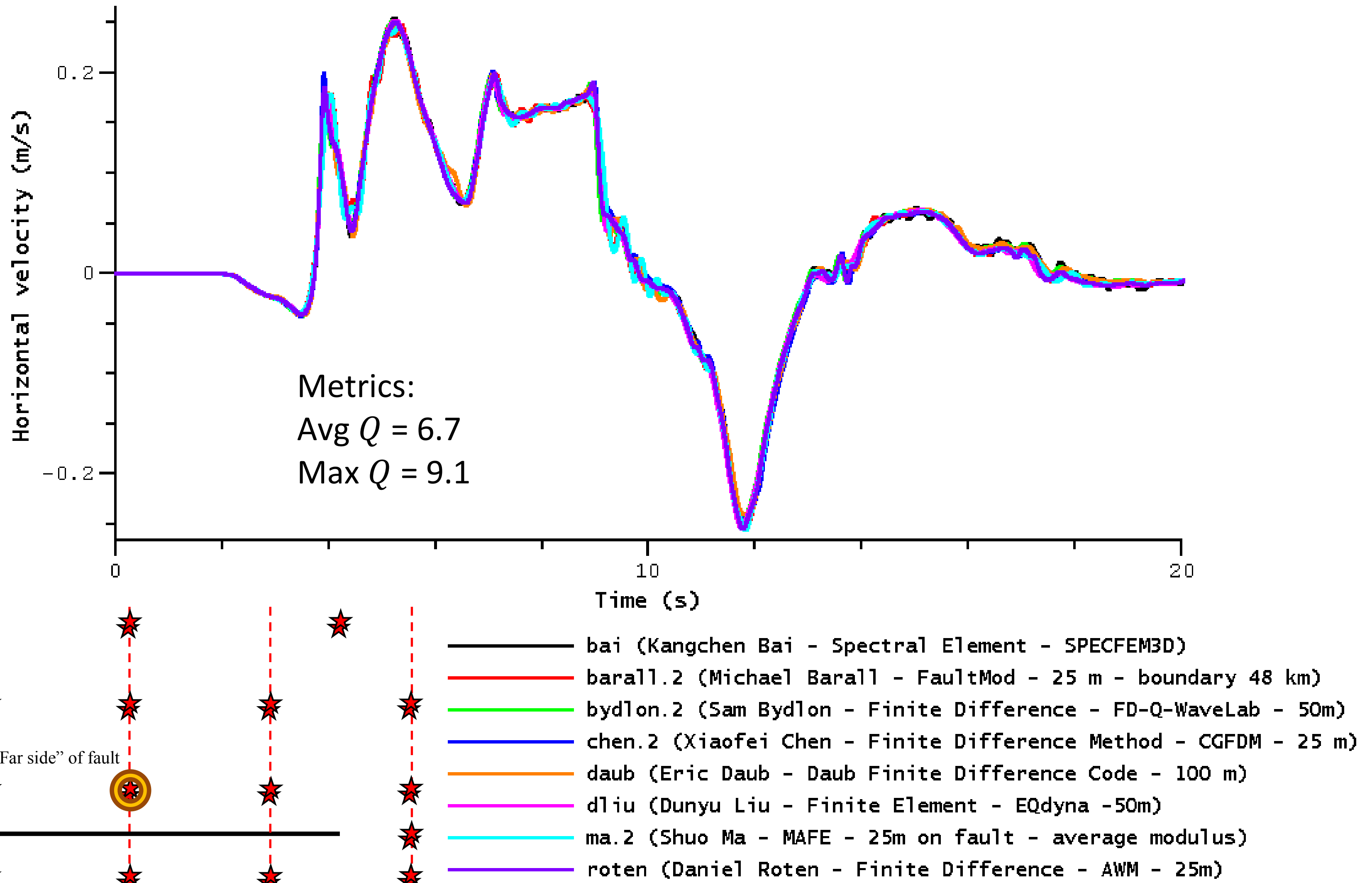
	3d-disp	3d-vel	t-shift	
body000st200dp000	17.7	21.9	0.038	In fault plane
body000st200dp024	18.1	21.8	0.034	
body030st000dp000	1.2	6.7	0.015	3 km from fault
body030st000dp024	1.1	5.5	0.013	
body030st100dp000	4.3	7.6	0.018	
body030st100dp024	3.8	8.9	0.019	
body030st200dp000	13.5	14.3	0.029	
body030st200dp024	13.6	16.7	0.030	
body090st000dp000	4.9	9.4	0.020	9 km from fault
body090st000dp024	4.4	9.6	0.017	
body090st100dp000	8.6	11.0	0.023	
body090st100dp024	8.3	12.7	0.024	
body090st200dp000	15.4	17.0	0.027	
body090st200dp024	15.4	20.2	0.033	
body150st000dp000	11.4	12.3	0.021	15 km from fault
body150st000dp024	10.5	13.6	0.021	
body150st150dp000	18.2	18.0	0.024	
body150st150dp024	18.5	19.4	0.022	

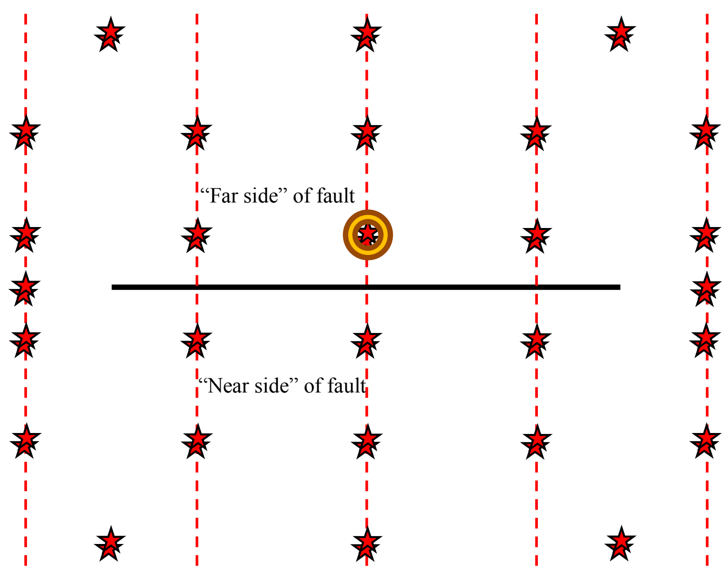
Looking at the **3d-vel** column:

- The highest values are in the fault plane, perhaps due to very strong stopping phases.
- Values increase with increasing distance along-strike, and with increasing distance from the fault.
- Stations at 6 km depth have only slightly larger values than stations at the earth's surface.



TPV34 – body030st000dp000 – Horizontal Velocity

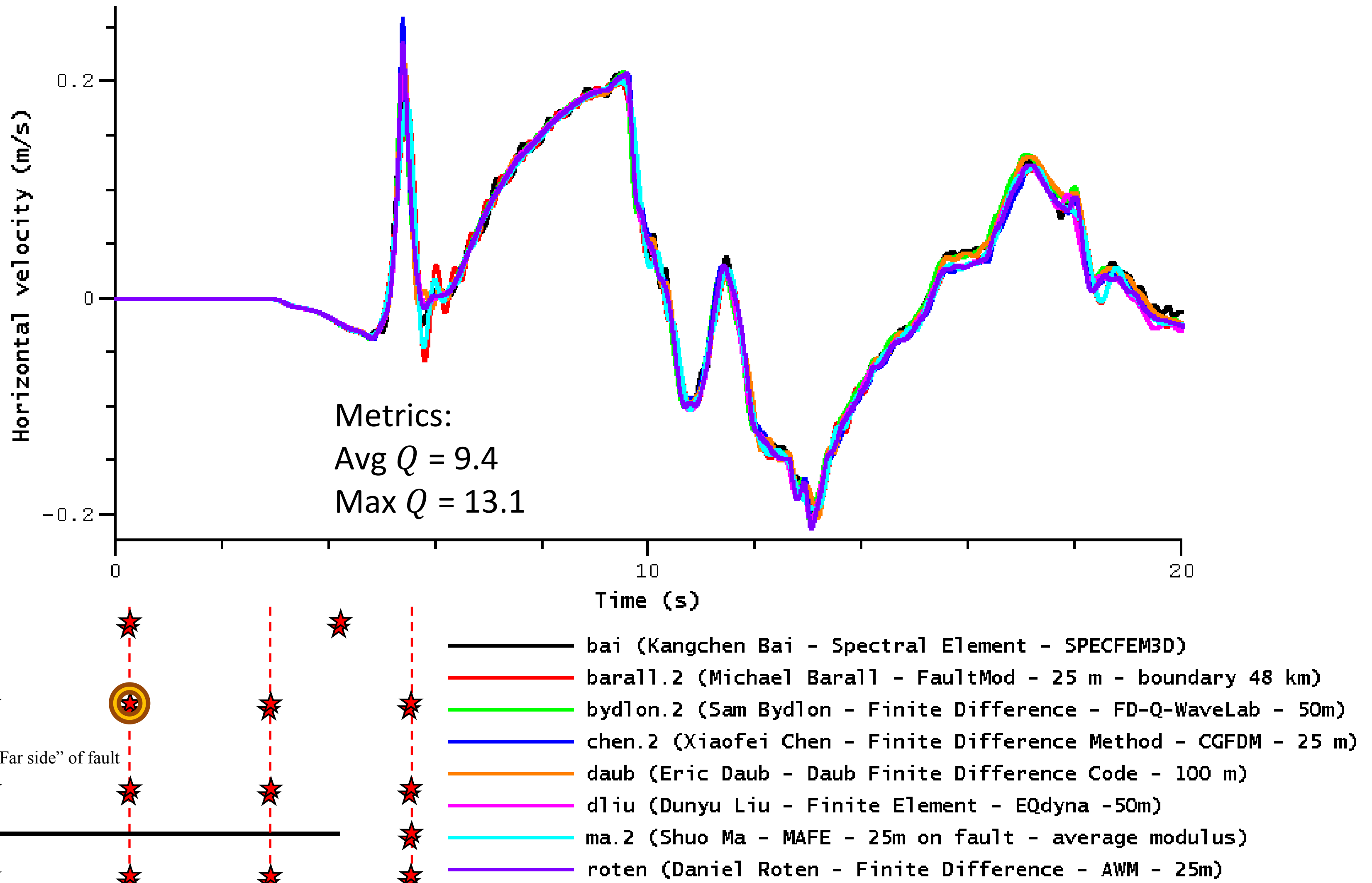


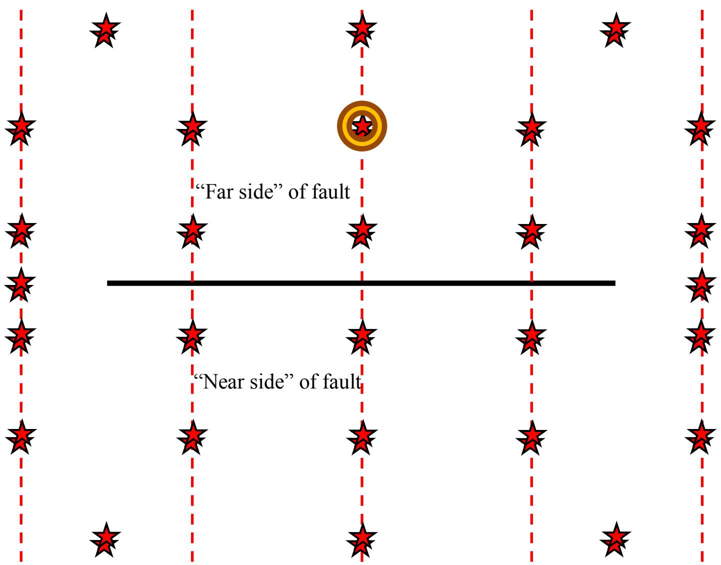


A very good match like we’re used to seeing.

Filtered at 5 Hz.

TPV34 – body090st000dp000 – Horizontal Velocity

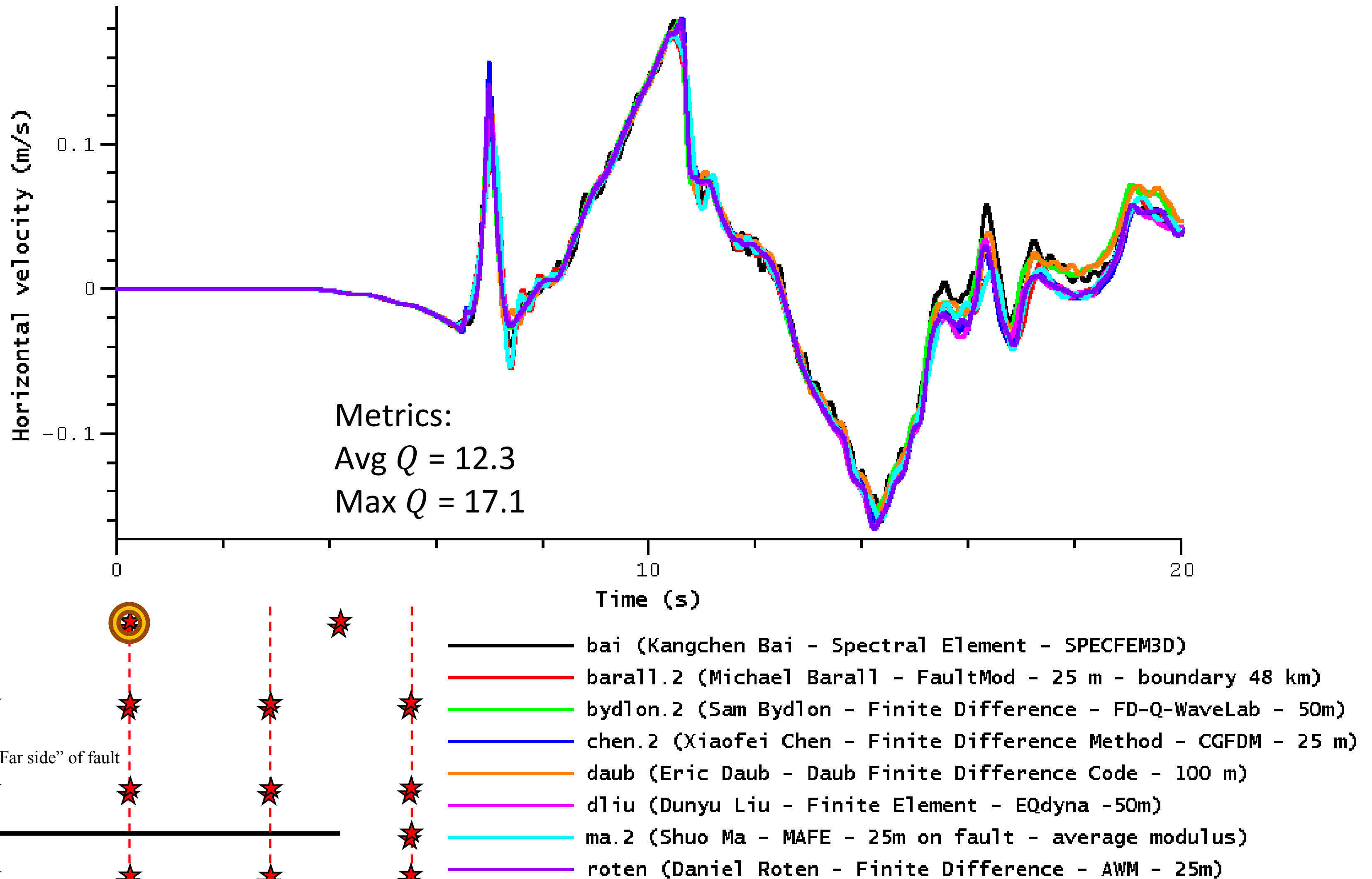


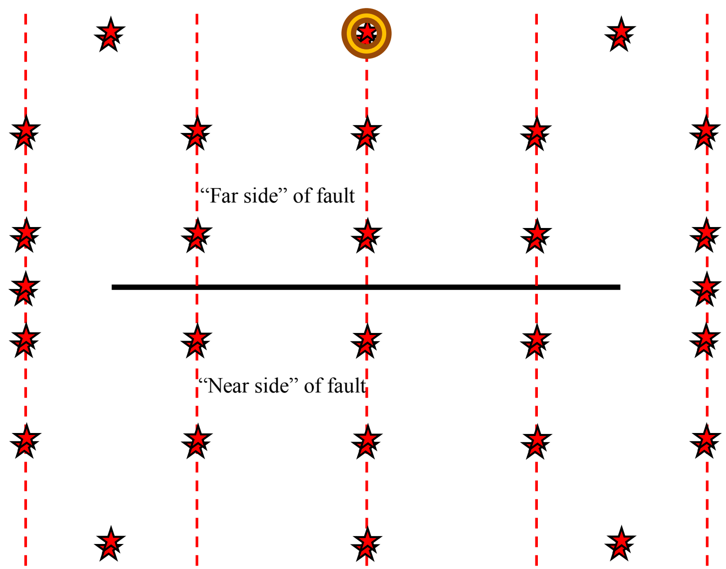


Match still looks good, metric values are a little higher.

Filtered at 5 Hz.

TPV34 – body150st000dp000 – Horizontal Velocity

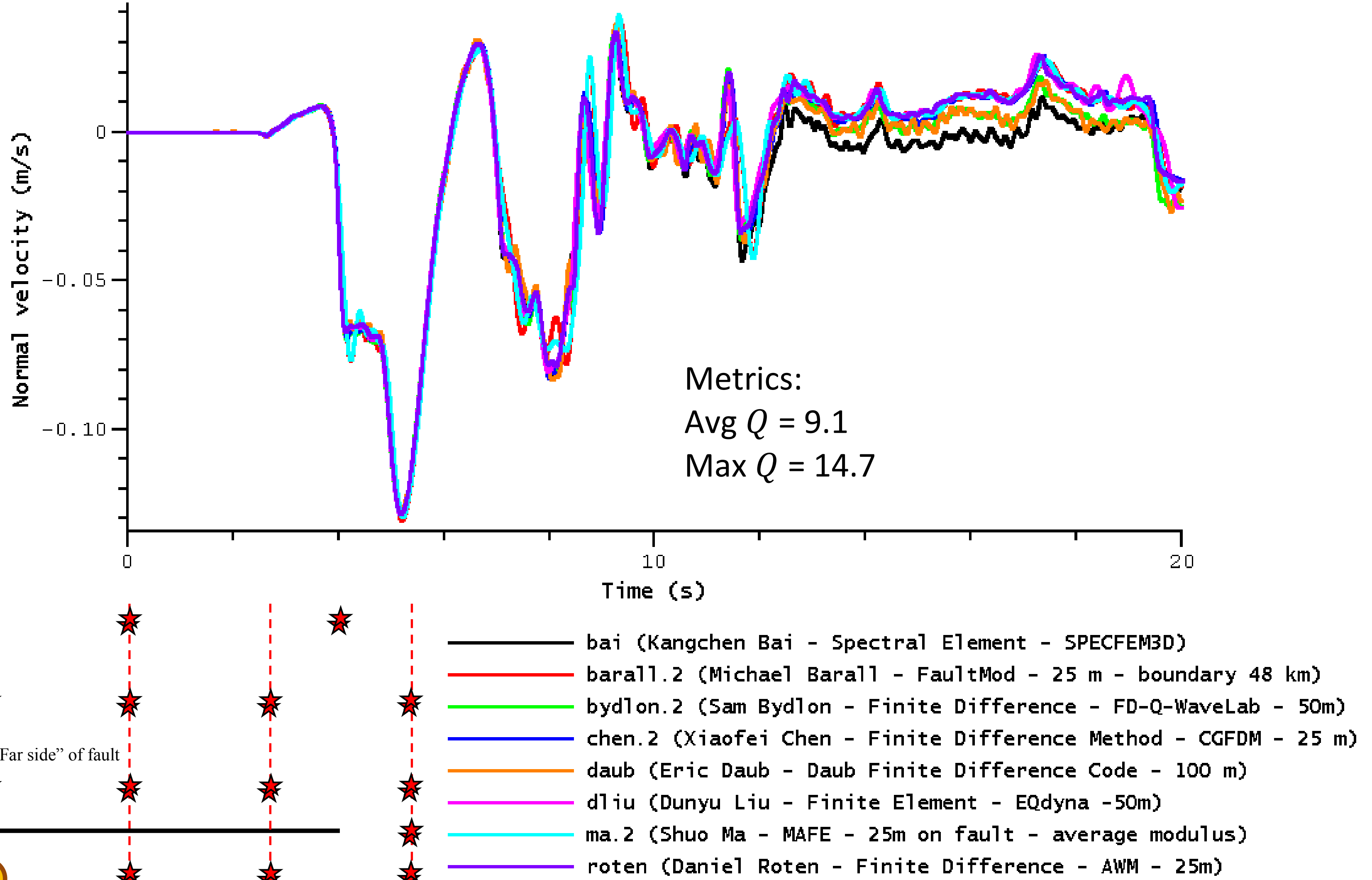


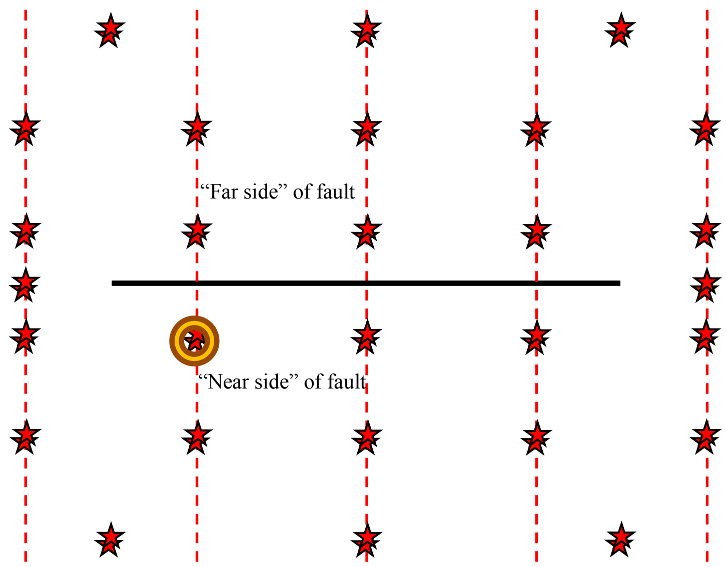


Match still looks good, metric values are a little higher.
Maybe some boundary effects.

Filtered at 5 Hz.

TPV34 – body-030st-100dp024 – Normal Velocity

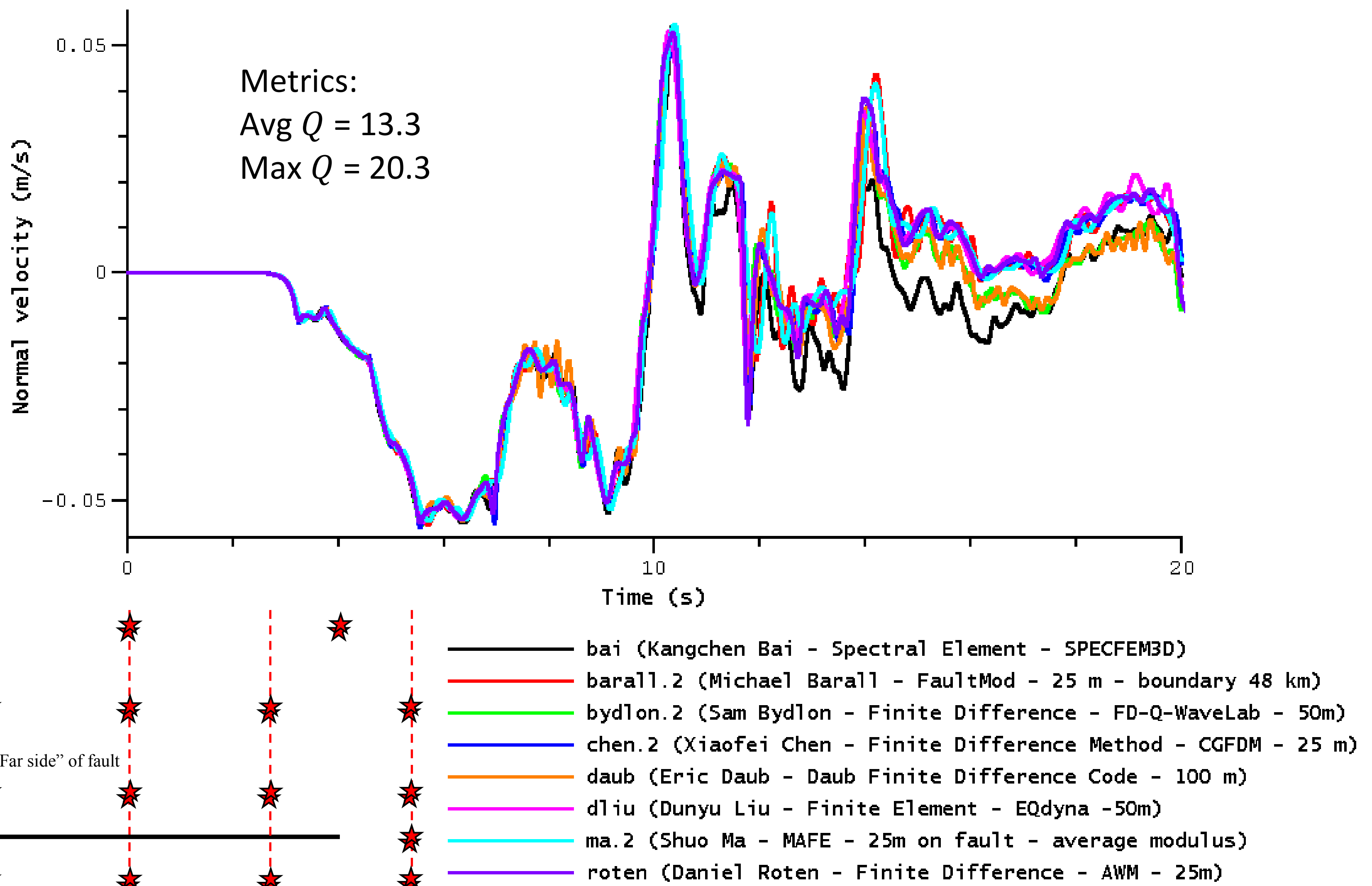


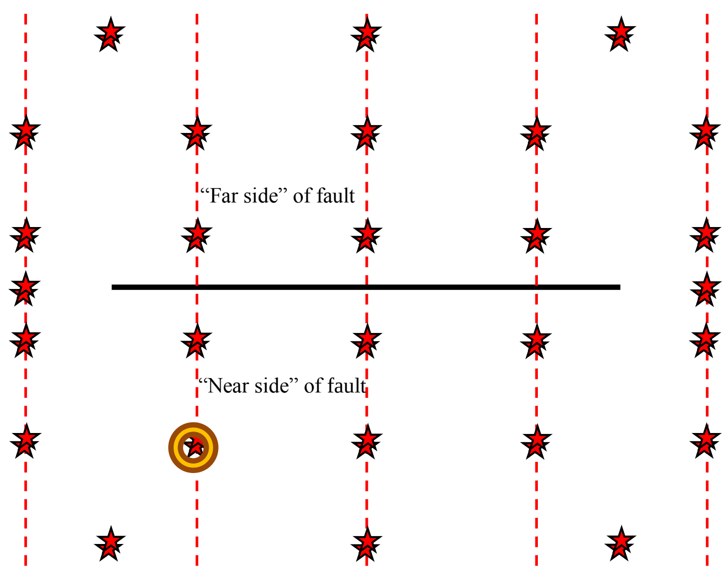


Match still looks good, but some differences appearing halfway through. Maybe some boundary effects.

Filtered at 5 Hz.

TPV34 – body-090st-100dp024 – Normal Velocity

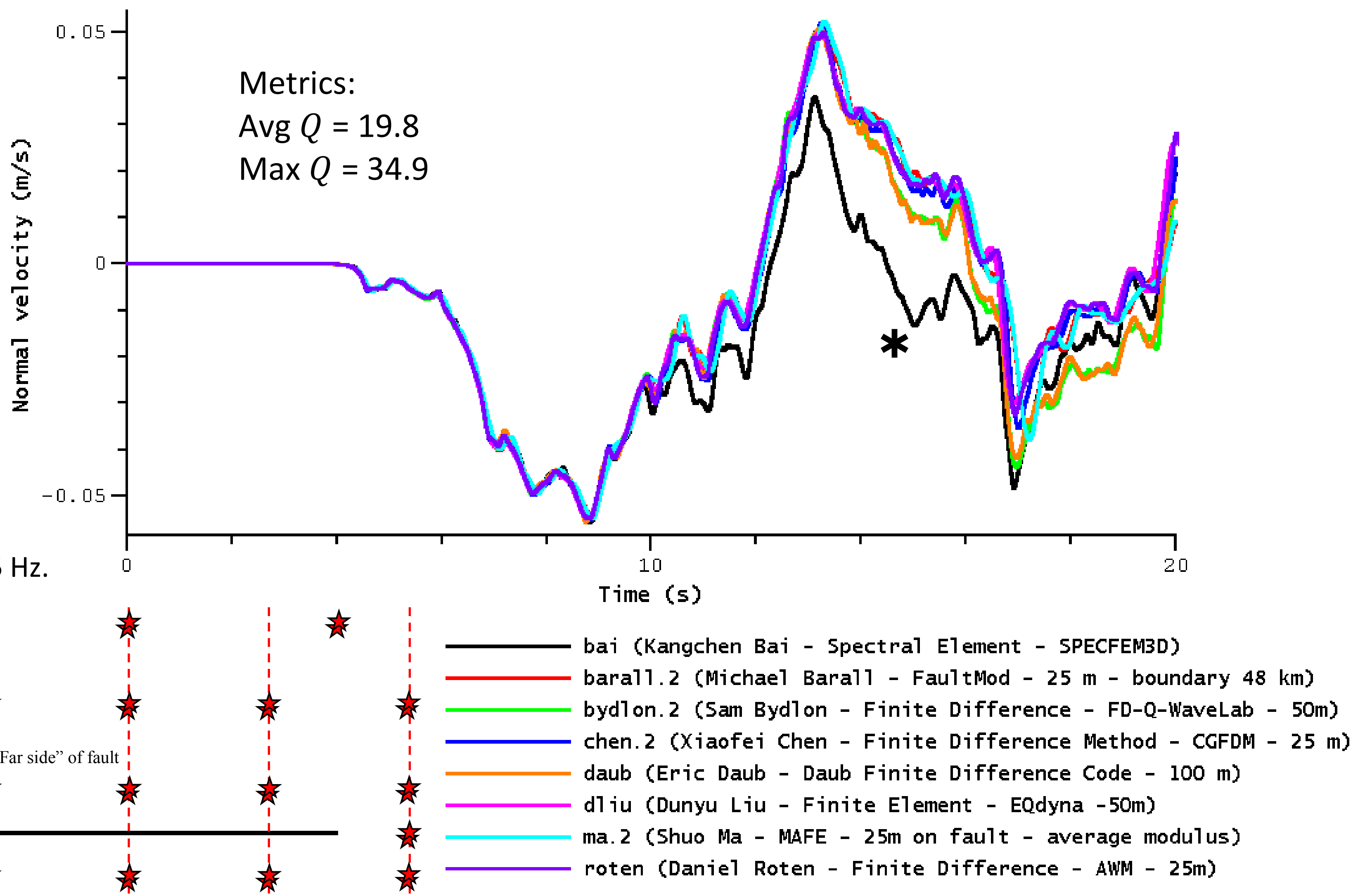




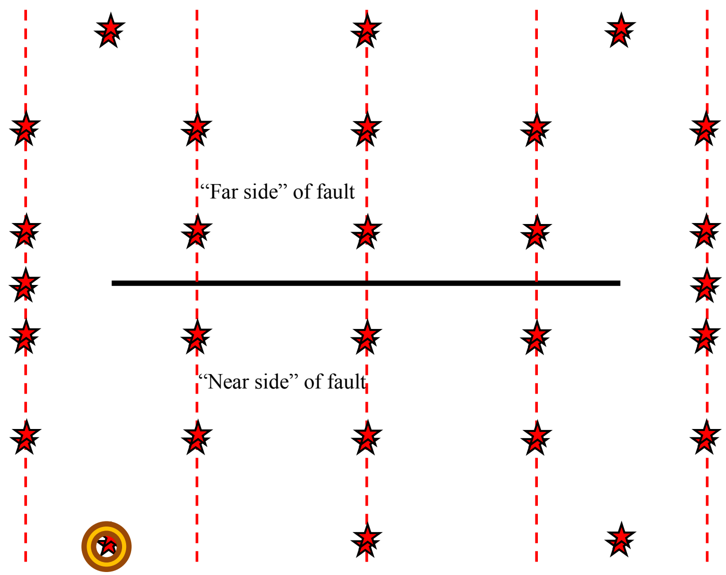
Additional differences appear as we move farther from the fault. Metric values are larger.

Filtered at 5 Hz.

TPV34 – body-150st-150dp024 – Normal Velocity



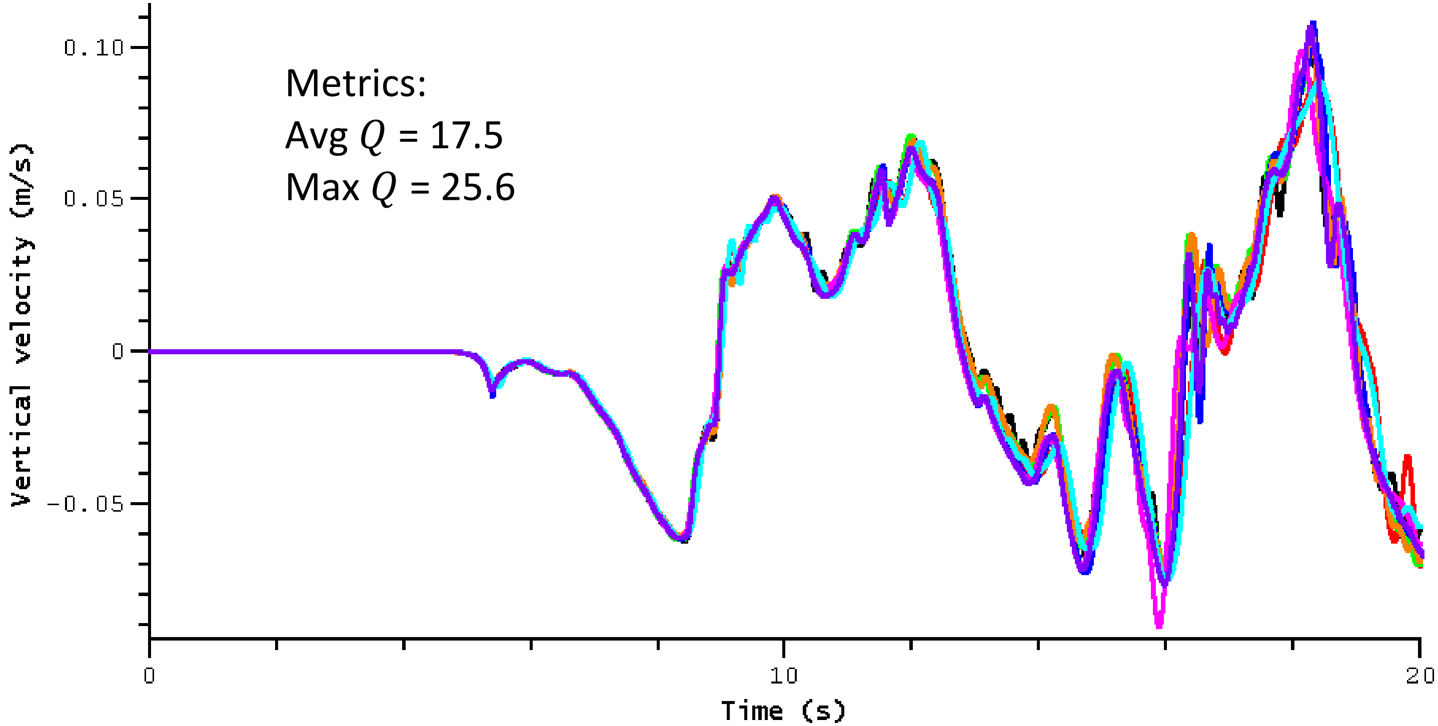
Filtered at 5 Hz.

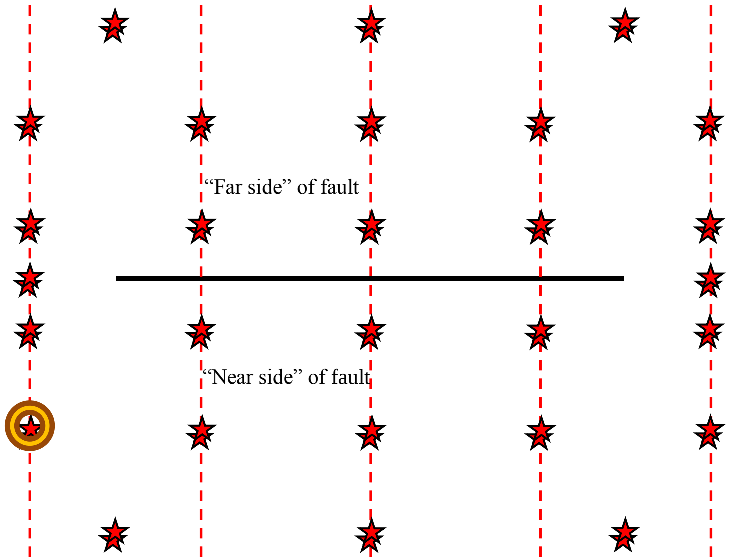


Additional differences appear as we move farther from the fault. Metric values are larger.

* Code bai differs from the others at a few off-fault stations.

TPV34 – body-090st-200dp000 – Vertical Velocity



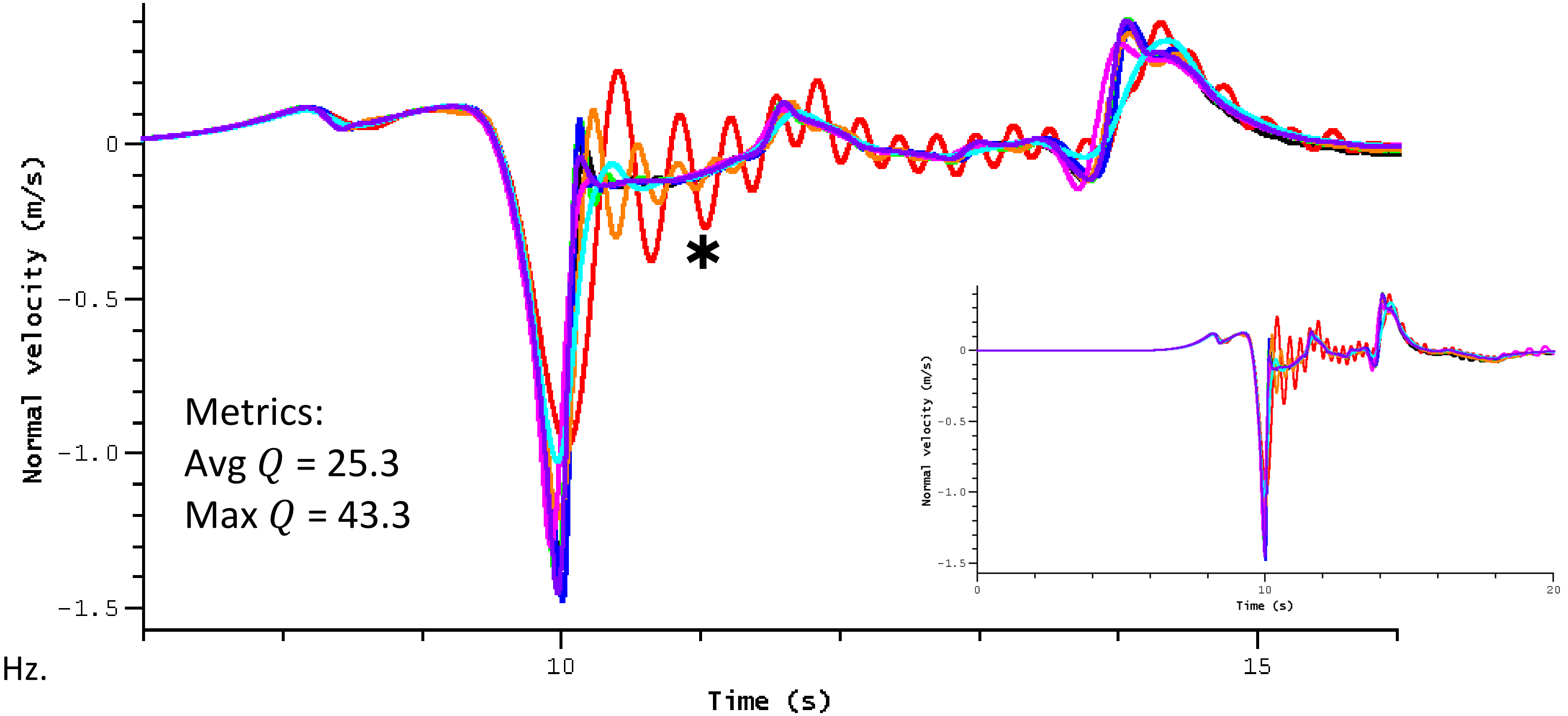


- bai (Kangchen Bai - Spectral Element - SPECFEM3D)
- barall.2 (Michael Barall - FaultMod - 25 m - boundary 48 km)
- bydlon.2 (Sam Bydlon - Finite Difference - FD-Q-WaveLab - 50m)
- chen.2 (Xiaofei Chen - Finite Difference Method - CGFDM - 25 m)
- daub (Eric Daub - Daub Finite Difference Code - 100 m)
- dliu (Dunyu Liu - Finite Element - EQdyna -50m)
- ma.2 (Shuo Ma - MAFE - 25m on fault - average modulus)
- roten (Daniel Roten - Finite Difference - AWM - 25m)

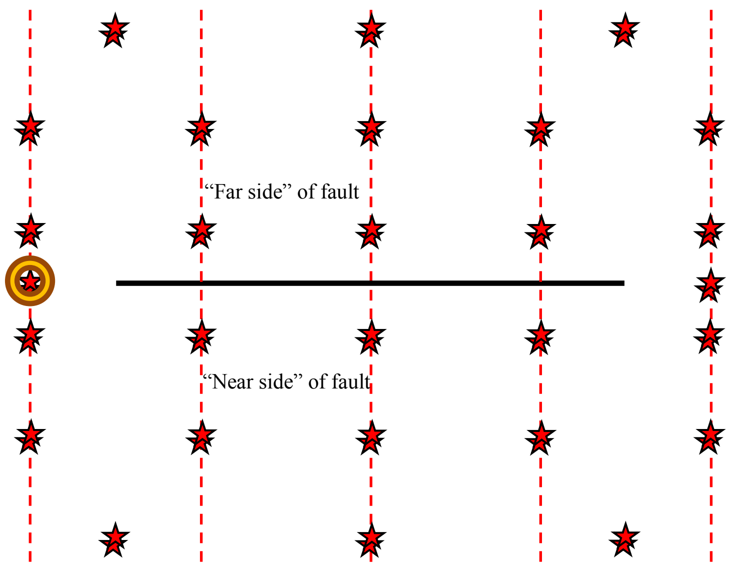
Vertical velocity is small, but codes show reasonable agreement with moderate differences.

Filtered at 5 Hz.

TPV34 – body000st-200dp000 – Normal Velocity



Filtered at 5 Hz.



- bai (Kangchen Bai - Spectral Element - SPECFEM3D)
- barall.2 (Michael Barall - FaultMod - 25 m - boundary 48 km)
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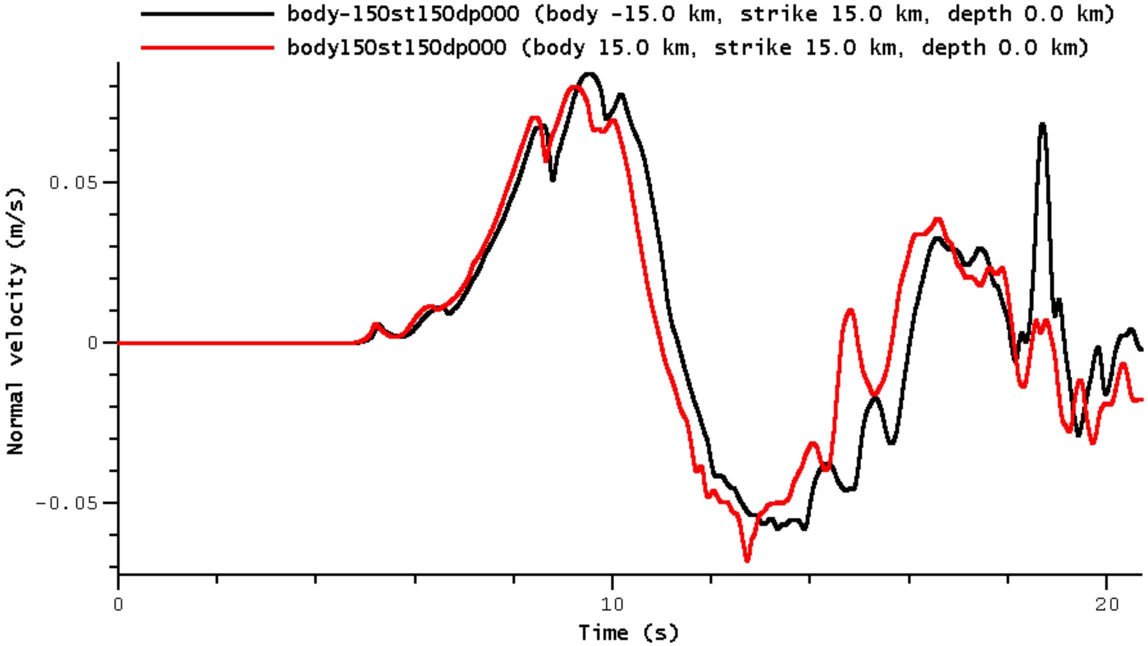
- chen.2 (Xiaofei Chen - Finite Difference Method - CGFDM - 25 m)
- daub (Eric Daub - Daub Finite Difference Code - 100 m)
- dliu (Dunyu Liu - Finite Element - EQdyna -50m)
- ma.2 (Shuo Ma - MAFE - 25m on fault - average modulus)
- roten (Daniel Roten - Finite Difference - AWM - 25m)

Stopping phase produces very high peak velocity 5 km past the end of the fault. Metrics are high here.

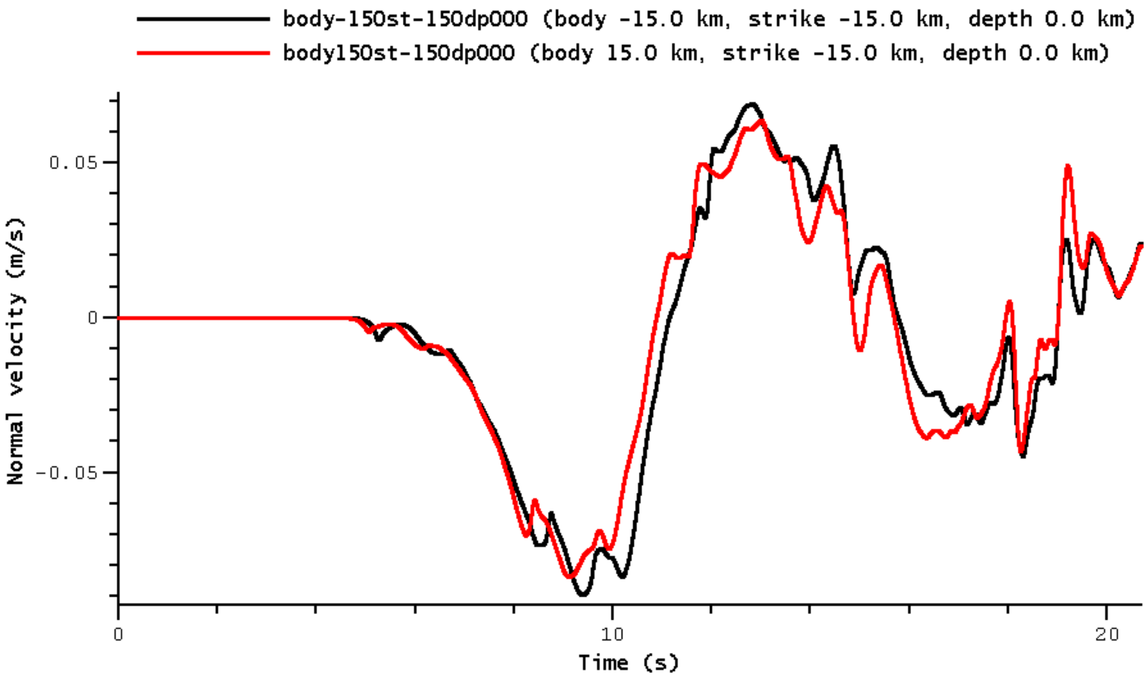
* Code barall produces more oscillations than others in response to stopping phases.

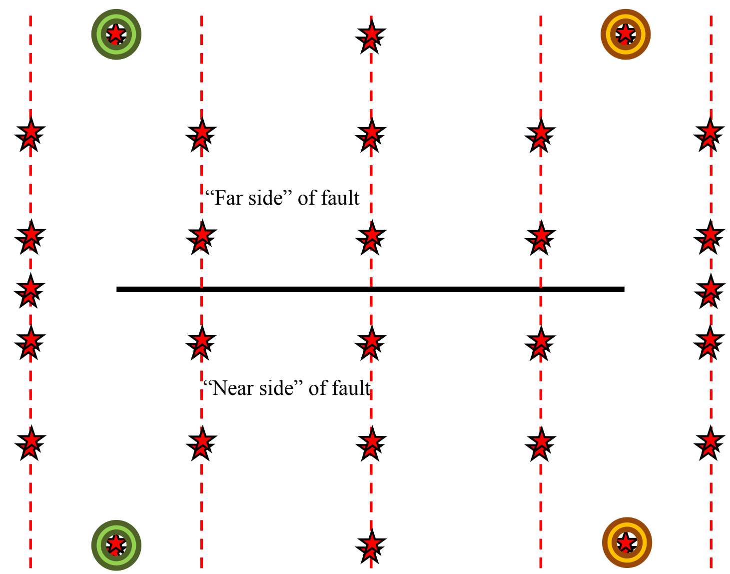


Stations Mirrored Across the Fault Plane — Normal Velocity

In a 1D velocity model, the red and black curves would coincide, and the bottom graph would be the negative of the top graph.

The differences show the effect of the 3D velocity model — distinct, but not very large.





Filtered at 5 Hz. Code: roten

Conclusions & Next Steps

Conclusions (Slide 1)

1. TPV34 is our first benchmark to use real-world data:

- We used SCEC Community Velocity Model CVM-H, with minimum V_S = 1400 m/s, in the neighborhood of the Imperial Fault.

2. Except for the 3D velocity model and station locations, TPV34 is the same as the earlier benchmarks TPV31 and TPV32 which used 1D velocity models.

3. Rupture front contours show very good agreement, but not as good as TPV31-32.

4. Codes agree well on process zone width.

- Process zone width shrinks as V_S shrinks.
- Process zone width shrinks as rupture propagates along-strike.

5. All participating codes perform well overall, but:

- Most codes have significant oscillations near the epicenter.
- Many codes have some noticeable differences from the others.

Conclusions (Slide 2)

6. Codes are generally in excellent agreement at on-fault stations.

- Agreement worsens for stations near the earth's surface with low V_S.

7. Propagating in mode III in low-velocity material seems to be numerically challenging.

- The usual rule-of-thumb, requiring three elements within the process zone, is not adequate.

8. We placed off-fault stations all around the fault, as we expect to do in the validation exercises.

- Agreement is generally OK.
- Agreement worsens with increasing distance from fault, and increasing distance along-strike.

9. The effects of propagating through the 3D velocity model (as opposed to a 1D velocity model) can be clearly seen, but they seem to be modest.

Moving to Validation (Slide 1)

Our group has focused on code *verification* — confirming that our codes operate correctly in a variety of circumstances. We do this by testing if our codes match each other.

We are now moving toward *validation* — confirming that our codes can correctly model what happens in nature.

Here is what we said in our 2016-2017 SCEC proposal:

> "For our primary 2016 dynamic rupture benchmark, we are aiming for code validation, a longtime goal that we are ready to try. We plan to use spontaneous (dynamic) rupture propagation to simulate the 1979 Imperial Valley earthquake set in 1D and 3D velocity structures and to test if we can reliably replicate aspects of its strong ground motions recordings."

TPV34 is our first step toward validation. We modeled a fault set in the 3D velocity structure surrounding the Imperial Fault, as given by SCEC Community Velocity Model CVM-H, with minimum V_S equal to 1400 m/s.

Moving to Validation (Slide 2)

TPV34 is a warm-up for the validation exercises coming in 2016-2017:

- TPV35 — Imperial Fault, Model 2 — Planar vertical fault.
- TPV36 — Imperial Fault, Model 2 — Fault geometry from the Community Fault Model.

And here are some of the challenges:

- Validation is hard. Successful validation may take several years.
- Our first attempt at validation may not be very good, but we'll learn a lot.
- There are a lot of open questions on how to go about validation, for example:
    - What does it mean for a simulation to "match" seismic data?
    - How do we go about constructing initial conditions and friction parameters?
    - What data should we use? Do we need new preliminary results, such as new source inversions? And how do we get them?