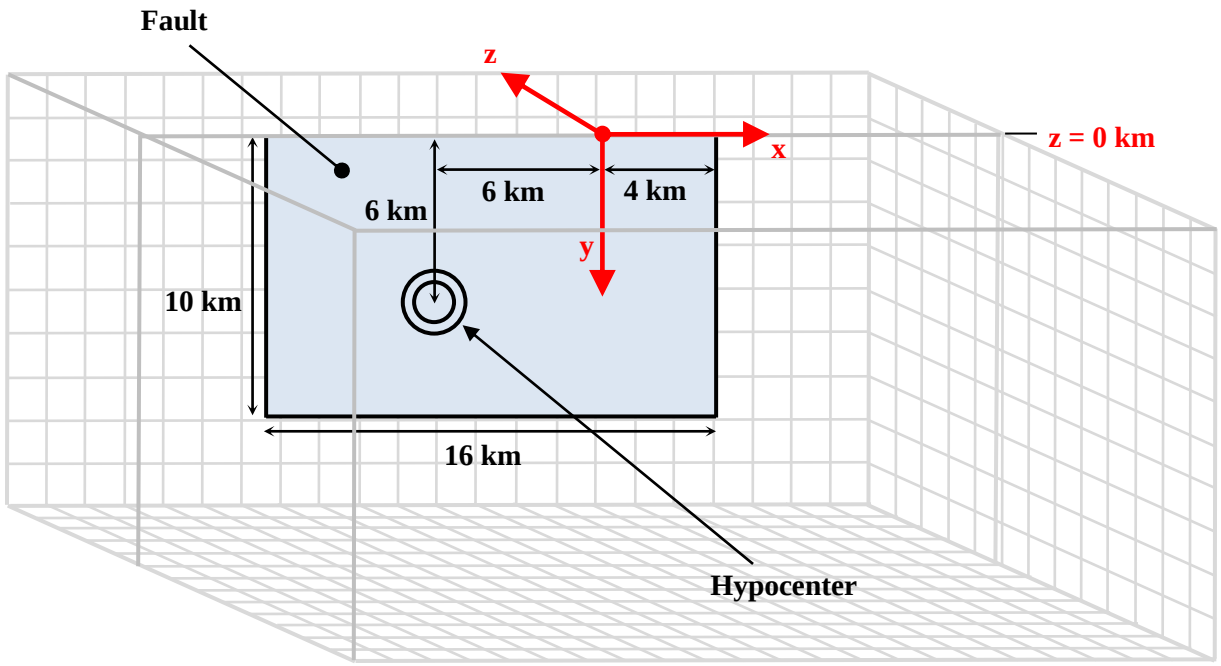
Planar Fault with Fault Zone Guided Waves
TPV33

Michael Barall
Invisible Software, Inc.

SCEC Rupture Dynamics Code Verification Workshop

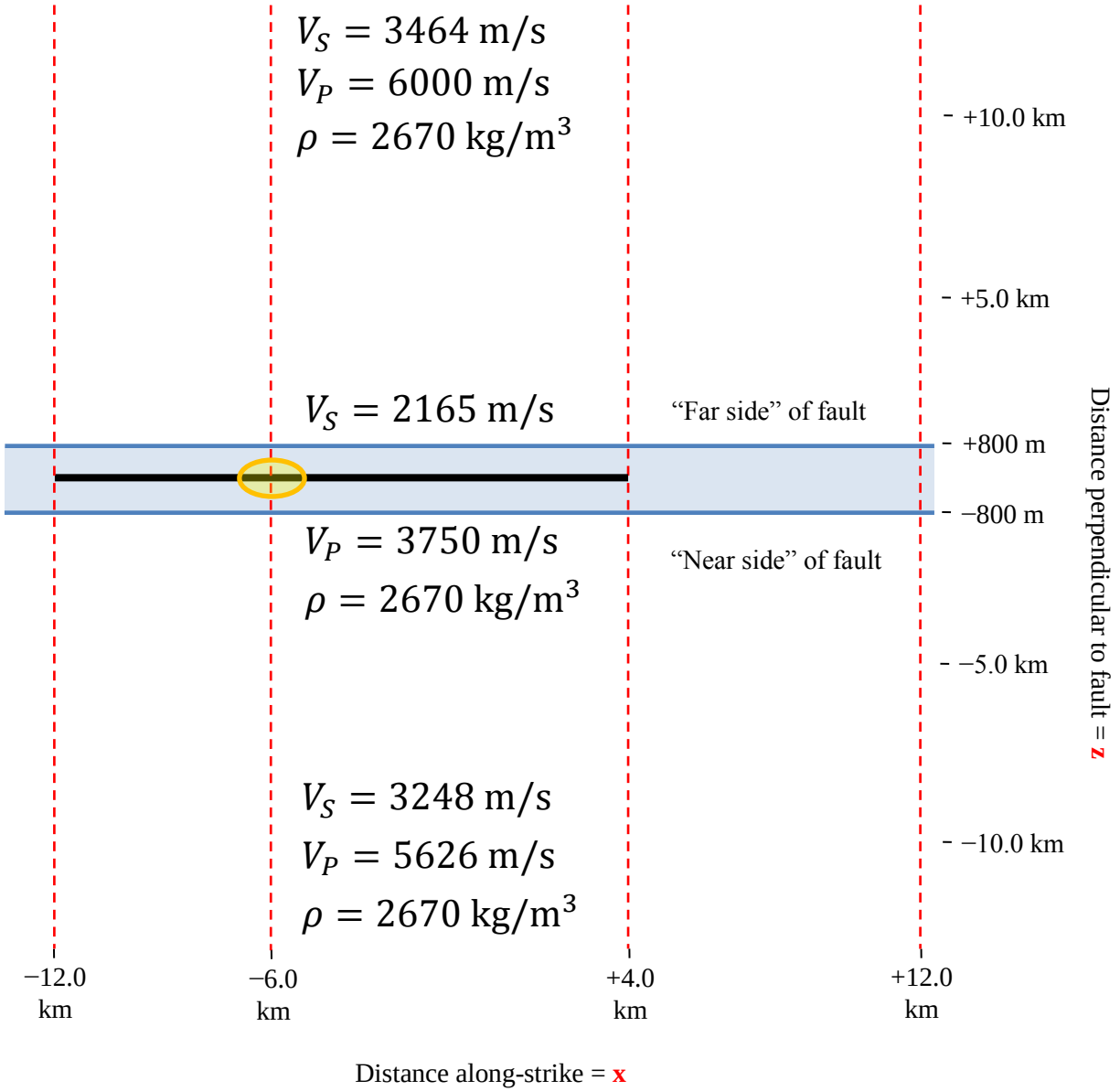
March 11, 2016

TPV33 —Planar Fault with Fault Zone Guided Waves



Right-lateral strike-slip fault in an elastic half-space, with a low-velocity fault zone.

The hypocenter is placed off-center to the left, to generate strong guided waves heading to the right.



Material Properties

The low-velocity fault zone extends for 800 meters on either side of the fault.

Shear modulus changes by more than 2-to-1 between the LVFZ and the surrounding rock.

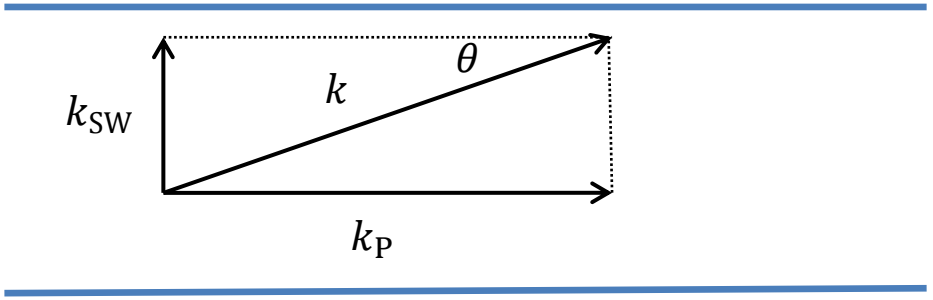
There is also a 14% difference in shear modulus between the surrounding rock on the two sides of the fault.

Waveguides

A waveguide works by setting up a *standing wave* in the direction perpendicular to the direction of propagation. For us, this is the direction perpendicular to the fault.

Our waveguide is 1600 meters thick, which means that the wavelength of the standing wave is:

- 3200 m for the fundamental.
- 1600 m for the first harmonic.



We need to use a relatively thick LVFZ so that our dynamic rupture codes have enough resolution to model wavelengths several times smaller than the wavelength of the standing wave.

In actuality, the standing wave extends slightly outside the LVFZ, which means:

- The wavelengths are actually a bit larger than 3200 m and 1600 m.
- The guided wave “feels” the different material properties on the two sides of the LVFZ, which makes the standing wave profile slightly asymmetrical.

TPV33 Design

Friction Parameters

Friction parameters:

Static coefficient of friction $\mu_s = 0.550$

Dynamic coefficient of friction $\mu_d = 0.450$

Slip-weakening critical distance $d_0 = 0.18$ m

Frictional cohesion $C_0 = 0$

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.

Initial Stress

The initial normal stress is constant:

$$\sigma_0(x, y) = 60 \text{ MPa}$$

The initial shear stress is chosen so that the rupture stops spontaneously before it reaches the top, bottom, left, or right edge of the fault:

$$\tau_0(x, y) = (30 \text{ MPa})(1 - R_\tau) + \tau_{\text{nuke}}(x, y)$$

The tapering term R_τ is chosen so that the initial shear stress is a constant 30 MPa in the central part of the fault, then tapers to lower values at the top, bottom, left, and right edges of the fault:

$$R_x = \begin{cases} (-x - 9800 \text{ m})/(10000 \text{ m}), & \text{if } x < -9800 \text{ m} \\ (x - 1100 \text{ m})/(10000 \text{ m}), & \text{if } x > 1100 \text{ m} \\ 0, & \text{otherwise} \end{cases}$$

$$R_y = \begin{cases} (-y + 2300 \text{ m})/(10000 \text{ m}), & \text{if } y < 2300 \text{ m} \\ (y - 8000 \text{ m})/(10000 \text{ m}), & \text{if } y > 8000 \text{ m} \\ 0, & \text{otherwise} \end{cases}$$

$$R_\tau = \min\left(1, \sqrt{R_x^2 + R_y^2}\right)$$

Nucleation — Overstress Method

- The nucleation zone is a circle of radius 800 m, centered at the hypocenter.
- Within the nucleation zone, we impose an additional initial shear stress.
- Within 550 m of the hypocenter, the initial shear stress is raised to just above the yield stress.
- Between 550 m and 800 m from the hypocenter, there is a cosine taper so that the initial stress is continuous.

The additional shear stress for nucleation is:

$$\tau_{\text{nuke}}(x,y) = \begin{cases} 3.150\ \text{MPa}, & \text{if } r \le 550\ \text{m} \\ (1.575\ \text{MPa})\left(1+\cos\left(\pi(r-550\ \text{m})/(250\ \text{m})\right)\right), & \text{if } 550\ \text{m} \le r \le 800\ \text{m} \\ 0, & \text{otherwise} \end{cases}$$

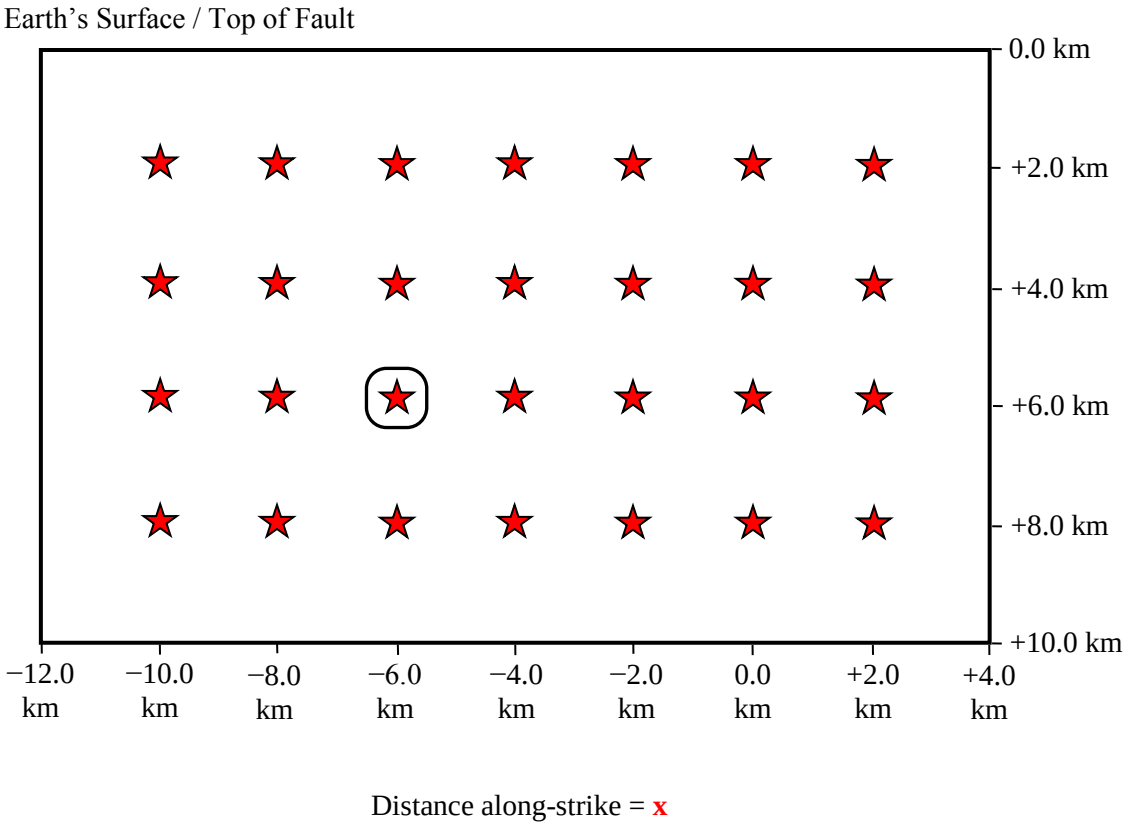
Where r is distance to the hypocenter:

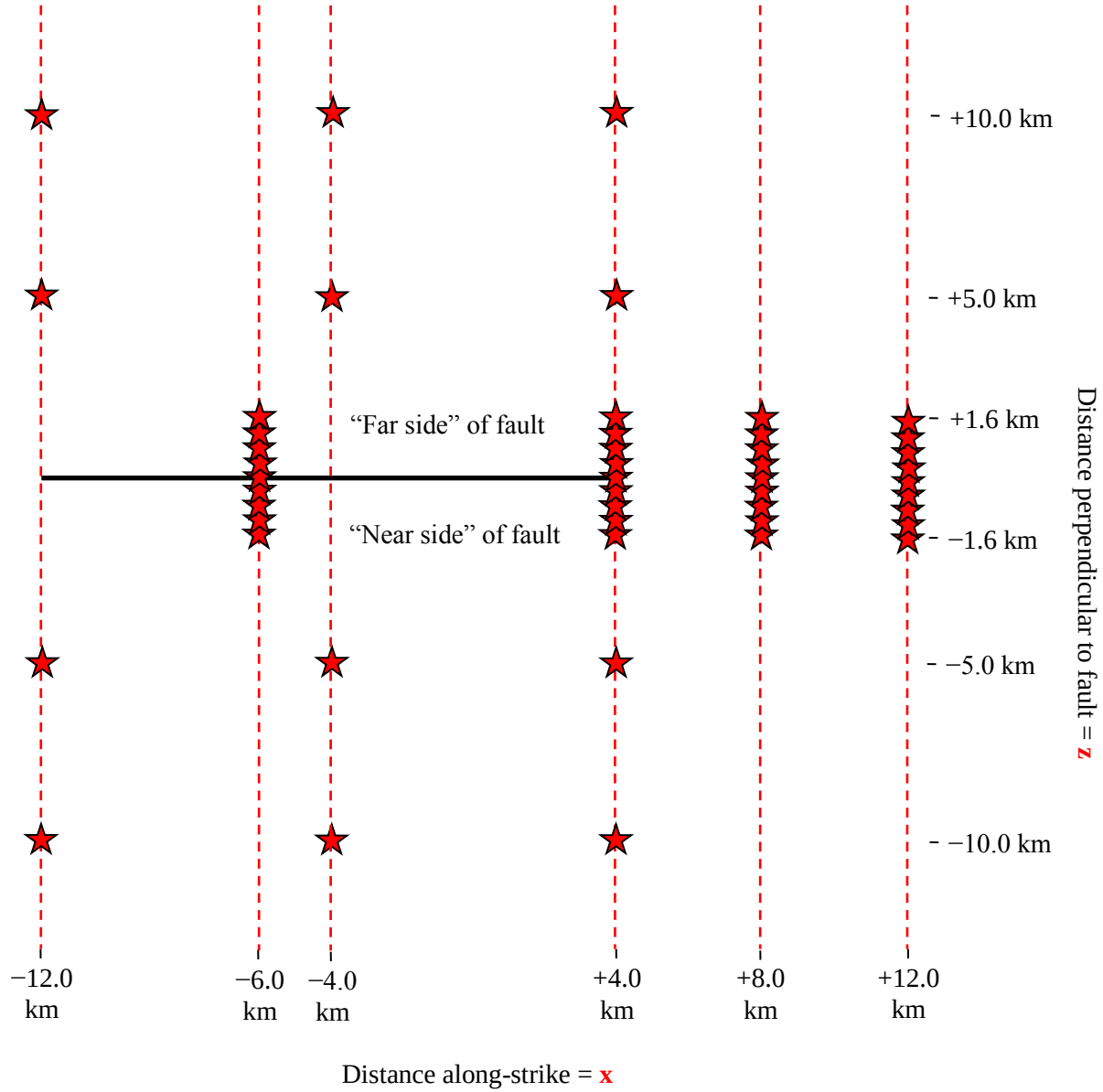
$$r = \sqrt{(x+6000\ \text{m})^2 + (y-6000\ \text{m})^2}$$

On-Fault Stations

Modelers are asked to submit slip, slip rate, and stress as a function of time, for 28 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.

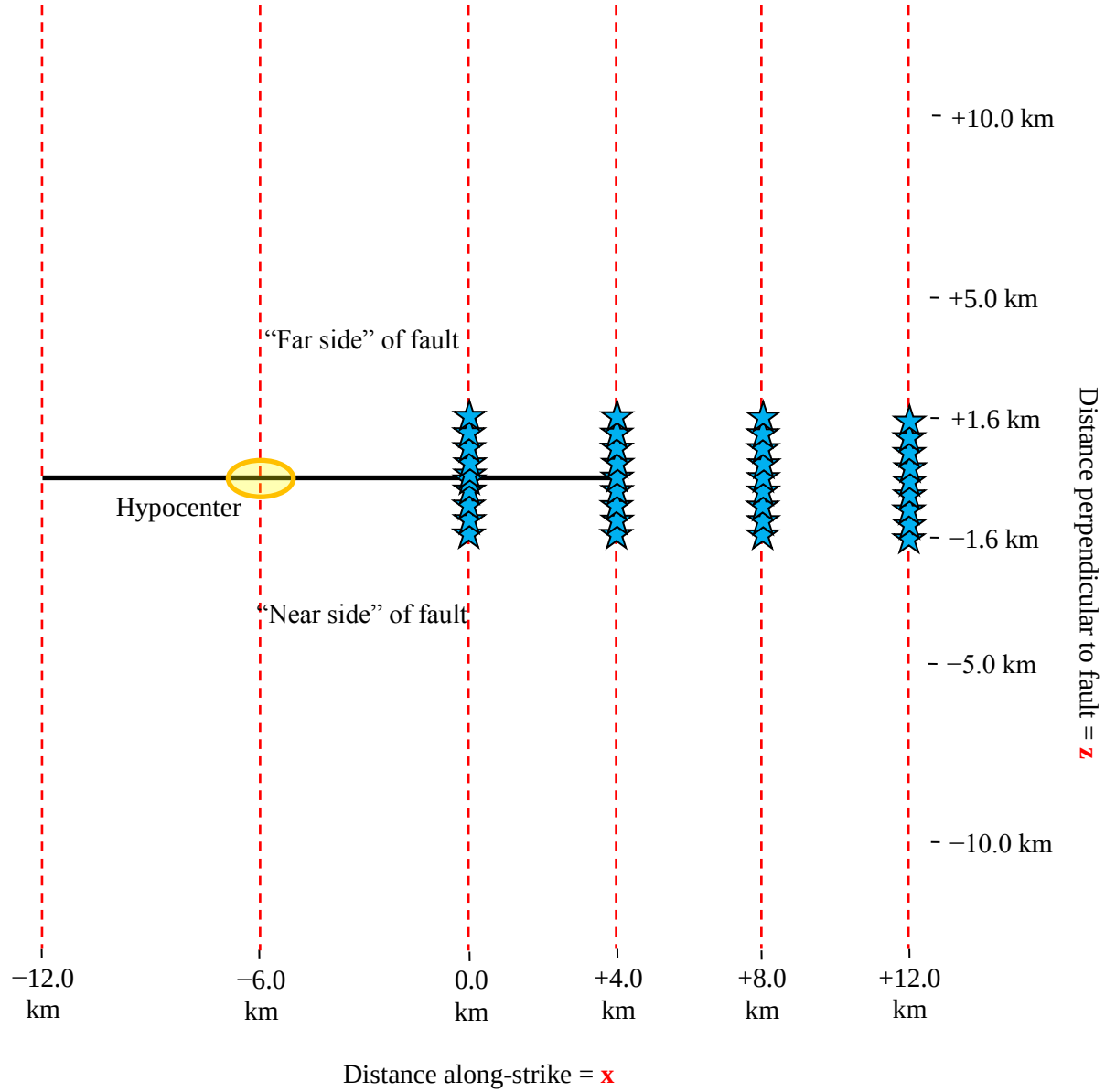




Off-Fault Stations, at the Earth's surface

Modelers are asked to submit displacement and velocity as a function of time, for 48 stations on the earth's surface.

36 of these stations are organized into four "transects" which cross the low-velocity zone.



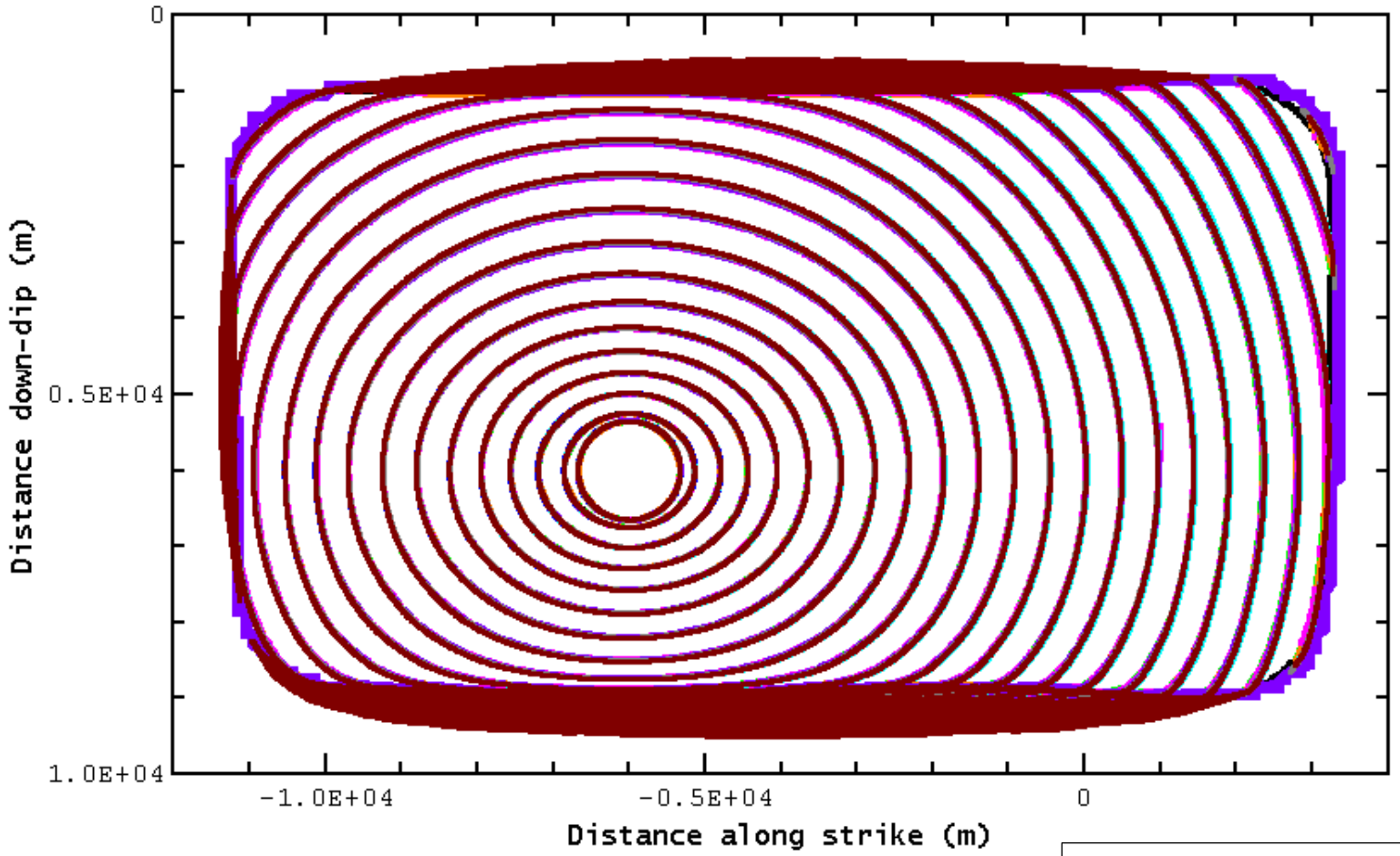
Off-Fault Stations, at a Depth of 6 km

Modelers are asked to submit displacement and velocity as a function of time, for 37 stations at a depth of 6 km (hypocentral depth).

These 37 stations are organized into four "transects" which cross the low-velocity zone.

TPV33 Rupture Contours

TPV33 Rupture Contours — Highest Resolution from Each of 10 Modelers



bai (Kangchen Bai - Spectral Element - SPECFEM3D)
barall (Michael Barall - FaultMod - 12.5 m)
bydlon (Sam Bydlon - Finite Difference - FD-Q-WaveLab - 25m)
chen.2 (Xiaofei Chen - Finite Difference Method - CGFDM - 12.5 m)
daub (Eric Daub - Daub Finite Difference Code - 50m)
kaneko (Yoshihiro Kaneko - SPECFEM3D (older version) - 50 m)
luo (Bin Luo - Finite Element - EQdyna - 12.5m)
ma.2 (Shuo Ma - MAFE - 12.5m on fault - absorbing boundary 50 km)
roten.2 (Daniel Roten - Finite Difference - AWM - 12.5m)
ulrich (Thomas Ulrich - DG Finite Element - SeisSol -100m on fault-o5)

Contours show excellent agreement!

Note rupture stops spontaneously at top, bottom , left, and right.

TPV33 Rupture Contours — Metrics (RMS Difference in Rupture Time)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) bai		3.5	6.8	4.4	5.3	11.5	11.5	7.3	3.6	7.5
(2) barall	3.5		4.8	6.1	3.9	10.0	14.3	6.9	6.1	10.2
(3) bydlon	6.8	4.8		9.0	4.2	7.7	17.6	6.4	8.8	13.5
(4) chen.2	4.4	6.1	9.0		6.9	13.0	9.6	9.0	5.8	7.8
(5) daub	5.3	3.9	4.2	6.9		8.0	15.0	5.5	7.1	12.2
(6) kaneko	11.5	10.0	7.7	13.0	8.0		21.3	5.4	11.9	18.5
(7) luo	11.5	14.3	17.6	9.6	15.0	21.3		17.4	11.0	7.2
(8) ma.2	7.3	6.9	6.4	9.0	5.5	5.4	17.4		8.5	14.8
(9) roten.2	3.6	6.1	8.8	5.8	7.1	11.9	11.0	8.5		7.3
(10) ulrich	7.5	10.2	13.5	7.8	12.2	18.5	7.2	14.8	7.3	

The maximum value is only 21.3 milliseconds, which is a very good value!

Reminder: For each pair of results, the metric value is the RMS difference in the rupture arrival time, with the average running over the part of the fault surface that ruptured. We generally consider values less than 50 milliseconds to be good agreement.

TPV33 Rupture Contours — Process Zone Width (in Meters)

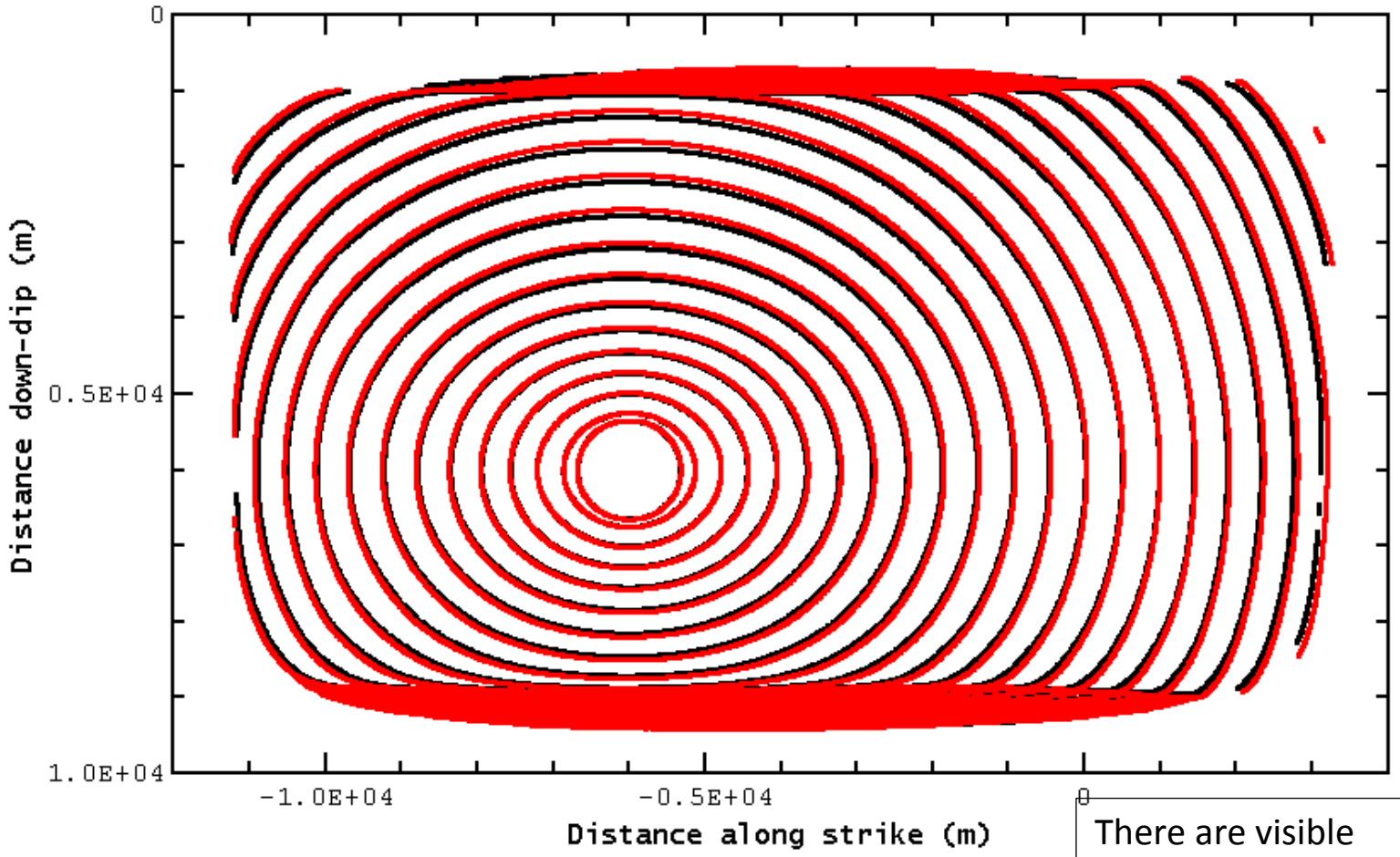
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
faultst-020dp020	104	100	97	110	100	110	107	96	101	94
faultst-020dp040	147	147	145	159	146	151	150	148	146	143
faultst-020dp060	174	177	172	188	173	180	176	180	175	181
faultst-020dp080	145	144	140	156	141	149	148	144	145	146
faultst-040dp020	120	116	113	120	109	121	121	116	119	120
faultst-040dp040	187	186	185	191	182	187	188	189	187	194
faultst-040dp060	245	246	247	252	243	245	247	250	246	234
faultst-040dp080	187	186	184	191	181	186	188	188	187	191
faultst-060dp020	125	122	119	122	112	123	125	122	125	123
faultst-060dp040	196	194	197	199	192	202	198	196	196	200
faultst-060dp060	---	---	---	---	---	---	---	---	---	---
faultst-060dp080	197	194	195	198	189	199	197	195	197	200
faultst-080dp020	119	116	112	119	109	120	121	115	119	116
faultst-080dp040	184	184	183	189	182	185	187	186	185	177

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
faultst-080dp060	242	241	242	248	238	241	244	244	242	240
faultst-080dp080	185	184	182	189	180	185	187	185	185	187
faultst-100dp020	107	103	98	113	102	113	112	99	105	103
faultst-100dp040	139	138	133	151	135	144	144	138	139	142
faultst-100dp060	157	160	150	172	153	161	161	163	157	153
faultst-100dp080	142	142	136	153	138	147	147	141	143	146
faultst000dp020	87	84	77	98	90	97	94	78	81	75
faultst000dp040	110	113	102	125	122	119	110	110	103	98
faultst000dp060	120	124	113	137	130	128	120	121	114	108
faultst000dp080	109	108	100	125	116	120	113	104	105	105
faultst020dp020	83	76	68	95	88	97	93	66	78	73
faultst020dp040	84	80	70	98	93	97	90	70	77	71
faultst020dp060	88	85	74	103	97	101	91	73	82	74
faultst020dp080	96	92	80	110	100	111	103	80	93	91

Horizontal color bands show good agreement between codes.

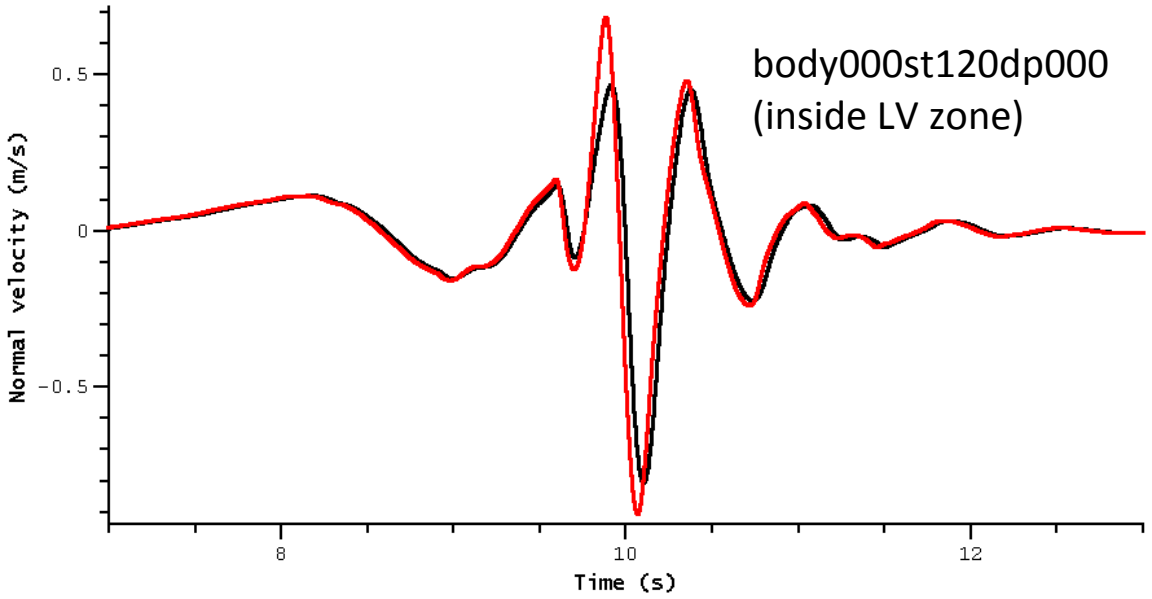
The smallest values, ~70 m, occur farthest from the hypocenter. Ordinarily this would be resolvable with 25 m resolution, but TPV33 seems to need higher resolution for at least some codes.

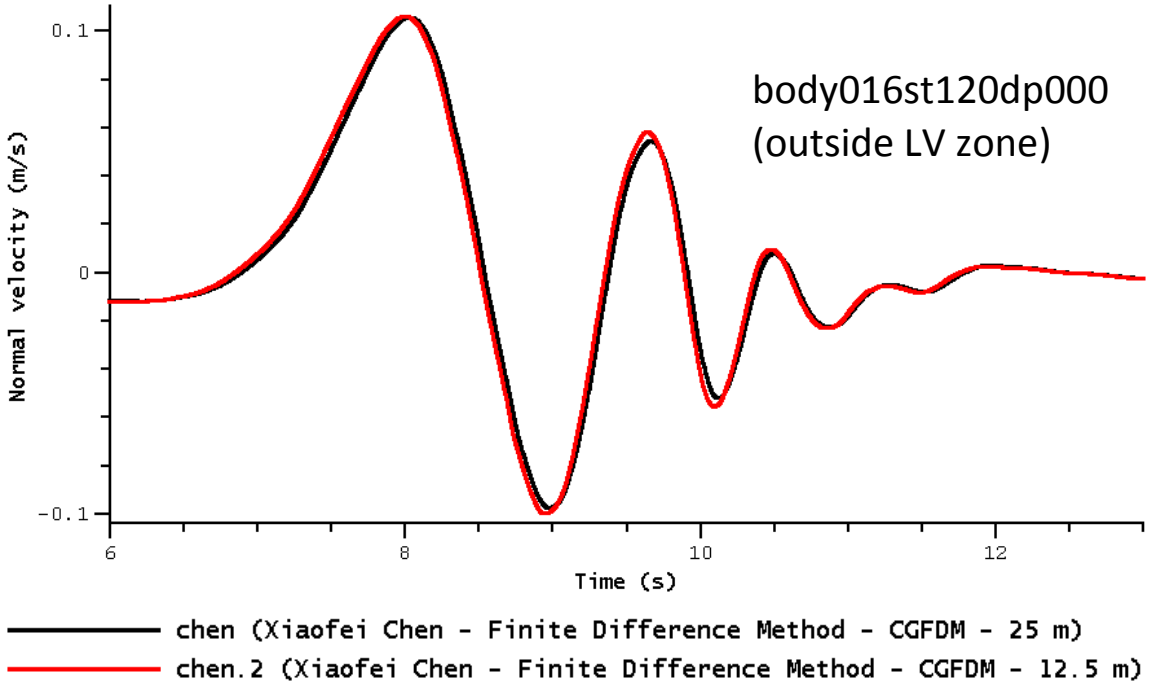
Need for Greater Resolution Than Expected Based on Process Zone Width



There are visible differences between 25 m and 12.5 m results, especially up-dip in the mode III direction. This is maybe due to the low velocity.

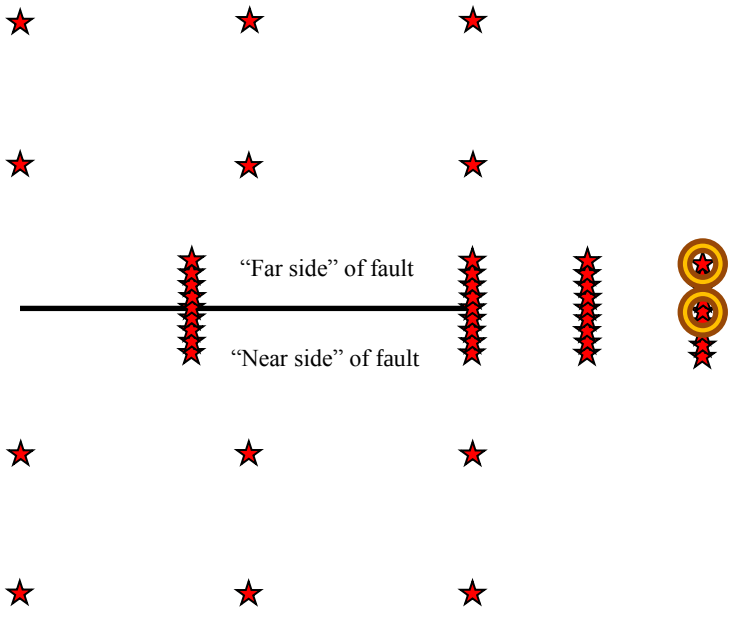
Varying Resolution on the Fault Produces Effects that Propagate Far in the LV Zone





Stations in the LV zone can "see" the effect of changing resolution on the fault surface from far away.

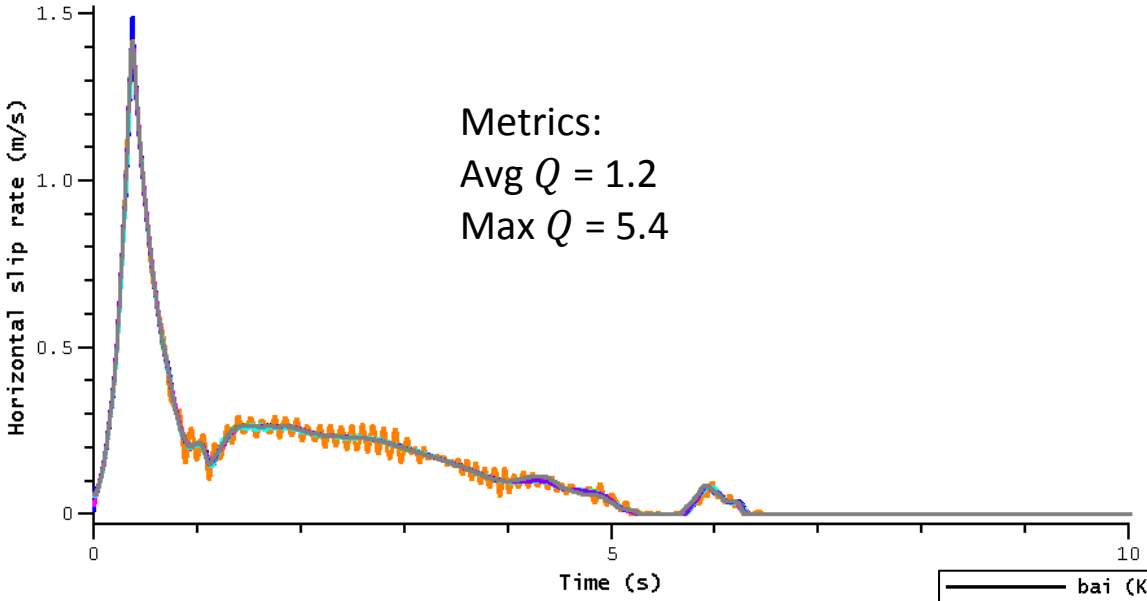
Stations outside the LV zone at the same distance are much less affected.



Filtered at 10 Hz.

TPV33 Results — On-Fault Stations

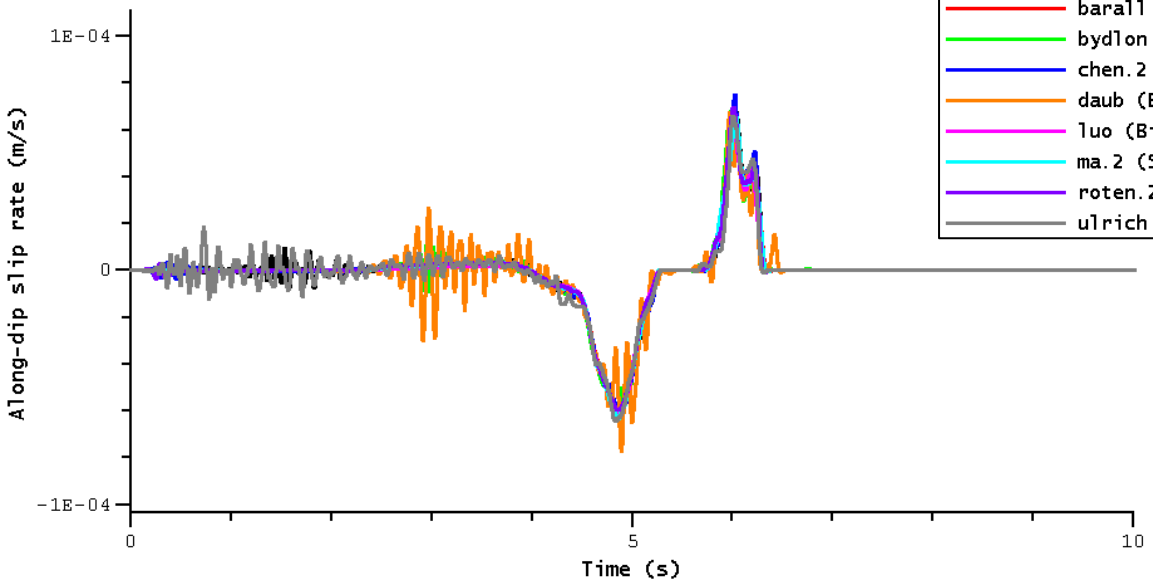
faultst-060dp060 (Hypocenter)

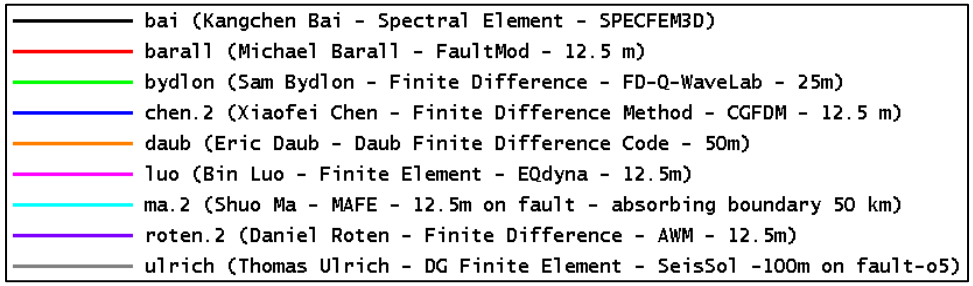


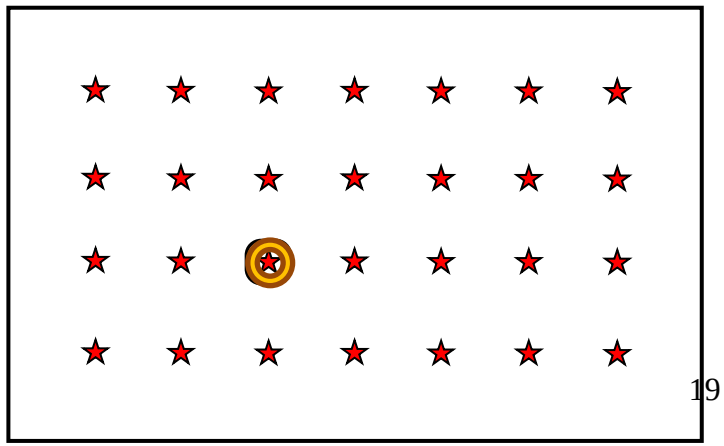
Metrics:
Avg Q = 1.2
Max Q = 5.4

There is near-perfect agreement among the 9 codes.

Vertical slip rate agrees very well despite being 4 orders of magnitude smaller than the horizontal slip rate.

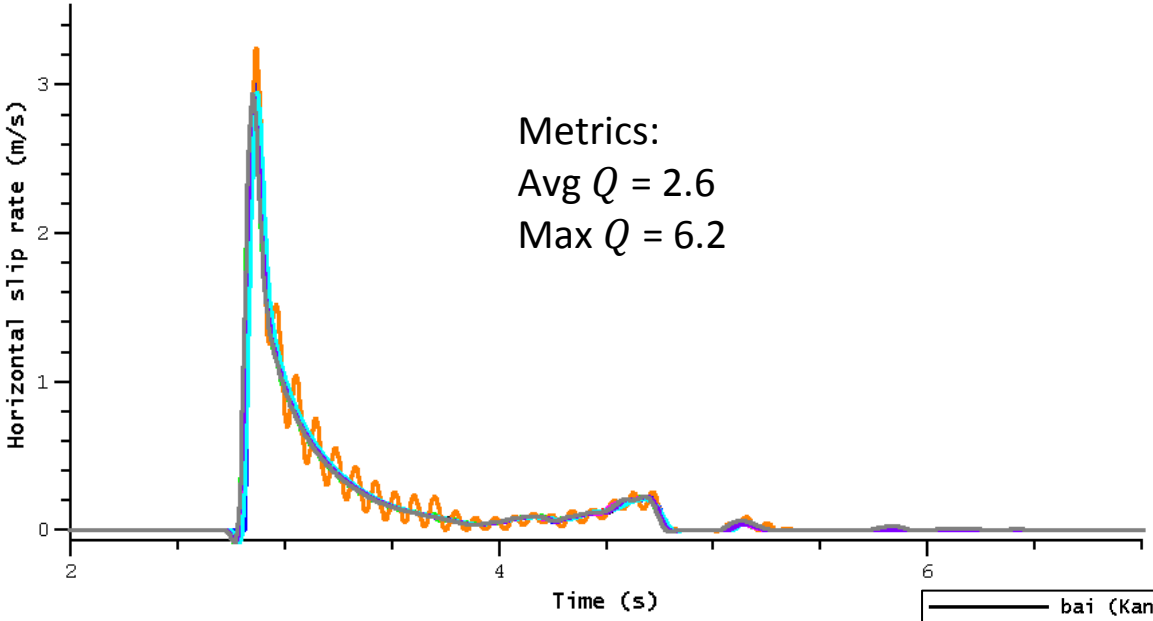






Filtered at 10 Hz.

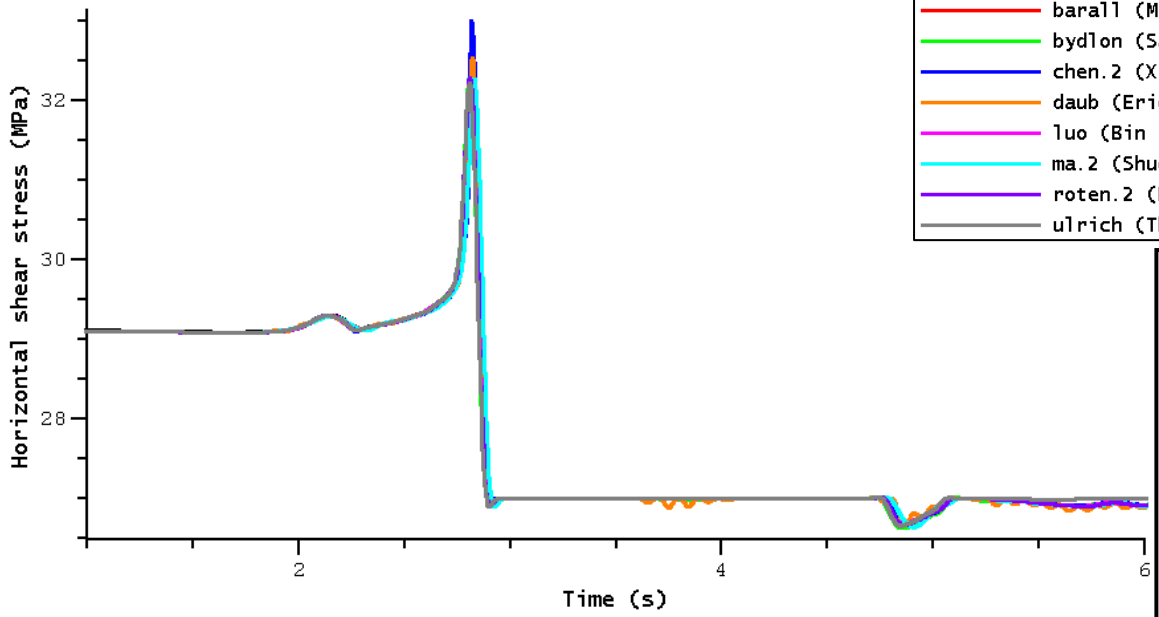
faultst-060dp060 (Updip from Hypocenter)

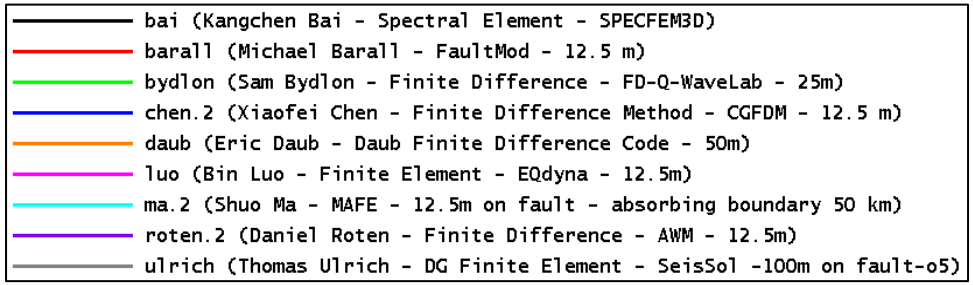


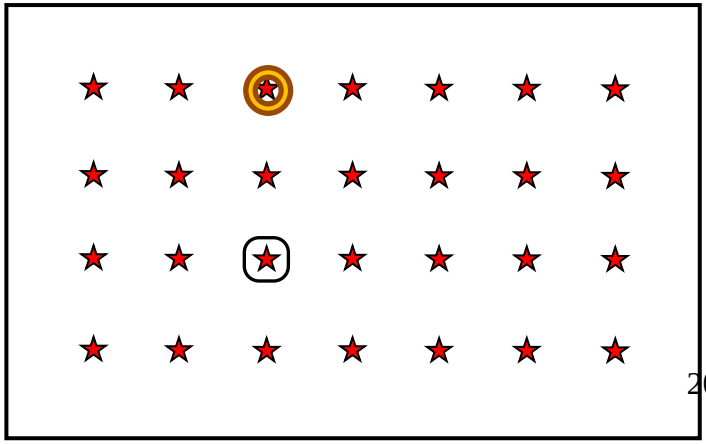
Metrics:
Avg Q = 2.6
Max Q = 6.2

There is near-perfect agreement among the 9 codes for both horizontal slip rate and horizontal shear stress.

One code shows some oscillations.

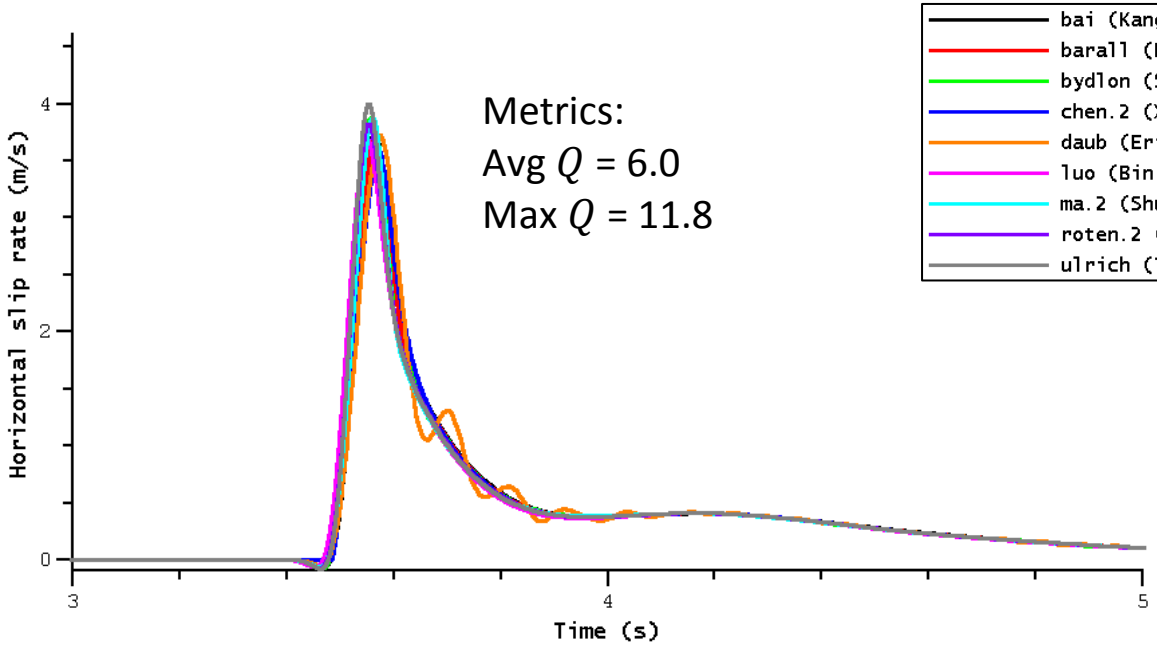


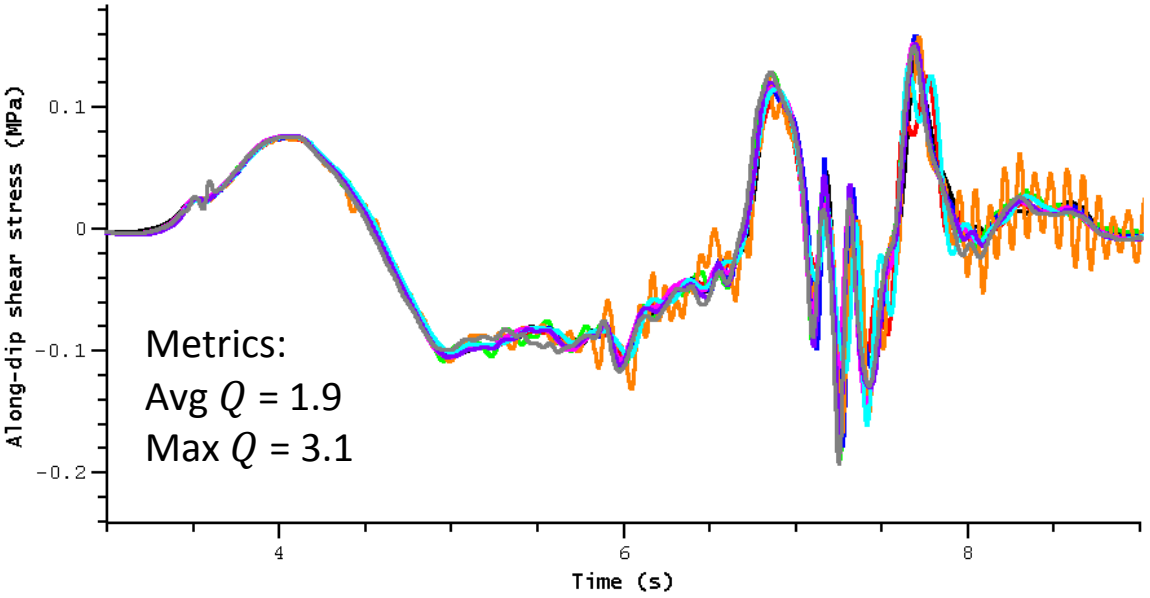




Filtered at 10 Hz.

faultst000dp060 (6 km Right of Hypocenter)



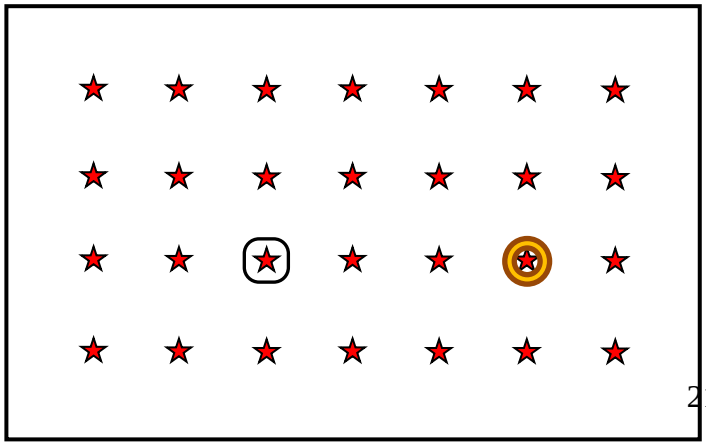


Filtered at 10 Hz.

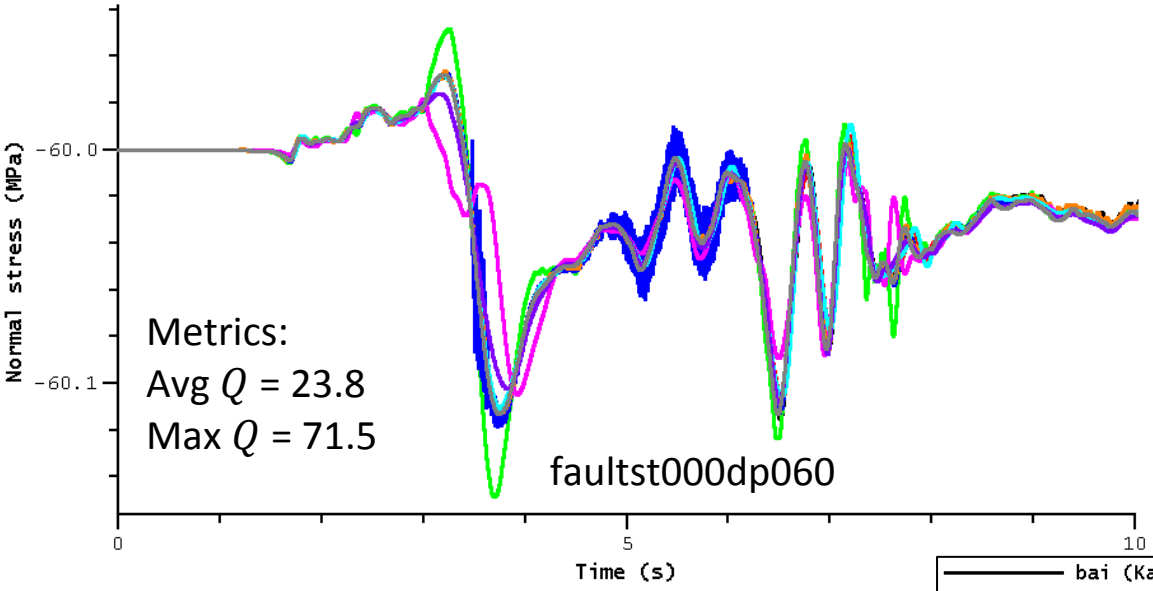
There is excellent agreement among the 9 codes, with only slight differences in the peak slip rate.

As usual, the slip rate peak gets higher and narrower as the rupture propagates (note time scale).

Vertical shear stress agrees very well despite being small and having a complicated waveform.

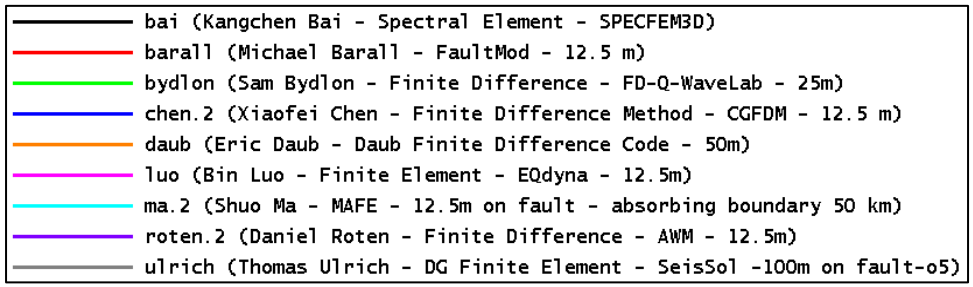


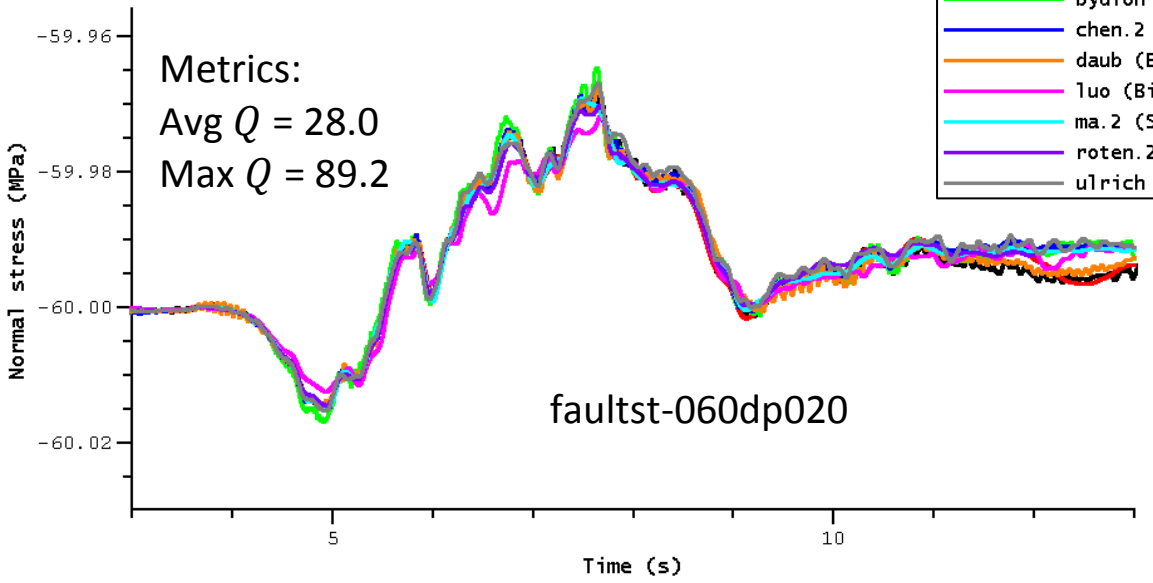
Normal Stress at Two Stations (faultst000dp060 and faultst-060dp020)



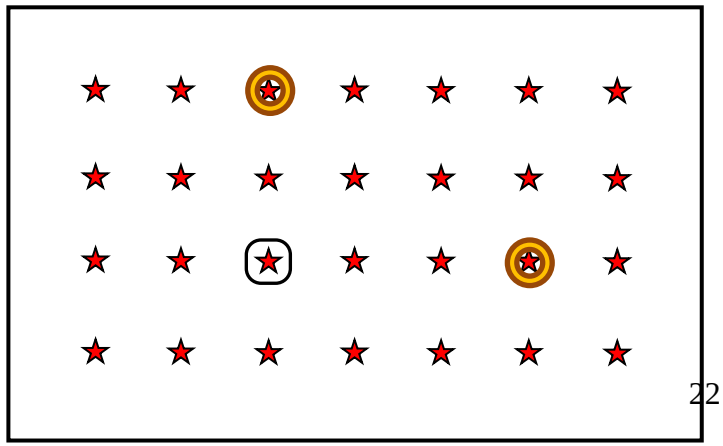
Normal stress can only vary because of the slightly different material properties on the two sides of the LV zone. So the effect is small: about 0.3% and 0.07% at the two stations shown.

Yet the codes agree well on these complicated waveforms.





Filtered at 10 Hz.



Metrics at On-Fault Stations (Summary Across 9 Codes, in Percent)

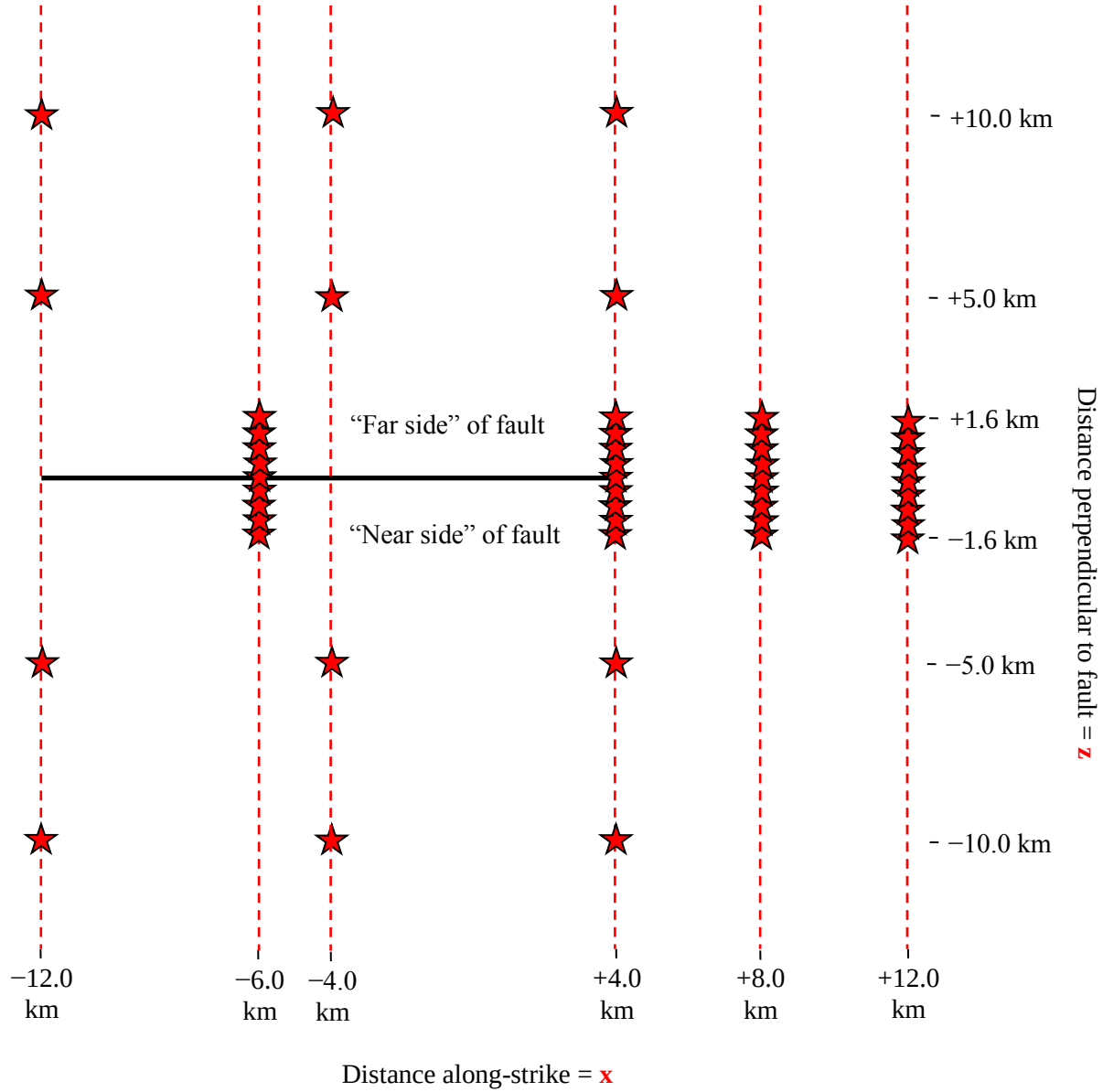
	2d-stress	2d-rate	2d-slip	n-stress	t-shift
faultst-020dp020	3.2	4.5	1.2	33.0	1.02e-002
faultst-020dp040	1.8	2.8	0.4	27.5	7.22e-003
faultst-020dp060	1.8	3.3	0.5	26.3	5.40e-003
faultst-020dp080	2.1	3.1	0.5	28.0	6.82e-003
faultst-040dp020	3.4	5.1	0.8	27.8	9.17e-003
faultst-040dp040	2.2	2.6	0.4	22.9	7.33e-003
faultst-040dp060	1.8	2.9	0.6	27.2	3.97e-003
faultst-040dp080	1.9	2.4	0.5	21.8	6.87e-003
faultst-060dp020	3.0	6.1	0.7	12.8	9.14e-003
faultst-060dp040	2.0	3.0	0.3	13.3	7.60e-003
faultst-060dp060	2.0	2.5	1.3	18.9	2.03e-003
faultst-060dp080	1.8	3.5	0.6	15.5	6.83e-003
faultst-080dp020	5.2	4.8	0.6	27.3	9.11e-003
faultst-080dp040	2.0	2.5	0.5	20.2	7.29e-003

	2d-stress	2d-rate	2d-slip	n-stress	t-shift
faultst-080dp060	1.9	2.6	0.4	26.2	3.59e-003
faultst-080dp080	2.0	2.5	1.1	21.0	6.45e-003
faultst-100dp020	3.9	4.2	0.6	23.4	8.78e-003
faultst-100dp040	2.6	3.5	1.3	15.8	6.15e-003
faultst-100dp060	2.4	3.9	0.7	16.6	4.96e-003
faultst-100dp080	2.7	3.6	0.8	20.1	6.11e-003
faultst000dp020	4.0	6.1	0.6	29.7	1.17e-002
faultst000dp040	1.8	5.8	0.5	24.4	8.44e-003
faultst000dp060	1.7	6.1	0.6	24.9	7.11e-003
faultst000dp080	2.4	5.9	0.6	28.6	8.83e-003
faultst020dp020	10.6	10.9	2.0	24.1	1.44e-002
faultst020dp040	12.2	11.0	1.6	19.4	1.18e-002
faultst020dp060	13.2	11.3	2.1	20.6	1.10e-002
faultst020dp080	11.6	11.1	2.7	25.3	1.27e-002

All codes are showing excellent agreement at all stations for stress, slip rate, and slip, with metric values well below 10%. (The last four stations show values > 10% only because of one code.)

Normal stress has large percentage errors because the change in normal stress is very small. There is actually good agreement.

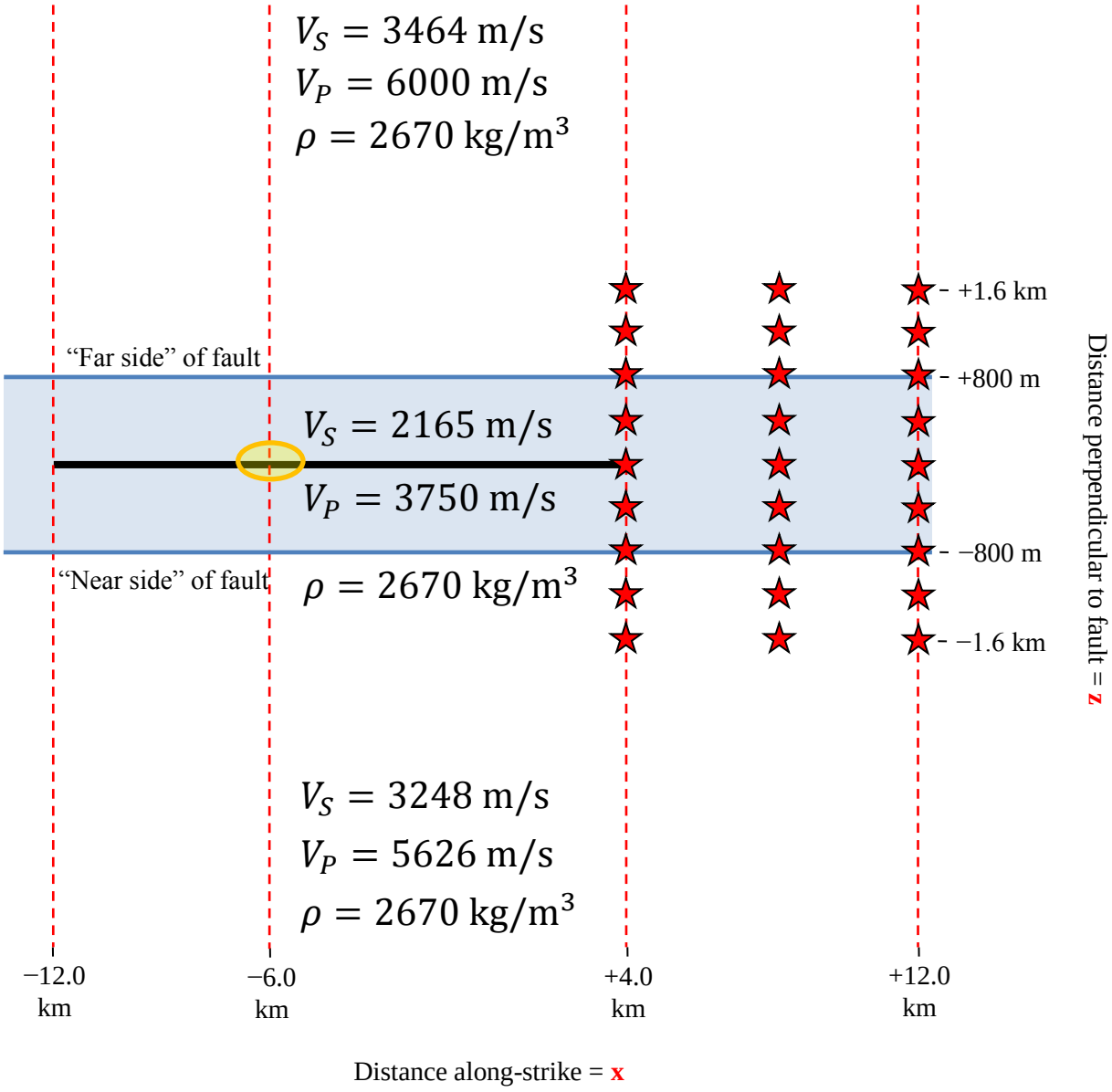
TPV33 Transects — Guided Waves



Off-Fault Stations, at the Earth's surface

Modelers are asked to submit displacement and velocity as a function of time, for 48 stations on the earth's surface.

36 of these stations are organized into four "transects" which cross the low-velocity zone.



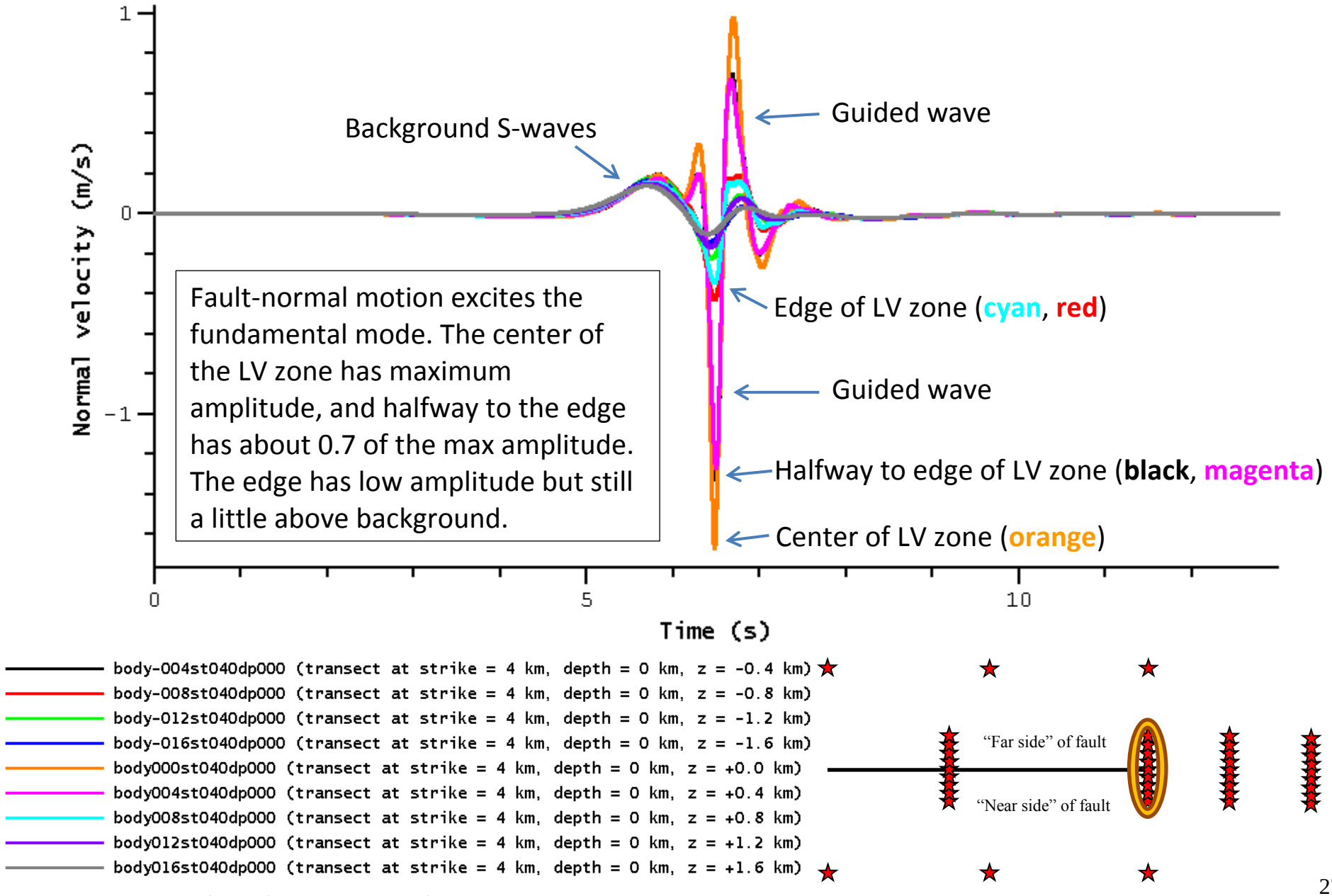
Transects Close-Up

The figure shows a close-up of three transects in relation to the low-velocity zone. **Note that the *z* scale is exaggerated.**

Each transect has 9 stations, spaced 400 m apart:

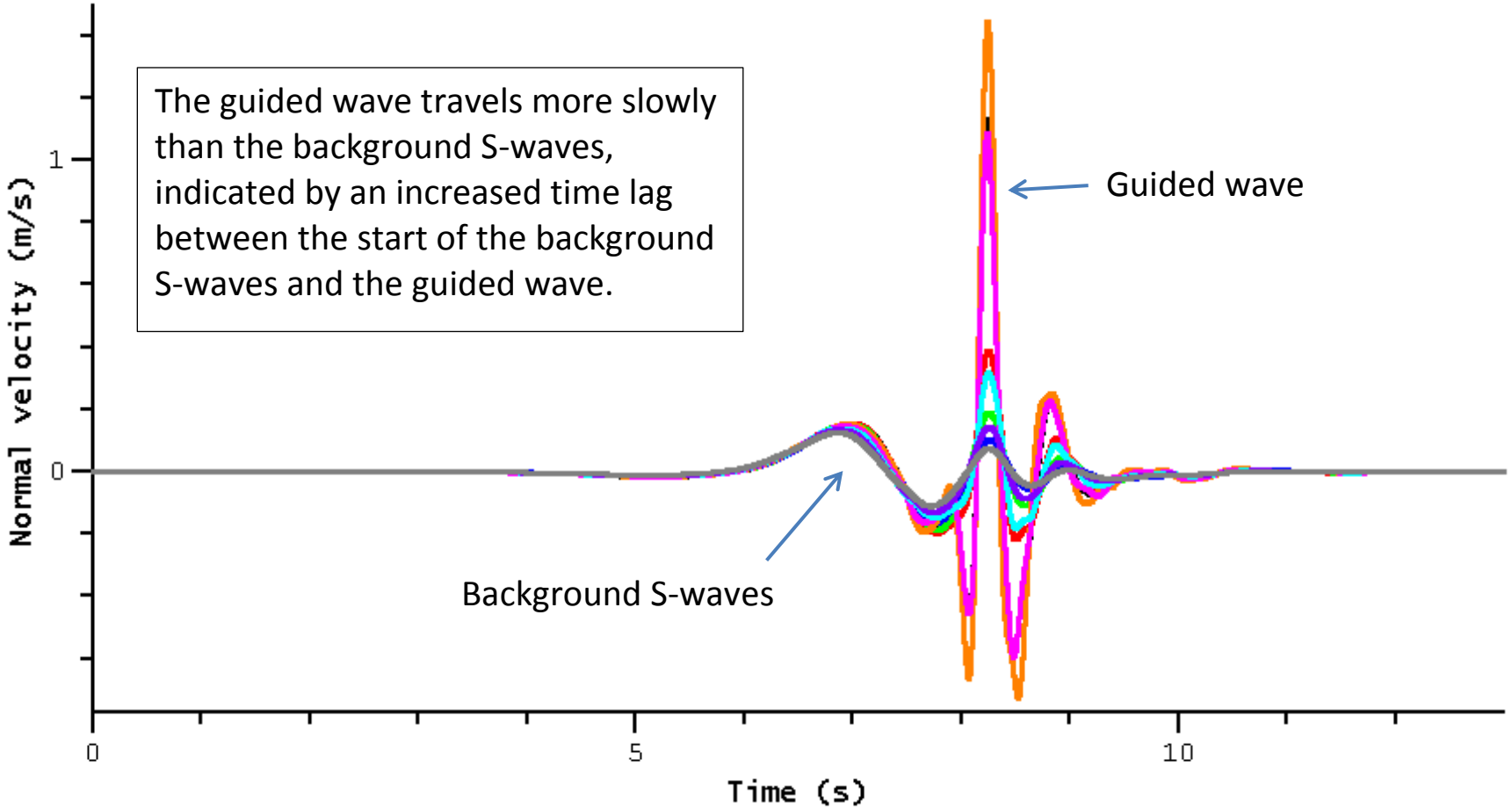
- One station in the center of the LV zone.
- Two stations halfway between the center and edges of the LV zone.
- Two stations at the edges of the LV zone.
- Four stations outside the LV zone.

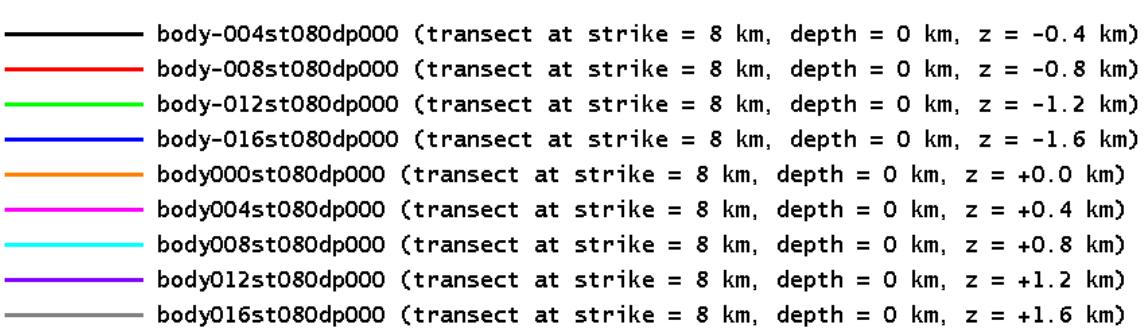
Transect at +4 km Along-Strike, at the Earth's Surface — Normal Velocity

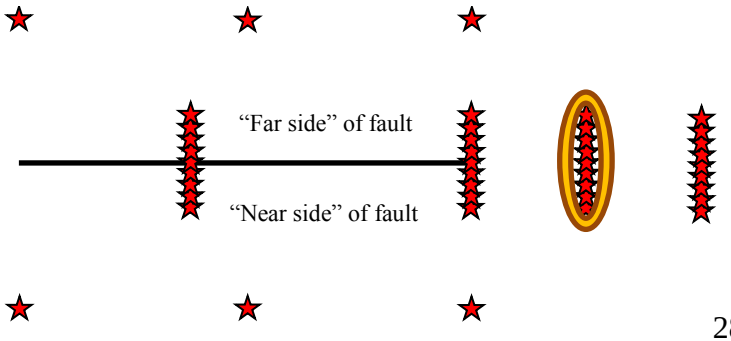


Filtered at 10 Hz. Code: ma.2

Transect at +8 km Along-Strike, at the Earth's Surface — Normal Velocity

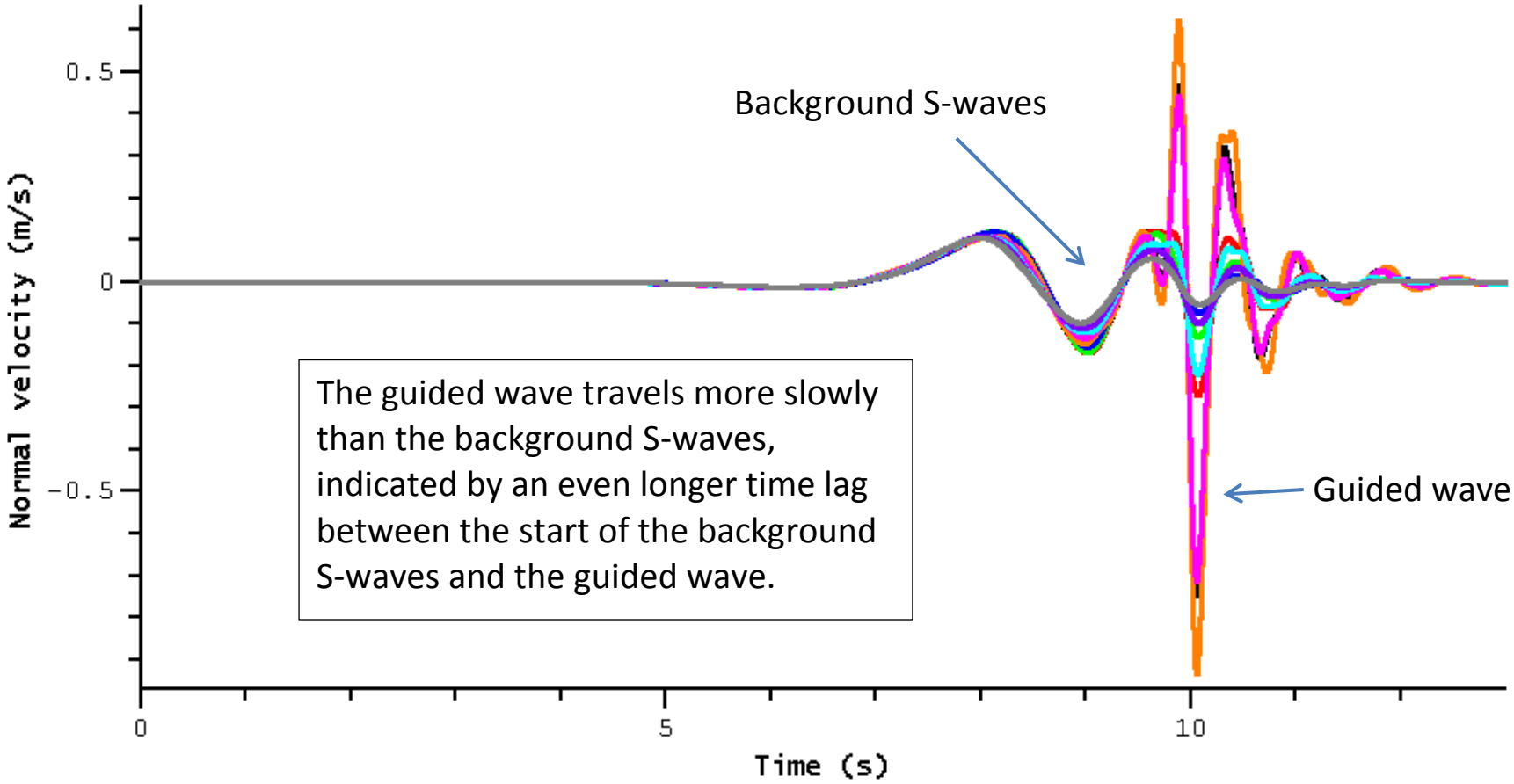




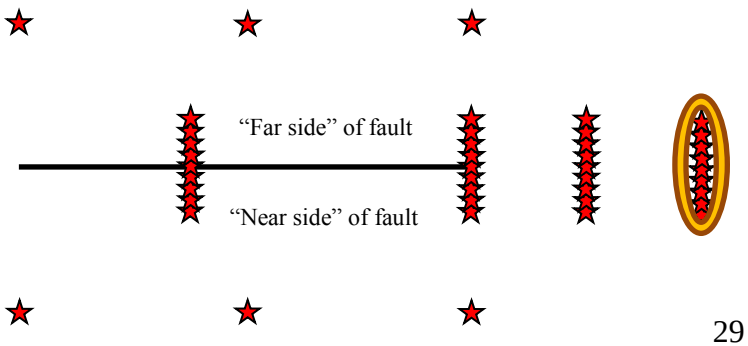


Filtered at 10 Hz. Code: ma.2

Transect at +12 km Along-Strike, at the Earth's Surface — Normal Velocity



body-004st120dp000 (transect at strike = 12 km, depth = 0 km, z = -0.4 km)
body-008st120dp000 (transect at strike = 12 km, depth = 0 km, z = -0.8 km)
body-012st120dp000 (transect at strike = 12 km, depth = 0 km, z = -1.2 km)
body-016st120dp000 (transect at strike = 12 km, depth = 0 km, z = -1.6 km)
body000st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.0 km)
body004st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.4 km)
body008st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.8 km)
body012st120dp000 (transect at strike = 12 km, depth = 0 km, z = +1.2 km)
body016st120dp000 (transect at strike = 12 km, depth = 0 km, z = +1.6 km)



Filtered at 10 Hz. Code: ma.2

Transect at +4 km Along-Strike, at the Earth's Surface — Horizontal Velocity

Fault-parallel motion excites the first harmonic. Maximum amplitudes are halfway to the edge of the LV zone, and with opposite signs.

Halfway to edge of LV zone (**black**, **magenta**)

Guided wave

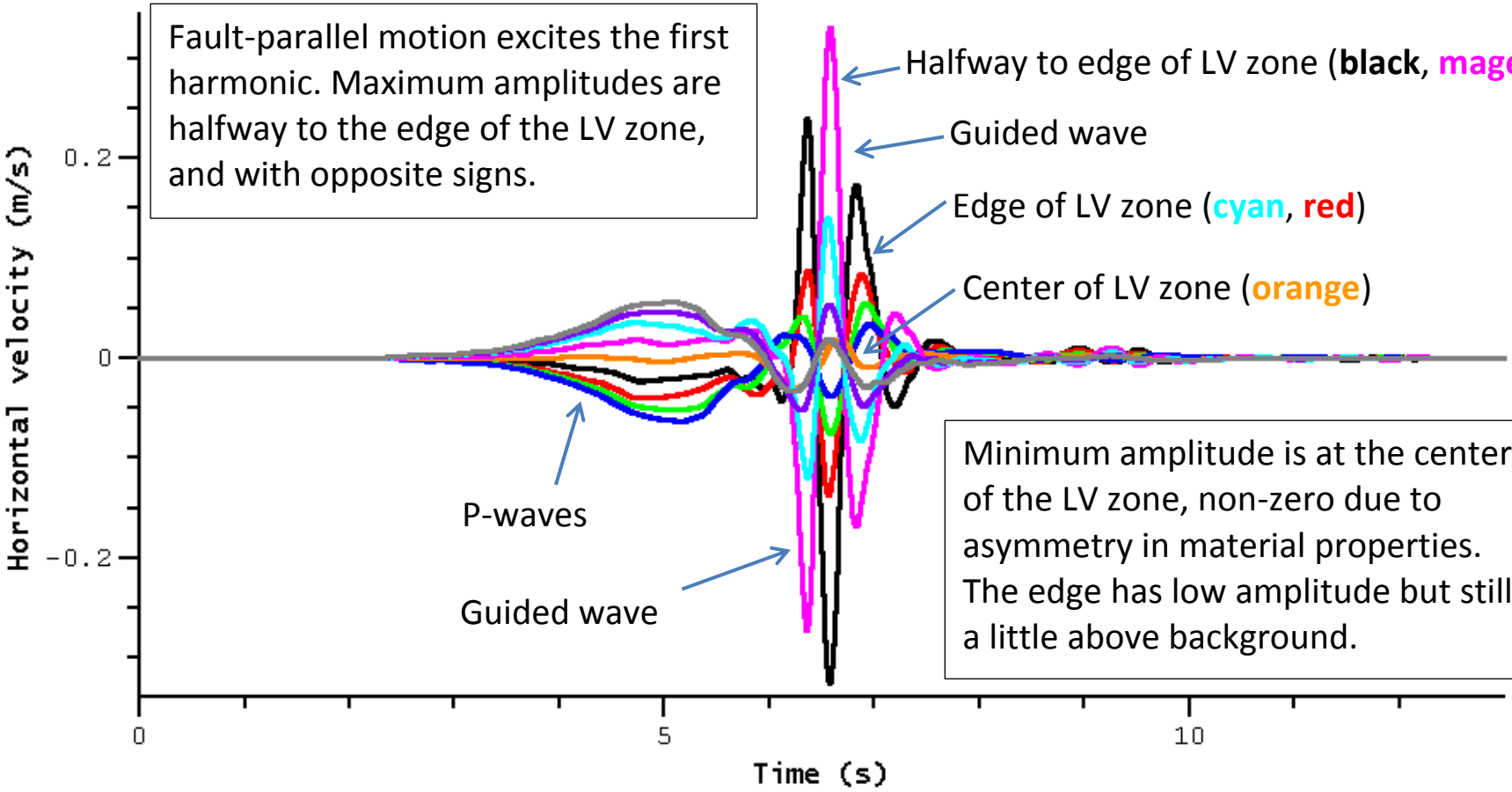
Edge of LV zone (**cyan**, **red**)

Center of LV zone (**orange**)

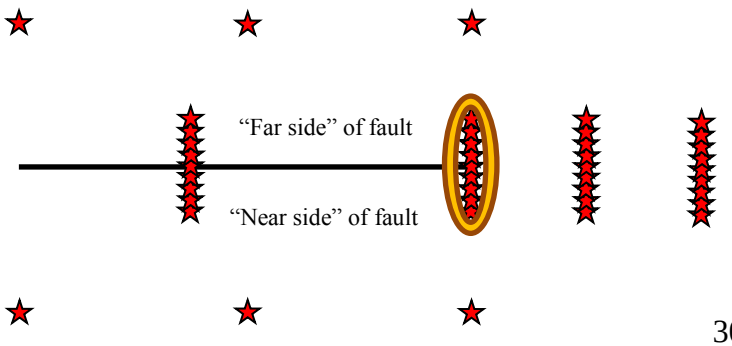
P-waves

Guided wave

Minimum amplitude is at the center of the LV zone, non-zero due to asymmetry in material properties. The edge has low amplitude but still a little above background.

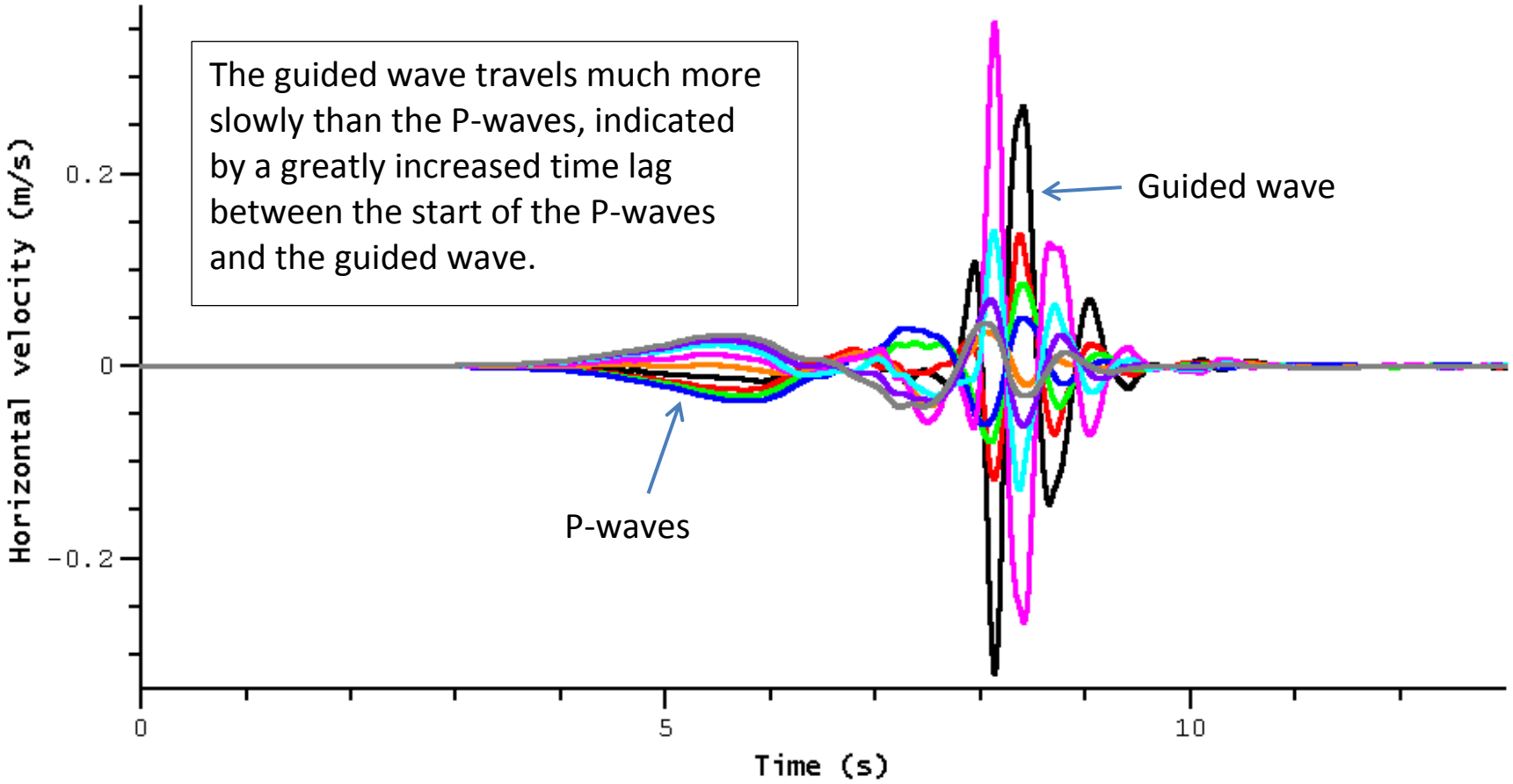


body-004st040dp000 (transect at strike = 4 km, depth = 0 km, z = -0.4 km)
body-008st040dp000 (transect at strike = 4 km, depth = 0 km, z = -0.8 km)
body-012st040dp000 (transect at strike = 4 km, depth = 0 km, z = -1.2 km)
body-016st040dp000 (transect at strike = 4 km, depth = 0 km, z = -1.6 km)
body000st040dp000 (transect at strike = 4 km, depth = 0 km, z = +0.0 km)
body004st040dp000 (transect at strike = 4 km, depth = 0 km, z = +0.4 km)
body008st040dp000 (transect at strike = 4 km, depth = 0 km, z = +0.8 km)
body012st040dp000 (transect at strike = 4 km, depth = 0 km, z = +1.2 km)
body016st040dp000 (transect at strike = 4 km, depth = 0 km, z = +1.6 km)

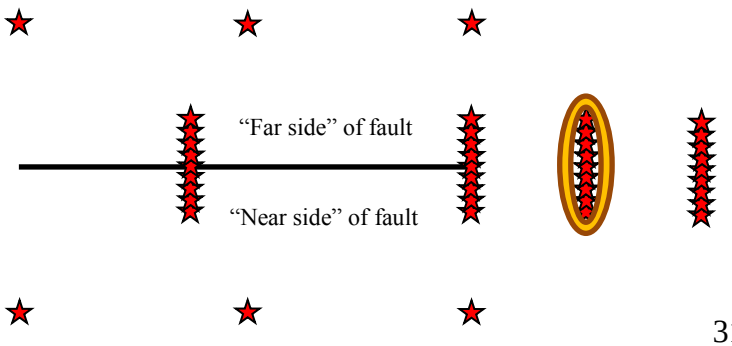


Filtered at 10 Hz. Code: roten.2

Transect at +8 km Along-Strike, at the Earth's Surface — Horizontal Velocity

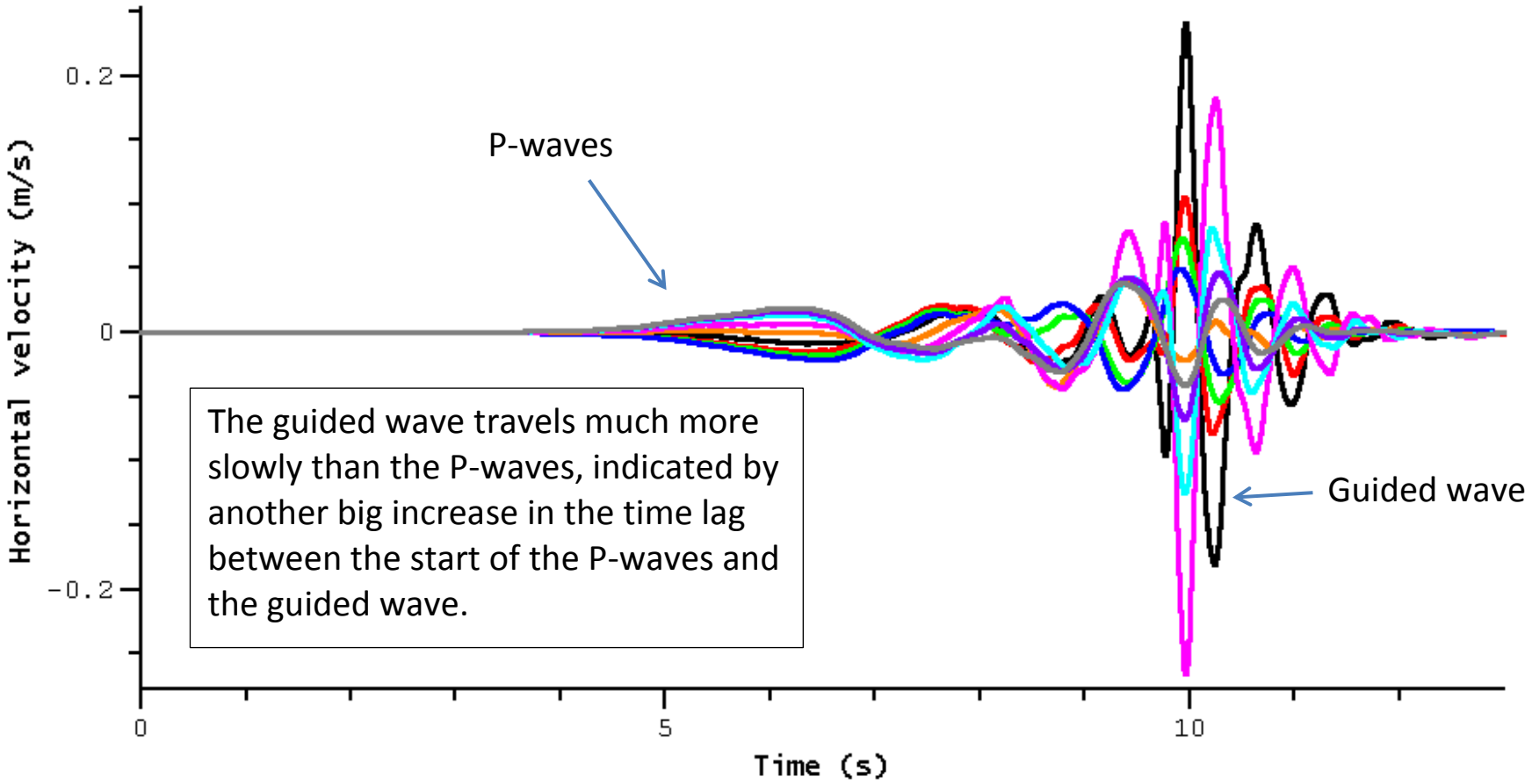


body-004st080dp000 (transect at strike = 8 km, depth = 0 km, z = -0.4 km)
body-008st080dp000 (transect at strike = 8 km, depth = 0 km, z = -0.8 km)
body-012st080dp000 (transect at strike = 8 km, depth = 0 km, z = -1.2 km)
body-016st080dp000 (transect at strike = 8 km, depth = 0 km, z = -1.6 km)
body000st080dp000 (transect at strike = 8 km, depth = 0 km, z = +0.0 km)
body004st080dp000 (transect at strike = 8 km, depth = 0 km, z = +0.4 km)
body008st080dp000 (transect at strike = 8 km, depth = 0 km, z = +0.8 km)
body012st080dp000 (transect at strike = 8 km, depth = 0 km, z = +1.2 km)
body016st080dp000 (transect at strike = 8 km, depth = 0 km, z = +1.6 km)

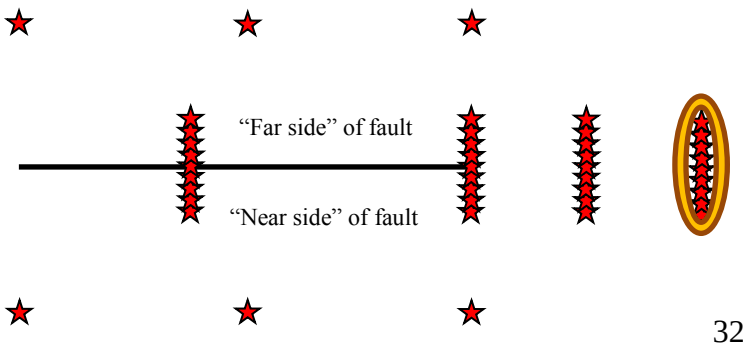


Filtered at 10 Hz. Code: roten.2

Transect at +12 km Along-Strike, at the Earth's Surface — Horizontal Velocity

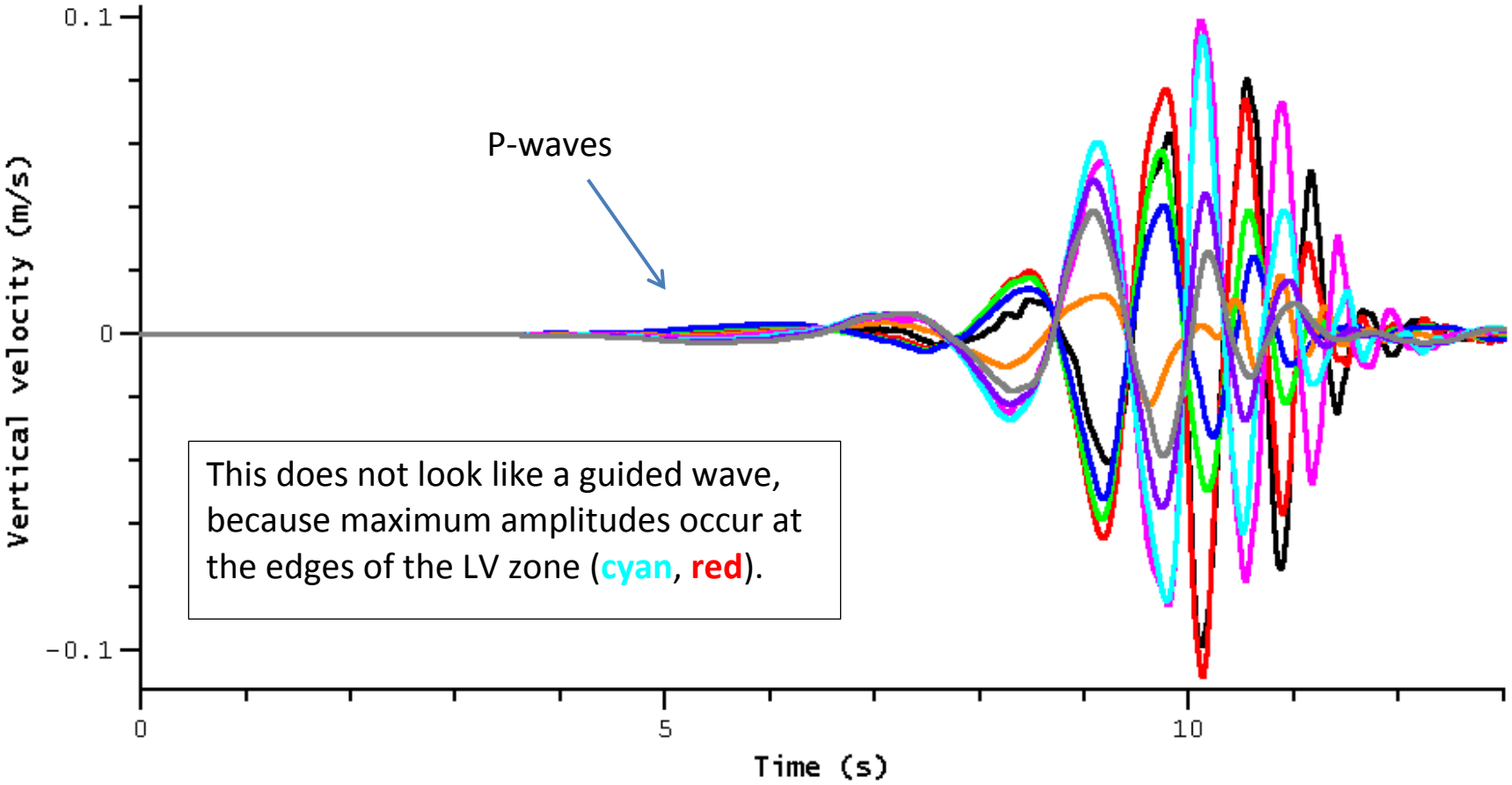


body-004st120dp000 (transect at strike = 12 km, depth = 0 km, z = -0.4 km)
body-008st120dp000 (transect at strike = 12 km, depth = 0 km, z = -0.8 km)
body-012st120dp000 (transect at strike = 12 km, depth = 0 km, z = -1.2 km)
body-016st120dp000 (transect at strike = 12 km, depth = 0 km, z = -1.6 km)
body000st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.0 km)
body004st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.4 km)
body008st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.8 km)
body012st120dp000 (transect at strike = 12 km, depth = 0 km, z = +1.2 km)
body016st120dp000 (transect at strike = 12 km, depth = 0 km, z = +1.6 km)



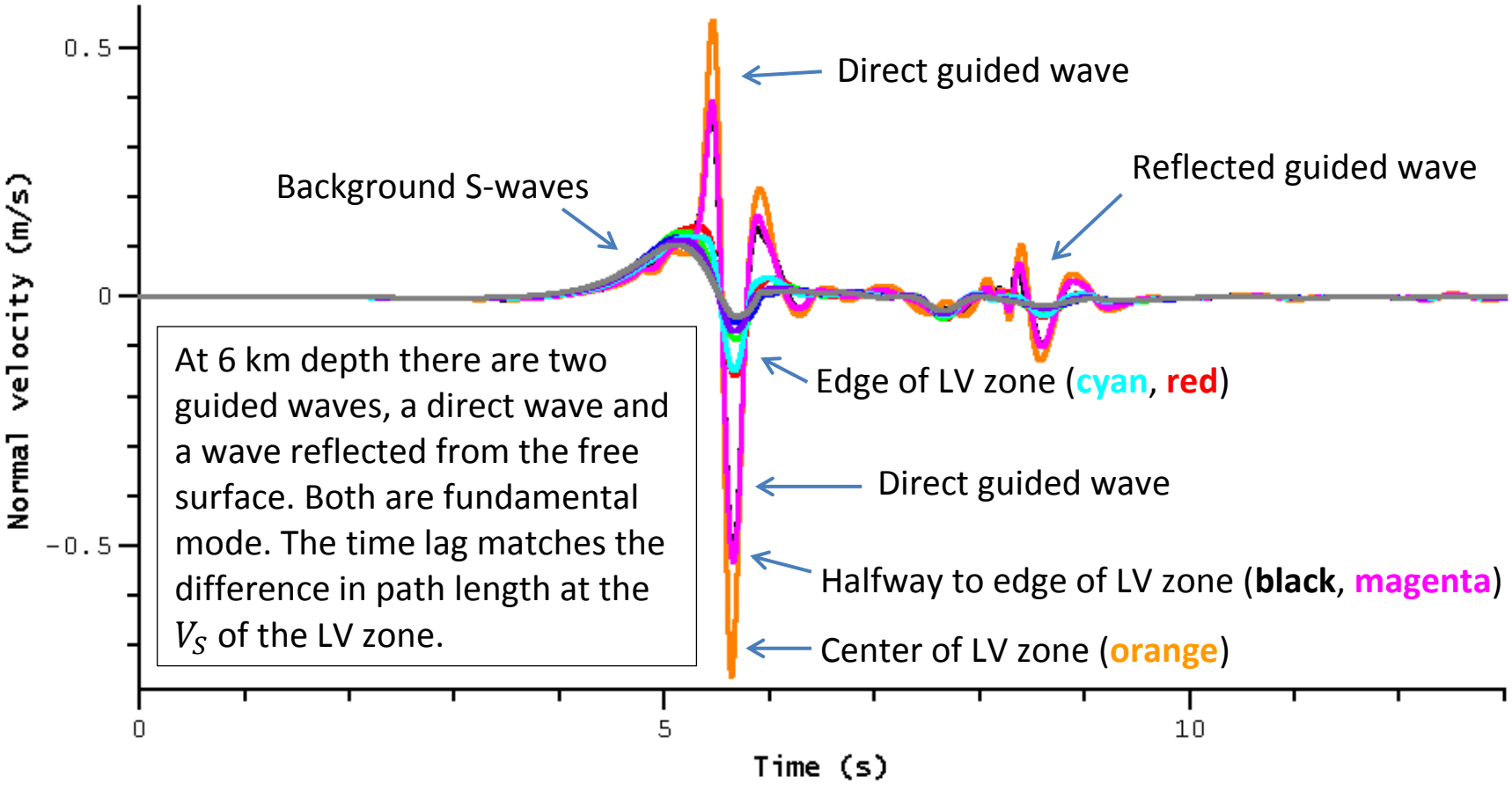
Filtered at 10 Hz. Code: roten.2

Transect at +12 km Along-Strike, at the Earth's Surface — Vertical Velocity

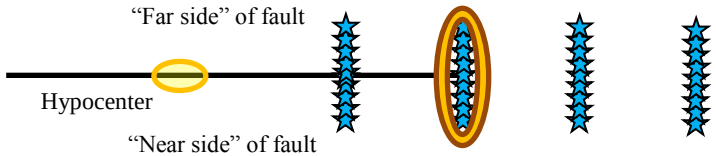


Filtered at 10 Hz. Code: daub

Transect at +4 km Along-Strike, at 6 km Depth — Normal Velocity

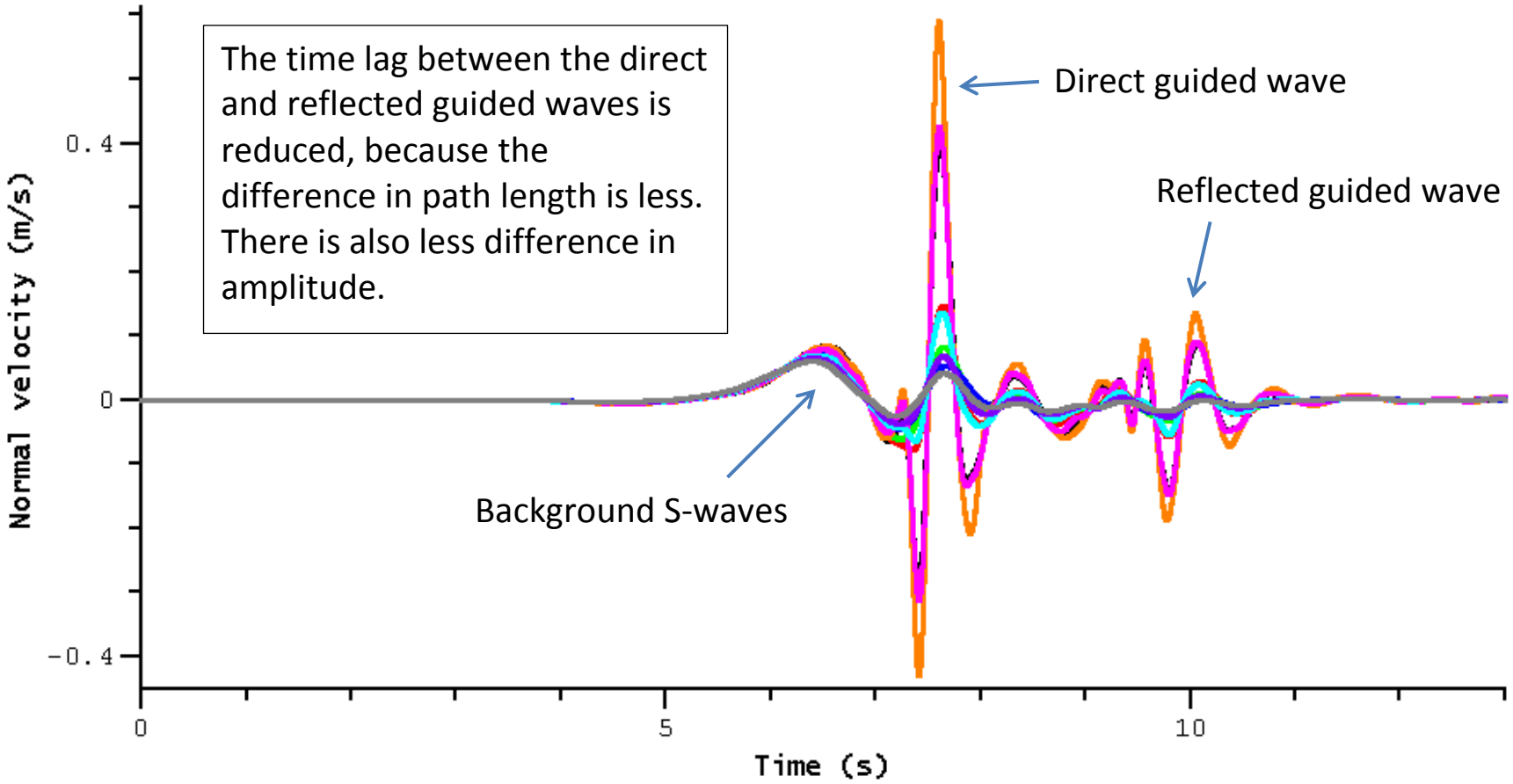


body-004st040dp060 (transect at strike = 4 km, depth = 6 km, z = -0.4 km)
body-008st040dp060 (transect at strike = 4 km, depth = 6 km, z = -0.8 km)
body-012st040dp060 (transect at strike = 4 km, depth = 6 km, z = -1.2 km)
body-016st040dp060 (transect at strike = 4 km, depth = 6 km, z = -1.6 km)
body000st040dp060 (transect at strike = 4 km, depth = 6 km, z = +0.0 km)
body004st040dp060 (transect at strike = 4 km, depth = 6 km, z = +0.4 km)
body008st040dp060 (transect at strike = 4 km, depth = 6 km, z = +0.8 km)
body012st040dp060 (transect at strike = 4 km, depth = 6 km, z = +1.2 km)
body016st040dp060 (transect at strike = 4 km, depth = 6 km, z = +1.6 km)

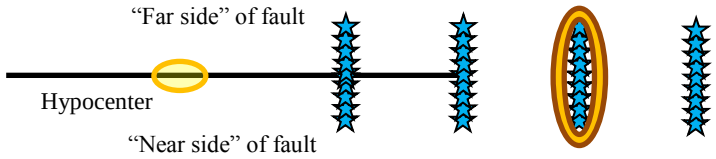


Filtered at 10 Hz. Code: luo

Transect at +8 km Along-Strike, at 6 km Depth — Normal Velocity

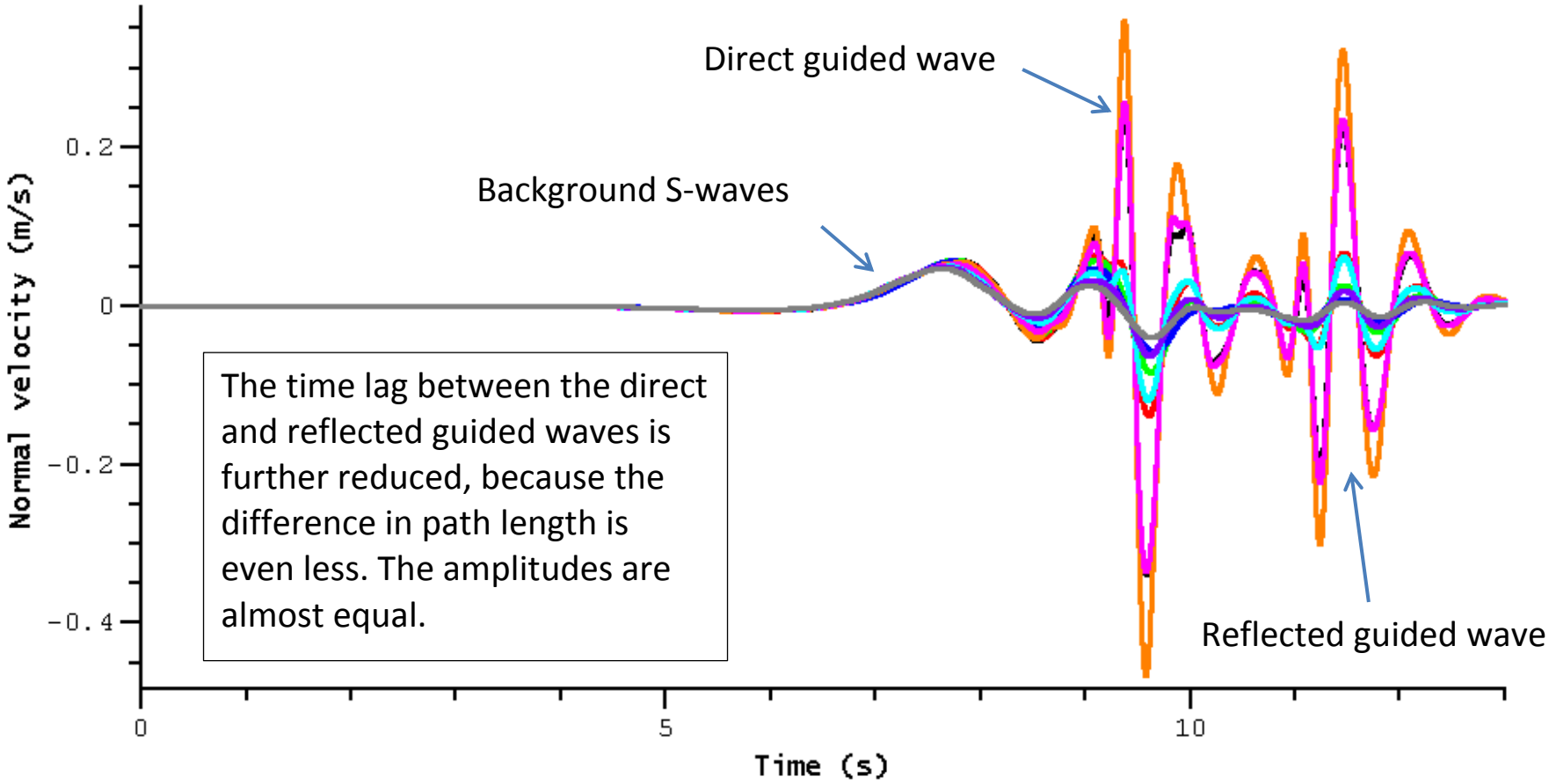


body-004st080dp060 (transect at strike = 8 km, depth = 6 km, z = -0.4 km)
body-008st080dp060 (transect at strike = 8 km, depth = 6 km, z = -0.8 km)
body-012st080dp060 (transect at strike = 8 km, depth = 6 km, z = -1.2 km)
body-016st080dp060 (transect at strike = 8 km, depth = 6 km, z = -1.6 km)
body000st080dp060 (transect at strike = 8 km, depth = 6 km, z = +0.0 km)
body004st080dp060 (transect at strike = 8 km, depth = 6 km, z = +0.4 km)
body008st080dp060 (transect at strike = 8 km, depth = 6 km, z = +0.8 km)
body012st080dp060 (transect at strike = 8 km, depth = 6 km, z = +1.2 km)
body016st080dp060 (transect at strike = 8 km, depth = 6 km, z = +1.6 km)



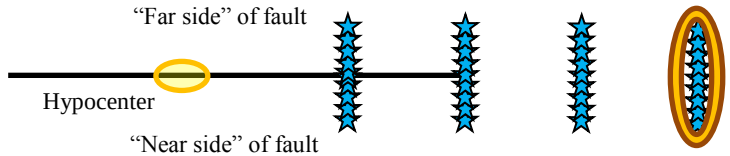
Filtered at 10 Hz. Code: luo

Transect at +12 km Along-Strike, at 6 km Depth — Normal Velocity



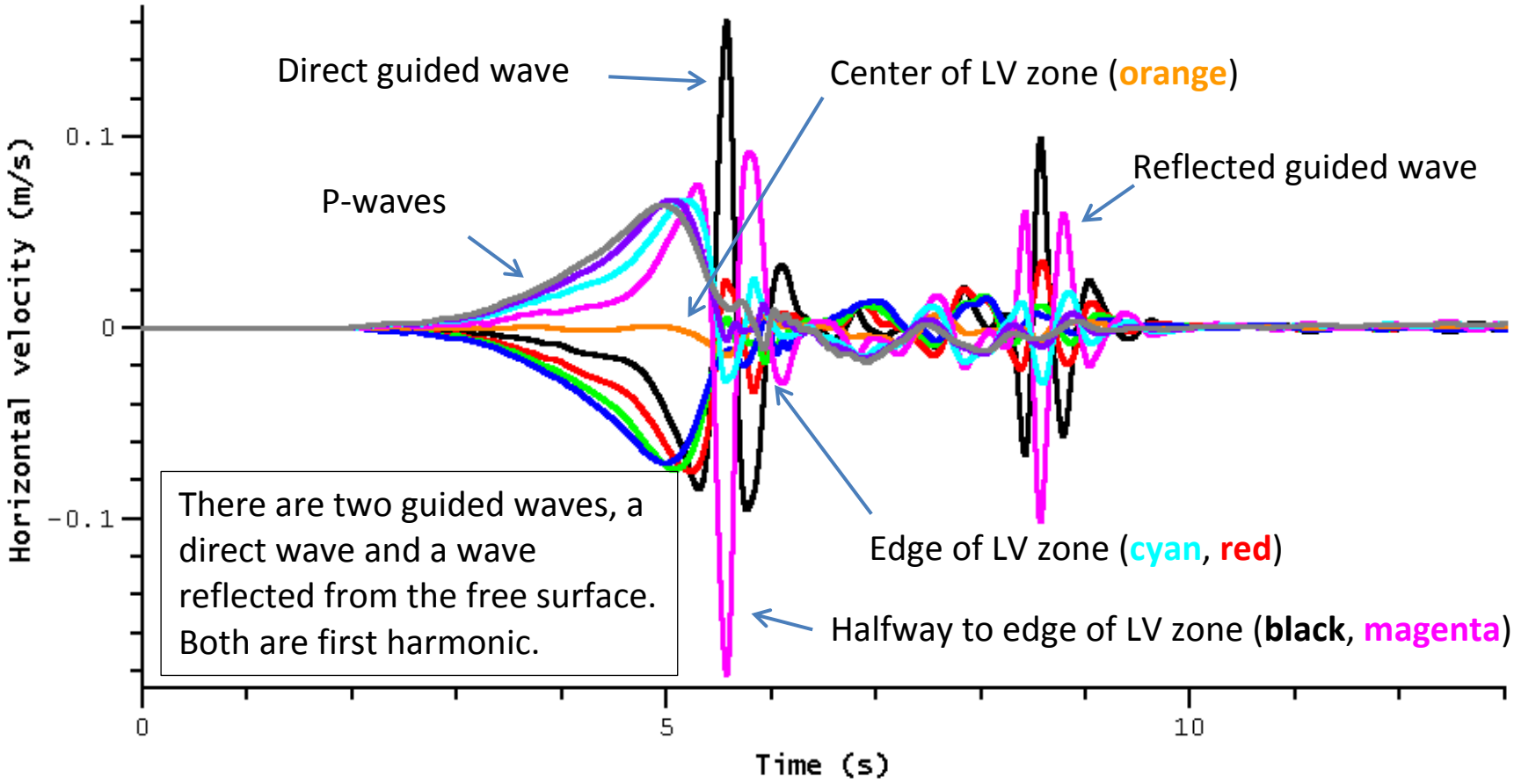
The time lag between the direct and reflected guided waves is further reduced, because the difference in path length is even less. The amplitudes are almost equal.

body-004st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.4 km)
body-008st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.8 km)
body-012st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.2 km)
body-016st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.6 km)
body000st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.0 km)
body004st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.4 km)
body008st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.8 km)
body012st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.2 km)
body016st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.6 km)

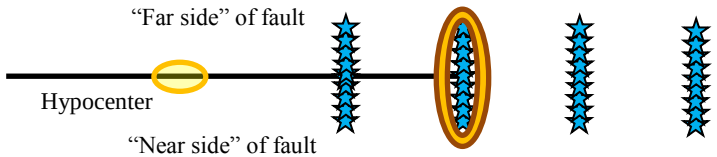


Filtered at 10 Hz. Code: luo

Transect at +4 km Along-Strike, at 6 km Depth — Horizontal Velocity

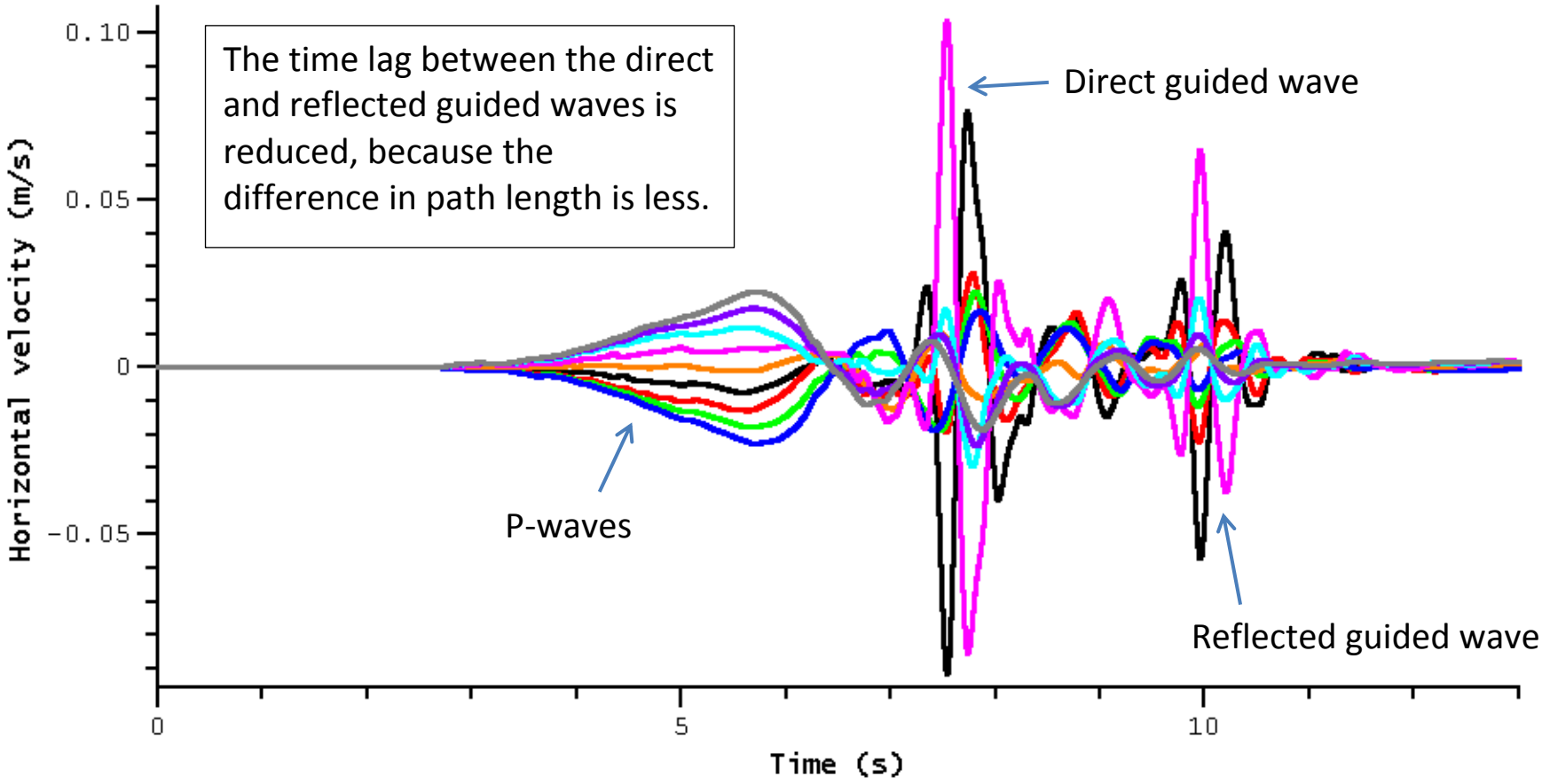


body-004st040dp060 (transect at strike = 4 km, depth = 6 km, z = -0.4 km)
body-008st040dp060 (transect at strike = 4 km, depth = 6 km, z = -0.8 km)
body-012st040dp060 (transect at strike = 4 km, depth = 6 km, z = -1.2 km)
body-016st040dp060 (transect at strike = 4 km, depth = 6 km, z = -1.6 km)
body000st040dp060 (transect at strike = 4 km, depth = 6 km, z = +0.0 km)
body004st040dp060 (transect at strike = 4 km, depth = 6 km, z = +0.4 km)
body008st040dp060 (transect at strike = 4 km, depth = 6 km, z = +0.8 km)
body012st040dp060 (transect at strike = 4 km, depth = 6 km, z = +1.2 km)
body016st040dp060 (transect at strike = 4 km, depth = 6 km, z = +1.6 km)

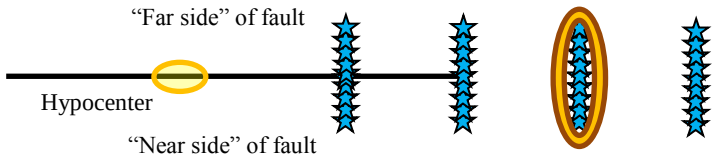


Filtered at 10 Hz. Code: barall

Transect at +8 km Along-Strike, at 6 km Depth — Horizontal Velocity

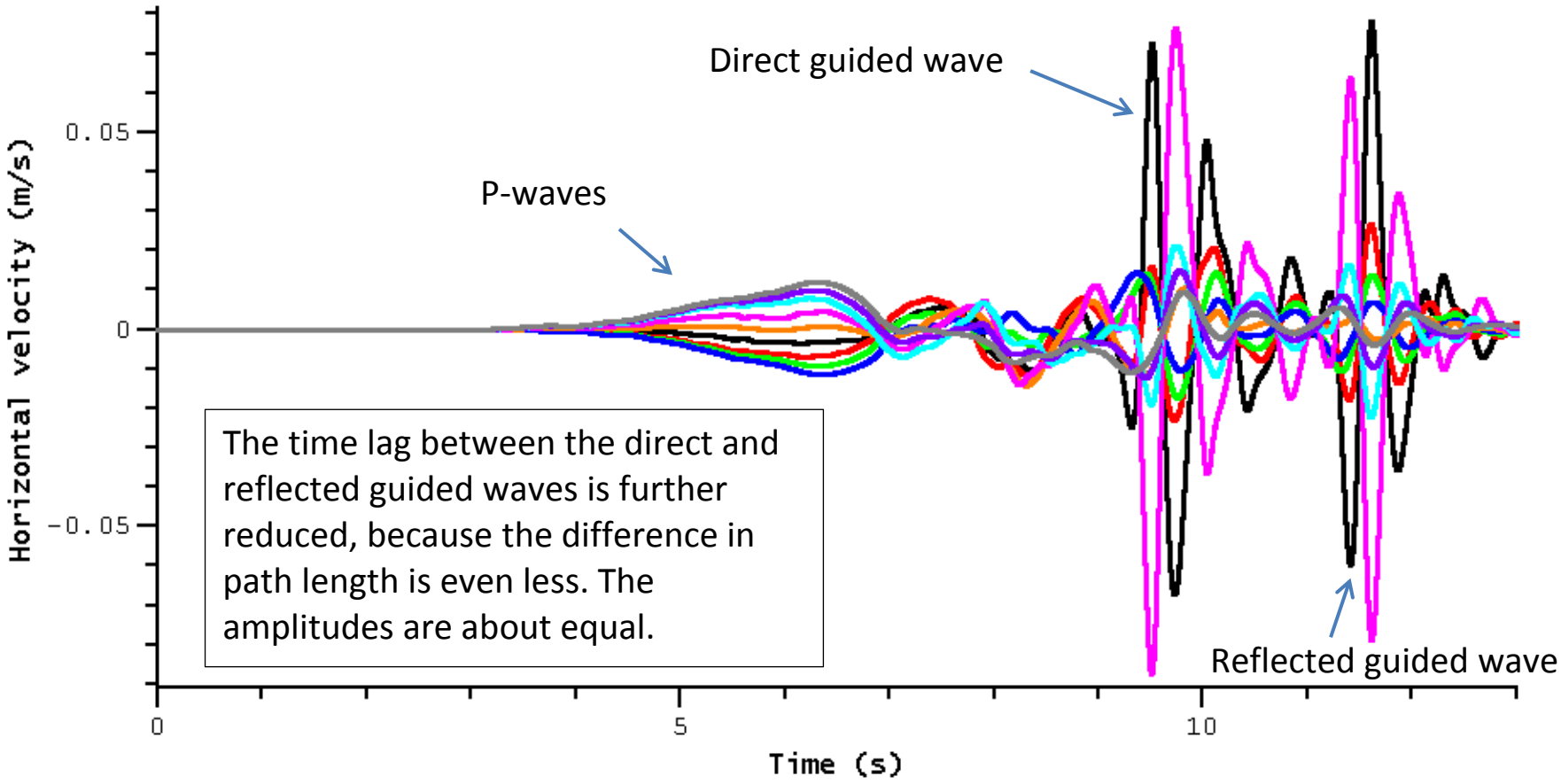


body-004st080dp060 (transect at strike = 8 km, depth = 6 km, z = -0.4 km)
body-008st080dp060 (transect at strike = 8 km, depth = 6 km, z = -0.8 km)
body-012st080dp060 (transect at strike = 8 km, depth = 6 km, z = -1.2 km)
body-016st080dp060 (transect at strike = 8 km, depth = 6 km, z = -1.6 km)
body000st080dp060 (transect at strike = 8 km, depth = 6 km, z = +0.0 km)
body004st080dp060 (transect at strike = 8 km, depth = 6 km, z = +0.4 km)
body008st080dp060 (transect at strike = 8 km, depth = 6 km, z = +0.8 km)
body012st080dp060 (transect at strike = 8 km, depth = 6 km, z = +1.2 km)
body016st080dp060 (transect at strike = 8 km, depth = 6 km, z = +1.6 km)

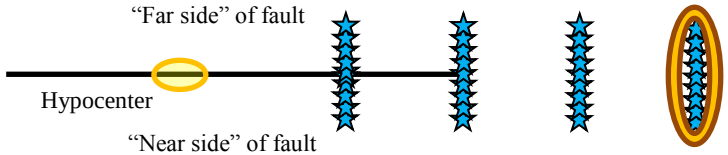


Filtered at 10 Hz. Code: barall

Transect at +12 km Along-Strike, at 6 km Depth — Horizontal Velocity

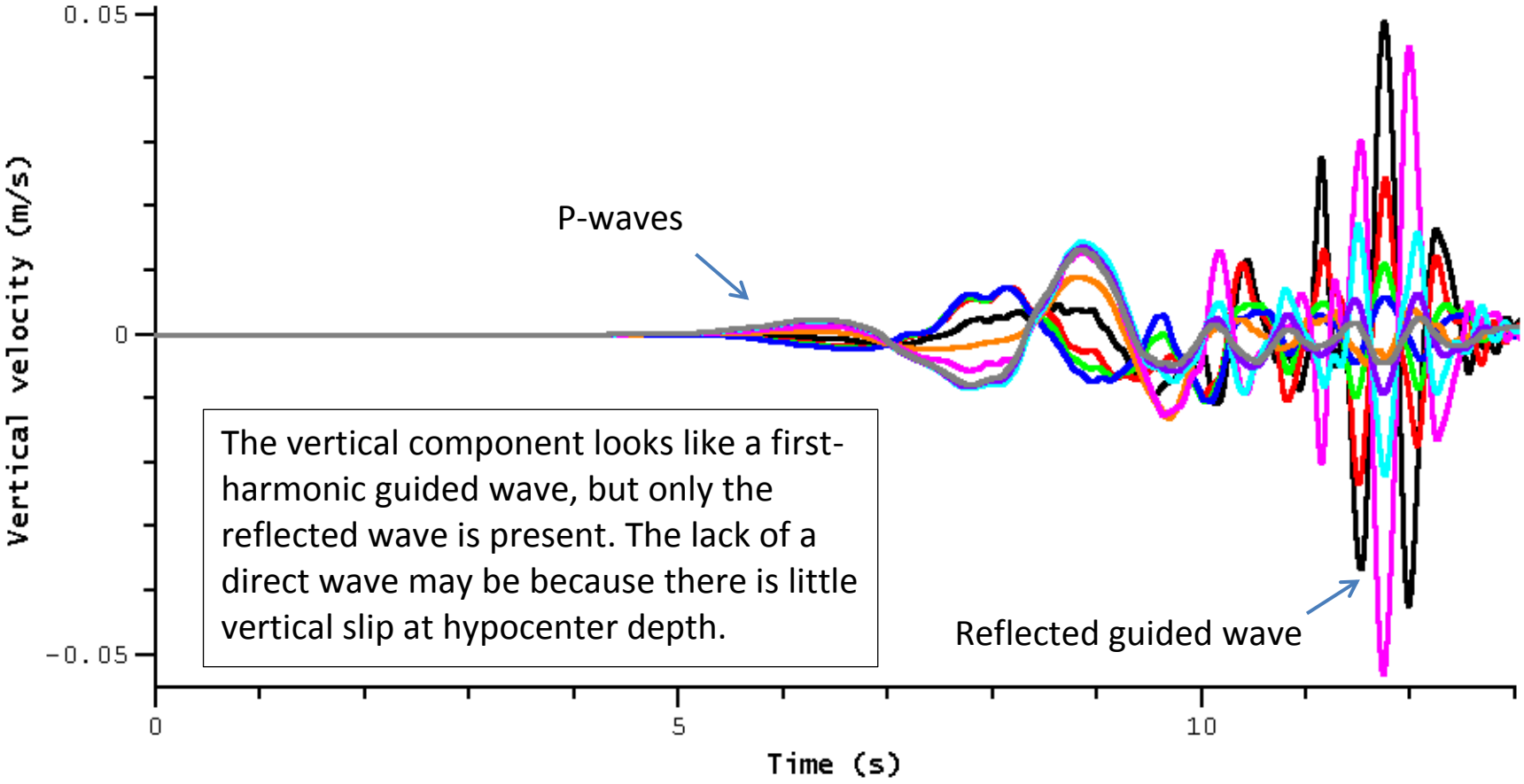


body-004st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.4 km)
body-008st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.8 km)
body-012st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.2 km)
body-016st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.6 km)
body000st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.0 km)
body004st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.4 km)
body008st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.8 km)
body012st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.2 km)
body016st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.6 km)

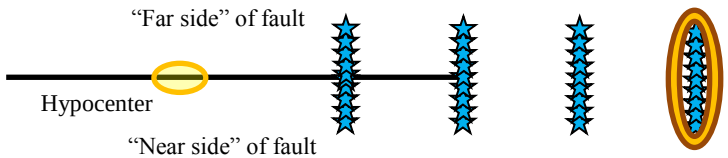


Filtered at 10 Hz. Code: barall

Transect at +12 km Along-Strike, at 6 km Depth — Vertical Velocity

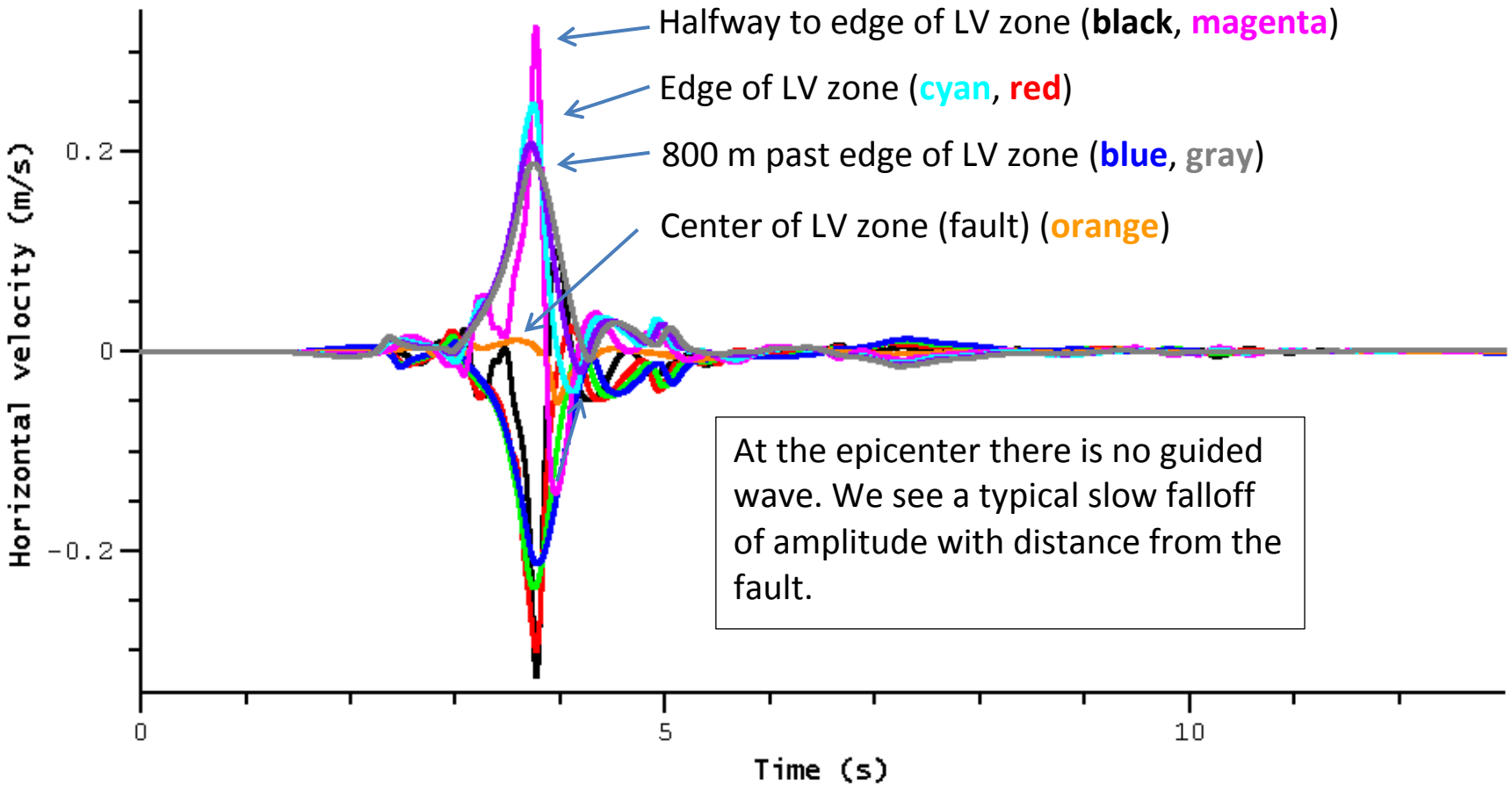


body-004st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.4 km)
body-008st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.8 km)
body-012st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.2 km)
body-016st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.6 km)
body000st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.0 km)
body004st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.4 km)
body008st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.8 km)
body012st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.2 km)
body016st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.6 km)



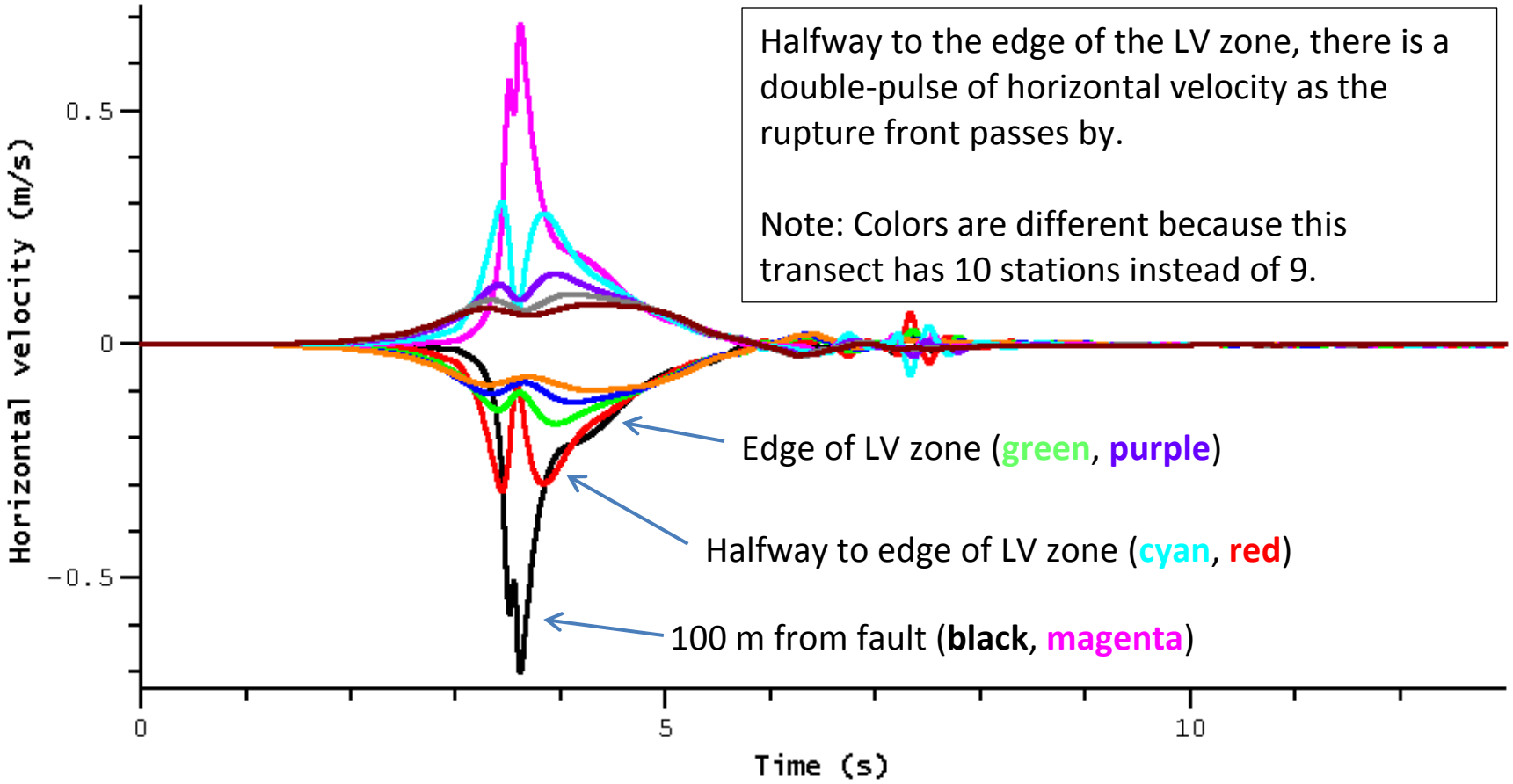
Filtered at 10 Hz. Code: bai

Transect at −6 km Along-Strike, at Earth's Surface (Epicenter) — Horizontal Velocity

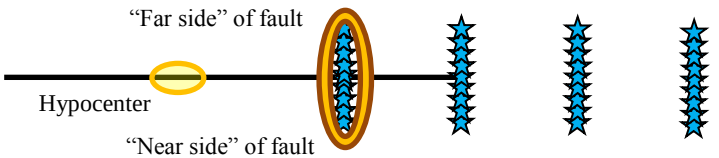


Filtered at 10 Hz. Code: bydlon

Transect at 0 km Along-Strike, at 6 km Depth — Horizontal Velocity

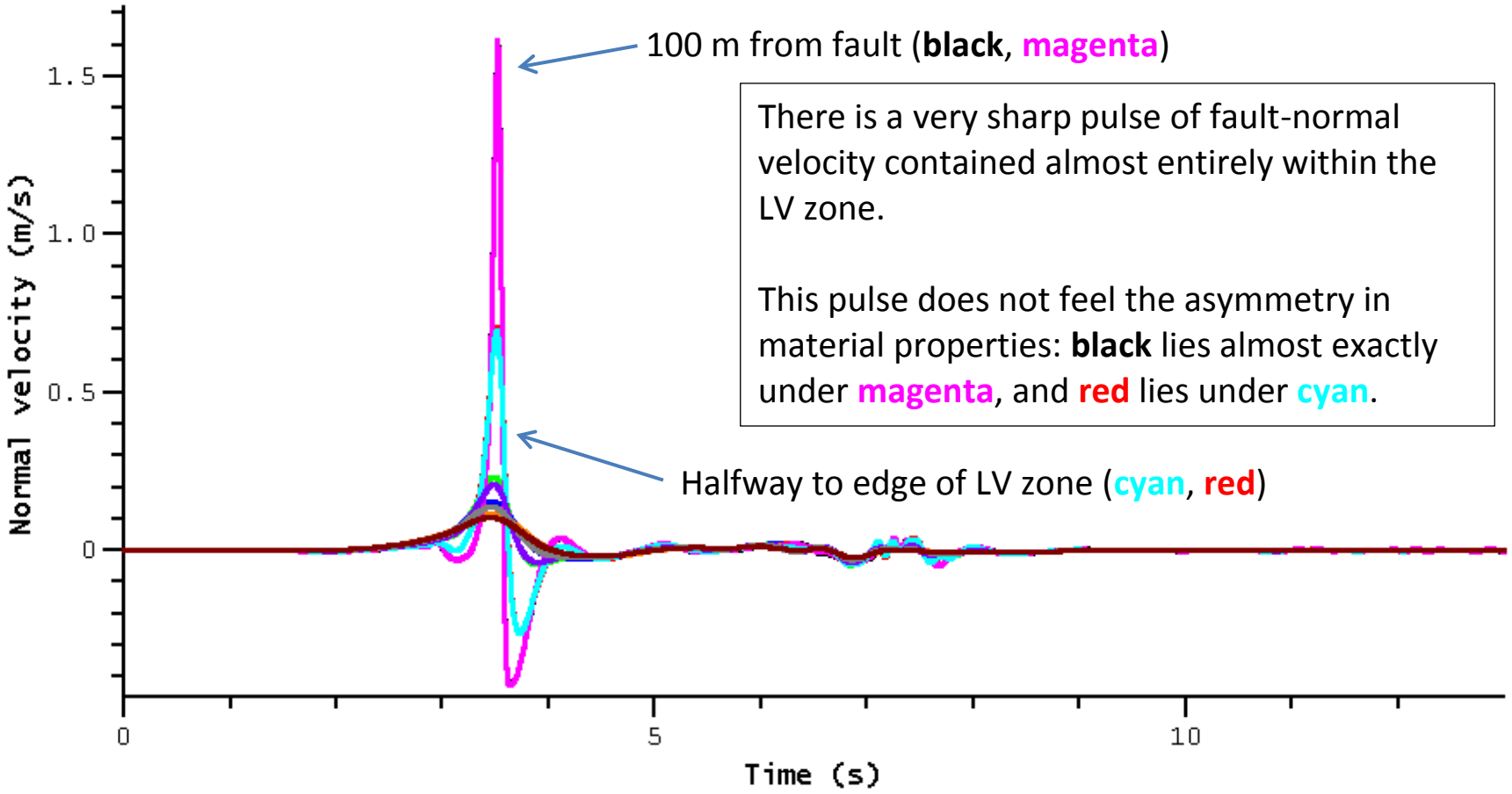


body-001st000dp060 (transect at strike = 0 km, depth = 6 km, z = -0.1 km)
body-004st000dp060 (transect at strike = 0 km, depth = 6 km, z = -0.4 km)
body-008st000dp060 (transect at strike = 0 km, depth = 6 km, z = -0.8 km)
body-012st000dp060 (transect at strike = 0 km, depth = 6 km, z = -1.2 km)
body-016st000dp060 (transect at strike = 0 km, depth = 6 km, z = -1.6 km)
body001st000dp060 (transect at strike = 0 km, depth = 6 km, z = +0.1 km)
body004st000dp060 (transect at strike = 0 km, depth = 6 km, z = +0.4 km)
body008st000dp060 (transect at strike = 0 km, depth = 6 km, z = +0.8 km)
body012st000dp060 (transect at strike = 0 km, depth = 6 km, z = +1.2 km)
body016st000dp060 (transect at strike = 0 km, depth = 6 km, z = +1.6 km)

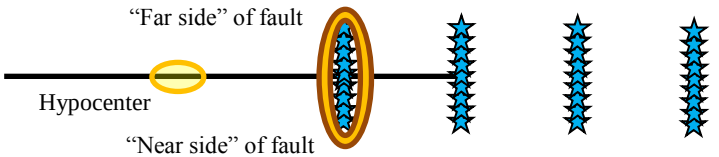


Filtered at 10 Hz. Code: ulrich

Transect at 0 km Along-Strike, at 6 km Depth — Normal Velocity



body-001st000dp060 (transect at strike = 0 km, depth = 6 km, z = -0.1 km)
body-004st000dp060 (transect at strike = 0 km, depth = 6 km, z = -0.4 km)
body-008st000dp060 (transect at strike = 0 km, depth = 6 km, z = -0.8 km)
body-012st000dp060 (transect at strike = 0 km, depth = 6 km, z = -1.2 km)
body-016st000dp060 (transect at strike = 0 km, depth = 6 km, z = -1.6 km)
body001st000dp060 (transect at strike = 0 km, depth = 6 km, z = +0.1 km)
body004st000dp060 (transect at strike = 0 km, depth = 6 km, z = +0.4 km)
body008st000dp060 (transect at strike = 0 km, depth = 6 km, z = +0.8 km)
body012st000dp060 (transect at strike = 0 km, depth = 6 km, z = +1.2 km)
body016st000dp060 (transect at strike = 0 km, depth = 6 km, z = +1.6 km)

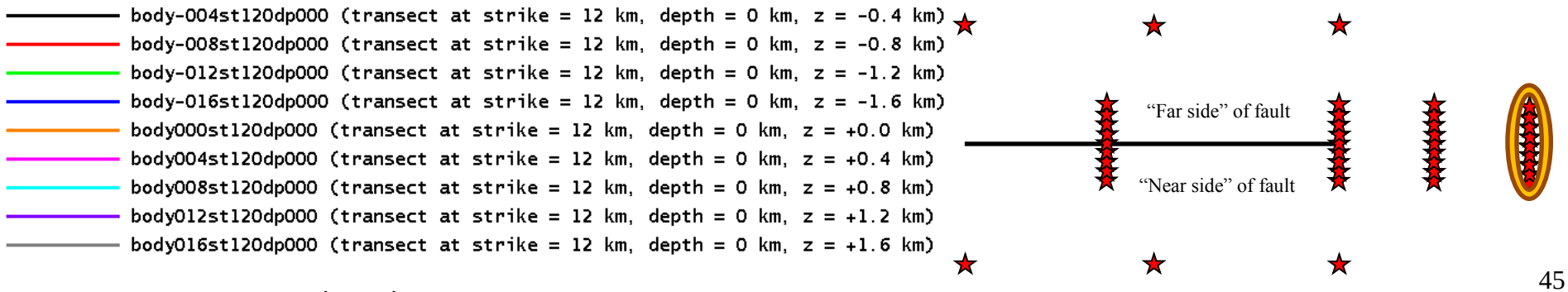


Filtered at 10 Hz. Code: ulrich

TPV33 Transects — Code Comparisons

Transect at +12 km Along-Strike, at the Earth's Surface — Horizontal Velocity

Code Comparison Movie #1.

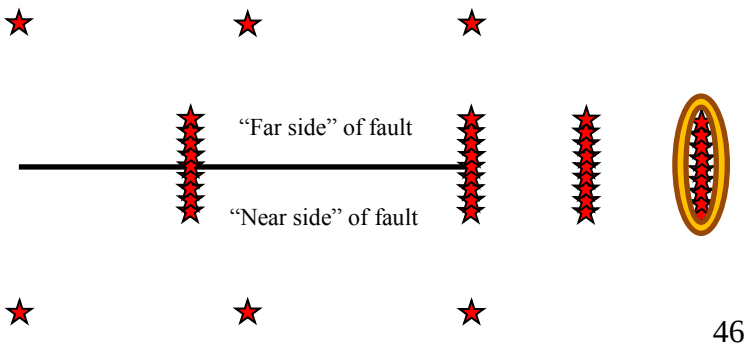


Filtered at 10 Hz.

Transect at +12 km Along-Strike, at the Earth's Surface — Normal Velocity

Code Comparison Movie #2.

body-004st120dp000 (transect at strike = 12 km, depth = 0 km, z = -0.4 km)
body-008st120dp000 (transect at strike = 12 km, depth = 0 km, z = -0.8 km)
body-012st120dp000 (transect at strike = 12 km, depth = 0 km, z = -1.2 km)
body-016st120dp000 (transect at strike = 12 km, depth = 0 km, z = -1.6 km)
body000st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.0 km)
body004st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.4 km)
body008st120dp000 (transect at strike = 12 km, depth = 0 km, z = +0.8 km)
body012st120dp000 (transect at strike = 12 km, depth = 0 km, z = +1.2 km)
body016st120dp000 (transect at strike = 12 km, depth = 0 km, z = +1.6 km)

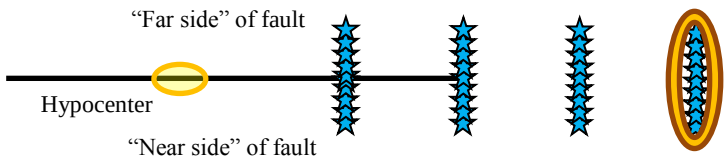


Filtered at 10 Hz.

Transect at +12 km Along-Strike, at 6 km Depth — Horizontal Velocity

Code Comparison Movie #3.

body-004st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.4 km)
body-008st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.8 km)
body-012st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.2 km)
body-016st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.6 km)
body000st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.0 km)
body004st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.4 km)
body008st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.8 km)
body012st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.2 km)
body016st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.6 km)

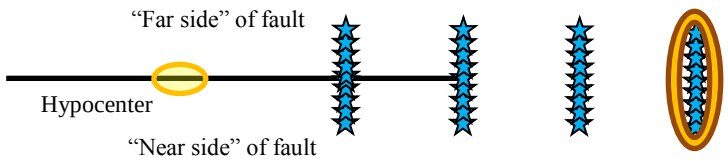


Filtered at 10 Hz.

Transect at +12 km Along-Strike, at 6 km Depth — Normal Velocity

Code Comparison Movie #4.

body-004st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.4 km)
body-008st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.8 km)
body-012st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.2 km)
body-016st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.6 km)
body000st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.0 km)
body004st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.4 km)
body008st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.8 km)
body012st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.2 km)
body016st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.6 km)

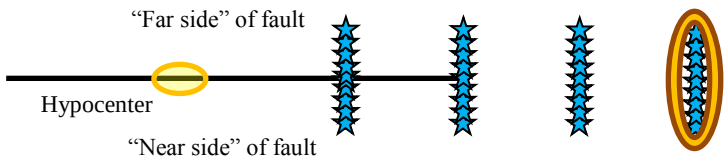


Filtered at 10 Hz.

Transect at +12 km Along-Strike, at 6 km Depth — Vertical Velocity

Code Comparison Movie #5.

body-004st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.4 km)
body-008st120dp060 (transect at strike = 12 km, depth = 6 km, z = -0.8 km)
body-012st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.2 km)
body-016st120dp060 (transect at strike = 12 km, depth = 6 km, z = -1.6 km)
body000st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.0 km)
body004st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.4 km)
body008st120dp060 (transect at strike = 12 km, depth = 6 km, z = +0.8 km)
body012st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.2 km)
body016st120dp060 (transect at strike = 12 km, depth = 6 km, z = +1.6 km)



Filtered at 10 Hz.

	3d-disp	3d-vel	t-shift	
body-016st120dp000	4.8	4.6	9.67e-003	Outside LVZ
body-016st120dp060	4.0	8.3	8.83e-003	
body-012st120dp000	4.9	5.3	1.08e-002	
body-012st120dp060	4.1	10.1	1.12e-002	
body-008st120dp000	5.2	9.4	1.21e-002	Edge of LVZ
body-008st120dp060	3.9	12.2	1.21e-002	
body-004st120dp000	6.9	16.9	1.56e-002	Inside LVZ
body-004st120dp060	6.6	23.9	1.66e-002	
body000st120dp000	7.6	18.3	1.45e-002	
body000st120dp060	6.7	20.7	1.51e-002	
body004st120dp000	7.5	17.6	1.55e-002	
body004st120dp060	7.2	24.7	1.68e-002	
body008st120dp000	6.4	11.1	1.24e-002	Edge of LVZ
body008st120dp060	5.2	15.0	1.29e-002	
body012st120dp000	6.1	5.9	1.09e-002	Outside LVZ
body012st120dp060	5.0	7.9	1.07e-002	
body016st120dp000	6.1	5.3	9.83e-003	
body016st120dp060	5.1	7.2	9.17e-003	

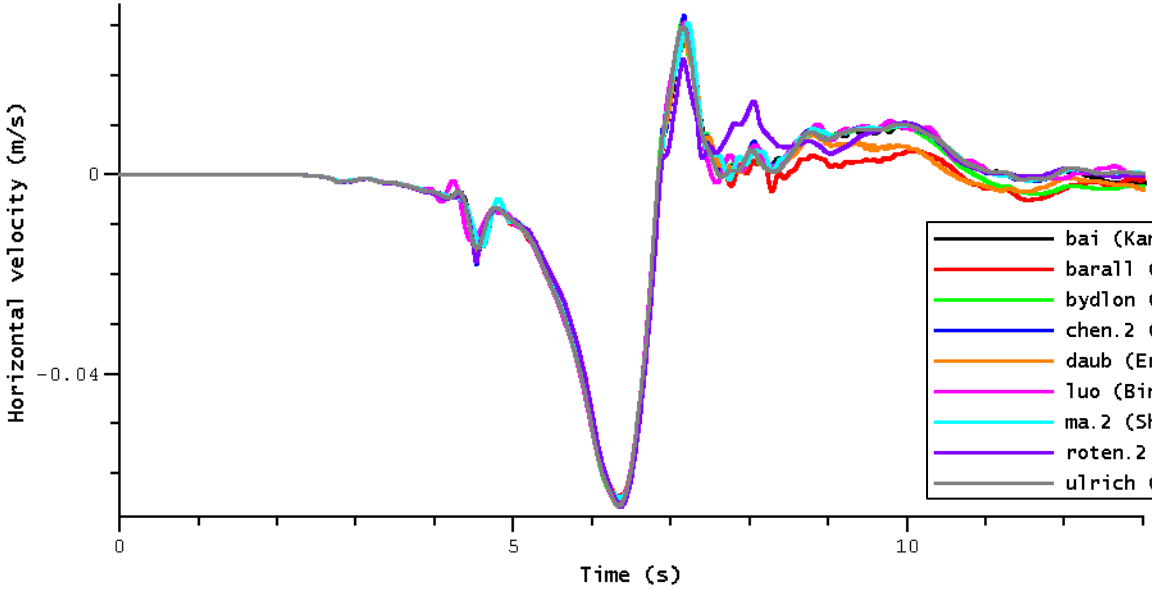
Metrics for Transects at 12 km Along-Strike (Summary Across 9 Codes, in Percent)

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

- Stations outside the LV zone have values mostly < 10%, showing very good agreement.
- Stations inside the LV zone have values ~ 20%, showing moderate differences between codes.
- Stations at the edge of the LV zone have intermediate values.
- Stations at 6 km depth have larger values than stations at the earth's surface, perhaps due to the reflected waves.

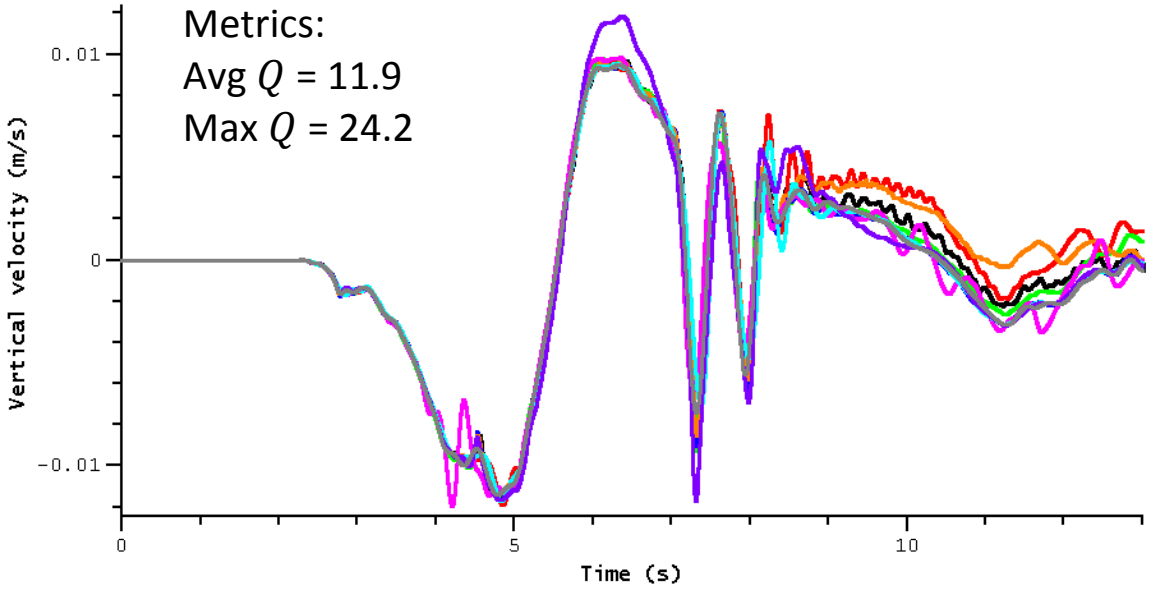
TPV33 Results — Off-Fault Stations

body-100st-120dp000 (Distant Station at Lower Left)

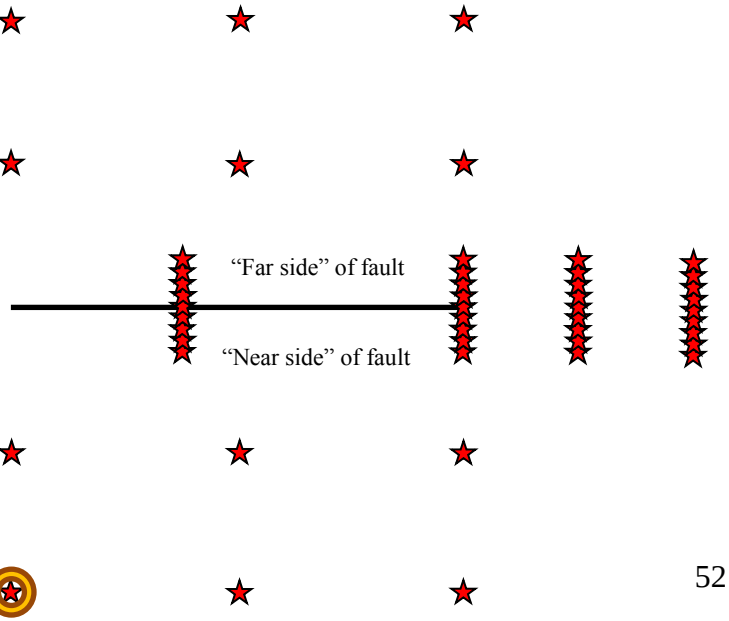


Codes agree OK, not perfectly, with one or two outliers. Differences late in simulation may be due to boundary interaction.

bai (Kangchen Bai - Spectral Element - SPECFEM3D)
barall (Michael Barall - FaultMod - 12.5 m)
bydlon (Sam Bydlon - Finite Difference - FD-Q-WaveLab - 25m)
chen.2 (Xiaofei Chen - Finite Difference Method - CGFDM - 12.5 m)
daub (Eric Daub - Daub Finite Difference Code - 50m)
luo (Bin Luo - Finite Element - EQdyna - 12.5m)
ma.2 (Shuo Ma - MAFE - 12.5m on fault - absorbing boundary 50 km)
roten.2 (Daniel Roten - Finite Difference - AWM - 12.5m)
ulrich (Thomas Ulrich - DG Finite Element - SeisSol -100m on fault-o5)

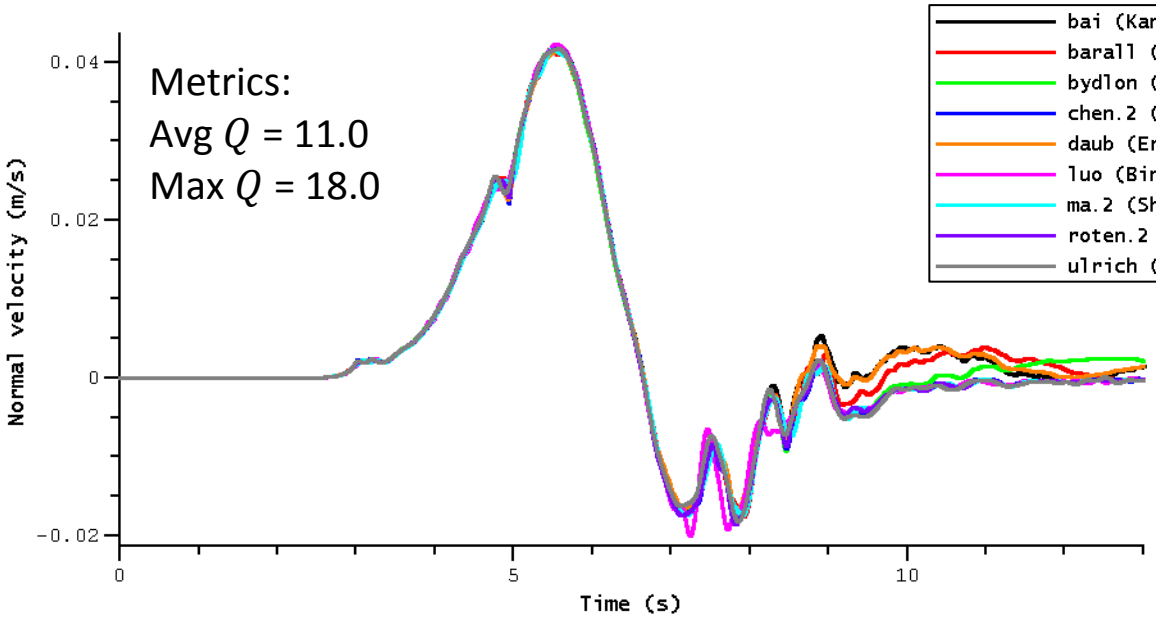


Metrics:
Avg Q = 11.9
Max Q = 24.2

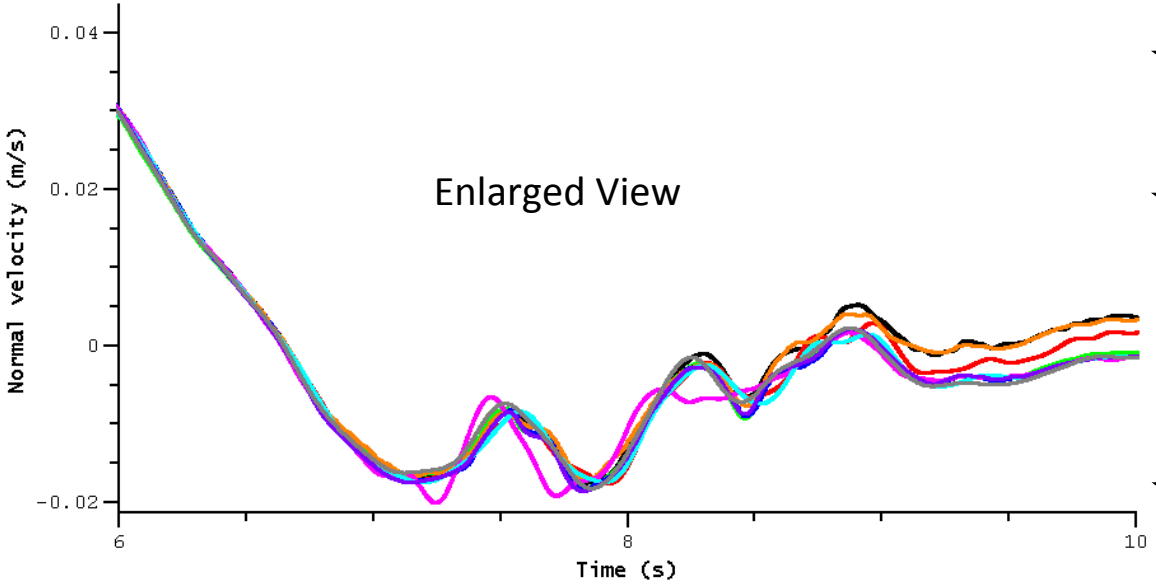


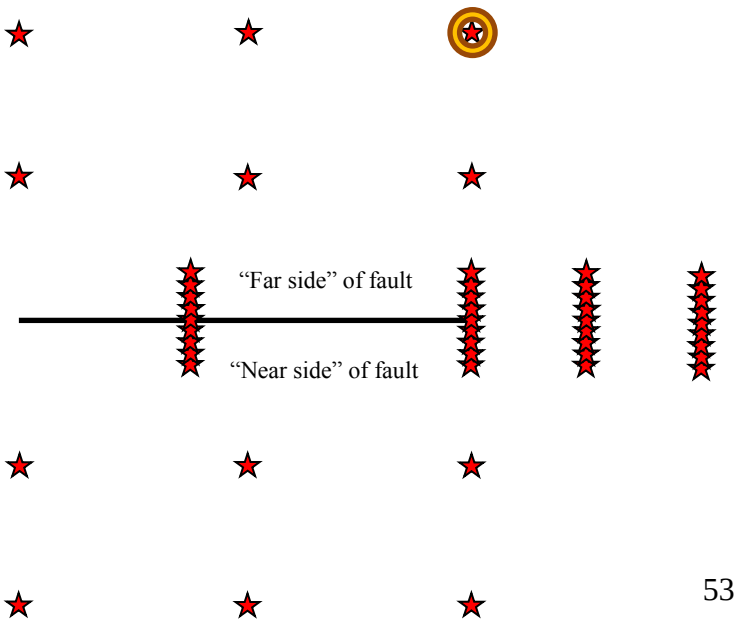
Filtered at 10 Hz.

body100st040dp000 (Distant Station at Upper Right)



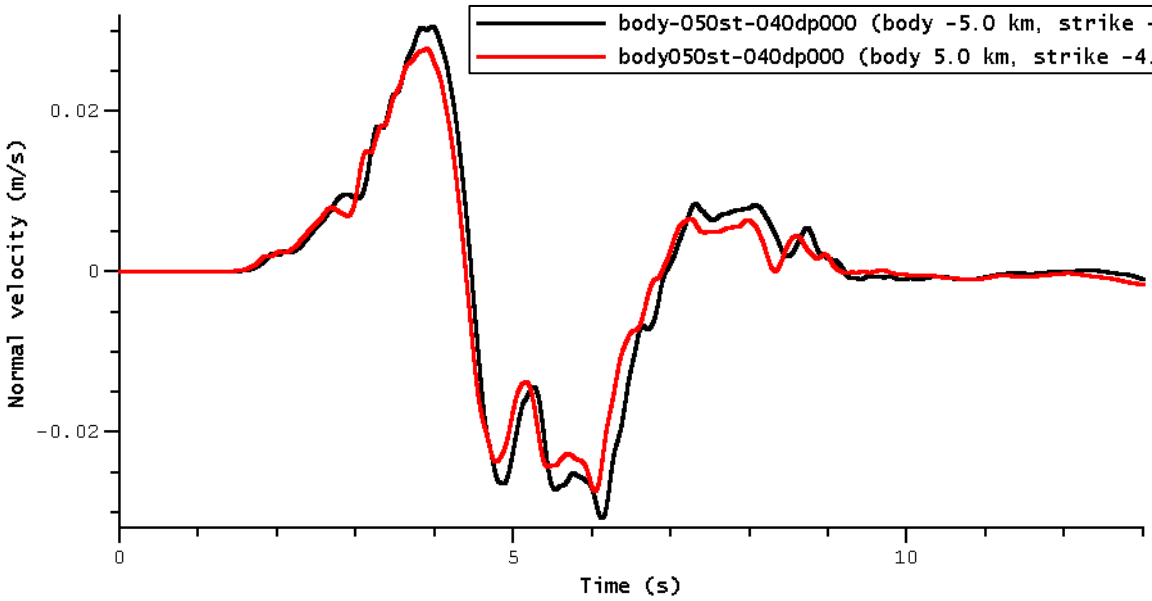
Enlarged view at bottom shows how each code is a bit different, despite OK overall agreement. Differences late in simulation may be due to boundary interaction.

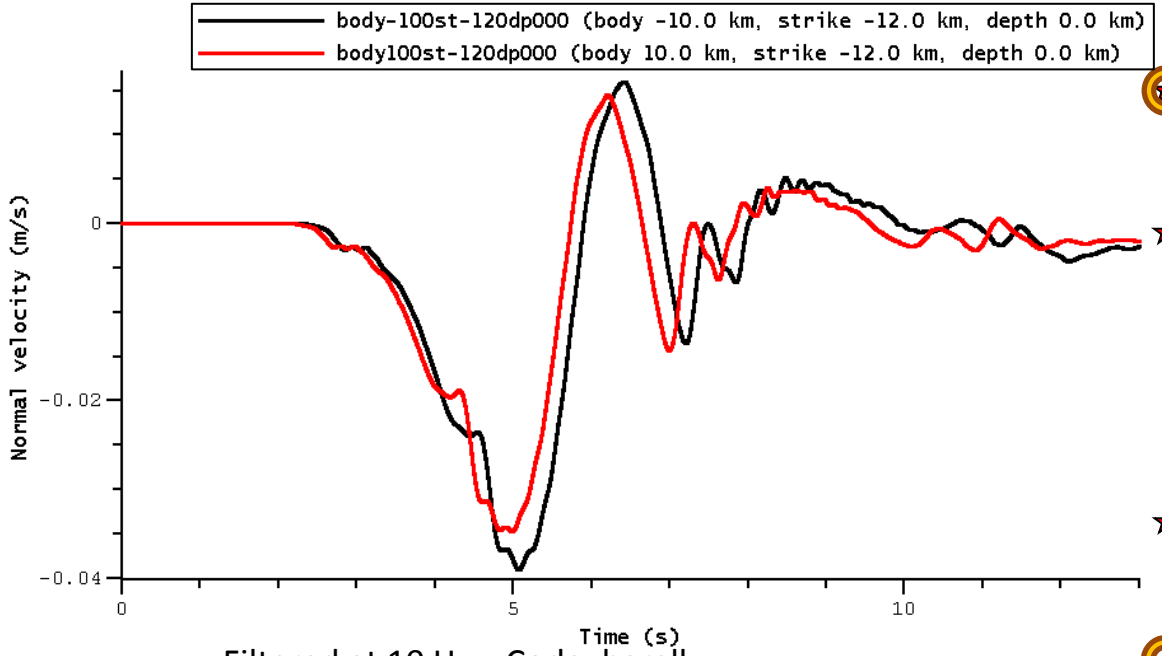




Filtered at 10 Hz.

Mirror-Pairs of Distant Off-Fault Stations

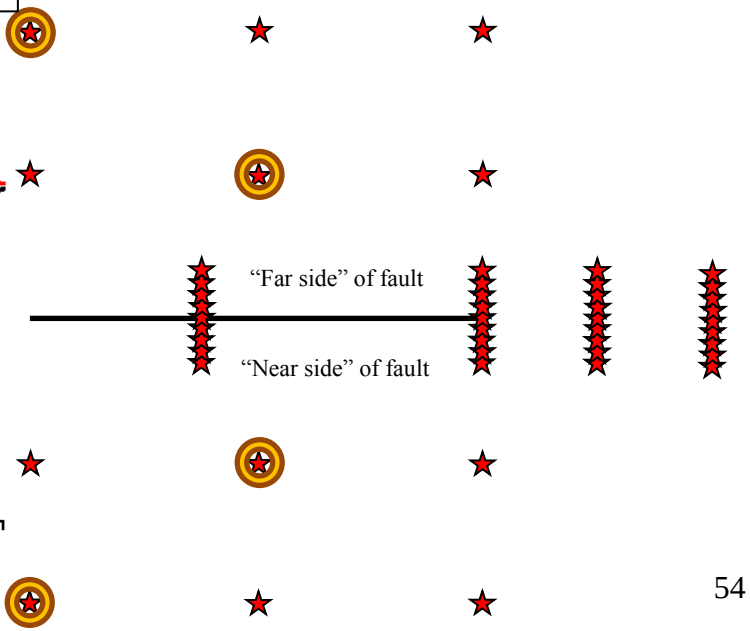




Filtered at 10 Hz. Code: barall

If the material properties were symmetrical, the normal velocity would be the same at each mirror-pair of stations.

The waves on the "fast" side (**red**) arrive earlier and with lower amplitude than the waves on the "slow" side (**black**).



	3d-disp	3d-vel	t-shift
body-050st-120dp000	4.1	7.6	1.09e-002
body050st-120dp000	4.7	8.0	1.01e-002
body-050st-040dp000	2.1	4.1	8.94e-003
body050st-040dp000	2.7	4.7	7.67e-003
body-050st040dp000	2.5	6.5	1.26e-002
body050st040dp000	3.0	7.0	1.16e-002
body-100st-120dp000	7.6	12.5	1.13e-002
body100st-120dp000	8.8	14.0	1.24e-002
body-100st-040dp000	4.9	6.7	8.94e-003
body100st-040dp000	6.4	7.6	7.78e-003
body-100st040dp000	5.4	10.5	1.75e-002
body100st040dp000	6.2	11.4	1.57e-002

5 km from fault

10 km from fault

Metrics for Off-Fault Stations (Summary Across 9 Codes, in Percent)

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

- Other than the four “corners”, values are < 10%, showing very good agreement.
- The four “corners” have values above 10%, but still good.
- Stations 5km from the fault have smaller values (better agreement) than stations 10 km from the fault.
- Stations on the “slow” side (body-050* and body-100*) have smaller values than stations on the “fast” side (body050* and body100*).

Conclusions

Conclusions

1. TPV33 is our first benchmark with a low-velocity fault zone.

2. Codes achieved excellent agreement at the source:

- Rupture contours.
- Waveforms at on-fault stations.
- Process zone widths.

3. Good results require higher resolution on the fault than might be expected from the process zone widths.

4. We demonstrated the existence of guided waves in the low-velocity fault zone.

- Fault-normal motion excites the fundamental mode of the waveguide.
- Fault-parallel motion excites the first harmonic of the waveguide.
- At depth there are two guided waves, a direct wave and a reflection from the free surface.

5. At off-fault stations outside the LV zone, codes achieved very good agreement.

6. Inside the LV zone, agreement is more challenging.

- Codes show some differences in amplitude and shape of the guided waves.
- Waveforms in the LV zone are surprisingly sensitive to good resolution of the source.
- But there is agreement on the general structure and phase of the guided waves.