Vertical Planar Fault in a 1D Velocity Structure Benchmarks

TPV31 — Discontinuous Case
TPV32 — Continuous Case

Michael Barall
Invisible Software, Inc.

SCEC Rupture Dynamics Code Verification Workshop

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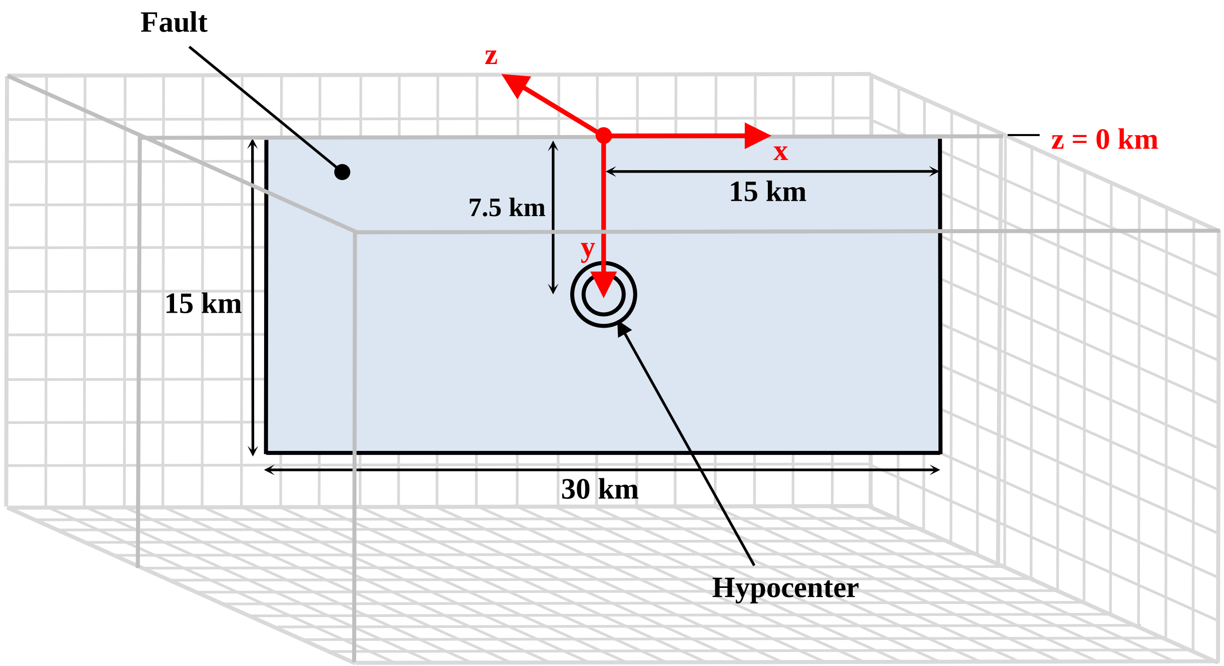
TPV31 (Discontinuous) and TPV32 (Continuous) — Vertical Planar Fault in a 1D Velocity Structure

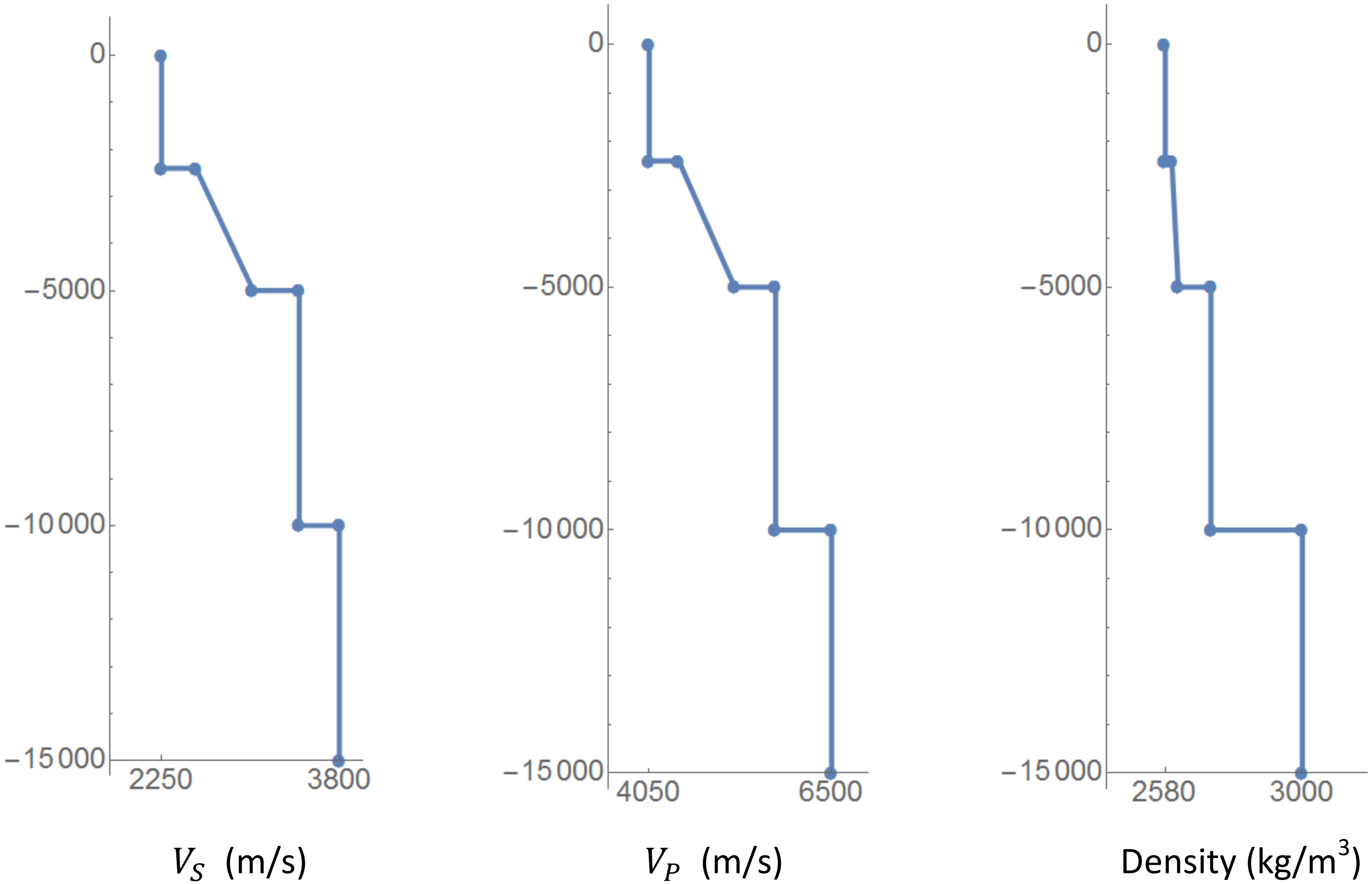


Right-lateral strike-slip fault in an elastic half-space with a 1D velocity structure.

TPV31 — Discontinuous 1D velocity model, minimum V_S = 2250 m/s.

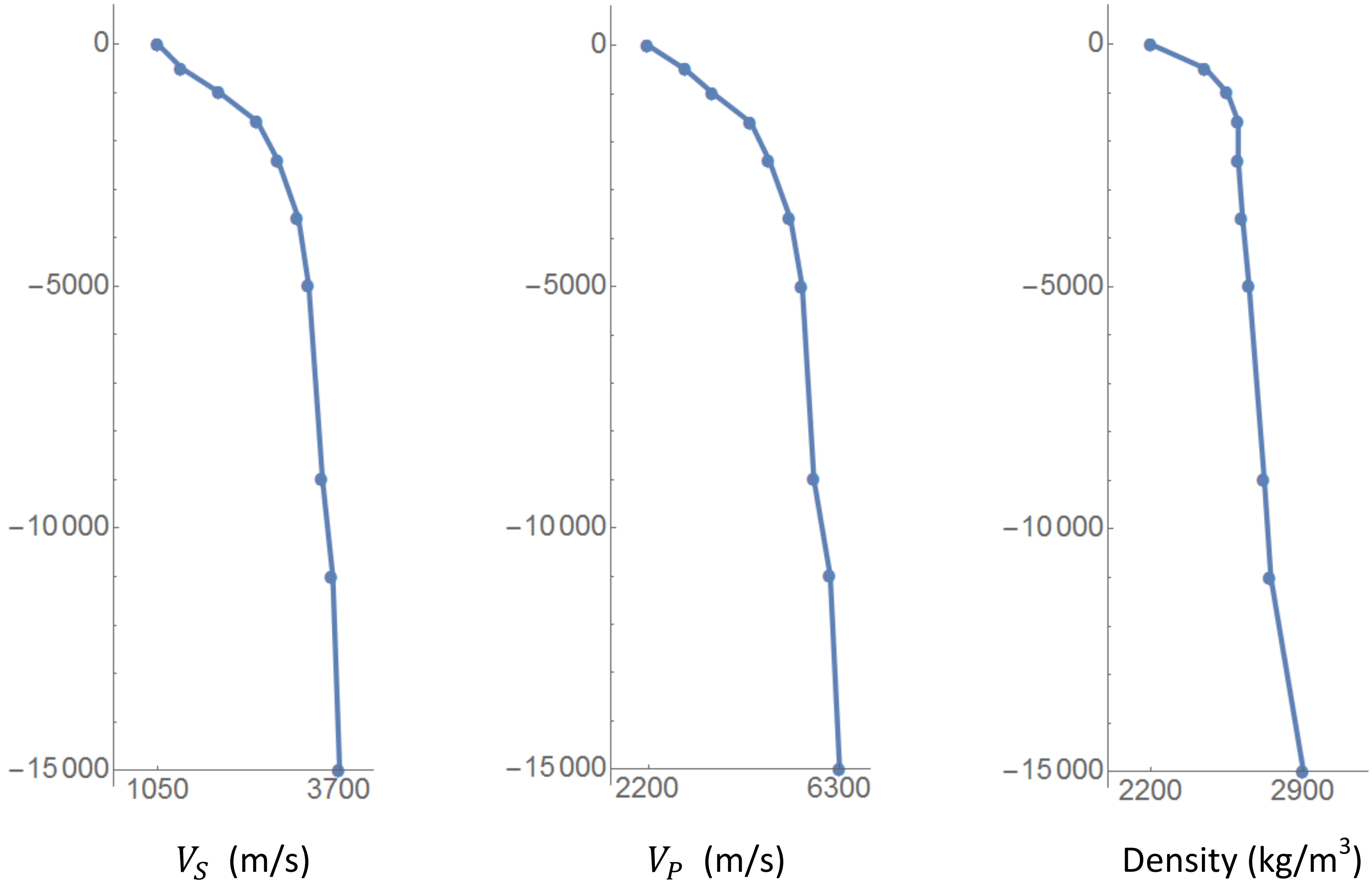
TPV32 — Continuous 1D velocity model, minimum V_S = 1050 m/s.

TPV31 Velocity Structure



There are discontinuities at depths of 2400 m, 5000 m, and 10000 m.
At each discontinuity, the shear modulus changes by about 30 percent.

TPV32 Velocity Structure



The velocity structure is continuous and piecewise-linear.
There is a sharp decrease in velocity in the uppermost 2 km.

Initial Stress Tensor – Constant Strain

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

Vertical stress $\sigma_{22} = 0 \text{ MPa}$

No gravity, so no vertical stress. (Also no fluid pressure.)

Fault-parallel stress $\sigma_{11} = (-60 \text{ MPa})(\mu/\mu_0)$

Fault-normal stress $\sigma_{33} = (-60 \text{ MPa})(\mu/\mu_0)$

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

Vertical shear stress $\sigma_{23} = 0 \text{ MPa}$

Fault-parallel shear stress $\sigma_{12} = 0 \text{ MPa}$

Stress proportional to shear modulus μ.

In the above formulas:

$\mu = \text{shear modulus}$

$\mu_0 = \text{TPV5 shear modulus} = 32.03812032 \text{ GPa}$

Parameters for Slip-Weakening Friction

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 = 1.02 MPa at the earth's surface.

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

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

- 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.

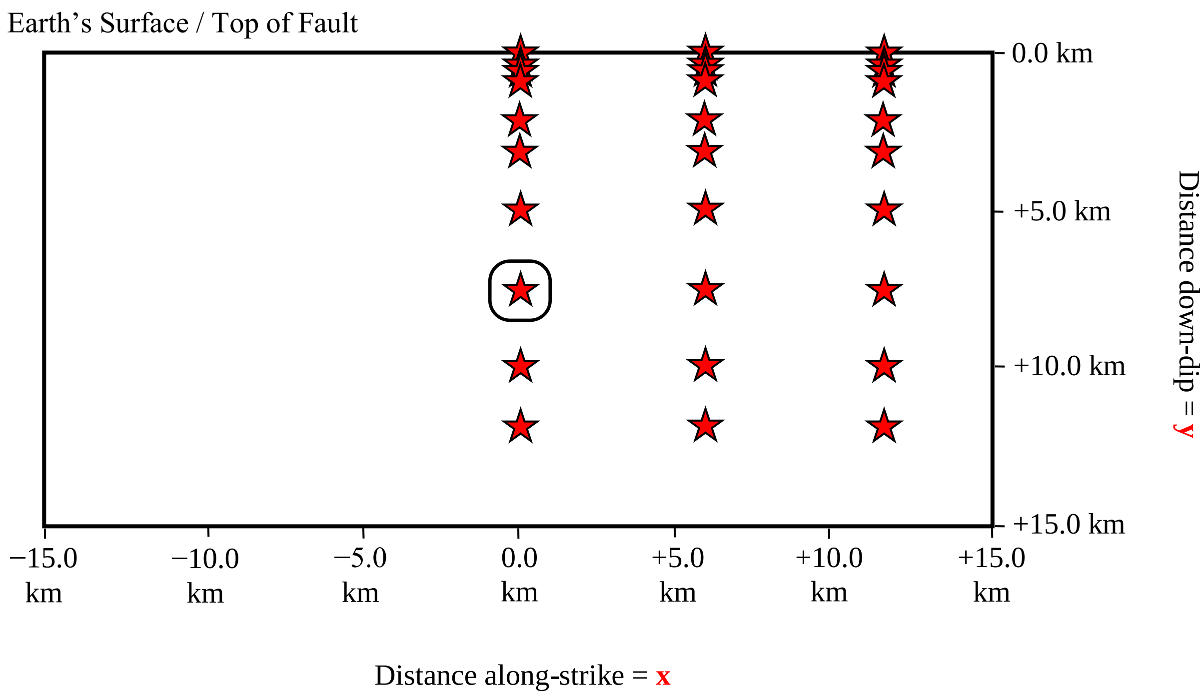
The additional shear stress for nucleation is:

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

Where r is distance to the hypocenter:

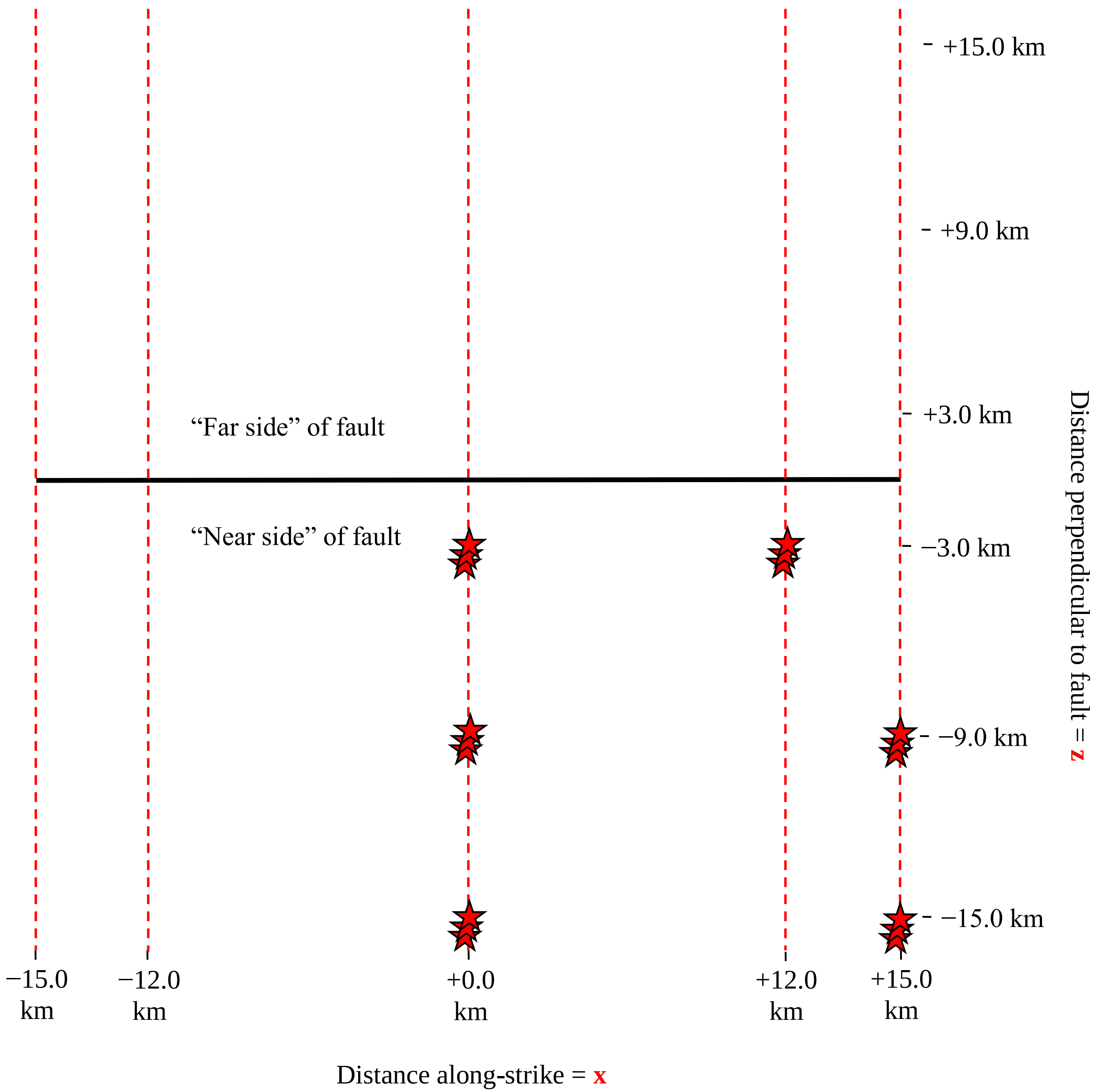
$$r = \sqrt{x^2 + (y - 7500\ \text{m})^2}$$

On-Fault Stations.



Modelers are asked to submit slip, slip rate, and stress as a function of time, for 30 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.



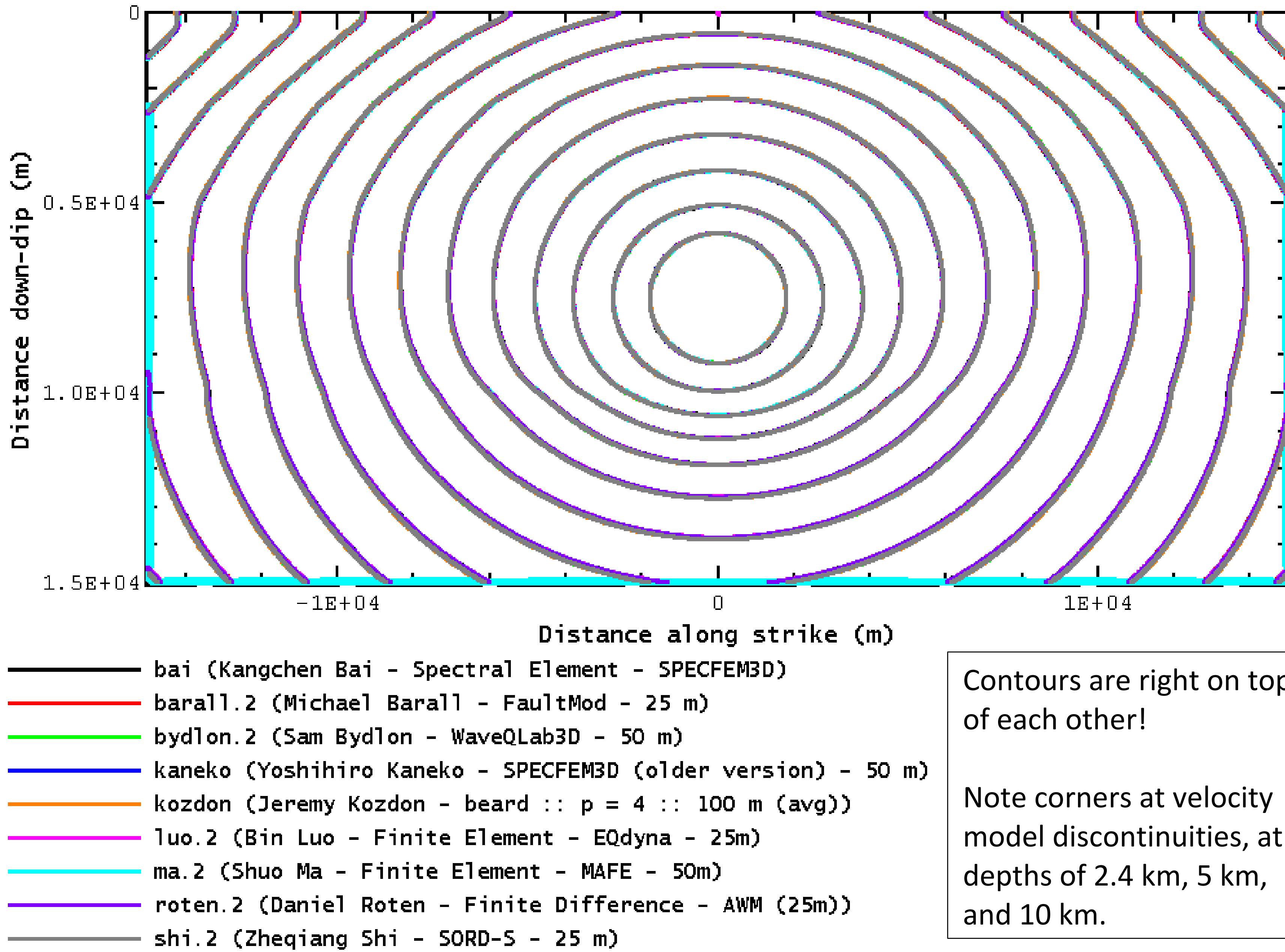
Off-Fault Stations.

Modelers are asked to submit displacement and velocity as a function of time, for 18 stations.

Stations are organized into 6 "boreholes" with stations at depths of 0 km, 0.5 km, and 2.4 km.

TPV31-32 Rupture Contours

TPV31 Rupture Contours — Highest Resolution from Each of 9 Modelers



Contours are right on top of each other!

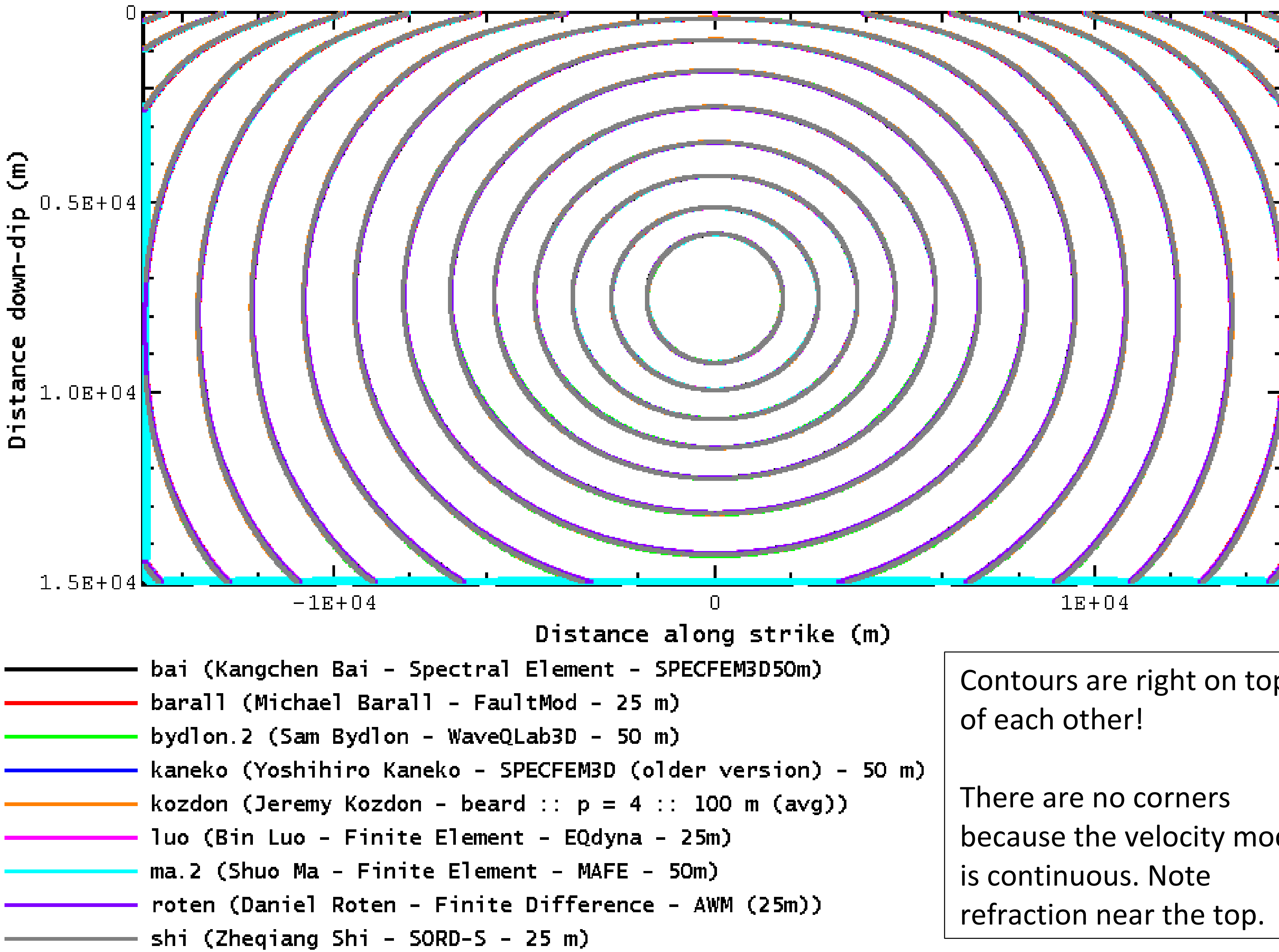
Note corners at velocity model discontinuities, at depths of 2.4 km, 5 km, and 10 km.

TPV31 Rupture Contours — Metrics (RMS Difference in Rupture Time)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) bai		3.8	13.8	2.5	16.0	3.0	8.4	3.4	14.1
(2) barall.2	3.8		14.0	4.7	16.1	5.8	6.8	6.3	13.9
(3) bydlon.2	13.8	14.0		11.8	2.6	13.7	9.1	12.2	2.2
(4) kaneko	2.5	4.7	11.8		13.9	3.2	7.4	2.2	12.1
(5) kozdon	16.0	16.1	2.6	13.9		15.8	11.2	14.2	2.8
(6) luo.2	3.0	5.8	13.7	3.2	15.8		9.5	2.7	14.2
(7) ma.2	8.4	6.8	9.1	7.4	11.2	9.5		9.0	8.9
(8) roten.2	3.4	6.3	12.2	2.2	14.2	2.7	9.0		12.7
(9) shi.2	14.1	13.9	2.2	12.1	2.8	14.2	8.9	12.7	

The maximum value is only 16.1 milliseconds!

TPV32 Rupture Contours — Highest Resolution from Each of 9 Modelers



Contours are right on top of each other!

There are no corners because the velocity model is continuous. Note refraction near the top.

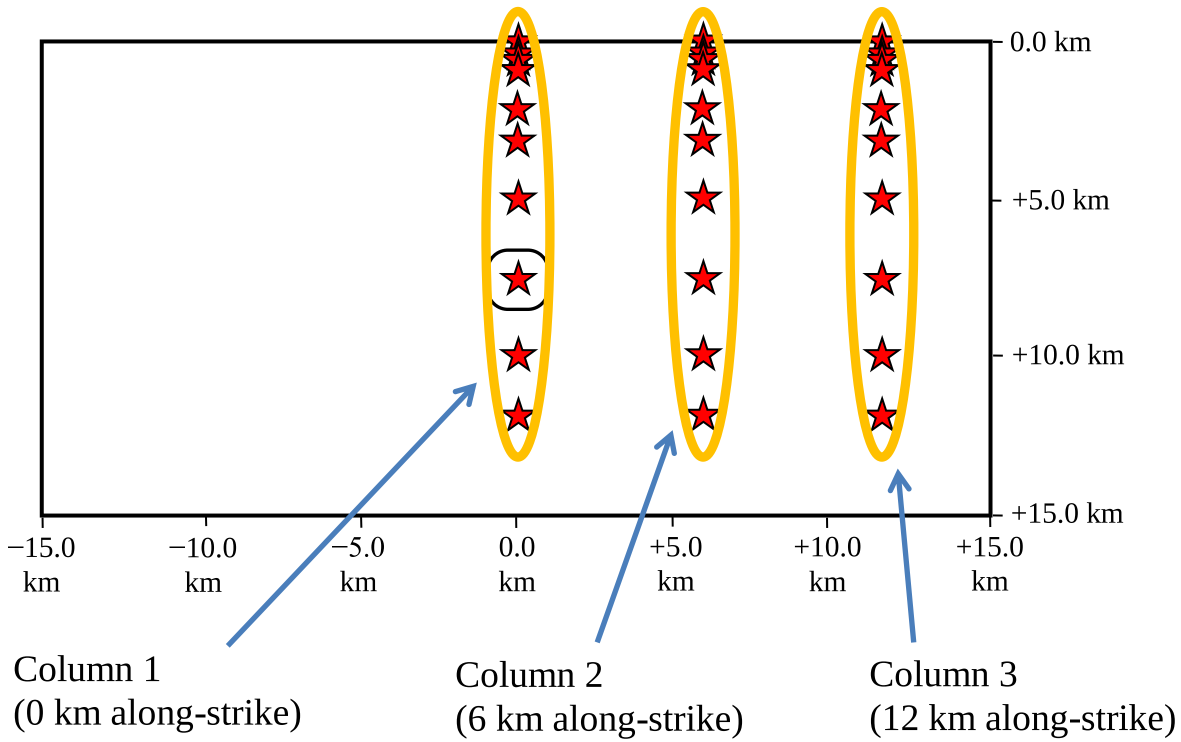
TPV32 Rupture Contours — Metrics (RMS Difference in Rupture Time)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) bai		3.4	12.3	2.1	15.3	2.6	4.9	3.2	13.1
(2) barall	3.4		13.3	4.3	16.4	5.0	4.5	6.0	13.8
(3) bydlon.2	12.3	13.3		11.0	9.0	12.6	10.1	11.2	8.1
(4) kaneko	2.1	4.3	11.0		13.5	3.0	4.1	2.2	11.4
(5) kozdon	15.3	16.4	9.0	13.5		15.3	12.6	13.2	3.2
(6) luo	2.6	5.0	12.6	3.0	15.3		6.0	2.6	13.3
(7) ma.2	4.9	4.5	10.1	4.1	12.6	6.0		5.6	10.0
(8) roten	3.2	6.0	11.2	2.2	13.2	2.6	5.6		11.5
(9) shi	13.1	13.8	8.1	11.4	3.2	13.3	10.0	11.5	

The maximum value is only 16.4 milliseconds!

Process Zone Width

Process Zone Width for TPV31 and TPV32



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

We have 30 stations, organized in 3 columns of 10 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.

TPV31 (Min V_S = 2250) Process Zone Width – Column 1 (at 0 km Along-Strike)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst000dp000	217	212	219	216	216	240	207	208	209
faultst000dp002	327	323	320	321	319	336	318	324	321
faultst000dp005	386	381	374	380	379	383	371	383	382
faultst000dp010	357	352	351	358	352	360	335	362	356
faultst000dp024	293	289	289	295	292	296	271	298	290
faultst000dp030	352	354	343	349	347	352	339	350	347
faultst000dp050	380	380	378	378	381	383	366	387	376
faultst000dp100	591	589	588	591	592	601	574	606	591
faultst000dp120	420	422	422	421	423	423	422	422	421

(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D	**(6) luo.2**	Bin Luo - Finite Element - EQdyna - 25m
(2) barall.2	Michael Barall - FaultMod - 25 m	**(7) ma.2**	Shuo Ma - Finite Element - MAFE - 50m
(3) bydlon.2	Sam Bydlon - WaveQLab3D - 50 m	**(8) roten.2**	Daniel Roten - Finite Difference - AWM (25m)
(4) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m	**(9) shi.2**	Zheqiang Shi - SORD-S - 25 m
(5) kozdon	Jeremy Kozdon - beard :: p = 4 :: 100 m (avg)		

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

TPV31 (Min V_S = 2250) Process Zone Width – Column 2 (at 6 km Along-Strike)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst060dp000	210	211	212	208	209	205	207	199	207
faultst060dp002	280	277	274	276	273	275	273	280	276
faultst060dp005	345	344	343	345	346	349	332	349	348
faultst060dp010	326	318	320	325	324	334	298	331	317
faultst060dp024	292	287	284	290	287	302	266	297	281
faultst060dp030	322	322	317	324	319	333	309	326	316
faultst060dp050	418	418	415	418	415	427	395	429	414
faultst060dp075	479	480	477	479	477	485	473	483	477
faultst060dp100	452	451	453	451	451	455	434	461	450
faultst060dp120	414	412	411	411	411	417	402	414	410

(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D	**(6) luo.2**	Bin Luo - Finite Element - EQdyna - 25m
(2) barall.2	Michael Barall - FaultMod - 25 m	**(7) ma.2**	Shuo Ma - Finite Element - MAFE - 50m
(3) bydlon.2	Sam Bydlon - WaveQLab3D - 50 m	**(8) roten.2**	Daniel Roten - Finite Difference - AWM (25m)
(4) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m	**(9) shi.2**	Zheqiang Shi - SORD-S - 25 m
(5) kozdon	Jeremy Kozdon - beard :: p = 4 :: 100 m (avg)		

Cohesive zone width is about the same as in column 1.

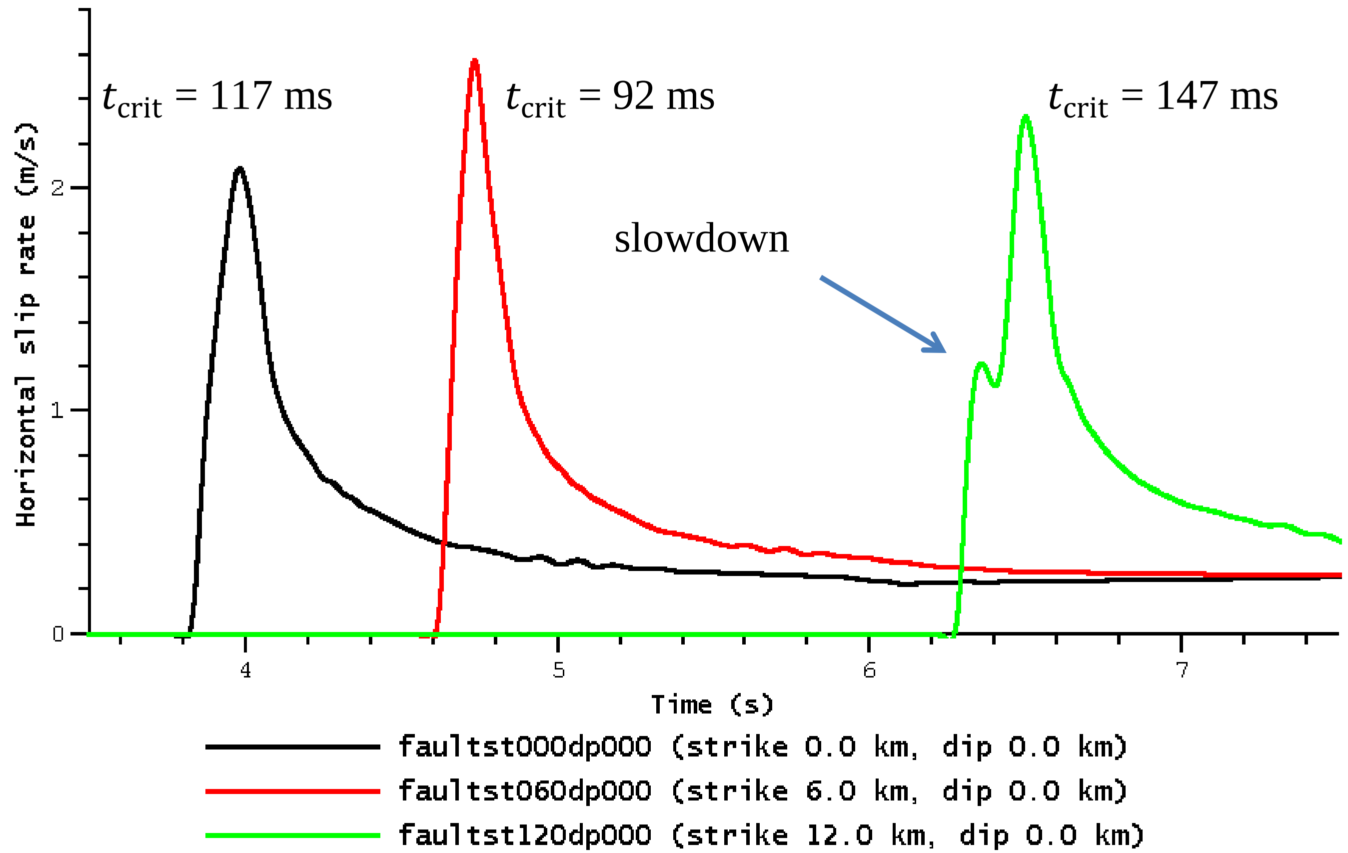
TPV31 (Min V_S = 2250) Process Zone Width – Column 3 (at 12 km Along-Strike)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst120dp000	478	488	475	475	478	465	471	463	485
faultst120dp002	350	362	339	345	342	341	354	334	349
faultst120dp005	228	229	221	225	221	237	213	224	215
faultst120dp010	224	212	212	216	215	239	192	222	202
faultst120dp024	222	216	206	213	209	235	192	221	201
faultst120dp030	242	241	230	239	232	260	223	242	226
faultst120dp050	344	345	338	343	338	355	320	354	338
faultst120dp075	328	331	319	327	321	342	312	333	320
faultst120dp100	313	316	303	327	305	329	286	323	303
faultst120dp120	324	325	317	322	317	337	309	326	316

(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D	**(6) luo.2**	Bin Luo - Finite Element - EQdyna - 25m
(2) barall.2	Michael Barall - FaultMod - 25 m	**(7) ma.2**	Shuo Ma - Finite Element - MAFE - 50m
(3) bydlon.2	Sam Bydlon - WaveQLab3D - 50 m	**(8) roten.2**	Daniel Roten - Finite Difference - AWM (25m)
(4) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m	**(9) shi.2**	Zheqiang Shi - SORD-S - 25 m
(5) kozdon	Jeremy Kozdon - beard :: p = 4 :: 100 m (avg)		

Reduced cohesive zone width in column 3, except at the earth's surface where it increased.

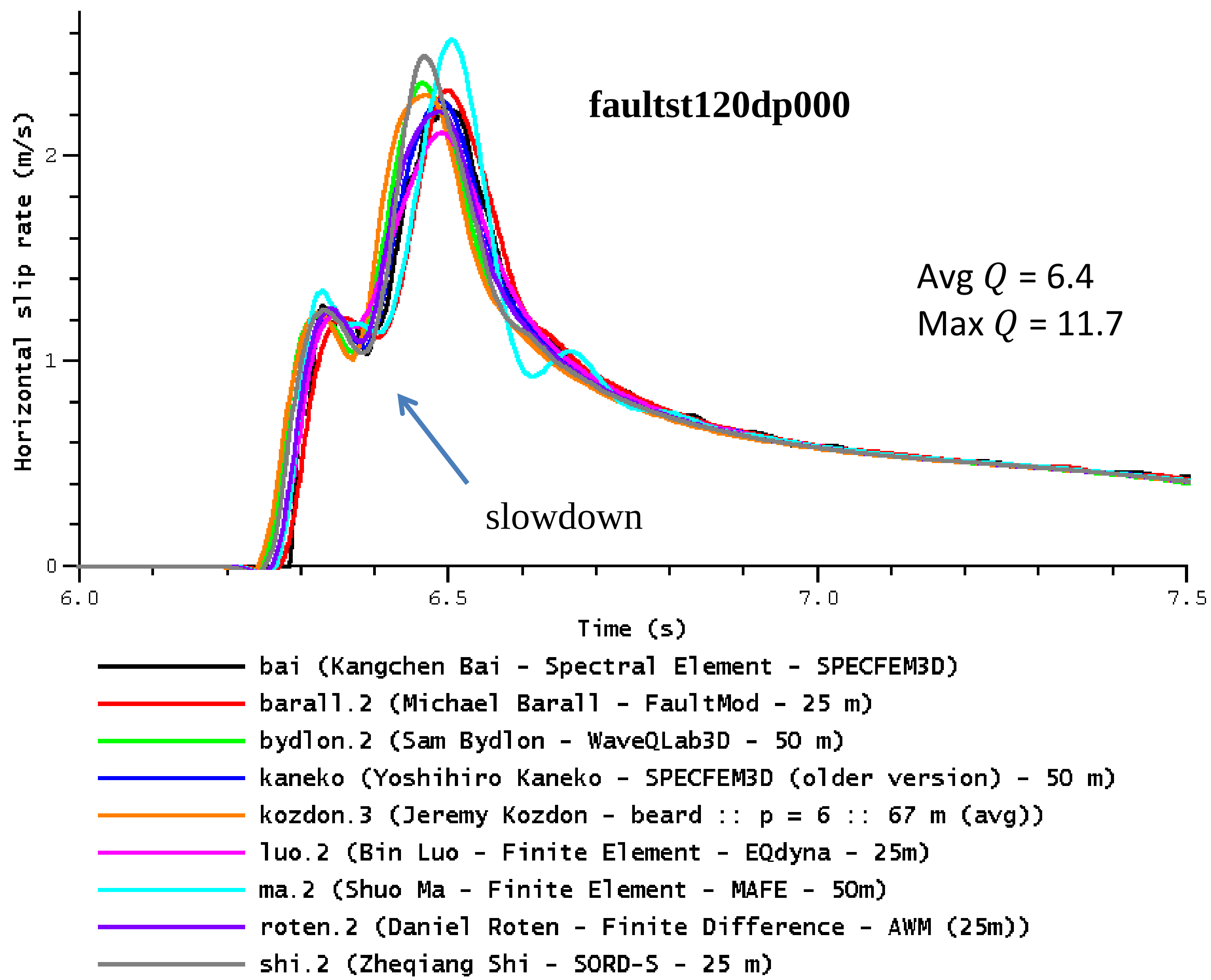
Increased Process Zone Width at 12 km Along Strike, on the Earth's Surface, in TPV31



Process zone width is computed as $V_R t_{\text{crit}}$ where V_R is rupture velocity and t_{crit} is the time required for accumulated slip to equal the critical slip distance.

Process zone width increases at 12 km along-strike mainly because a brief slowdown in the slip rate increases t_{crit}.

Increased Process Zone Width at 12 km Along Strike, on the Earth's Surface, in TPV31



All the codes show this slowdown in slip rate. Low metric Q values indicate good agreement.

TPV32 (Min V_S = 1050) Process Zone Width – Column 1 (at 0 km Along-Strike)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst000dp000	93	85	97	91	96	98	87	94	81
faultst000dp002	198	186	193	195	191	202	182	200	185
faultst000dp005	179	176	181	180	187	186	167	187	174
faultst000dp010	236	229	227	236	235	238	213	240	228
faultst000dp024	345	346	343	346	348	350	337	349	345
faultst000dp030	377	379	374	376	378	380	371	379	374
faultst000dp050	436	434	431	433	437	440	431	437	432
faultst000dp100	465	463	472	237	468	473	464	471	465
faultst000dp120	432	432	437	433	434	436	436	435	434

(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D50m	**(6) luo**	Bin Luo - Finite Element - EQdyna - 25m
(2) barall	Michael Barall - FaultMod - 25 m	**(7) ma.2**	Shuo Ma - Finite Element - MAFE - 50m
(3) bydlon.2	Sam Bydlon - WaveQLab3D - 50 m	**(8) roten**	Daniel Roten - Finite Difference - AWM (25m)
(4) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m	**(9) shi**	Zheqiang Shi - SORD-S - 25 m
(5) kozdon	Jeremy Kozdon - beard :: p = 4 :: 100 m (avg)		

Good agreement between codes. Note very small widths at the earth's surface.

TPV32 (Min V_S = 1050) Process Zone Width – Column 2 (at 6 km Along-Strike)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst060dp000	80	72	81	78	82	79	78	80	67
faultst060dp002	175	166	166	177	171	182	150	180	165
faultst060dp005	169	162	165	168	172	178	149	174	158
faultst060dp010	221	210	210	217	217	226	195	221	205
faultst060dp024	322	323	321	325	322	334	309	327	319
faultst060dp030	354	354	351	355	351	362	342	357	349
faultst060dp050	433	434	432	433	431	440	425	437	431
faultst060dp075	478	479	478	478	475	485	477	481	476
faultst060dp100	461	461	456	462	459	467	456	465	459
faultst060dp120	419	417	416	417	417	424	413	420	415

(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D50m	**(6) luo**	Bin Luo - Finite Element - EQdyna - 25m
(2) barall	Michael Barall - FaultMod - 25 m	**(7) ma.2**	Shuo Ma - Finite Element - MAFE - 50m
(3) bydlon.2	Sam Bydlon - WaveQLab3D - 50 m	**(8) roten**	Daniel Roten - Finite Difference - AWM (25m)
(4) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m	**(9) shi**	Zheqiang Shi - SORD-S - 25 m
(5) kozdon	Jeremy Kozdon - beard :: p = 4 :: 100 m (avg)		

Cohesive zone width slightly reduced, as compared to column 1.

TPV32 (Min V_S = 1050) Process Zone Width – Column 3 (at 12 km Along-Strike)

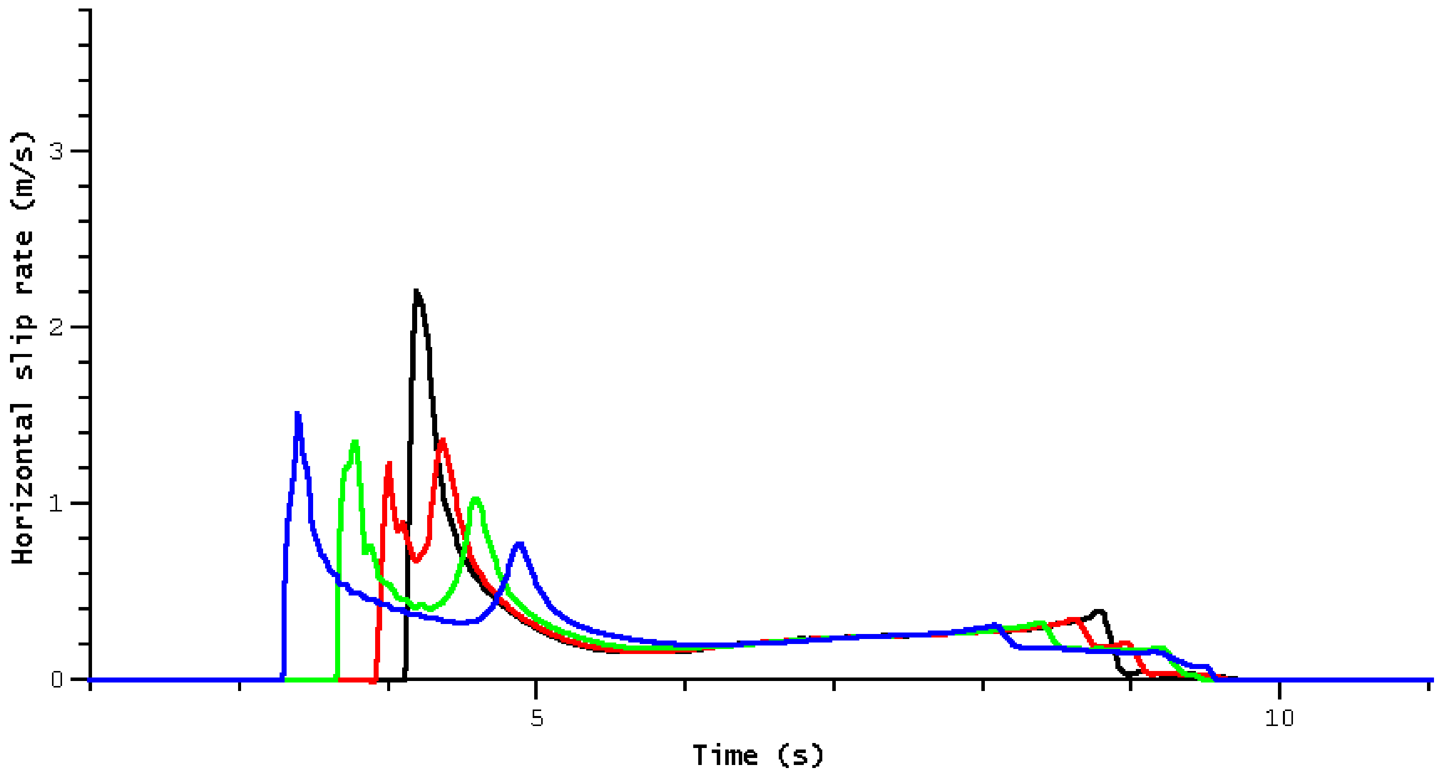
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst120dp000	60	58	62	59	63	62	66	63	53
faultst120dp002	136	123	116	137	132	149	105	143	119
faultst120dp005	139	124	126	134	135	148	113	137	117
faultst120dp010	181	169	170	178	174	192	152	179	159
faultst120dp024	253	249	241	249	243	267	235	253	238
faultst120dp030	271	270	261	269	262	286	252	273	258
faultst120dp050	308	310	299	306	301	322	291	312	299
faultst120dp075	319	323	312	318	311	333	304	324	311
faultst120dp100	323	326	306	322	316	337	307	328	315
faultst120dp120	323	323	310	321	315	336	309	326	314

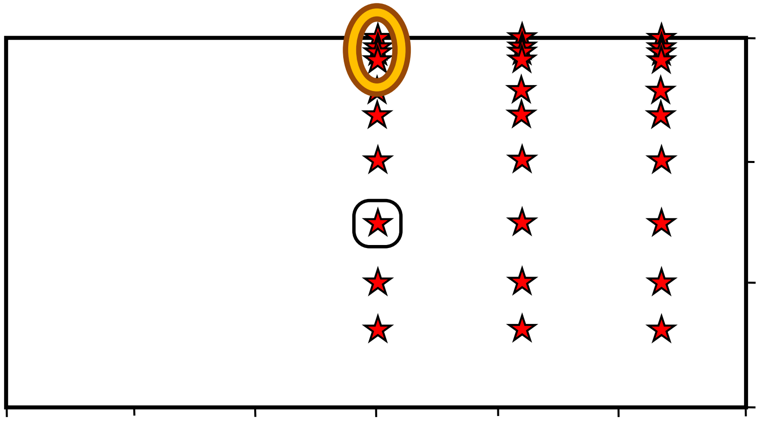
(1) bai	Kangchen Bai - Spectral Element - SPECFEM3D50m	**(6) luo**	Bin Luo - Finite Element - EQdyna - 25m
(2) barall	Michael Barall - FaultMod - 25 m	**(7) ma.2**	Shuo Ma - Finite Element - MAFE - 50m
(3) bydlon.2	Sam Bydlon - WaveQLab3D - 50 m	**(8) roten**	Daniel Roten - Finite Difference - AWM (25m)
(4) kaneko	Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m	**(9) shi**	Zheqiang Shi - SORD-S - 25 m
(5) kozdon	Jeremy Kozdon - beard :: p = 4 :: 100 m (avg)		

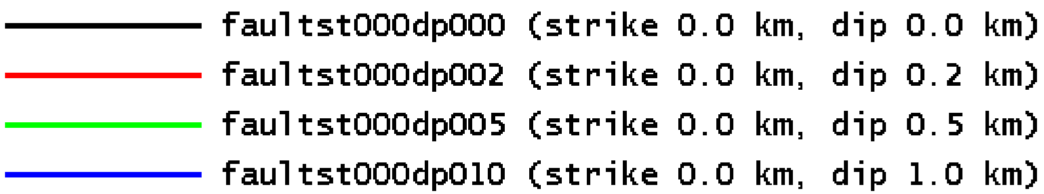
Reduced cohesive zone width in column 3.

Time Series:
On-Fault Stations

TPV32 (Min V_S = 1050) – Behavior of Top Four Stations On-Fault (Slide 1 of 3)

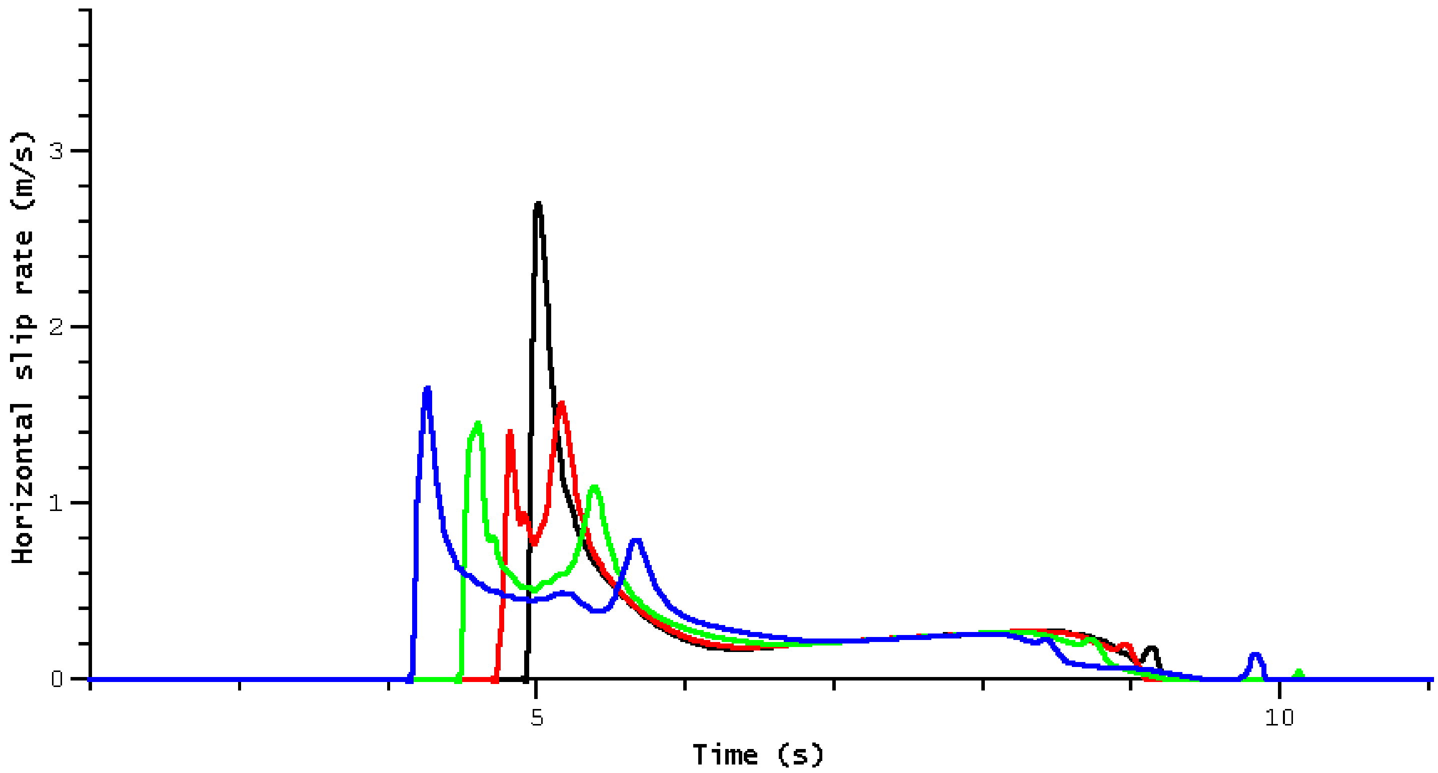


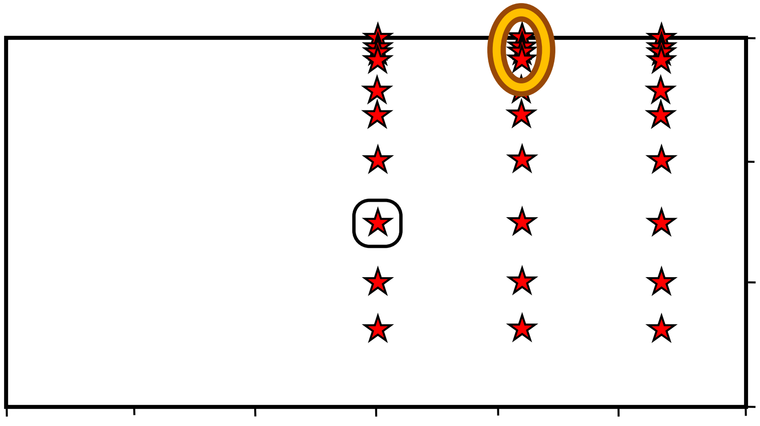




The station at the earth's surface has almost twice the peak slip rate of the station at a depth of 200 meters, which has a distinctive double-peak.

TPV32 (Min V_S = 1050) – Behavior of Top Four Stations On-Fault (Slide 2 of 3)

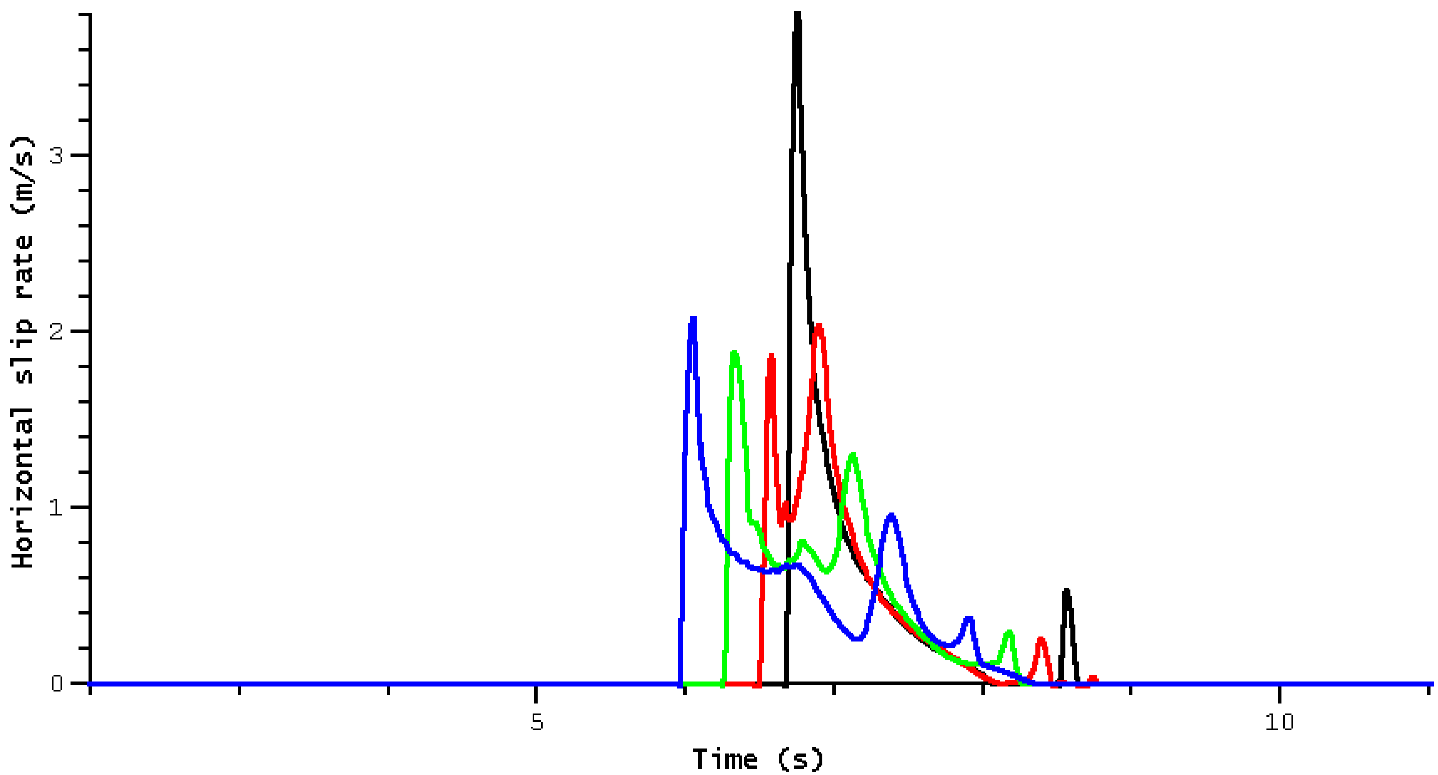


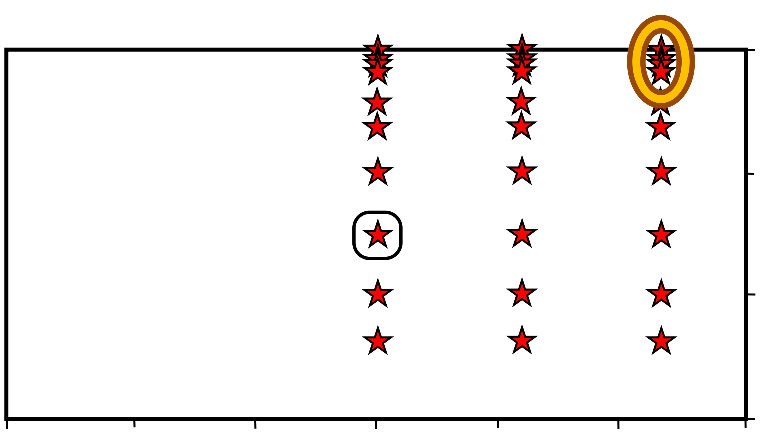


faultst060dp000 (strike 6.0 km, dip 0.0 km)
faultst060dp002 (strike 6.0 km, dip 0.2 km)
faultst060dp005 (strike 6.0 km, dip 0.5 km)
faultst060dp010 (strike 6.0 km, dip 1.0 km)

The station at the earth's surface has almost twice the peak slip rate of the station at a depth of 200 meters, which has a distinctive double-peak.

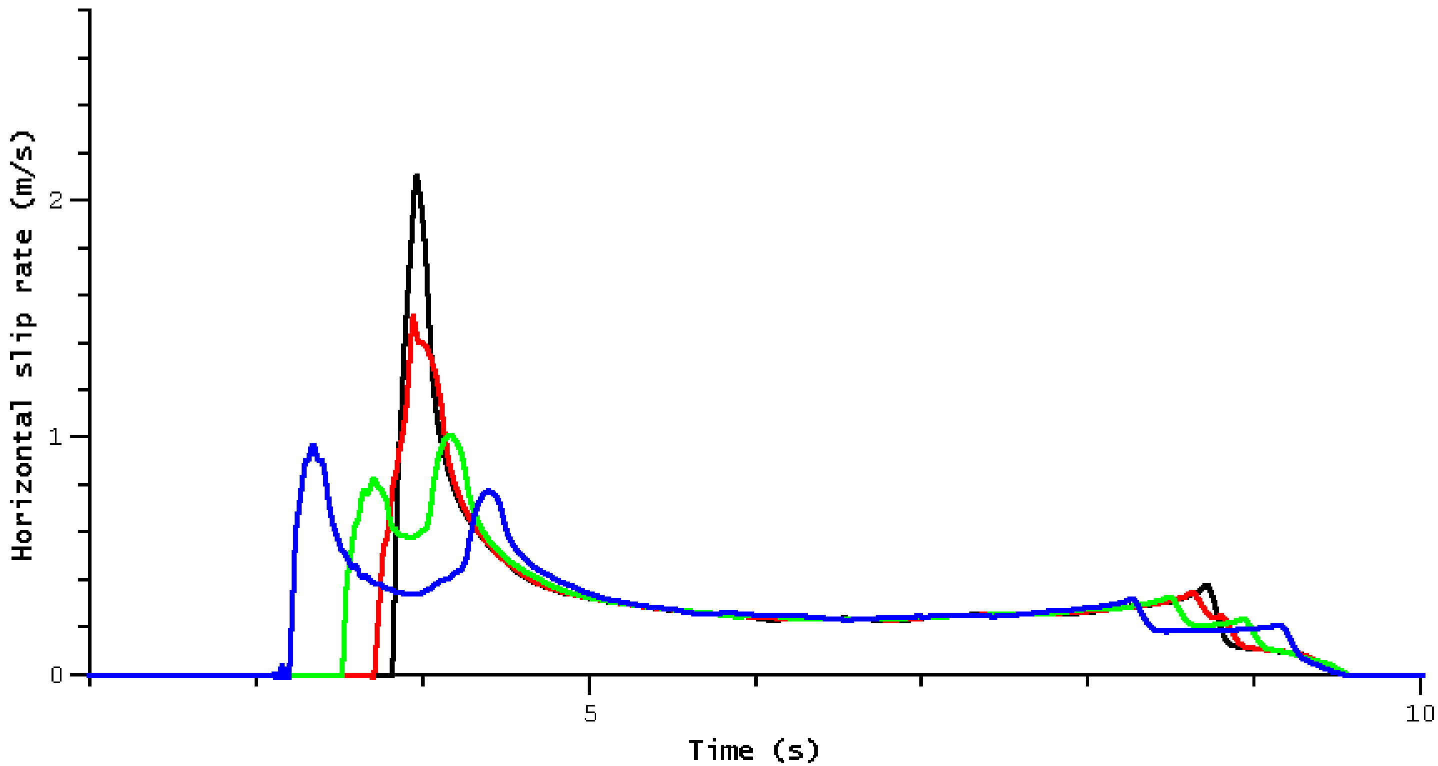
TPV32 (Min V_S = 1050) – Behavior of Top Four Stations On-Fault (Slide 3 of 3)

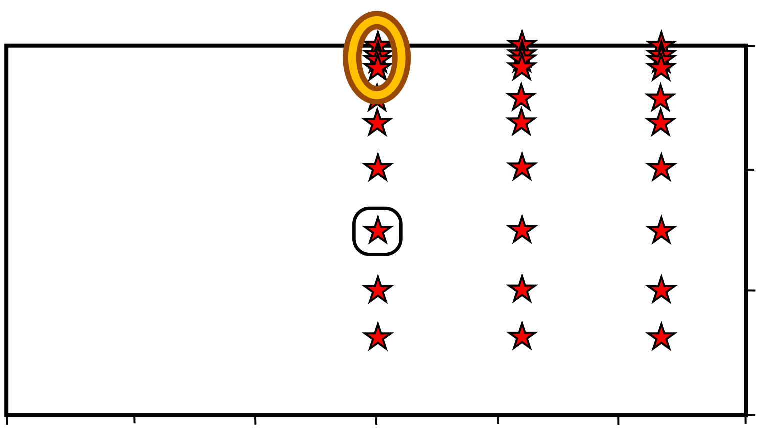




The station at the earth's surface has almost twice the peak slip rate of the station at a depth of 200 meters, which has a distinctive double-peak.

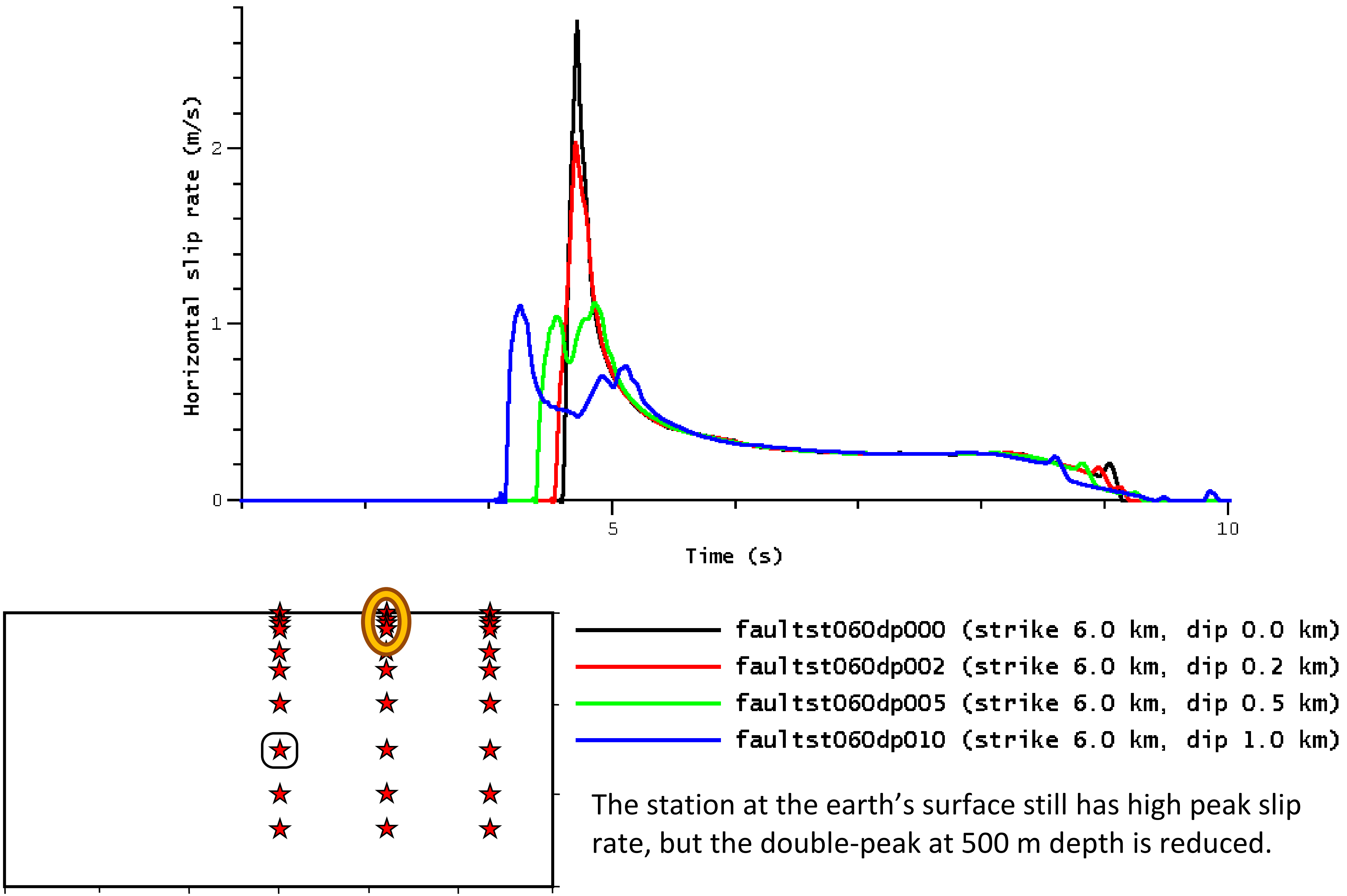
TPV31 (Min V_S = 2250) – Behavior of Top Four Stations On-Fault (Slide 1 of 3)





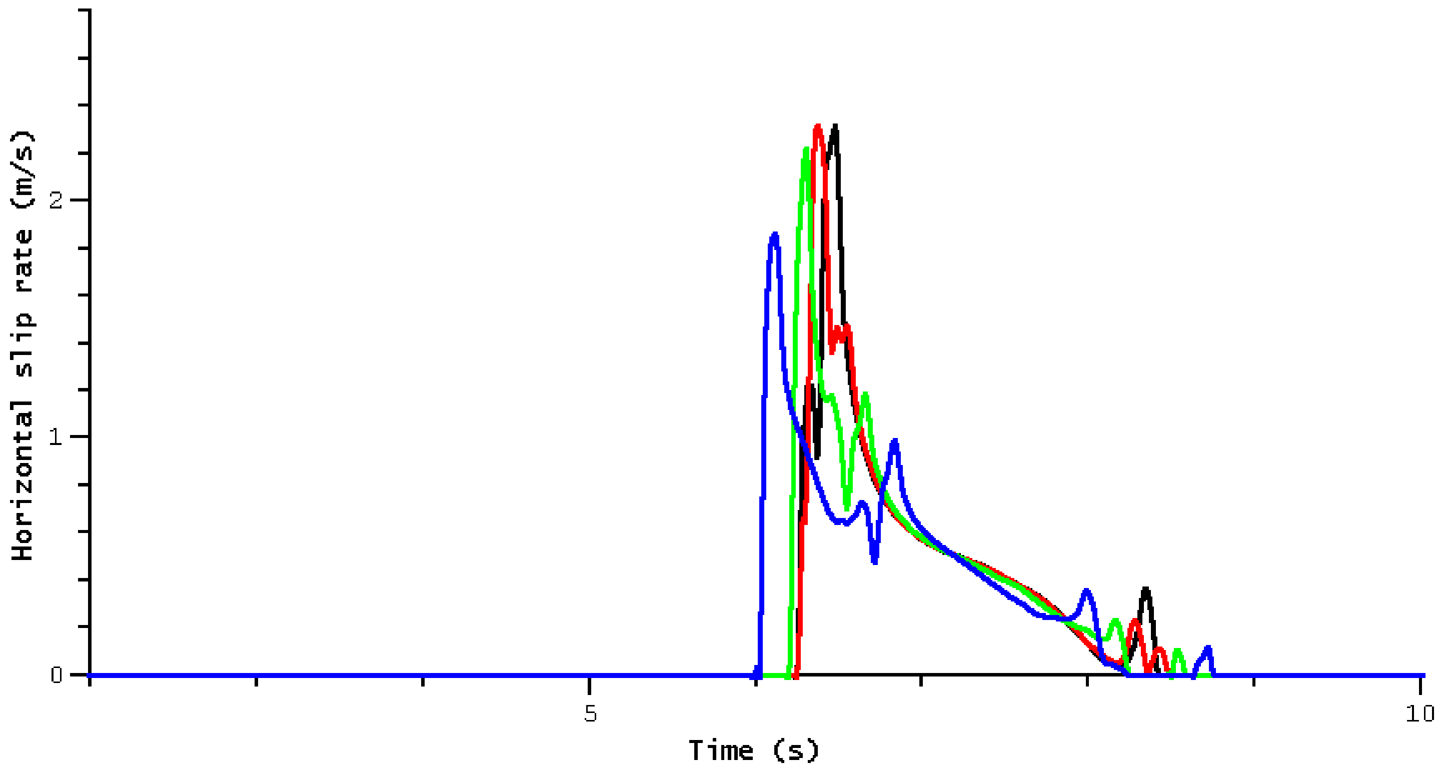
The station at the earth's surface has almost twice the peak slip rate of the station at a depth of 500 meters, which has a double-peak less pronounced than in TPV32.

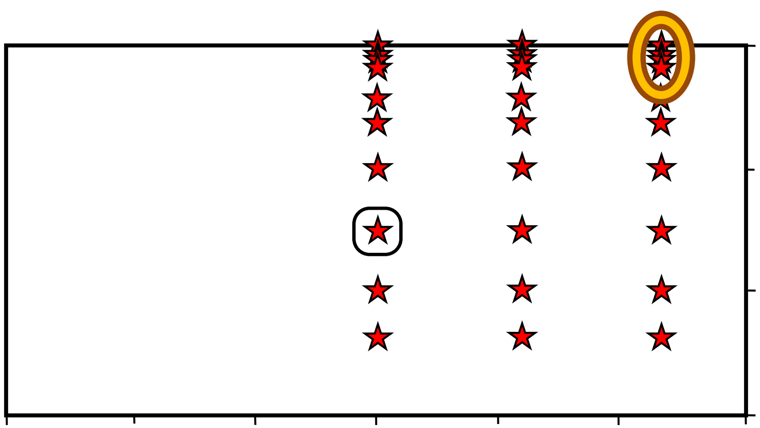
TPV31 (Min V_S = 2250) – Behavior of Top Four Stations On-Fault (Slide 2 of 3)

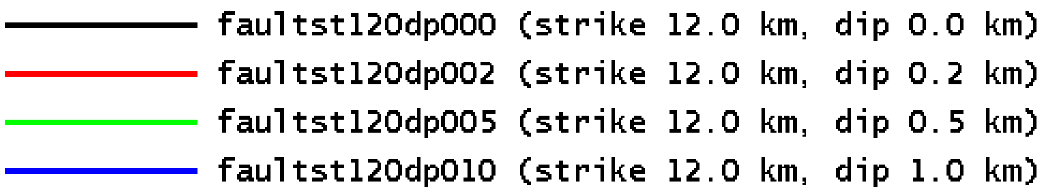


The station at the earth's surface still has high peak slip rate, but the double-peak at 500 m depth is reduced.

TPV31 (Min V_S = 2250) – Behavior of Top Four Stations On-Fault (Slide 3 of 3)







The pattern has changed – peak slip rate at the earth's surface is reduced and no longer exceeds the lower stations; the double peaks are gone.

TPV32 (Continuous, Min V_S = 1050) – Summary Metrics for All On-Fault Stations

	2d-stress	2d-rate
faultst000dp000	7.2	9.1
faultst000dp002	6.7	8.6
faultst000dp005	13.1	6.1
faultst000dp010	9.1	4.1
faultst000dp024	5.8	3.8
faultst000dp030	7.8	4.2
faultst000dp050	8.3	3.6
faultst000dp075	7.6	3.6
faultst000dp100	34.8	24.9
faultst000dp120	4.5	4.3

	2d-stress	2d-rate
faultst060dp000	15.3	9.0
faultst060dp002	9.4	7.2
faultst060dp005	14.8	5.3
faultst060dp010	9.4	3.8
faultst060dp024	5.7	2.8
faultst060dp030	5.6	2.7
faultst060dp050	5.0	2.7
faultst060dp075	3.4	3.4
faultst060dp100	2.8	4.0
faultst060dp120	2.6	3.4

	2d-stress	2d-rate
faultst120dp000	28.3	12.2
faultst120dp002	15.0	9.1
faultst120dp005	11.9	7.0
faultst120dp010	9.6	6.0
faultst120dp024	5.2	4.5
faultst120dp030	5.7	4.0
faultst120dp050	5.3	3.8
faultst120dp075	3.6	4.1
faultst120dp100	3.3	4.4
faultst120dp120	3.0	4.2

These are the waveform comparison metrics, averaged over all pairs of codes, using the best version from each of 9 codes.

Looking at the “2d-rate” column, the stations near the earth’s surface have the most disagreement (highest metric value).

TPV31 (Discontinuous, Min V_S = 2250) – Summary Metrics for All On-Fault Stations

	2d-stress	2d-rate
faultst000dp000	9.2	2.7
faultst000dp002	7.3	2.4
faultst000dp005	7.1	2.5
faultst000dp010	6.9	3.0
faultst000dp024	9.2	3.0
faultst000dp030	4.3	2.9
faultst000dp050	8.6	3.3
faultst000dp075	12.8	3.6
faultst000dp100	6.6	3.9
faultst000dp120	3.1	3.5

	2d-stress	2d-rate
faultst060dp000	10.1	2.9
faultst060dp002	8.6	1.9
faultst060dp005	9.3	2.1
faultst060dp010	7.4	2.8
faultst060dp024	10.3	2.7
faultst060dp030	5.1	2.4
faultst060dp050	9.6	2.5
faultst060dp075	3.1	3.2
faultst060dp100	7.2	3.1
faultst060dp120	2.4	2.9

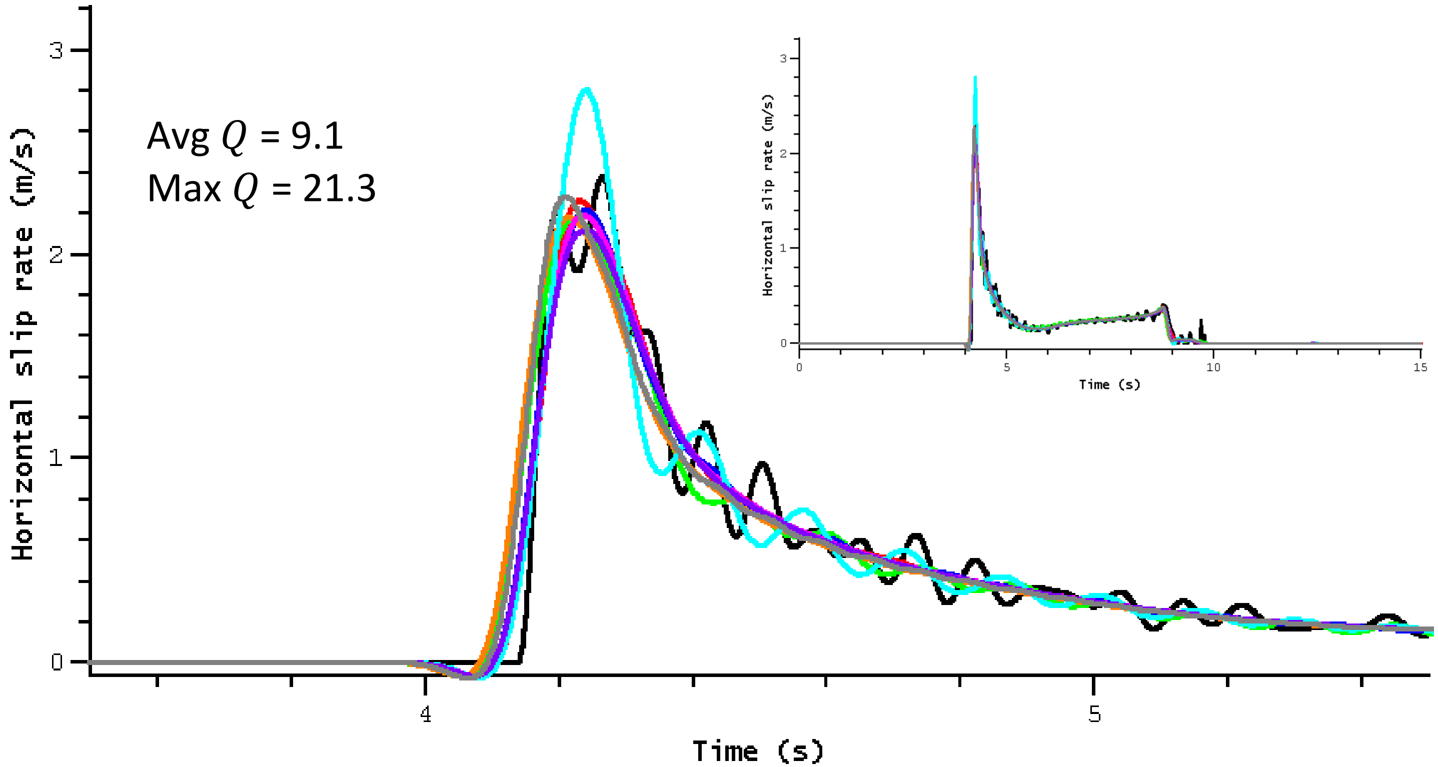
	2d-stress	2d-rate
faultst120dp000	16.3	6.4
faultst120dp002	9.1	3.9
faultst120dp005	9.0	4.4
faultst120dp010	8.4	4.9
faultst120dp024	11.1	4.6
faultst120dp030	6.4	4.0
faultst120dp050	11.3	3.2
faultst120dp075	3.1	3.8
faultst120dp100	27.8	10.4
faultst120dp120	3.0	3.7

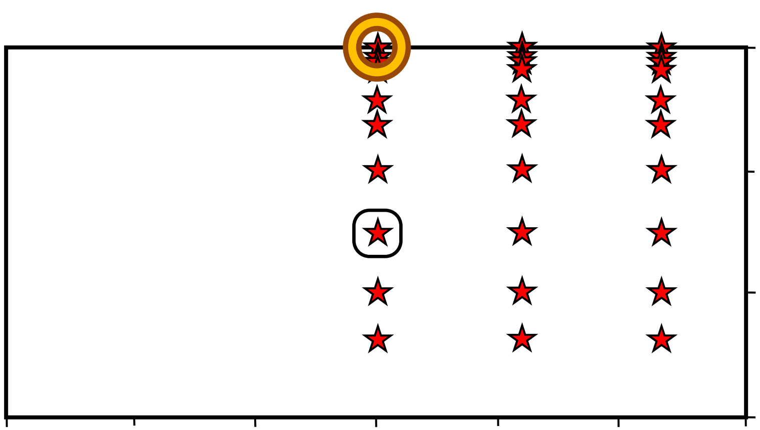
These are the waveform comparison metrics, averaged over all pairs of codes, using the best version from each of 9 codes.

Looking at the “2d-rate” column, the stations near the earth’s surface have little or no tendency to be worse than deeper stations, and have lower metric values (better agreement) than TPV32.

Looking at the “2d-stress” column, stations located at discontinuities (2.4, 5.0, and 10.0 km depth) seem to have higher metric values (worse agreement) than other nearby stations. But this may be a reporting artifact, since the slip rates do not show the same pattern.

TPV32 (Continuous, Min V_S = 1050) – faultst000dp000 – Horizontal Slip Rate

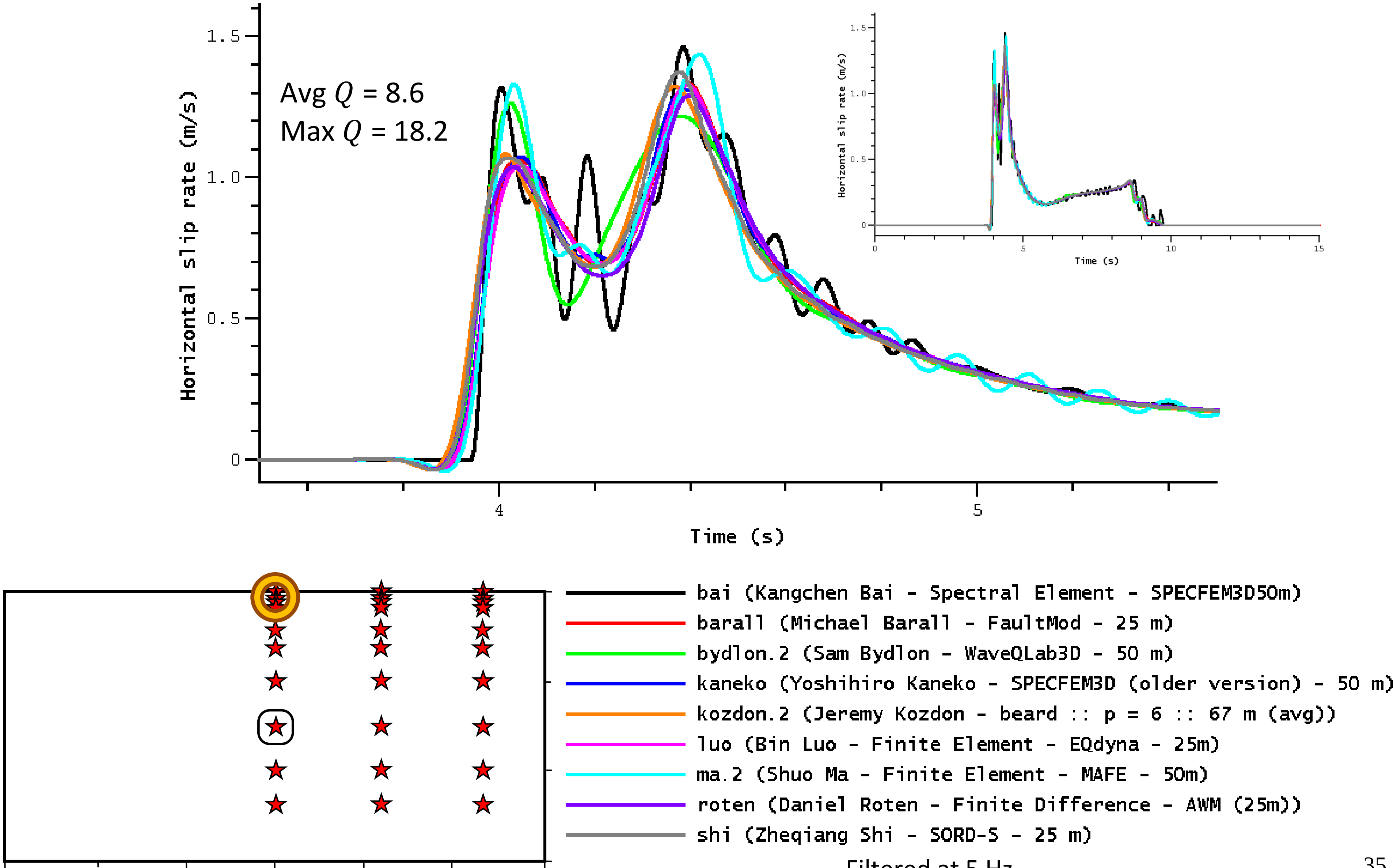




bai (Kangchen Bai - Spectral Element - SPECFEM3D50m)
barall (Michael Barall - FaultMod - 25 m)
bydlon.2 (Sam Bydlon - WaveQLab3D - 50 m)
kaneko (Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m)
kozdon.2 (Jeremy Kozdon - beard :: p = 6 :: 67 m (avg))
luo (Bin Luo - Finite Element - EQdyna - 25m)
ma.2 (Shuo Ma - Finite Element - MAFE - 50m)
roten (Daniel Roten - Finite Difference - AWM (25m))
shi (Zheqiang Shi - SORD-S - 25 m)

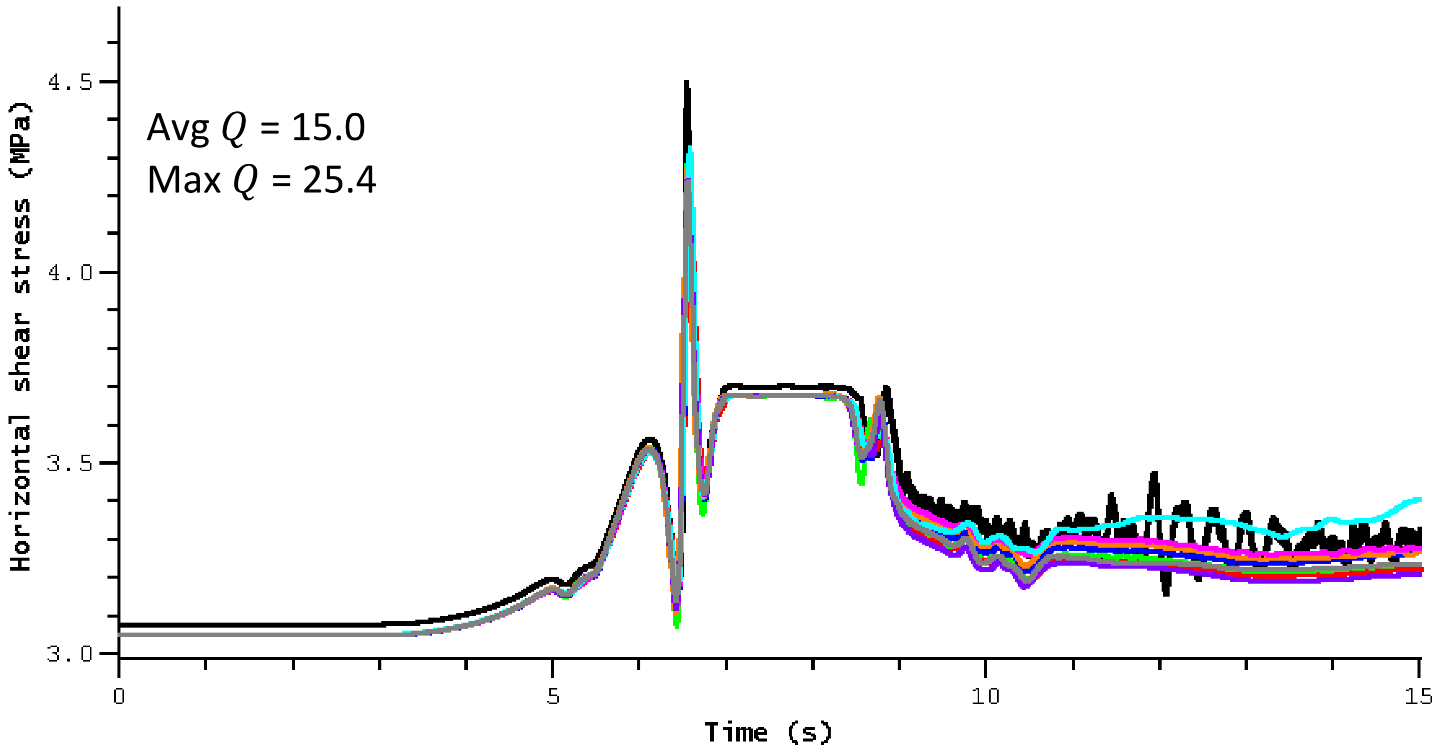
Filtered at 5 Hz.

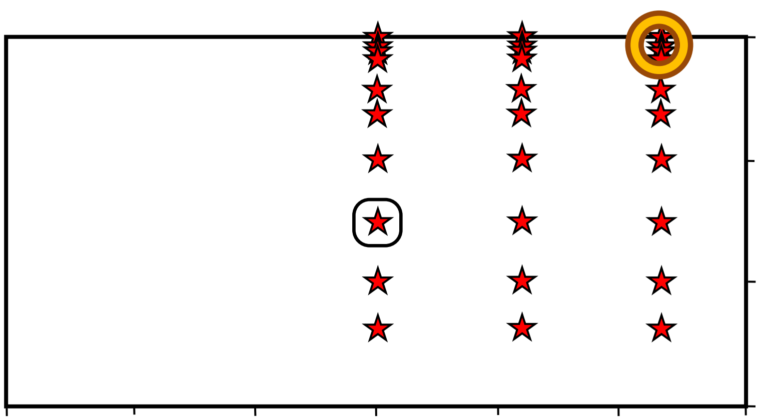
TPV32 (Continuous, Min V_S = 1050) – faultst000dp002 – Horizontal Slip Rate

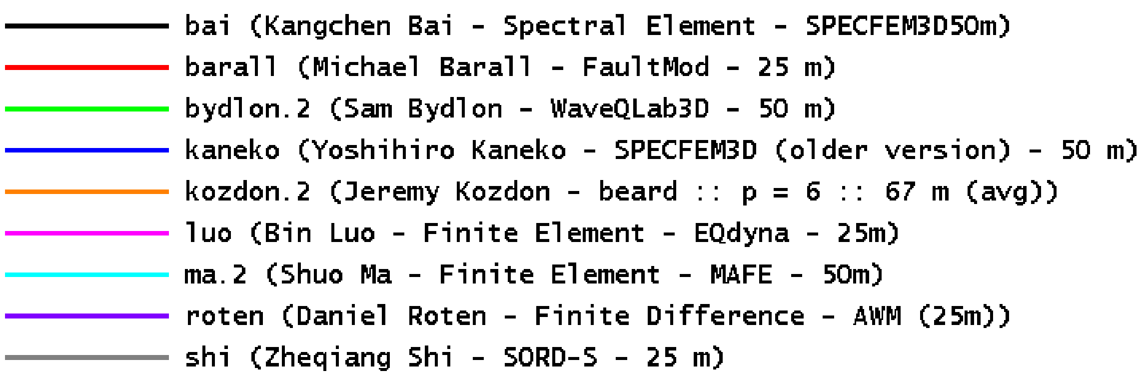


Filtered at 5 Hz.

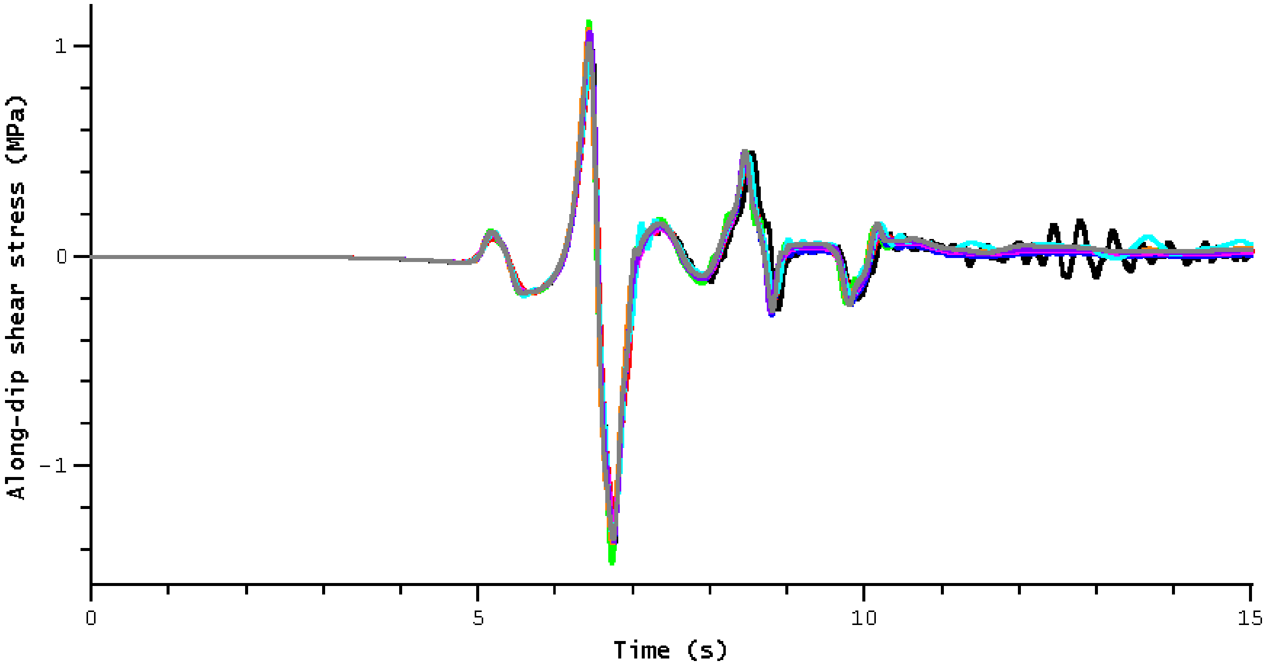
TPV32 (Continuous, Min V_S = 1050) – faultst120dp002 – Horizontal Shear Stress







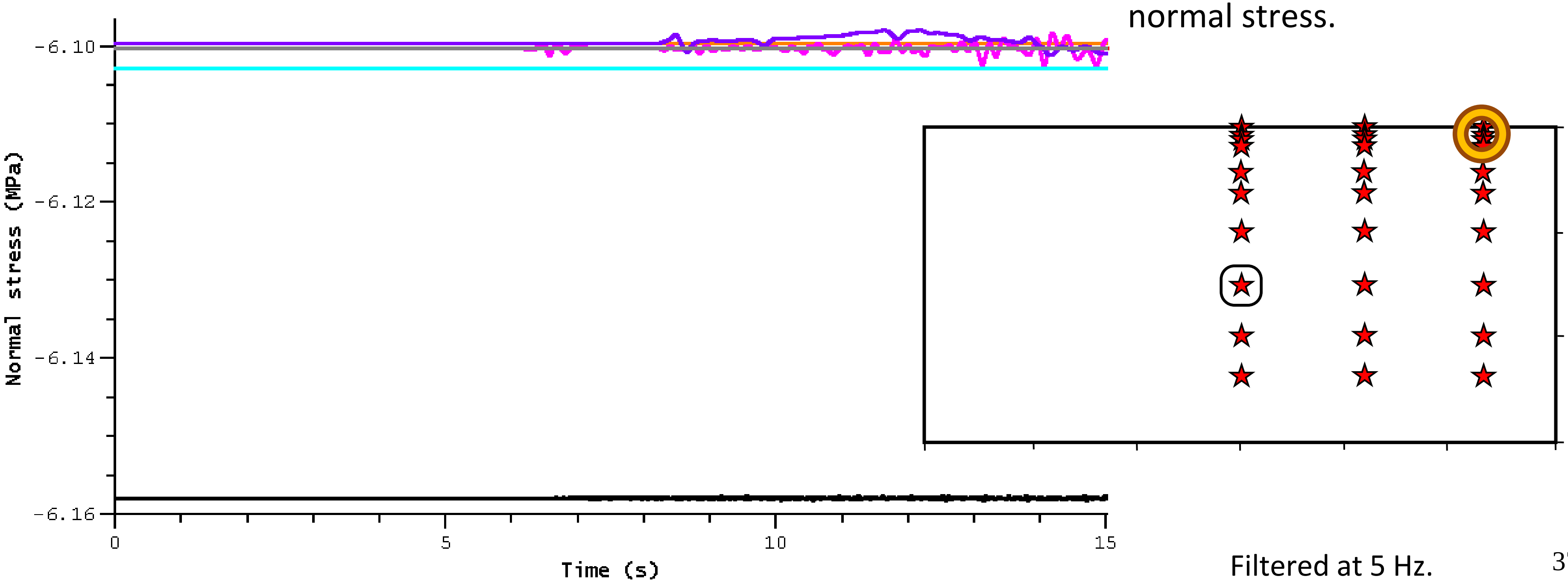
Filtered at 5 Hz.



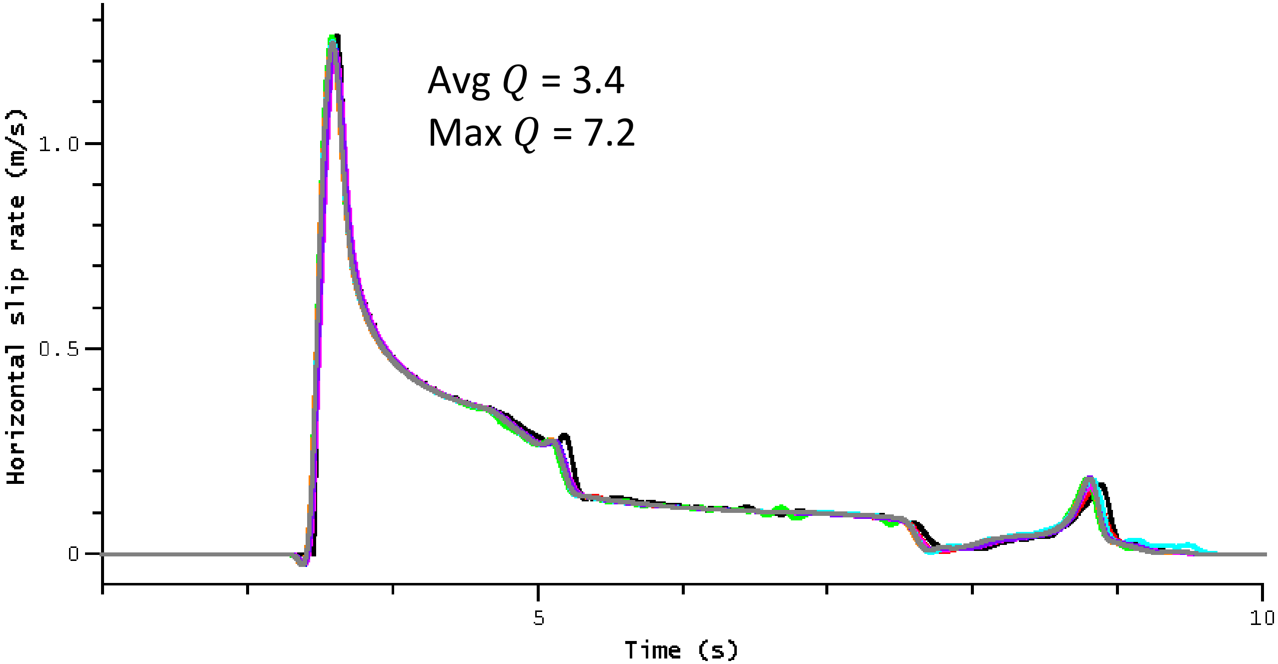
TPV32 – faultst120dp002 – Vertical Shear Stress and Normal Stress

Normal stress cannot change due to symmetry.

Between the 9 codes there are 4 different values of normal stress.

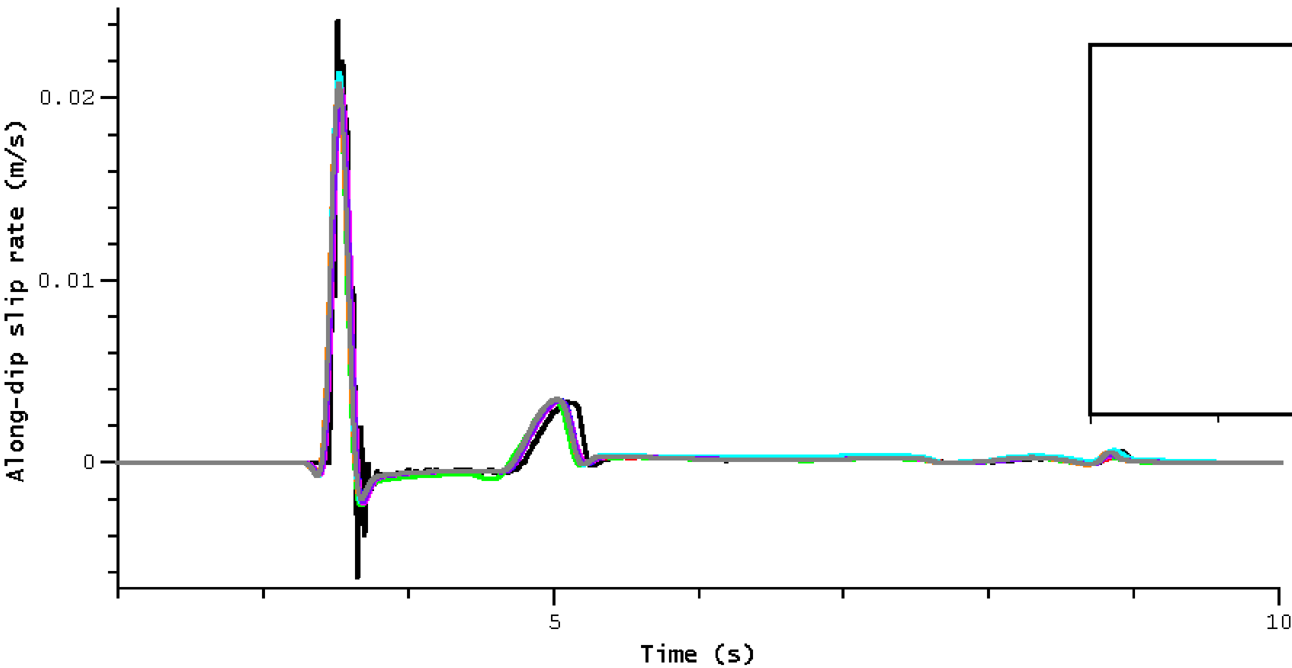


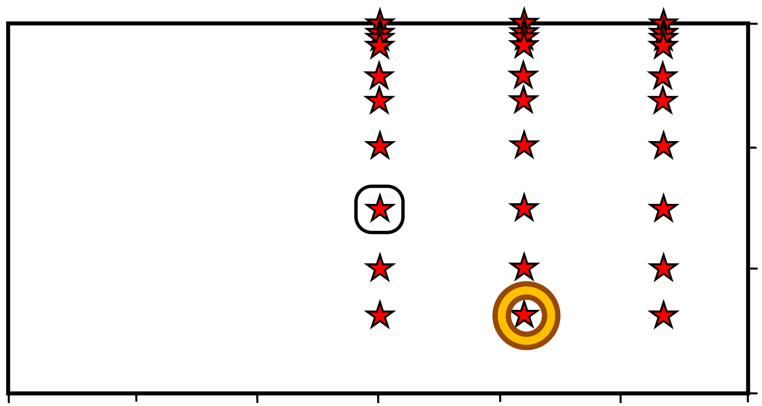
Filtered at 5 Hz.



TPV32 – faultst060dp120 – Horizontal and Vertical Slip Rates

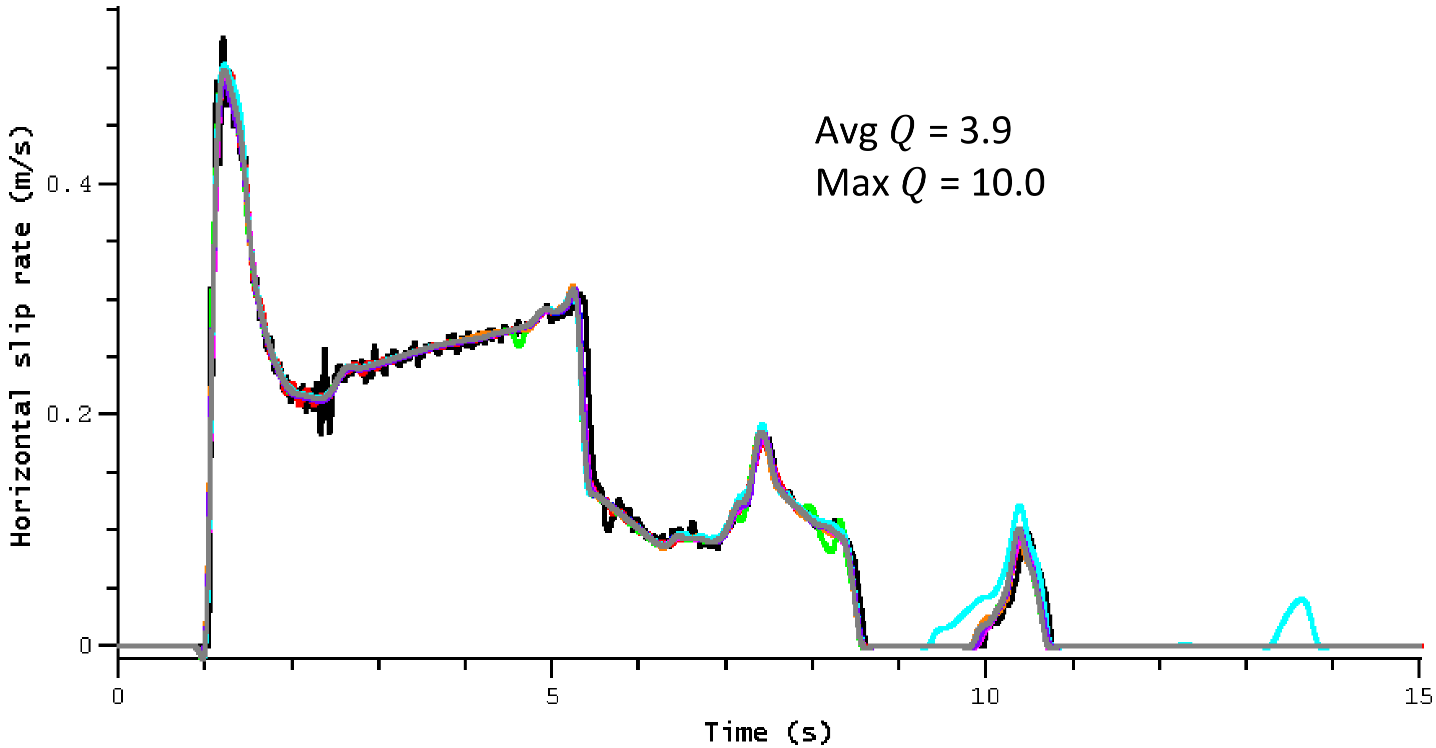
Note excellent agreement in vertical slip rate, despite it being 50 times smaller than the horizontal slip rate.



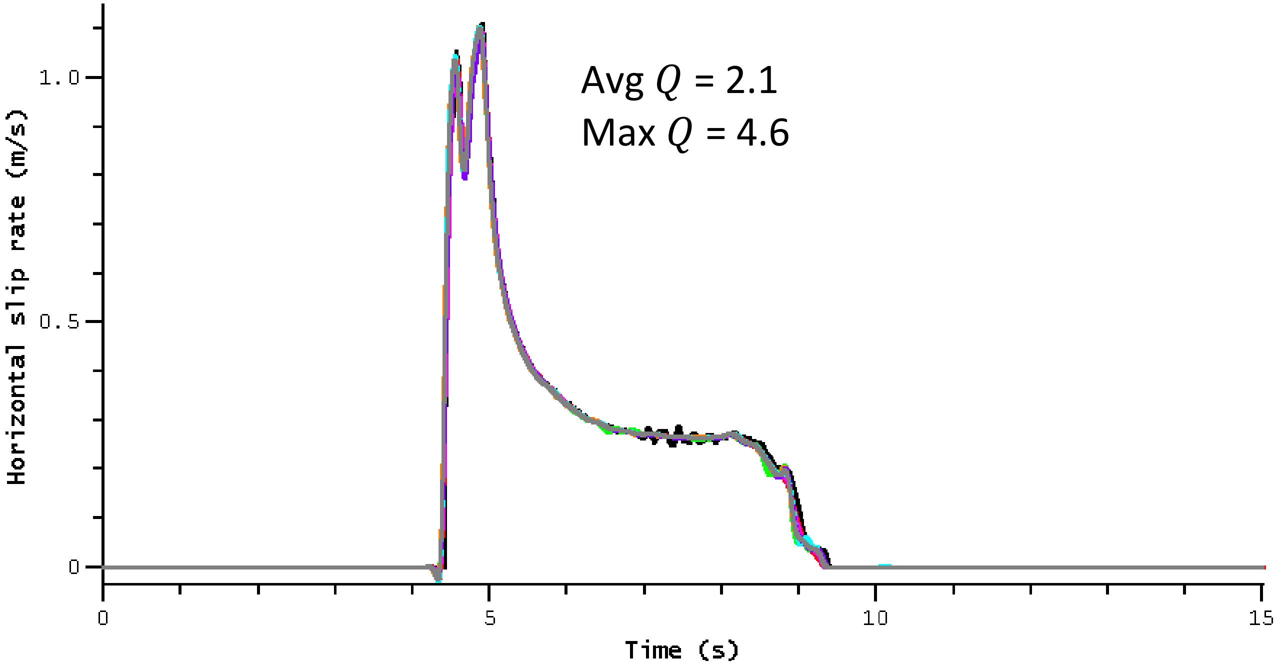


Filtered at 5 Hz.

TPV31 (Discontinuous, Min V_S = 2250) – faultst000dp100 – Horizontal Slip Rate

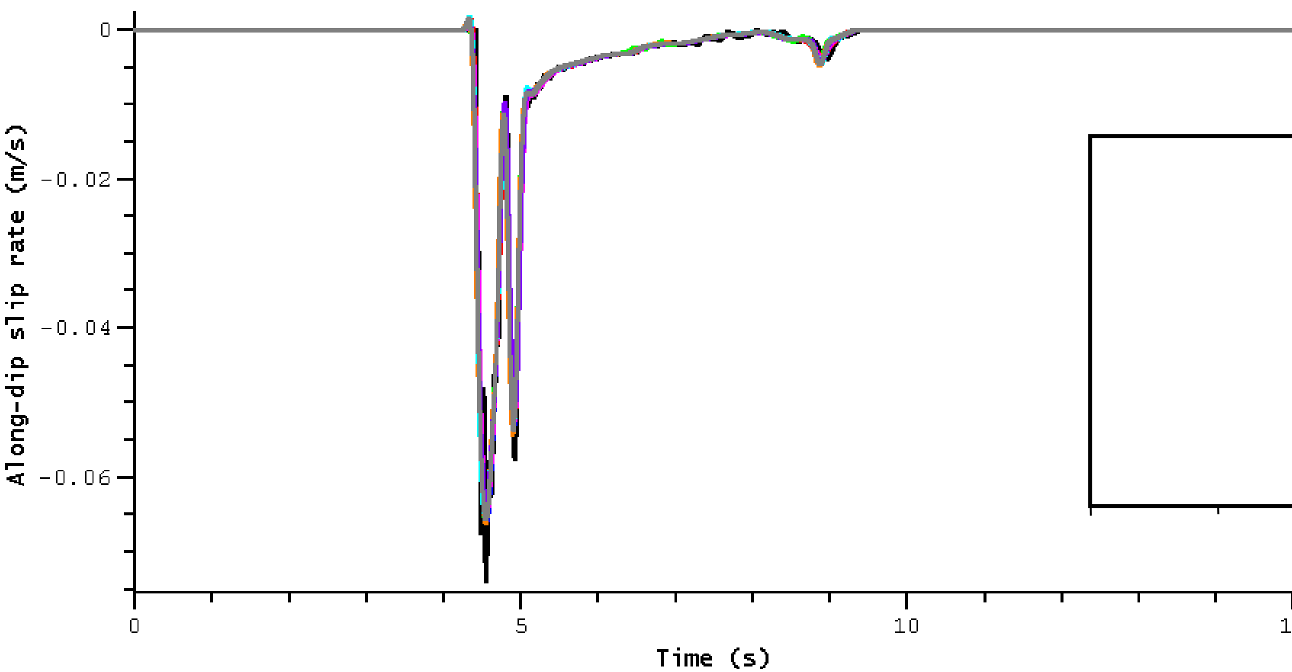


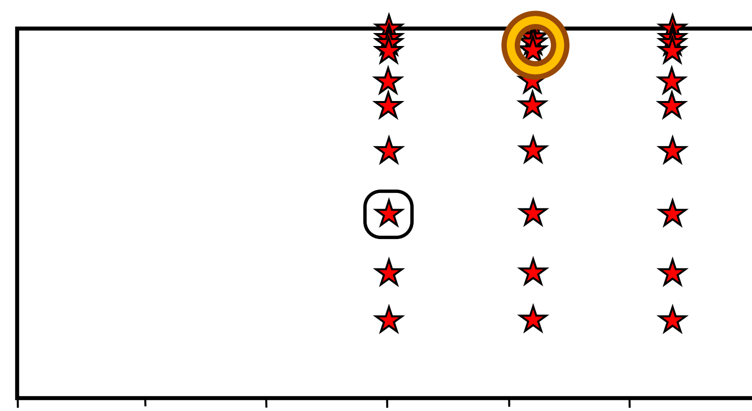
Filtered at 5 Hz.



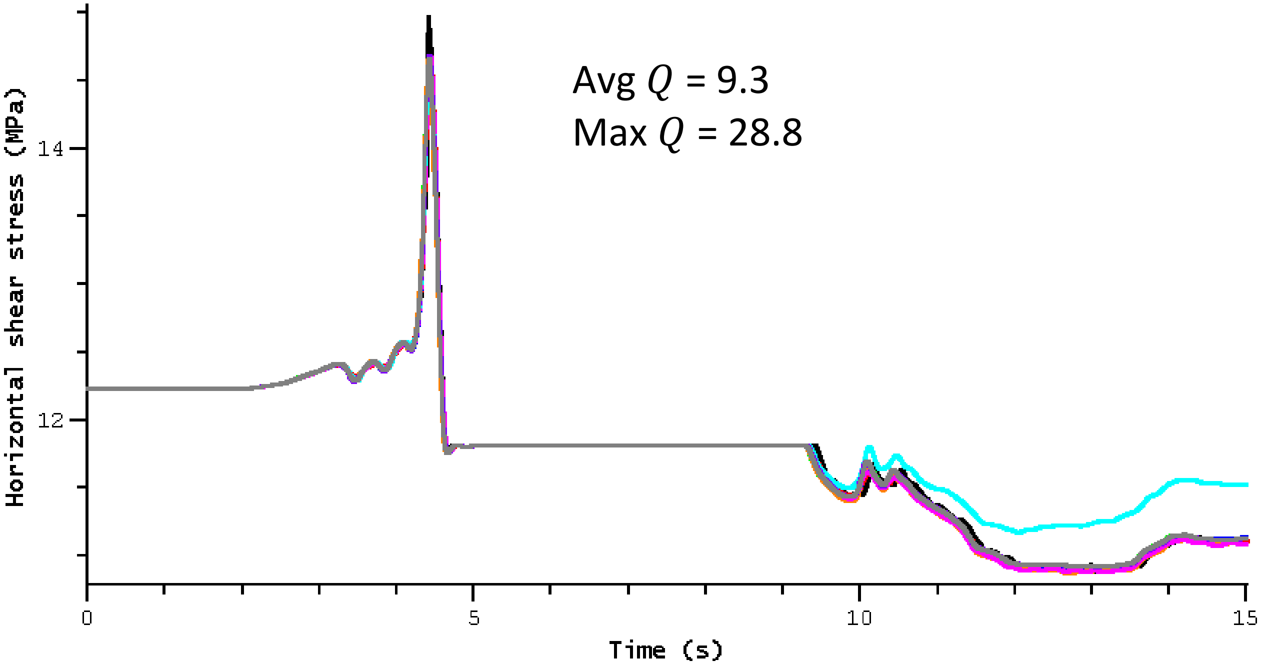
TPV31 – faultst060dp005 – Horizontal and Vertical Slip Rates

Note excellent agreement, including the double-peak, as indicated by the very low metric Q value.



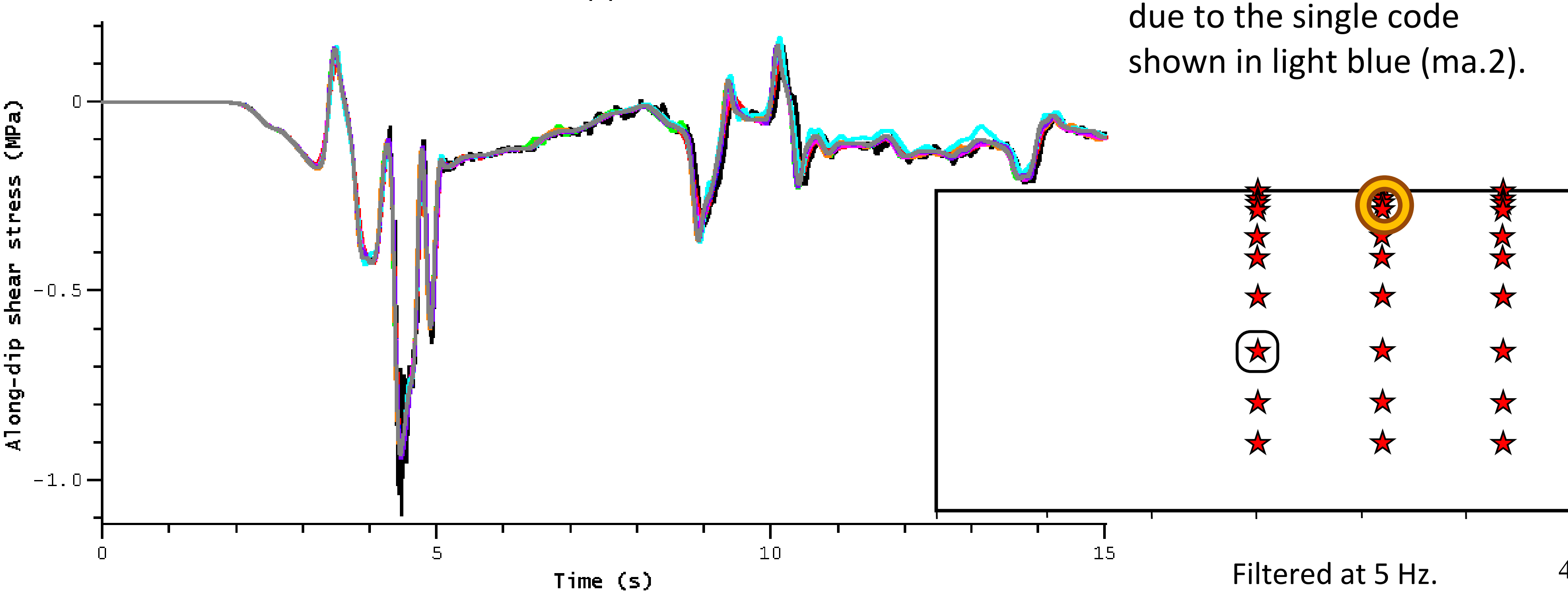


Filtered at 5 Hz.



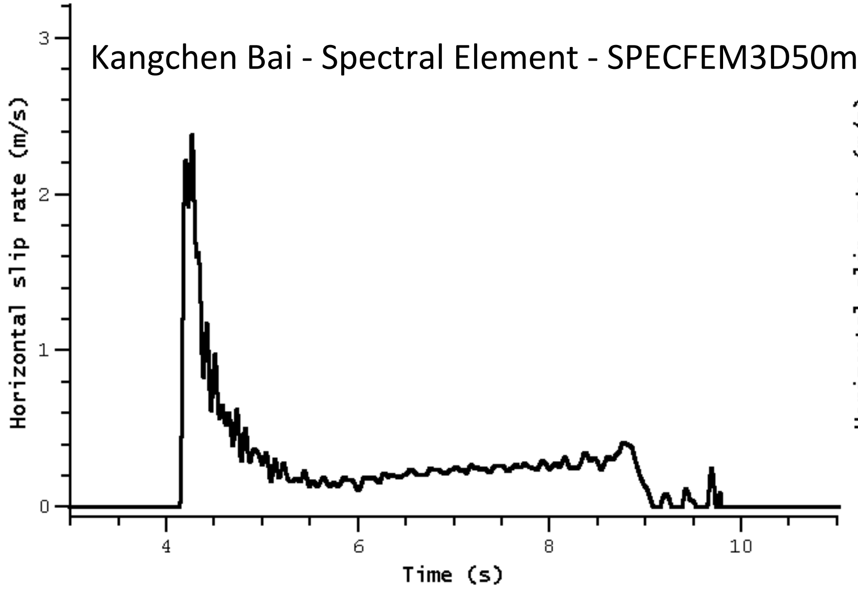
TPV31 – faultst060dp005 – Horizontal and Vertical Shear Stress

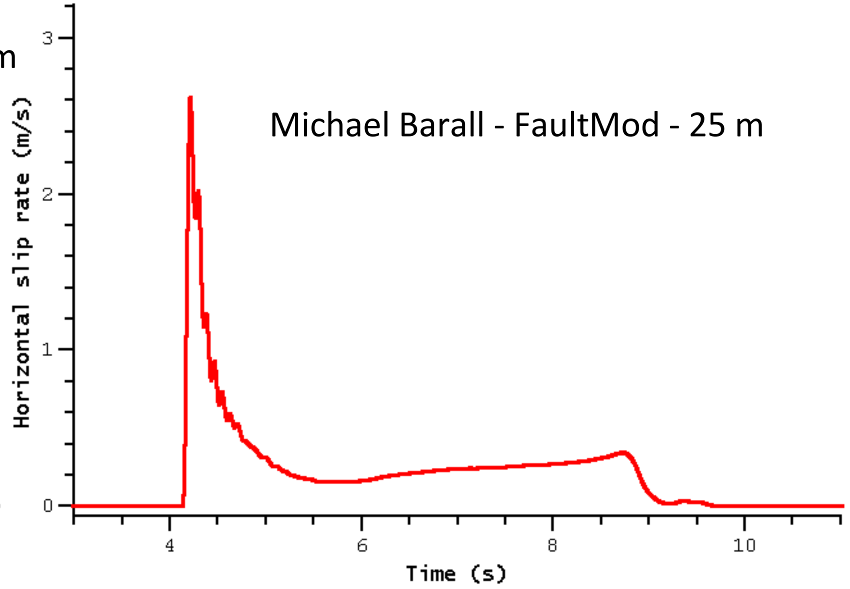
Note excellent agreement until about 9 seconds, then some deviation among the codes late in the simulation. The above-average Q values are all due to the single code shown in light blue (ma.2).



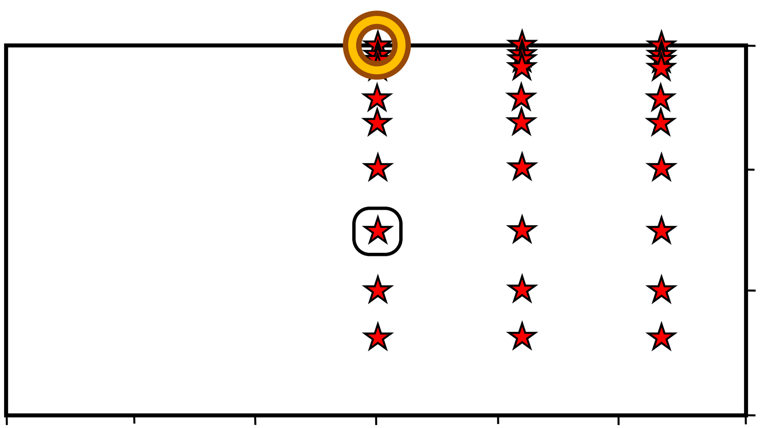
Filtered at 5 Hz.

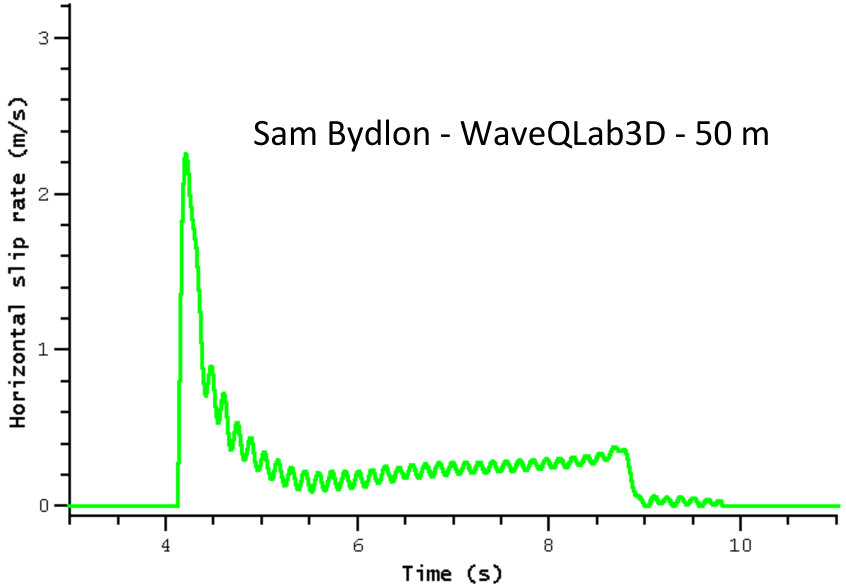
Oscillation Comparison – TPV32 Station faultst000dp000 (Slide 1 of 3)



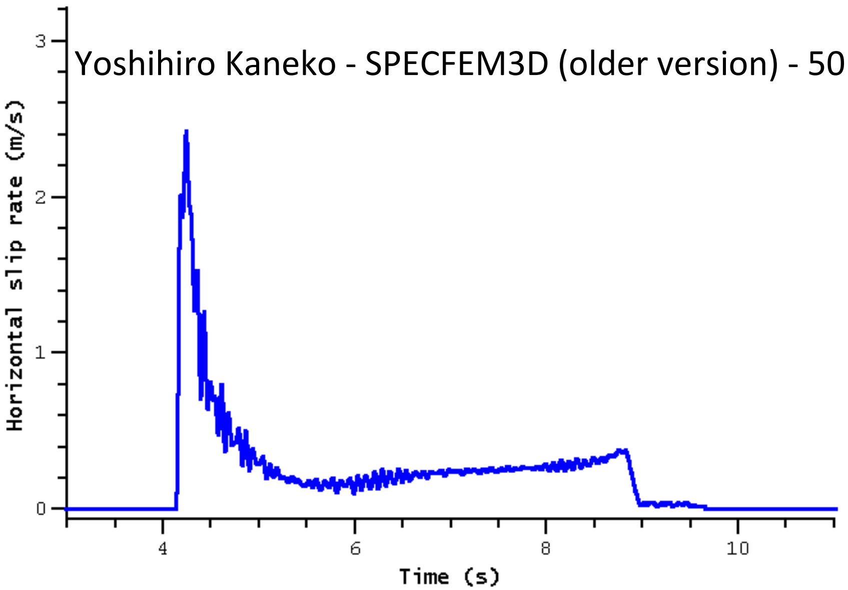


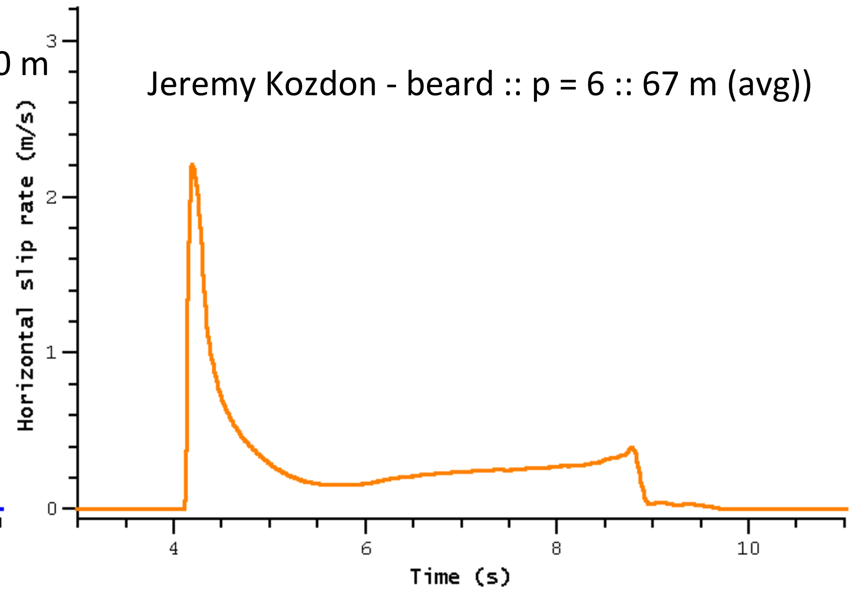
These unfiltered plots of slip rate at the top center of the fault show the sorts of oscillations produced by the different codes.



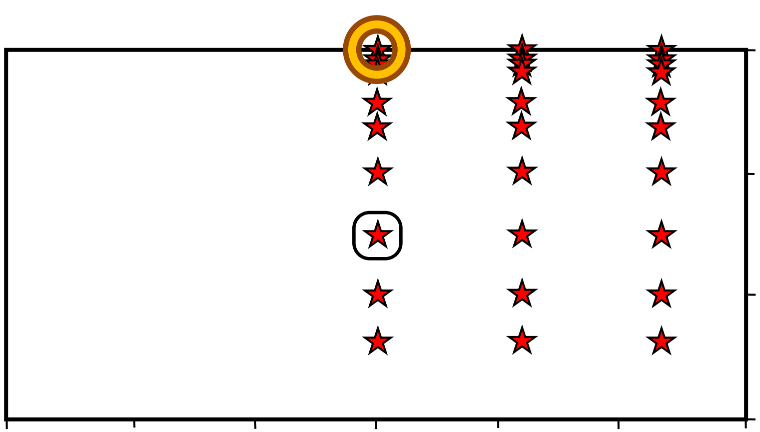


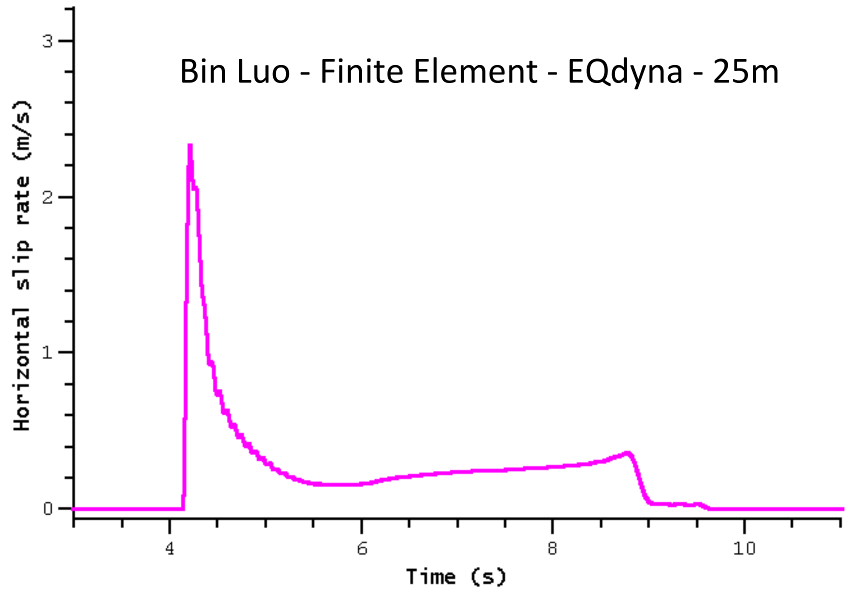
Oscillation Comparison – TPV32 Station faultst000dp000 (Slide 2 of 3)



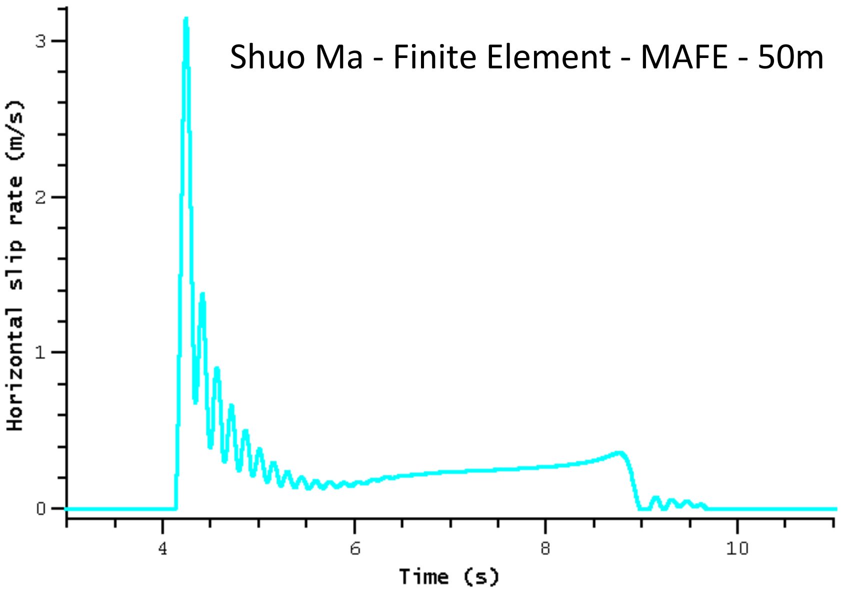


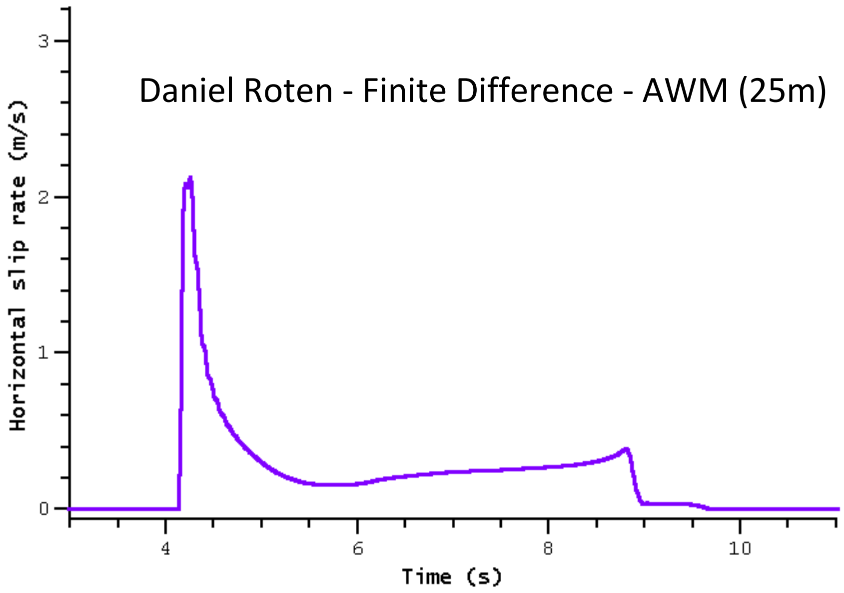
These unfiltered plots of slip rate at the top center of the fault show the sorts of oscillations produced by the different codes.



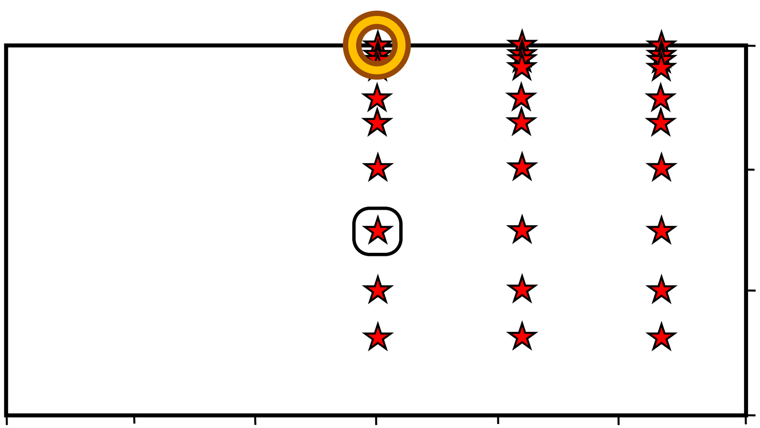


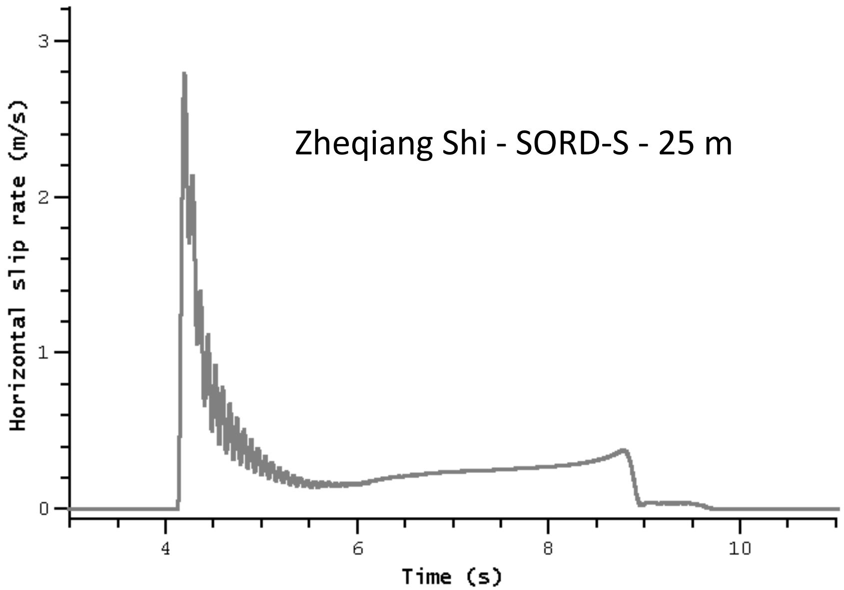
Oscillation Comparison – TPV32 Station faultst000dp000 (Slide 3 of 3)



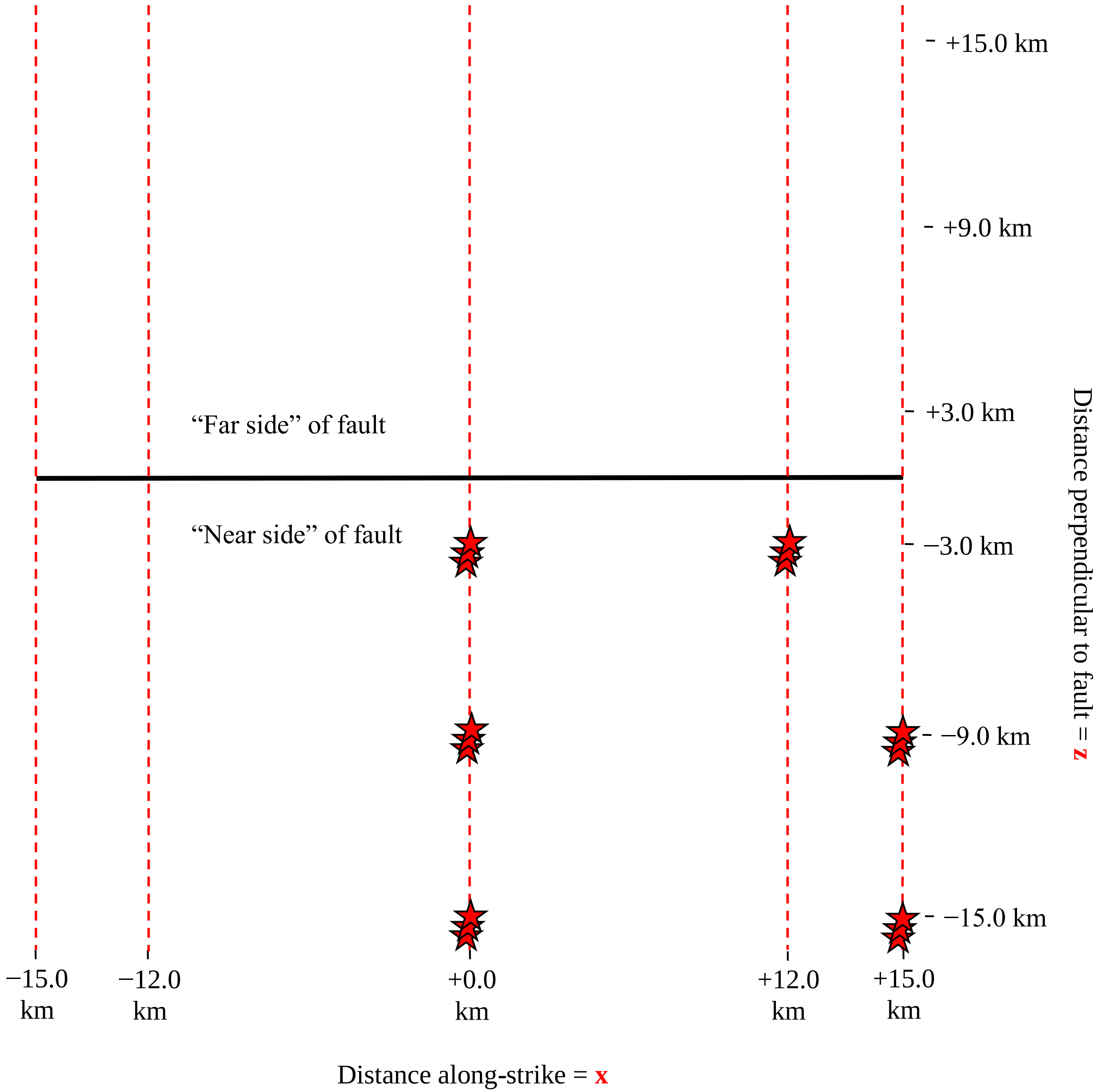


These unfiltered plots of slip rate at the top center of the fault show the sorts of oscillations produced by the different codes.





Time Series:
Off-Fault Stations



Off-Fault Stations

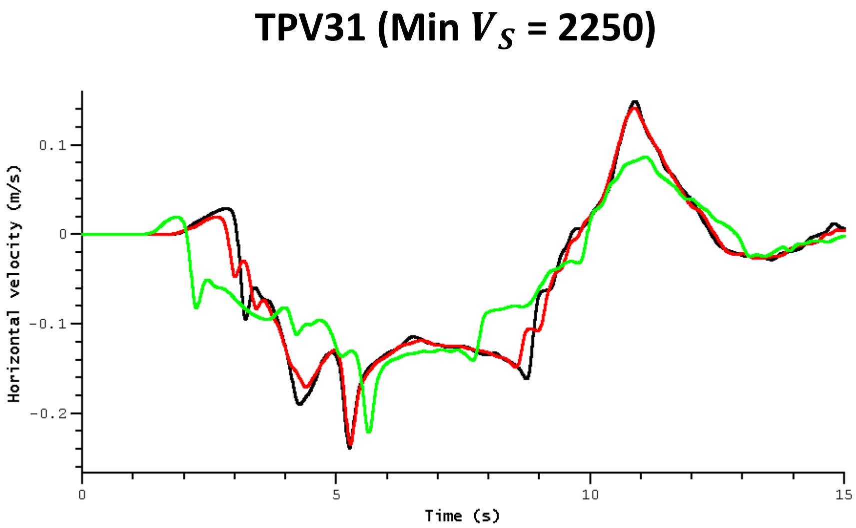
Stations are organized into 6 "boreholes" with stations at depths of 0 km, 0.5 km, and 2.4 km.

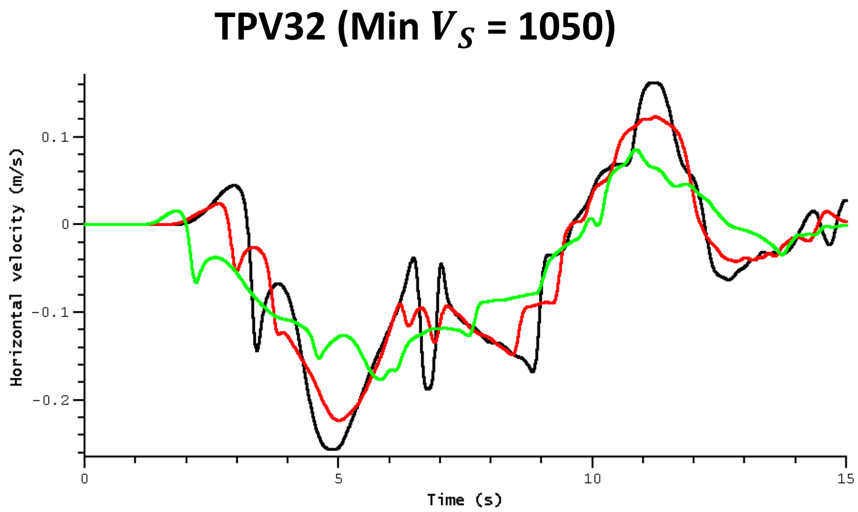
Velocity varies with depth, as shown here:

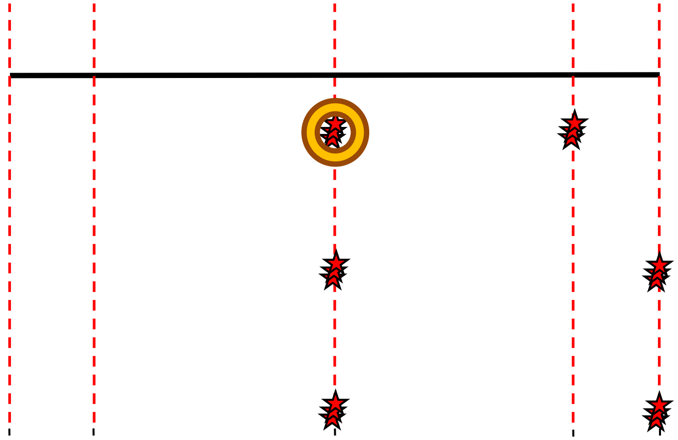
Depth	***TPV31*** V_S	***TPV32*** V_S
0 km	2250 m/s	1050 m/s
0.5 km	2250 m/s	1400 m/s
2.4 km	2250 to 2550 m/s	1950 m/s

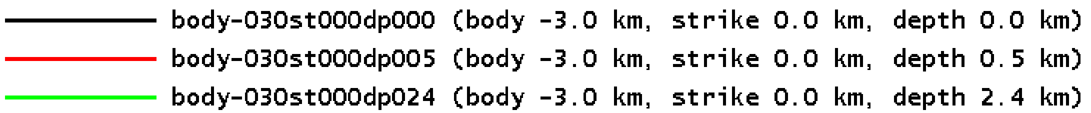
Due to symmetry, stations located at 0 km along-strike can only move in one direction, horizontally parallel to the fault.

Variation of Velocity with Depth – 3 km From the Fault, 0 km Along-Strike





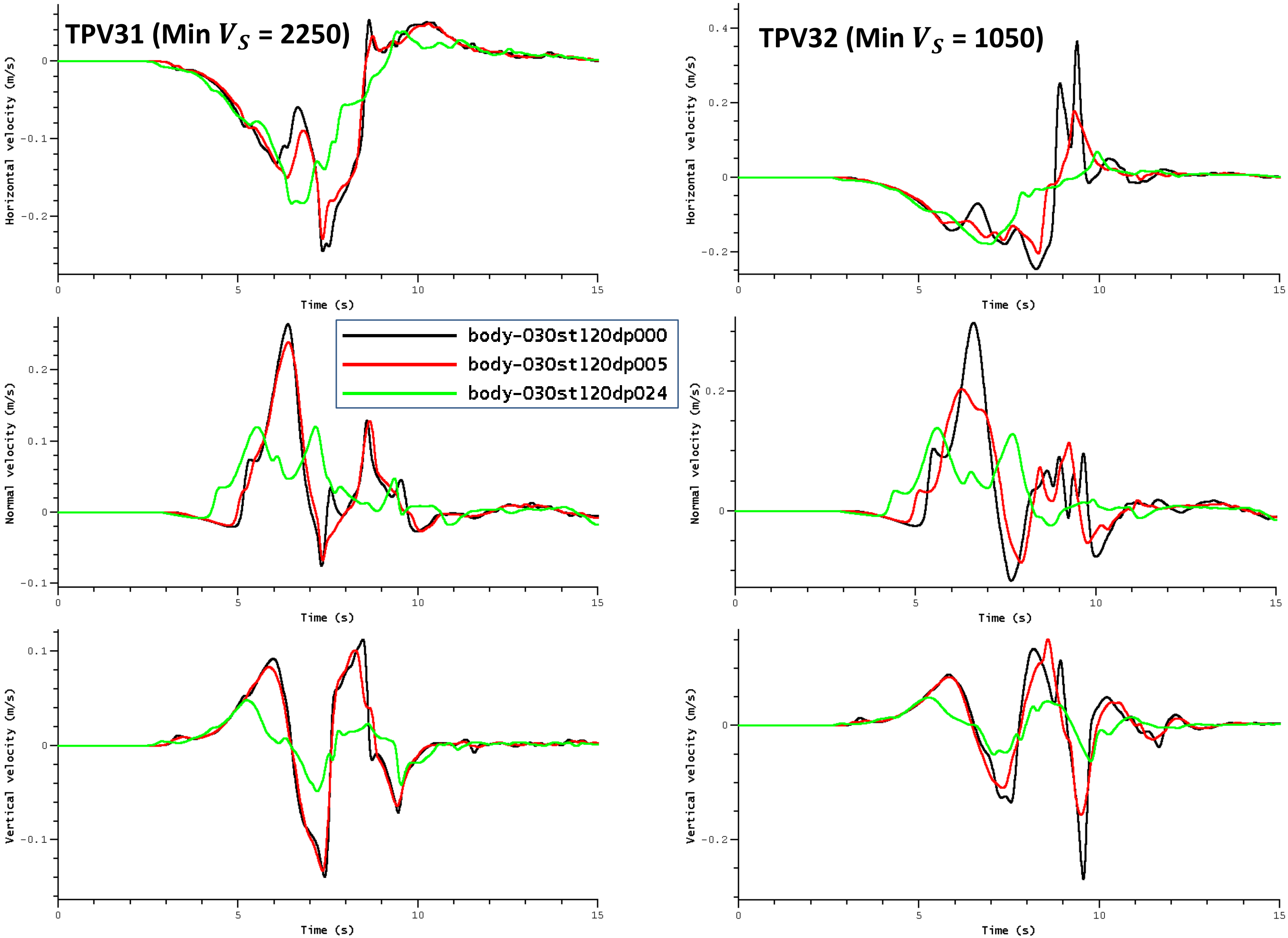




For TPV31, stations at 0 km and 0.5 km depth have about the same velocity. For TPV32, stations at 0 km depth tend to have higher peak velocity than at 0.5 km depth. For both benchmarks, stations at 2.4 km depth tend to have lower peak velocity.

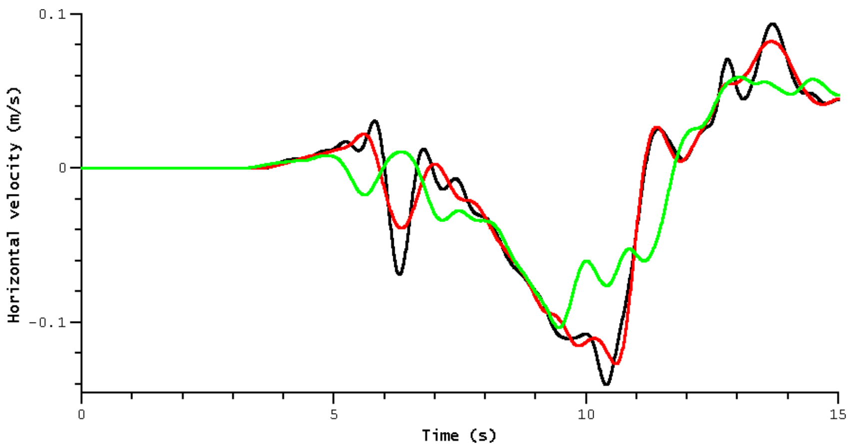
Filtered at 3 Hz.

Variation of Velocity with Depth – 3 km From the Fault, 12 km Along-Strike

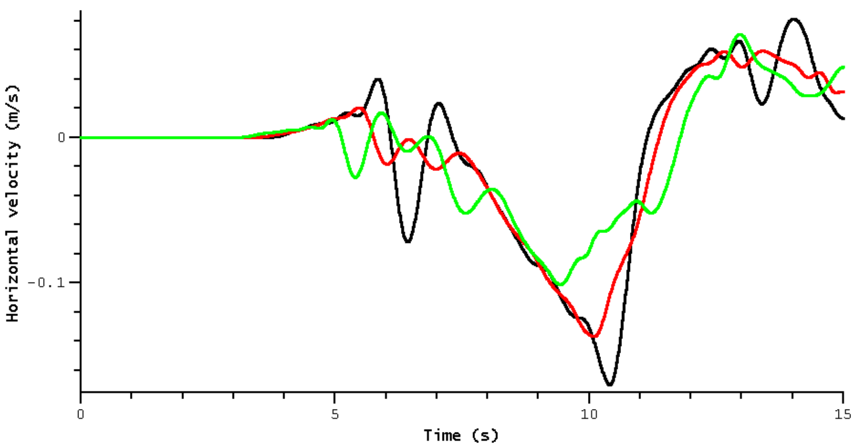


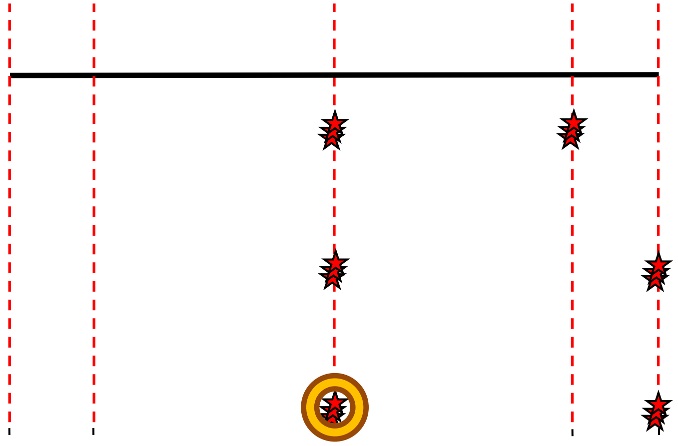
Variation of Velocity with Depth – 15 km from the Fault, 0 km Along-Strike

TPV31 (Min V_S = 2250)



TPV32 (Min V_S = 1050)



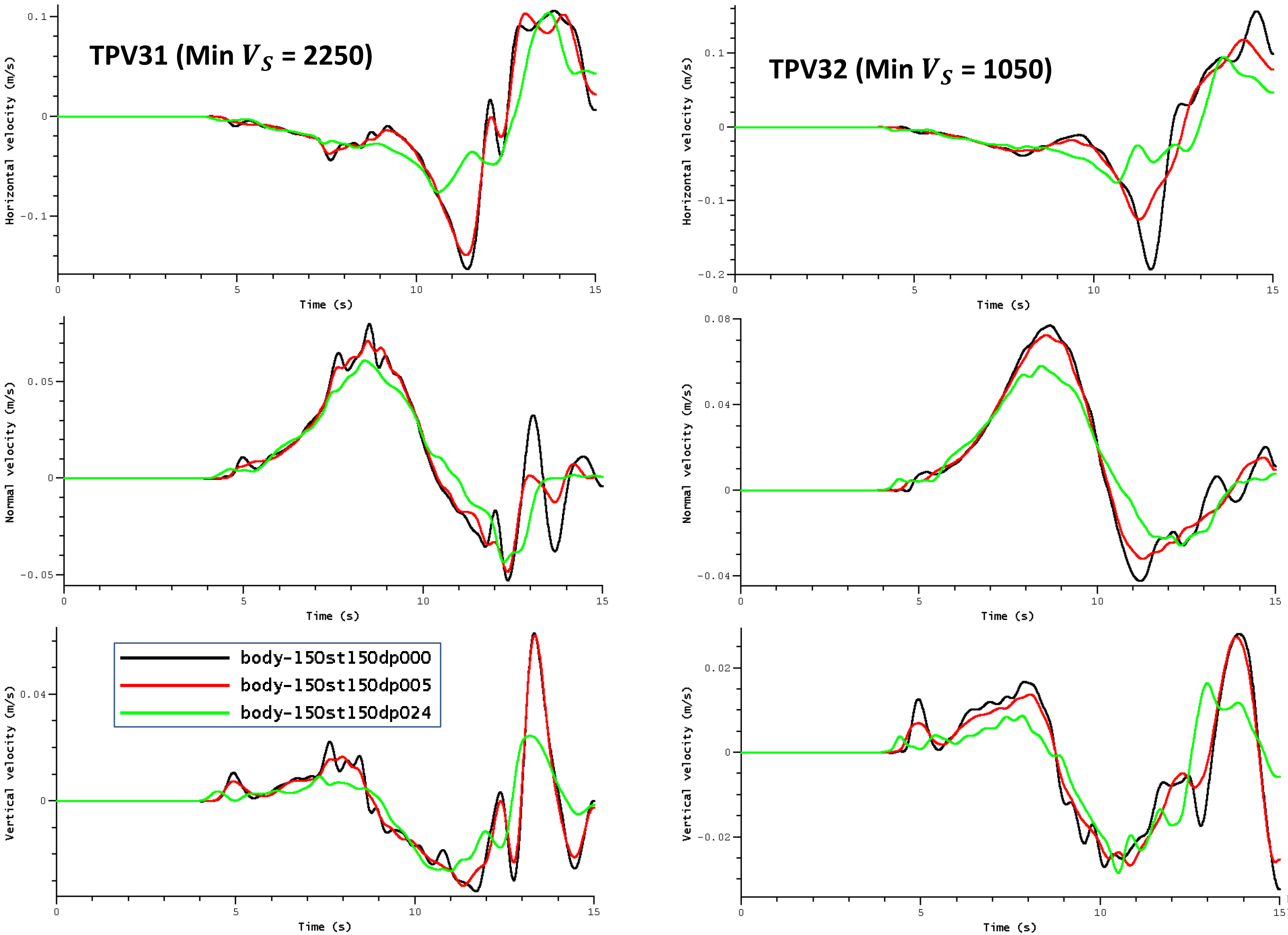


body-150st000dp000 (body -15.0 km, strike 0.0 km, depth 0.0 km)
body-150st000dp005 (body -15.0 km, strike 0.0 km, depth 0.5 km)
body-150st000dp024 (body -15.0 km, strike 0.0 km, depth 2.4 km)

For TPV31, stations at 0 km and 0.5 km depth have about the same velocity. For TPV32, stations at 0 km depth tend to have higher peak velocity than at 0.5 km depth. For both benchmarks, stations at 2.4 km depth tend to have lower peak velocity.

Filtered at 3 Hz.

Variation of Velocity with Depth – 15 km from the Fault, 15 km Along-Strike



TPV31 (Discontinuous, Min V_S = 2250) – Summary Metrics for All Off-Fault Stations

	3d-vel	6 codes
body-030st000dp000	5.0	4.6
body-030st000dp005	4.7	4.3
body-030st000dp024	4.7	4.1
body-090st000dp000	11.3	9.3
body-090st000dp005	9.9	7.4
body-090st000dp024	11.7	9.8
body-150st000dp000	16.8	13.3
body-150st000dp005	14.0	9.4
body-150st000dp024	15.9	12.0

	3d-vel	6 codes
body-030st120dp000	10.0	7.7
body-030st120dp005	8.7	6.0
body-030st120dp024	11.4	8.7
body-090st150dp000	20.9	11.9
body-090st150dp005	19.1	9.2
body-090st150dp024	20.0	9.4
body-150st150dp000	40.7	17.0
body-150st150dp005	37.3	12.5
body-150st150dp024	31.8	12.7

These are the waveform comparison metrics, averaged over all pairs of codes, using the best version from each of 8 codes. The "3d-vel" column is the average 3D velocity metric for all 8 codes. The "6 codes" column is the average metric for only the 6 best-matching codes.

The stations farthest from the fault have the most disagreement (highest metric value). Also, stations farther to the right have higher disagreement than stations at 0 km along-strike.

In most cases, the station at the earth's surface has a higher metric than deeper stations.

TPV32 (Continuous, Min V_S = 1050) – Summary Metrics for All Off-Fault Stations

	3d-vel	6 codes
body-030st000dp000	10.0	10.3
body-030st000dp005	6.3	6.0
body-030st000dp024	4.1	3.0
body-090st000dp000	18.4	17.1
body-090st000dp005	12.3	9.7
body-090st000dp024	10.5	7.5
body-150st000dp000	19.9	17.5
body-150st000dp005	17.4	13.9
body-150st000dp024	16.6	12.0

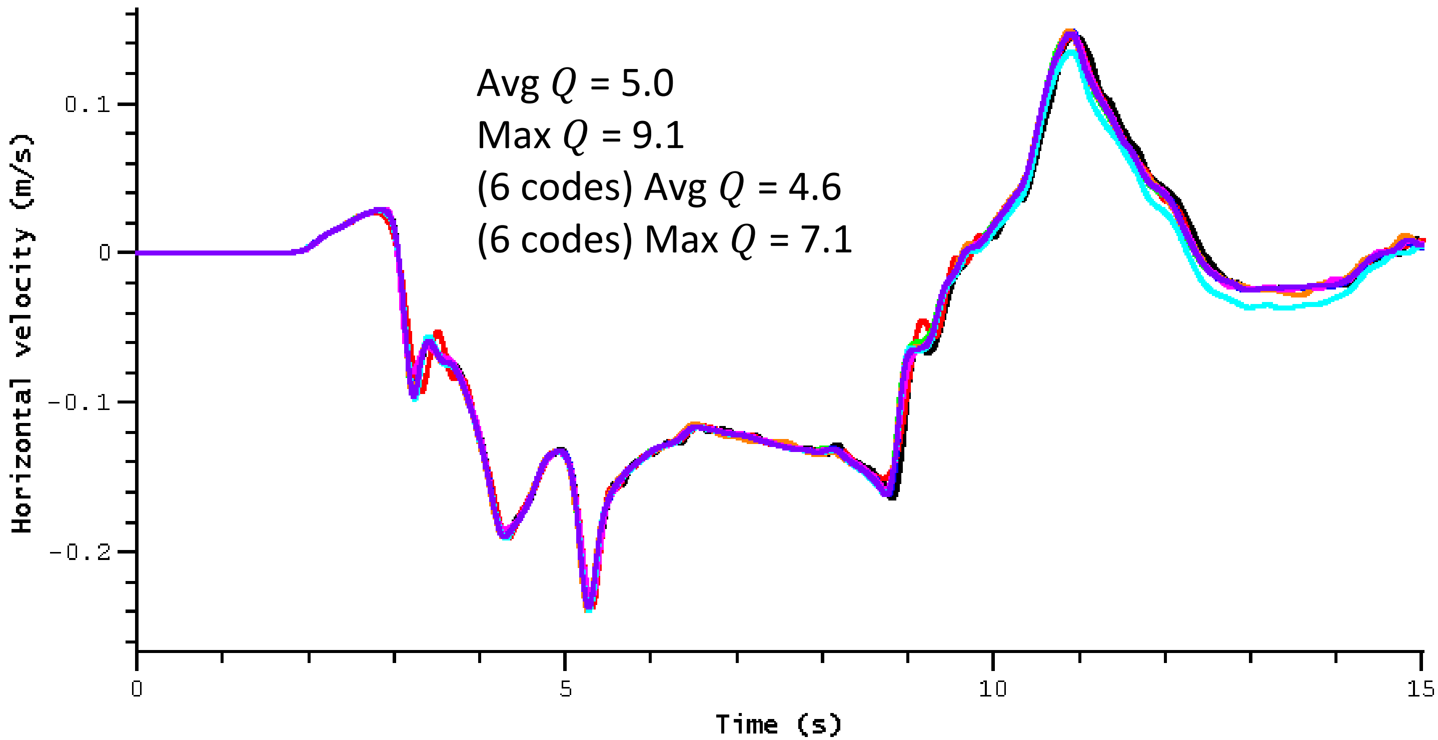
	3d-vel	6 codes
body-030st120dp000	18.7	17.8
body-030st120dp005	11.2	9.5
body-030st120dp024	9.2	5.9
body-090st150dp000	31.5	15.9
body-090st150dp005	28.0	11.6
body-090st150dp024	40.9	32.9
body-150st150dp000	40.6	10.5
body-150st150dp005	36.6	8.6
body-150st150dp024	36.2	10.4

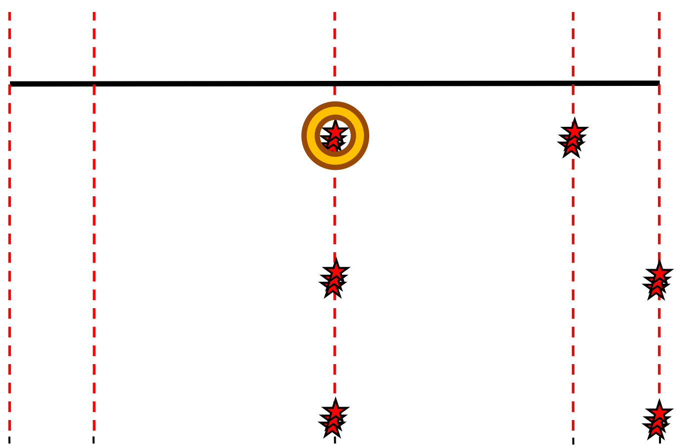
These are the waveform comparison metrics, averaged over all pairs of codes, using the best version from each of 8 codes. The “3d-vel” column is the average 3D velocity metric for all 8 codes. The “6 codes” column is the average metric for only the 6 best-matching codes.

Unlike TPV31, the 6 best-matching stations do not show a clear pattern of higher metric values (worse agreement) with increasing distance from the fault.

In most cases, the station at the earth’s surface has a higher metric than deeper stations.

TPV31 (Discontinuous, Min V_S = 2250) – body-030st000dp000 – Horizontal Velocity



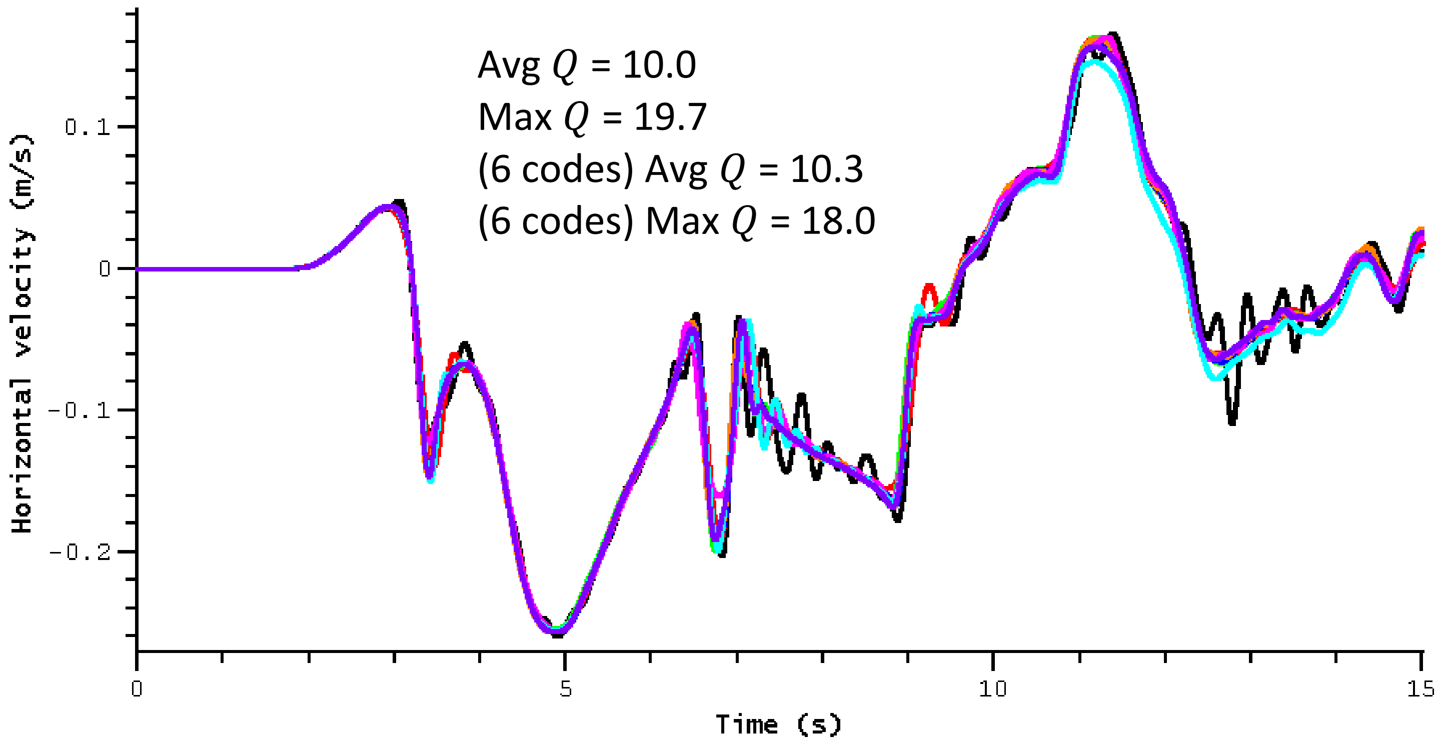


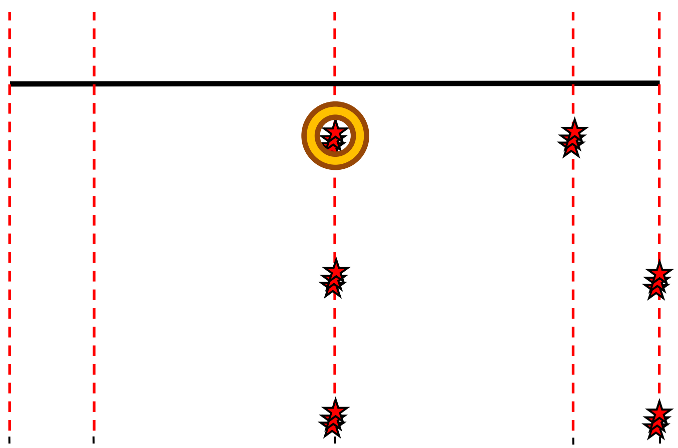
bai (Kangchen Bai - Spectral Element - SPECFEM3D)
barall.2 (Michael Barall - FaultMod - 25 m)
bydlon.2 (Sam Bydlon - WaveQLab3D - 50 m)
kaneko (Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m)
kozdon.3 (Jeremy Kozdon - beard :: p = 6 :: 67 m (avg))
luo.2 (Bin Luo - Finite Element - EQdyna - 25m)
ma.2 (Shuo Ma - Finite Element - MAFE - 50m)
shi.2 (Zheqiang Shi - SORD-S - 25 m)

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

Filtered at 3 Hz.

TPV32 (Continuous, Min V_S = 1050) – body-030st000dp000 – Horizontal Velocity



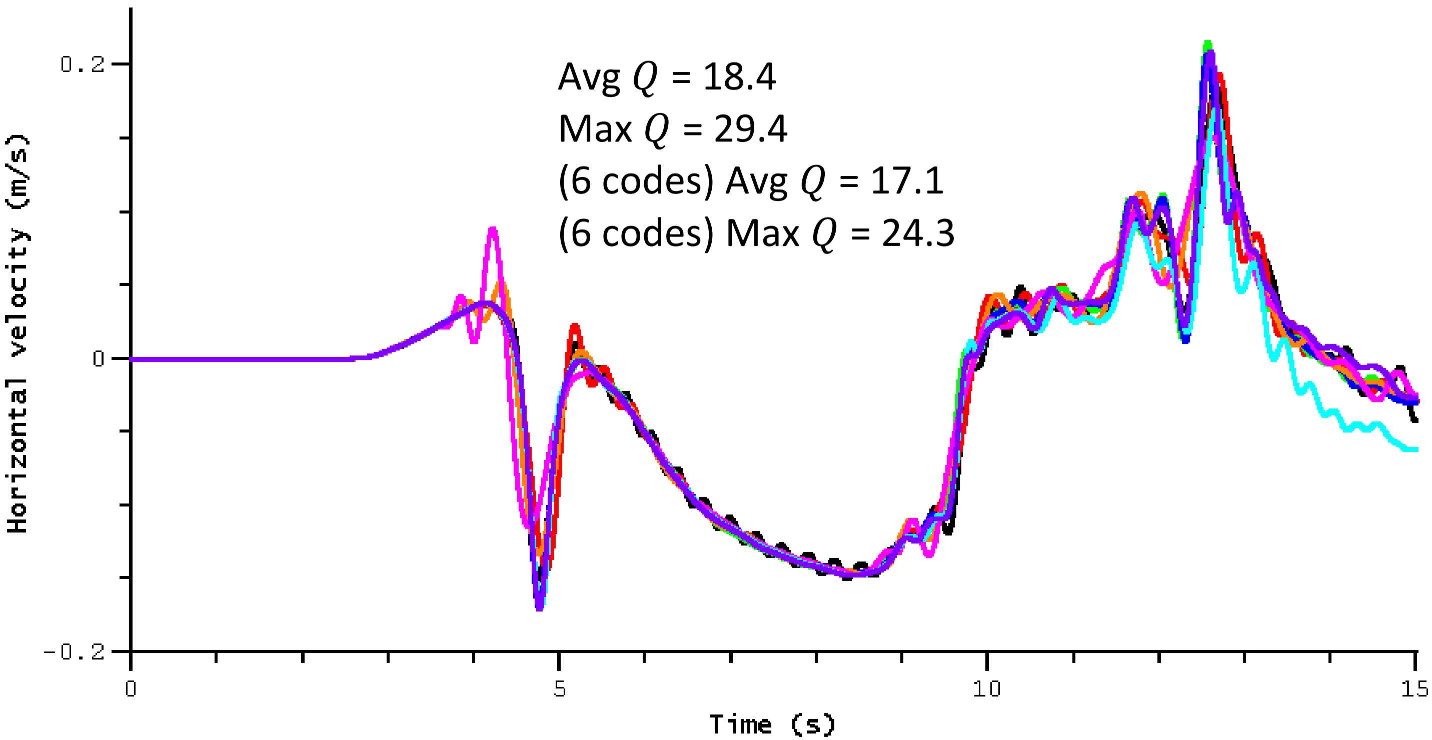


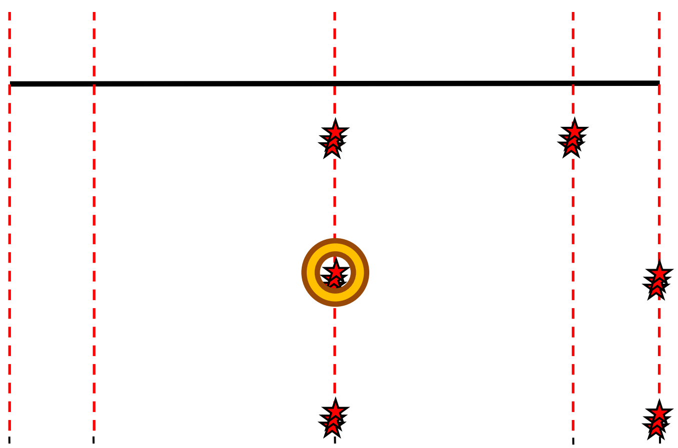
bai (Kangchen Bai - Spectral Element - SPECFEM3D50m)
barall (Michael Barall - FaultMod - 25 m)
bydlon.2 (Sam Bydlon - WaveQLab3D - 50 m)
kaneko (Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m)
kozdon.2 (Jeremy Kozdon - beard :: p = 6 :: 67 m (avg))
luo (Bin Luo - Finite Element - EQdyna - 25m)
ma.2 (Shuo Ma - Finite Element - MAFE - 50m)
shi (Zheqiang Shi - SORD-S - 25 m)

Matches less well than TPV31 at the same station.

Filtered at 3 Hz.

TPV32 (Continuous, Min V_S = 1050) – body-090st000dp000 – Horizontal Velocity





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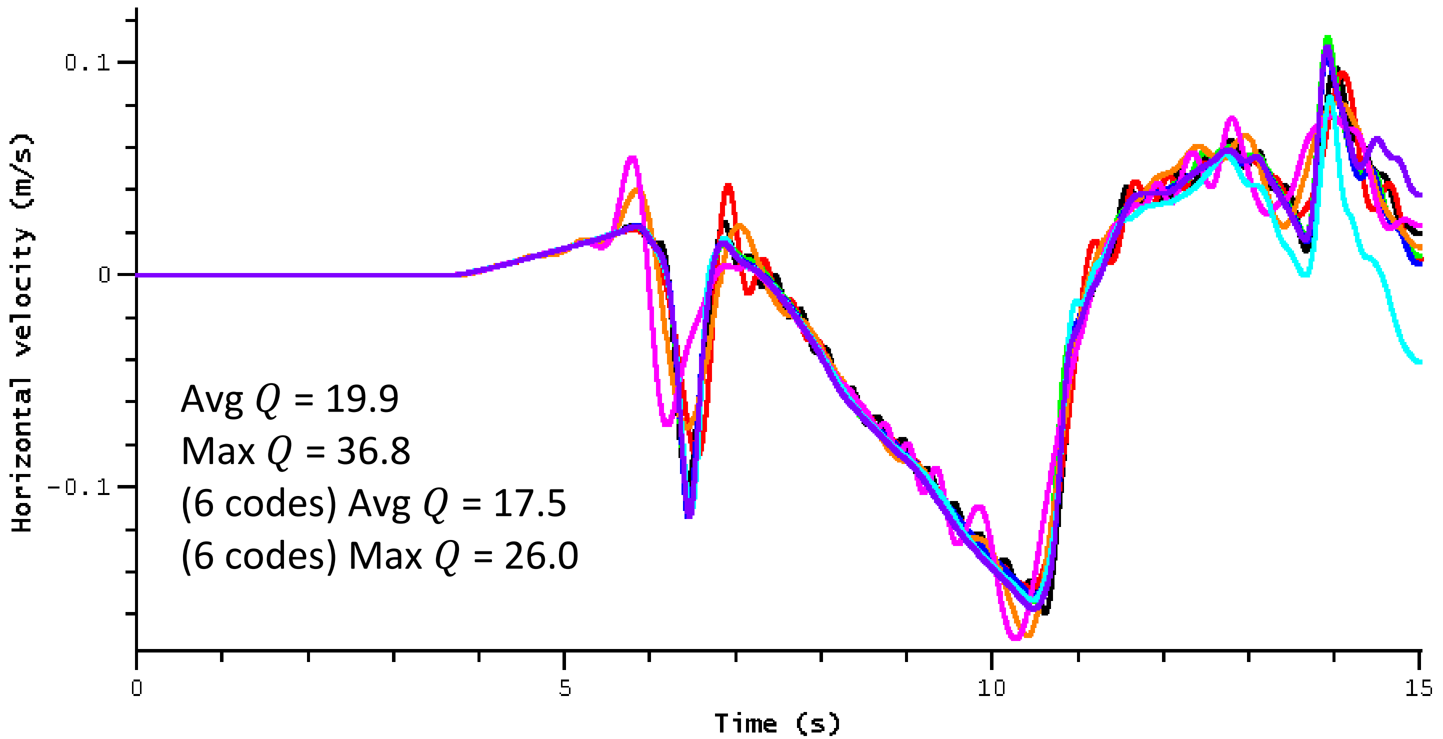
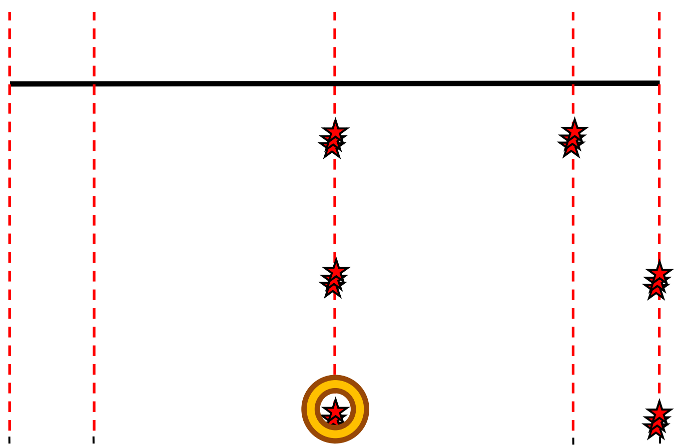
kaneko (Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m)
kozdon.2 (Jeremy Kozdon - beard :: p = 6 :: 67 m (avg))
luo (Bin Luo - Finite Element - EQdyna - 25m)
ma.2 (Shuo Ma - Finite Element - MAFE - 50m)
shi (Zheqiang Shi - SORD-S - 25 m)

Matches worse than at 3 km from the fault.

Filtered at 3 Hz.

TPV32 (Continuous, Min V_S = 1050) – body-150st000dp000 – Horizontal Velocity





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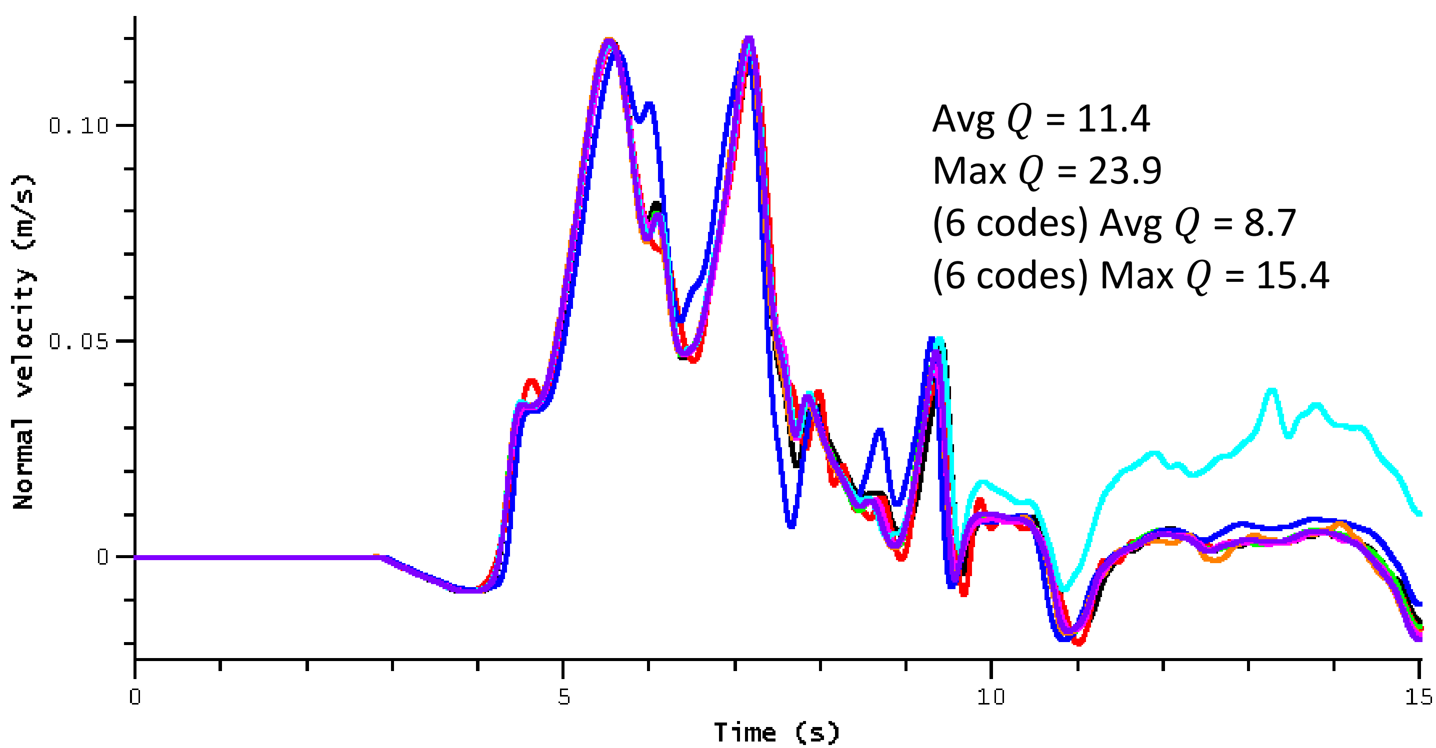
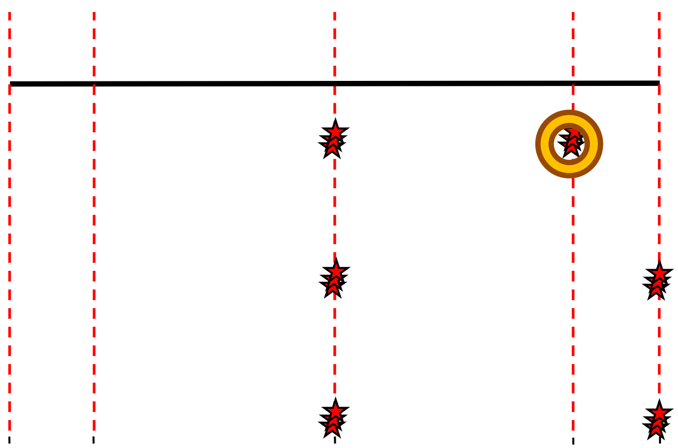
ma.2 (Shuo Ma - Finite Element - MAFE - 50m)
shi (Zheqiang Shi - SORD-S - 25 m)

Match worsens far from the fault.

Filtered at 3 Hz.

TPV31 (Discontinuous, Min V_S = 2250) – body-030st120dp024 – Normal Velocity

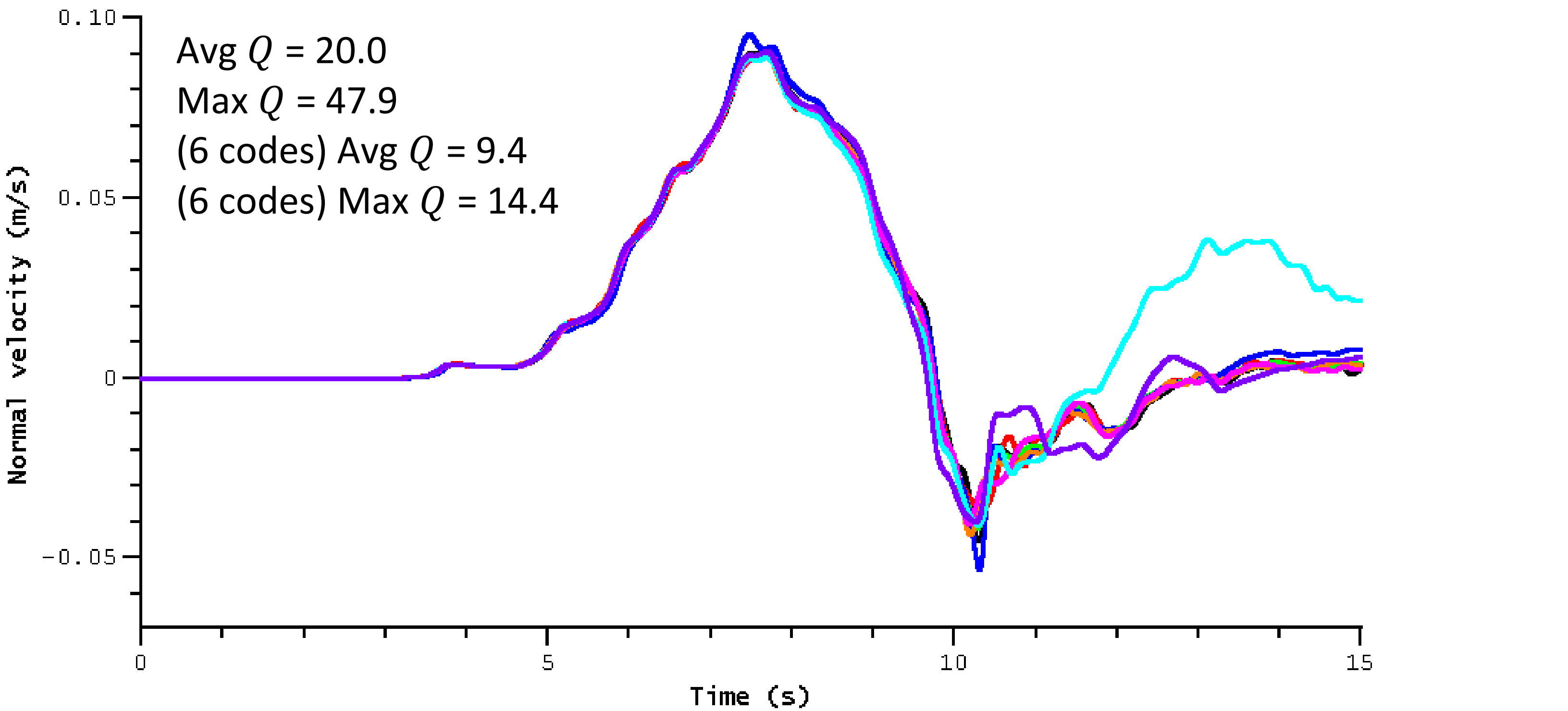


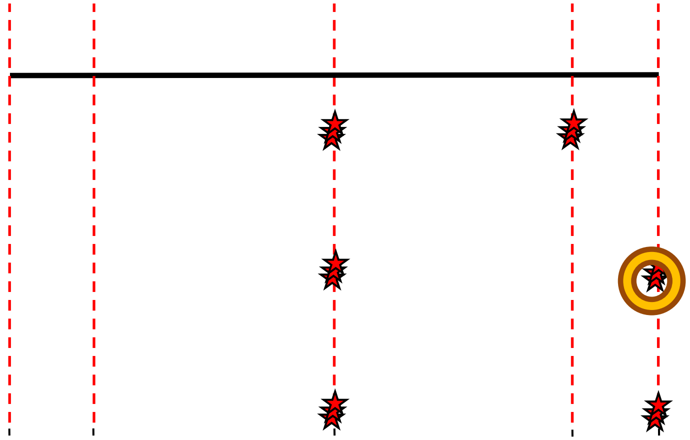


Discontinuity may cause poorer than expected match.

Filtered at 3 Hz.

TPV31 (Discontinuous, Min V_S = 2250) – body-090st150dp024 – Normal Velocity

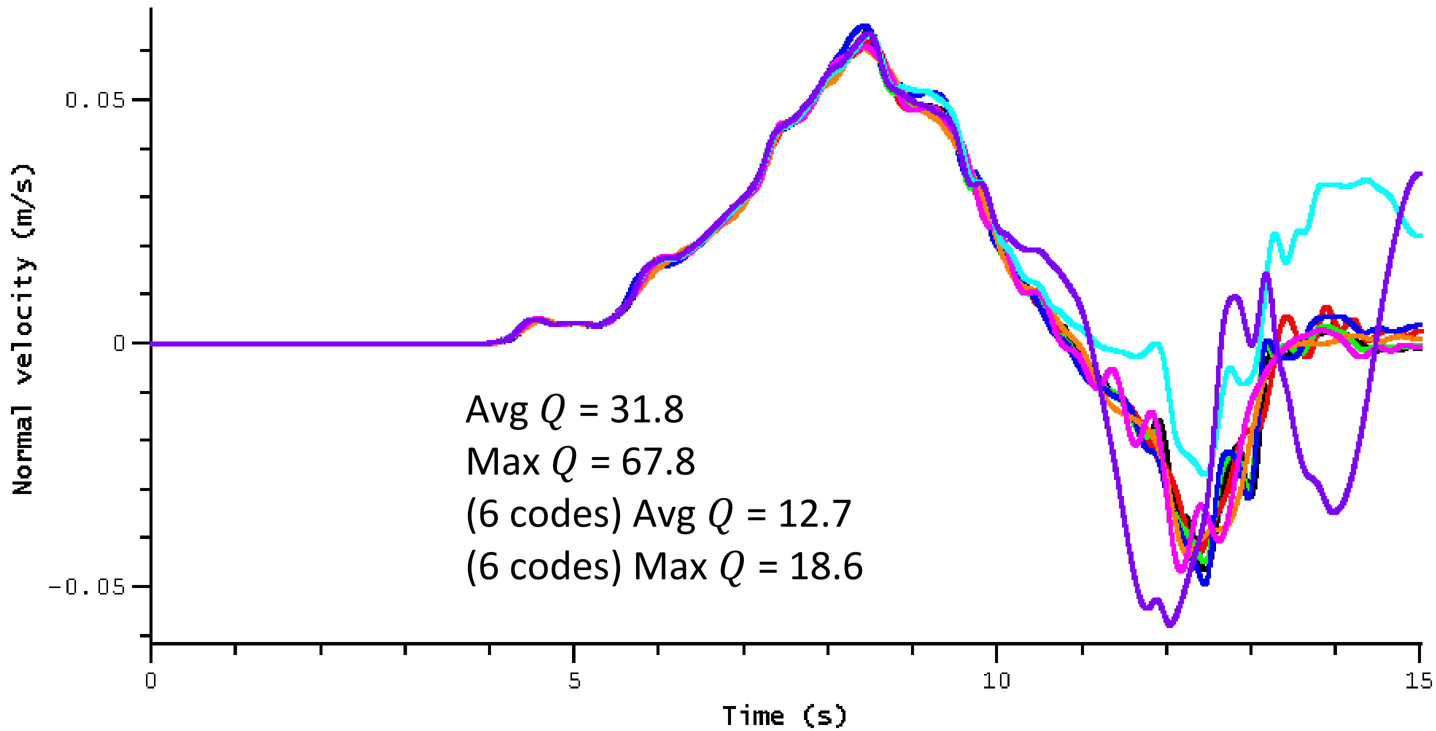


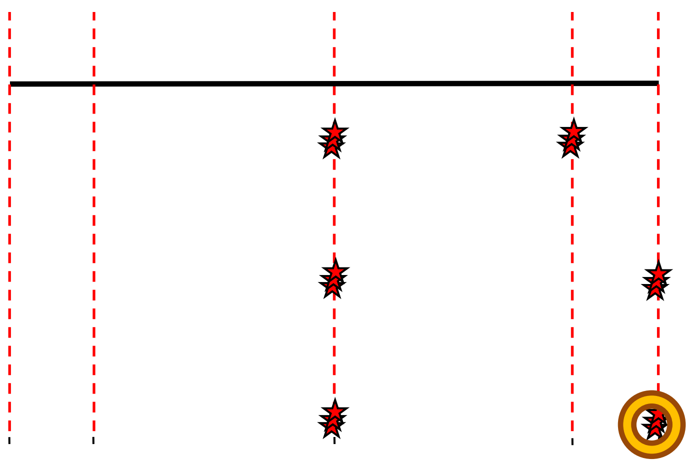


8-code metrics increase compared to 3 km from fault.

Filtered at 3 Hz.

TPV31 (Discontinuous, Min V_S = 2250) – body-150st150dp024 – Normal Velocity





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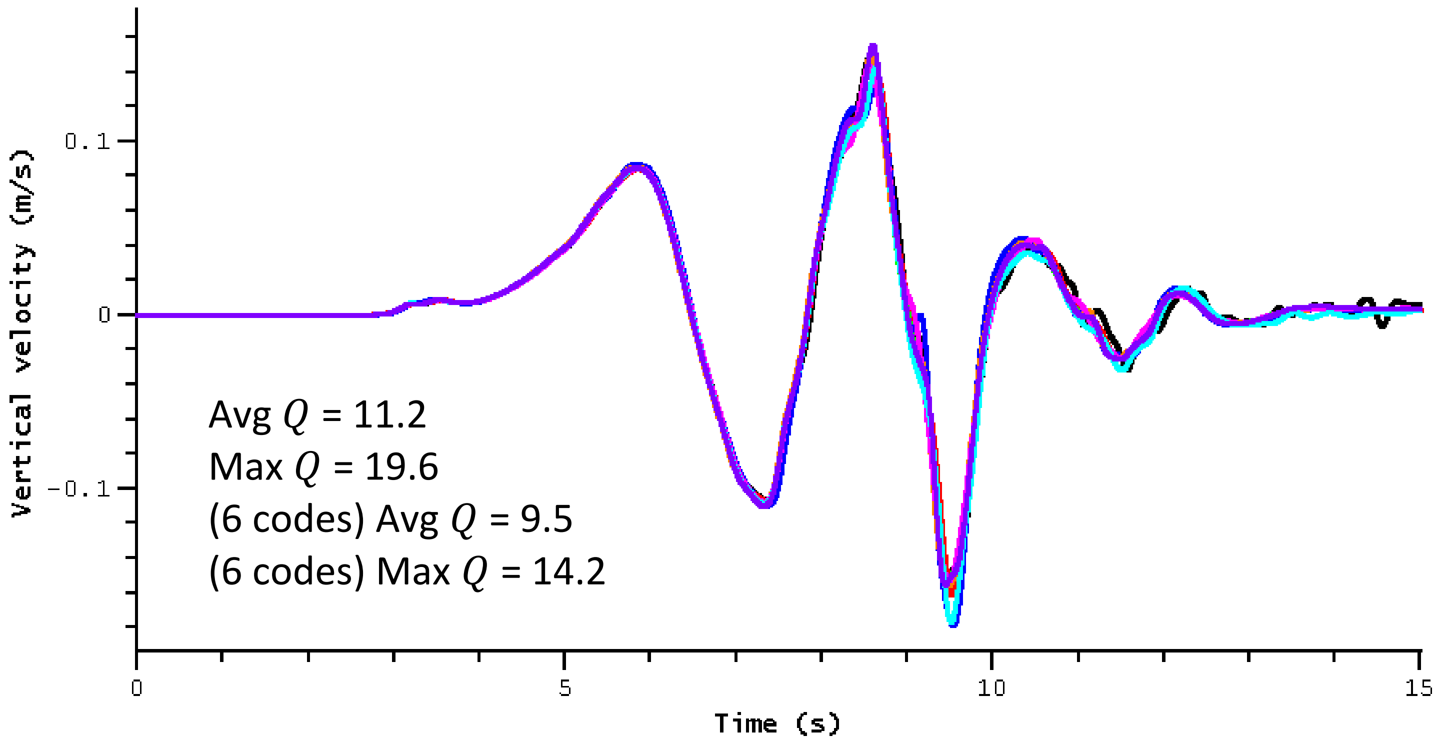
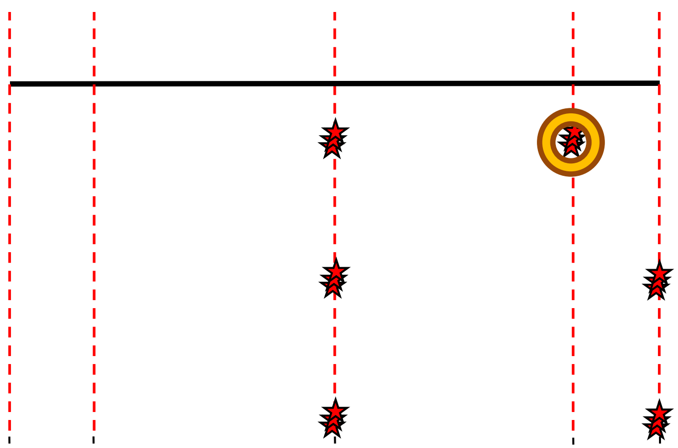
shi.2 (Zheqiang Shi - SORD-S - 25 m)

Some codes show large differences far from the fault.

Filtered at 3 Hz.

TPV32 (Continuous, Min V_S = 1050) – body-030st120dp005 – Vertical Velocity





bai (Kangchen Bai - Spectral Element - SPECFEM3D50m)
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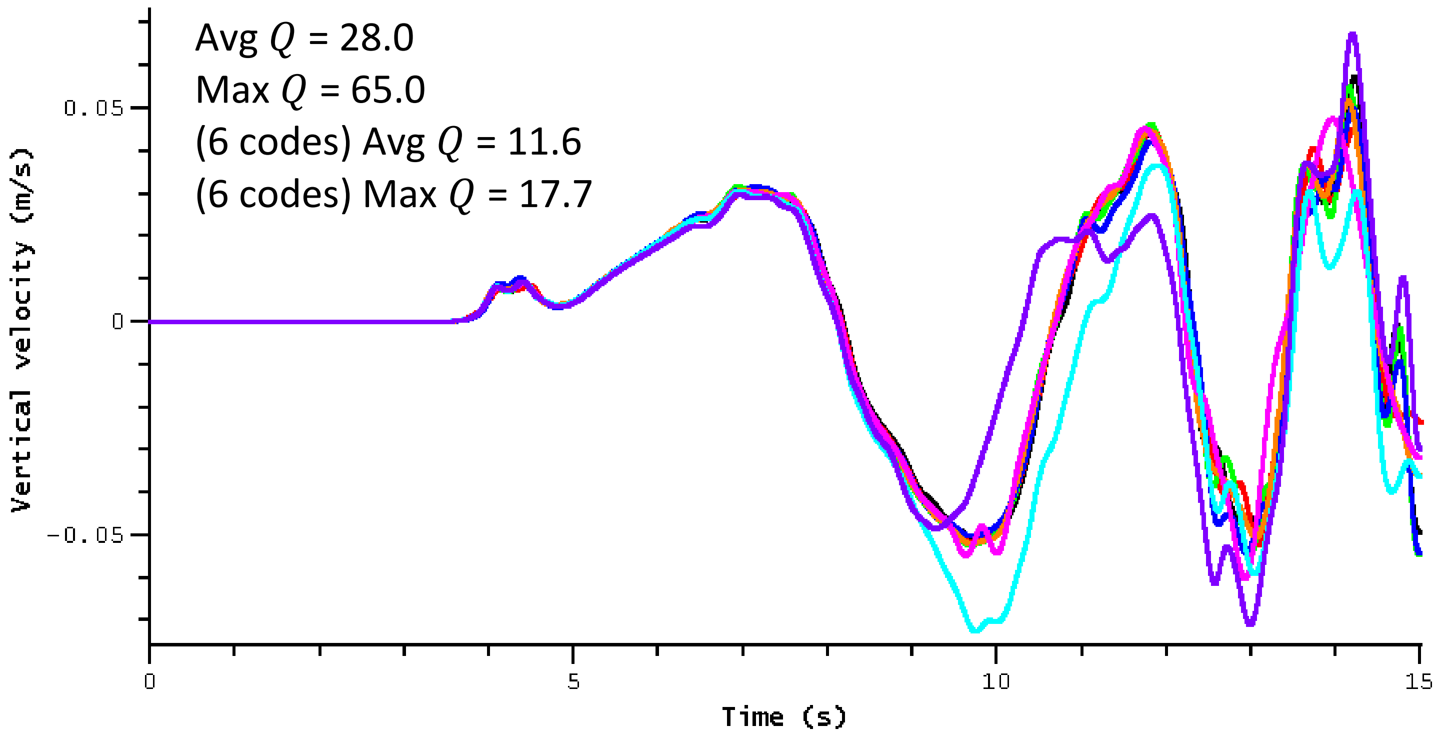
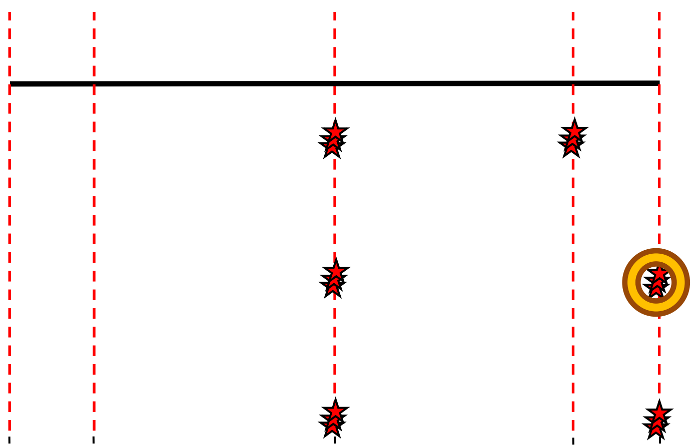
kaneko (Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m)
kozdon.2 (Jeremy Kozdon - beard :: p = 6 :: 67 m (avg))
luo (Bin Luo - Finite Element - EQdyna - 25m)
ma.2 (Shuo Ma - Finite Element - MAFE - 50m)
shi (Zheqiang Shi - SORD-S - 25 m)

Good match close to the fault.

Filtered at 3 Hz.

TPV32 (Continuous, Min V_S = 1050) – body-090st150dp005 – Vertical Velocity

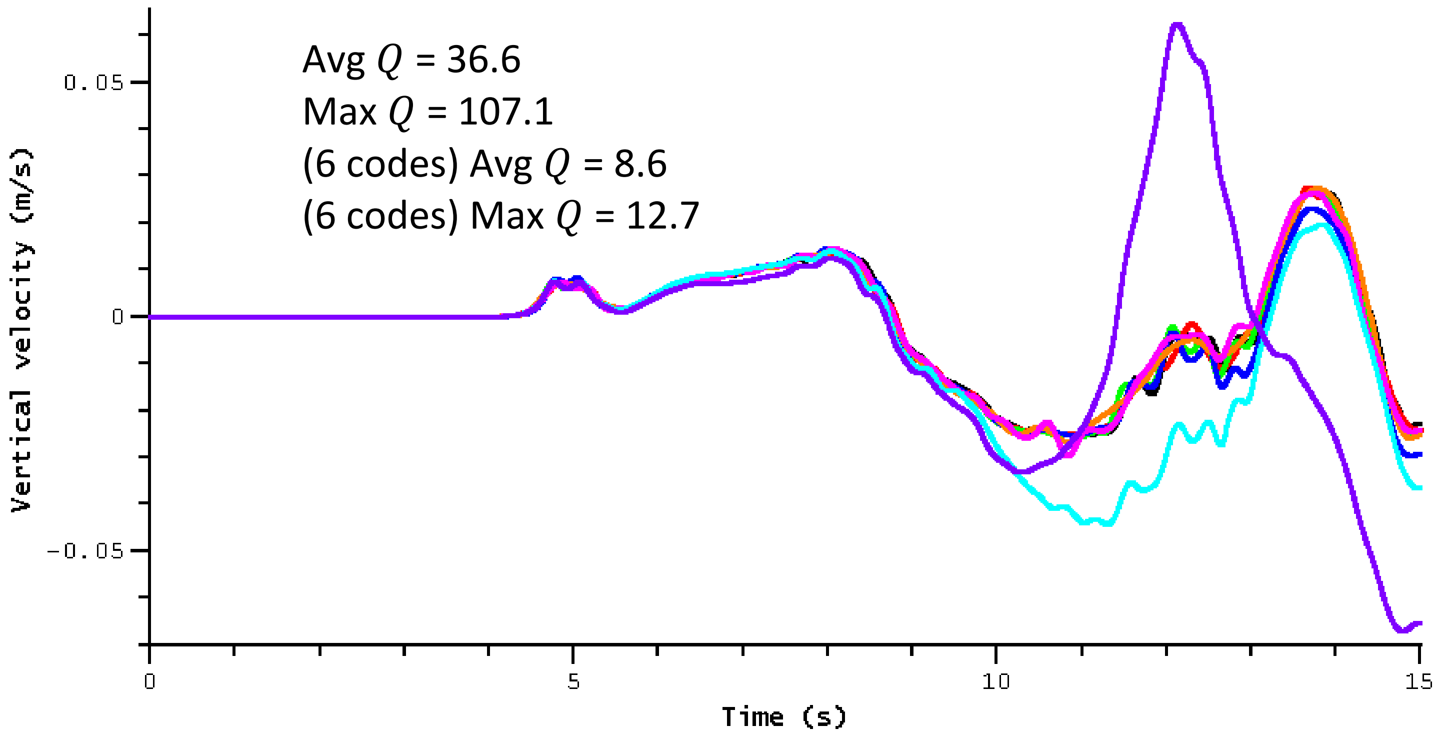


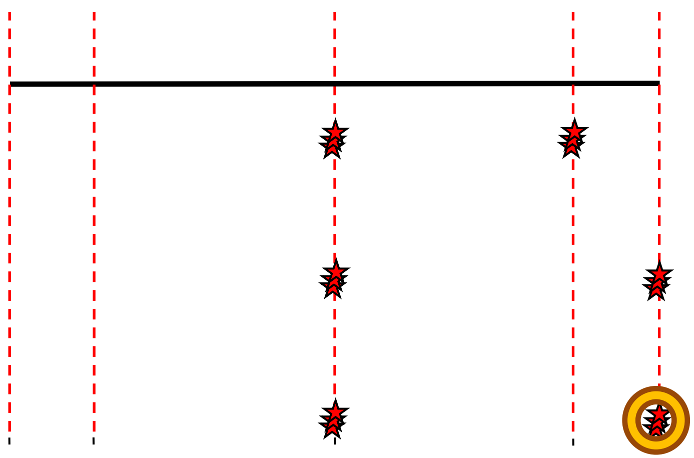


Slight increase in metric for the 6 best-matching codes, some large differences appear.

Filtered at 3 Hz.

TPV32 (Continuous, Min V_S = 1050) – body-150st150dp005 – Vertical Velocity





Large differences for two codes, others agree OK.

Filtered at 3 Hz.

Conclusions

Conclusions

1. We did two benchmarks with a 1D velocity structure:

- TPV31 – Discontinuous 1D velocity structure, minimum V_S = 2250 m/s.
- TPV32 – Continuous 1D velocity structure, minimum V_S = 1050 m/s.

2. Rupture front contours show effects of velocity structure, and codes are in excellent agreement.

3. Codes agree well on process zone width.

- Process zone width shrinks as V_S shrinks, except for one station in TPV31.
- Process zone width shrinks as rupture propagates along-strike.
- TPV32 has very small process zone (~80 m) at earth's surface, requiring high resolution.

4. Peak slip rate at earth's surface is double the peak slip rate just a few 100 meters down, although for TPV31 this effect disappears as the rupture propagates along-strike.

5. Codes are generally in excellent agreement at on-fault stations. Agreement worsens, and oscillation increases, for the stations near the earth's surface with low V_S.

6. These are our first benchmarks with distant off-fault stations.

- For TPV31, agreement generally worsens as we look farther away from the fault.
- In most cases, agreement is worse at the earth's surface than at deeper stations.
- Most codes agree reasonably well, but some show large differences.