Non-Planar Fault with Two Hills Benchmark
TPV28

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SCEC Rupture Dynamics Code Verification Workshop

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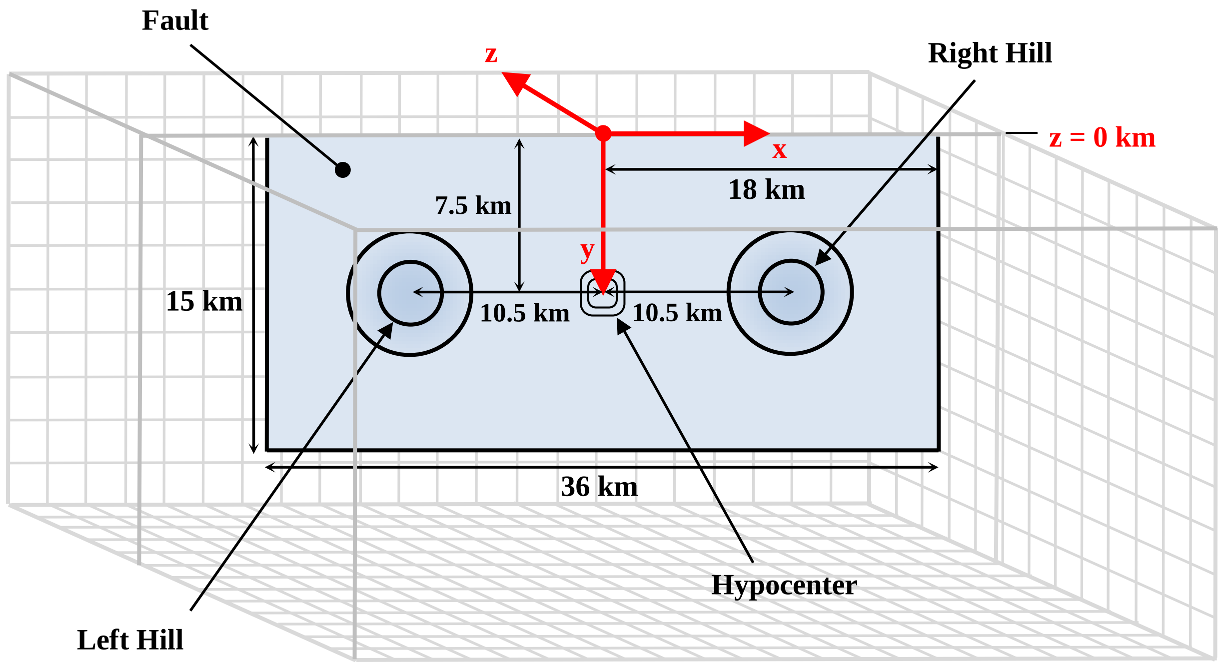
TPV28 — Non-Planar Fault with Two Hills



Right-lateral strike-slip fault in a uniform half-space.

Each hill has a radius of 3000 m and a height of 600 m. So the aspect ratio is 10%.

Fault Shape

- The fault is a vertical plane, except for the two hills.
- Each hill is shaped like a cosine pulse, with the hill radius equal to one-half wavelength.
- So, the fault surface is smooth (has a continuous first derivative).

The shape of the fault is described by a function:

$$z = f(x, y)$$

Let r_1 and r_2 be the two-dimensional distances from the centers of the left and right hills:

$$r_1 = \sqrt{(x + 10500\text{ m})^2 + (y - 7500\text{ m})^2}$$

$$r_2 = \sqrt{(x - 10500\text{ m})^2 + (y - 7500\text{ m})^2}$$

Then the shape of the fault is

$$f(x, y) = \begin{cases} -(300\text{ m})\big(1 + \cos\big(\pi r_1/(3000\text{ m})\big)\big), & \text{if } r_1 < 3000\text{ m} \\ -(300\text{ m})\big(1 + \cos\big(\pi r_2/(3000\text{ m})\big)\big), & \text{if } r_2 < 3000\text{ m} \\ 0, & \text{otherwise} \end{cases}$$

TPV28 Design

Material Properties and Friction Parameters

(Equivalent to TPV5)

Material properties:

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

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

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

Friction parameters:

Static coefficient of friction $\mu_s = 0.677$

Dynamic coefficient of friction $\mu_d = 0.373$

Slip-weakening critical distance $d_0 = 0.40\ \mathrm{m}$

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.

Constant Initial Stress Tensor

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

Fault-parallel stress $\sigma_{11} = -60.00 \text{ MPa}$

Fault-normal stress $\sigma_{33} = -60.00 \text{ MPa}$

Horizontal shear stress $\sigma_{13} = 29.38 \text{ MPa}$

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

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

Setting vertical stress to zero means:

- No need for gravity.
- No need for fluid pressure.
- No need for stress to vary with depth.
- But — There are large vertical shear stresses where the fault dip differs from 90 degrees.

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).

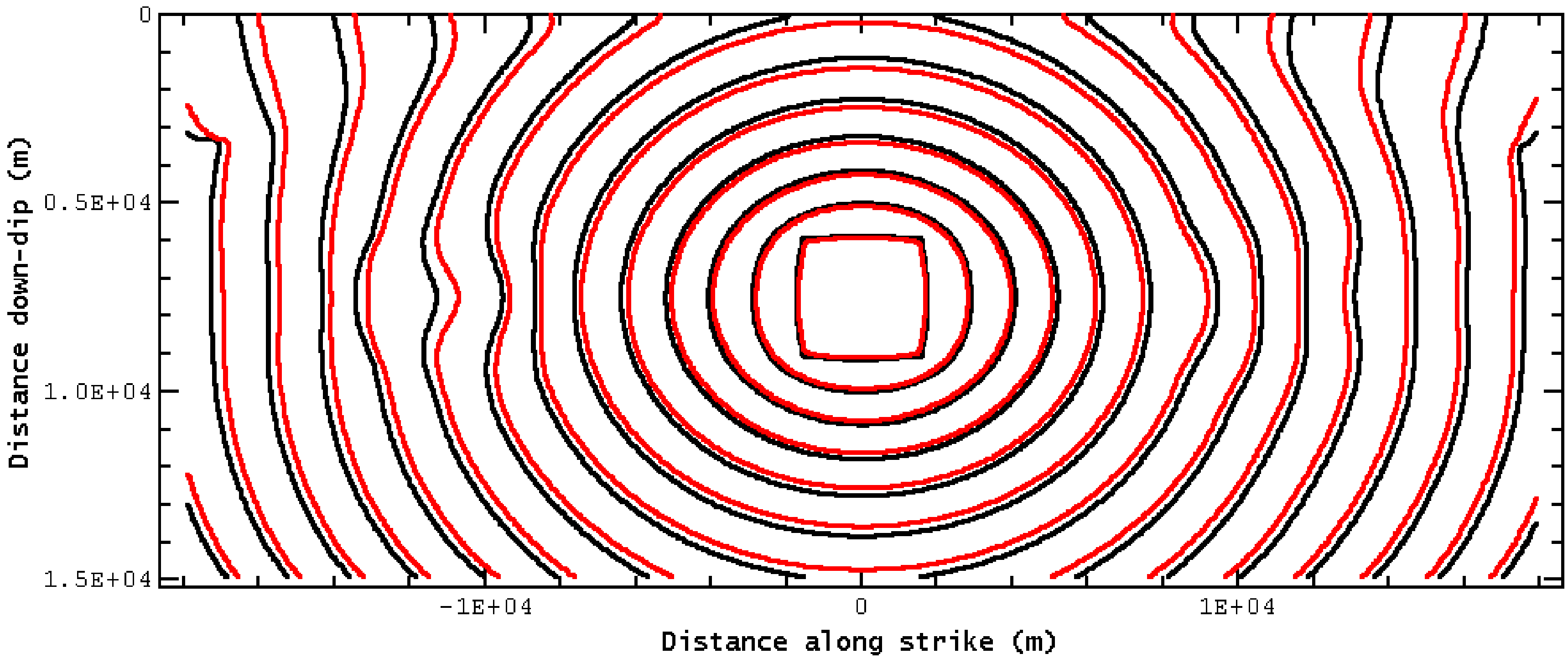
The additional shear stress for nucleation is:

$$\tau_{\mathrm{nuke}}(x,y) = \begin{cases} 11.60\ \mathrm{MPa}, & \text{if } r \le 1400\ \mathrm{m} \\ (5.80\ \mathrm{MPa})\big(1+\cos\big(\pi(r-1400\ \mathrm{m})/(600\ \mathrm{m})\big)\big), & \text{if } 1400\ \mathrm{m} \le r \le 2000\ \mathrm{m} \\ 0, & \text{otherwise} \end{cases}$$

Where r is distance to the hypocenter:

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

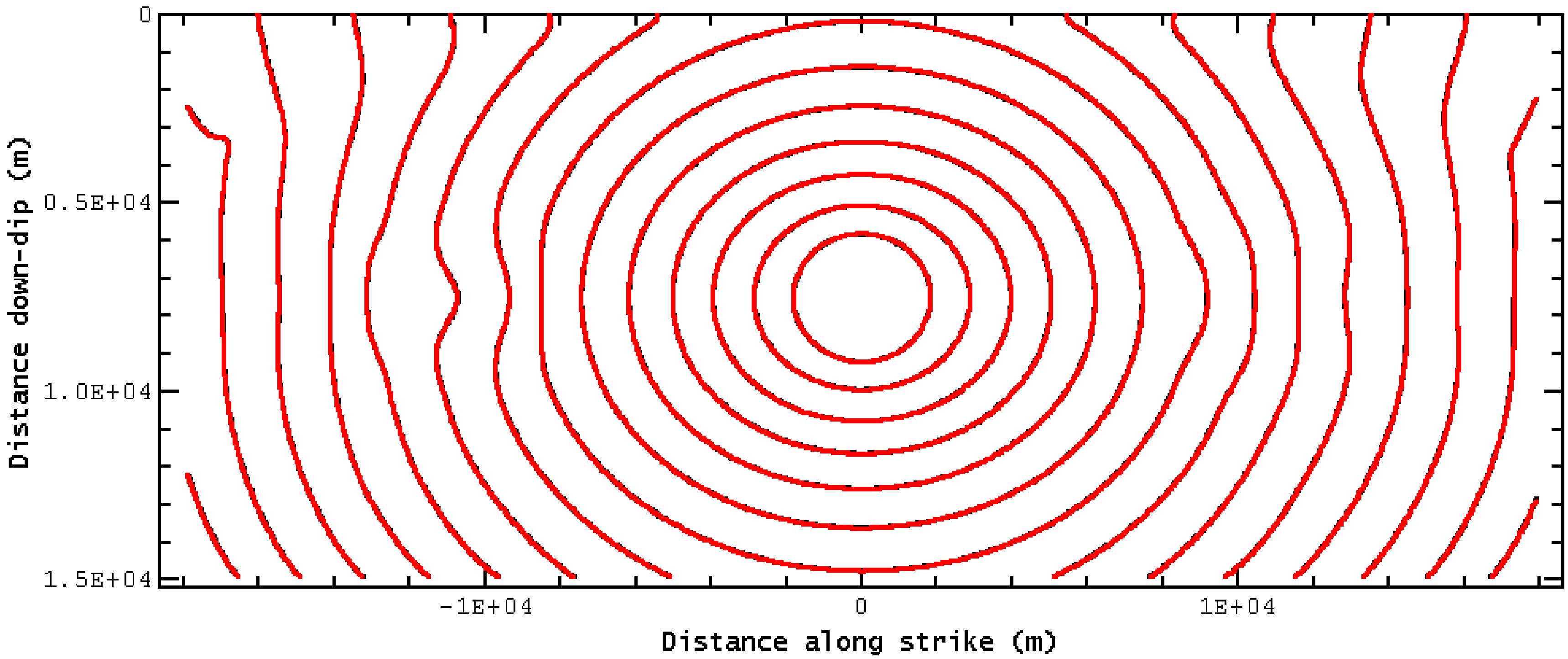
Nucleation Example — TPV5 Method



Black — Assign initial stress to each node based on its location (TPV5).
Red — Assign initial stress to each node by averaging over its sub-fault.

The method of handling nodes that lie on the border of the square nucleation zone affects the entire rupture.

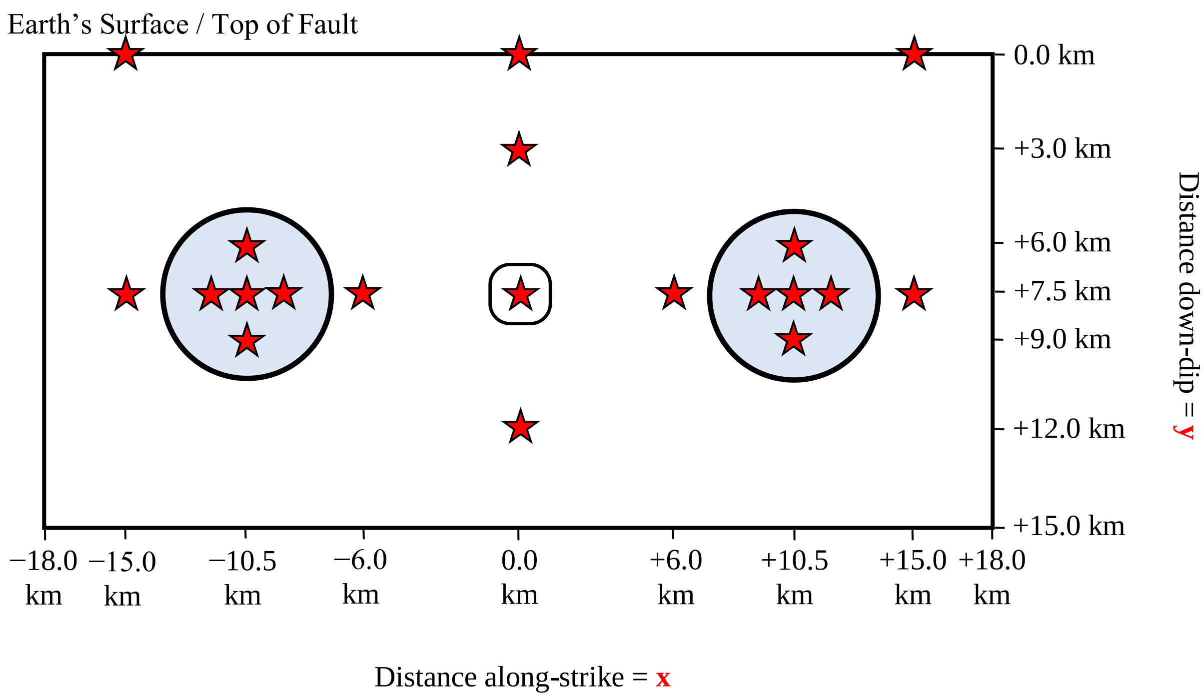
Nucleation Example — TPV28 Method



Black — Assign initial stress to each node by averaging over its sub-fault.
Red — Assign initial stress to each node based on its location.

Smoothing the border of the nucleation zone makes results insensitive to how initial stresses are assigned to nodes.

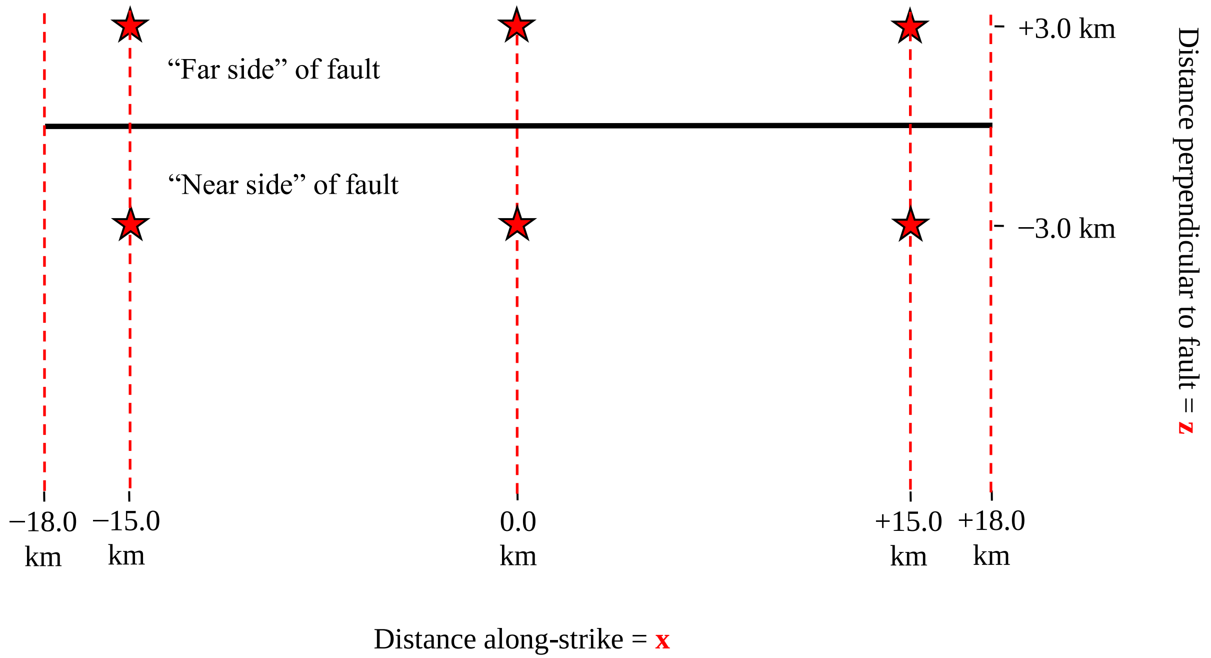
On-Fault Stations.



Modelers are asked to submit slip, slip rate, and stress as a function of time, for 20 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.

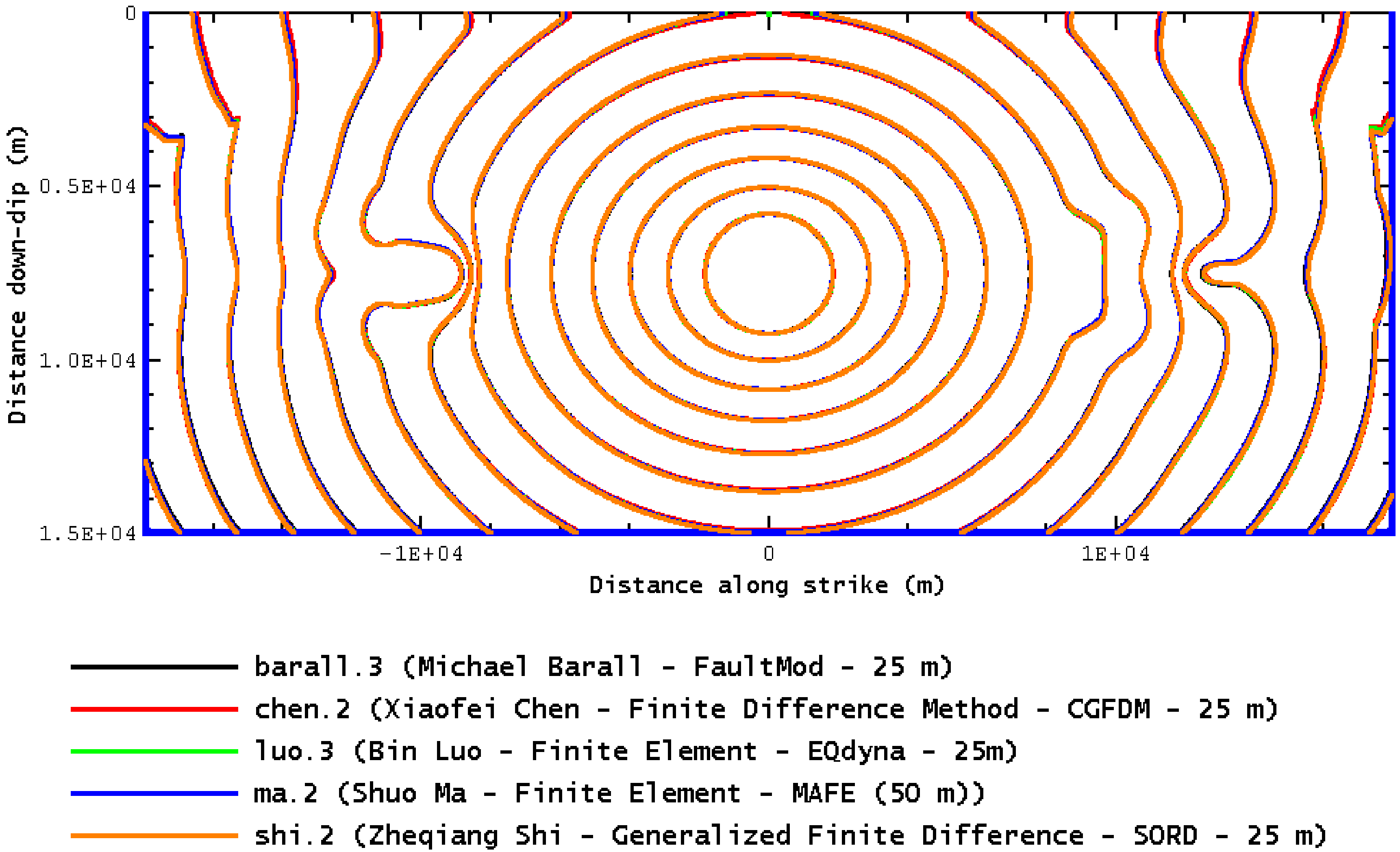
Off-Fault Stations.



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

TPV28 Rupture Contours

TPV28 Rupture Contours — Highest Resolution from each Modeler



The contours are right on top of each other!

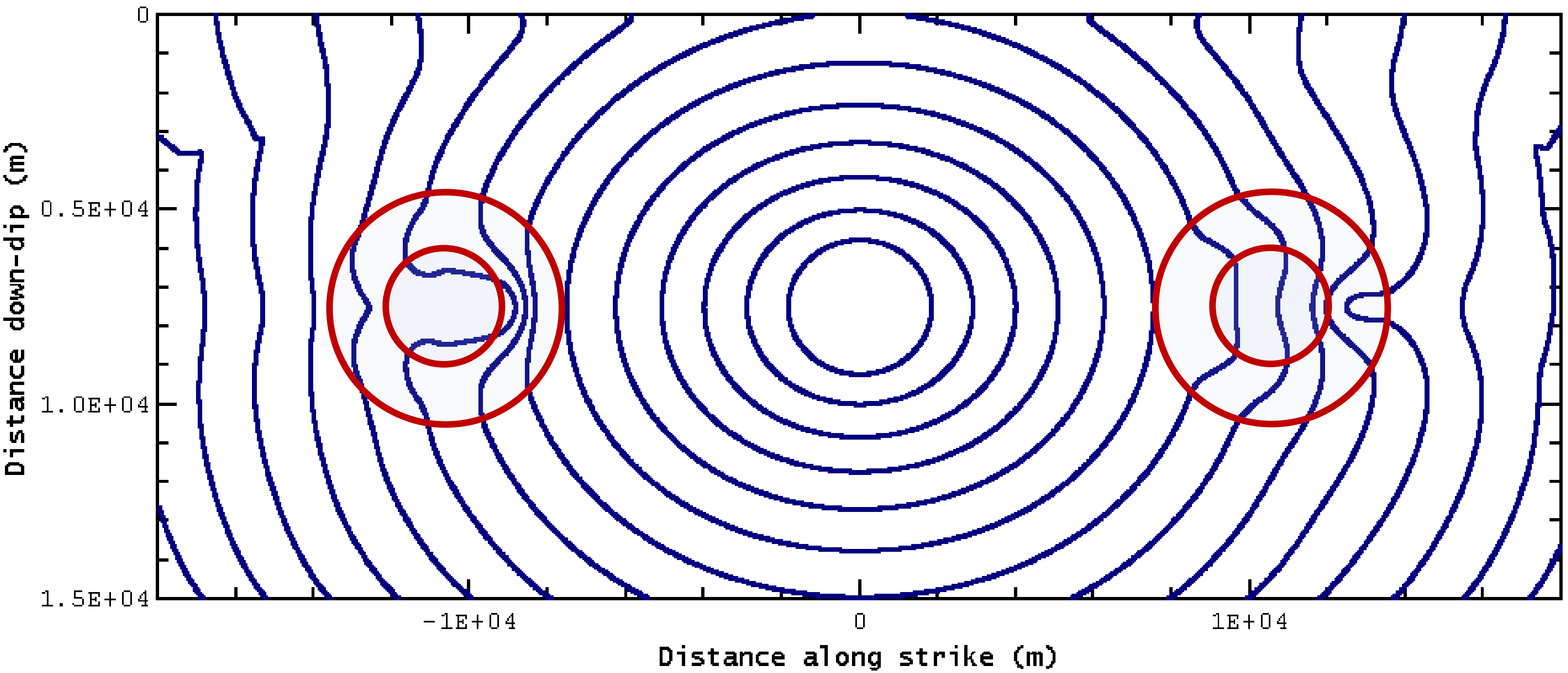
TPV28 Rupture Contours — Metrics

RMS difference in rupture time (milliseconds)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	
(1) barall		47.3	61.2	35.9	65.8	64.6	52.1	71.1	23.9	65.5	62.1	75.2	— 100 m
(2) barall.2	47.3		14.1	23.4	21.0	19.3	19.8	24.3	26.3	18.7	15.2	28.3	— 50 m
(3) barall.3	61.2	14.1		34.5	11.8	10.4	23.9	10.9	39.8	6.0	2.8	14.4	— 25 m
(4) chen	35.9	23.4	34.5		34.3	34.3	20.2	42.0	22.9	38.1	35.2	46.7	— 50 m
(5) chen.2	65.8	21.0	11.8	34.3		7.5	21.4	10.2	45.3	11.5	11.4	14.4	— 25 m
(6) luo	64.6	19.3	10.4	34.3	7.5		19.8	9.5	43.9	10.7	10.2	14.8	— 50 m
(7) luo.2	52.1	19.8	23.9	20.2	21.4	19.8		28.3	34.8	26.5	24.4	33.2	— 100 m
(8) luo.3	71.1	24.3	10.9	42.0	10.2	9.5	28.3		49.7	8.3	10.2	6.2	— 25 m
(9) ma	23.9	26.3	39.8	22.9	45.3	43.9	34.8	49.7		43.5	40.5	53.5	— 100 m
(10) ma.2	65.5	18.7	6.0	38.1	11.5	10.7	26.5	8.3	43.5		4.8	10.7	— 50 m
(11) shi	62.1	15.2	2.8	35.2	11.4	10.2	24.4	10.2	40.5	4.8		13.4	— 50 m
(12) shi.2	75.2	28.3	14.4	46.7	14.4	14.8	33.2	6.2	53.5	10.7	13.4		— 25 m

For the highest resolution results from each modeler, the maximum value is only 14.4 milliseconds.

TPV28 Rupture Contours — Relation to the Hills

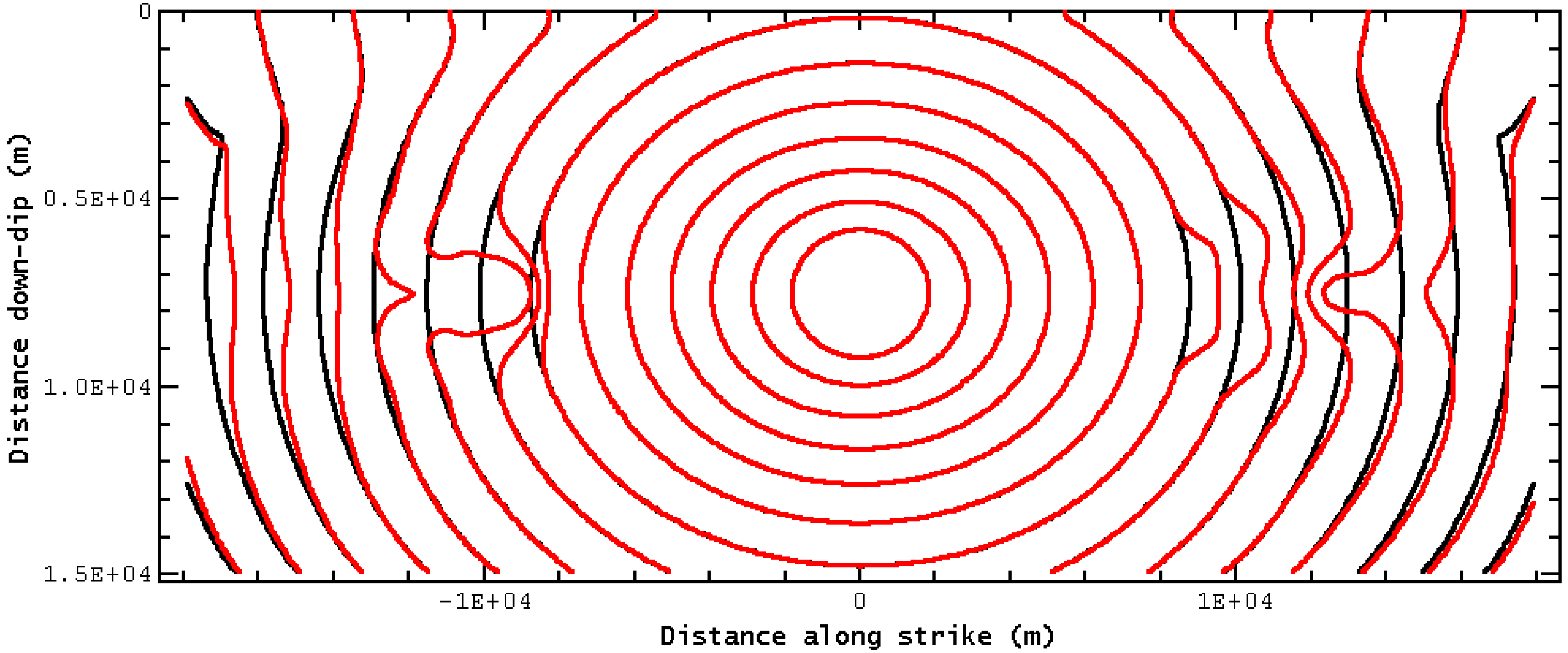


The large circles are the total area of the hills.

The small circles are half-way up the hills (300 meters in front of the fault plane), which is also the inflection point where the hills change from concave to convex.

The center of each hill is 600 meters in front of the fault plane.

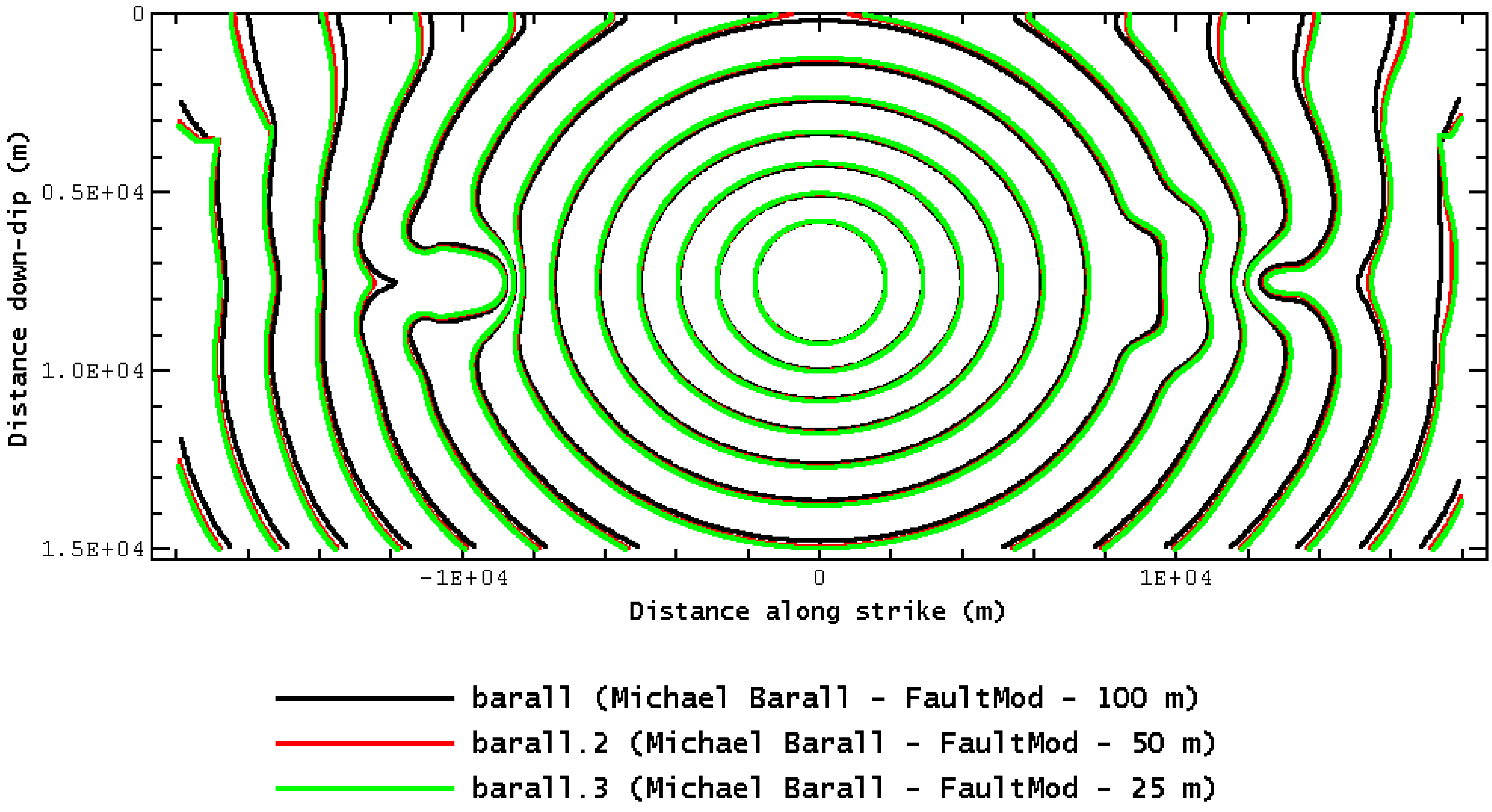
TPV28 Rupture Contours —Hills versus Flat Fault



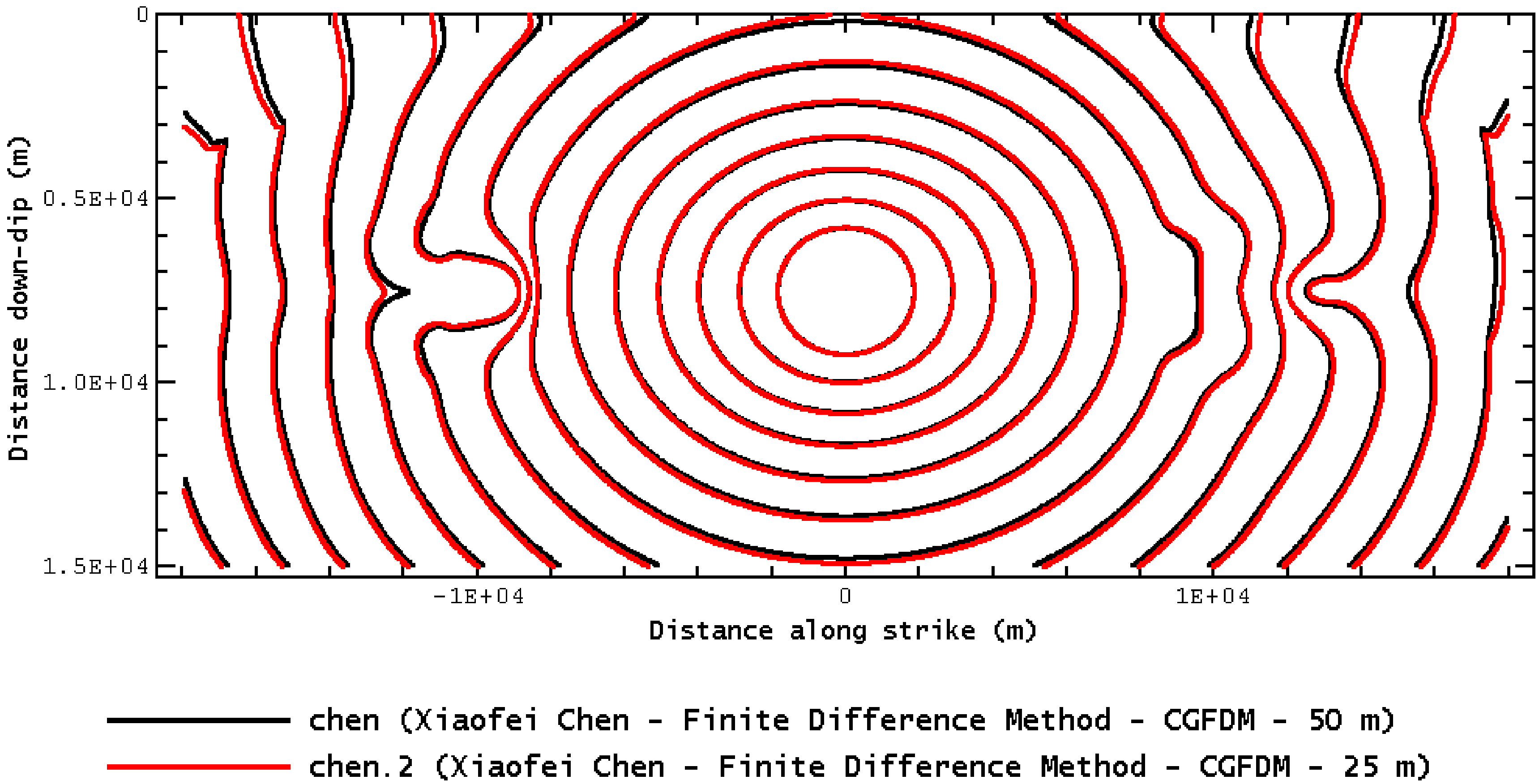
Black — Planar fault.
Red — Non-planar fault with hills.

TPV28 Results — 25 vs. 50 vs. 100 Meters

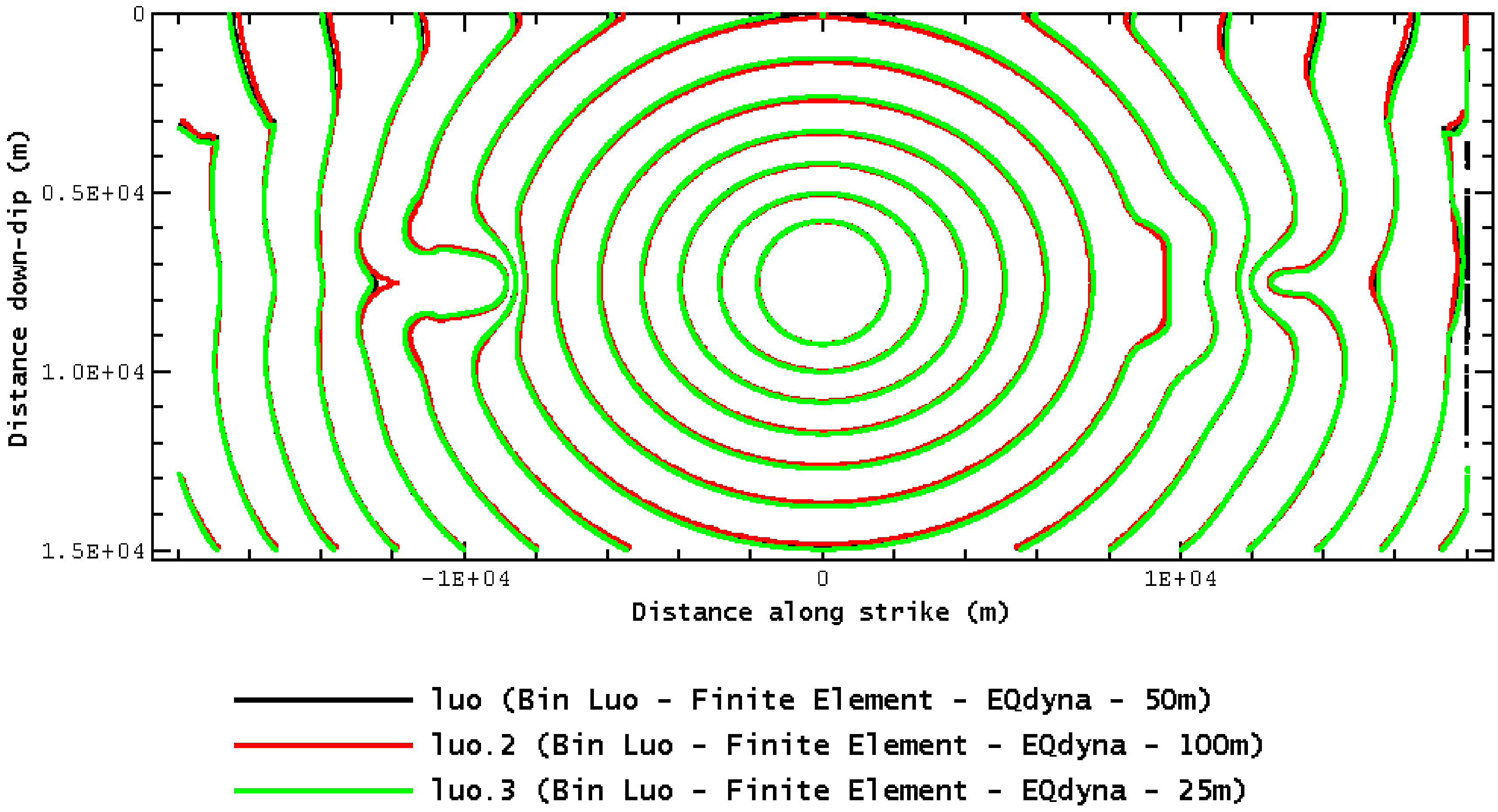
Barall — 25 vs. 50 vs. 100 Meters



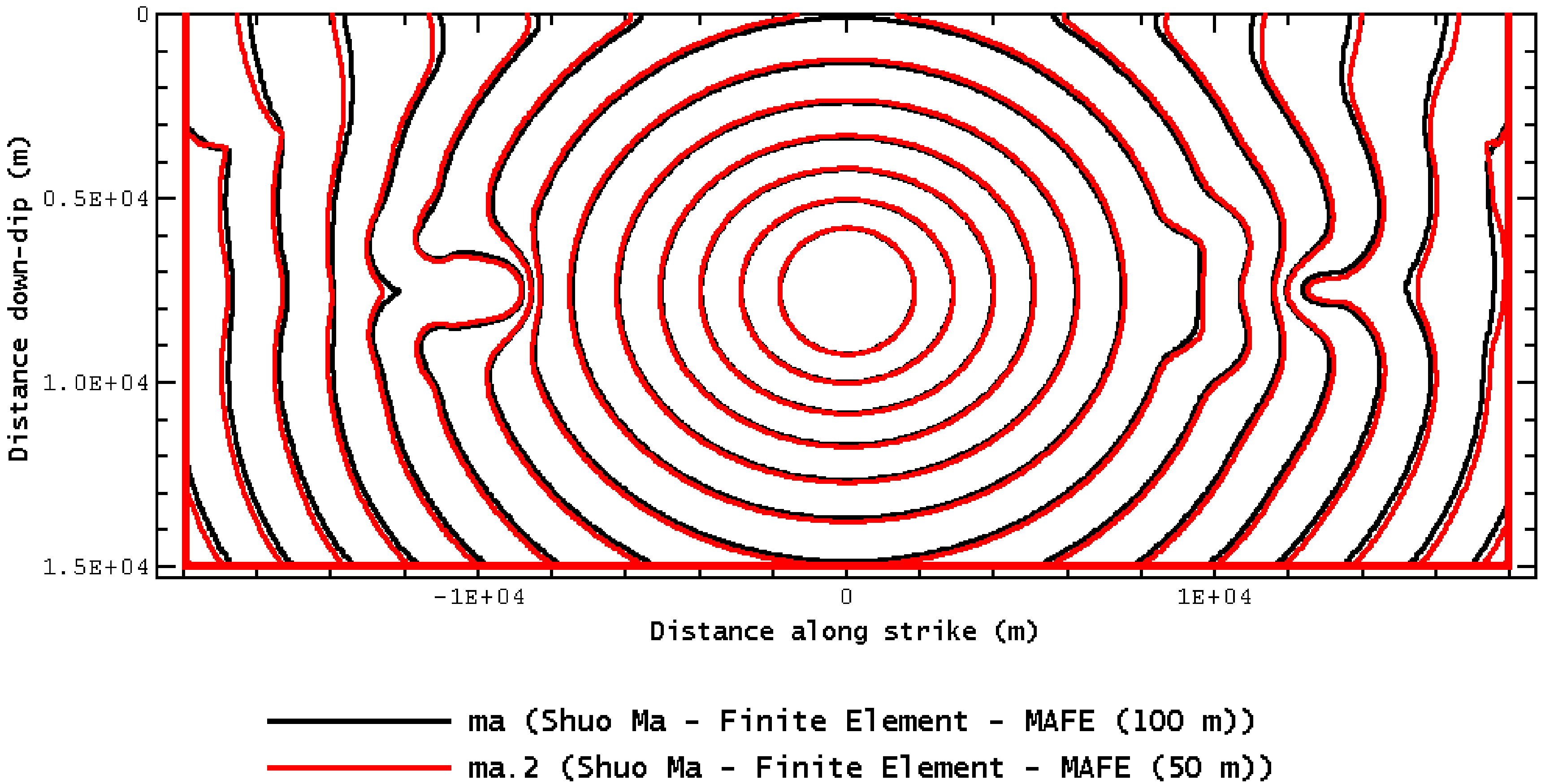
Chen — 25 vs. 50 Meters



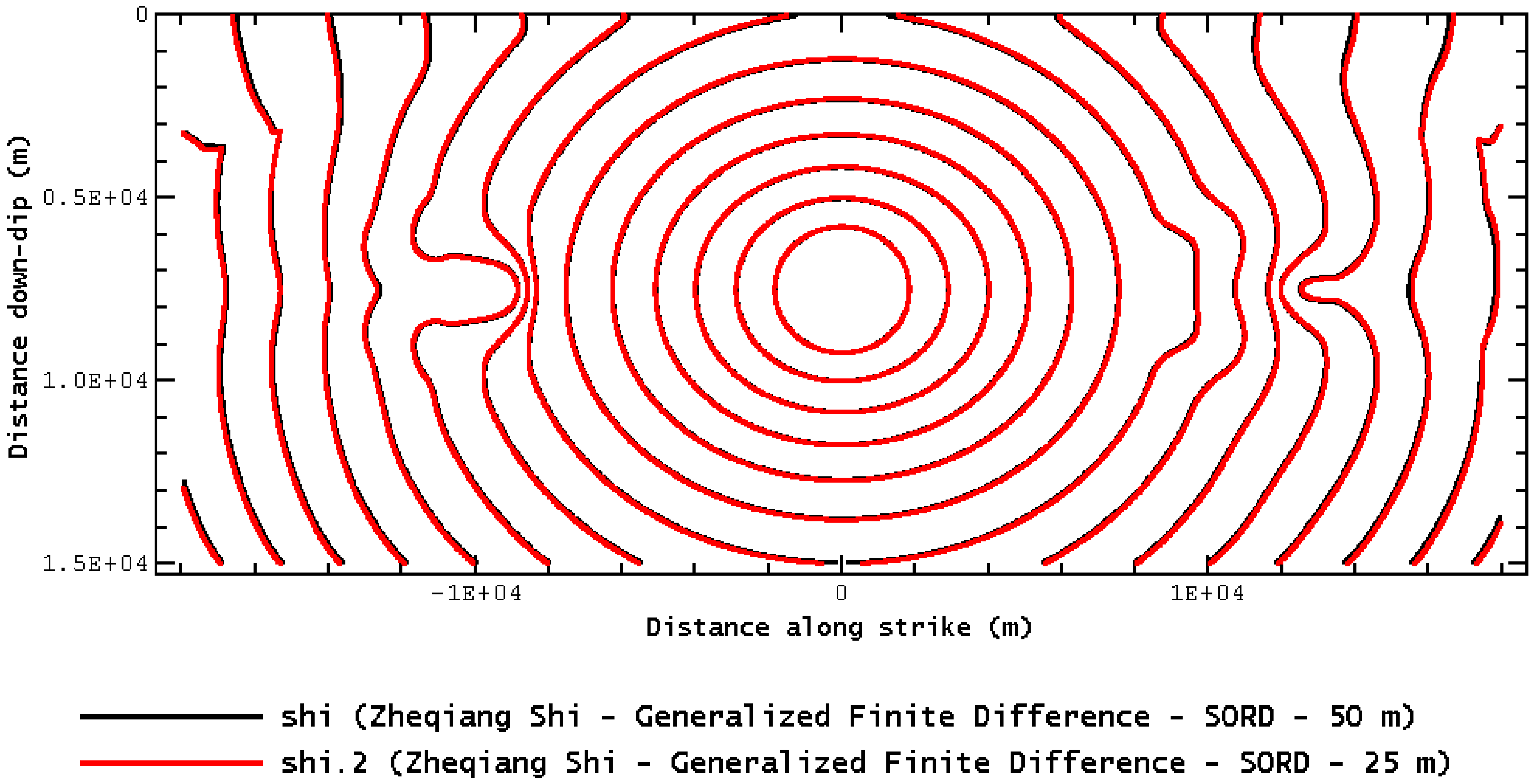
Luo — 25 vs. 50 vs. 100 Meters



Ma — 50 vs. 100 Meters



Shi — 25 vs. 50 Meters



Process zone width (m)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
faultst-060dp075	457	459	458	490	474	472	526	461	443	452	452	454
faultst-090dp075	178	180	176	173	171	181	190	176	182	183	183	181
faultst-105dp060	687	693	696	725	727	733	724	711	670	692	685	684
faultst-105dp075	---	---	---	---	---	---	---	---	468	638	---	---
faultst-105dp090	702	720	721	698	724	730	684	731	671	693	703	709
faultst-120dp000	412	422	425	430	420	428	431	422	352	386	386	410
faultst-120dp075	---	---	---	---	---	---	967	---	---	---	---	---
faultst-150dp075	300	266	256	277	252	285	341	253	257	233	237	232
faultst000dp000	197	183	182	176	175	525	51	378	172	173	173	177
faultst000dp030	357	386	389	397	397	402	407	395	368	391	388	391
faultst000dp075	---	---	---	---	---	---	---	---	---	---	---	---
faultst000dp120	360	389	392	398	400	406	411	398	375	390	392	394
faultst060dp075	459	461	460	491	476	473	531	463	447	452	454	456
faultst090dp075	819	834	839	815	841	828	818	843	863	862	852	865
faultst105dp060	460	475	483	491	494	492	496	487	482	491	479	486
faultst105dp075	328	320	317	323	316	314	356	315	316	312	310	311
faultst105dp090	469	486	495	510	510	504	507	501	467	486	491	500
faultst120dp000	434	426	432	440	429	436	446	428	354	397	391	415
faultst120dp075	254	256	254	296	279	265	293	257	257	264	262	263
faultst150dp075	444	457	462	436	446	439	402	450	420	448	456	461

TPV28 Process Zone Width

Several stations have process zone widths in the range 170 to 300 m.

We would expect 100 m resolution to be not adequate, but 50 m and 25 m resolution should be adequate, as we have seen.

TPV28 Results — On-Fault Stations

Summary across all users (click to drill down)

	2d-stress	2d-rate	2d-slip	n-stress	t-shift
faultst-060dp075	2.3	3.8	0.4	6.3	0.015
faultst-090dp075	2.9	4.2	2.4	0.9	0.032
faultst-105dp060	1.1	4.3	0.7	6.8	0.030
faultst-105dp075	5.1	4.5	0.5	2.3	0.033
faultst-105dp090	62.1	5.8	0.8	9.2	0.030
faultst-120dp000	4.8	11.4	0.4	6.4	0.036
faultst-120dp075	1.2	5.1	2.4	0.9	0.029
faultst-150dp075	3.1	7.2	0.7	4.6	0.028
faultst000dp000	3.6	3.1	0.2	6.7	0.033
faultst000dp030	2.9	3.6	0.3	9.5	0.024
faultst000dp075	3.2	4.0	0.3	17.2	0.008
faultst000dp120	2.0	4.5	0.4	9.4	0.021
faultst060dp075	2.5	3.5	0.4	4.6	0.015
faultst090dp075	0.8	5.1	2.5	0.7	0.014
faultst105dp060	0.9	4.8	0.8	5.9	0.014
faultst105dp075	3.3	5.5	0.5	1.7	0.014
faultst105dp090	63.9	4.1	0.8	7.0	0.016
faultst120dp000	4.6	9.9	0.4	7.1	0.035
faultst120dp075	3.6	4.8	2.4	1.4	0.034
faultst150dp075	3.0	5.6	0.6	11.4	0.034

Metrics at On-Fault Stations

All codes are in very good agreement at all on-fault stations.

Summary across all users (click to drill down)

	2d-stress	2d-rate	2d-slip	n-stress	t-shift
faultst-060dp075	2.3	3.8	0.4	6.3	0.015
faultst-090dp075	2.9	4.2	2.4	0.9	0.032
faultst-105dp060	1.1	4.3	0.7	6.8	0.030
faultst-105dp075	5.1	4.5	0.5	2.3	0.033
faultst-105dp090	62.1	5.8	0.8	9.2	0.030
faultst-120dp000	4.8	11.4	0.4	6.4	0.036
faultst-120dp075	1.2	5.1	2.4	0.9	0.029
faultst-150dp075	3.1	7.2	0.7	4.6	0.028
faultst000dp000	3.6	3.1	0.2	6.7	0.033
faultst000dp030	2.9	3.6	0.3	9.5	0.024
faultst000dp075	3.2	4.0	0.3	17.2	0.008
faultst000dp120	2.0	4.5	0.4	9.4	0.021
faultst060dp075	2.5	3.5	0.4	4.6	0.015
faultst090dp075	0.8	5.1	2.5	0.7	0.014
faultst105dp060	0.9	4.8	0.8	5.9	0.014
faultst105dp075	3.3	5.5	0.5	1.7	0.014
faultst105dp090	63.9	4.1	0.8	7.0	0.016
faultst120dp000	4.6	9.9	0.4	7.1	0.035
faultst120dp075	3.6	4.8	2.4	1.4	0.034
faultst150dp075	3.0	5.6	0.6	11.4	0.034

Metrics at On-Fault Stations

The circled values are large only because one code reports vertical shear stress with incorrect sign.

If the sign error were corrected, the values would be comparable to the rest of the 2d-stress column.

Summary across all users (click to drill down)

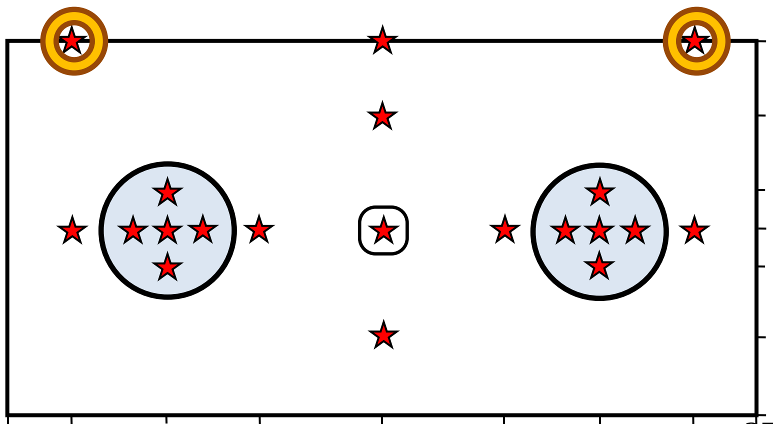
	2d-stress	2d-rate	2d-slip	n-stress	t-shift
faultst-060dp075	2.3	3.8	0.4	6.3	0.015
faultst-090dp075	2.9	4.2	2.4	0.9	0.032
faultst-105dp060	1.1	4.3	0.7	6.8	0.030
faultst-105dp075	5.1	4.5	0.5	2.3	0.033
faultst-105dp090	62.1	5.8	0.8	9.2	0.030
faultst-120dp000	4.8	11.4	0.4	6.4	0.036
faultst-120dp075	1.2	5.1	2.4	0.9	0.029
faultst-150dp075	3.1	7.2	0.7	4.6	0.028
faultst000dp000	3.6	3.1	0.2	6.7	0.033
faultst000dp030	2.9	3.6	0.3	9.5	0.024
faultst000dp075	3.2	4.0	0.3	17.2	0.008
faultst000dp120	2.0	4.5	0.4	9.4	0.021
faultst060dp075	2.5	3.5	0.4	4.6	0.015
faultst090dp075	0.8	5.1	2.5	0.7	0.014
faultst105dp060	0.9	4.8	0.8	5.9	0.014
faultst105dp075	3.3	5.5	0.5	1.7	0.014
faultst105dp090	63.9	4.1	0.8	7.0	0.016
faultst120dp000	4.6	9.9	0.4	7.1	0.035
faultst120dp075	3.6	4.8	2.4	1.4	0.034
faultst150dp075	3.0	5.6	0.6	11.4	0.034

Metrics at On-Fault Stations

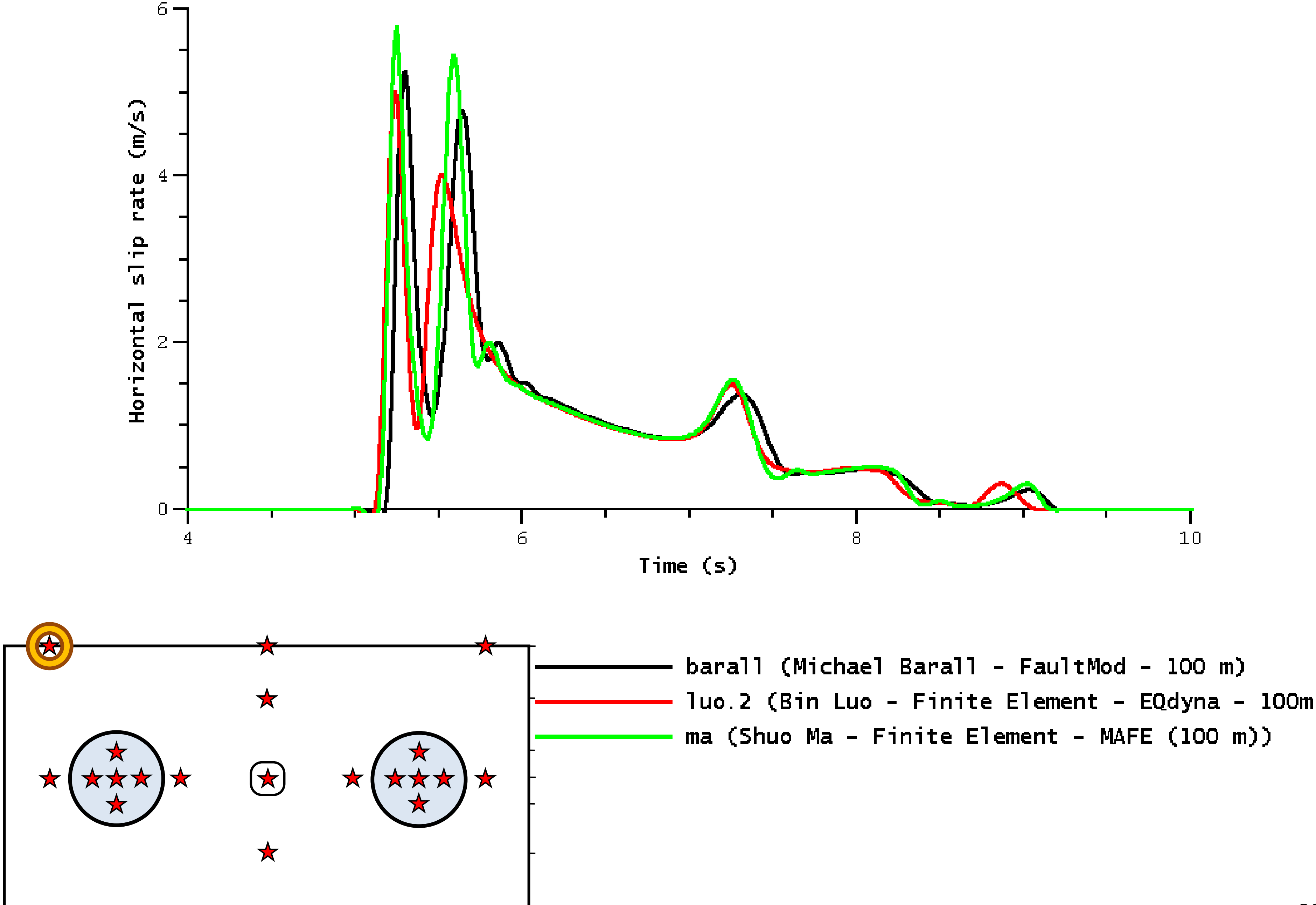
The circled values are larger than other 2d-rate values because of the 100 m runs.

The two stations are located in the upper-left and upper-right corners of the fault, where the 100 m runs had the most trouble.

If we considered just the 50 m and 25 m runs, the values would be comparable to the rest of the 2d-rate column.

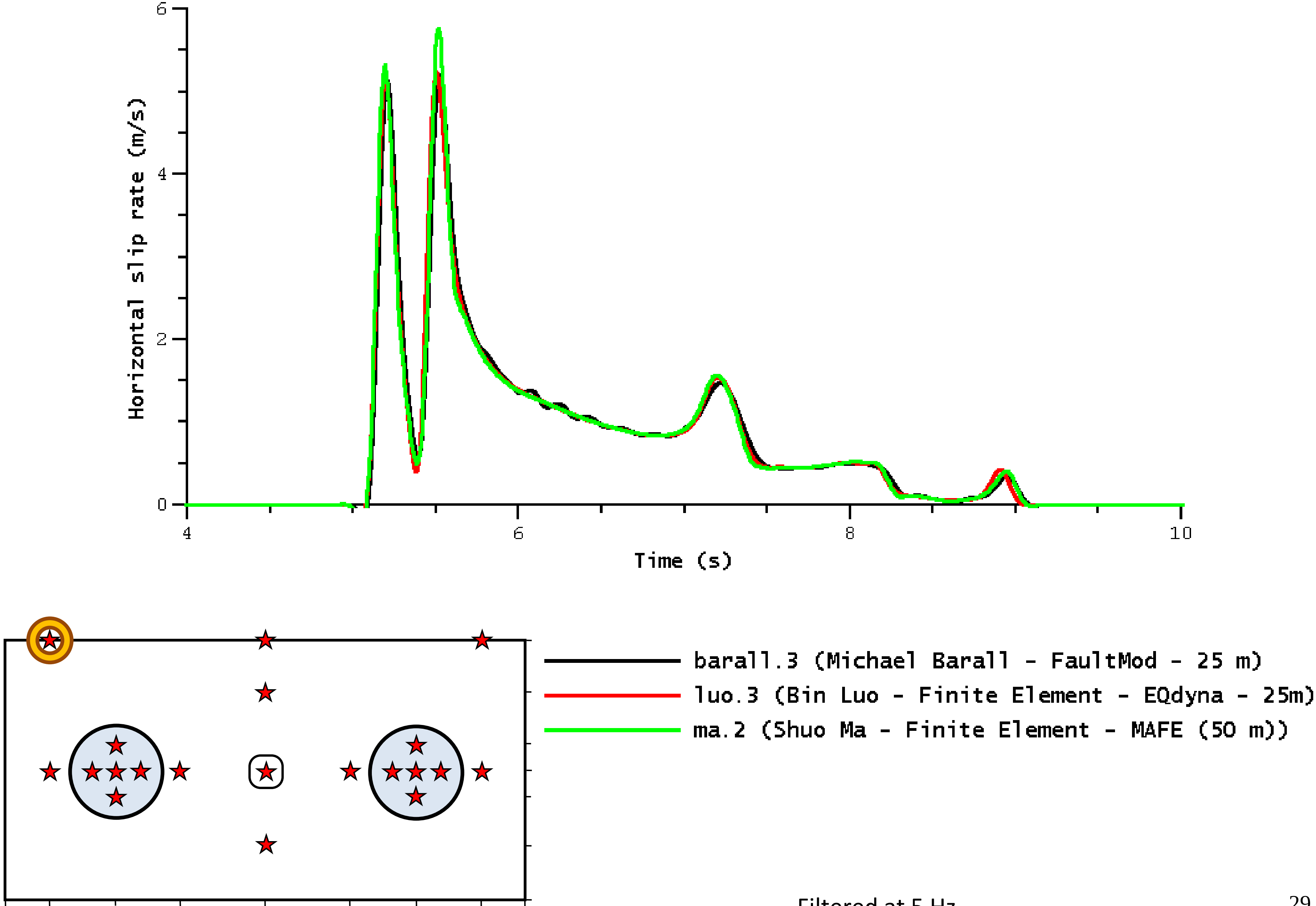


faultst-120dp000 — 100 m Runs



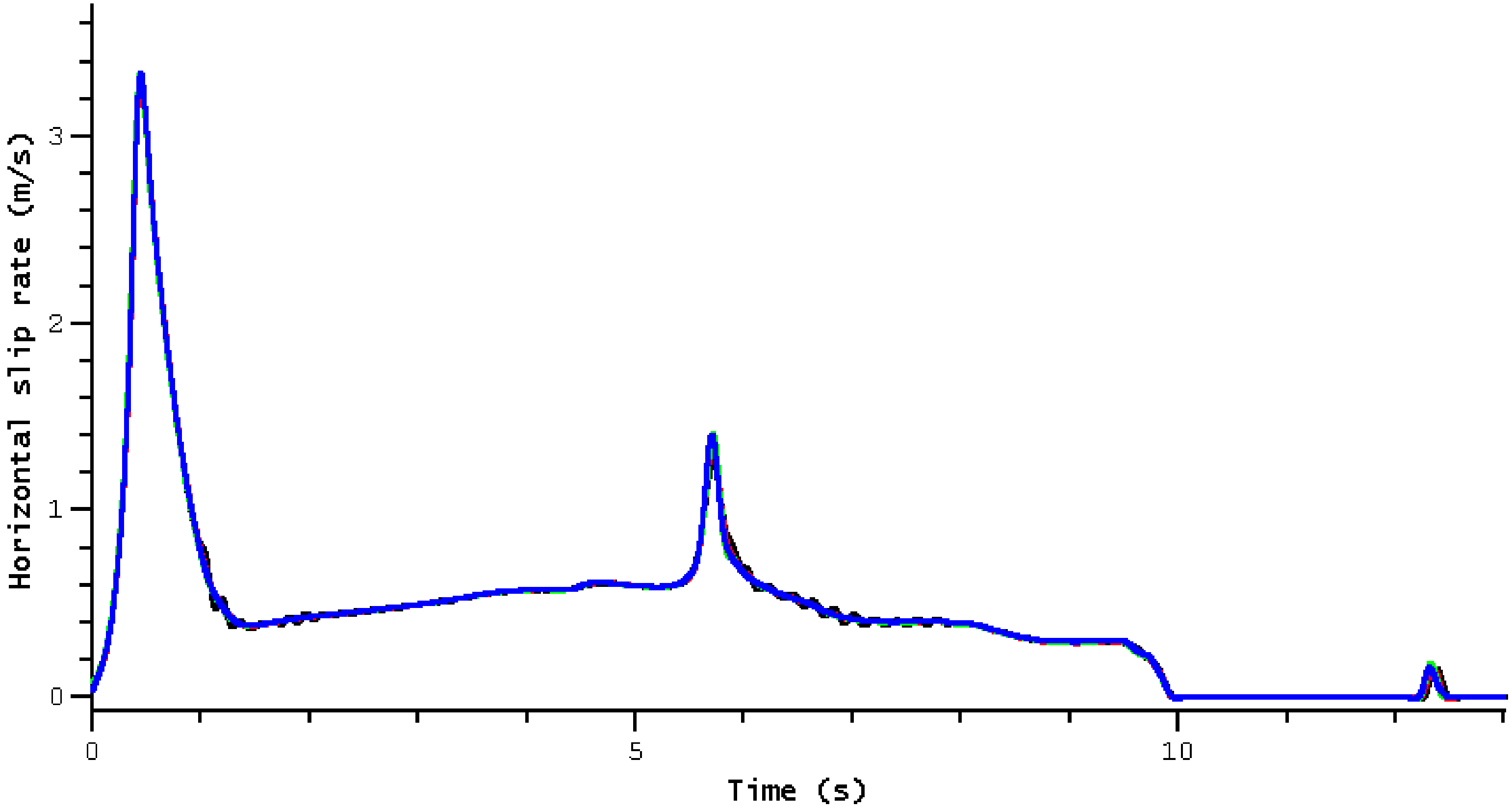
Filtered at 5 Hz.

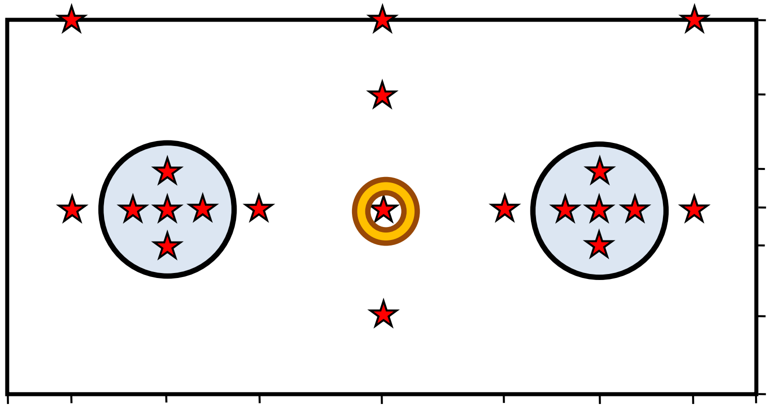
faultst-120dp000 — 25 and 50 m Runs



Filtered at 5 Hz.

faultst000dp075 (hypocenter) — Horizontal Slip Rate

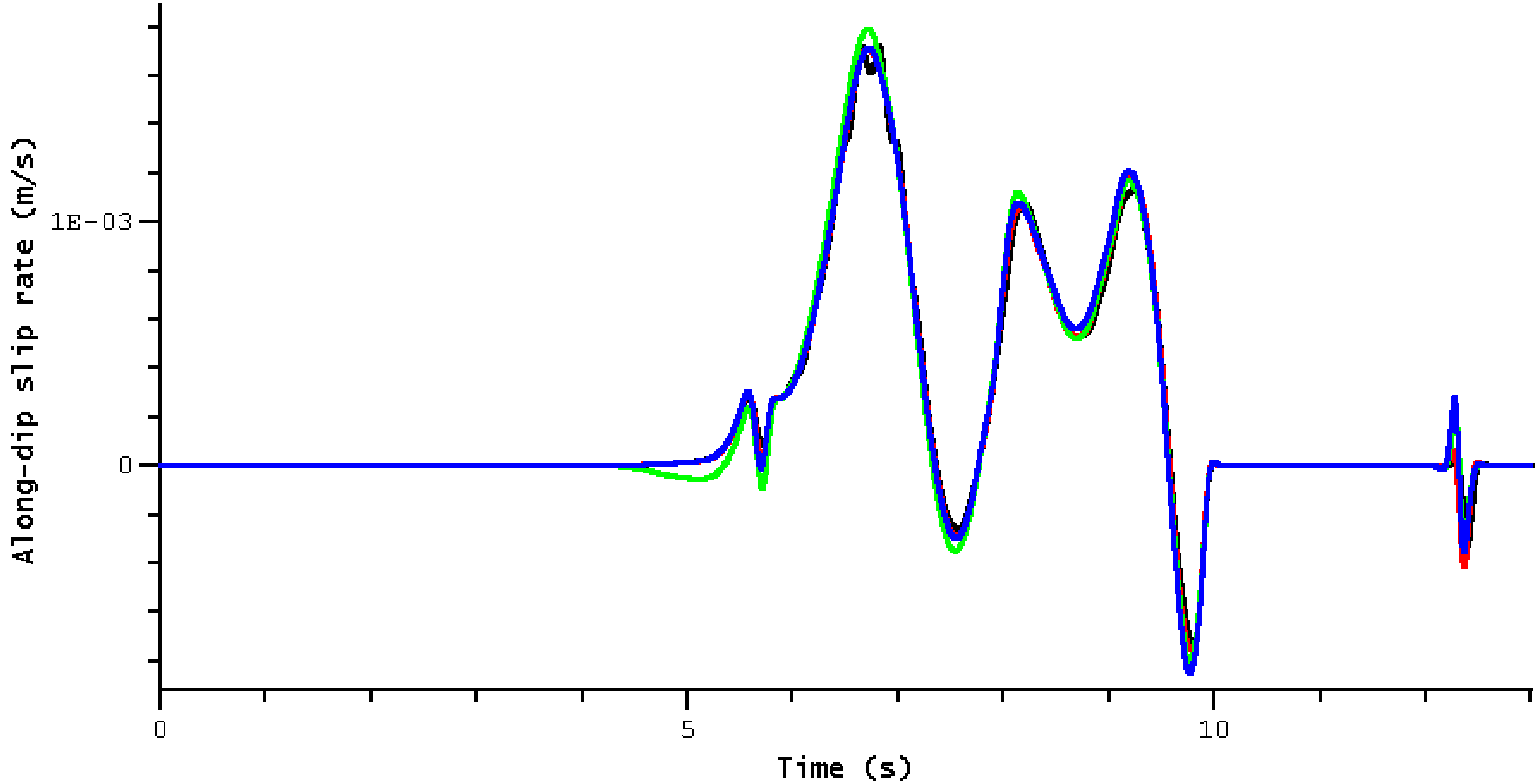


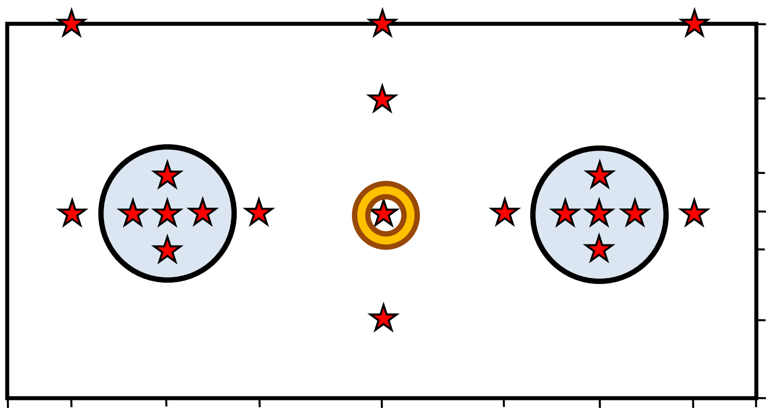


barall.3 (Michael Barall - FaultMod - 25 m)
luo.3 (Bin Luo - Finite Element - EQdyna - 25m)
ma.2 (Shuo Ma - Finite Element - MAFE (50 m))
shi.2 (Zheqiang Shi - Generalized Finite Difference - SORD - 25 m)

Filtered at 5 Hz.

faultst000dp075 (hypocenter) — Vertical Slip Rate





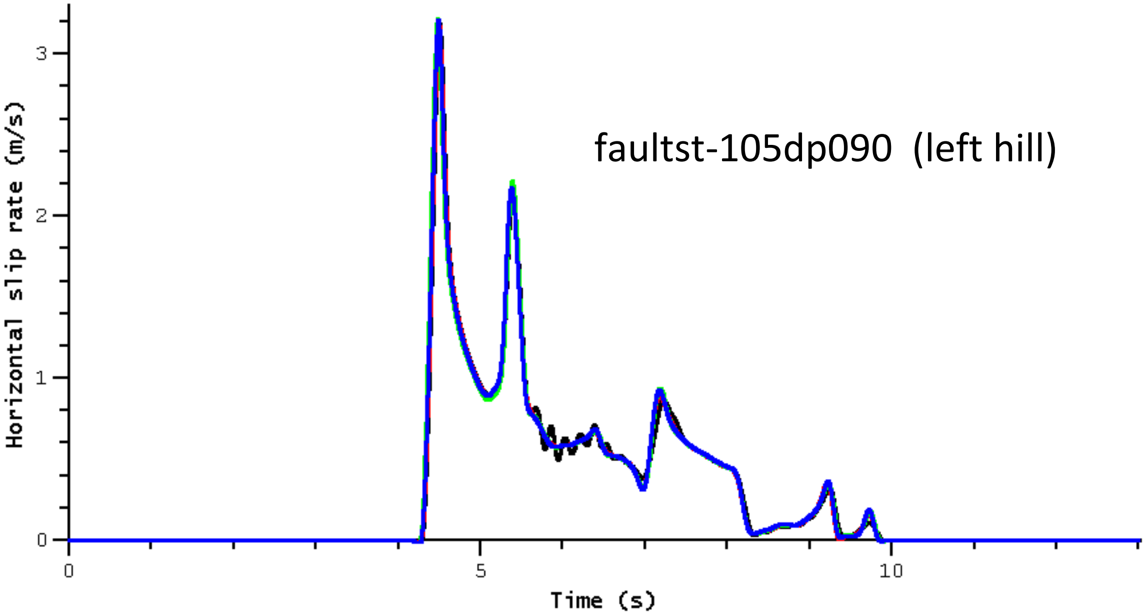
This is constructive interference of seismic waves arriving from the two hills.

If the hills pointed to opposite sides of the fault, or if the fault were planar, then vertical slip would be zero.

- barall.3 (Michael Barall - FaultMod - 25 m)
- luo.3 (Bin Luo - Finite Element - EQdyna - 25m)
- ma.2 (Shuo Ma - Finite Element - MAFE (50 m))
- shi.2 (Zheqiang Shi - Generalized Finite Difference - SORD - 25 m)

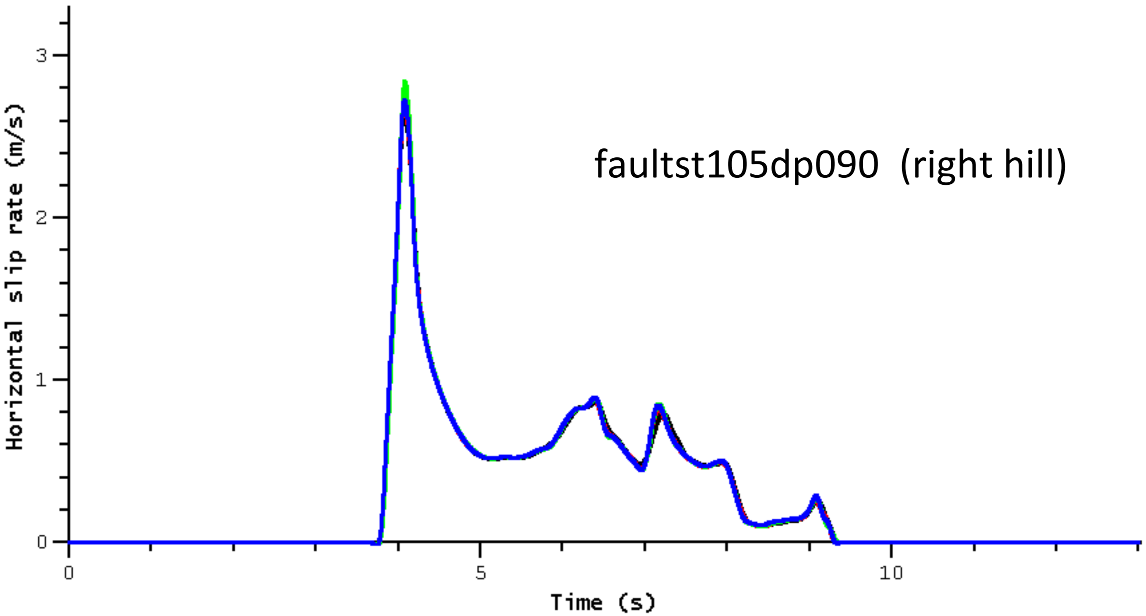
Filtered at 5 Hz.

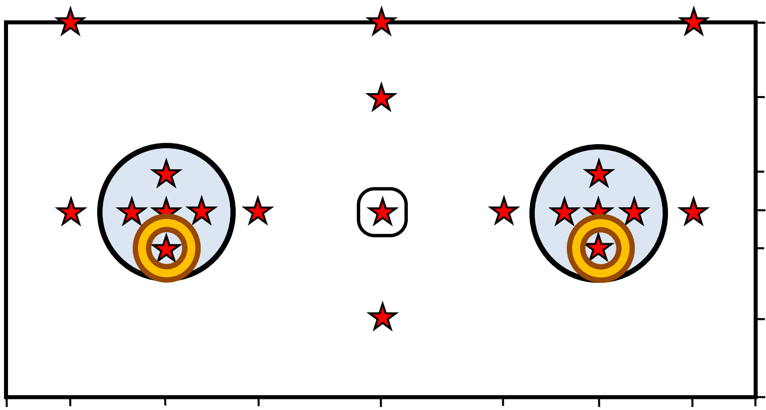
Stations on the Bottom Slope of the Hills — Horizontal Slip Rate



On the left hill, slip rate is double-peaked.

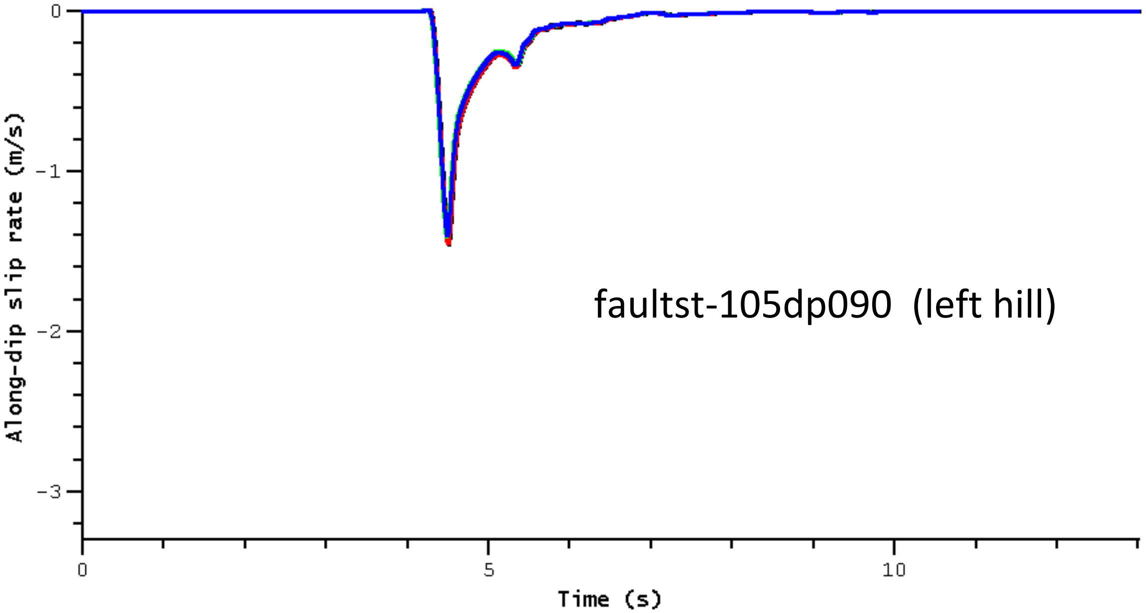
On the right hill, there is a single peak.

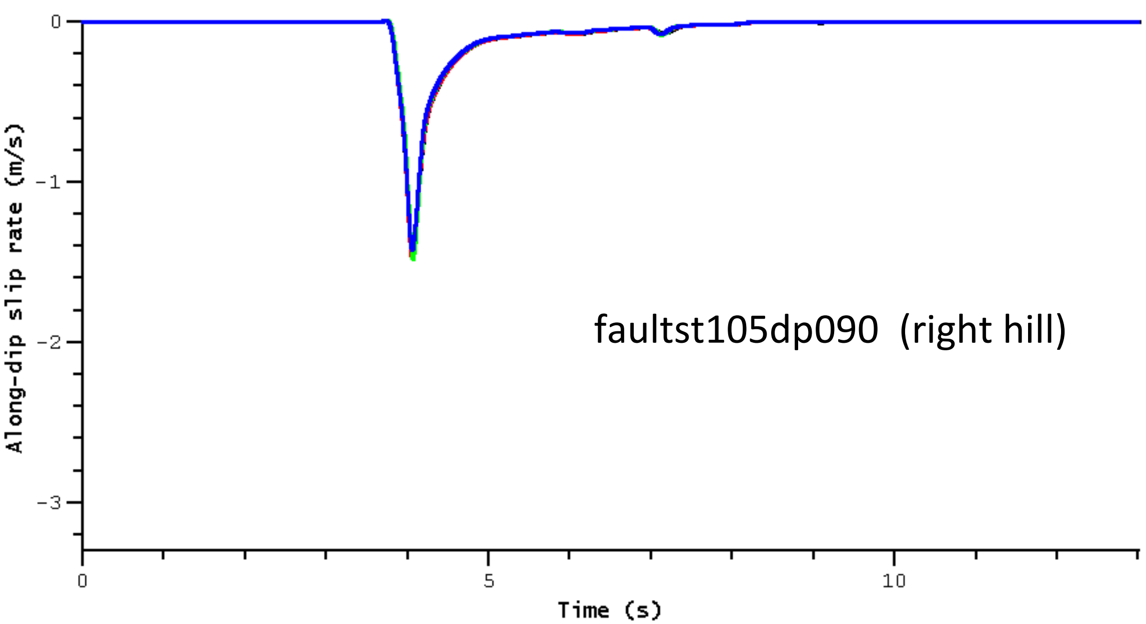


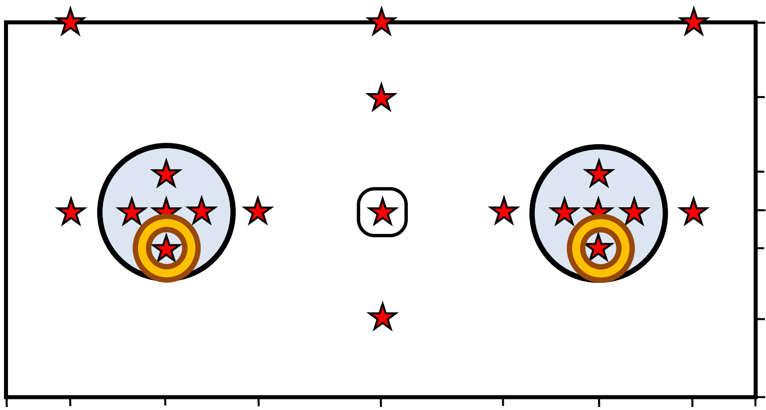


Filtered at 5 Hz.

Stations on the Bottom Slope of the Hills — Vertical Slip Rate

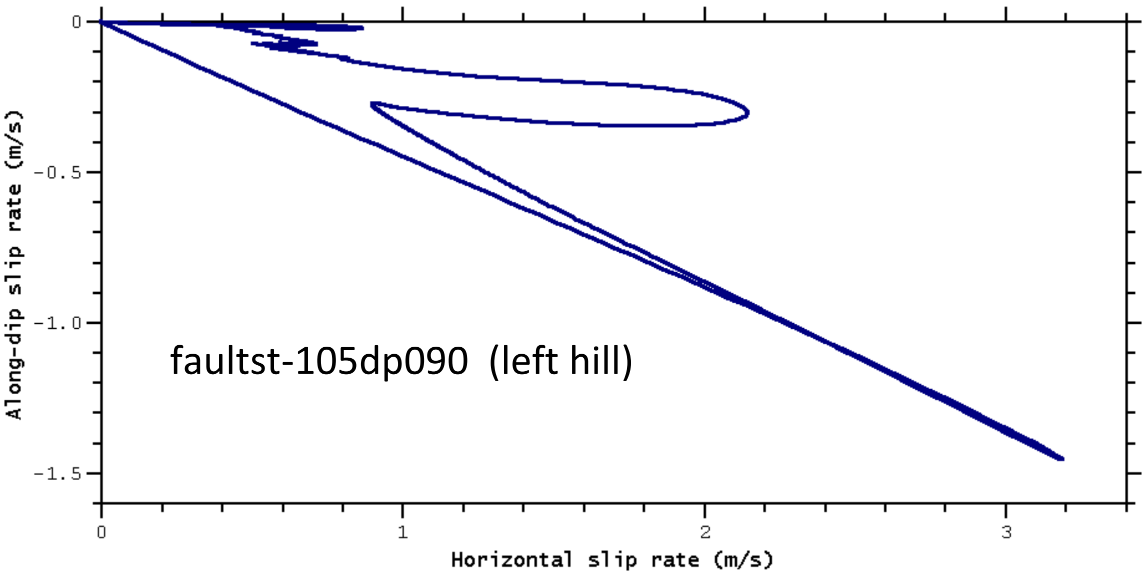






Filtered at 5 Hz.

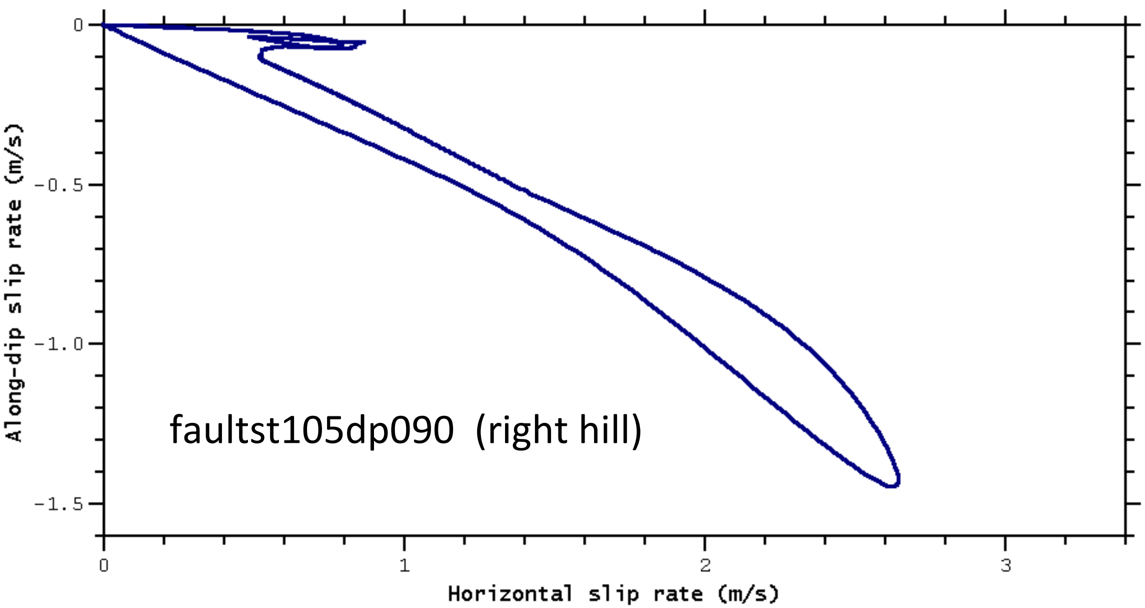
Stations on the Bottom Slope of the Hills — Slip Rate Vectors and Rake Angles

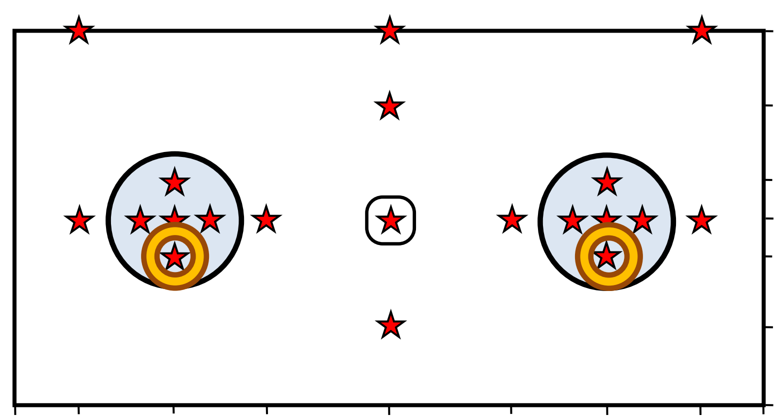


These plots show the slip vector as a function of time.

The axes are horizontal and vertical slip rate, with origin at the upper left corner. Each curve starts at the origin.

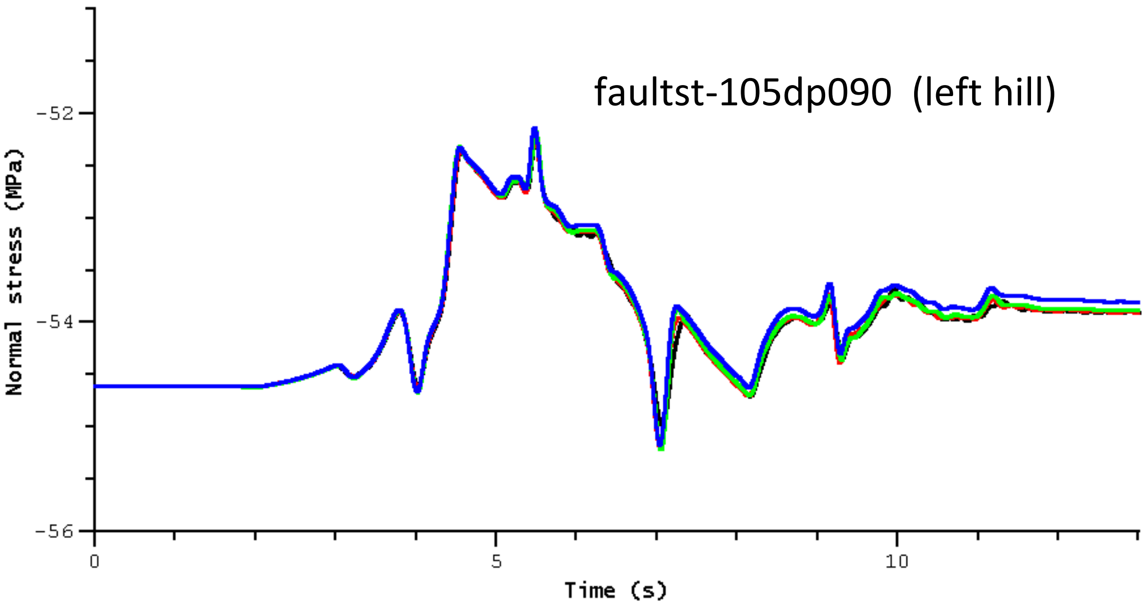
Rake angle is the angle at the origin.





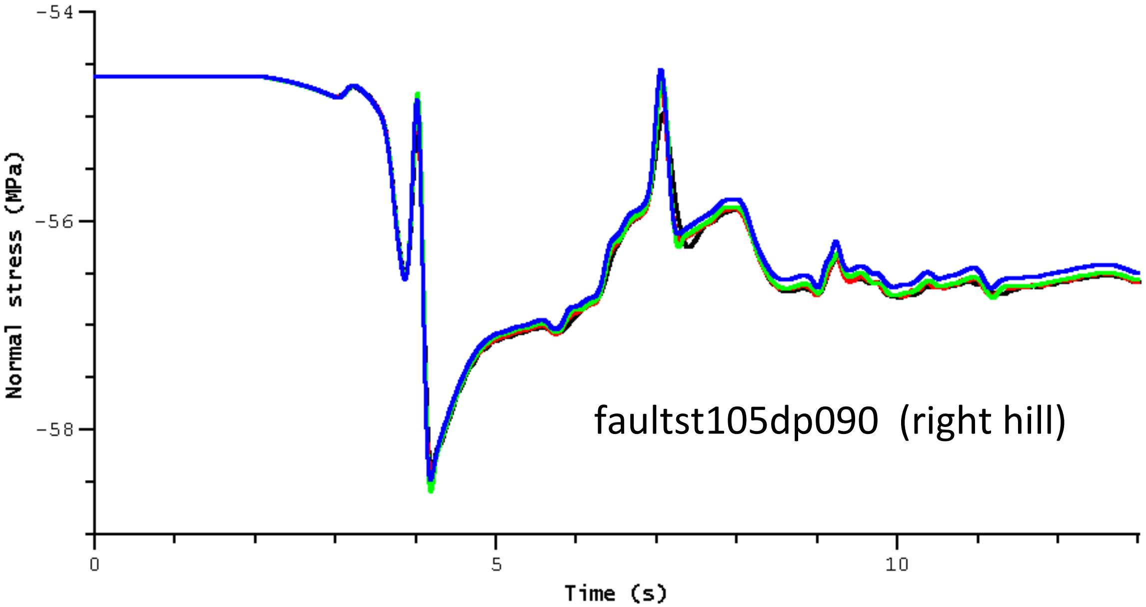
Filtered at 5 Hz.

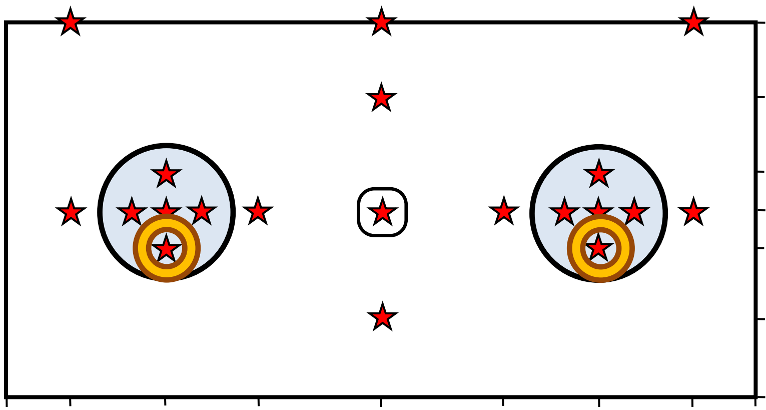
Stations on the Bottom Slope of the Hills — Normal Stress



On the left hill, normal stress decreases.

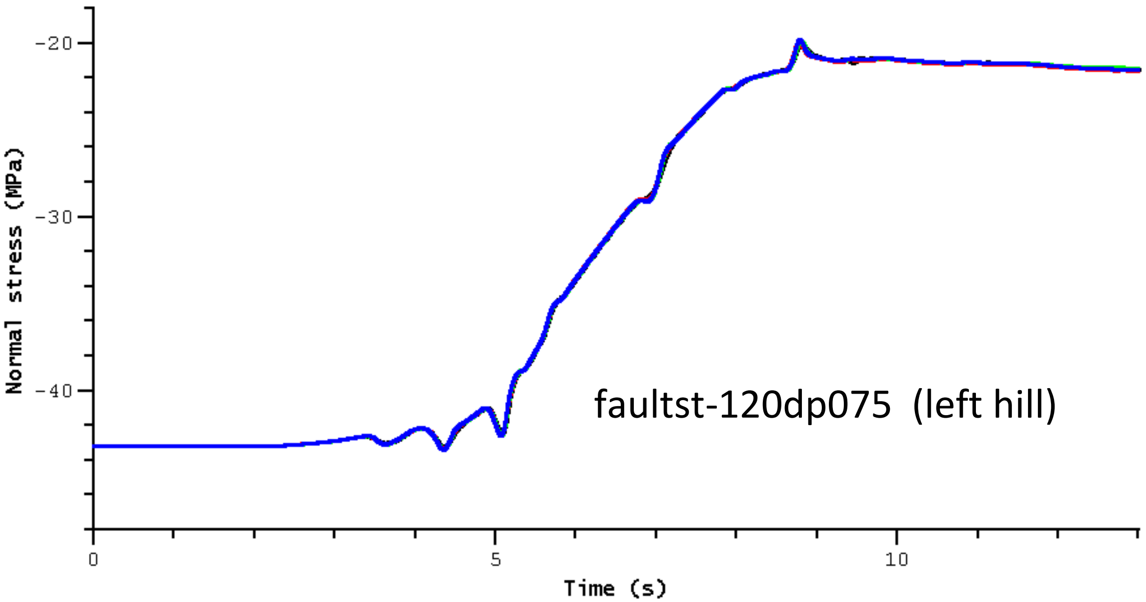
On the right hill, normal stress increases.





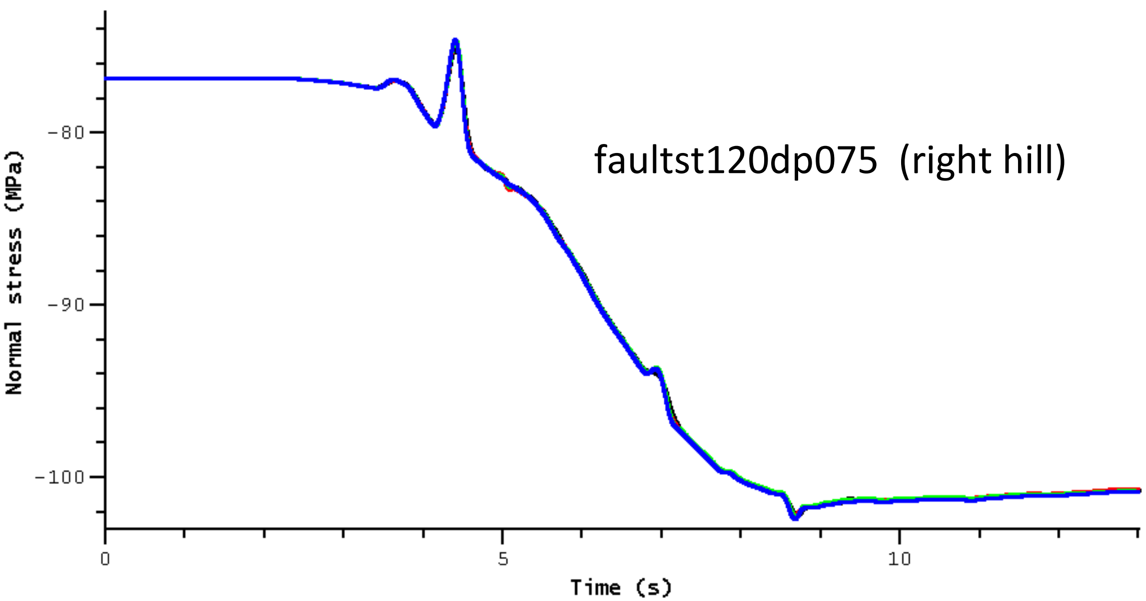
Filtered at 5 Hz.

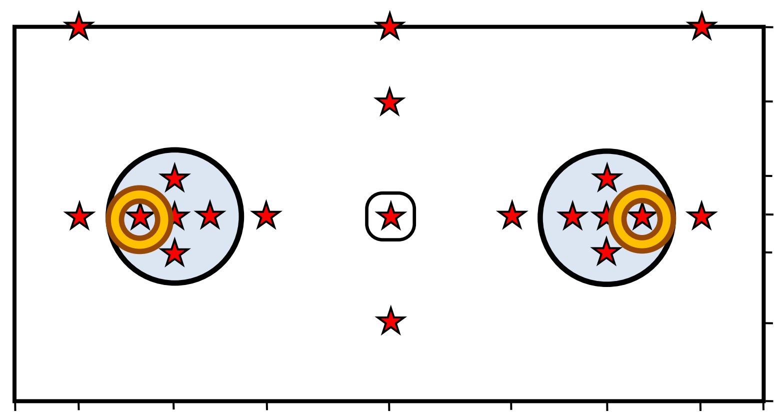
Stations on the Outer Slope of the Hills — Normal Stress



On the left hill, normal stress starts at 43 MPa and drops to 21 MPa.

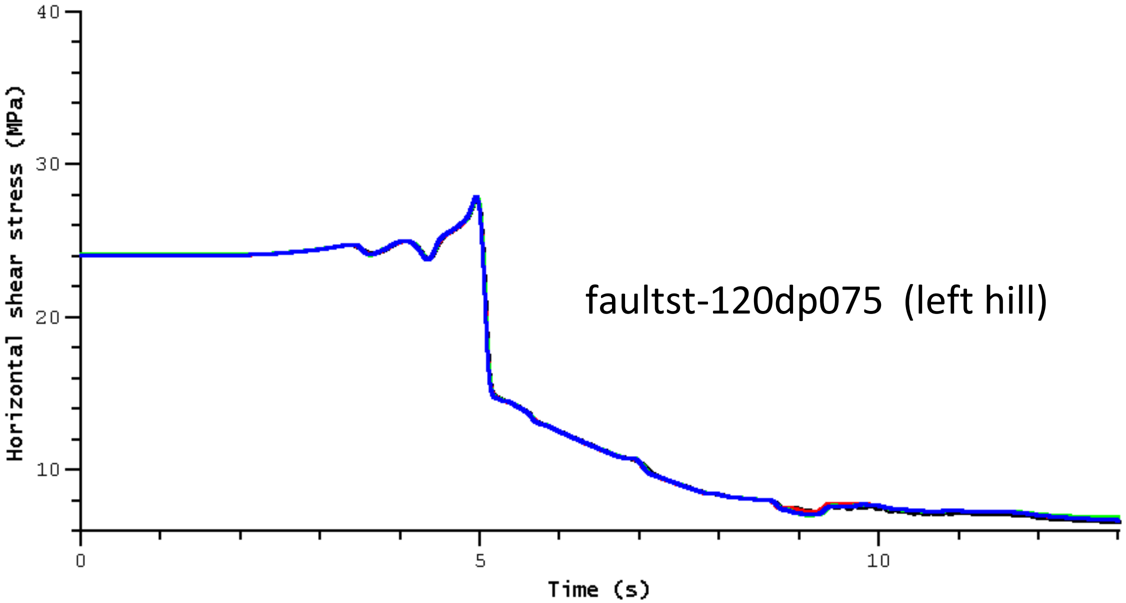
On the right hill, normal stress starts at 83 MPa and increases to 102 MPa.





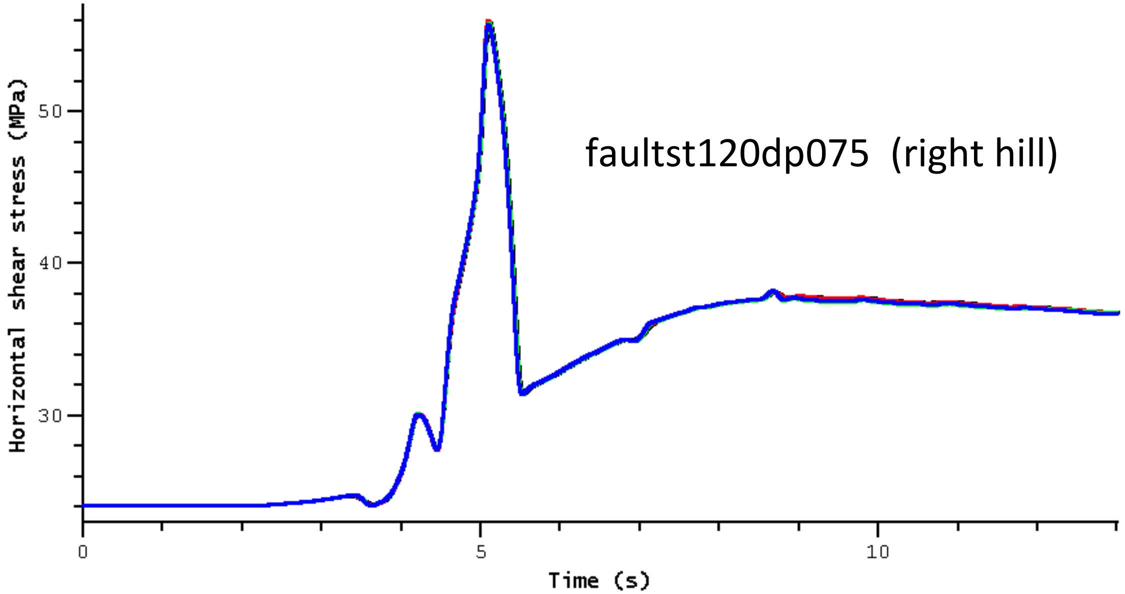
Filtered at 5 Hz.

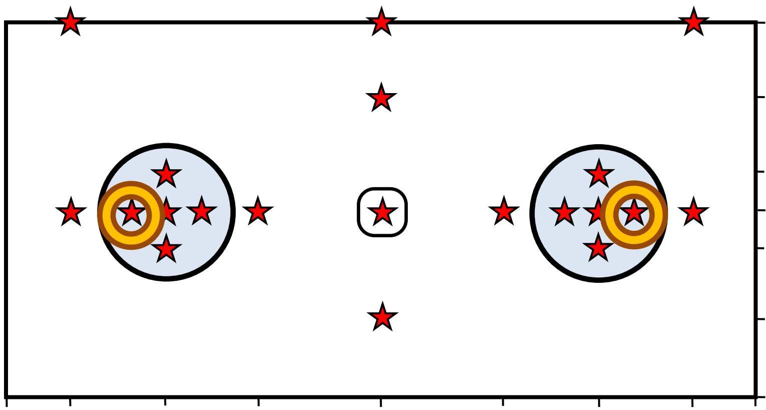
Stations on the Outer Slope of the Hills — Horizontal Shear Stress



On the left hill, horizontal shear stress starts at 24 MPa, peaks at 28 MPa, and ends up at 7 MPa.

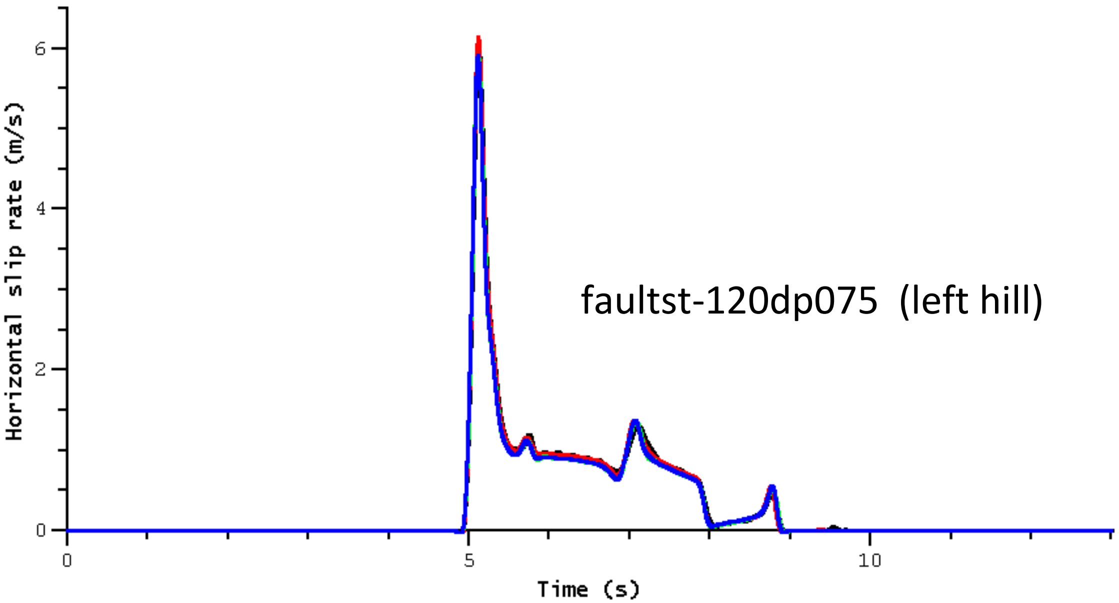
On the right hill, normal stress starts at 24 MPa, peaks at 55 MPa, and ends up at 36 MPa.





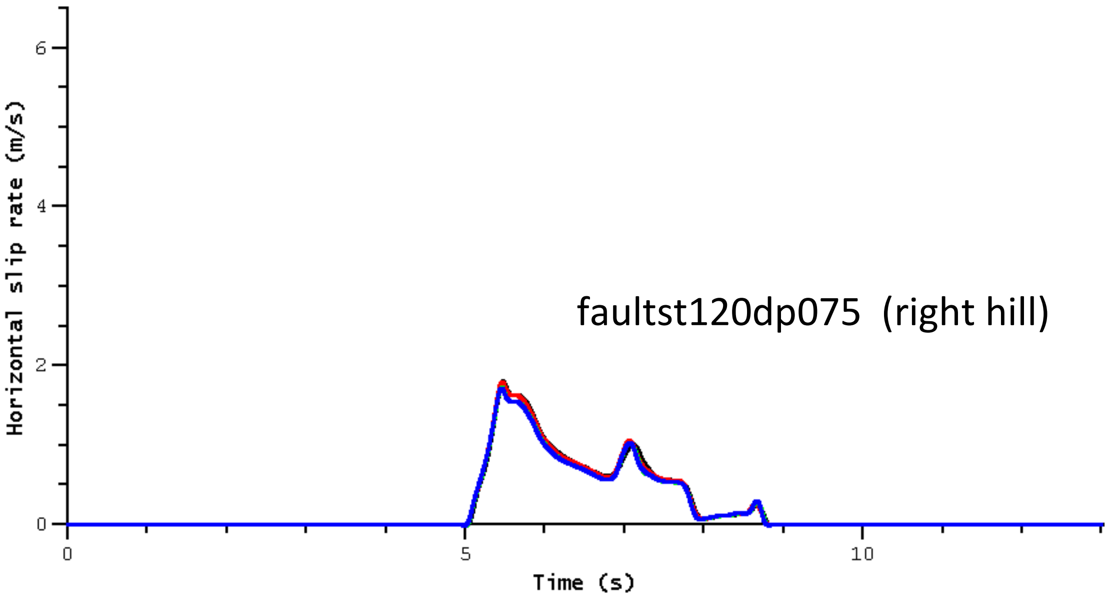
Filtered at 5 Hz.

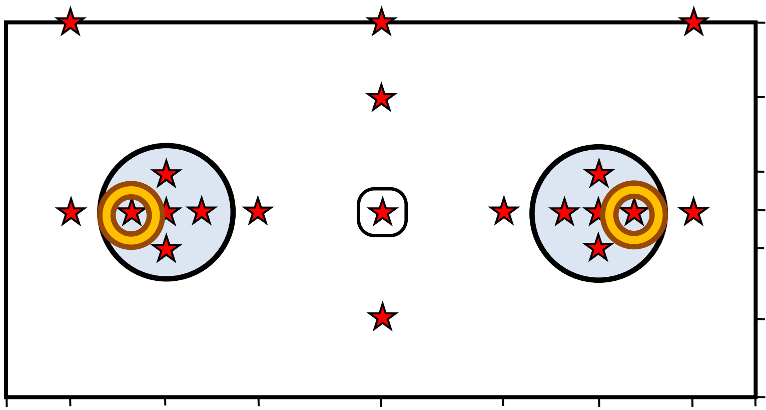
Stations on the Outer Slope of the Hills — Horizontal Slip Rate



On the left hill, the peak horizontal slip rate is 6 m/s.

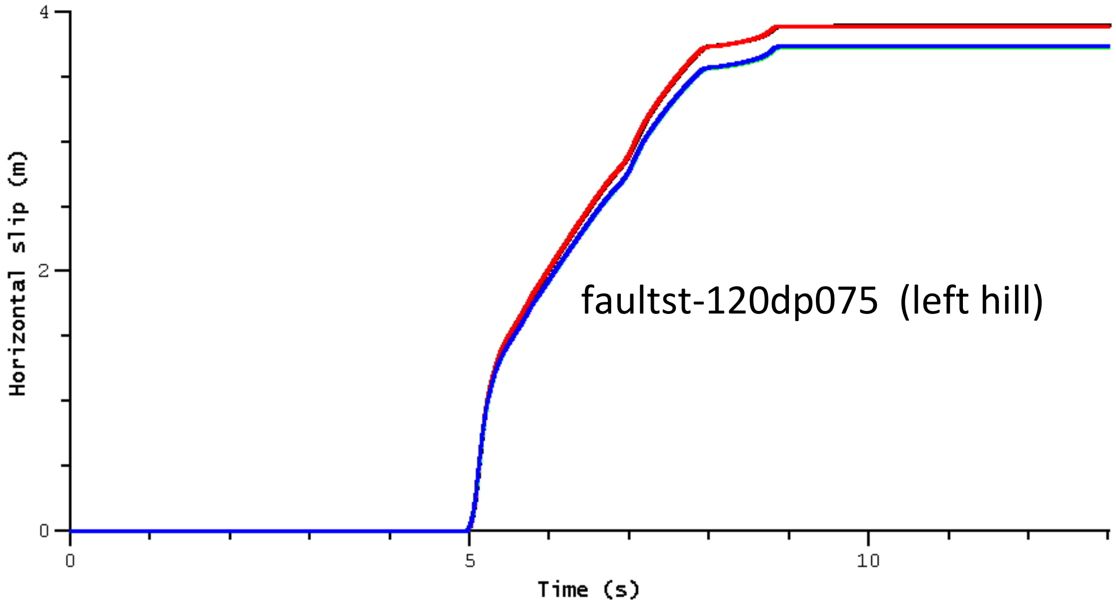
On the right hill, the peak horizontal slip rate is less than 2 m/s.





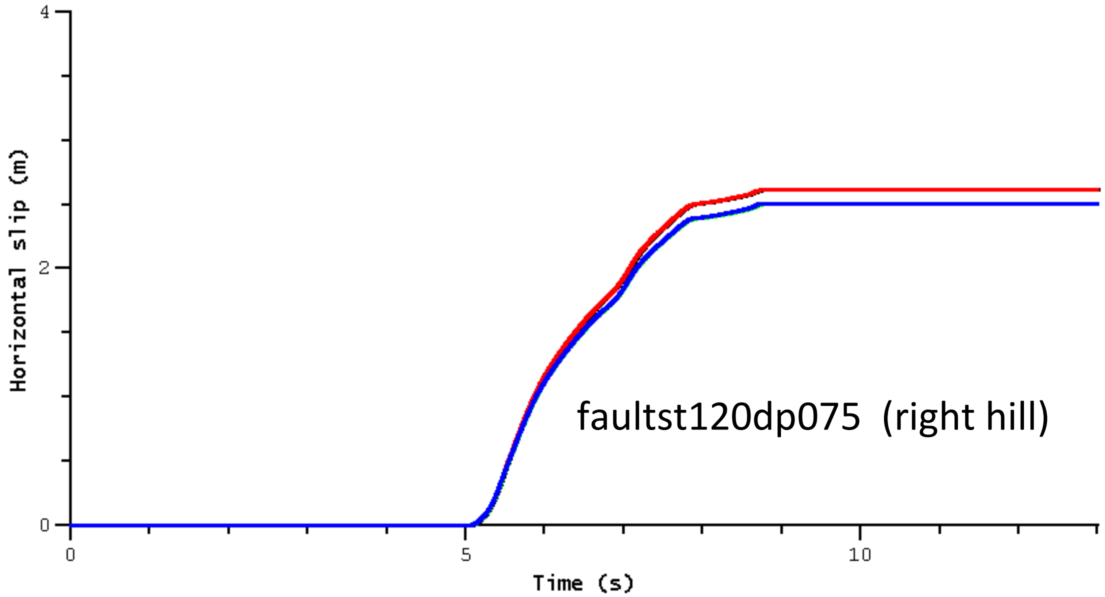
Filtered at 5 Hz.

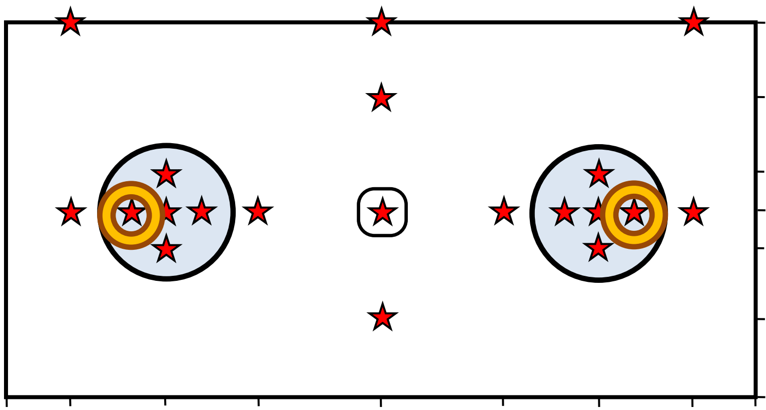
Stations on the Outer Slope of the Hills — Horizontal Slip



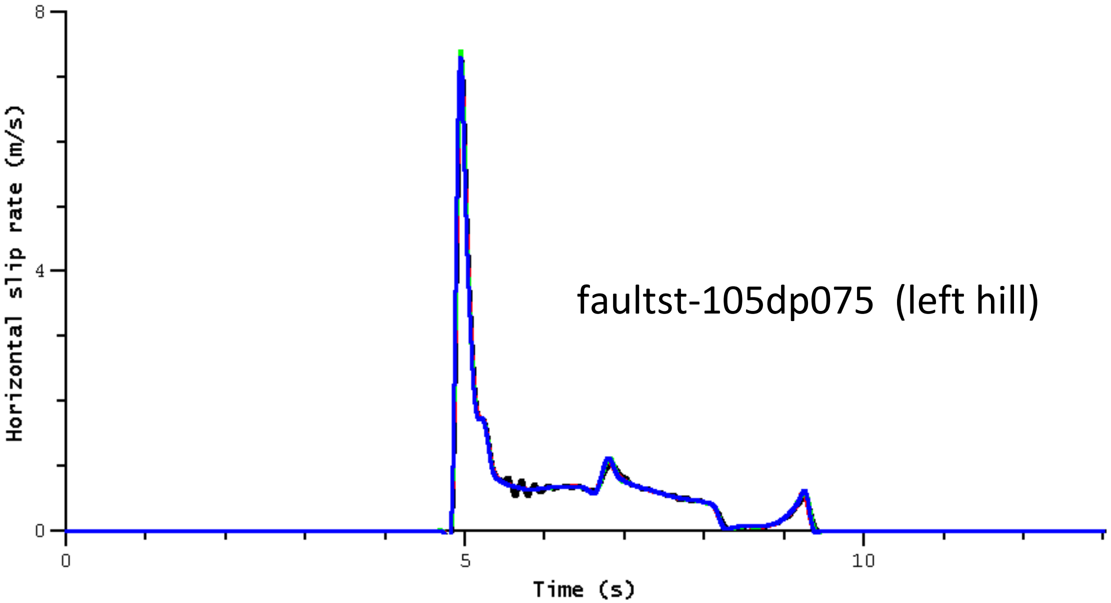
On the left hill, final slip is almost 4 m.

On the right hill, final slip is about 2.5 m.





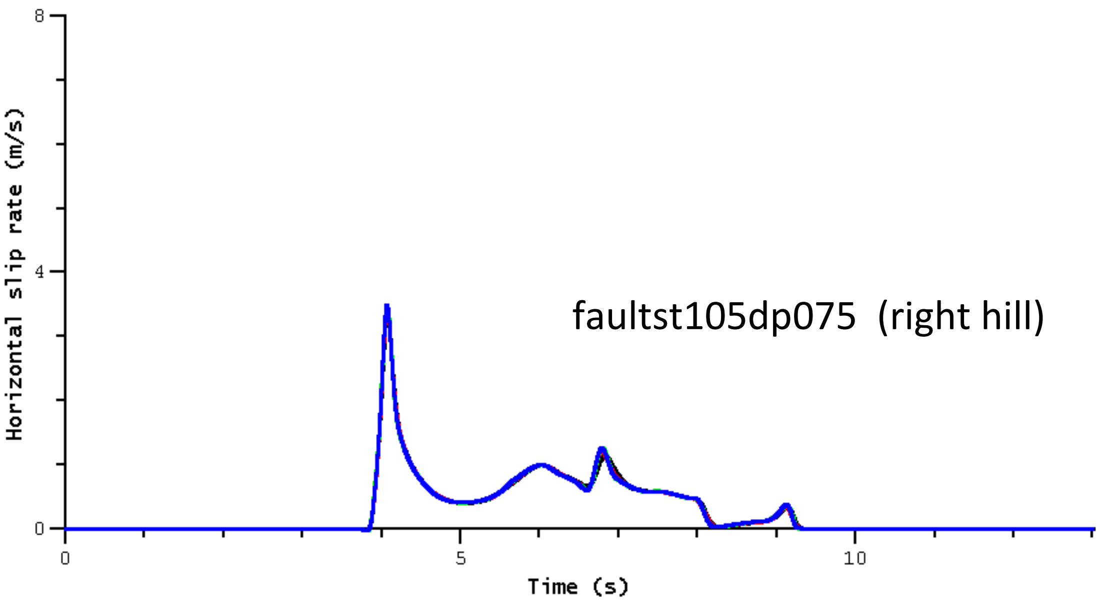
Stations on the Peak of the Hills — Horizontal Slip Rate

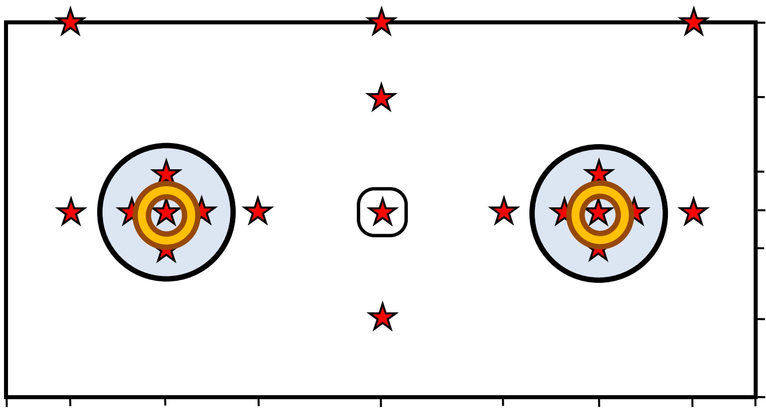


On the left hill, the peak horizontal slip rate is 7.5 m/s.

On the right hill, the peak horizontal slip rate 3.5 m/s.

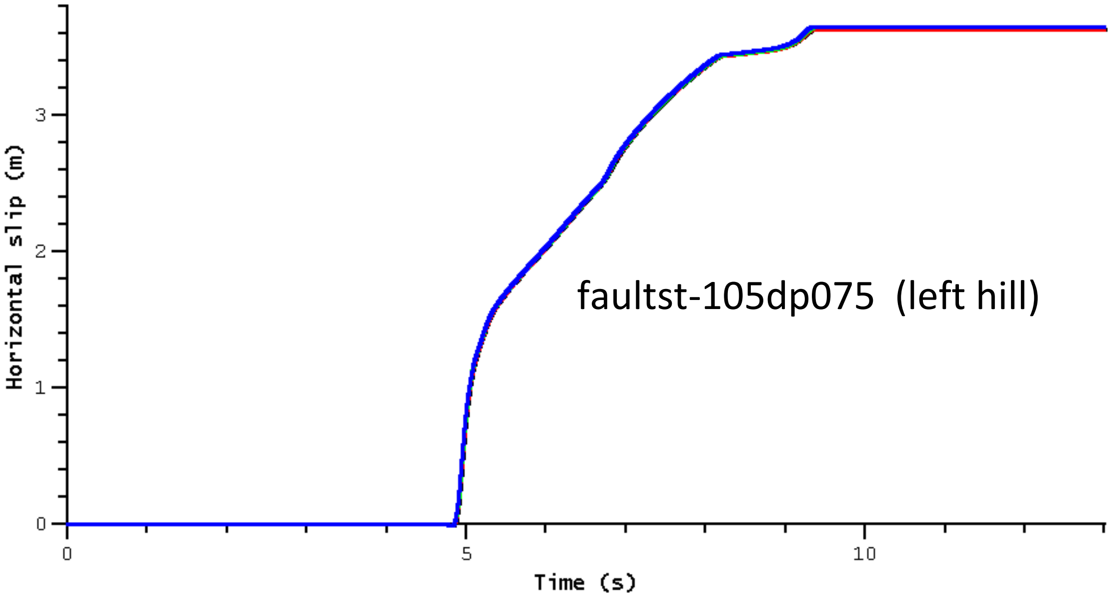
The left hill starts slipping about 1 second after the right hill slips.



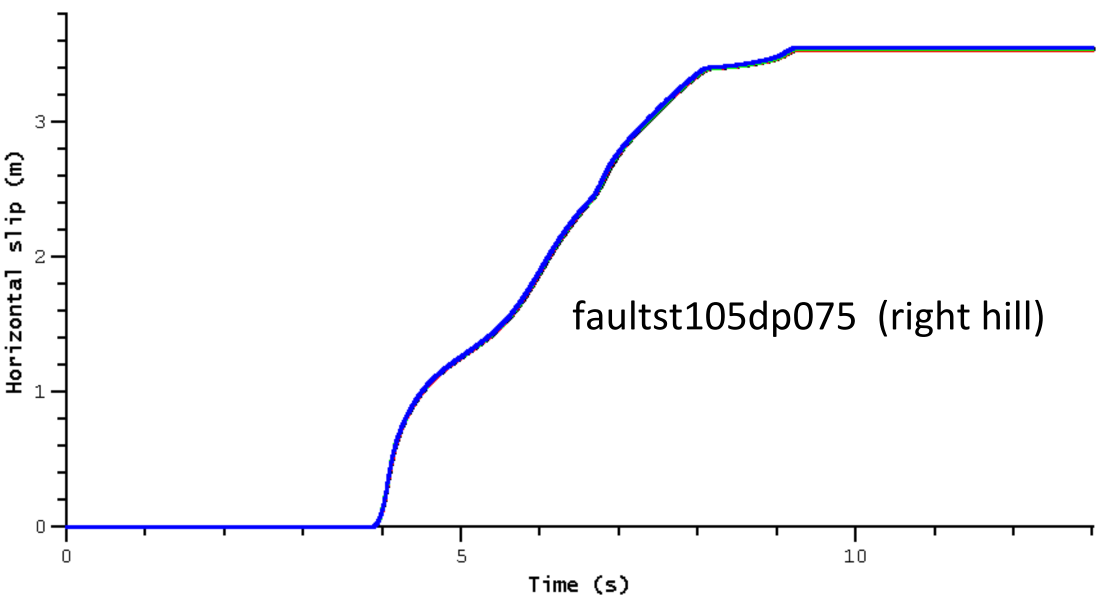


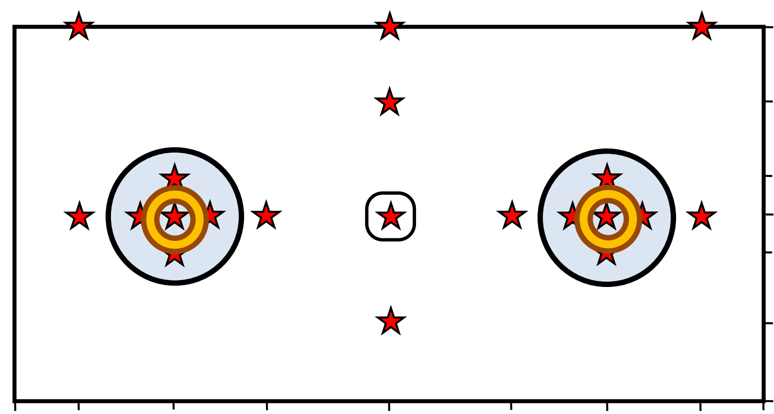
Filtered at 5 Hz.

Stations on the Peak of the Hills — Horizontal Slip

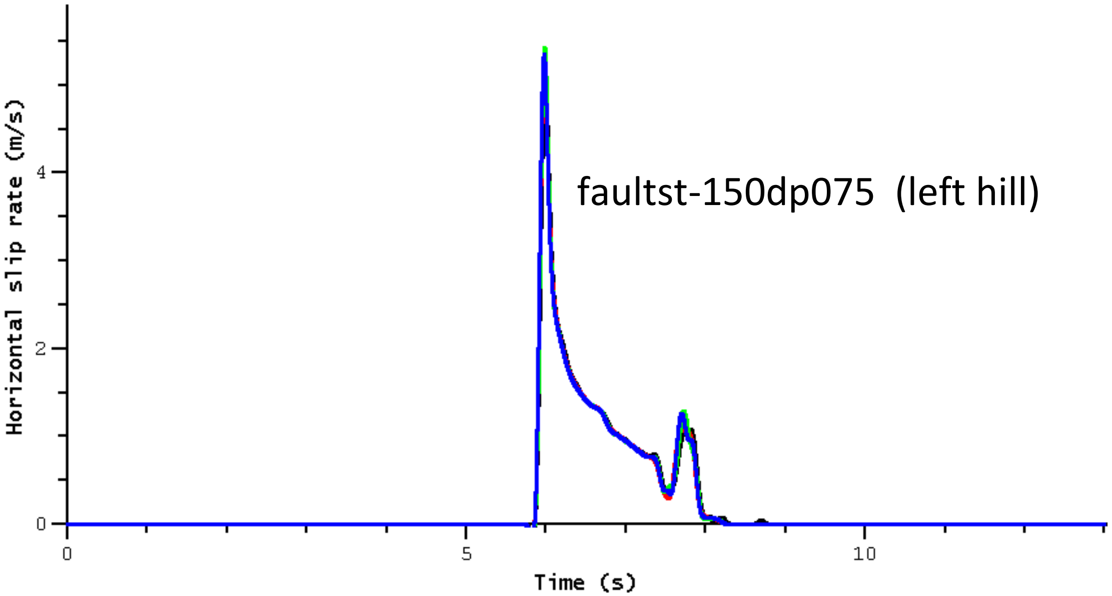


Final slip is about the same on both hills, 3.6 m.



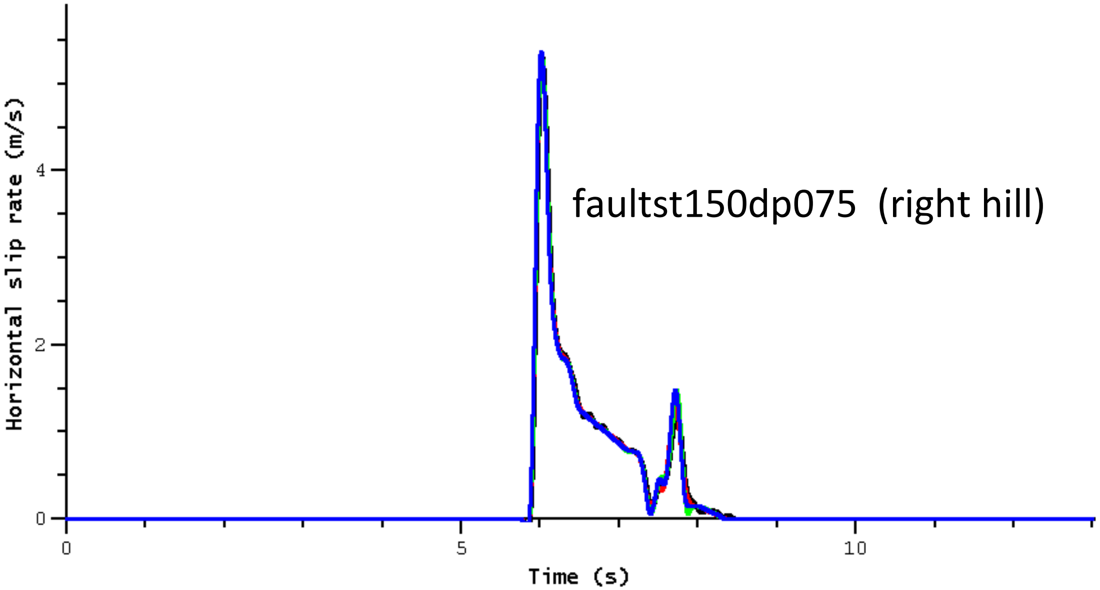


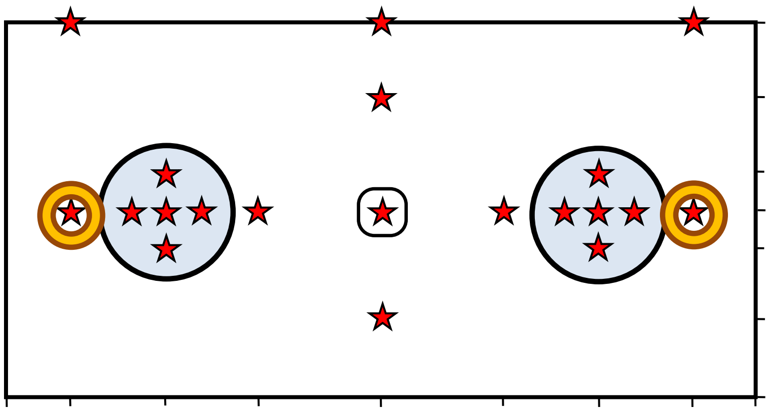
Stations Downstream From the Hills — Horizontal Slip Rate



Stations downstream from the two hills have almost the same slip history.

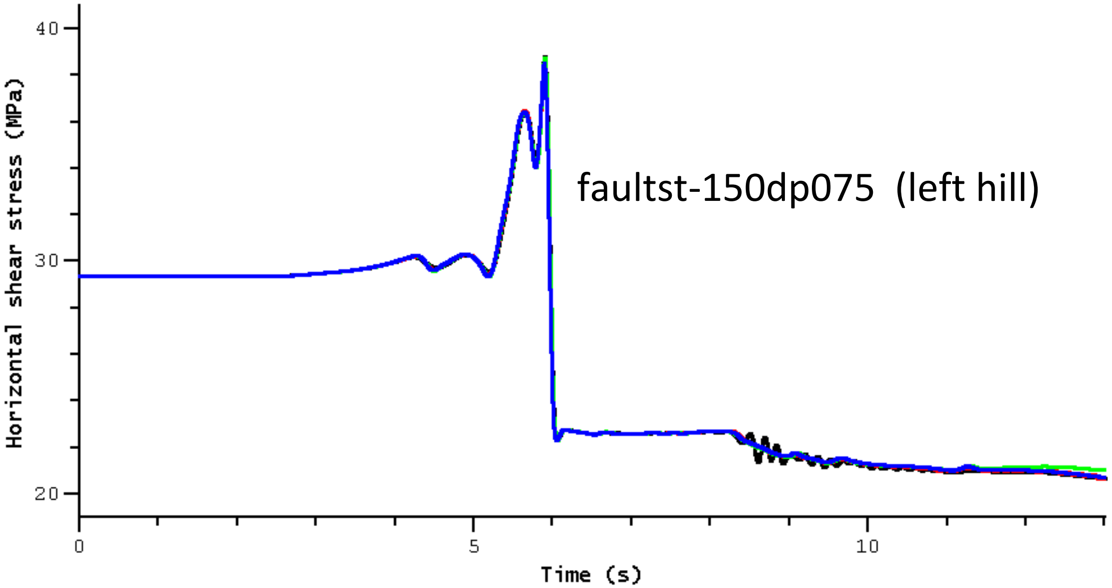
Peak slip rate is 5.3 m/s.





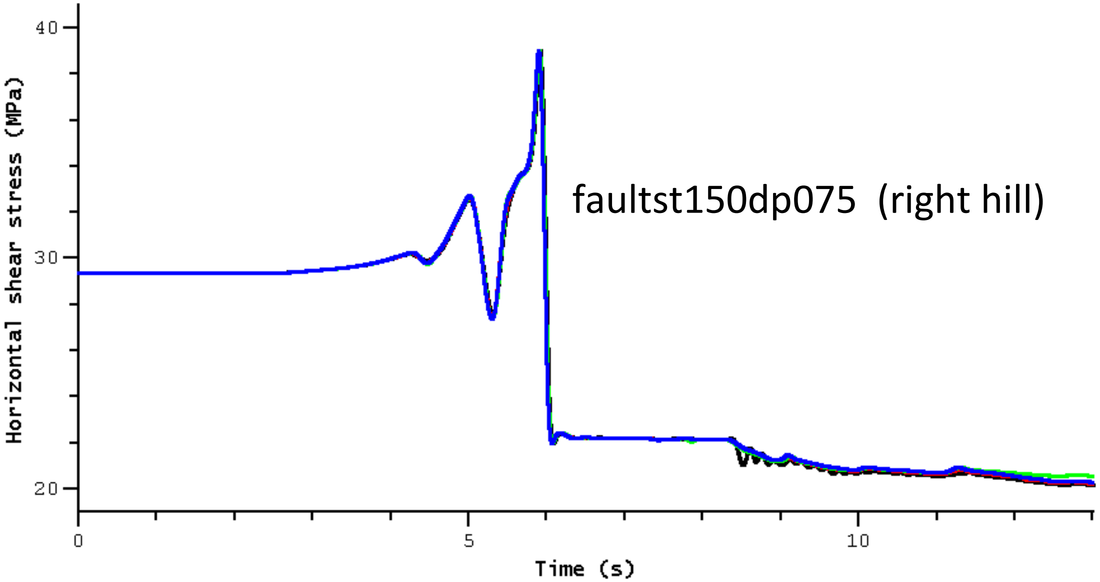
Filtered at 5 Hz.

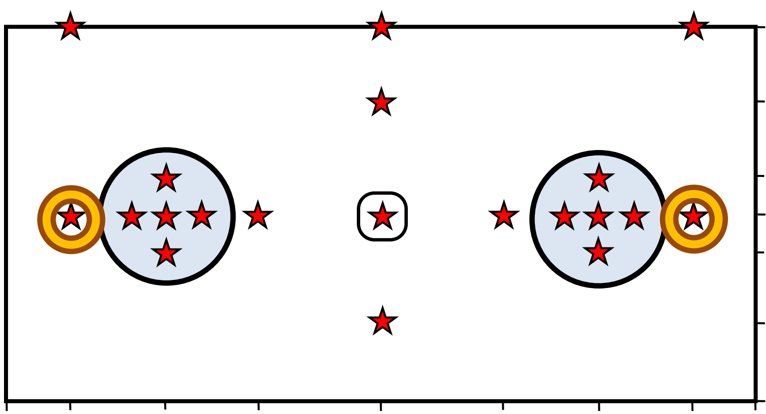
Stations Downstream From the Hills — Horizontal Shear Stress



Horizontal shear stress is different before slip begins, but almost the same during slip.

Once the rupture passes the hills, it quickly "forgets" that the hills were there.

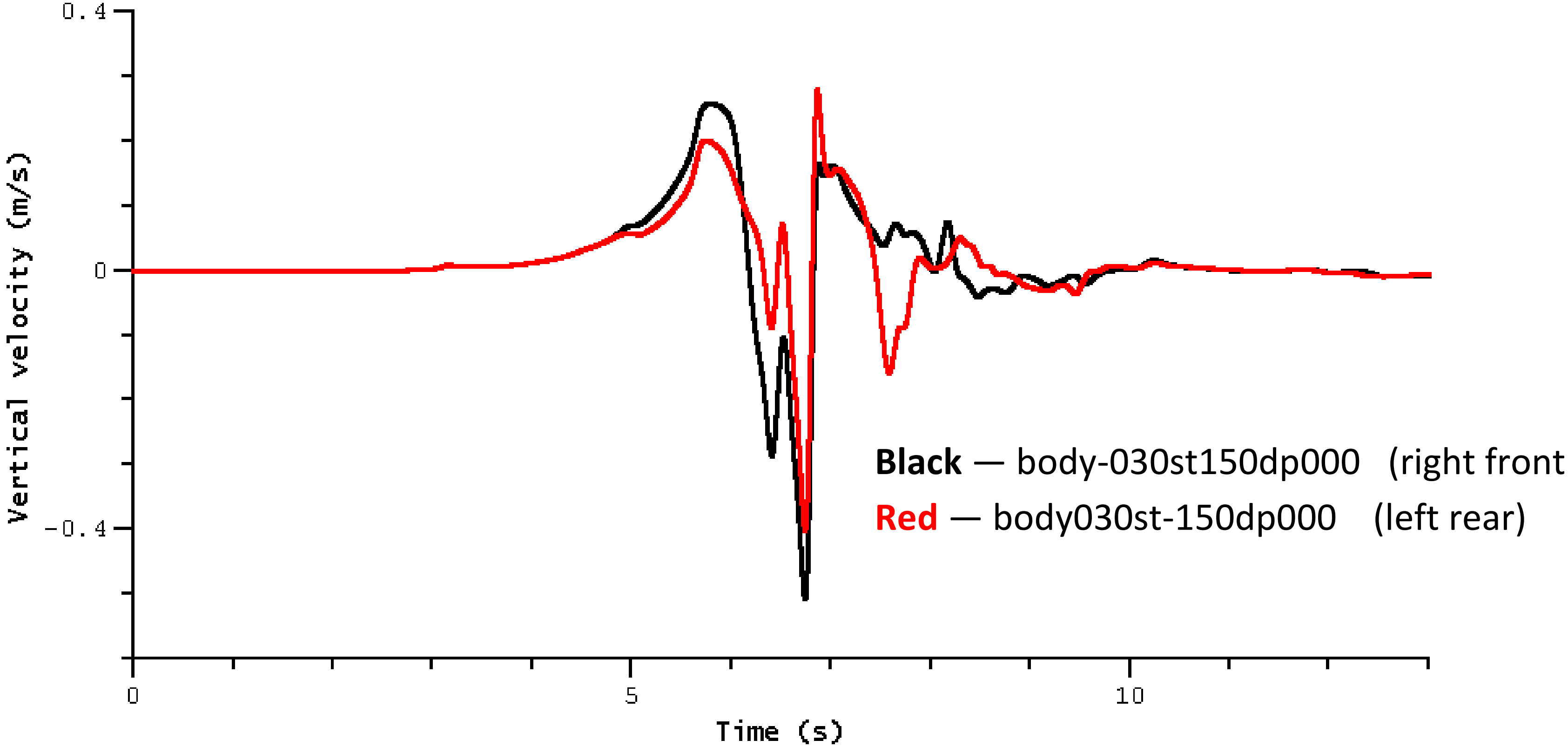


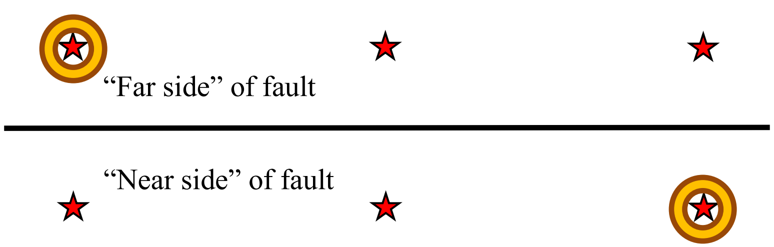


Filtered at 5 Hz.

TPV28 Results — Off-Fault Stations

body-030st150dp000 and body030st-150dp000 — Vertical Velocity



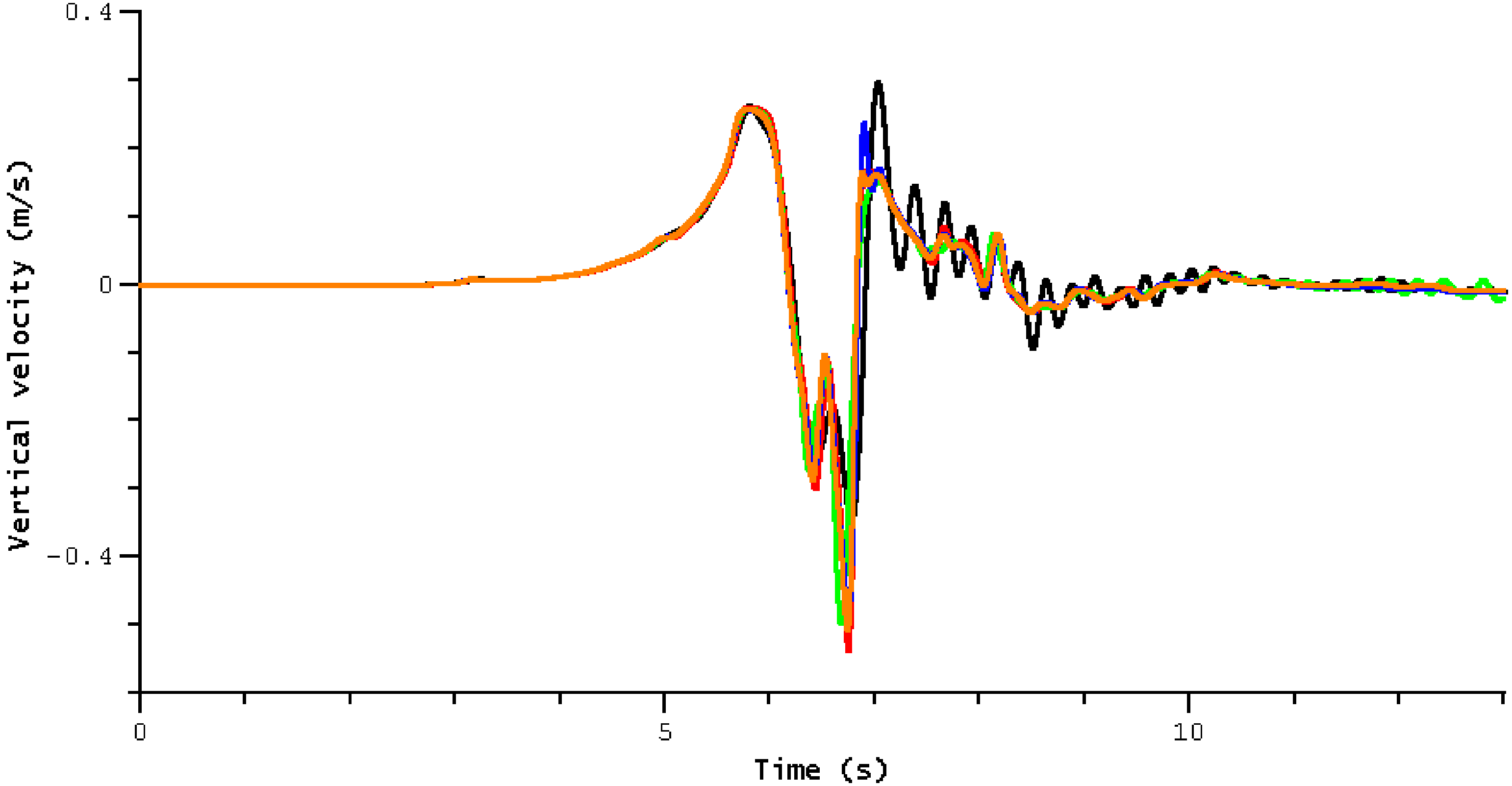


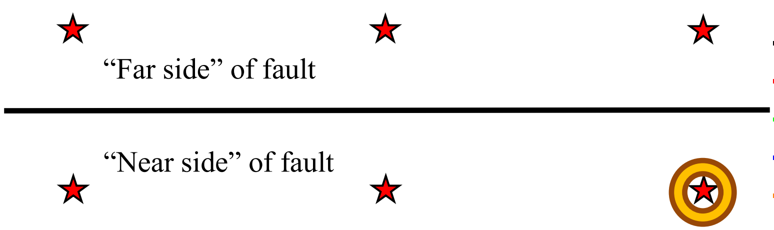
The difference between these curves is caused by seismic waves coming from the two hills.

If the hills pointed to opposite sides of the fault, or if the fault were planar, then these two stations would have the same vertical velocity.

Filtered at 5 Hz.

body-030st150dp000 — Vertical Velocity

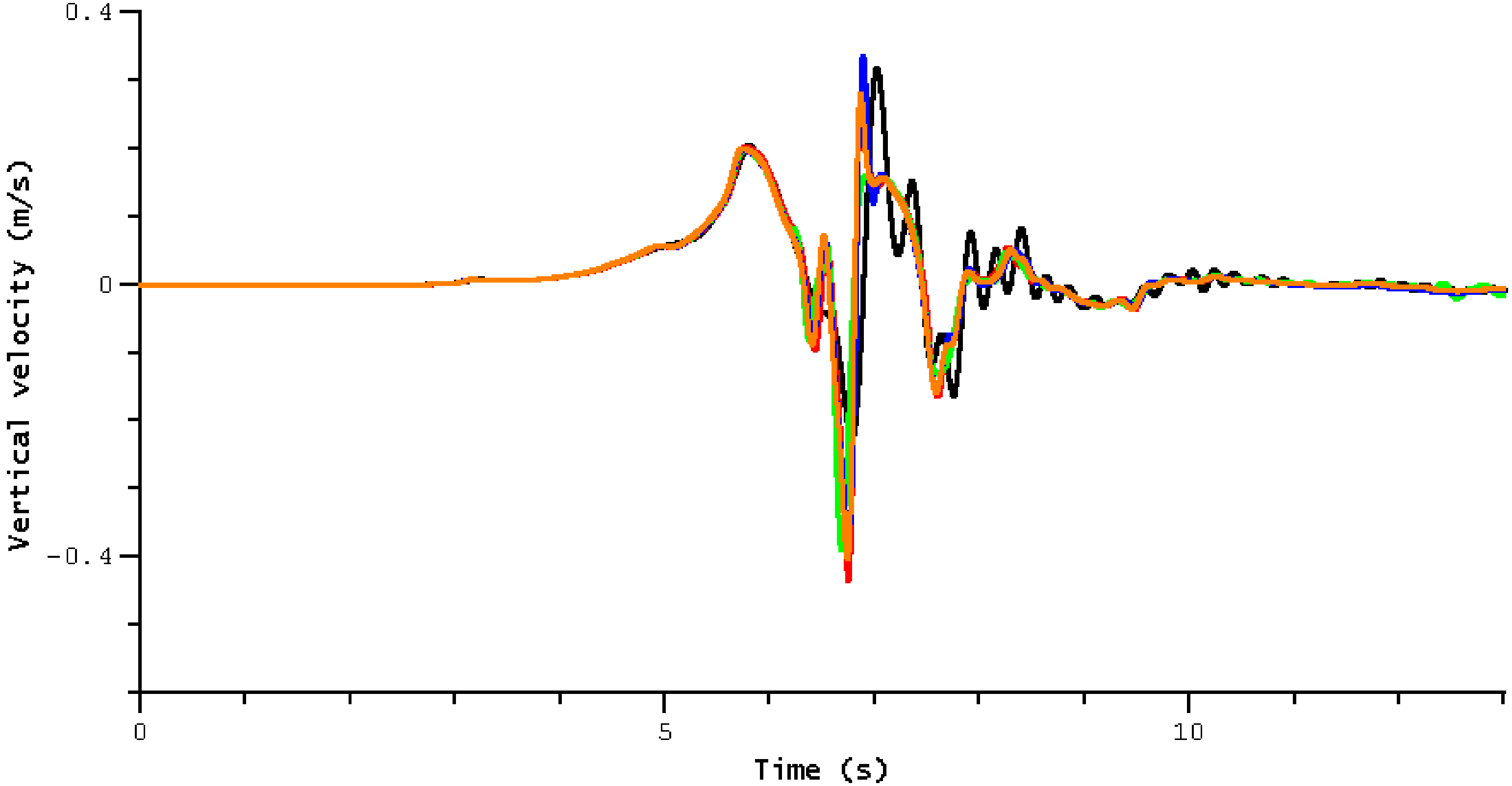


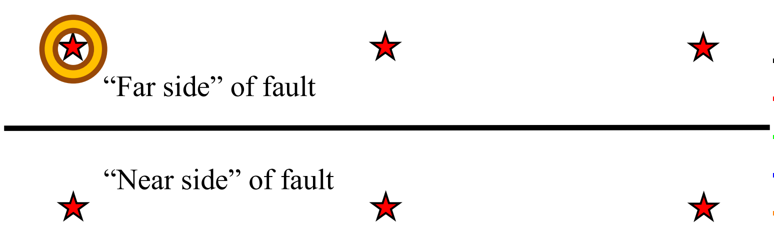


baral1.3 (Michael Barall - FaultMod - 25 m)
chen.2 (Xiaofei Chen - Finite Difference Method - CGFDM - 25 m)
luo.3 (Bin Luo - Finite Element - EQdyna - 25m)
ma.2 (Shuo Ma - Finite Element - MAFE (50 m))
shi.2 (Zheqiang Shi - Generalized Finite Difference - SORD - 25 m)

Filtered at 5 Hz.

body030st-150dp000 — Vertical Velocity





Filtered at 5 Hz.

Conclusions

Conclusions

TPV28 is a non-planar vertical strike-slip fault with two hills.

- Our first benchmark with a non-planar fault.
- Our first benchmark with initial stress that is not at a constant rake angle.
- Uses material properties and friction equivalent to TPV5.
- Uses overstress nucleation, with tapered shear stress for smoothness.
- Demonstrates both clamping and unclamping.

All participating codes are in excellent agreement, when using resolutions of 50 m or 25 m.