TPV35 — Parkfield 2004 M6 Earthquake

Michael Barall
Invisible Software, Inc.

SCEC Rupture Dynamics Code Validation Workshop

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Validation versus Verification

The difference between validation and verification can be summarized as:

- Verification — Are we building the software right?
- Validation — Are we building the right software?

For computer models and simulations, we can elaborate:

- Verification — Does the software correctly implement the developer's conceptual model?
- Validation — Is the model a sufficiently accurate representation of reality so that it can be relied on for its intended application?

You can't validate software in isolation. You must validate software for some particular application, and possibly as part of some larger workflow.

Verification of Dynamic Rupture Codes

In our group we have verified dynamic rupture codes with a three-step process:

1. Publish a benchmark which is a highly detailed conceptual model of an earthquake. It specifies fault geometry, friction, stress, velocity model, etc.

2. Each modeler uses his or her own code to simulate the resulting earthquake.

3. The results from all the modelers are compared with each other. If the results agree, then we consider the codes to be verified (at least for that particular benchmark).

Validation à la TPV35

TPV35, like the SCEC BBP, tries to validate by reproducing the ground motions of historical earthquakes.

1. Pick some historical earthquake.

    - Problem: There are very few large earthquakes that are sufficiently simple and sufficiently well-recorded so that you can hope to reproduce them.

2. Select model parameters.

    - Some parameters may be chosen *a priori*, for example, a pre-existing velocity model.

    - Other parameters may be chosen by inversion (adjust them until you're happy).

3. If the simulation results "match" the recorded ground motions, then you consider the code to be validated.

    - What counts as a "match" ought to depend on the intended application. The application should determine *what part* of the ground motion to look at (entire waveform? peak? spectrum? duration?), and *how closely* it must agree with reality to be useful.

BUT: This method of validation only works if the intended application is to reproduce historical earthquakes.

Validation for Other Applications

I suspect that most users are interested in determining the likely or possible characteristics of future earthquakes, rather than reproducing past earthquakes.

Possible applications:

- Determine the probability distribution of some ground motion parameter (*e.g.*, peak intensity, spectral content, duration).

- Generate a suite of representative synthetic seismograms.

- Determine the probability of some event (*e.g.*, probability of exceedance, probability of a fault-to-fault jump).

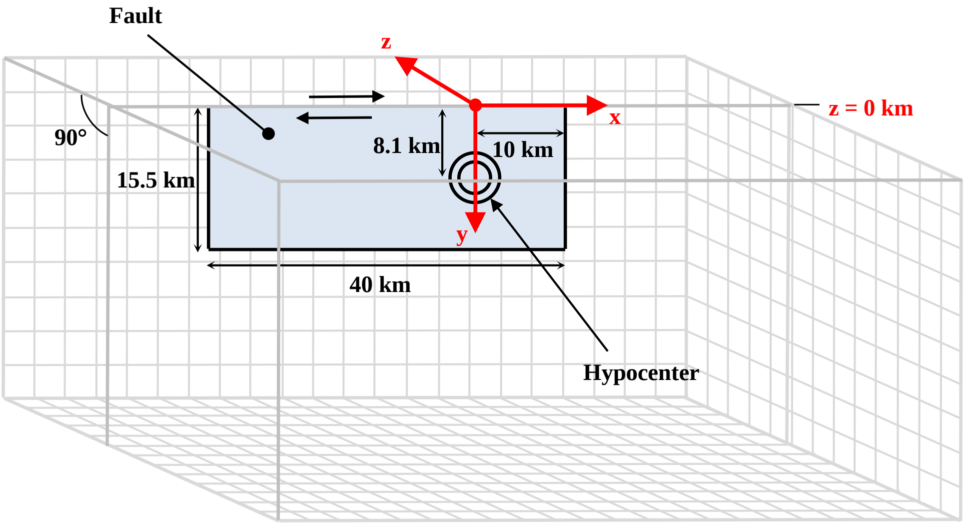
For these kinds of applications, the dynamic rupture code is used to generate a suite of *realizations* or possible earthquakes. Each simulation has model parameters and initial conditions that are varied in some prescribed way (*e.g.*, randomly generated, or from multi-cycle simulations).

So, the dynamic rupture code is part of a larger workflow. To validate dynamic rupture for use in such applications, it is necessary to validate *the entire workflow*, and not just the dynamic rupture code in isolation.

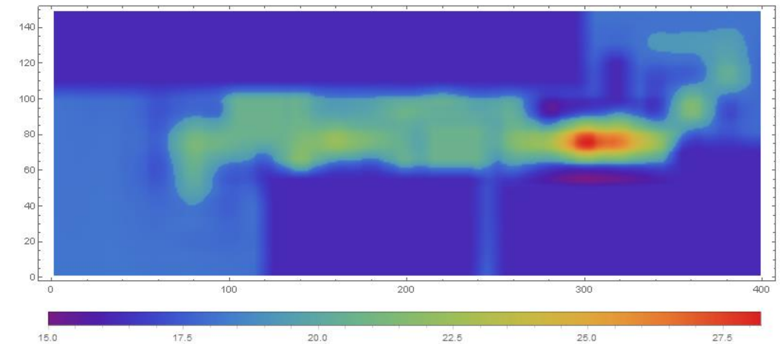
TPV35 Design

TPV35 Parameters

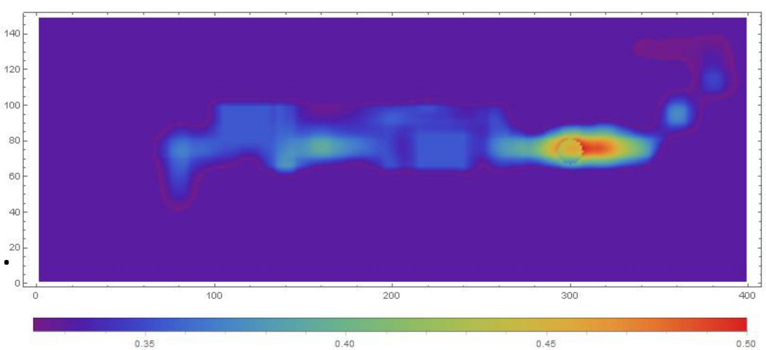
Fault Geometry



Initial Shear Stress



Static Coefficient of Friction



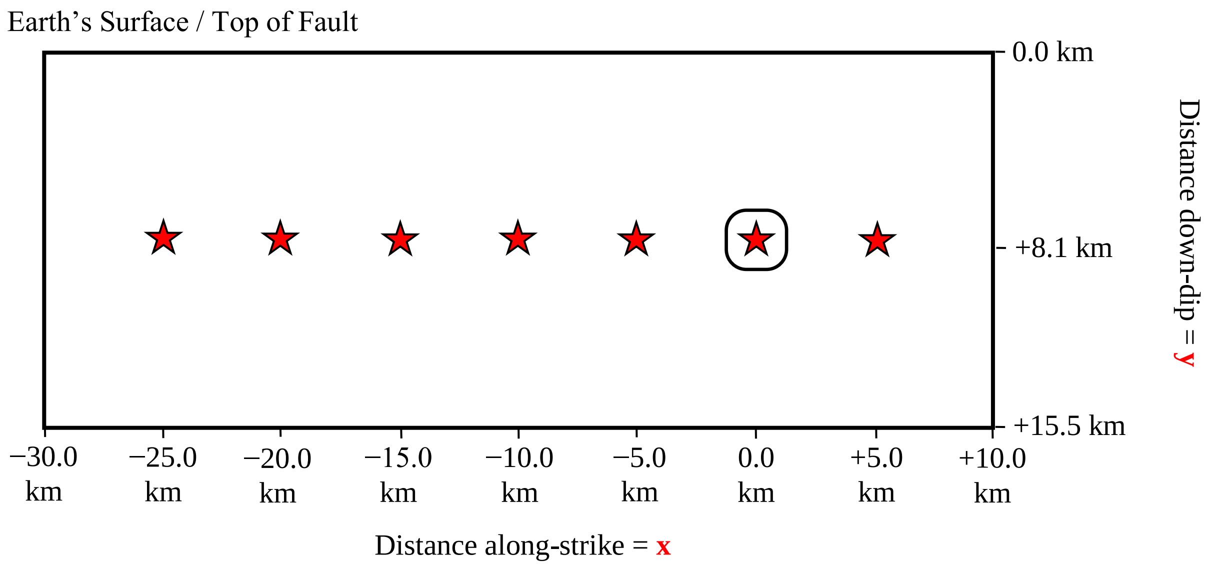
Vertical, planar, strike-slip fault, 40 km by 15.5 km.

Hypocenter depth 8.1 km, located 10 km from end of fault.

Bi-material 1D velocity model, minimum V_S = 1100 m/s.

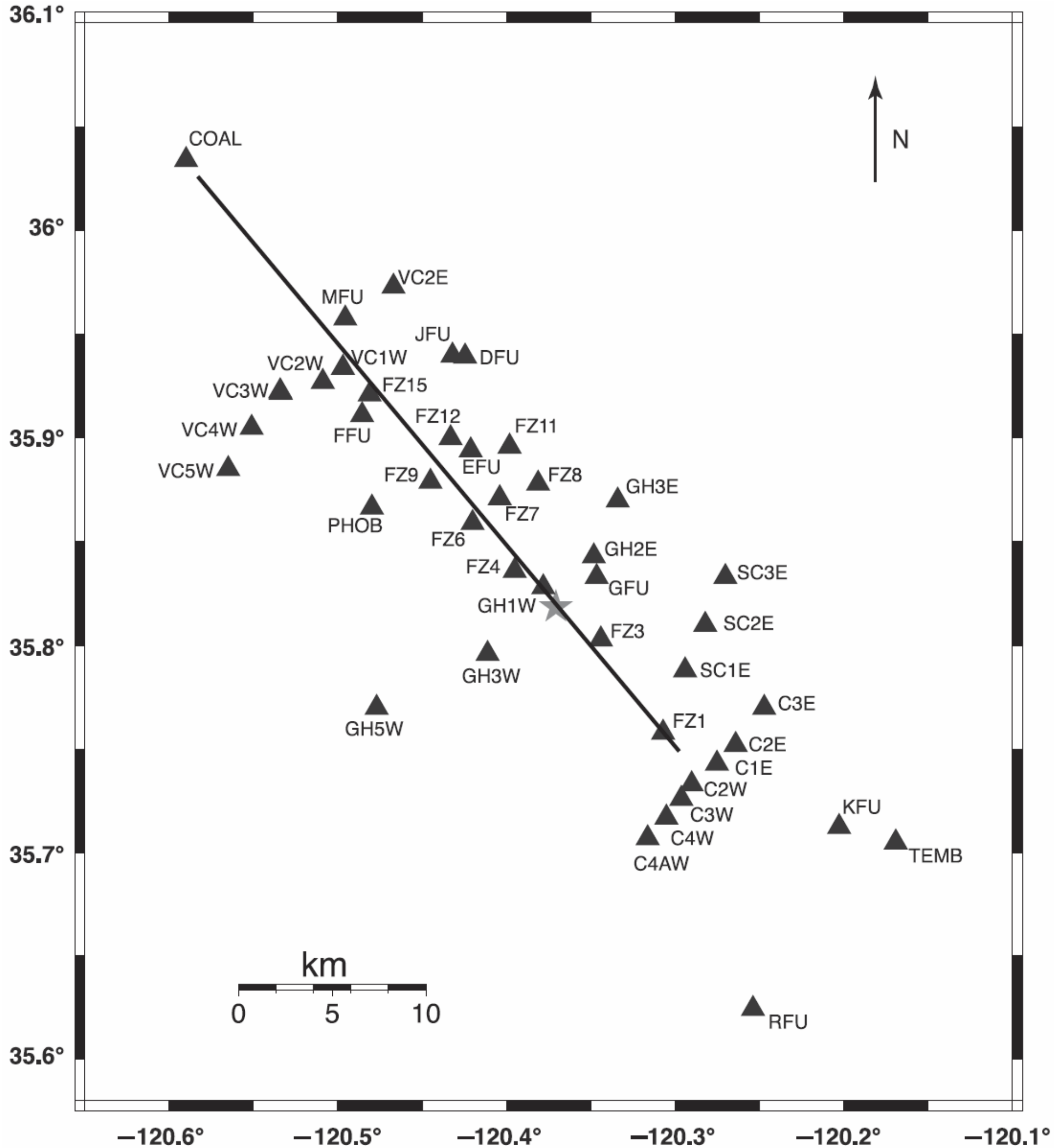
Nucleation by overstress in a circle with radius 0.5 km.

On-Fault Stations



Modelers are asked to submit slip, slip rate, and stress as a function of time, for 7 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.



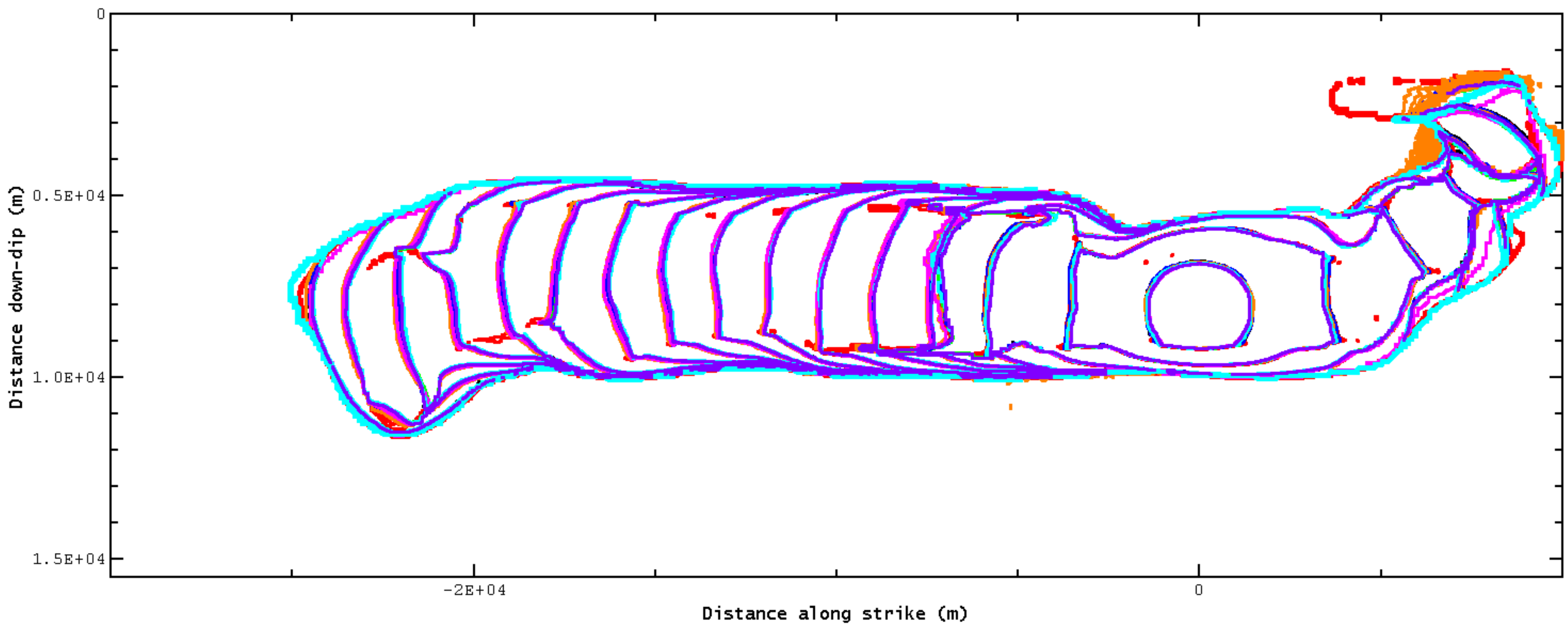
Off-Fault Stations, at the Earth's surface

Modelers are asked to submit displacement and velocity as a function of time, for 43 stations on the earth's surface.

The stations match the locations of actual seismic recordings of the 2004 Parkfield earthquake.

TPV35 Rupture Contours

TPV35 Rupture Contours — Results from 8 of 9 Modelers

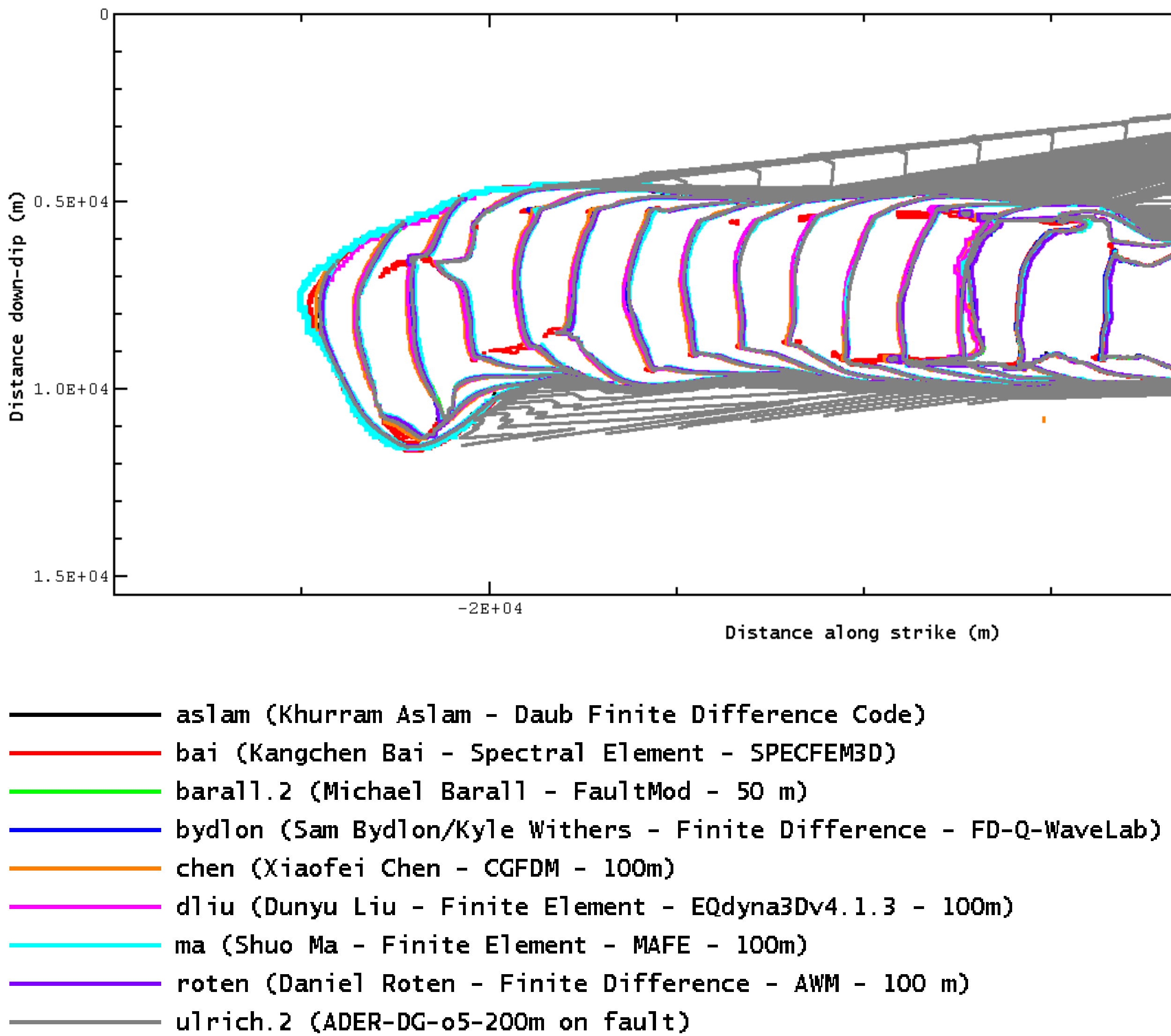


- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai (Kangchen Bai - Spectral Element - SPECFEM3D)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- roten (Daniel Roten - Finite Difference - AWM - 100 m)

Contours show excellent agreement!

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

TPV35 Rupture Contours — Results from 9 Modelers



The ulrich code propagates very slowly into the concave areas of the rupture, filling them in, so the final rupture is convex.

TPV35 Rupture Contours — Metrics (RMS Difference in Rupture Time)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) aslam		45.4	30.3	5.8	24.5	25.1	36.4	30.1
(2) bai	45.4		54.6	45.3	49.0	48.3	50.6	54.3
(3) barall.2	30.3	54.6		28.1	42.9	33.9	17.1	23.0
(4) bydlon	5.8	45.3	28.1		25.1	24.8	34.3	28.3
(5) chen	24.5	49.0	42.9	25.1		19.1	51.0	40.4
(6) dliu	25.1	48.3	33.9	24.8	19.1		41.5	30.0
(7) ma	36.4	50.6	17.1	34.3	51.0	41.5		21.9
(8) roten	30.1	54.3	23.0	28.3	40.4	30.0	21.9	

The maximum value is 54.6 milliseconds, which is a 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.

TPV35 Rupture Contours — Process Zone Width (in Meters)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
faultst-050dp081	2997	3007	3011	3008	2923	3008	2989	3056	3025
faultst-100dp081	1115	1070	1113	1114	1172	1313	1148	1199	1055
faultst-150dp081	723	714	730	720	752	770	737	770	705
faultst-200dp081	765	740	791	767	769	859	743	821	737
faultst-250dp081	---	---	---	---	---	---	---	---	---
faultst000dp081	---	---	---	---	---	---	---	---	---
faultst050dp081	1727	1472	1705	1688	1996	1892	1737	1833	1674

On-Fault Stations	
faultst-050dp081	strike -5.0 km, dip 8.1 km
faultst-100dp081	strike -10.0 km, dip 8.1 km
faultst-150dp081	strike -15.0 km, dip 8.1 km
faultst-200dp081	strike -20.0 km, dip 8.1 km
faultst-250dp081	strike -25.0 km, dip 8.1 km
faultst000dp081	strike 0.0 km, dip 8.1 km
faultst050dp081	strike 5.0 km, dip 8.1 km

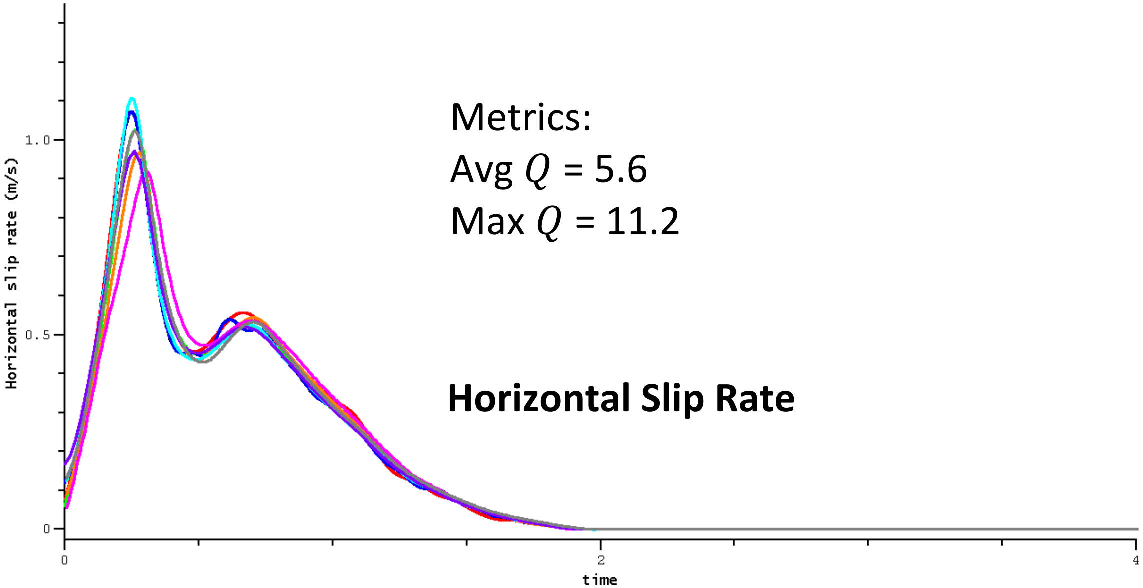
Users	
(1) aslam	Khurram Aslam - Daub Finite Difference Code
(2) bai	Kangchen Bai - Spectral Element - SPECFEM3D
(3) barall.2	Michael Barall - FaultMod - 50 m
(4) bydlon	Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab
(5) chen	Xiaofei Chen - CGFDM - 100m
(6) dliu	Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m
(7) ma	Shuo Ma - Finite Element - MAFE - 100m
(8) roten	Daniel Roten - Finite Difference - AWM - 100 m
(9) ulrich.2	ADER-DG-o5-200m on fault

Horizontal color bands show good agreement between codes.

TPV35 Results — On-Fault Stations

faultst000dp081 (Hypocenter)

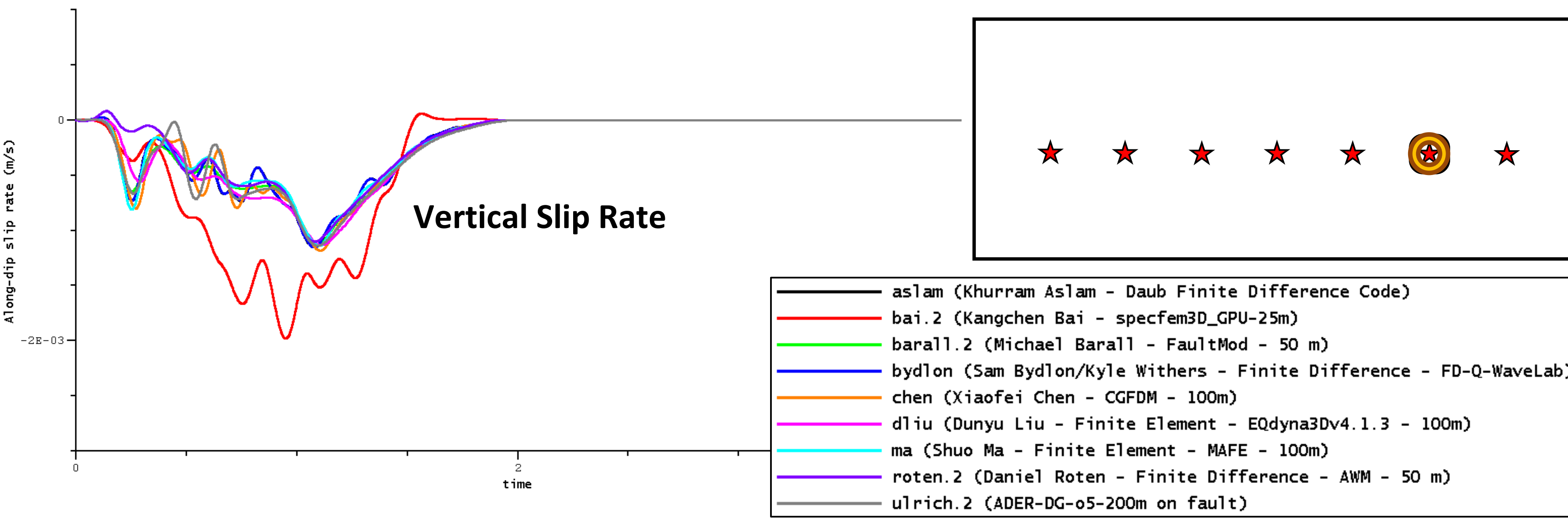
Metrics:
Avg Q = 5.6
Max Q = 11.2



There is good agreement among the 9 codes.

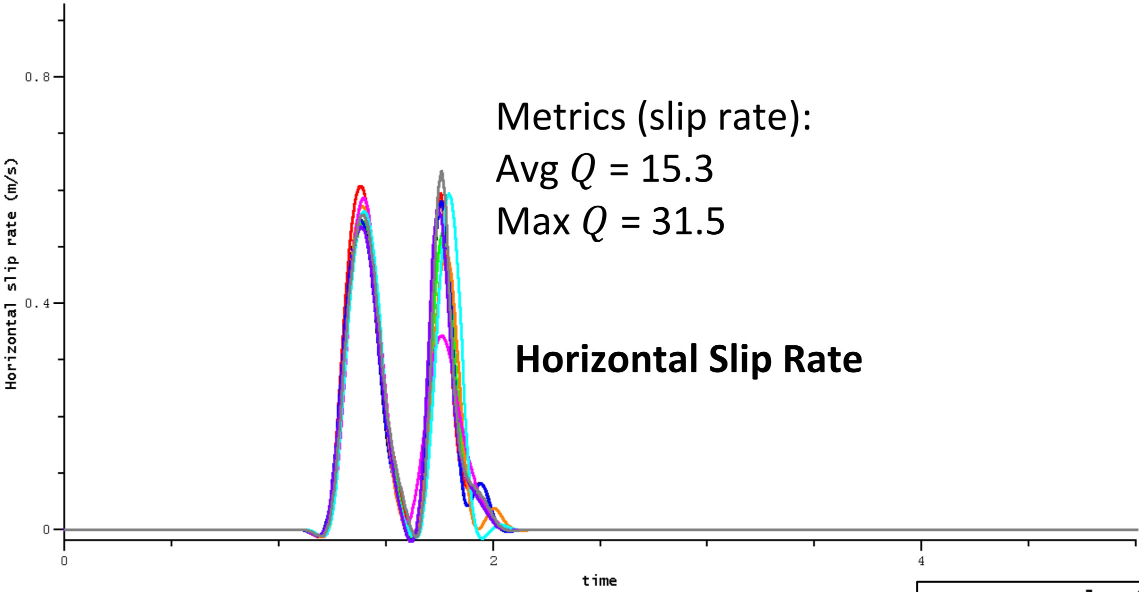
There is some variation in the magnitude and timing of peak slip rate.

Vertical slip rate agrees very well among most codes despite being 3 orders of magnitude smaller than the horizontal slip rate.



Filtered at 5 Hz.

faultst050dp081 (5 km Right of Hypocenter)

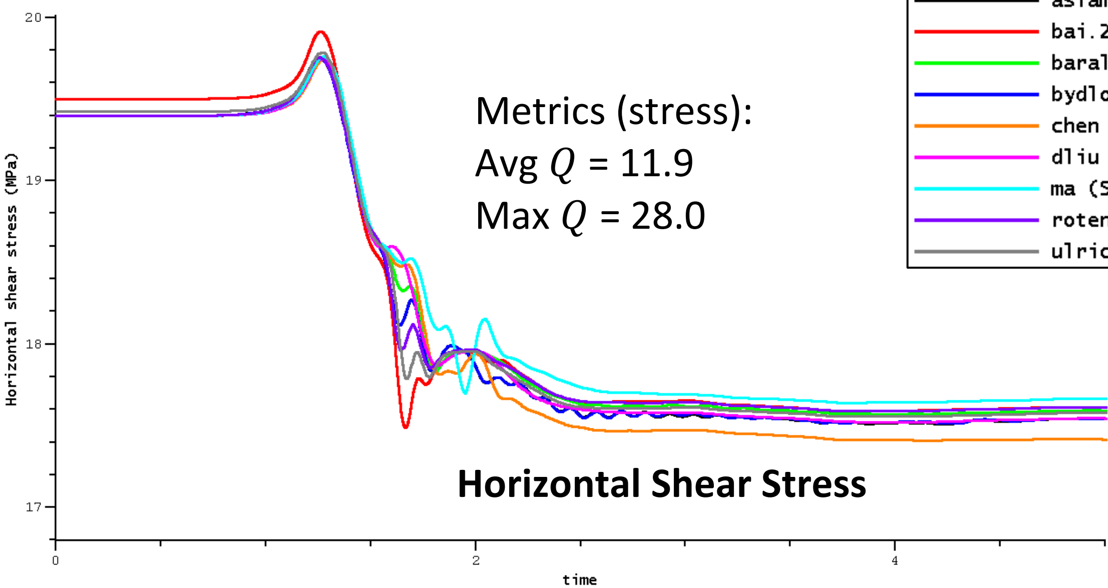


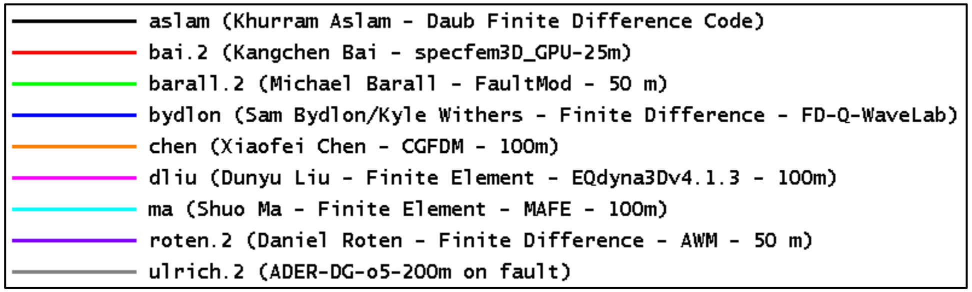
Metrics (slip rate):
Avg Q = 15.3
Max Q = 31.5

Horizontal Slip Rate

The slip rate has a double peak. One code has a lower second peak than the others.

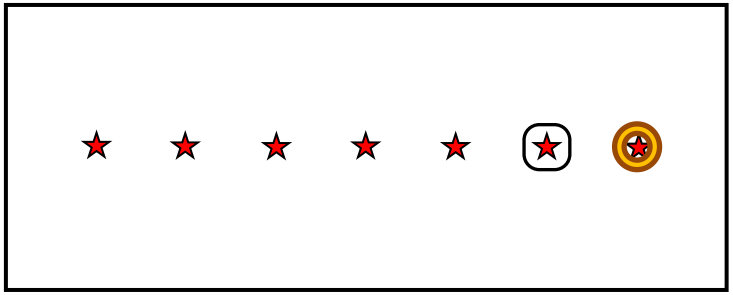
For horizontal shear stress, one code starts out higher than the others. The codes separate somewhat later in the simulation.





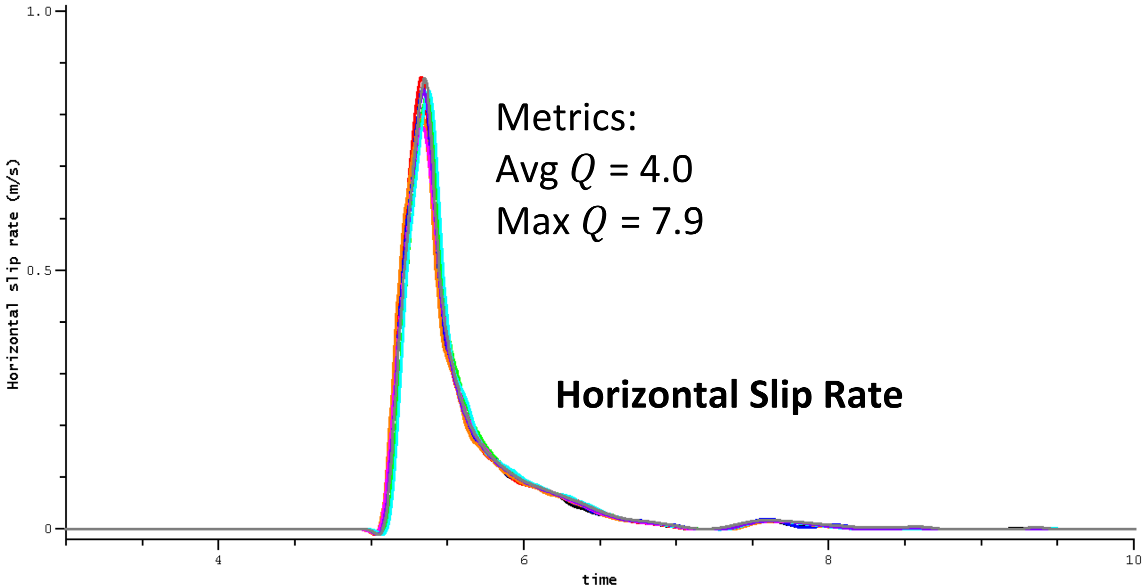
Metrics (stress):
Avg Q = 11.9
Max Q = 28.0

Horizontal Shear Stress



Filtered at 5 Hz.

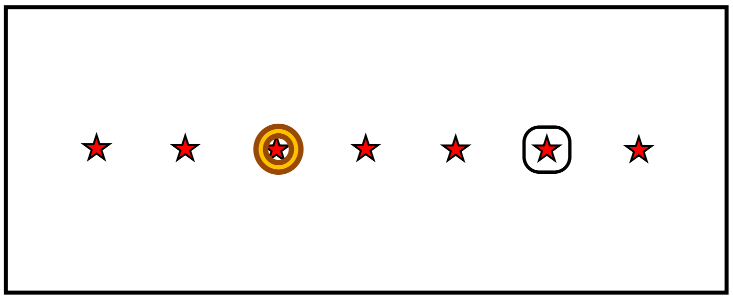
faultst-150dp081 (15 km Left of Hypocenter)

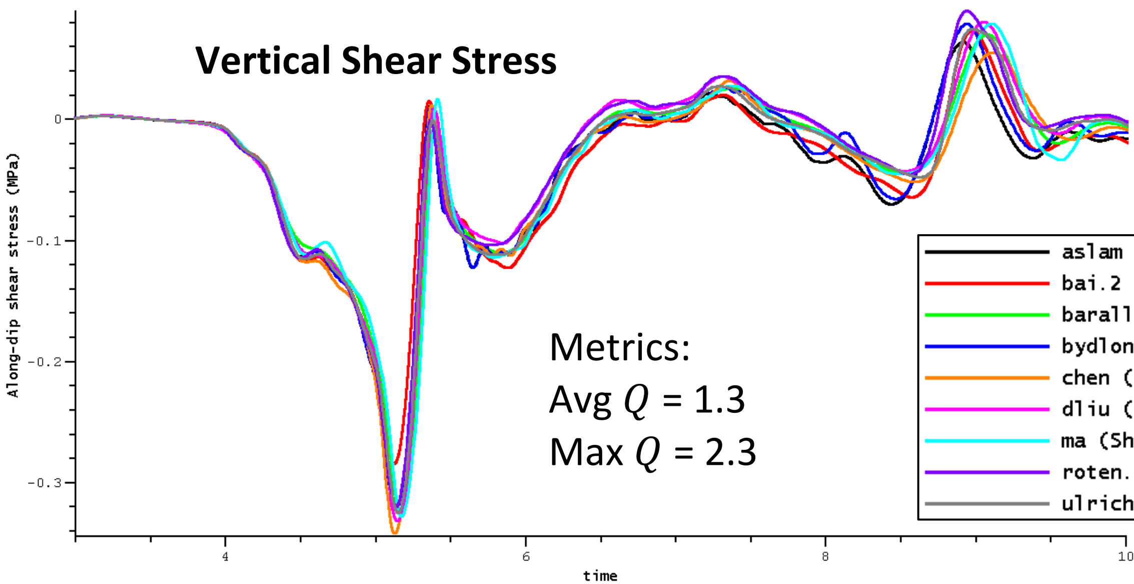


Excellent agreement between the codes.

Horizontal slip rate is a single pulse that tails off.

Vertical shear stress has a complicated history which all the codes succeed at.



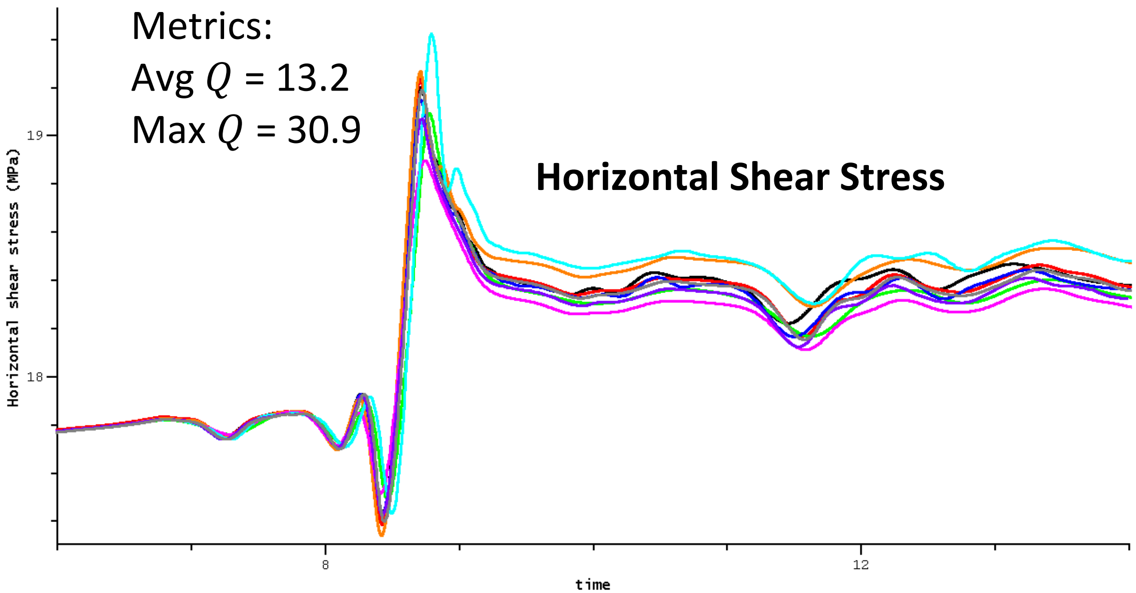


Filtered at 5 Hz.

faultst-250dp081 (25 km Left of Hypocenter)

Metrics:
Avg Q = 13.2
Max Q = 30.9

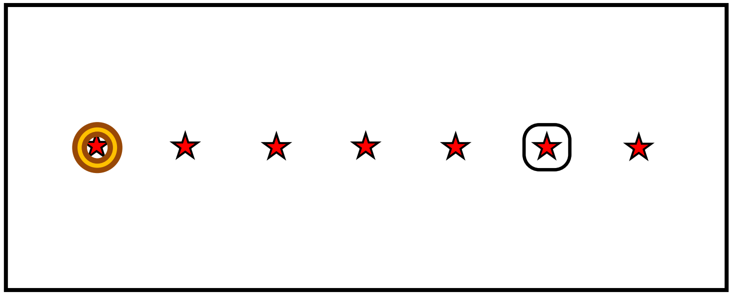
Horizontal Shear Stress



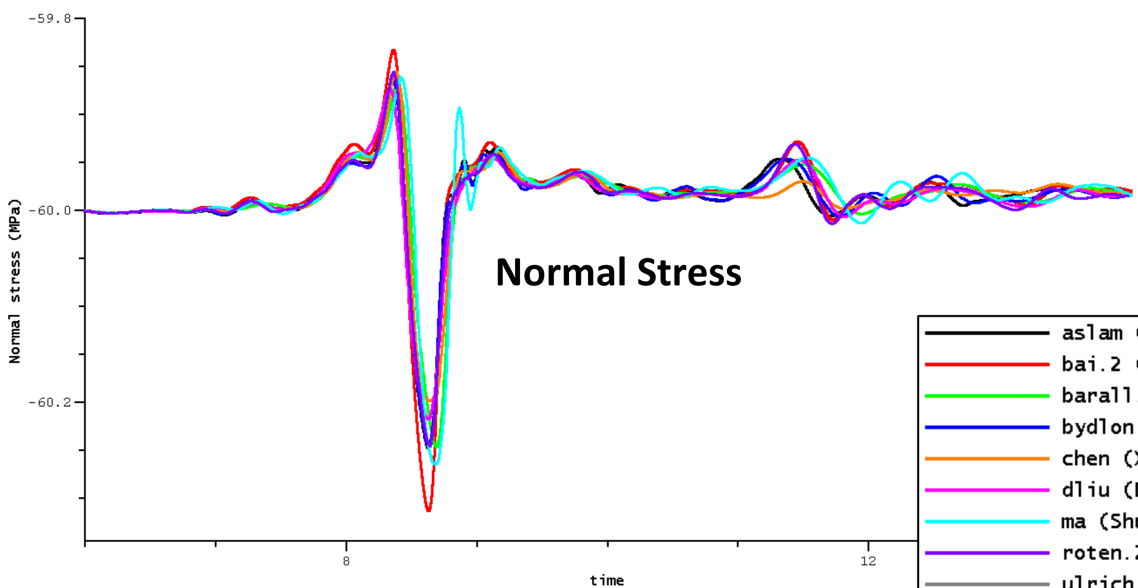
This node does not slip, so we only show stresses.

All codes show similar patterns, but there are significant differences as indicated by the metric values.

The normal stress is non-constant only because the velocity structure is different on the two sides of the fault.



Normal Stress



Filtered at 5 Hz.

TPV35 Results — Off-Fault Stations

Including Comparisons to Seismic Data

What Data?

There are three plausible sources of data for this benchmark:

1. Data from Ma *et al.* 2008, and Custódio *et al.* 2005.

    - Pros: Data is processed for this kind of modeling.
      Data is already filtered and time-shifted.
    - Cons: It's a one-off effort. Not available for other earthquakes.

2. Data from NGA West 2.

    - Pros: Available for a collection of large earthquakes.
    - Cons: Data is processed for a different purpose (constructing GMPEs).
      Data must be filtered and time-shifted for our use.

3. Raw data from the seismometer.

    - Pros: No one has messed with it.
    - Cons: May require intimate knowledge of the instrumentation to use correctly.

For TPV35, we use both the data from Ma *et al.* 2008, and the data from NGA West 2.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) aslam		29.0	28.6	21.9	32.7	31.8	30.3	121.1	120.5	23.1	28.5
(2) bai.2	29.0		7.1	13.5	11.9	9.2	7.7	117.5	118.0	6.2	4.2
(3) barall.2	28.6	7.1		12.4	13.7	9.0	6.2	117.7	118.1	6.7	7.5
(4) bydlon	21.9	13.5	12.4		18.2	16.9	15.0	118.3	118.6	8.2	13.2
(5) chen	32.7	11.9	13.7	18.2		14.4	13.1	116.9	117.6	12.9	12.3
(6) dliu	31.8	9.2	9.0	16.9	14.4		9.3	117.0	117.3	9.1	9.1
(7) ma	30.3	7.7	6.2	15.0	13.1	9.3		117.3	117.8	8.7	8.2
(8) nature.2	121.1	117.5	117.7	118.3	116.9	117.0	117.3		52.0	114.6	117.8
(9) nature.3	120.5	118.0	118.1	118.6	117.6	117.3	117.8	52.0		114.8	118.1
(10) roten.2	23.1	6.2	6.7	8.2	12.9	9.1	8.7	114.6	114.8		5.5
(11) ulrich.2	28.5	4.2	7.5	13.2	12.3	9.1	8.2	117.8	118.1	5.5	

Summary Metrics for All Off-Fault Stations

Each number is the metric value, averaged over all 43 stations, for a pair of codes; or for a code and a data set; or for the two data sets.

Lower numbers (green) are better, higher numbers (red) are worse.

(1) aslam	Khurram Aslam - Daub Finite Difference Code
(2) bai.2	Kangchen Bai - specfem3D_GPU-25m
(3) barall.2	Michael Barall - FaultMod - 50 m
(4) bydlon	Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab
(5) chen	Xiaofei Chen - CGFDM - 100m
(6) dliu	Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m
(7) ma	Shuo Ma - Finite Element - MAFE - 100m
(8) nature.2	Nature - Data from NGA West 2
(9) nature.3	Nature - Data from Ma et al. JGR 2008, unfilterable
(10) roten.2	Daniel Roten - Finite Difference - AWM - 50 m
(11) ulrich.2	ADER-DG-o5-200m on fault

- There is very good agreement between any two codes, except the Daub code for which agreement is only fair.
- There is poor agreement between any code and either data set.
- There is fair-to-poor agreement between the two data sets — worse than for any two codes.

Caveats for Looking at Off-Fault Waveforms

1. Parkfield 2004 data does not contain absolute time. So, the waveforms have been time-shifted to match modeling results. *Any apparent agreement in timing between the data and the models is artificial, and should be ignored.*

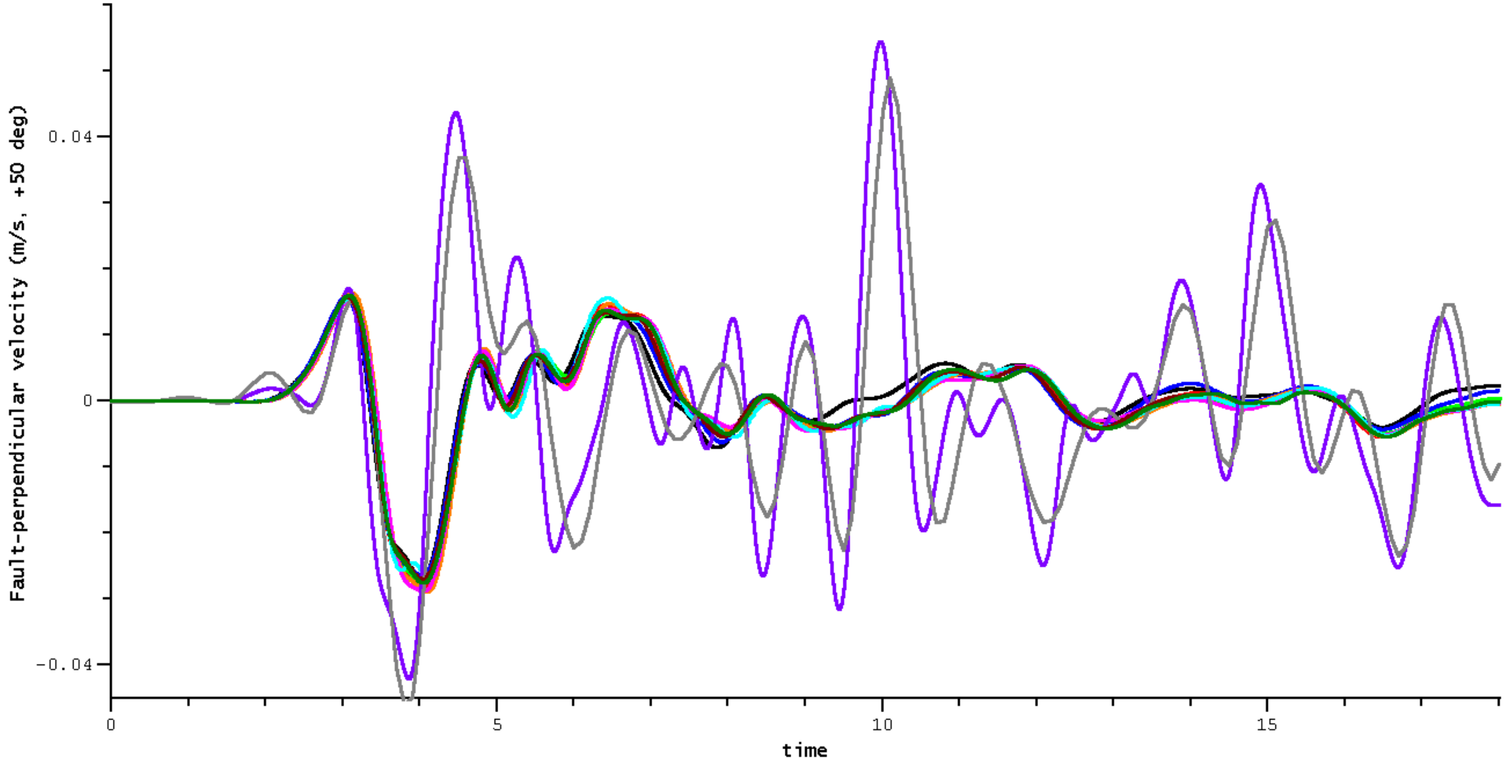
    - For Ma *et al.* data, the data was already time-shifted when I received it, and so I did not modify it.

    - For NGA West 2 data, I time-shifted the data by visually aligning it with my modeling results.

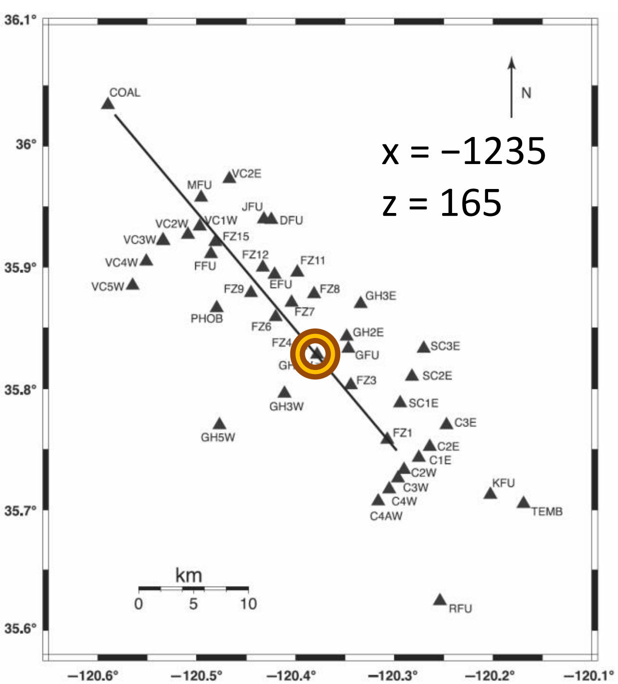
2. The maximum usable frequency is 1 Hz.

    - For NGA West 2 data, and for all modeling results, I applied our website's standard low-pass filter with a cutoff frequency of 1 Hz.

    - For Ma *et al.* data, the data was already bandpass filtered between 0.16 Hz and 1 Hz when I received it, and so I did not apply any additional filtering.



Metrics:
Qcc = 14
Qcd = 145
Qdd = 36

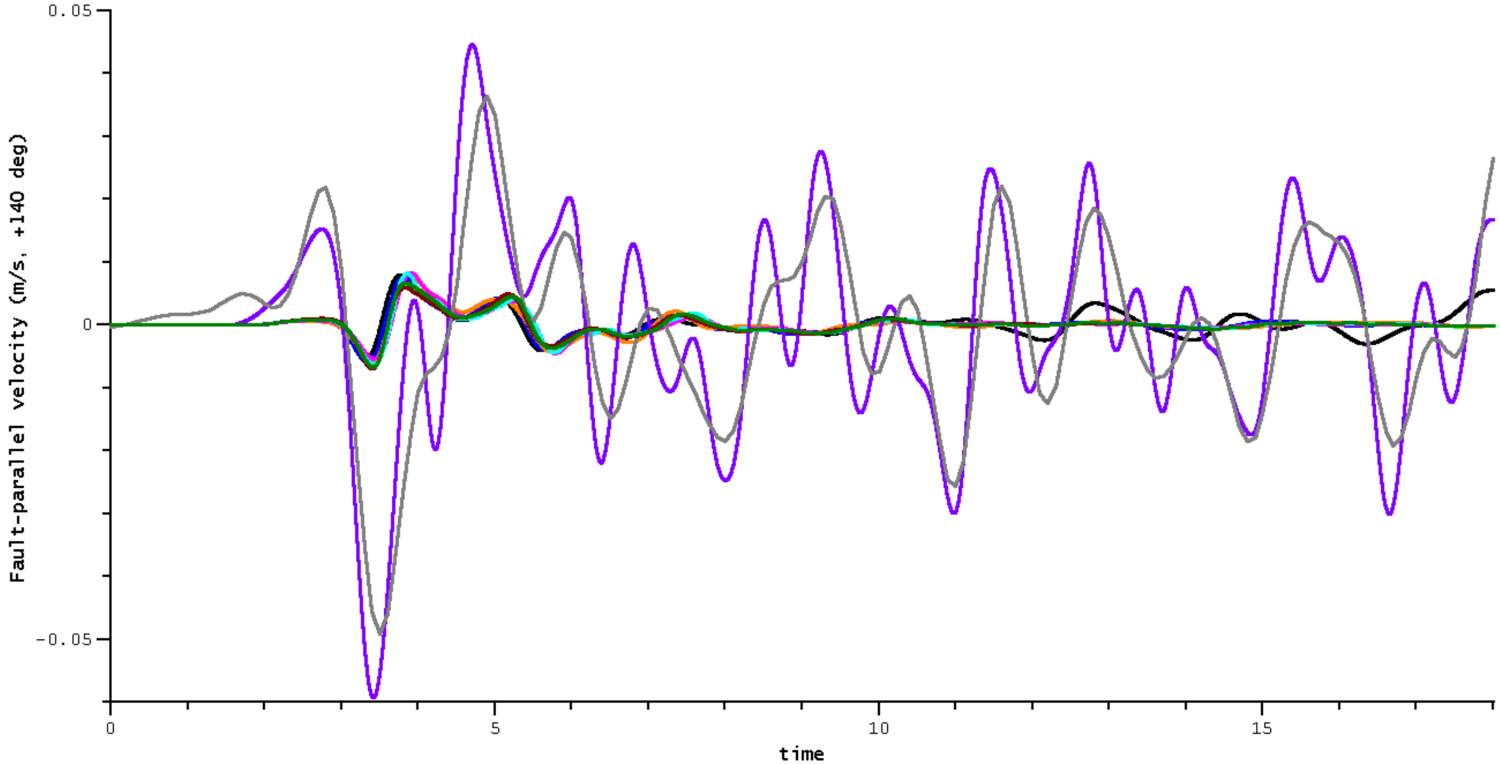


x = −1235
z = 165

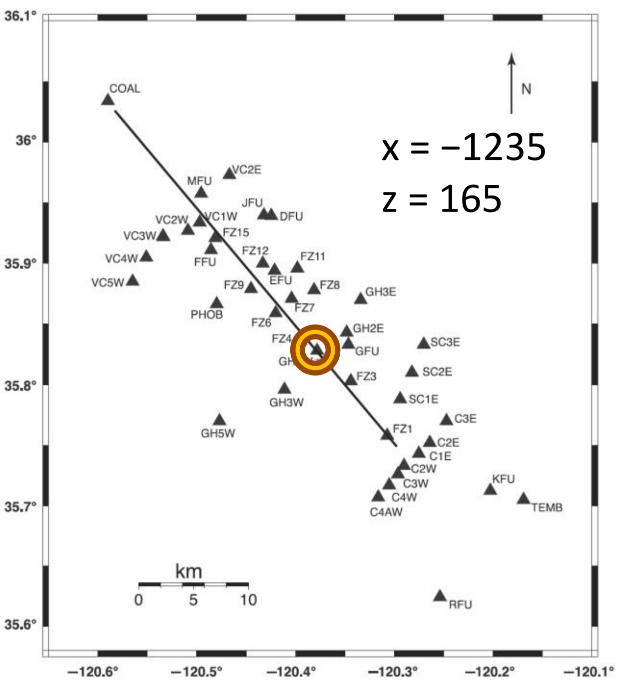
4118_pg1 [GH1W] — Gold Hill 1W — Fault-Perpendicular

Model peak is ~30% lower than data.
Model calms down after initial peak, data does not.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



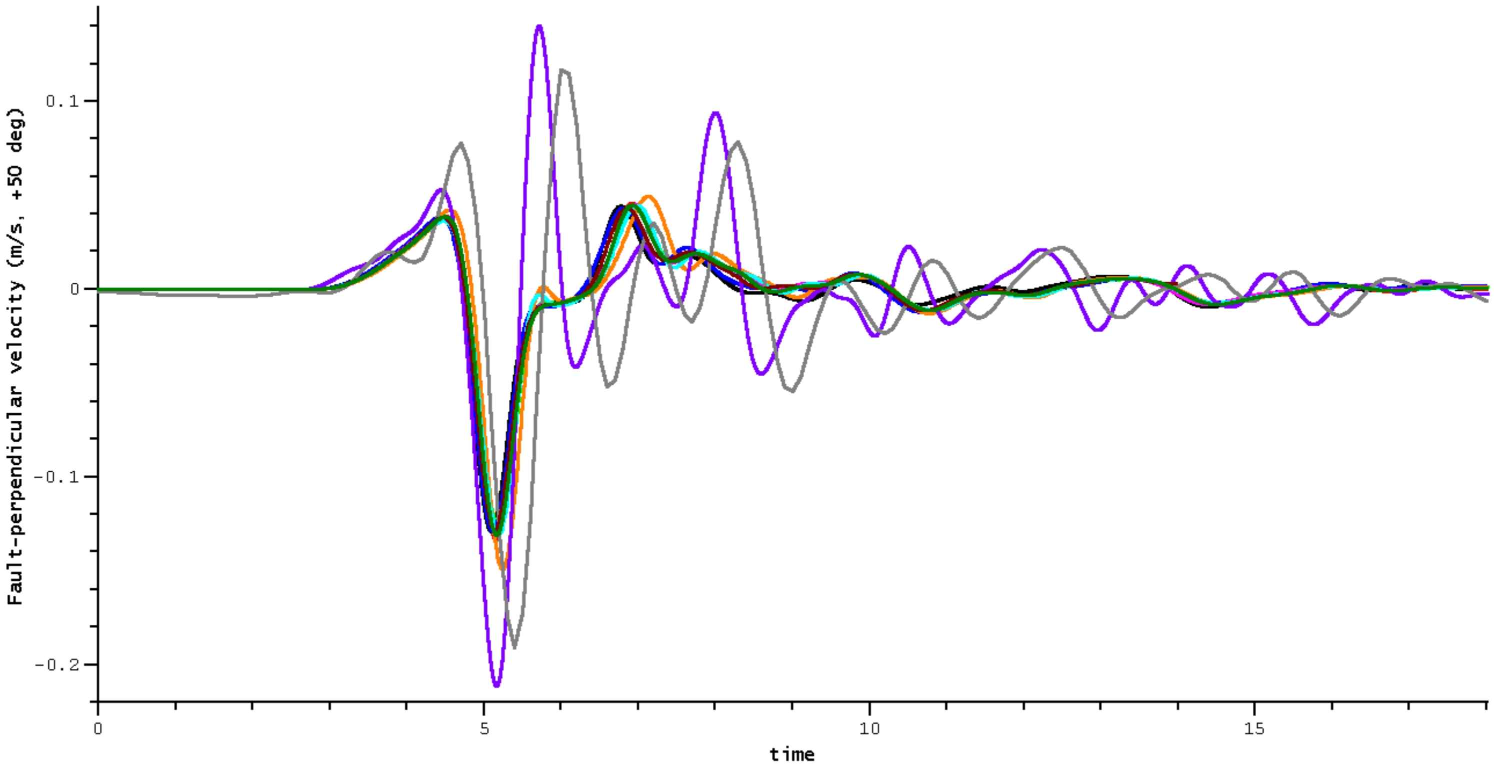
Metrics:
Qcc = 14
Qcd = 145
Qdd = 36



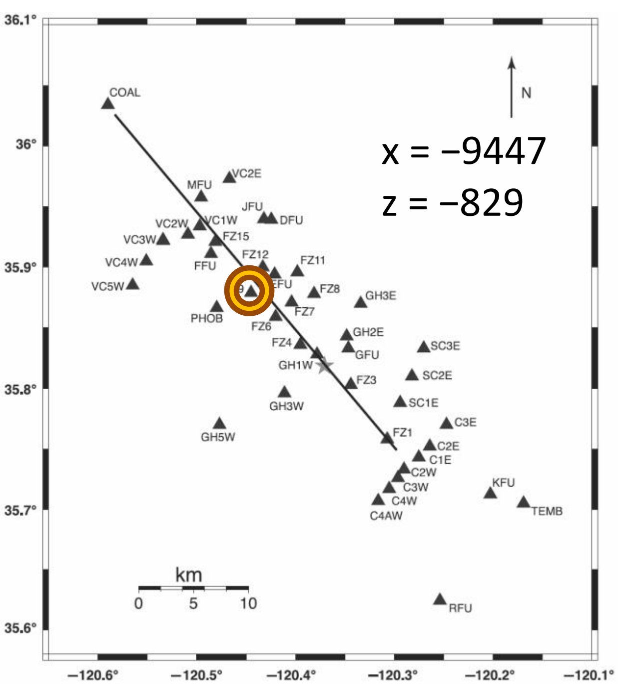
4118_pg1 [GH1W] — Gold Hill 1W — Fault-Parallel

Model peak is smaller than fault-perpendicular, not so for data.

aslam (Khurram Aslam - Daub Finite Difference Code)
bai.2 (Kangchen Bai - specfem3D_GPU-25m)
barall.2 (Michael Barall - FaultMod - 50 m)
bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
chen (Xiaofei Chen - CGFDM - 100m)
dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
ma (Shuo Ma - Finite Element - MAFE - 100m)
nature.2 (Nature - Data from NGA West 2)
nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
ulrich.2 (ADER-DG-o5-200m on fault)



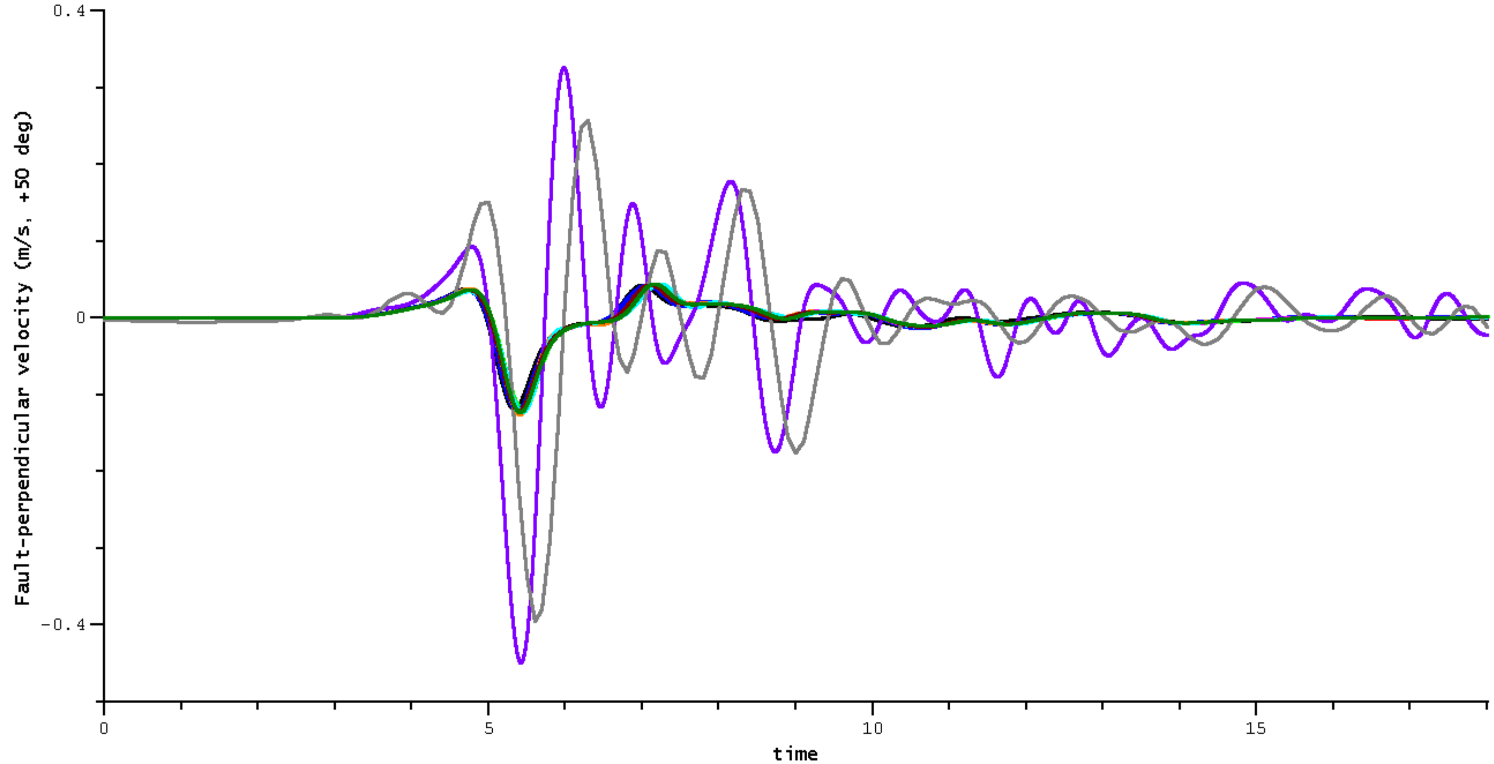
Metrics:
Qcc = 11
Qcd = 99
Qdd = 30



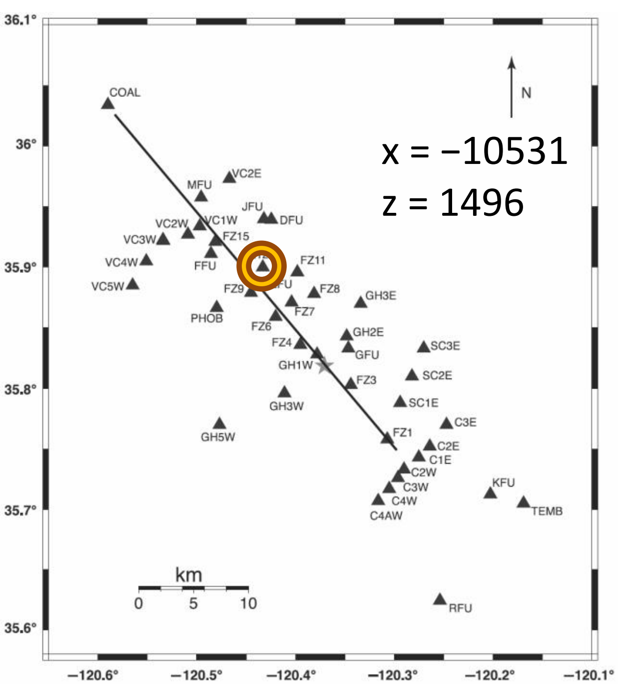
4113_z09 [FZ9] — Fault Zone 9 — Fault-Perpendicular

Data tapers off somewhat like the model.
Next slide shows station on other side of fault.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



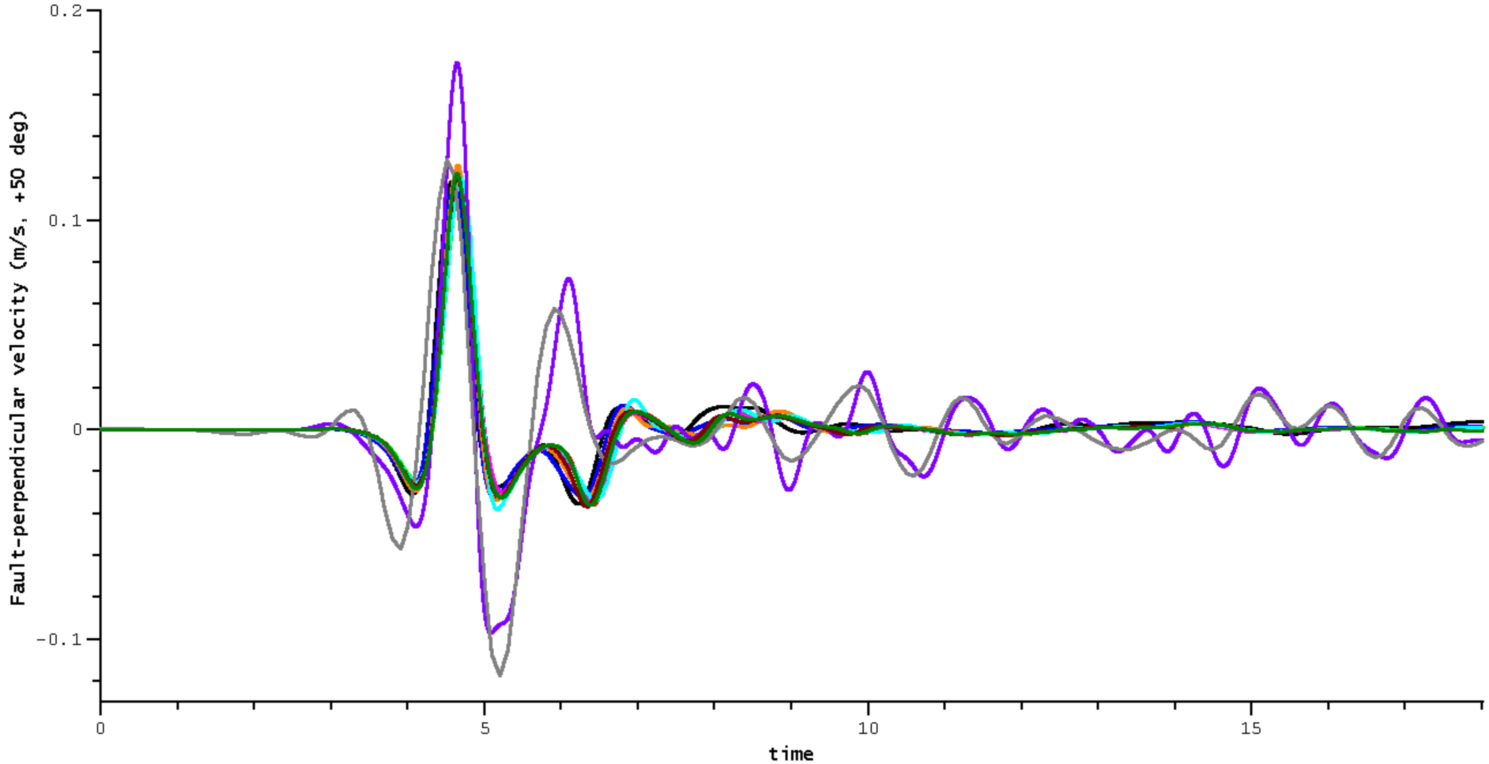
Metrics:
Qcc = 9
Qcd = 143
Qdd = 33



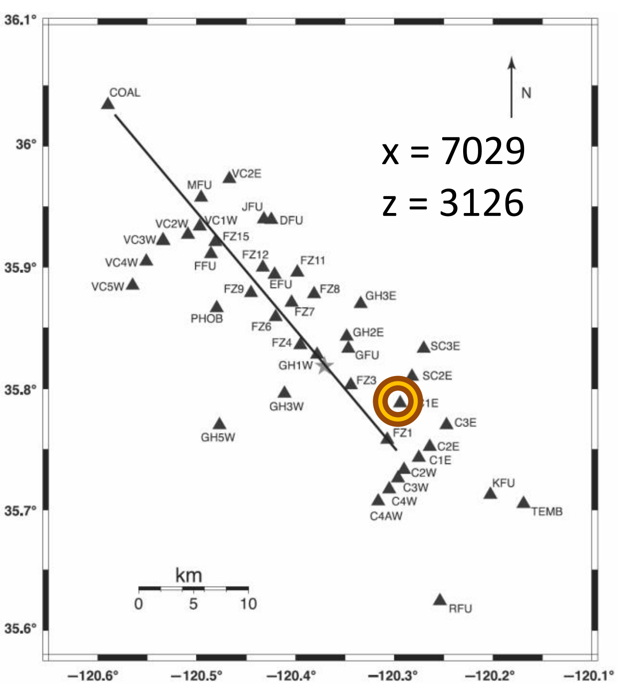
4115_prk [FZ12] — Fault Zone 12 — Fault-Perpendicular

Model peak velocity is the same as on the other side of the fault (noting change in scale), but data peak velocity is twice as large.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



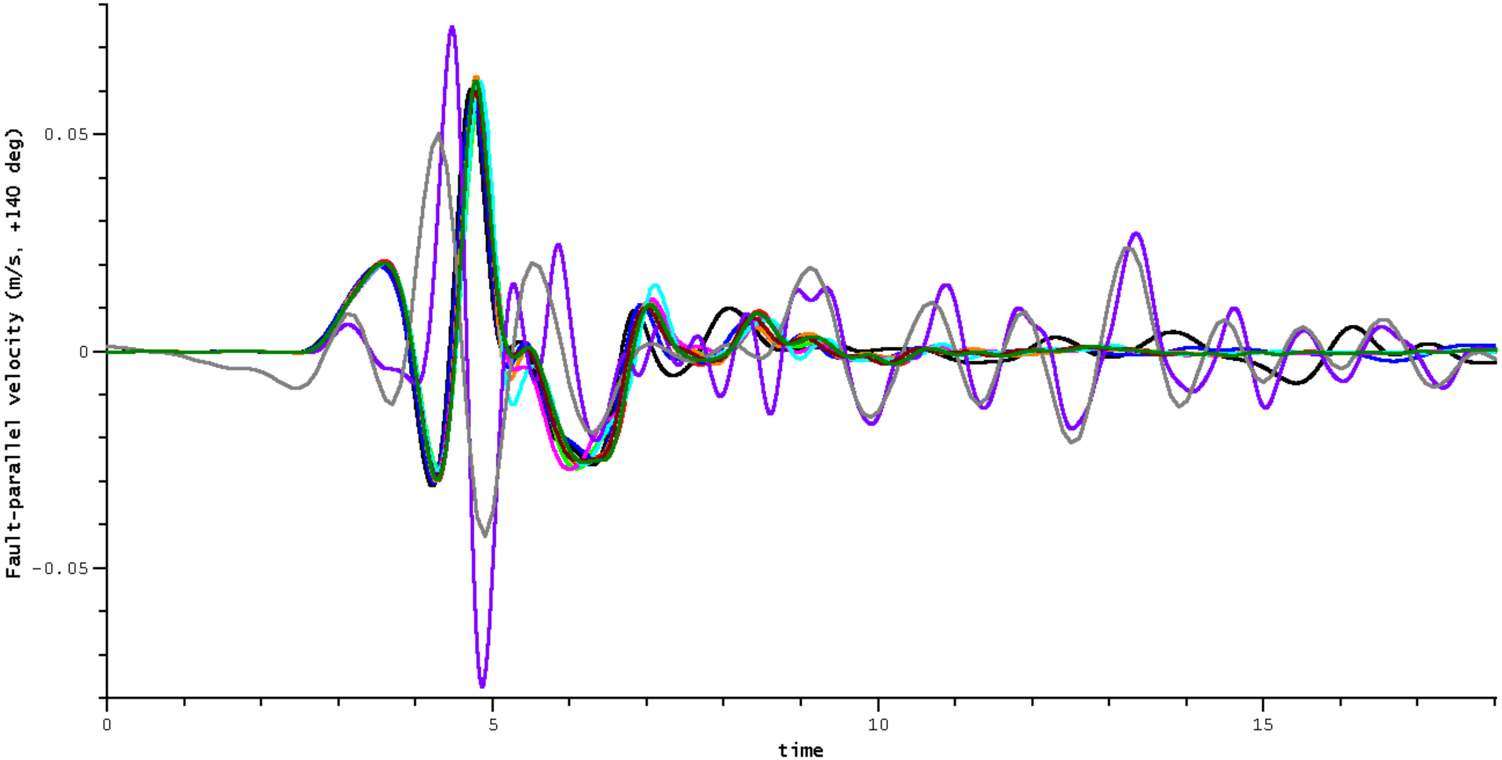
Metrics:
Qcc = 13
Qcd = 107
Qdd = 46



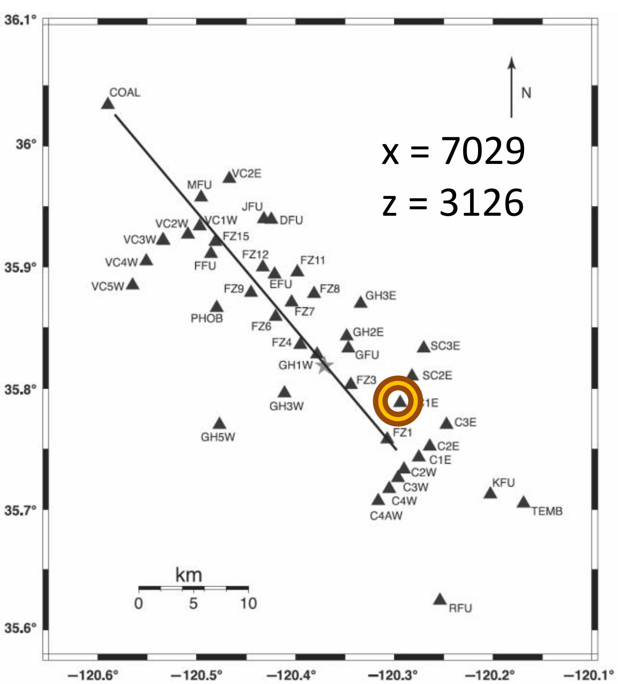
4126_sc1 [SC1E] — Stone Corral 1E — Fault-Perpendicular

Model peak velocity matches the peak for Ma et al. data, but is below NGA West 2 peak, and does not match 2nd and 3rd peaks.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



Metrics:
Qcc = 13
Qcd = 107
Qdd = 46

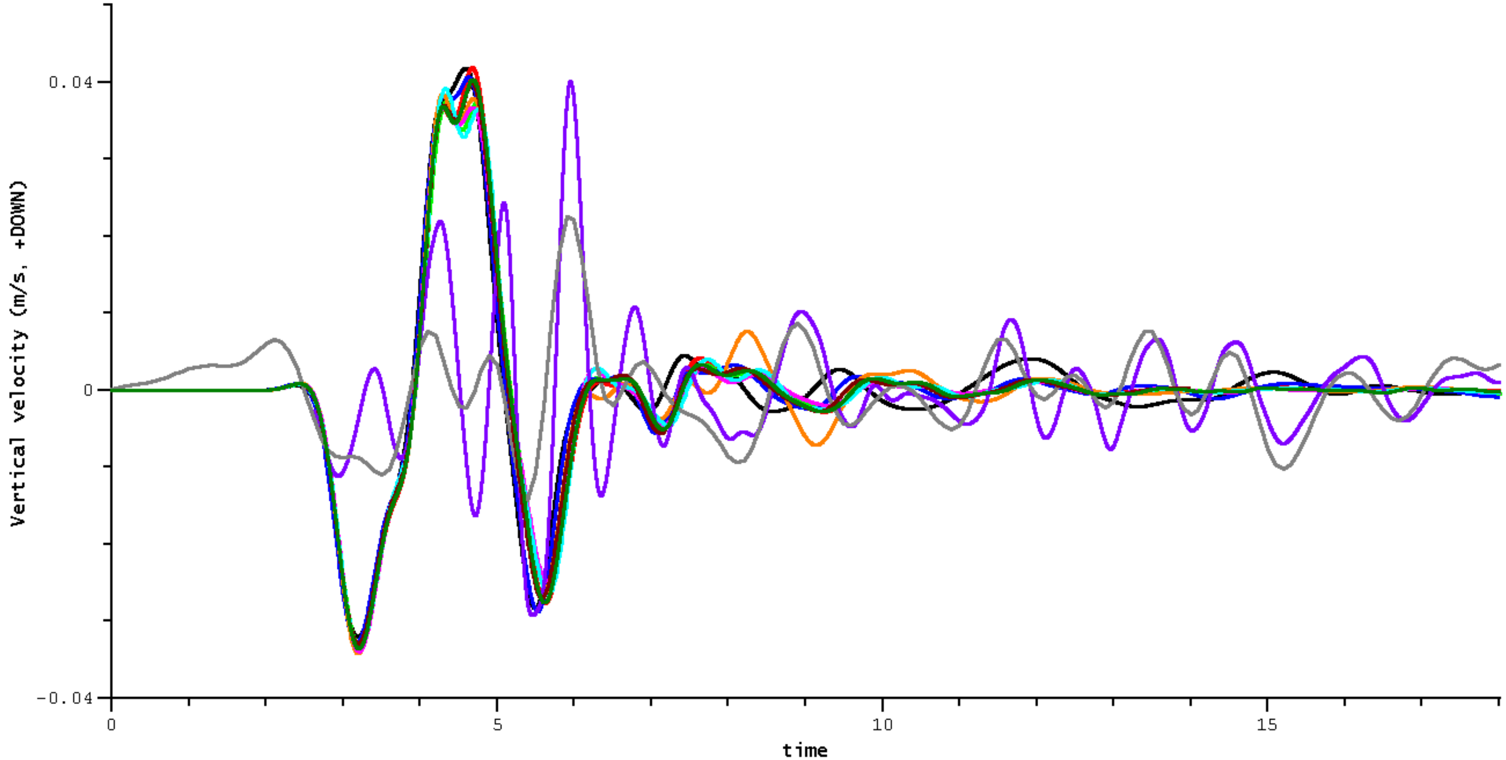


x = 7029
z = 3126

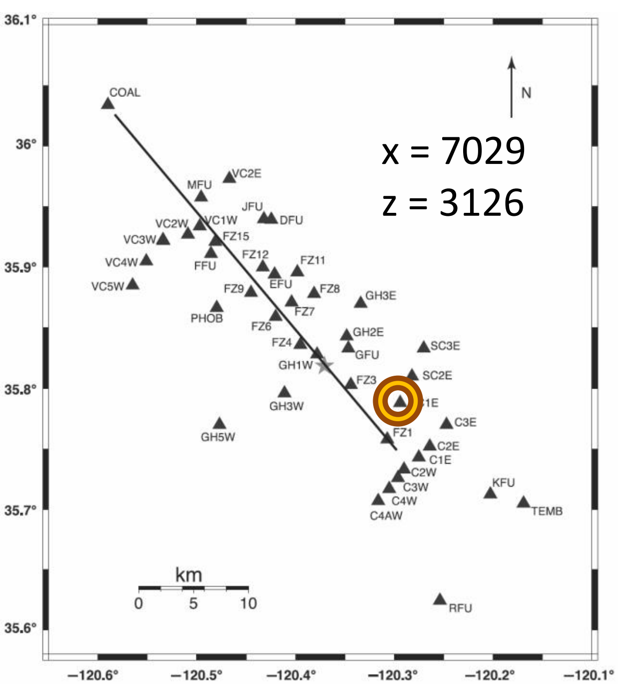
4126_sc1 [SC1E] — Stone Corral 1E — Fault-Parallel

Model seems to have incorrect polarity at the velocity peaks.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



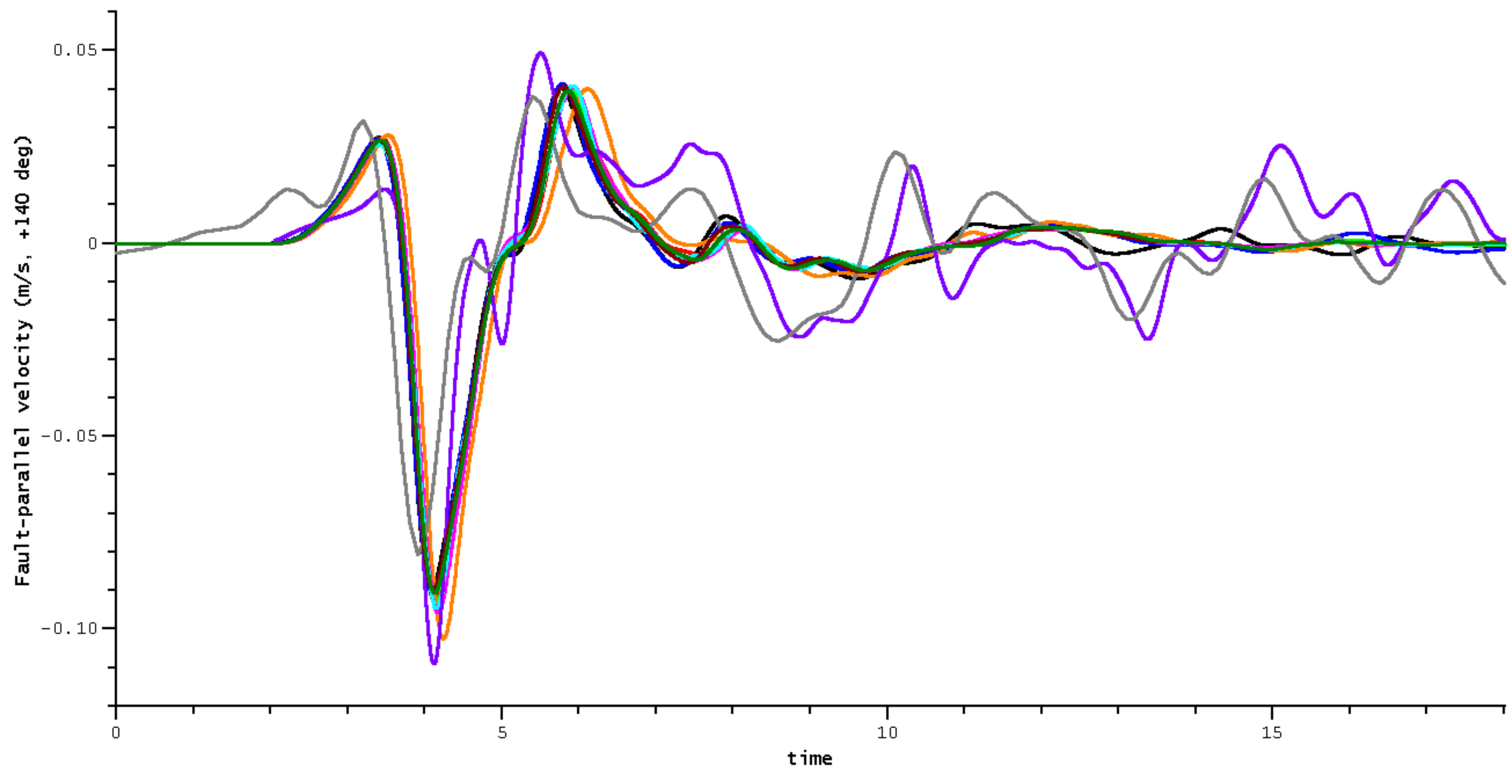
Metrics:
Qcc = 13
Qcd = 107
Qdd = 46



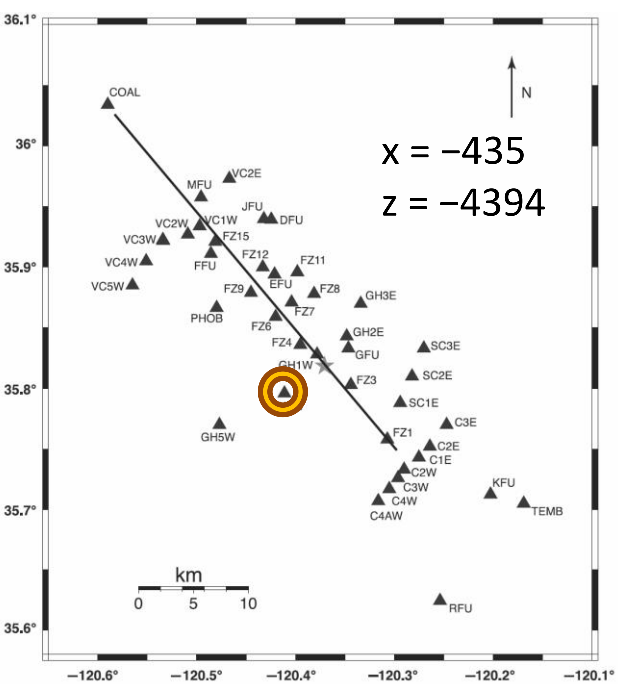
4126_sc1 [SC1E] — Stone Corral 1E — Vertical

Peak amplitude is about right, but waveforms are not similar.

aslam (Khurram Aslam - Daub Finite Difference Code)
bai.2 (Kangchen Bai - specfem3D_GPU-25m)
barall.2 (Michael Barall - FaultMod - 50 m)
bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
chen (Xiaofei Chen - CGFDM - 100m)
dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
ma (Shuo Ma - Finite Element - MAFE - 100m)
nature.2 (Nature - Data from NGA West 2)
nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
ulrich.2 (ADER-DG-o5-200m on fault)



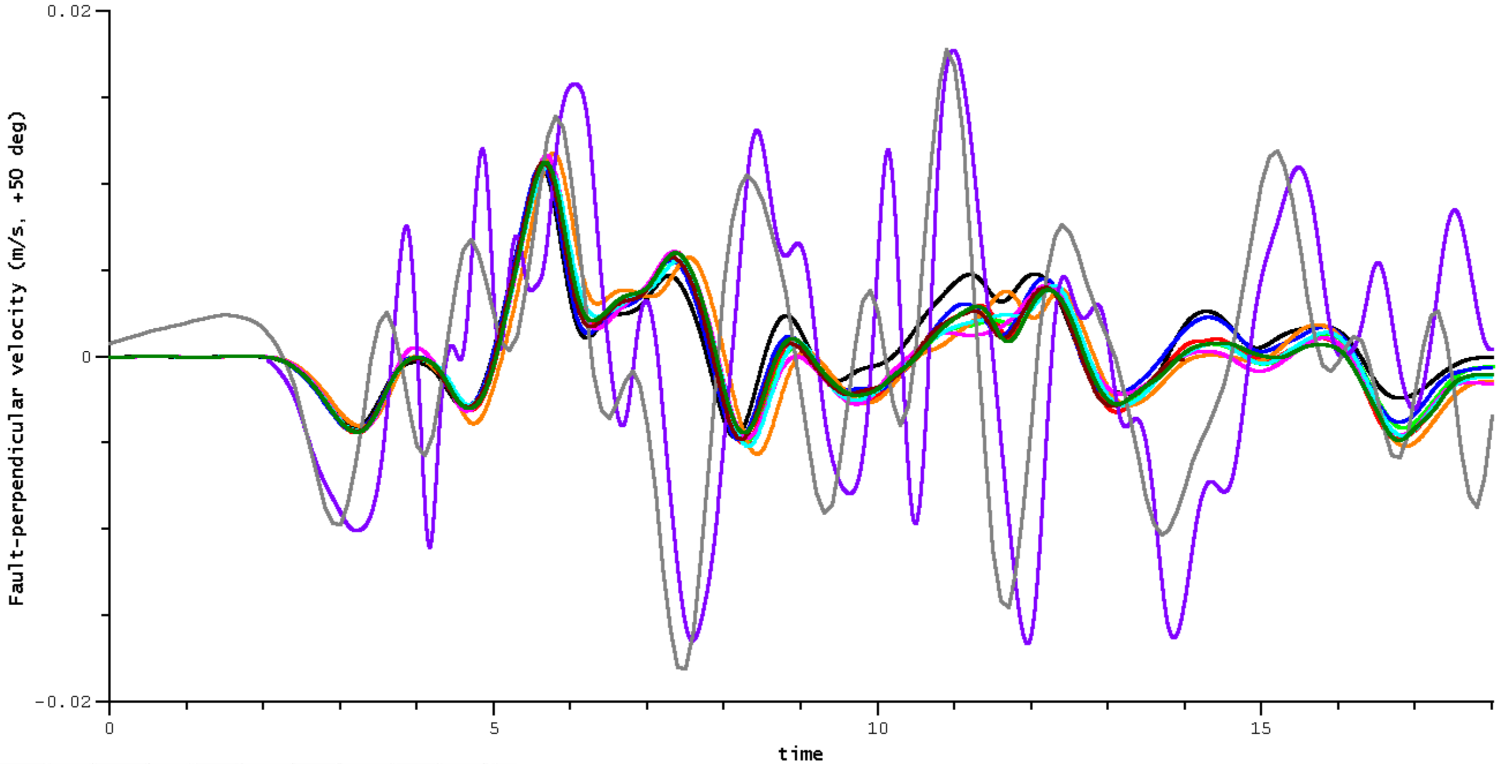
Metrics:
Qcc = 10
Qcd = 75
Qdd = 47



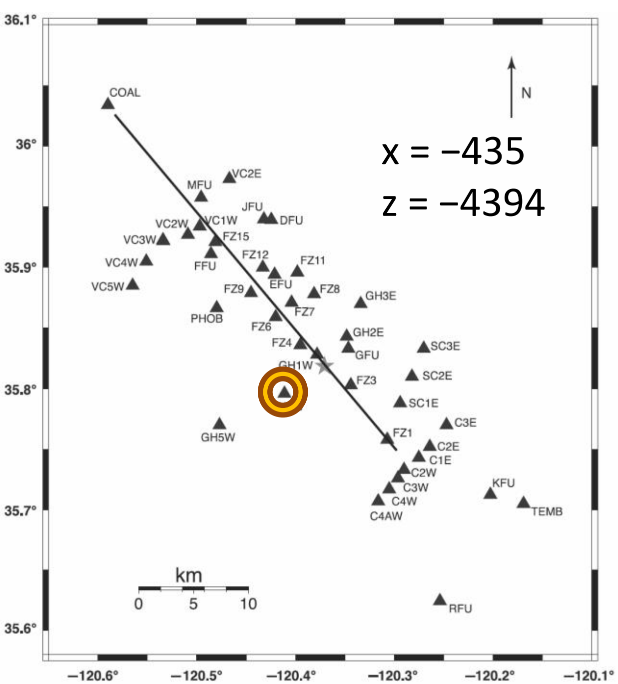
4122_pg3 [GH3W] — Gold Hill 3W — Fault-Parallel

Good agreement between model and data on amplitude and shape of initial peaks. Note comparatively low value of Qcd.

aslam (Khurram Aslam - Daub Finite Difference Code)
bai.2 (Kangchen Bai - specfem3D_GPU-25m)
barall.2 (Michael Barall - FaultMod - 50 m)
bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
chen (Xiaofei Chen - CGFDM - 100m)
dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
ma (Shuo Ma - Finite Element - MAFE - 100m)
nature.2 (Nature - Data from NGA West 2)
nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
ulrich.2 (ADER-DG-o5-200m on fault)



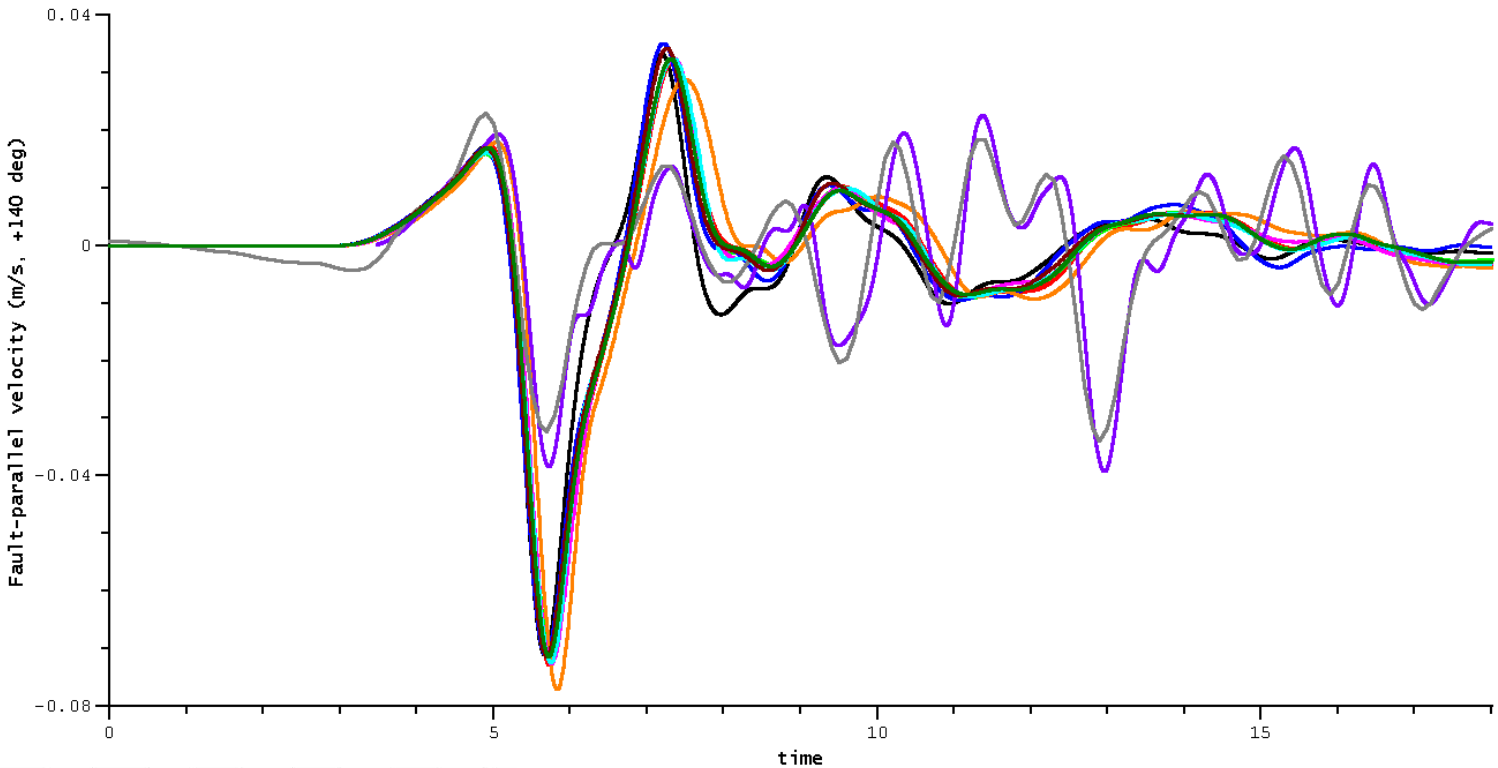
Metrics:
Qcc = 10
Qcd = 75
Qdd = 47



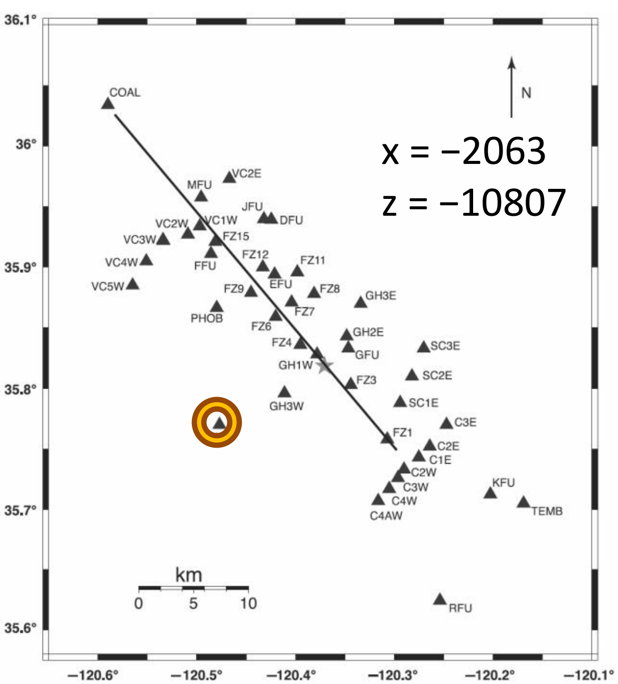
4122_pg3 [GH3W] — Gold Hill 3W — Fault-Perpendicular

Parallel/perpendicular peak velocity ratio is about 7 for models, 5 for data.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



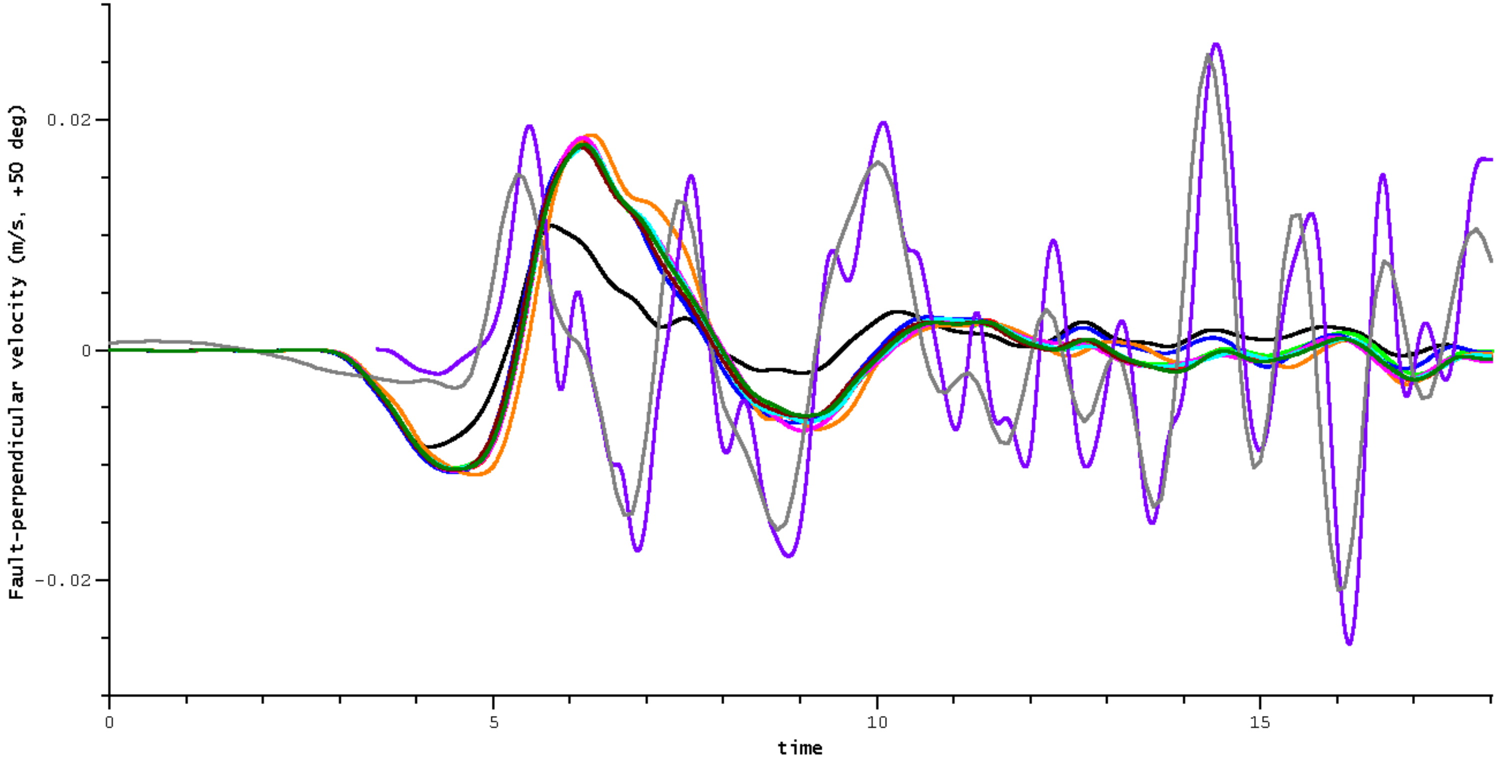
Metrics:
Qcc = 14
Qcd = 114
Qdd = 31



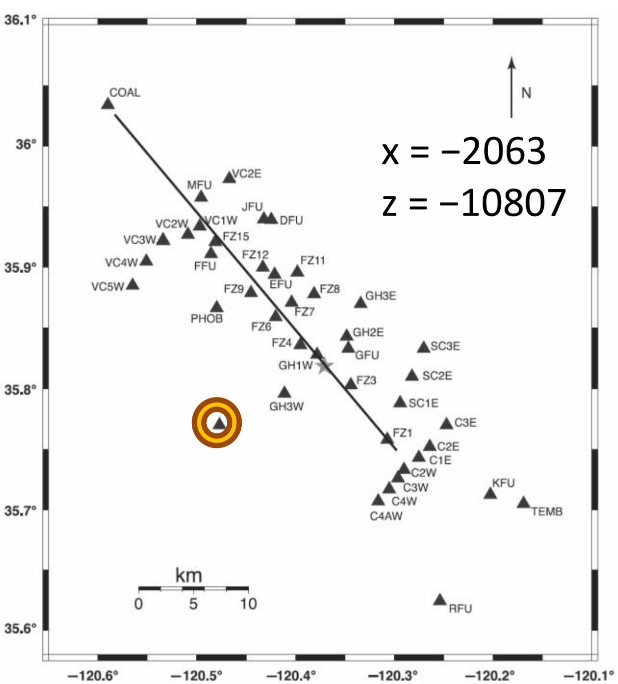
4124_pg5 [GH5W] — Gold Hill 5W — Fault-Parallel

This station has the largest -z. The two data sets agree well.
Model peak velocity is twice as large as the data peak velocity.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



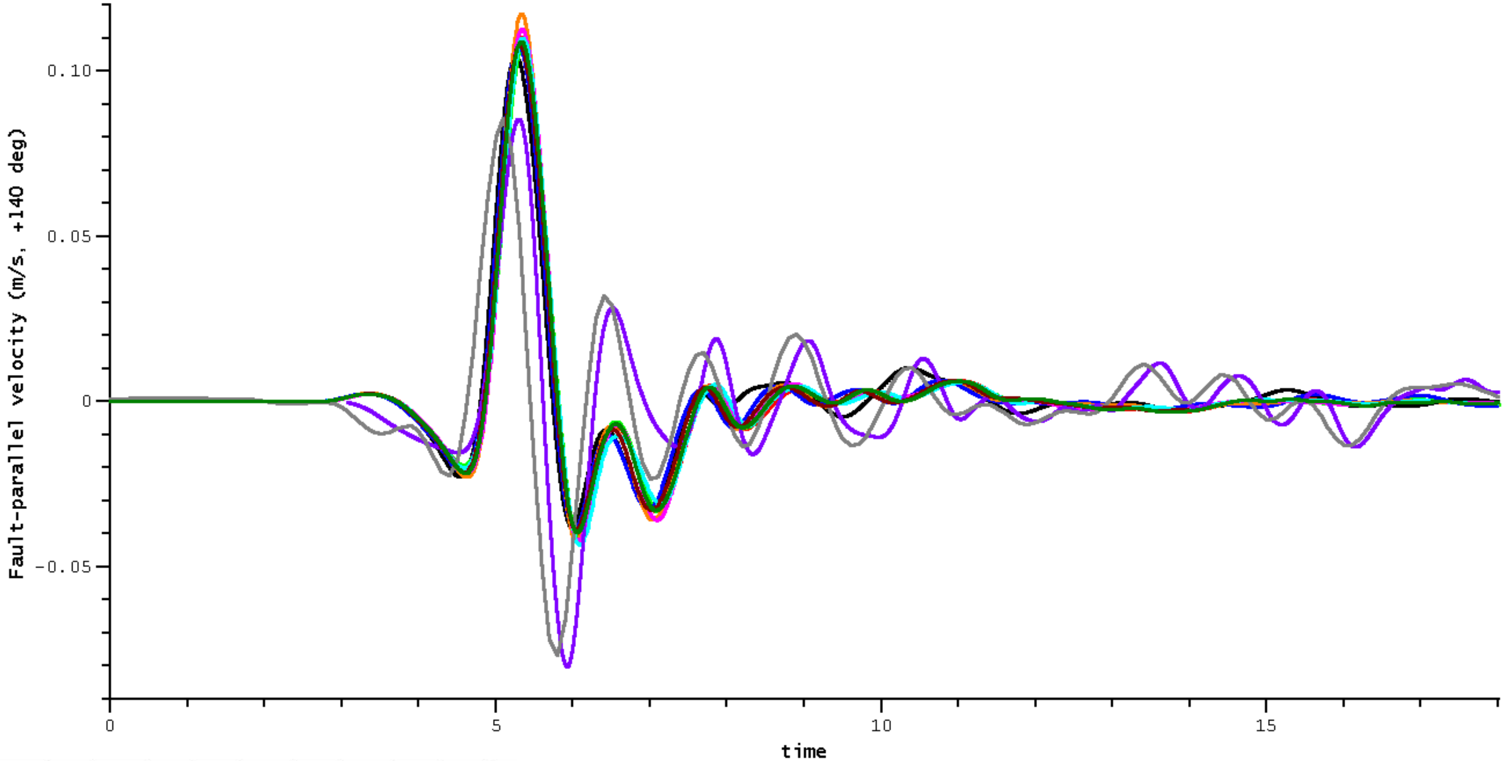
Metrics:
Qcc = 14
Qcd = 114
Qdd = 31



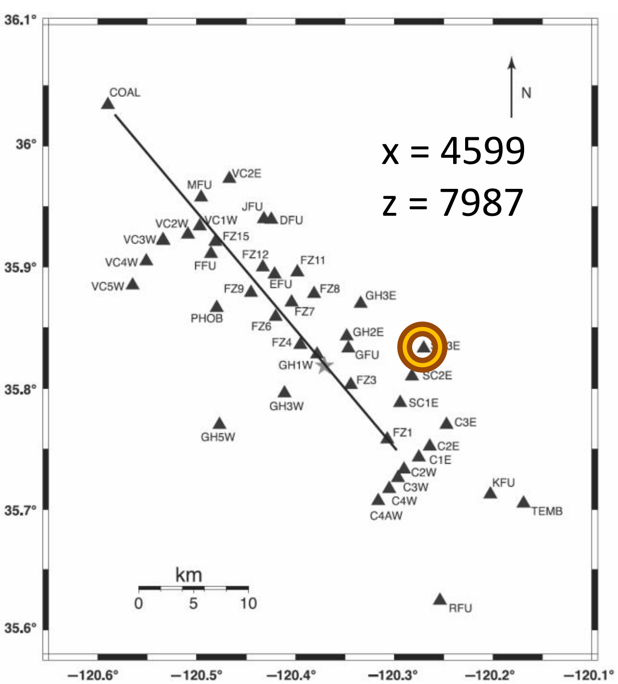
4124_pg5 [GH5W] — Gold Hill 5W — Fault-Perpendicular

Parallel/perpendicular peak velocity ratio is about 4 for models, 1.5 for data. Waveforms are not similar.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



Metrics:
Qcc = 10
Qcd = 83
Qdd = 22

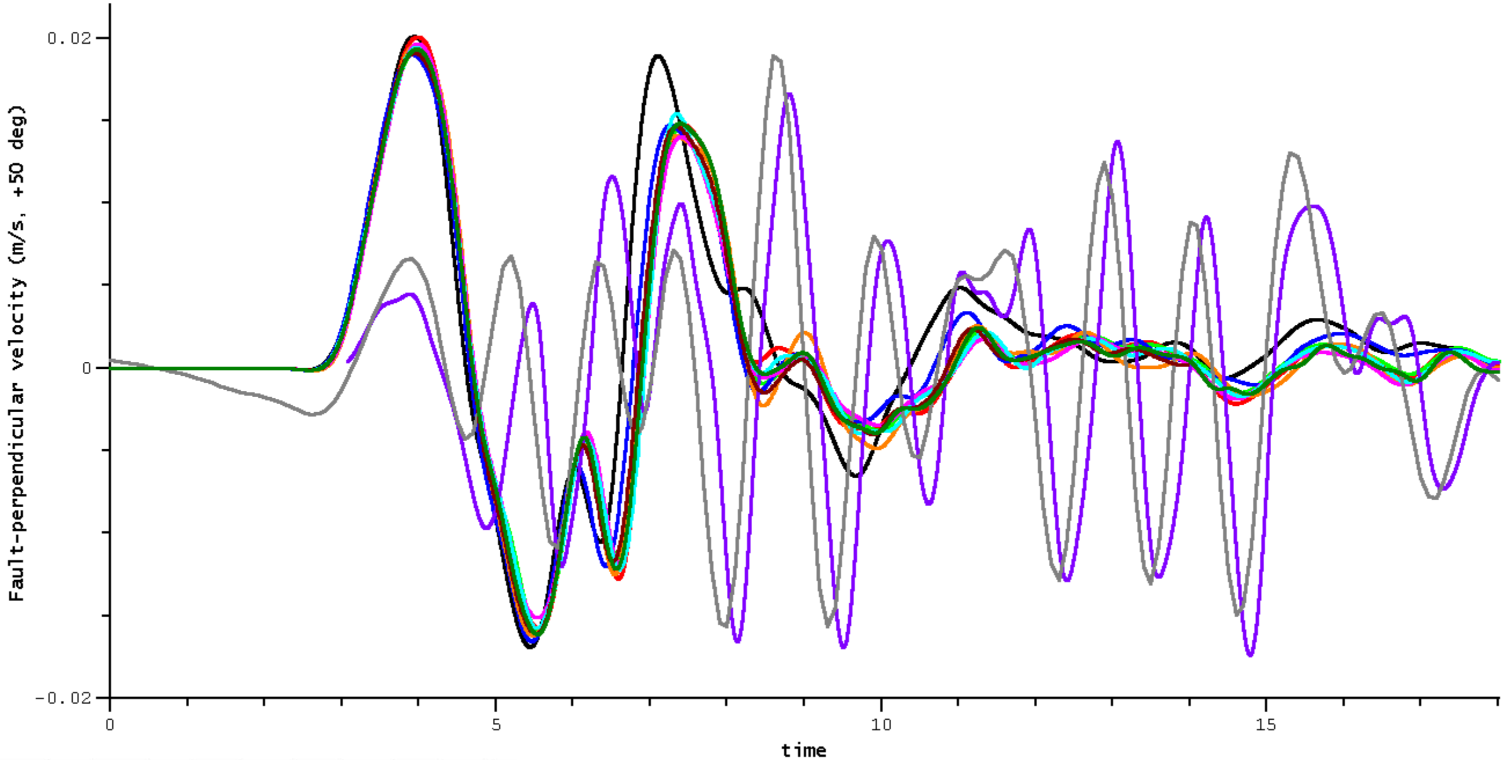


x = 4599
z = 7987

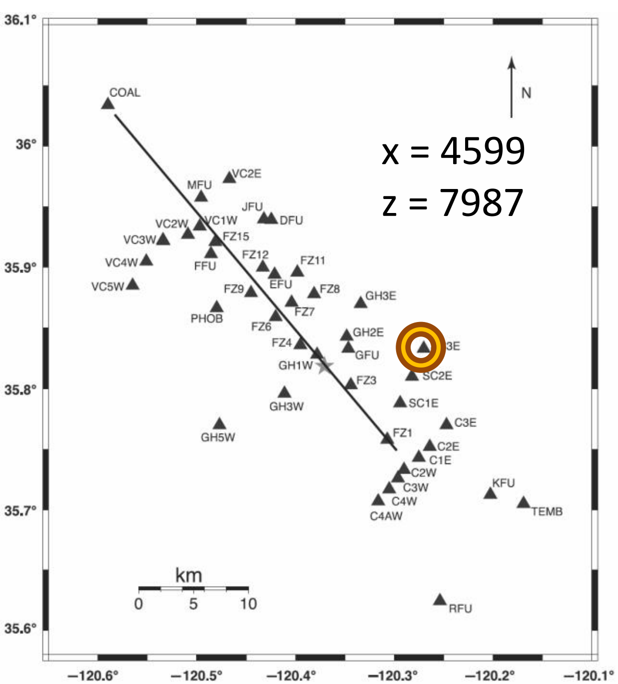
4128_sc3 [SC3E] — Stone Corral 3E — Fault-Parallel

This station has the largest +z. The two data sets agree well. Model peak velocity is a little larger than the data peak velocity.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



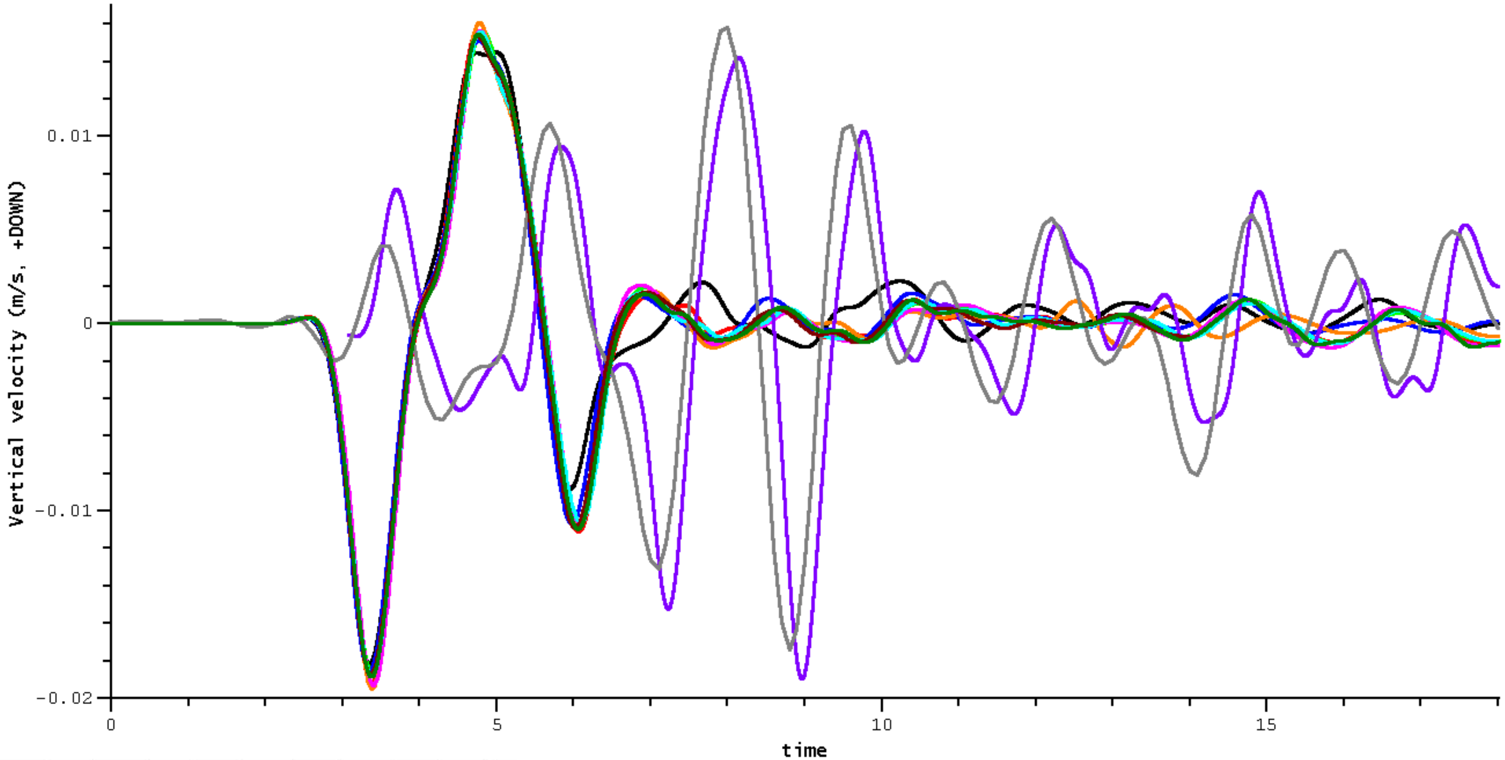
Metrics:
Qcc = 10
Qcd = 83
Qdd = 22



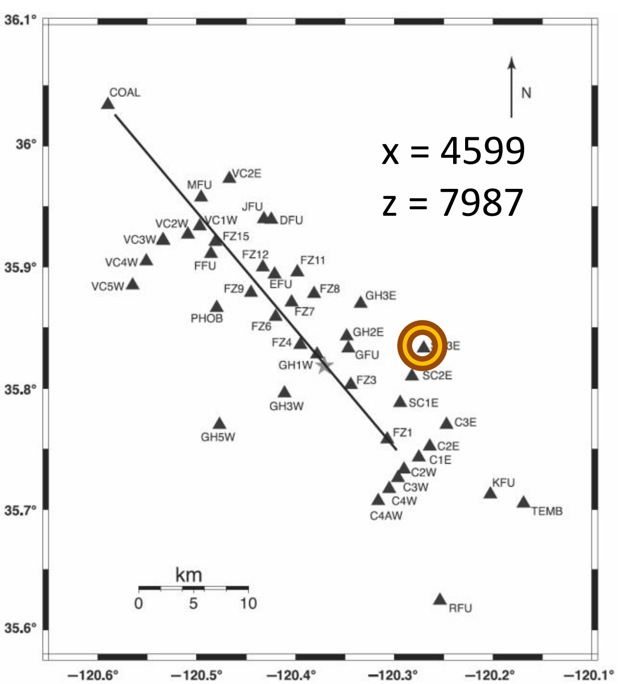
4128_sc3 [SC3E] — Stone Corral 3E — Fault-Perpendicular

Parallel/perpendicular peak velocity ratio is about 5 for models, 4 for data. Waveforms are not similar.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



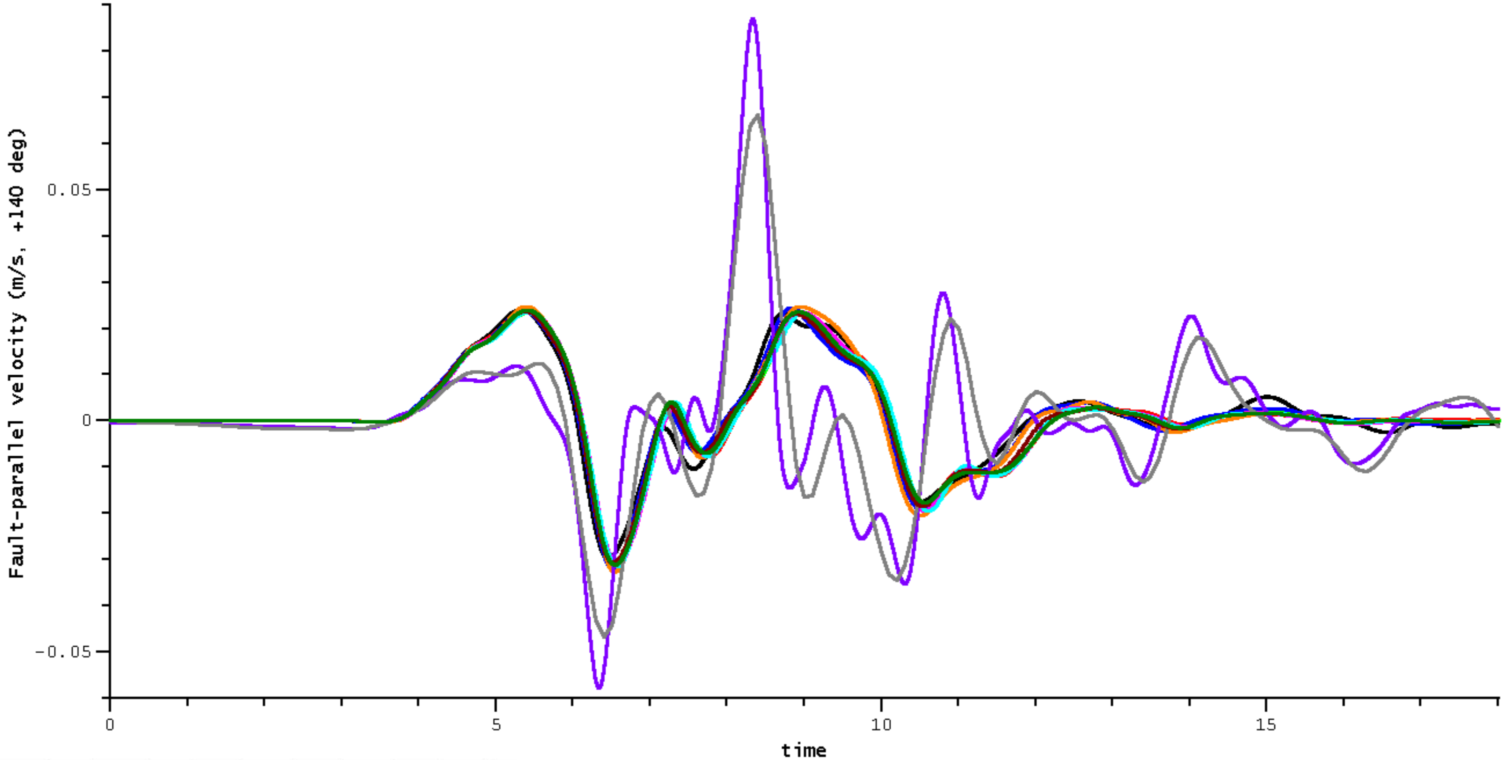
Metrics:
Qcc = 10
Qcd = 83
Qdd = 22



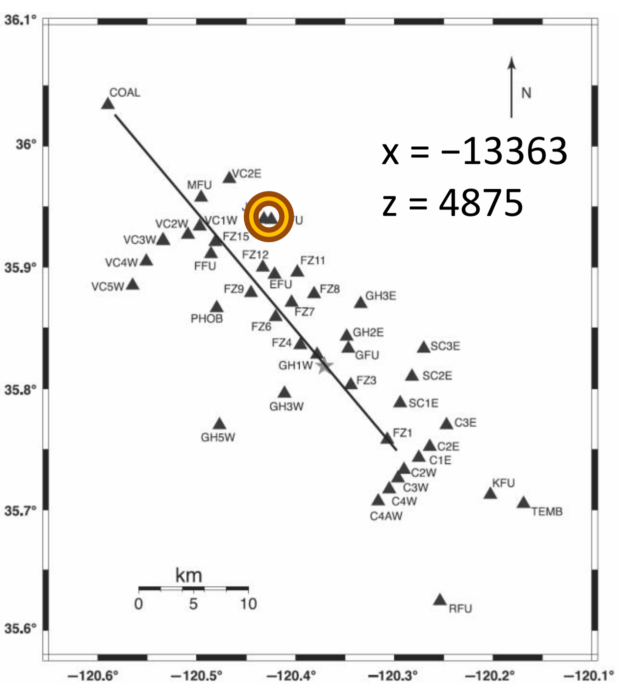
4128_sc3 [SC3E] — Stone Corral 3E — Vertical

Model and data have similar amplitude, but waveforms are different.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



Metrics:
Qcc = 11
Qcd = 101
Qdd = 38

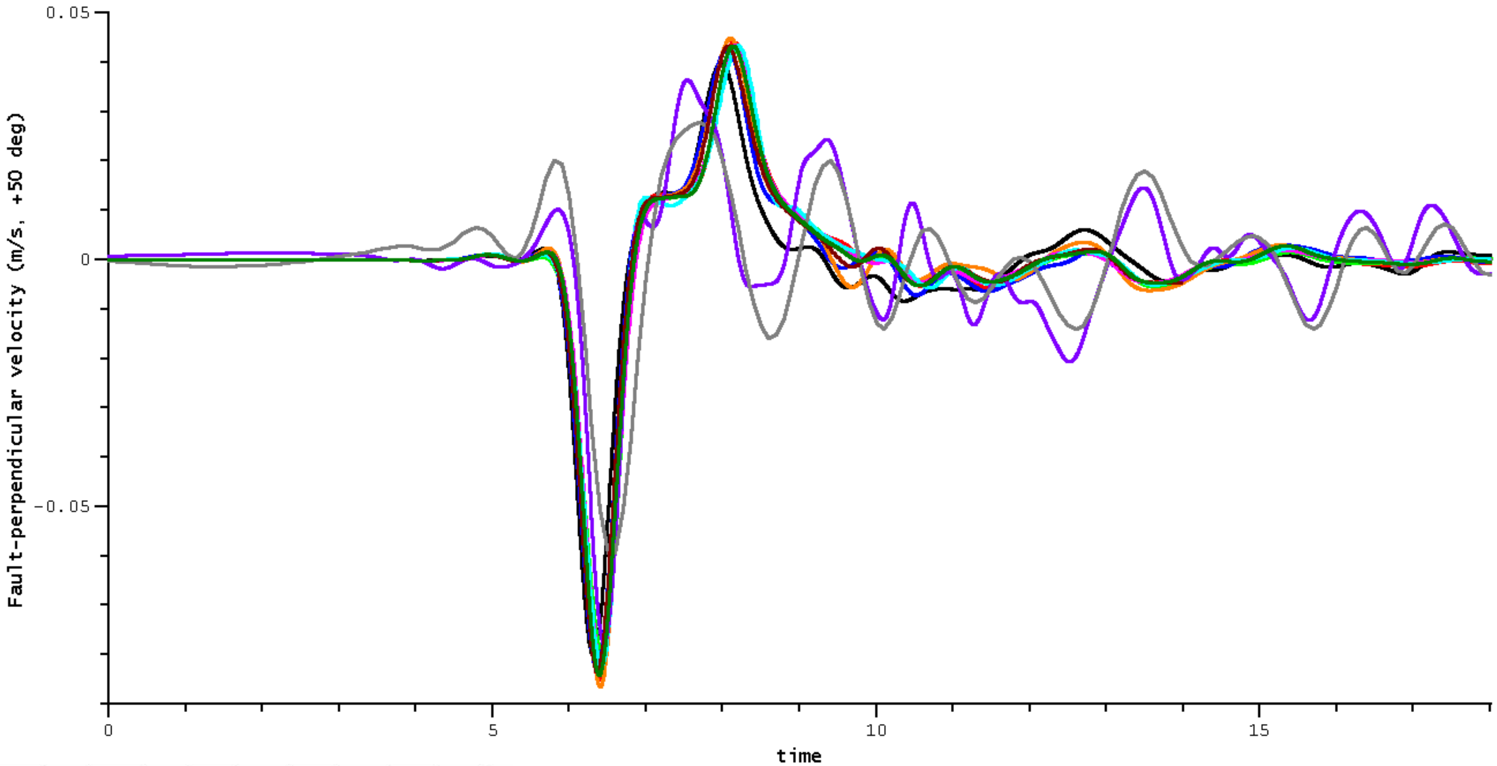


x = −13363
z = 4875

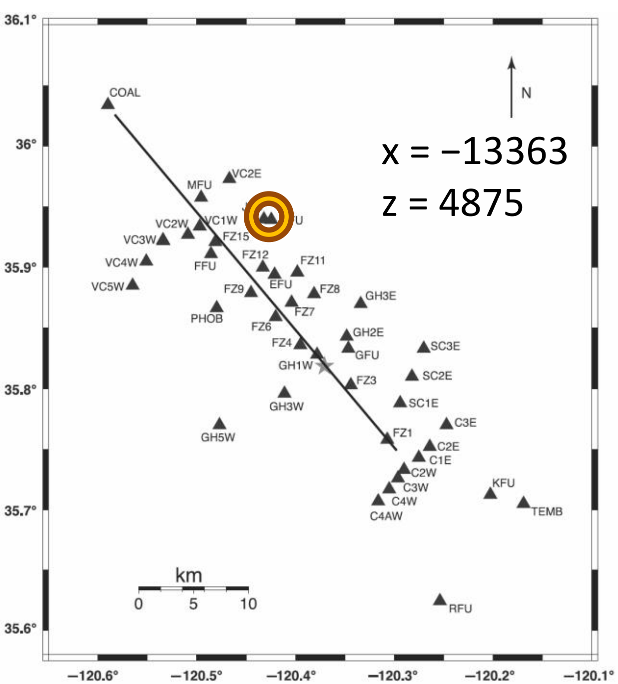
4064_donna [DFU] — Donna Lee — Fault-Parallel

Model misses the sharp peak in the data at about 8.5 seconds.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



Metrics:
Qcc = 11
Qcd = 101
Qdd = 38

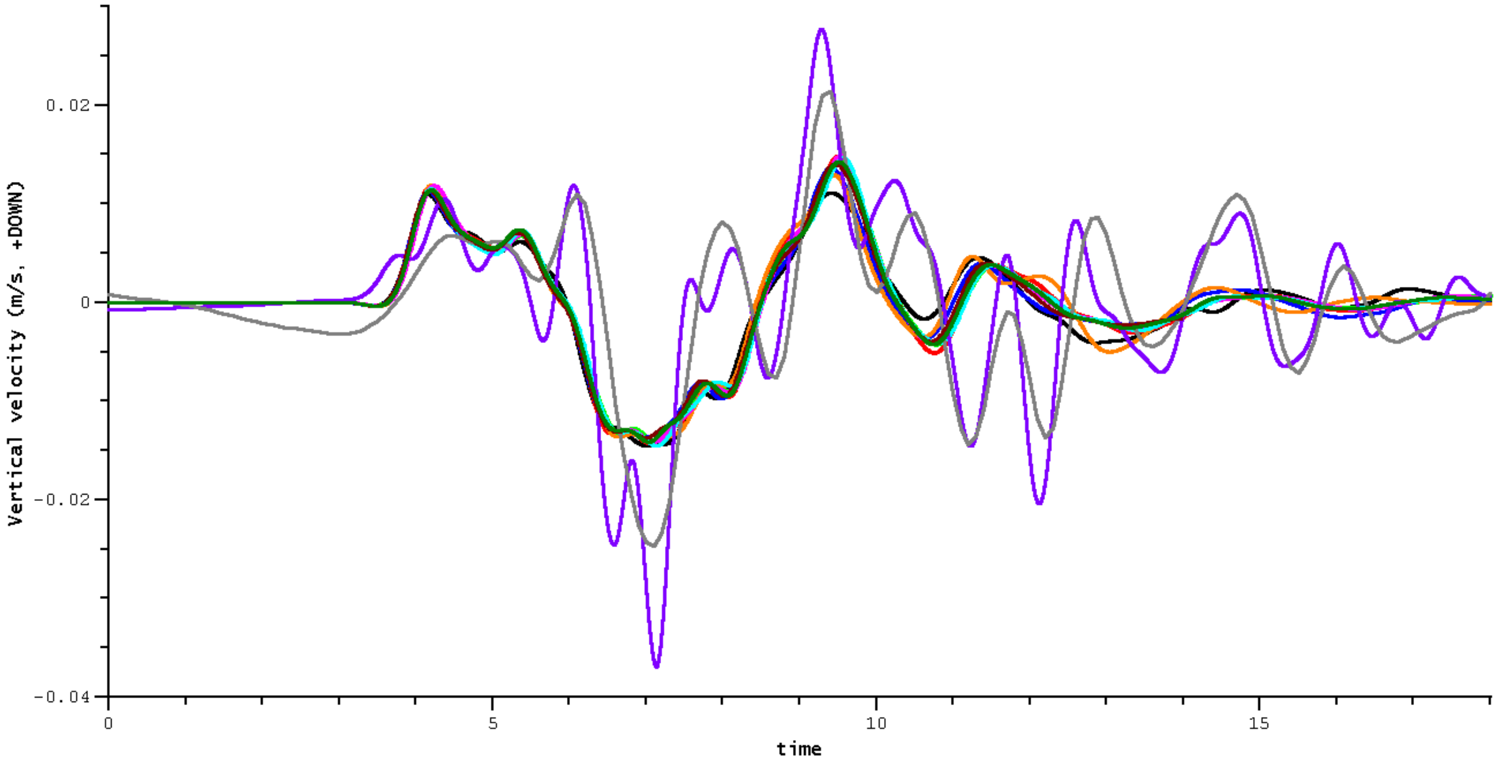


x = −13363
z = 4875

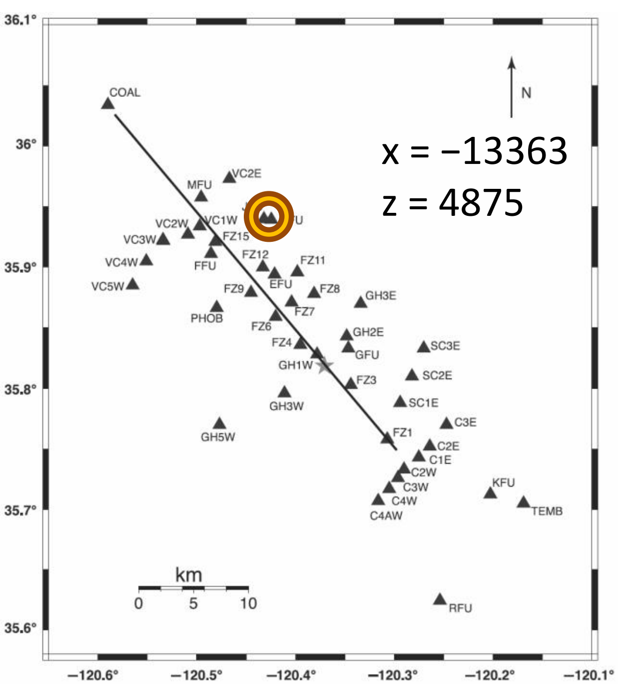
4064_donna [DFU] — Donna Lee — Fault-Perpendicular

Model peak velocity agrees with NGA West 2 data.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



Metrics:
Qcc = 11
Qcd = 101
Qdd = 38

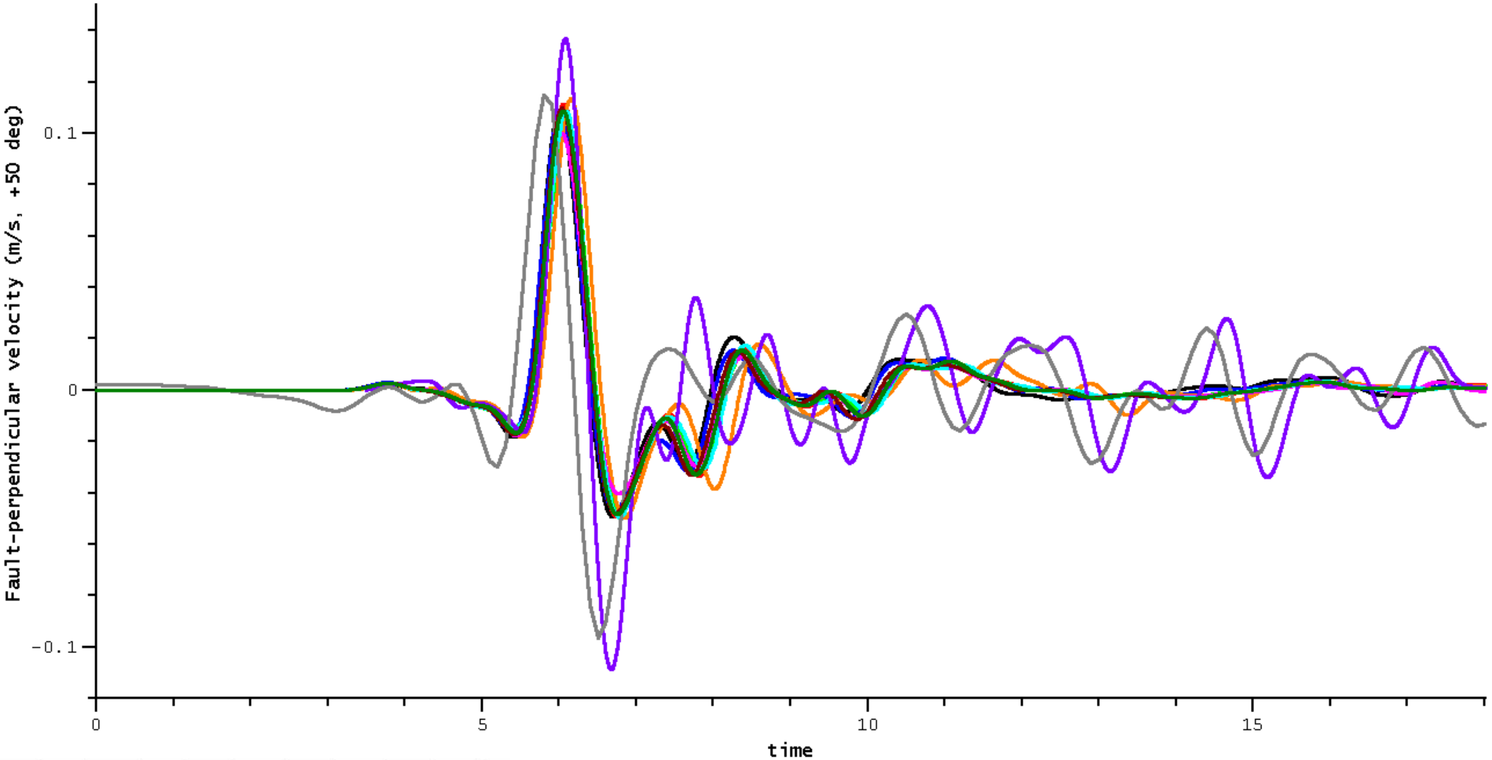


x = −13363
z = 4875

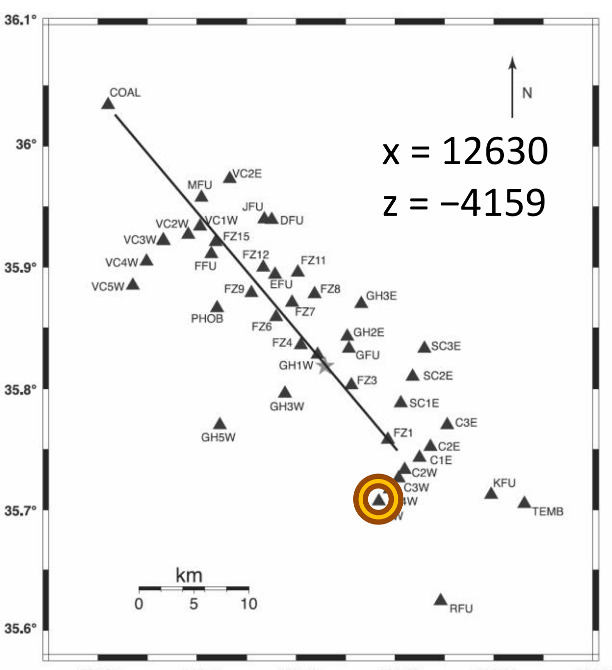
4064_donna [DFU] — Donna Lee — Vertical

Model and data waveforms are similar for first 11 seconds, but data has more wiggles.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



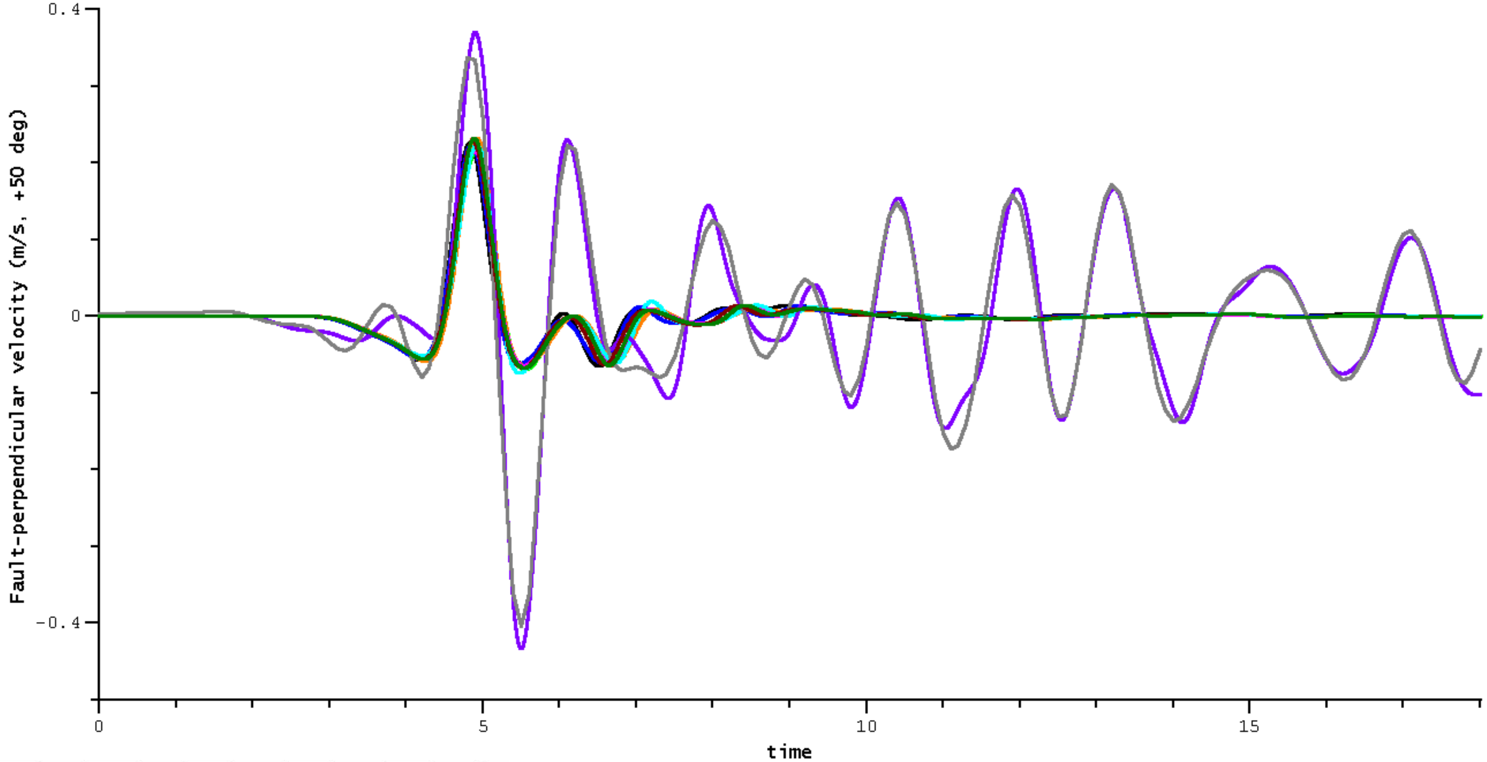
Metrics:
Qcc = 17
Qcd = 84
Qdd = 41



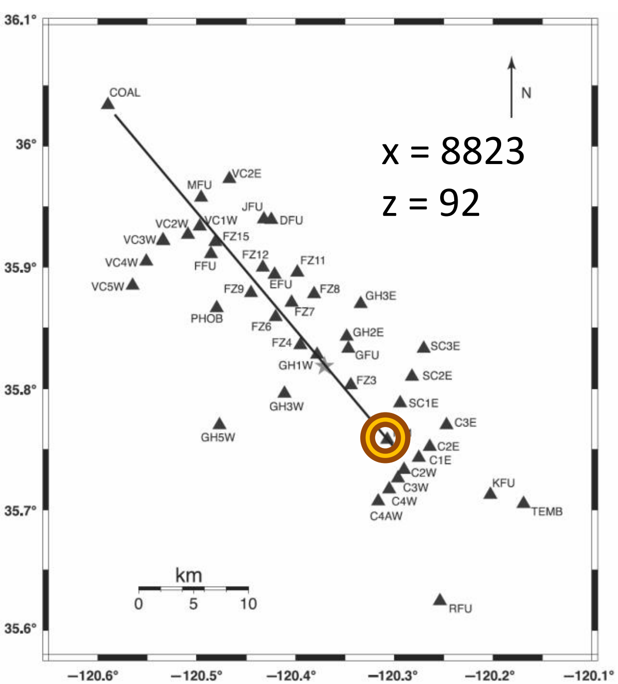
4104_c4a [C4AW] — Cholame 4AW — Fault-Perpendicular

Model peak velocity agrees with data.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



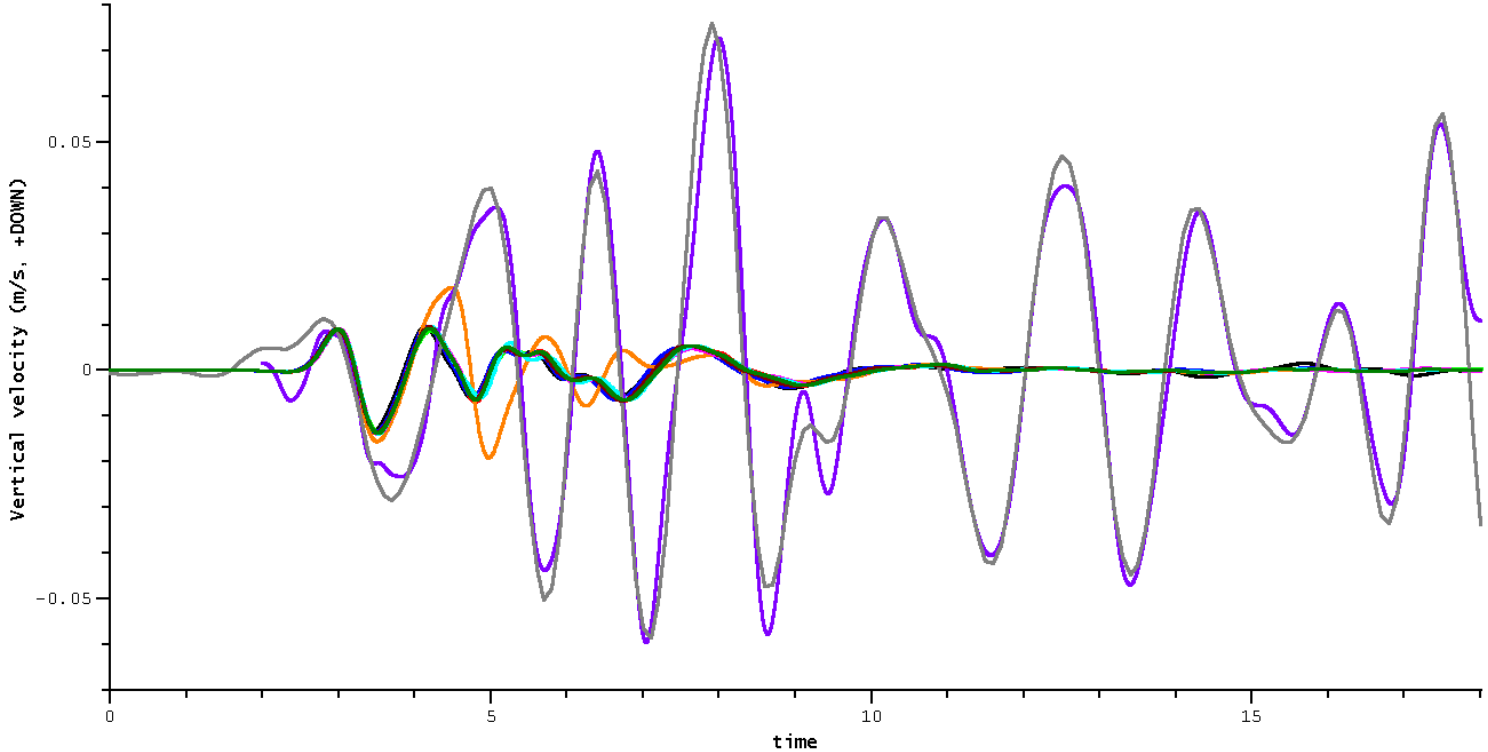
Metrics:
Qcc = 11
Qcd = 140
Qdd = 27



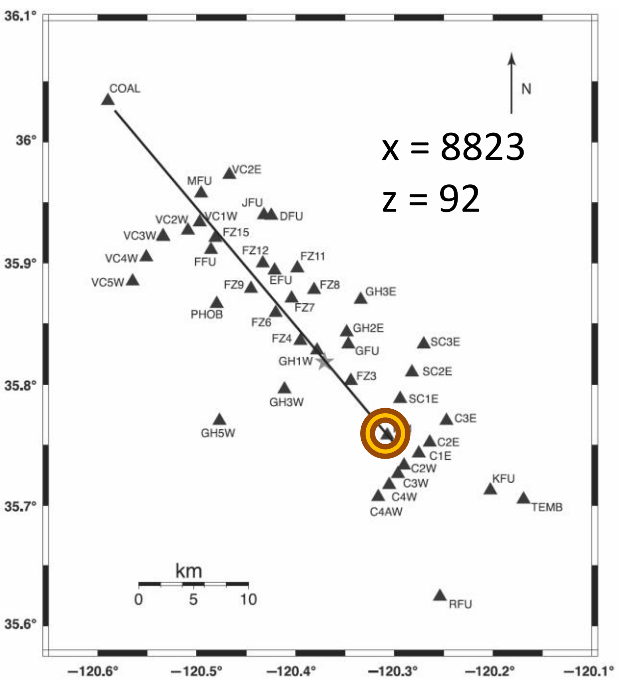
4107_cow [FZ1] — Fault Zone 1 — Fault-Perpendicular

Model peak velocity is only half the data peak velocity. Data continues oscillating long after the model has stopped.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



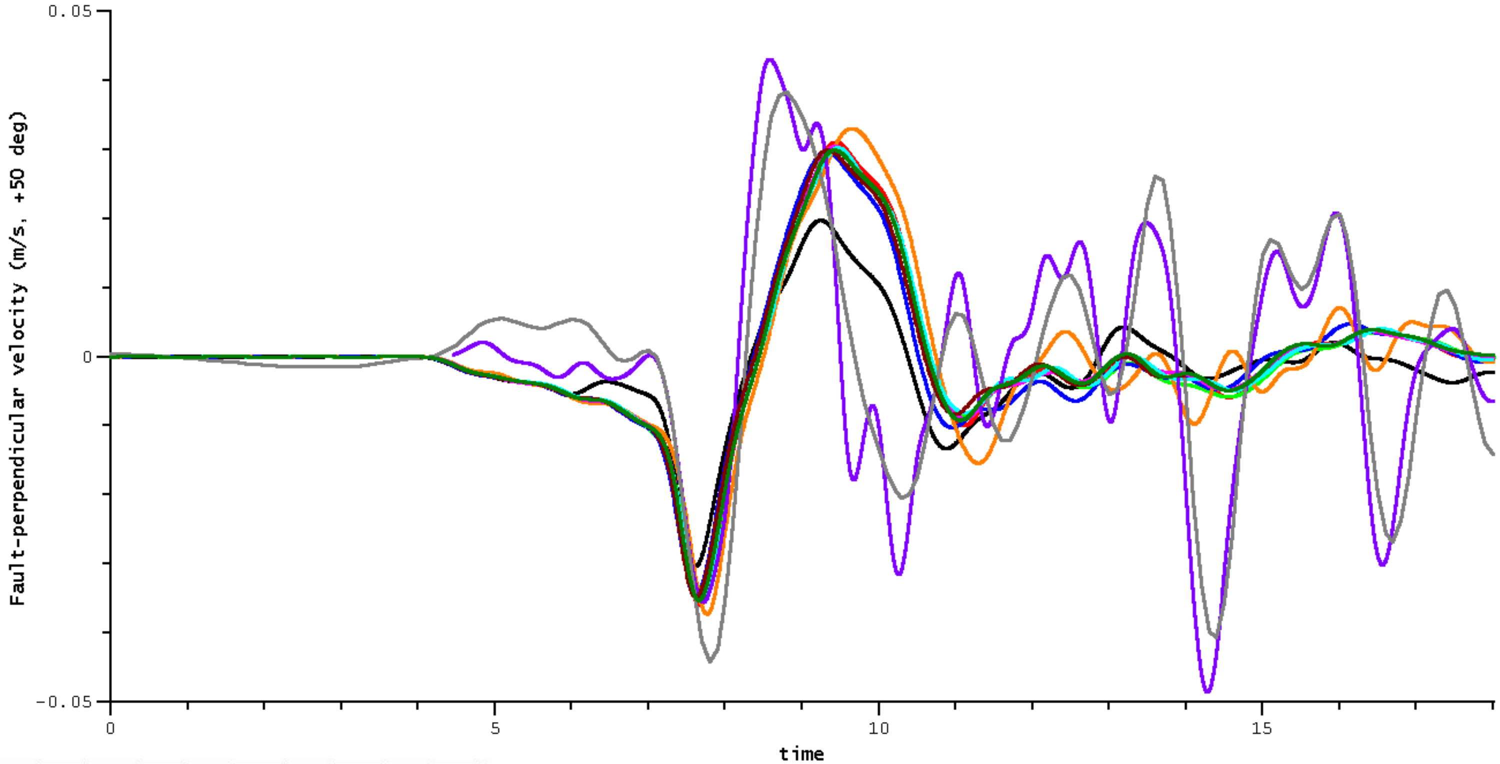
Metrics:
Qcc = 11
Qcd = 140
Qdd = 27



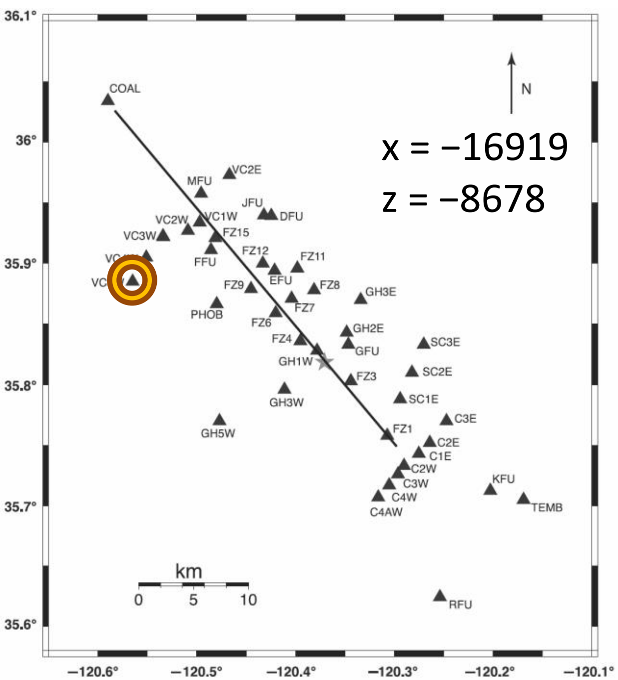
4107_cow [FZ1] — Fault Zone 1 — Vertical

Model peak velocity is much smaller than the data peak velocity, and arrives much earlier.

aslam (Khurram Aslam - Daub Finite Difference Code)
bai.2 (Kangchen Bai - specfem3D_GPU-25m)
barall.2 (Michael Barall - FaultMod - 50 m)
bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
chen (Xiaofei Chen - CGFDM - 100m)
dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
ma (Shuo Ma - Finite Element - MAFE - 100m)
nature.2 (Nature - Data from NGA West 2)
nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
ulrich.2 (ADER-DG-o5-200m on fault)



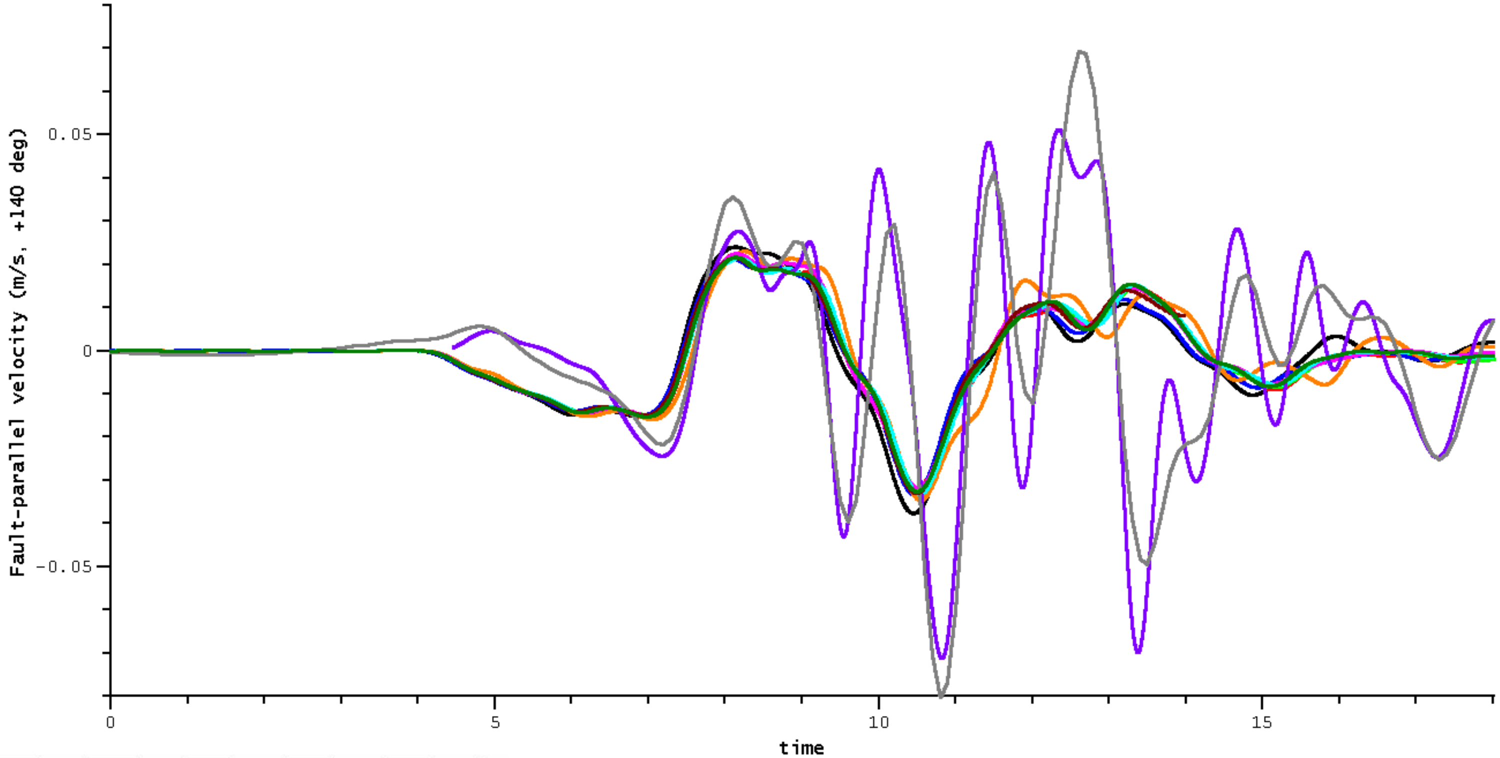
Metrics:
Qcc = 16
Qcd = 124
Qdd = 40



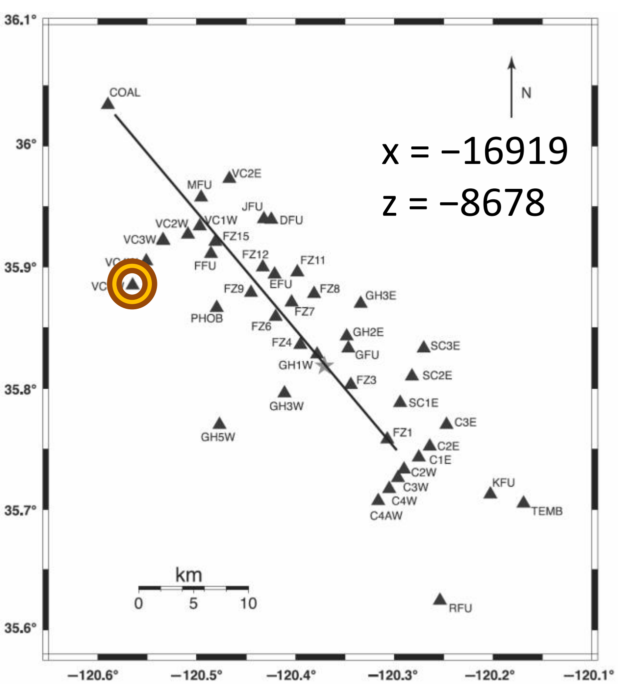
4136_vc5 [VC5W] — Vineyard Canyon 5W — Fault-Perpendicular

Model and data maybe have some similarity, but it's questionable.

aslam (Khurram Aslam - Daub Finite Difference Code)
bai.2 (Kangchen Bai - specfem3D_GPU-25m)
barall.2 (Michael Barall - FaultMod - 50 m)
bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
chen (Xiaofei Chen - CGFDM - 100m)
dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
ma (Shuo Ma - Finite Element - MAFE - 100m)
nature.2 (Nature - Data from NGA West 2)
nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
ulrich.2 (ADER-DG-o5-200m on fault)



Metrics:
Qcc = 16
Qcd = 124
Qdd = 40



x = −16919
z = −8678

4136_vc5 [VC5W] — Vineyard Canyon 5W — Fault-Parallel

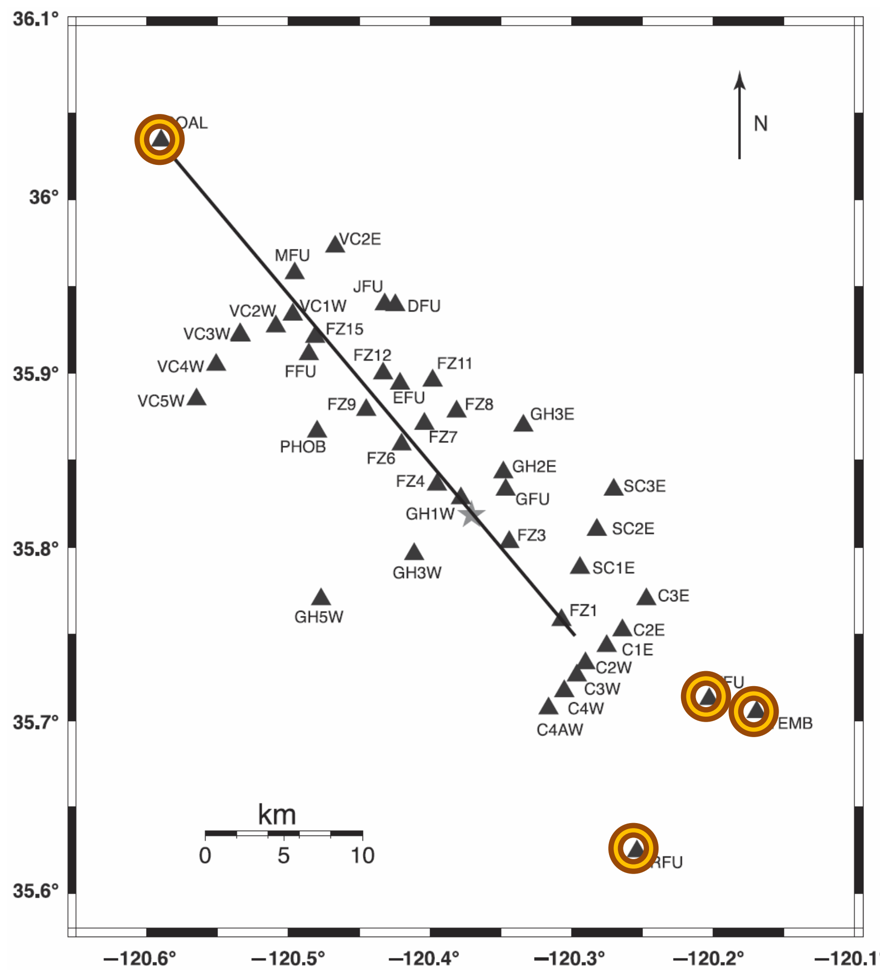
Model and data maybe have some similarity, but it’s questionable.

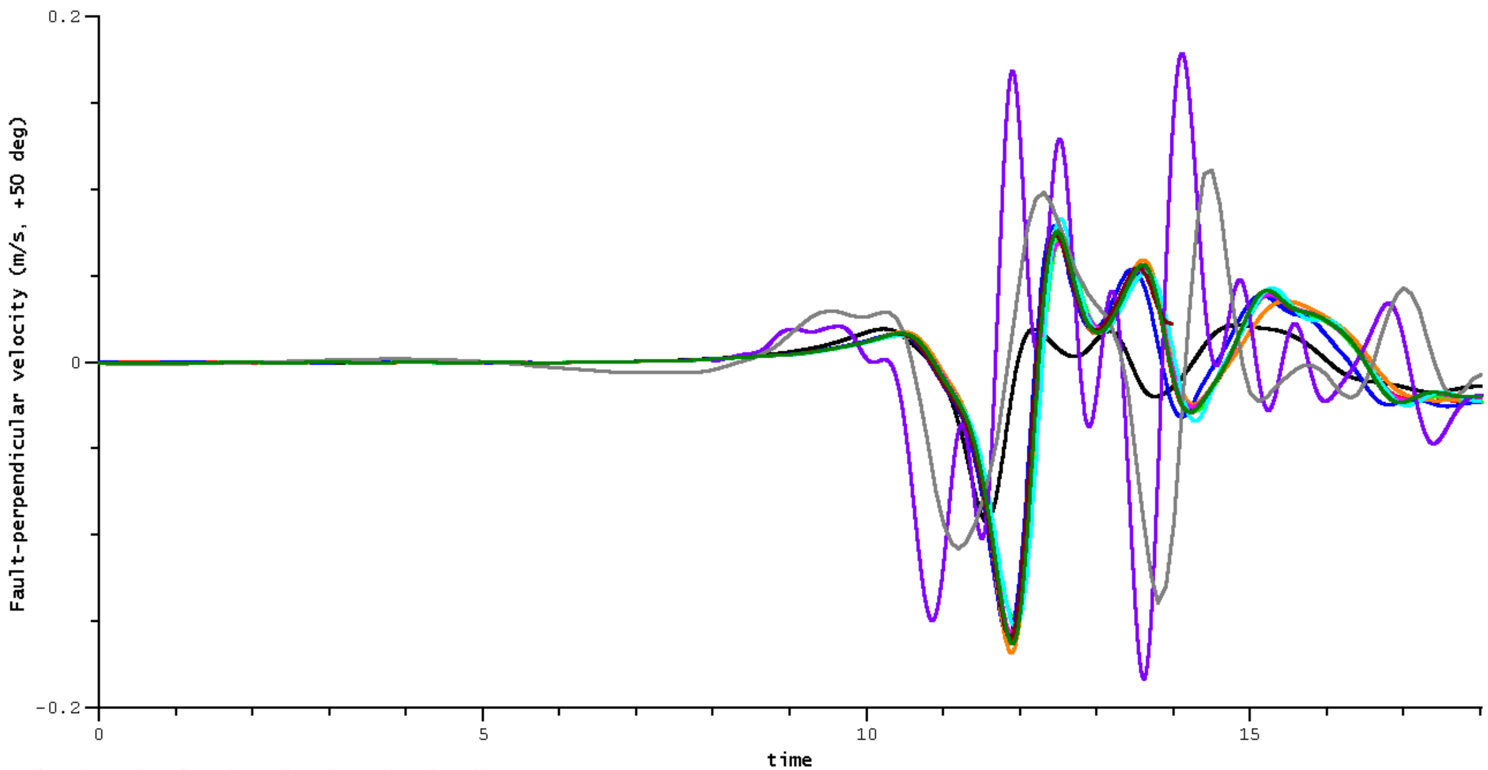
- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)

	3d-disp	3d-vel	t-shift		3d-disp	3d-vel	t-shift
4064_donna	11.9	11.0	0.038	4112_z08	7.0	11.1	0.032
4065_eades	11.2	9.9	0.032	4113_z09	14.7	11.1	0.048
4066_froel	15.5	9.5	0.051	4114_z11	8.5	12.3	0.035
4067_gold	9.3	11.1	0.031	4115_prk	12.6	9.4	0.037
4069_jack	24.8	21.8	0.064	4117_z15	16.9	9.4	0.044
4070_joaqu	12.0	10.4	0.045	4118_pg1	19.4	14.4	0.036
4071_middl	16.5	9.6	0.051	4119_gh2	7.7	10.9	0.033
4072_redh	26.2	33.3	0.096	4121_gh3	7.0	9.5	0.036
4074_viney	14.9	12.4	0.054	4122_pg3	8.6	10.0	0.048
4097_scn	26.5	23.5	0.100	4124_pg5	13.7	13.6	0.064
4098_c01	18.6	12.8	0.031	4126_sc1	14.6	13.2	0.036
4099_tm2	17.8	13.5	0.041	4127_sc2	11.7	12.1	0.033
4100_c02	20.3	15.9	0.048	4128_sc3	11.7	10.0	0.034
4101_tm3	16.0	15.2	0.037	4129_36510	26.9	26.3	0.058
4102_c03	17.9	14.0	0.051	4131_vc1	17.3	10.2	0.053
4103_c04	16.8	14.9	0.050	4132_pgd	14.6	11.4	0.043
4104_c4a	16.4	17.2	0.053	4133_vc2	15.9	9.9	0.056
4107_cow	18.2	11.3	0.035	4134_vyc	15.8	13.3	0.056
4108_coh	21.2	12.4	0.029	4135_vc4	15.6	13.8	0.055
4109_z04	14.8	11.9	0.047	4136_vc5	17.9	16.2	0.061
4110_z06	13.7	10.1	0.043	8486_nphob	10.4	13.2	0.053
4111_z07	10.2	9.2	0.032				

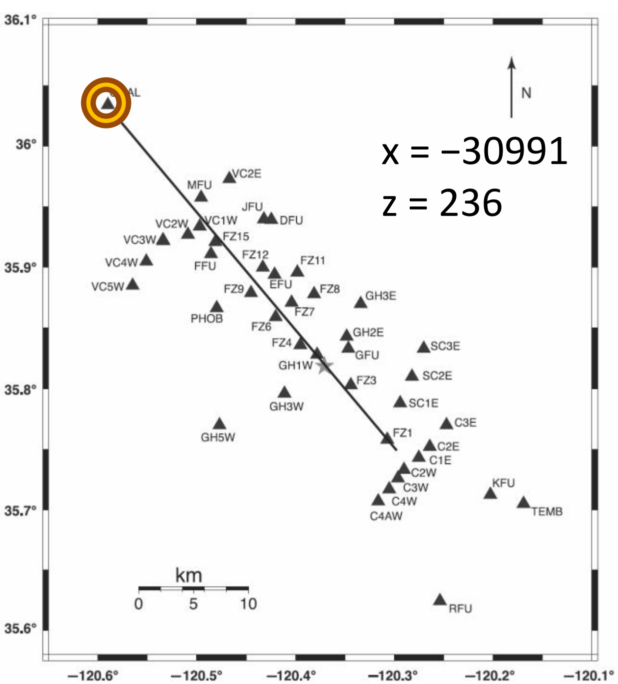
This table shows the average metric values, across all 9 modeling codes (*not* data), for each of the 43 stations.

The 4 stations with the highest (worst) values are the stations about 10 km off the ends of the rupture.





Metrics:
Qcc = 24
Qcd = 123
Qdd = 50

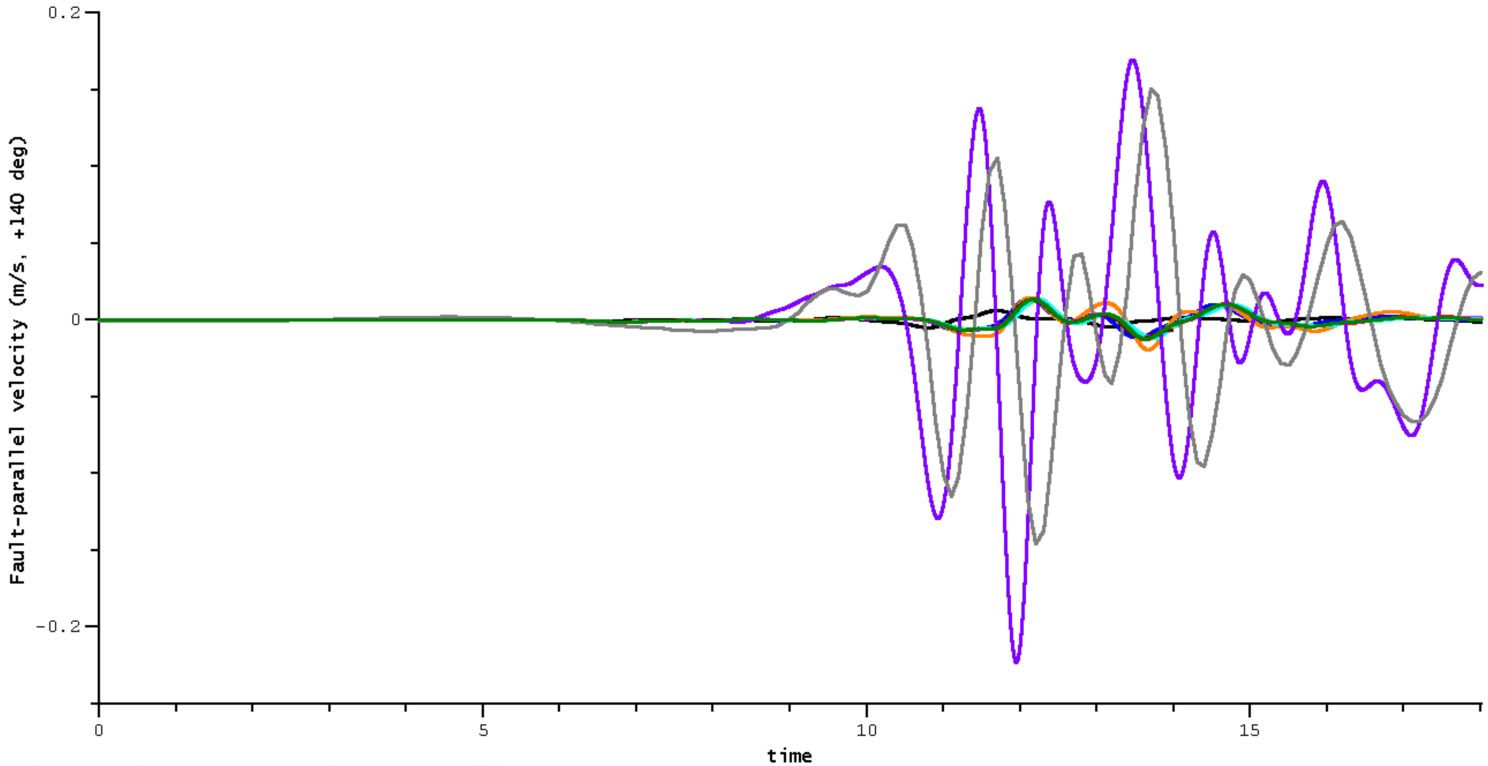


x = −30991
z = 236

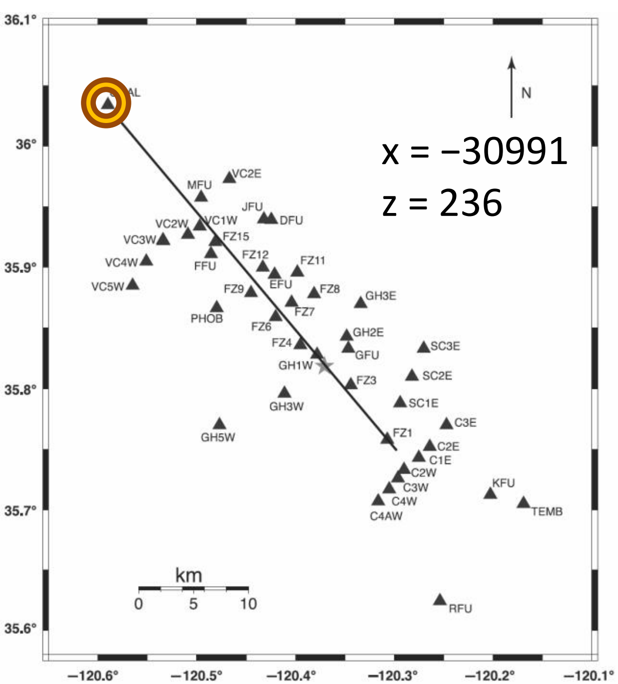
4097_scn [COAL] — Slack Canyon — Fault-Perpendicular

Model and data have roughly the same peak velocity, but waveforms are not too similar. About 7 km from end of rupture.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



Metrics:
Qcc = 24
Qcd = 123
Qdd = 50

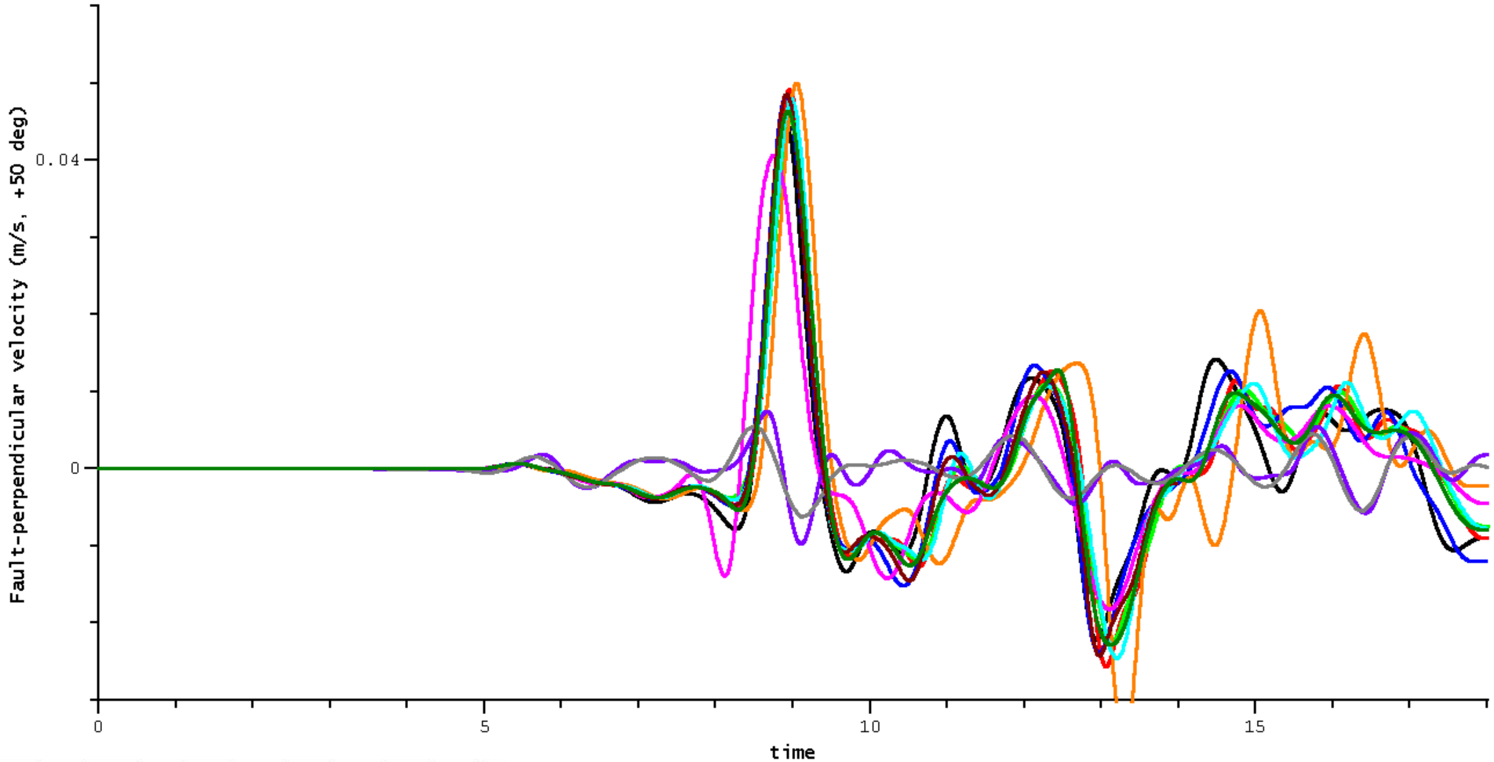


x = −30991
z = 236

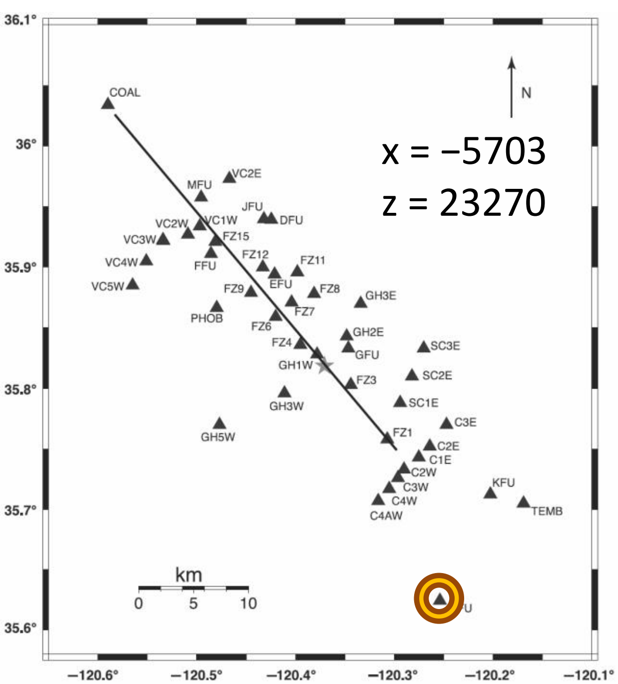
4097_scn [COAL] — Slack Canyon — Fault-Parallel

Data has roughly the same peak velocity as the fault-perpendicular case, but data is an order of magnitude smaller.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)



Metrics:
Qcc = 33
Qcd = 144
Qdd = 50



4072_redh [RFU] — Red Hills — Fault-Perpendicular

Model peak velocity is 5 times the data peak velocity. About 13 km from end of rupture.

- aslam (Khurram Aslam - Daub Finite Difference Code)
- bai.2 (Kangchen Bai - specfem3D_GPU-25m)
- barall.2 (Michael Barall - FaultMod - 50 m)
- bydlon (Sam Bydlon/Kyle Withers - Finite Difference - FD-Q-WaveLab)
- chen (Xiaofei Chen - CGFDM - 100m)
- dliu (Dunyu Liu - Finite Element - EQdyna3Dv4.1.3 - 100m)
- ma (Shuo Ma - Finite Element - MAFE - 100m)
- nature.2 (Nature - Data from NGA West 2)
- nature.3 (Nature - Data from Ma et al. JGR 2008, unfilterable)
- roten.2 (Daniel Roten - Finite Difference - AWM - 50 m)
- ulrich.2 (ADER-DG-o5-200m on fault)

Conclusions

1. All 9 participating codes successfully executed the dynamic rupture model of the 2004 Parkfield earthquake. Agreement between the codes was very good.
2. We compared results to two data sets for the 2004 Parkfield earthquake, one from Ma *et al.* 2008, and one from NGA West 2.
    - Surprisingly, the two data sets are more different from each other than the results of any pair of participating codes.
    - We performed the comparisons using the same techniques, metrics, and standards that we used for earlier (verification) benchmarks.
    - In most cases the synthetic seismograms bear some resemblance to the data. But by our standards, agreement was poor.
3. Did we validate anything?
    - The purpose of validation is to establish that a computer model is a sufficiently accurate representation of reality so that it can be relied upon in some given application.
    - Since we have not specified an application, we cannot say how modeling results should be compared to data, nor can we say how close a match is required.
    - For many applications, the dynamic rupture code would be part of a larger workflow, and we have not addressed how to validate the entire workflow.