Evaluation of the USGS 3D Seismic Model of the San Francisco Bay Area from Moderate Earthquake Waveform Modeling

Arthur Rodgers[1,2], Albert Kottke[3] and Norman Abrahamson[4]

[1]Lawrence Livermore National Laboratory, Livermore, CA

[2]University of California, Berkeley Seismology Laboratory, Berkeley, CA

[3]Pacific Gas and Electric, San Francisco, CA

[3]University of California, Berkeley, Dept. of Civil & Environmental Engineering

USGS San Francisco Bay Area
Seismic Velocity Models for Seismic Hazard
May 16, 2019

This work was supported by
Pacific Gas & Electric Corporation

PG&E Corporation

LLNL-PRES-772607

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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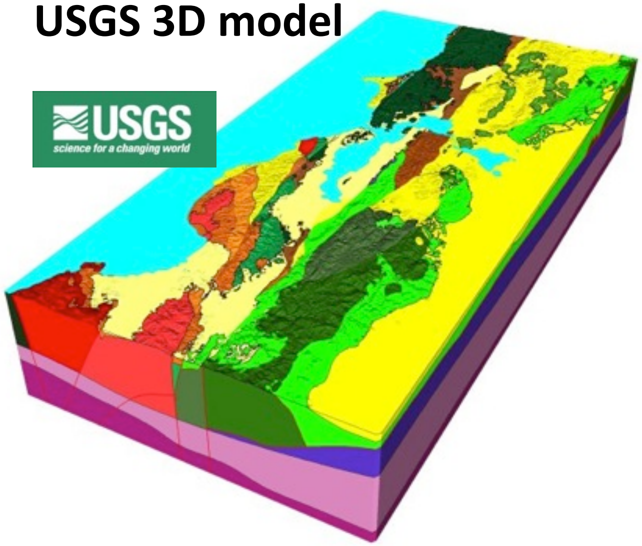
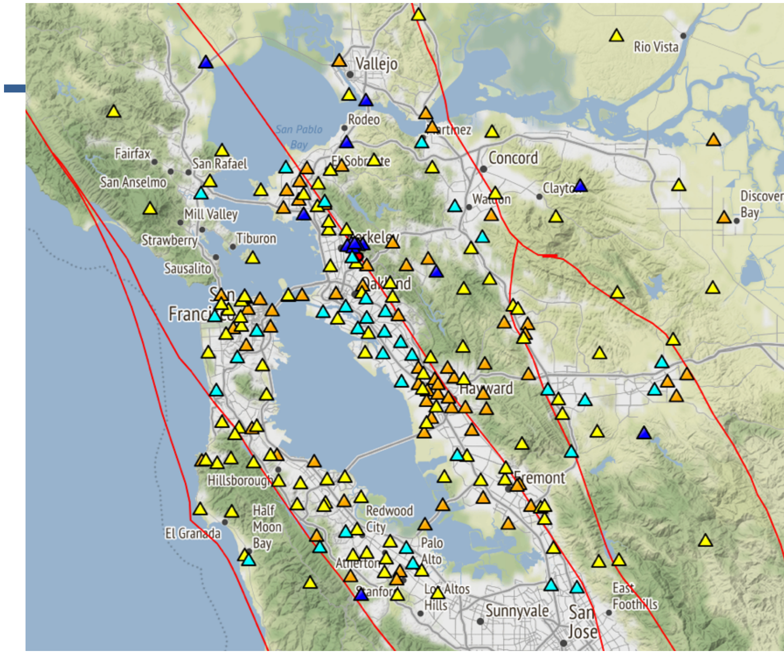
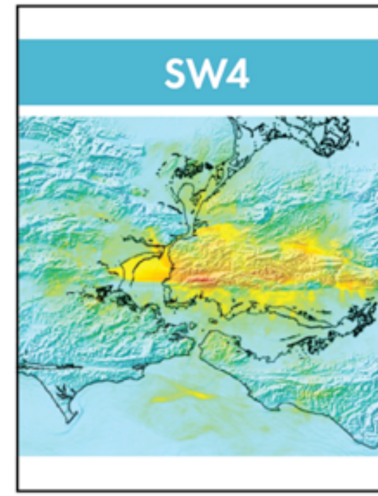
USGS 3D model



Outline





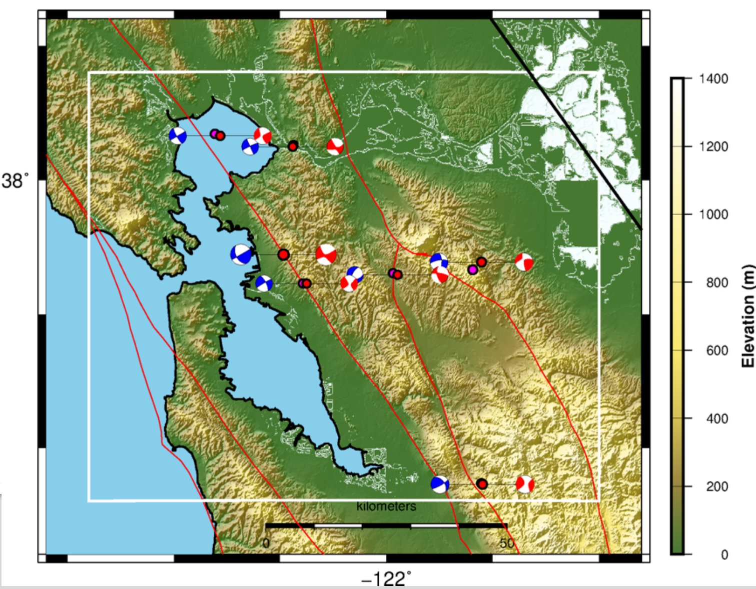
Simulate waveforms with SW4

Moderate earthquakes

Source parameters:

NCSS & DD locations

BSL MT's & NCSN FPFIT



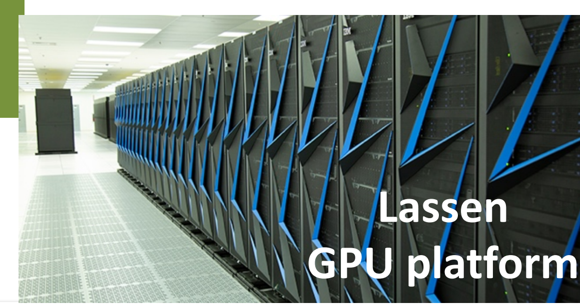
Waveforms from NCEDC

BK (UC Berkeley)

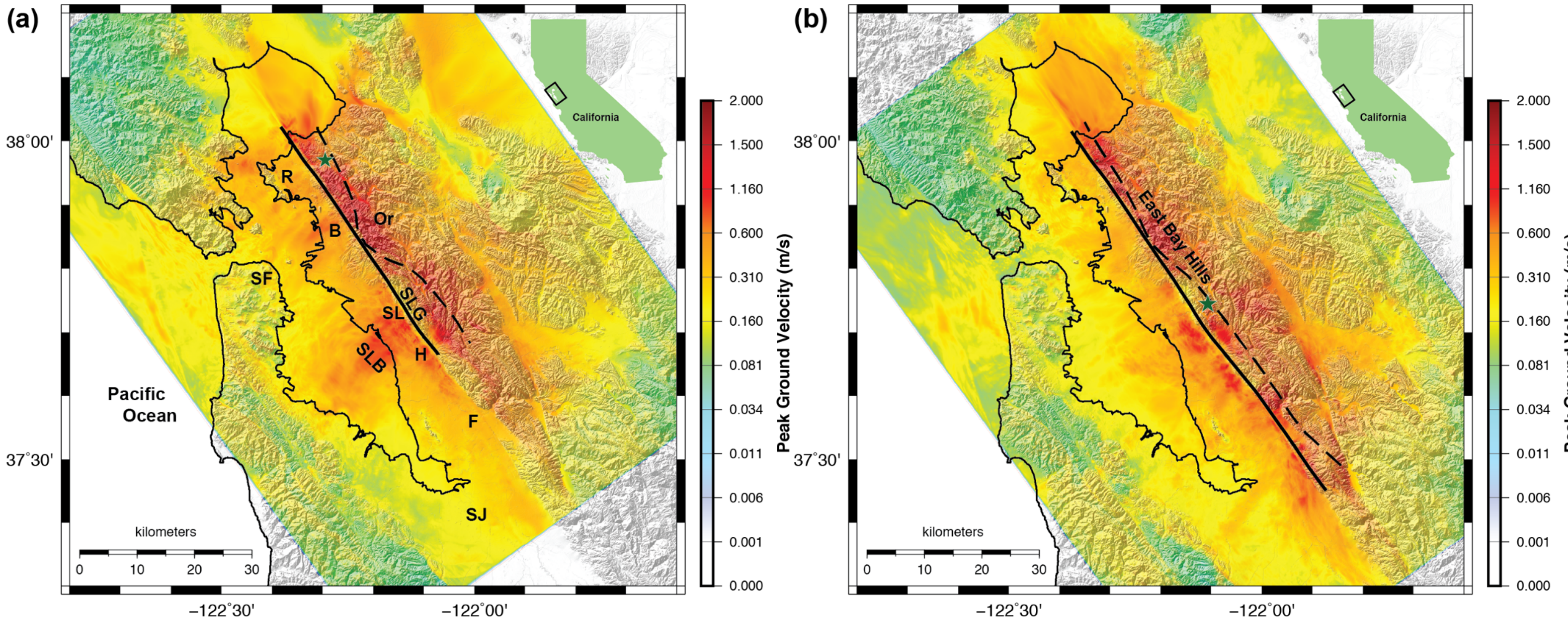
NC (USGS Menlo Park)

NP (ANSS/USGS Golden)

CE (CSMIP/CGS)



3D Hayward Fault M_W 7.0 ground motions (to 4-5 Hz) with USGS 3D model show strong asymmetry



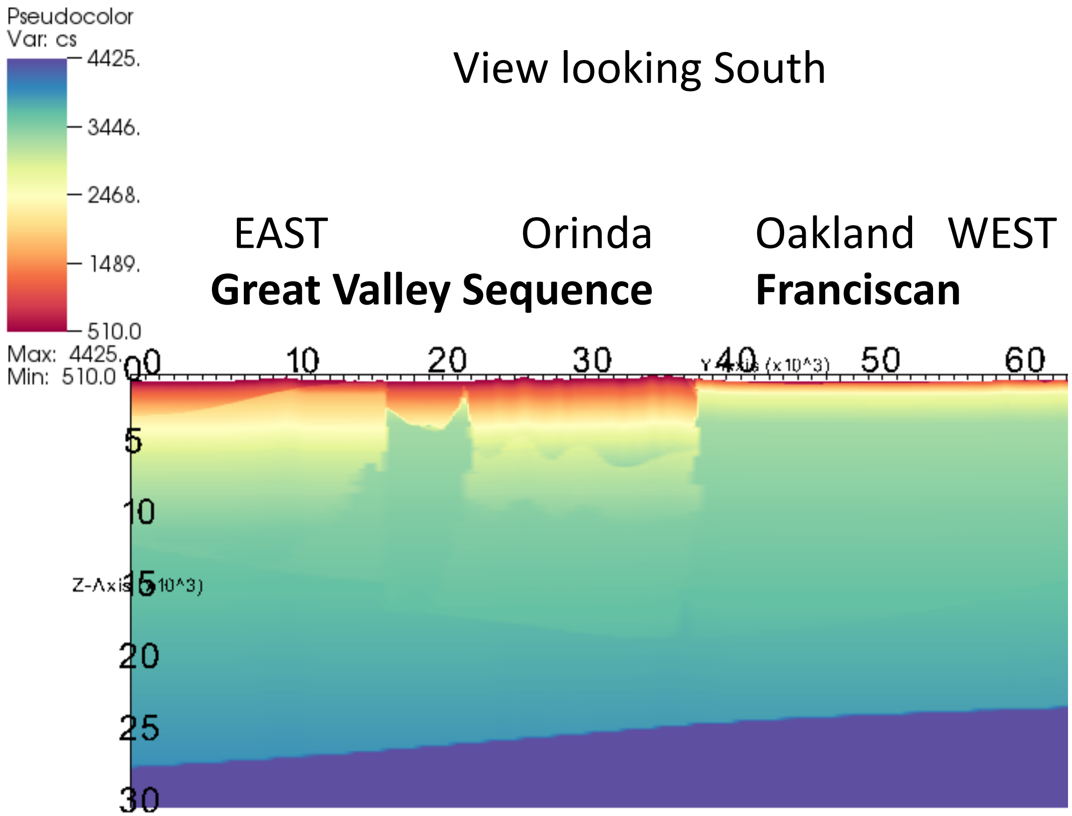
Fault length = 50 km
Resolved frequencies: 0 – 4.2 Hz
Rodgers et al. (GRL, 2018)

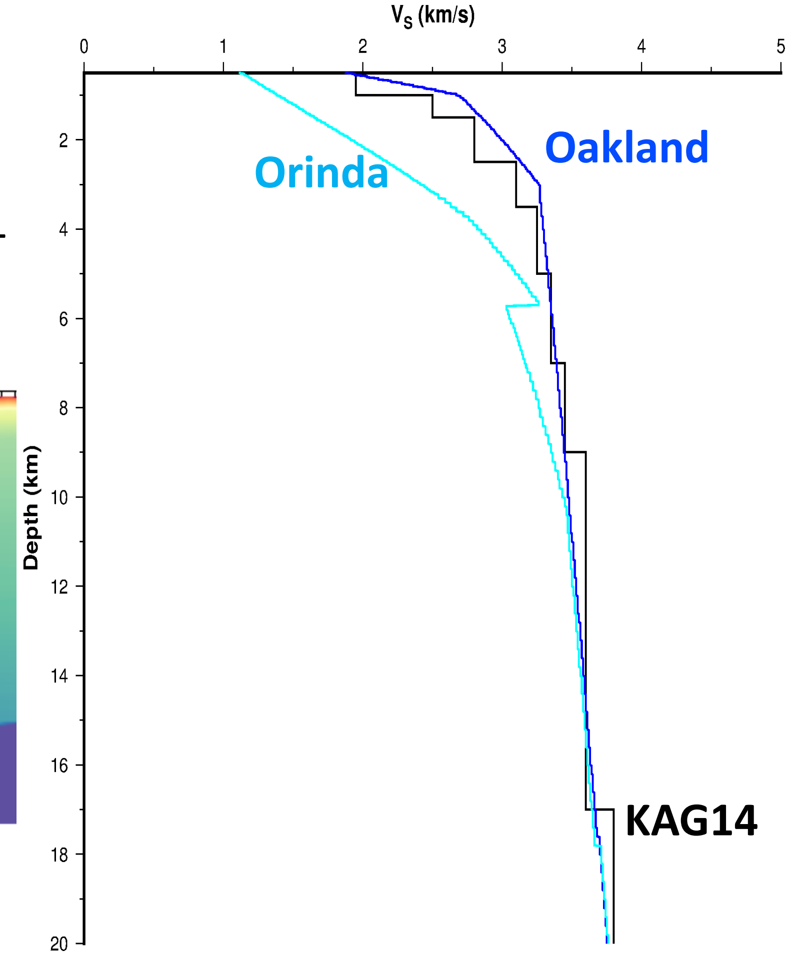
Fault length = 77 km
Resolved frequencies: 0 – 5.0 Hz
Rodgers et al. (SRL, 2019)

The effect of fault dip and minimum shear wavespeed near HF (BSSA, 2019)

Shear wavespeed across the northern Hayward Fault: cross-section and profiles

View looking South





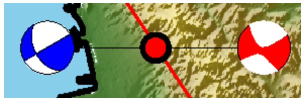
Differences of Vs on either side of the Hayward Fault persists to ~10 km

We started with seven (7) selected events 2016-present, M_W 3.5-4.4

Event locations:

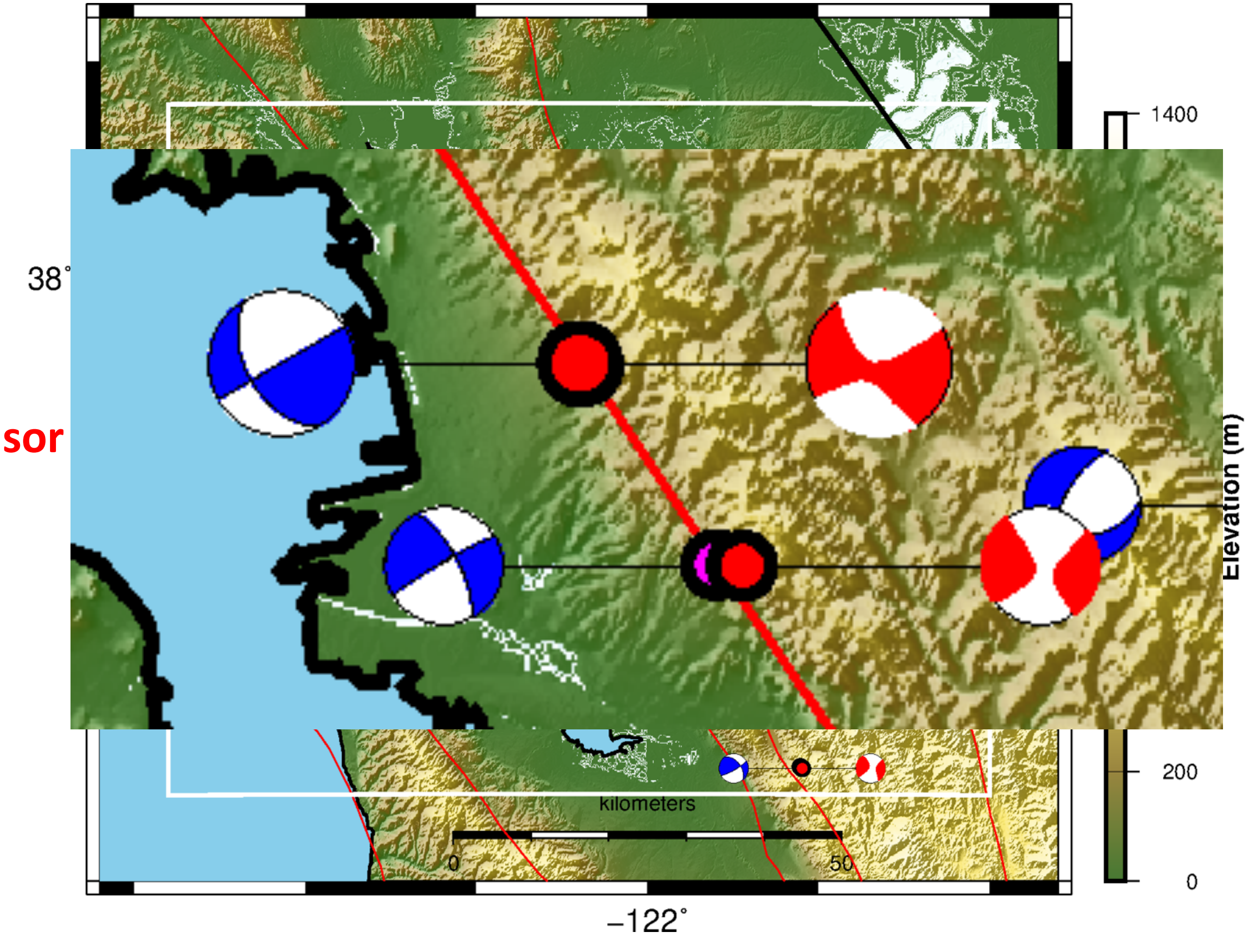
NCSS (routine)

DD (relative)



DC = First-motion focal mechanism

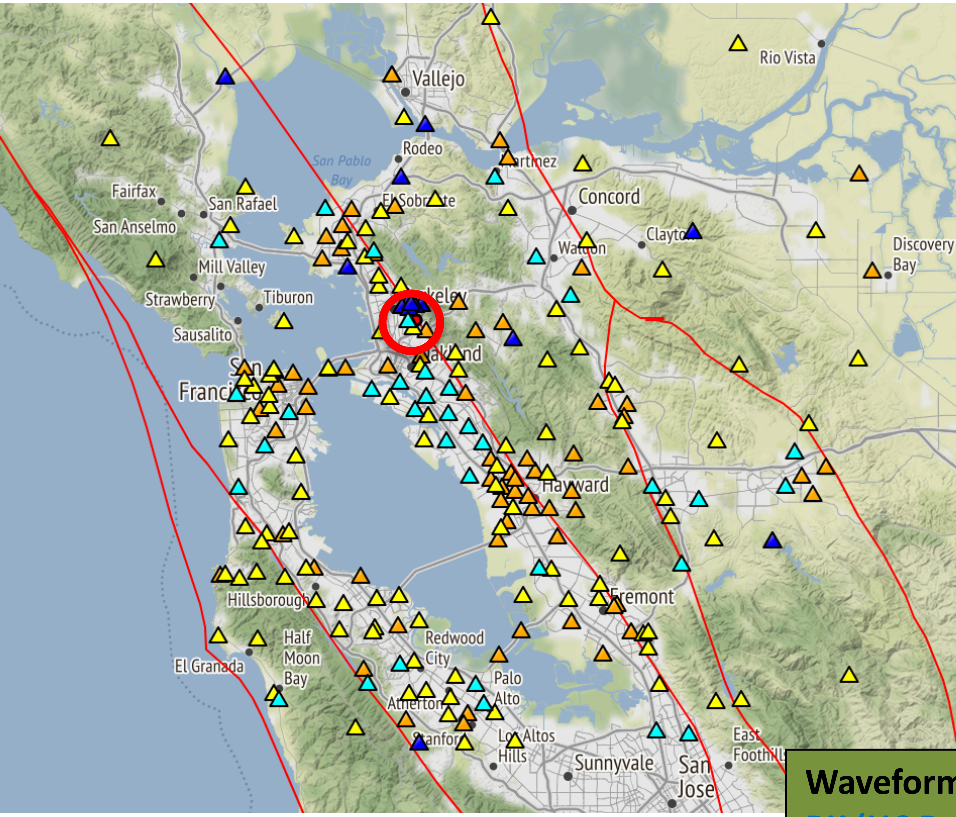
MT = BSL moment tensor



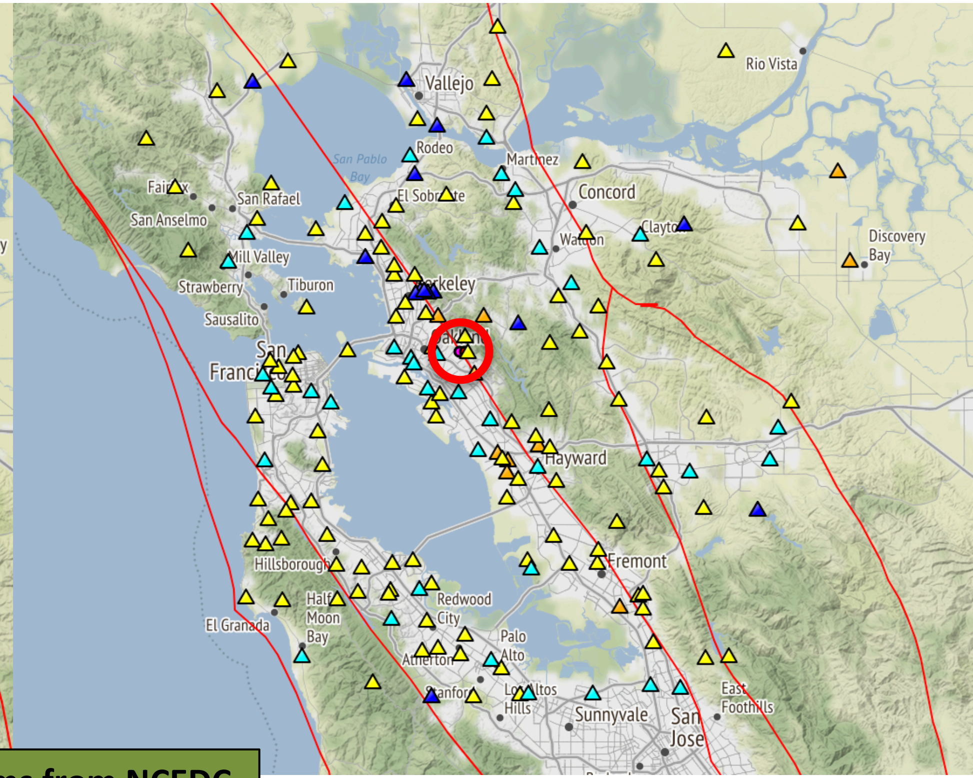
Recent improvements in network operations have increased available data from moderate events

Here, we consider just two events on the Hayward Fault (Berkeley and Piedmont)

2018/01/04 Berkeley (M_W 4.36, z=12.1 km)



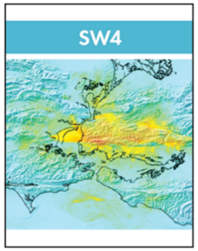
2016/09/13 Piedmont (M_W 3.54, z=3.8 km)



Many CGS/CSMIP stations report!

Waveforms from NCEDC
BK (UC Berkeley)
NC (USGS Menlo Park)
NP (ANSS/USGS Golden)
CE (CSMIP/CGS)

SW4 3D finite difference simulations



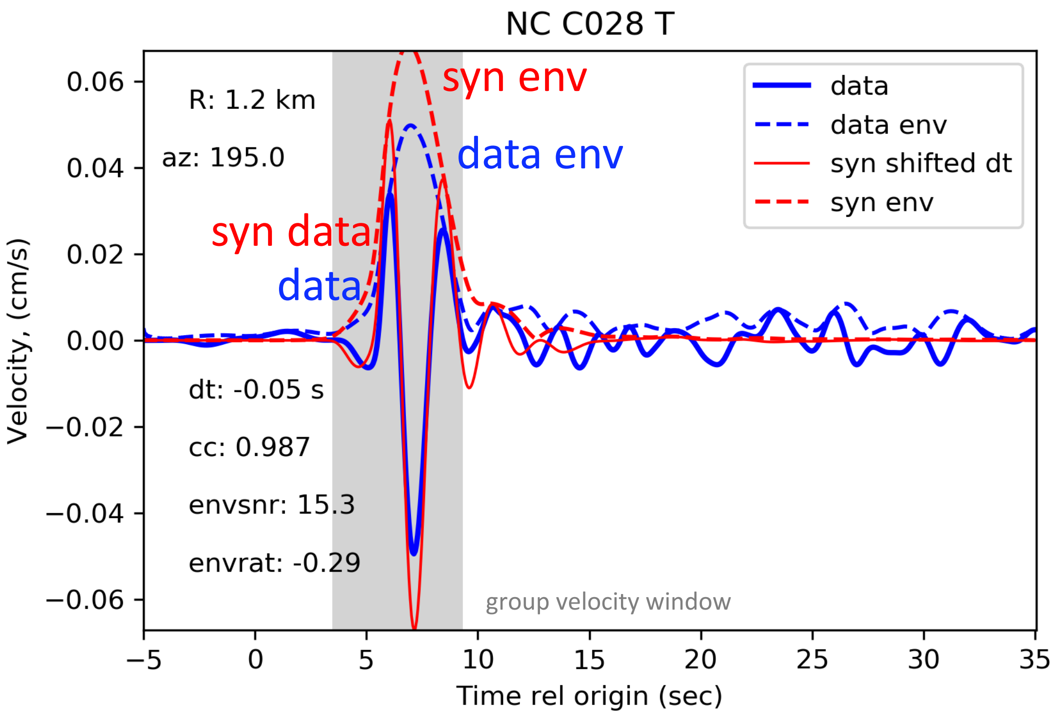
- Domain:
  - 50 x 50 x 30 km, small area, centered on event
- Source parameters:
  - Double difference location and origin time
  - Focal mechanism:
    - MT = BSL (full) moment tensor; or
    - DC = USGS FPFIT double couple focal mechanism
  - Source corner frequency, f_c, following Brune (1970) model
- Earth models:
  - 1DFLAT = Kamai et al. (2014) average 1D model for SFBA, no topography
    - v_{Smin} = 700 m/s
  - 3DTOPO = USGS 3D model with surface topography
    - v_{Smin} = 500 m/s
- Frequency content: resolve up to 3-4 Hz
  - Compare waveforms below 0.5 Hz

Waveform processing and comparison

- Observed waveforms instrument corrected to ground velocity
  - Rotate horizontals, work with transverse and radial
- Bandpass filter data and synthetic: 0.1 – 0.5 Hz (10 – 2 seconds)
- Window direct arrivals with group velocities
  - Use rupture distance: $R_{rup} = \mathrm{sqrt}(R_{JB}^2 + Z^2)$
  - Vertical & radial components (P-SV): 6.0 – 2.0 km/s
  - Transverse (SH): 3.5 – 2.0 km/s
  - Minimum window length, T_{win}: 5 seconds
- Cross-correlate to align traces within δT_{win}
  - δT_{win} depends on distance, allow larger delay time with distance
- Measure
  - dt, delay time – travel time of largest direct waves
  - cc, correlation coeff. – goodness-of-fit, waveform shape (**accept cc $\geq$ 0.5**)
  - evnsrn, envelope signal-to-noise ratio (**accept envsnr $\geq$ 2**)
  - envrat, natural log envelope ratio – compares amplitudes
  - Peak Ground Velocity (PGV) geometric mean of horizontals

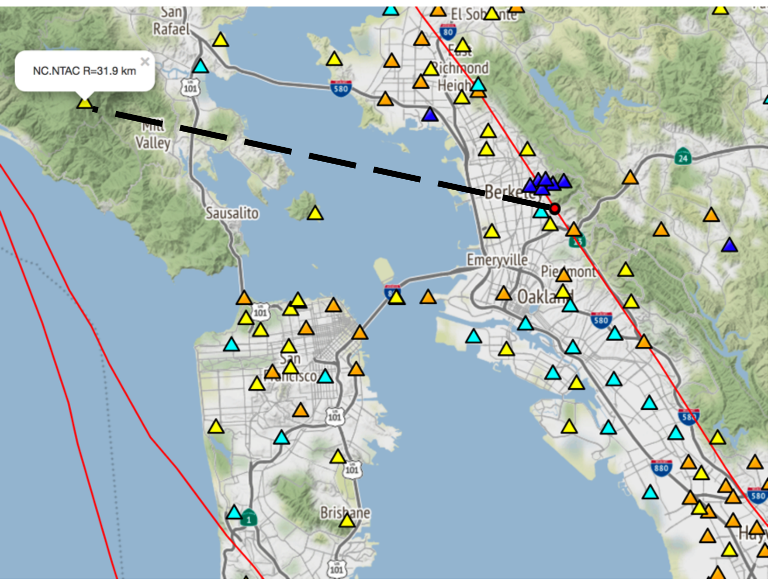
Good fit means: dt near 0, cc near 1.0 and ln(envrat) near 0

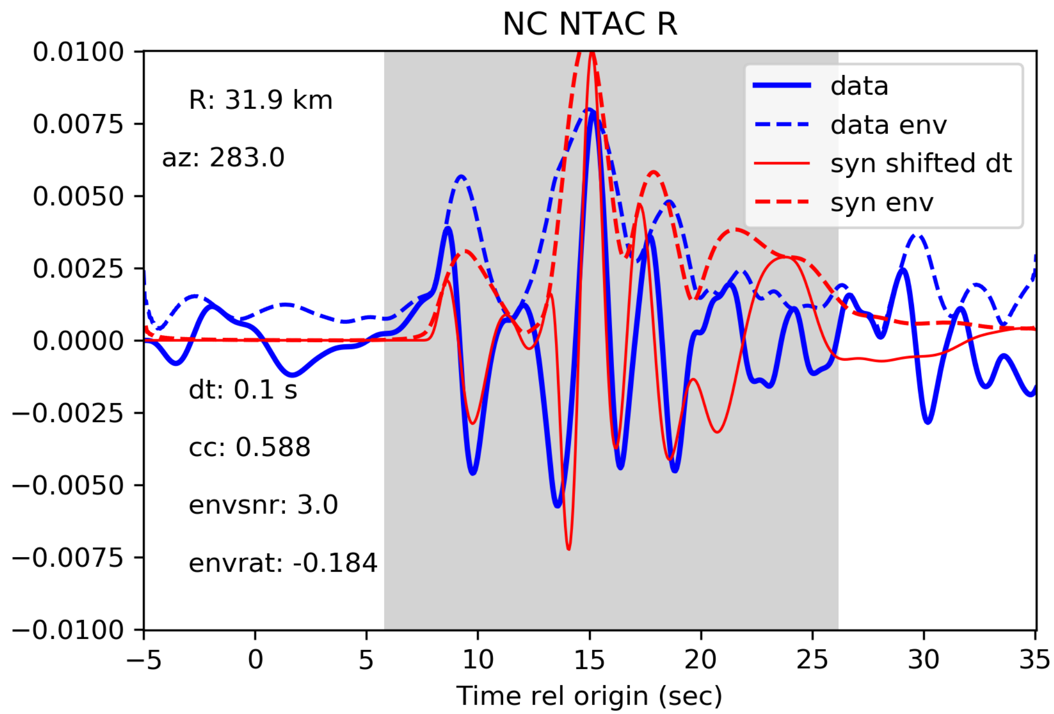
Example waveform comparison
2018/01/04 Berkeley NC.C028 (N. Oakland)



High signal-to-noise ratio and high cc at very close station, accept

Example waveform comparison 2018/01/04 Berkeley at NC.NTAC (Mt Tam Marin)

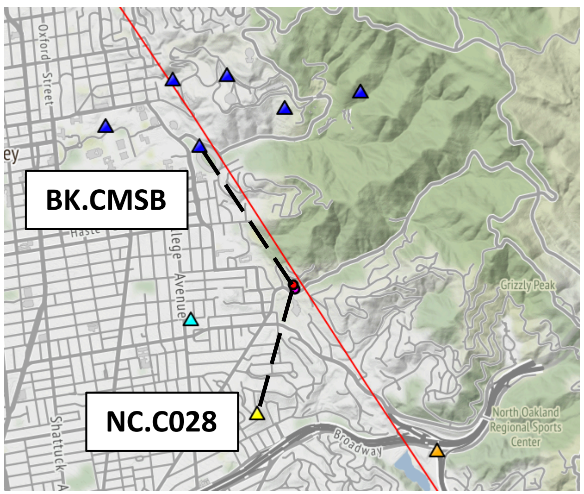




Lower signal-to-noise ratio (envsnr=3.0), but good fit (cc=0.588), accept

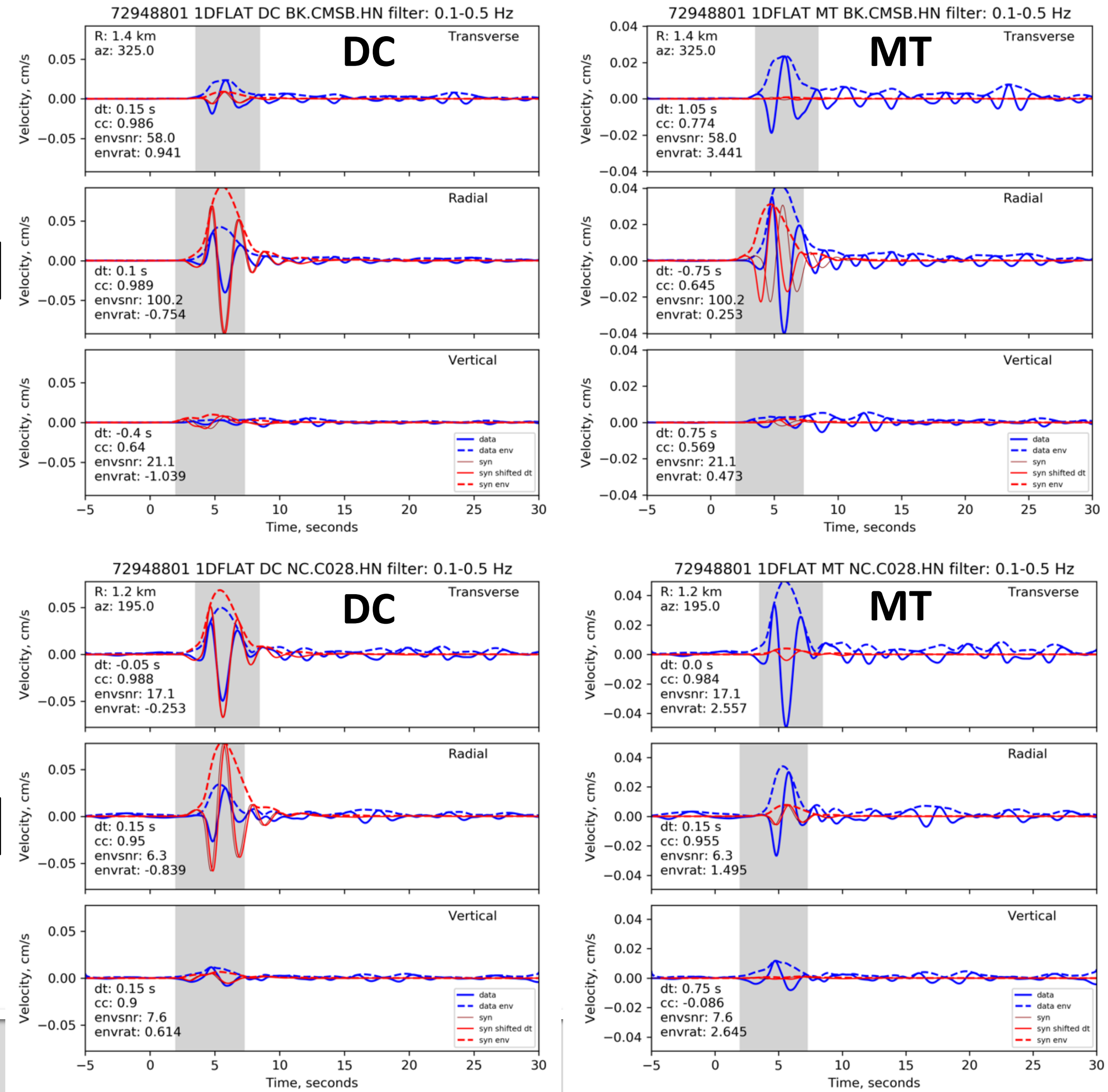
Source mechanism tested with close stations: DC focal mechanisms give better fit than MT

Berkeley Event (2018/01/04)
M_W 4.36
Depth 12.1 km
Earth model: 1DFLAT



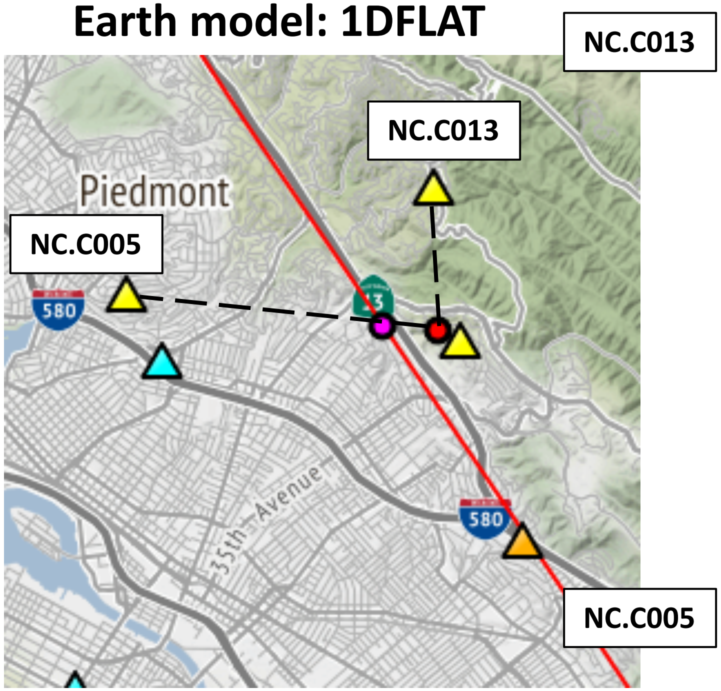
BK.CMSB

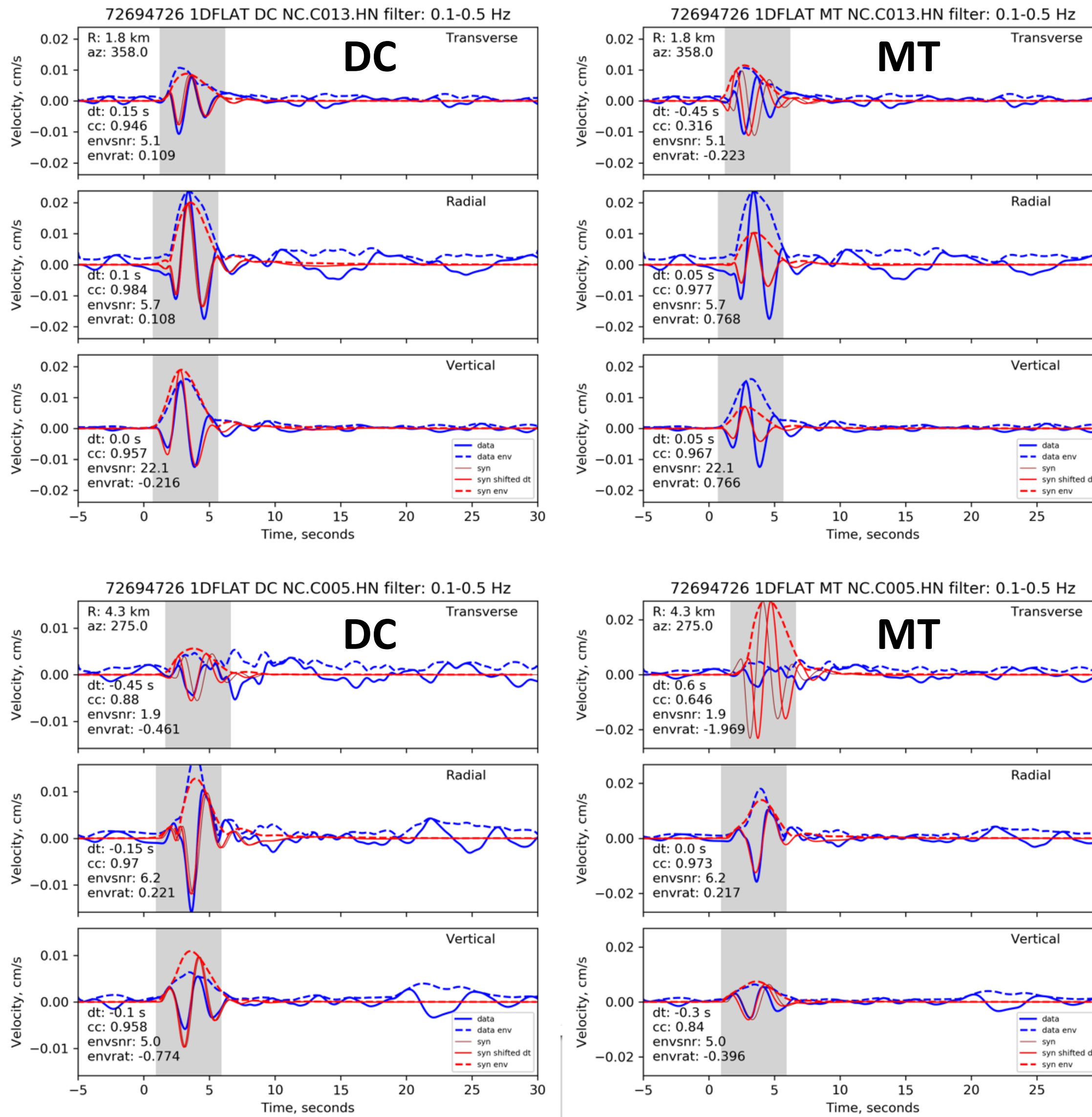
NC.C028



Source mechanism tested with close stations: DC focal mechanisms give better fit than MT

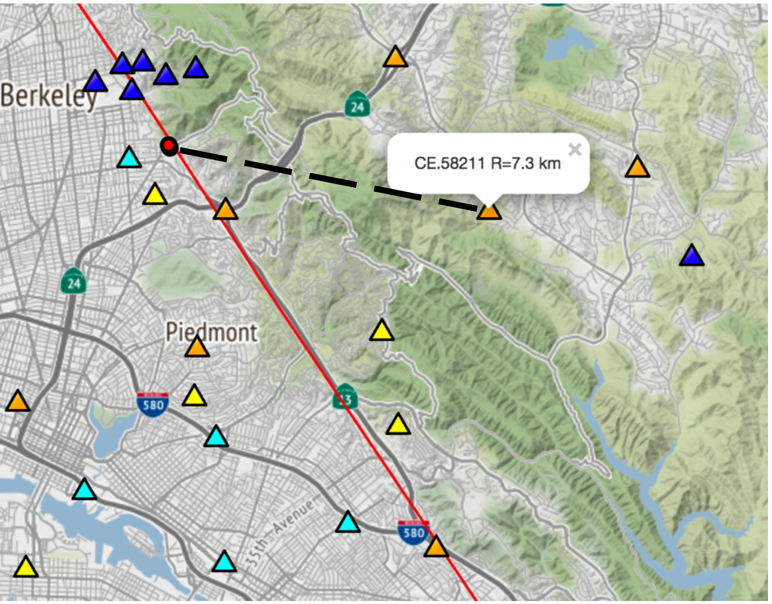
Piedmont Event (2016/09/13)
M_W 3.54
Depth 3.8 km
Earth model: 1DFLAT

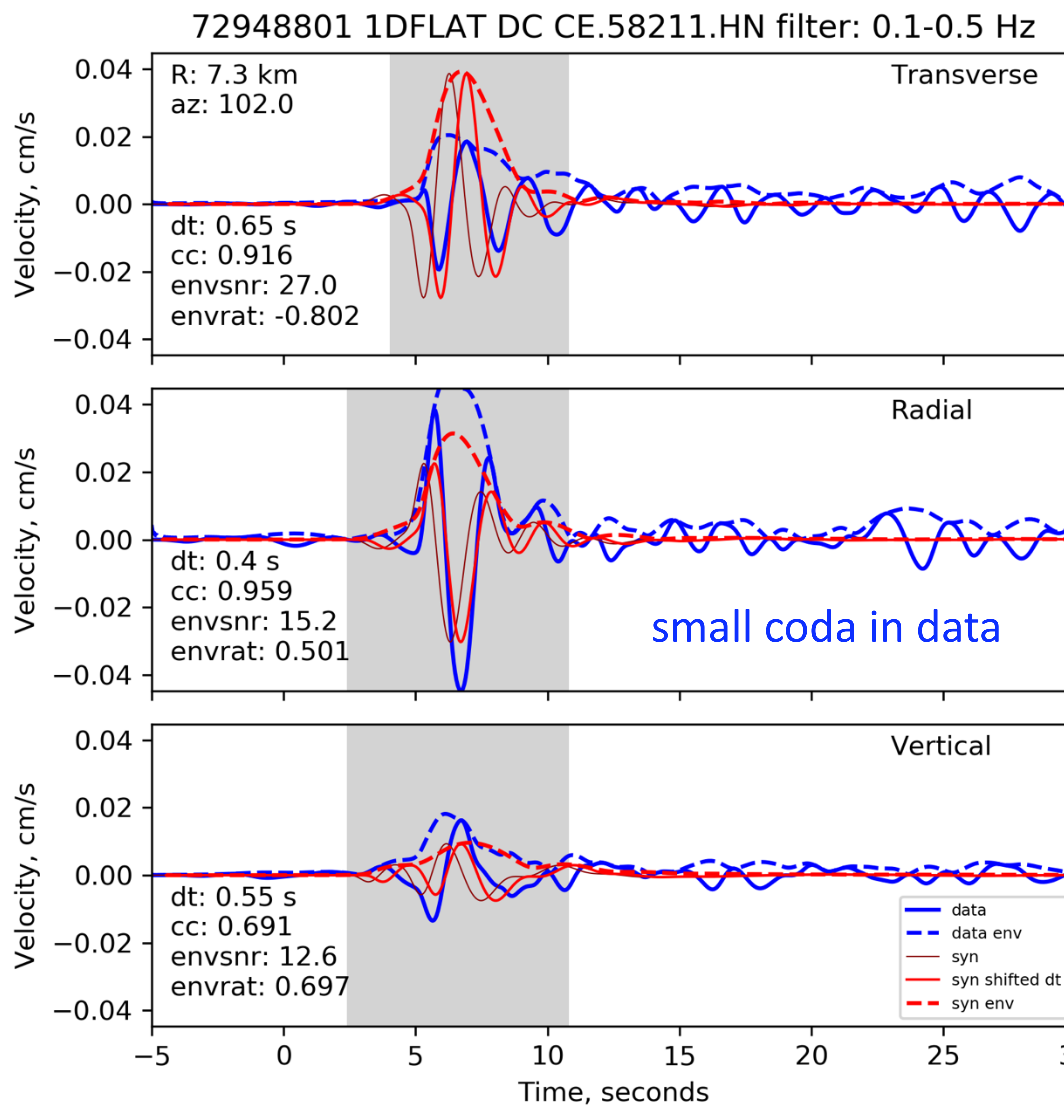




Paths sampling Great Valley Sequence 2018/01/04 Berkeley at CE.58211 (Orinda)

Earth model: 1DFLAT
Focal mech: DC



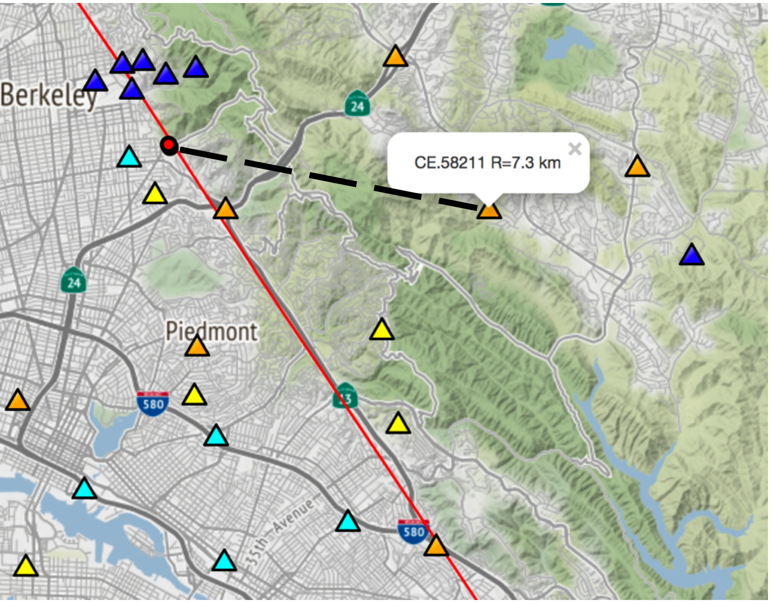


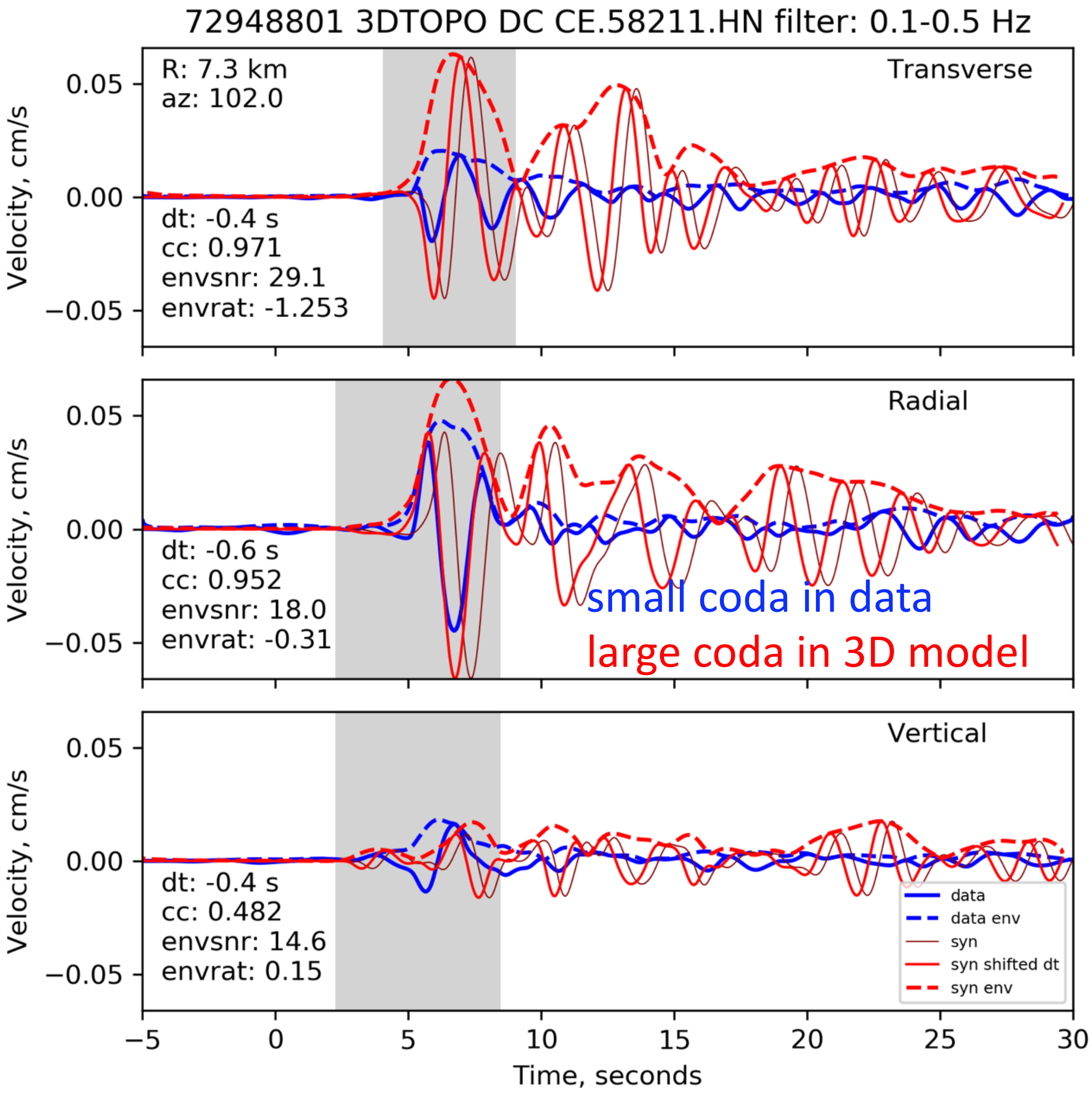
1D model synthetic

- arrives early relative to data
- produces no coda

Paths sampling Great Valley Sequence
2018/01/04 Berkeley at CE.58211 (Orinda)

Earth model: 3DTOPO
Focal mech: DC



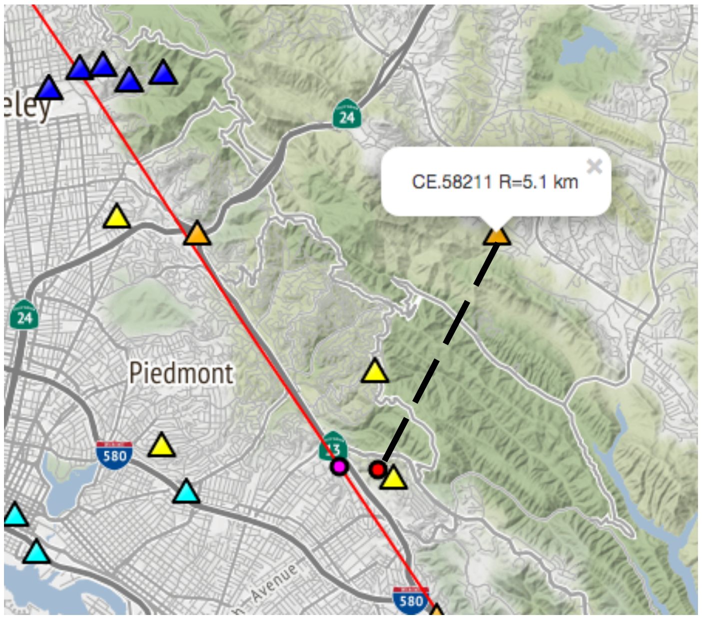


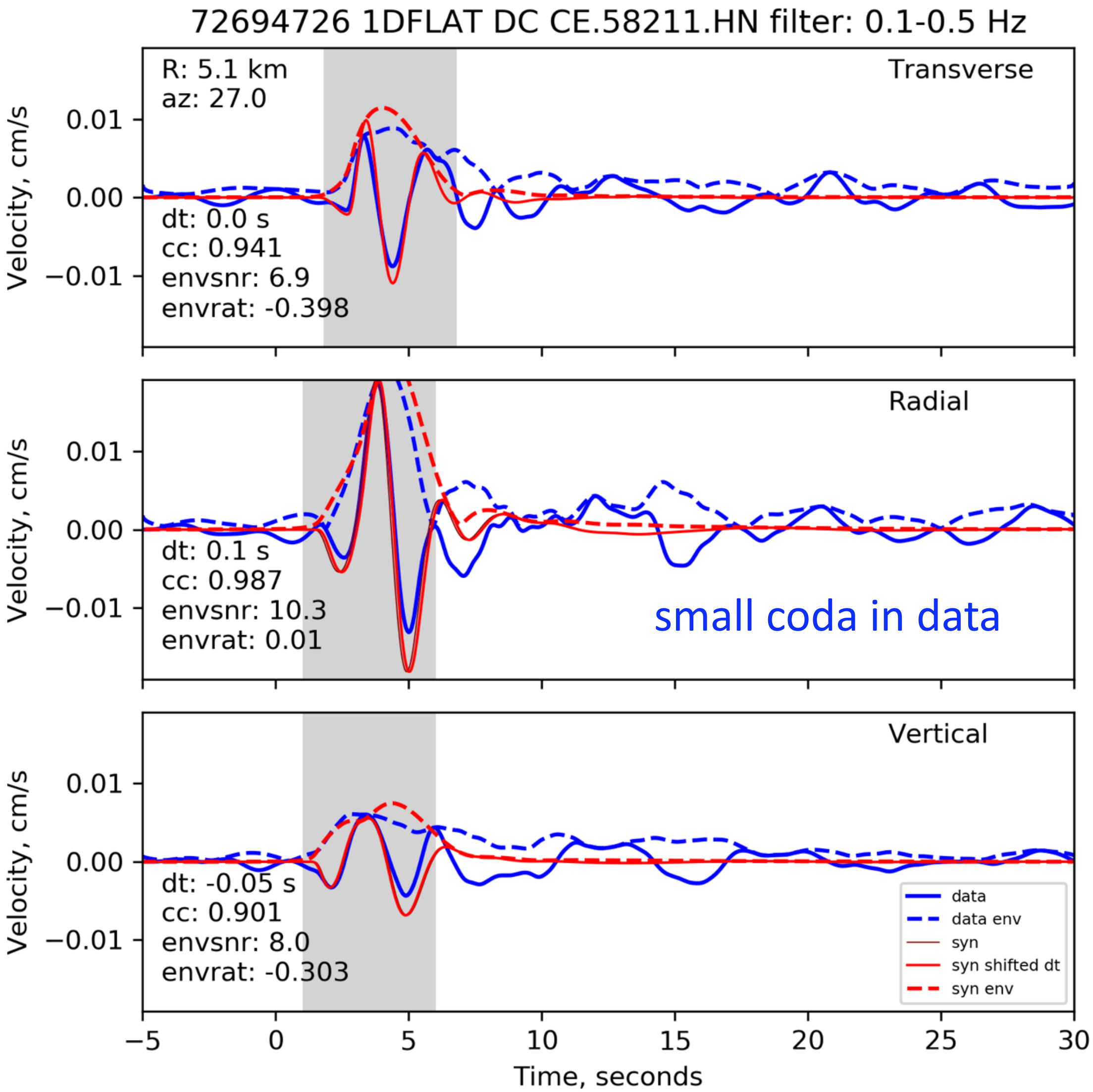
3D model synthetic

- arrives late relative to data
- produces large amplitude coda

Paths sampling Great Valley Sequence 2016/09/13 Piedmont at CE.58211 (Orinda)

Earth model: 1DFLAT
Focal mech: DC



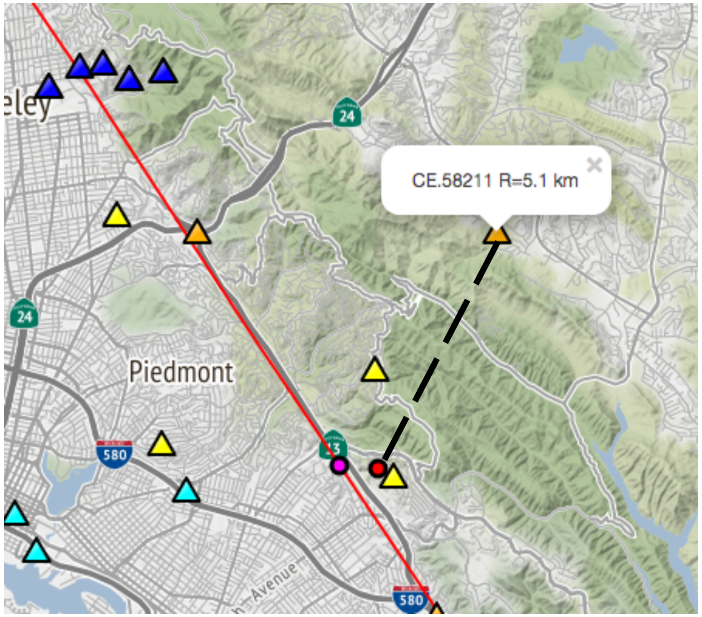


1D model synthetic

- arrives with data, very small delay
- produces no coda

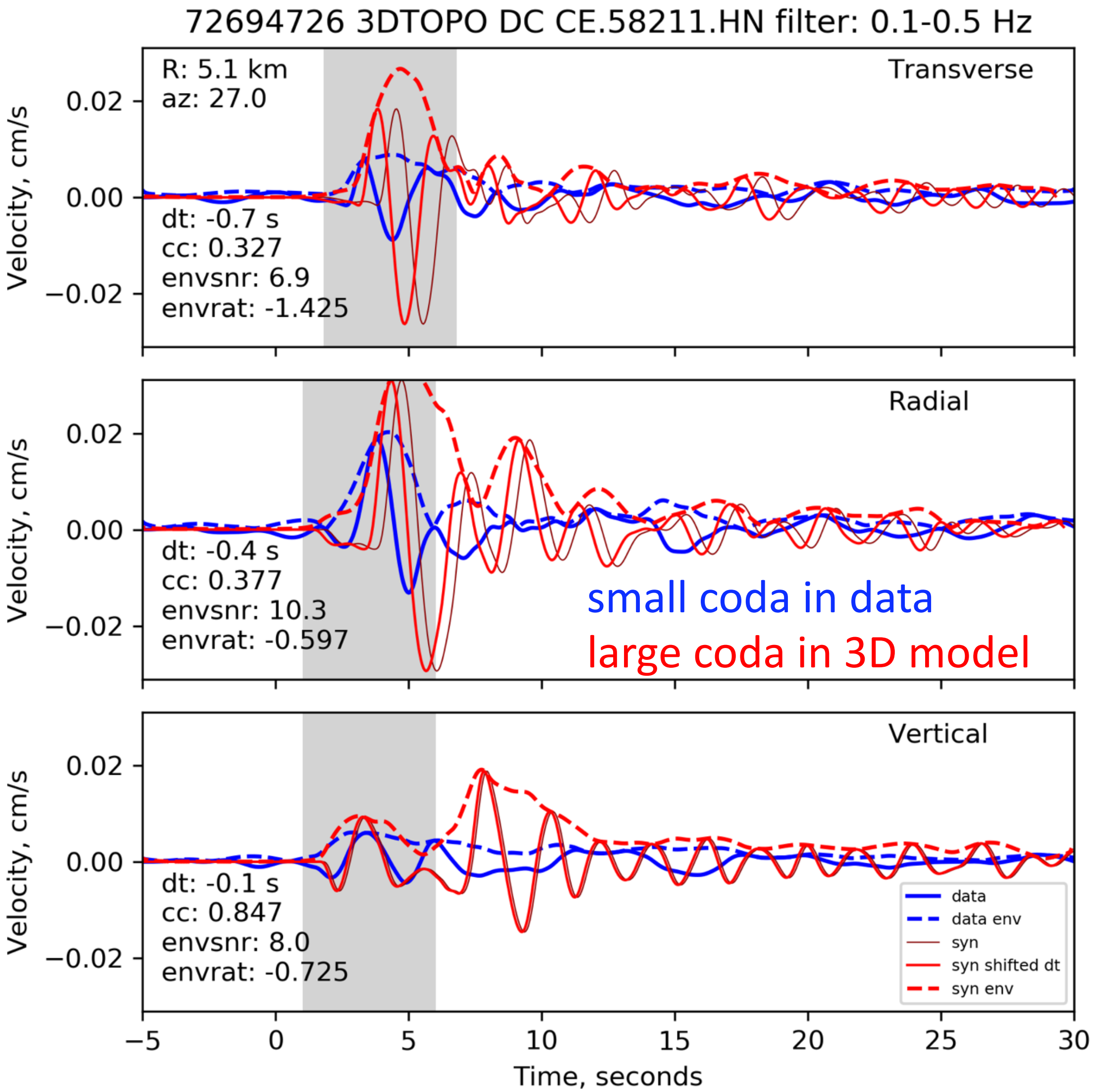
Paths sampling Great Valley Sequence 2016/09/13 Piedmont at CE.58211 (Orinda)

Earth model: 3DTOPO
Focal mech: DC



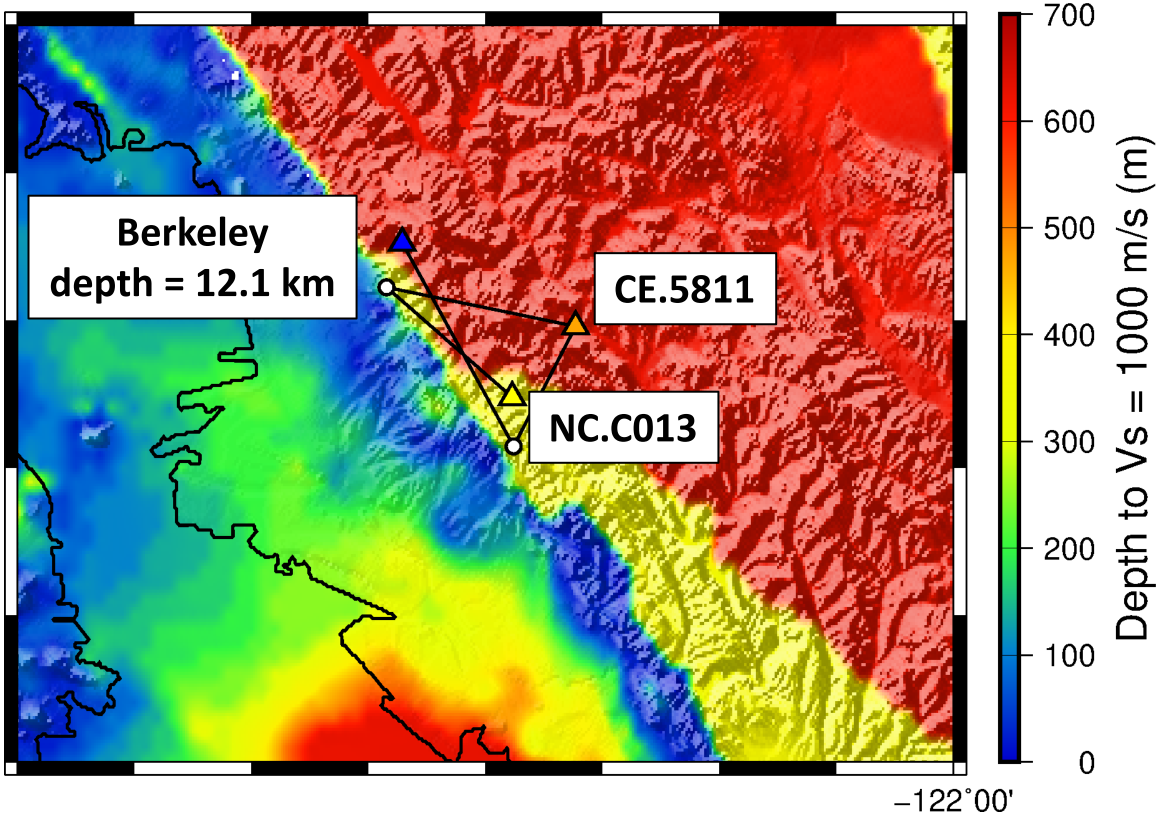
3D model synthetic

- arrives late relative to data
- produces large amplitude coda

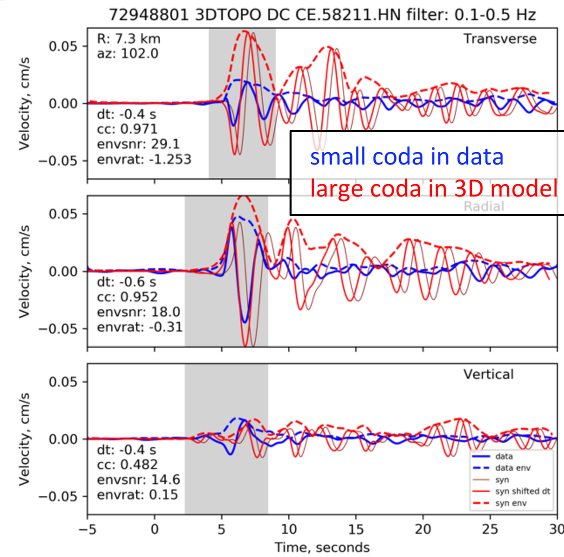


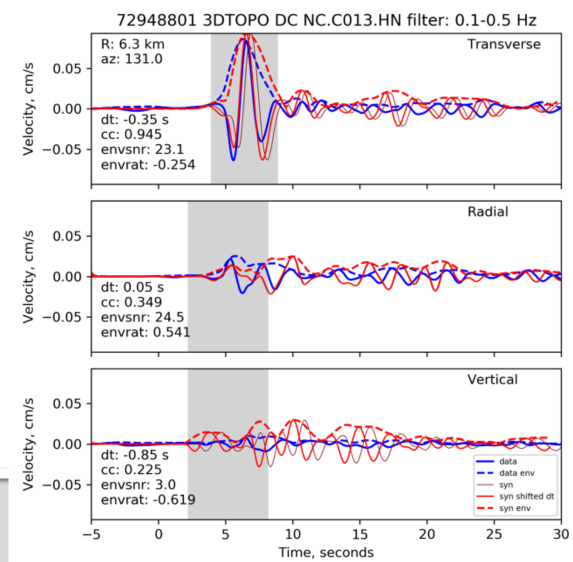
Paths sampling Great Valley Sequence close to Hayward Fault

Depth to v_S = 1 km/s in USGS 3D model shows complex structure near Berkeley & Oakland



Berkeley CE.58211

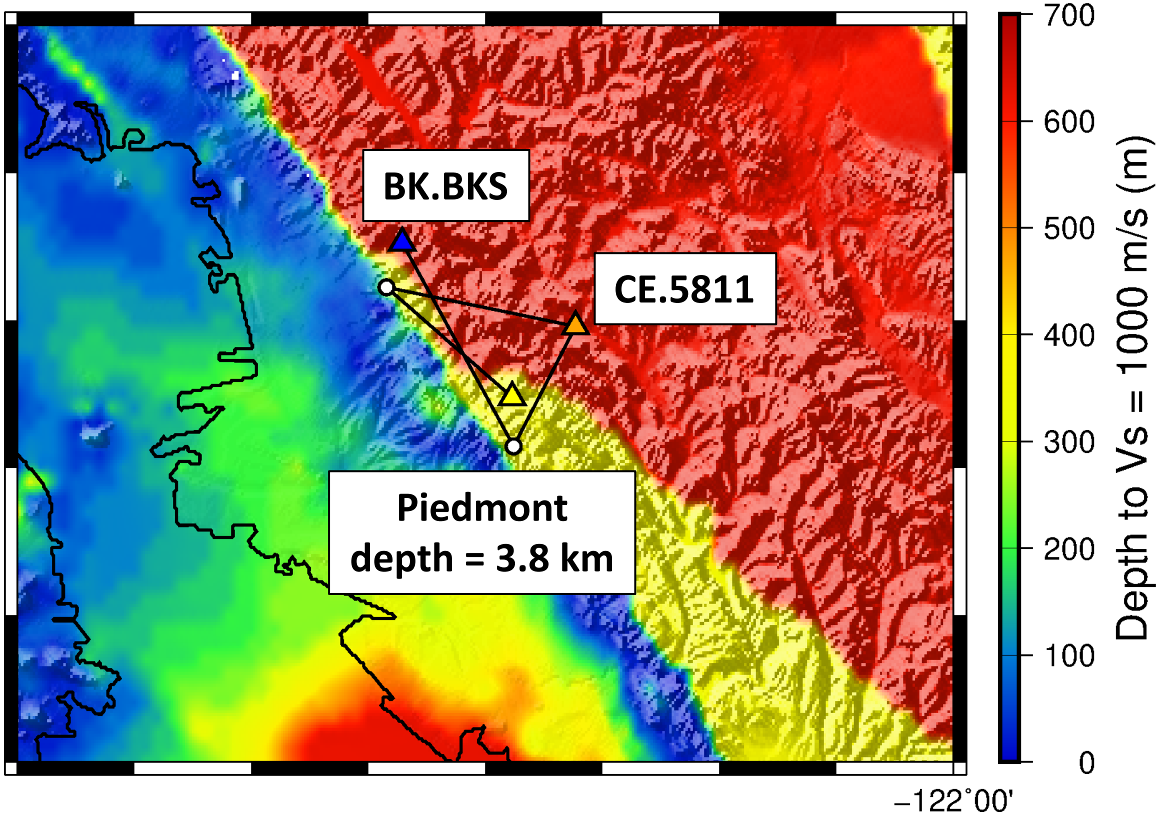




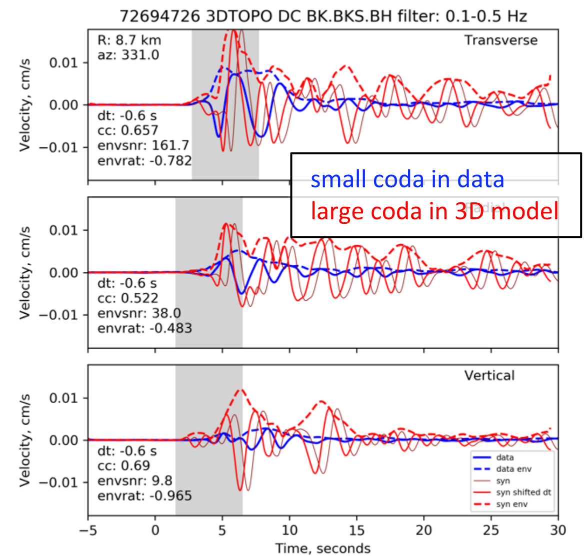
Berkeley NC.C013

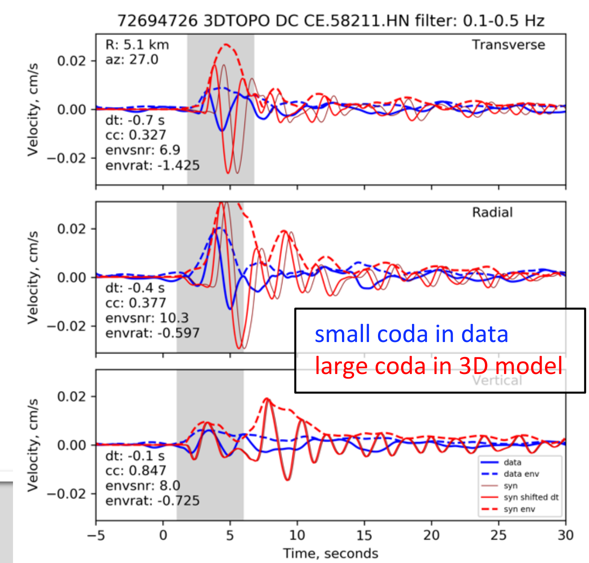
Paths sampling Great Valley Sequence close to Hayward Fault

Depth to v_S = 1 km/s in USGS 3D model shows complex structure near Berkeley & Oakland



Piedmont BK.BKS

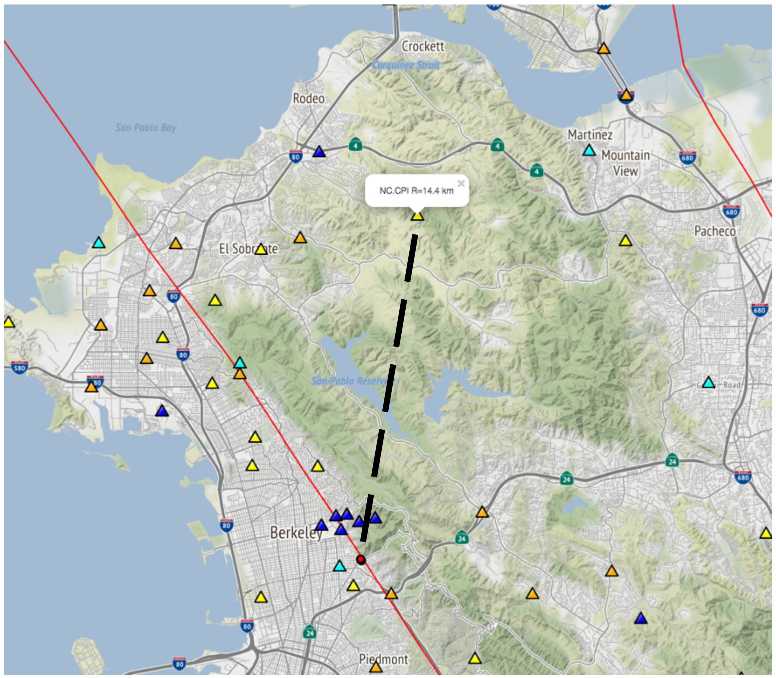


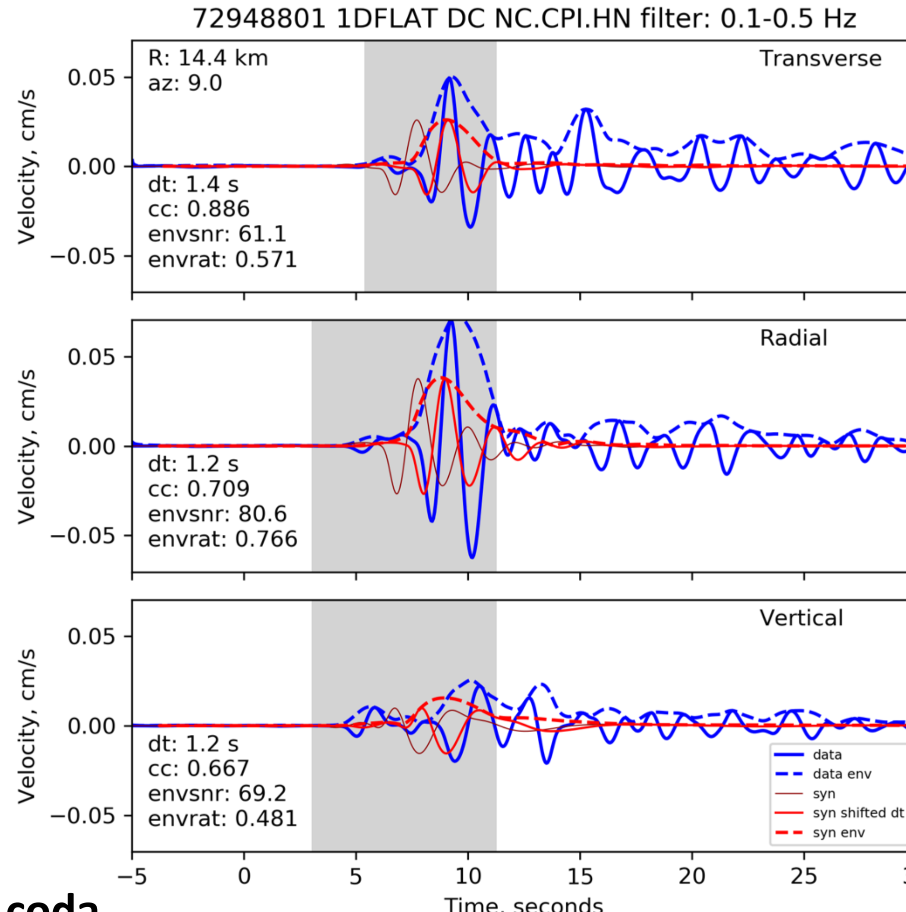


Piedmont CE.58211

3-component waveform comparisons 2018/01/04 Berkeley at NC.CPI (Orinda)

Earth model: 1DFLAT
Focal mech: DC



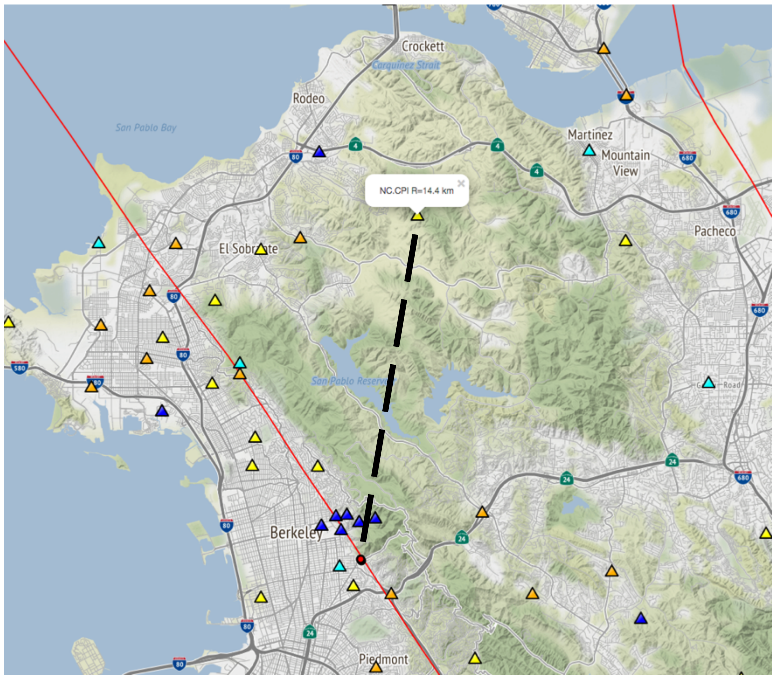


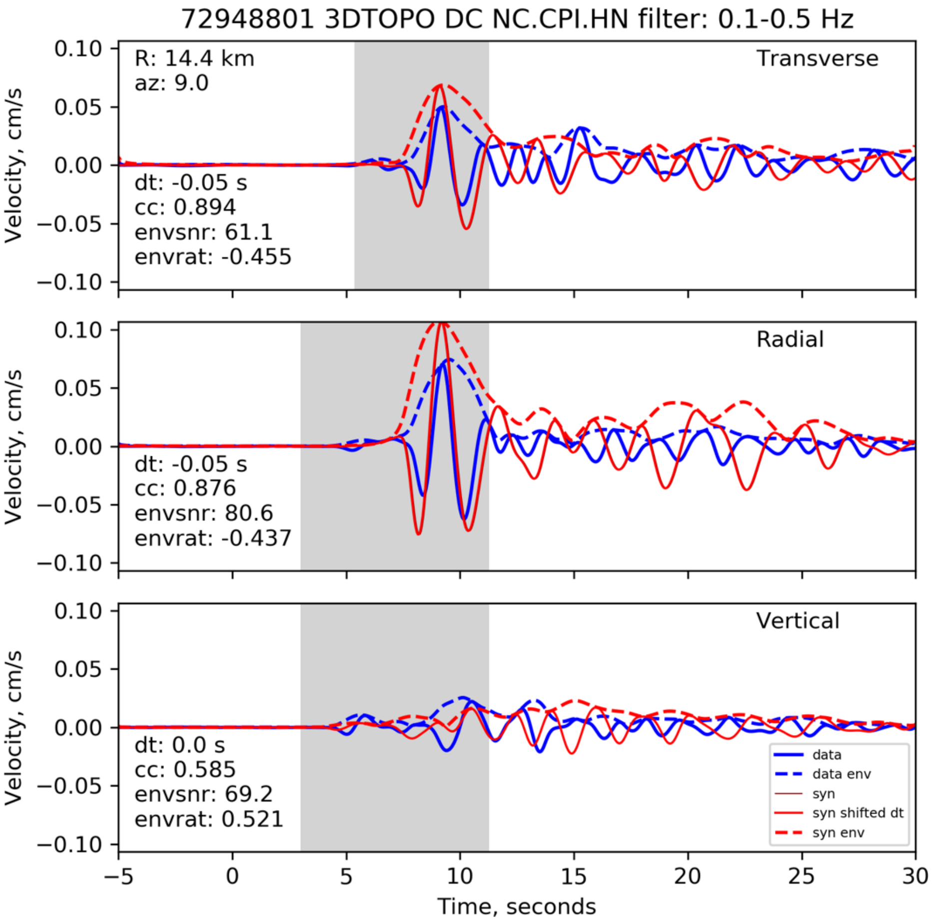
1DFLAT synthetic

- **requires large delay time**
- **goes flat after surface wave, does not fit coda**

3-component waveform comparisons 2018/01/04 Berkeley at NC.CPI (Orinda)

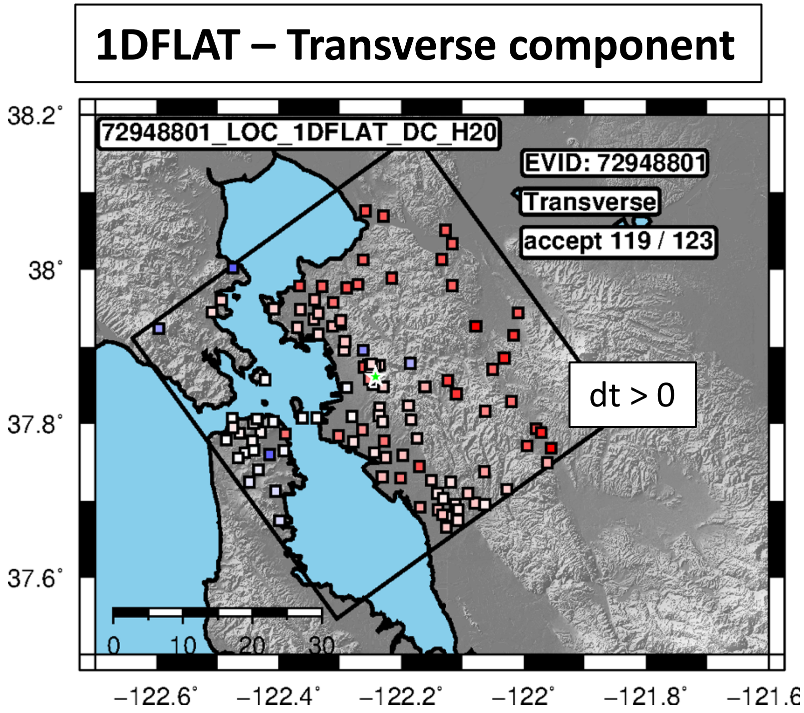
Earth model: 3DTOPO
Focal mech: DC

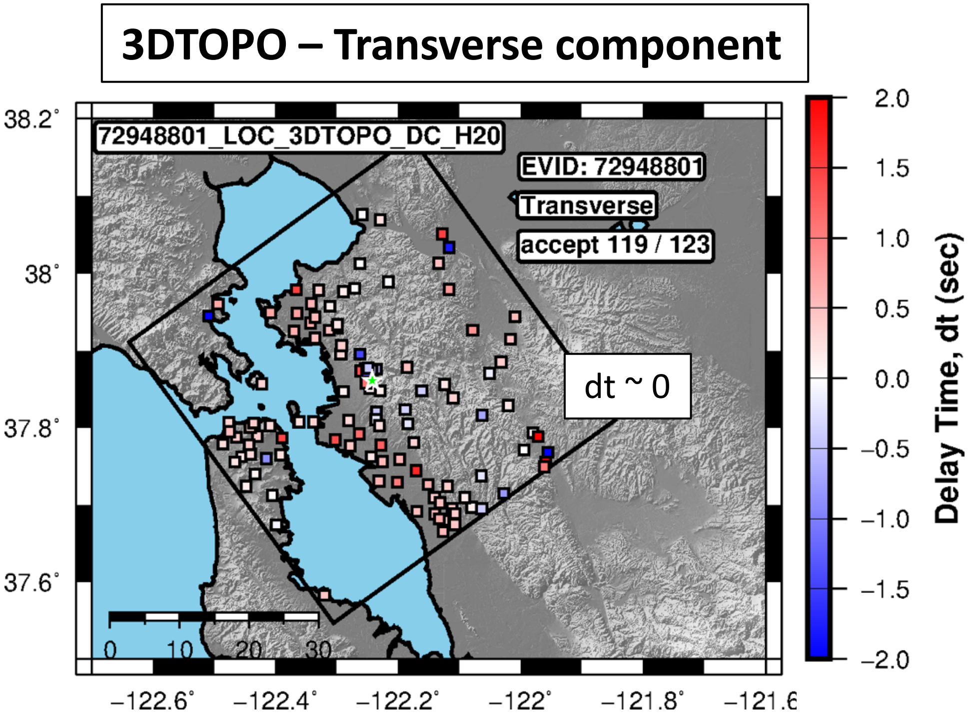




3DTOPO synthetic
- **aligns with little or no delay time**
- **produces coda**

Berkeley event delay time map
3DTOPO model performs better than 1DFLAT

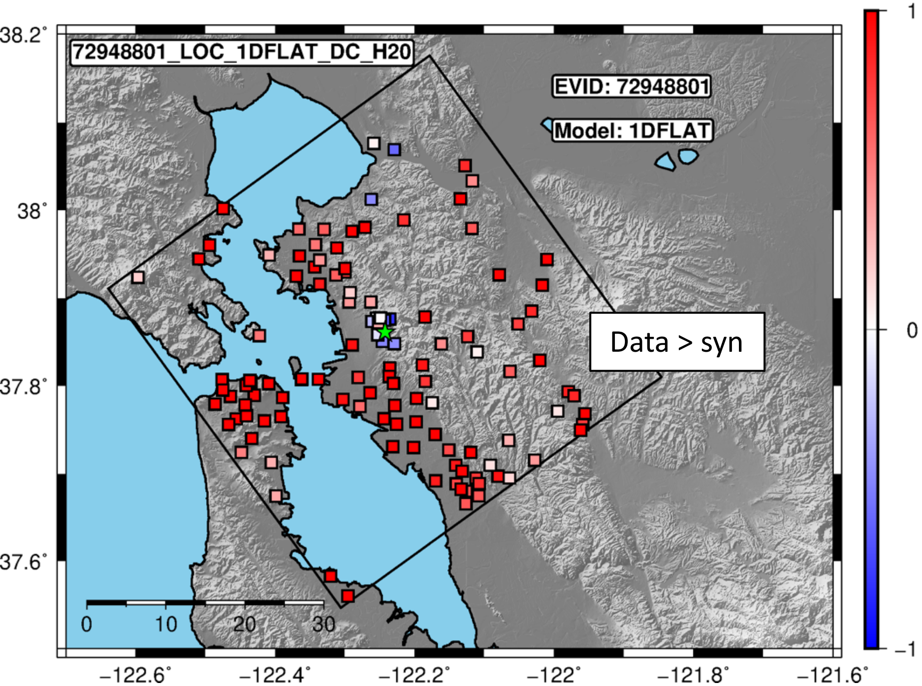




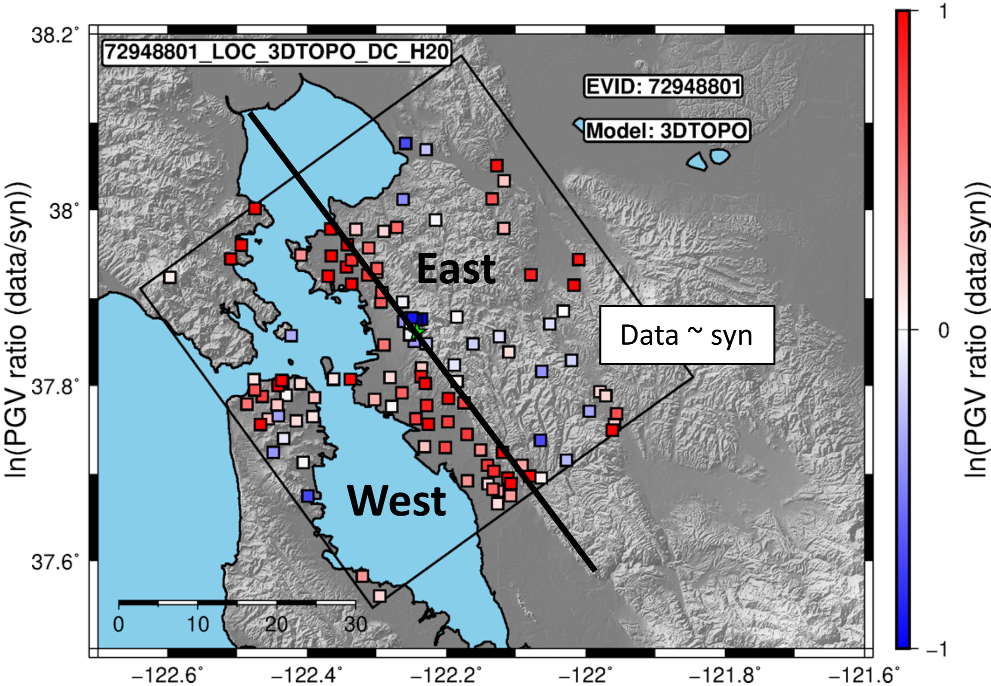
Paths east of the Hayward Fault are slower than the average 1D model

Band-limited (0.1-1 Hz) PGV comparison Berkeley M_W 4.36 2018/01/04

Berkeley 1DFLAT model

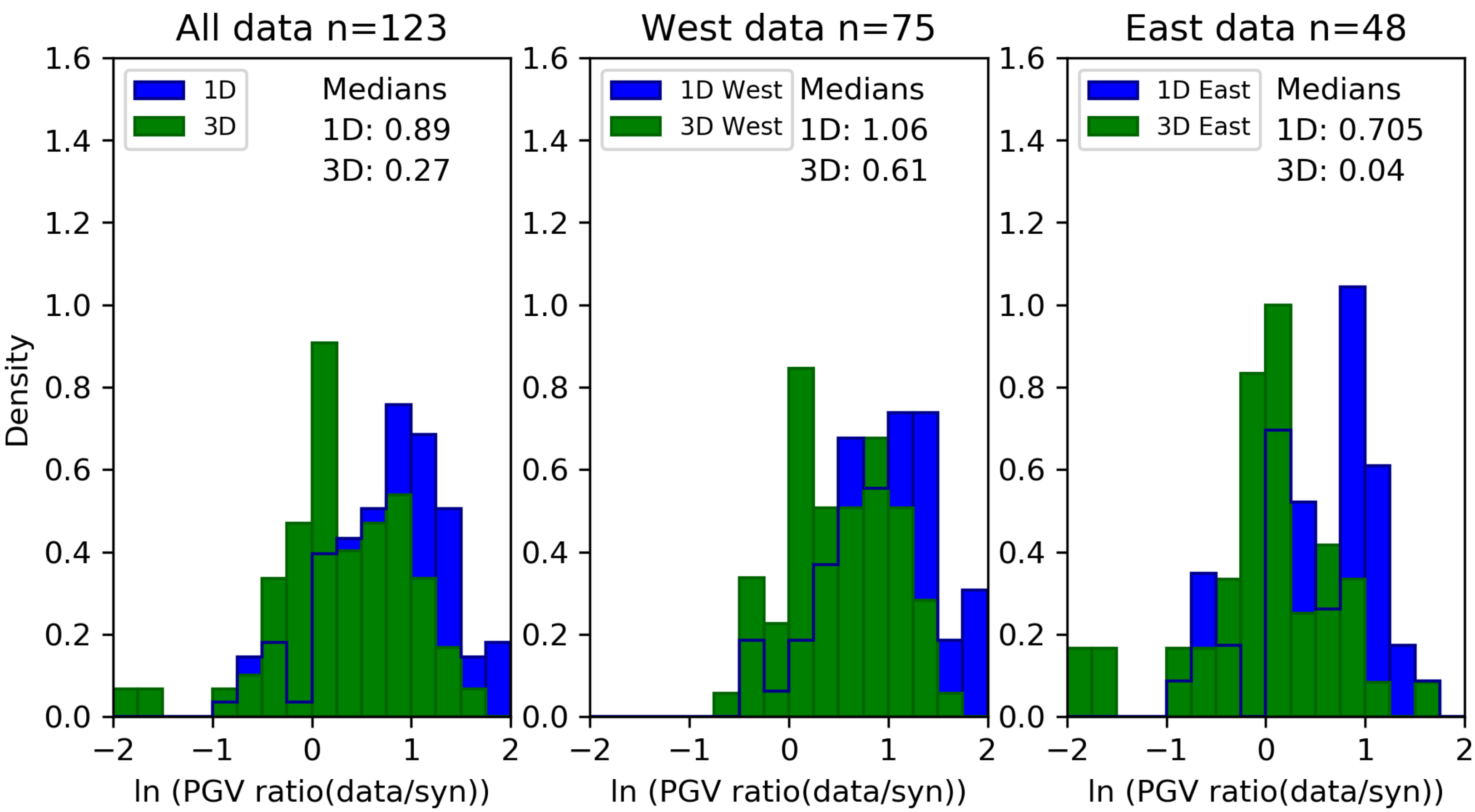


Berkeley 3DTOPO model



Filter data and synthetic 0.1 – 1.0 Hz (10 – 1 seconds)
Compute geometric mean of horizontal component PGVs
Form natural log PGV ratio (data/syn)

Peak ground velocity (PGV) comparison Berkeley M_W 4.36 2018/01/04



This event shows East/West differences in PGV ratios & 3DTOPO model reduces bias

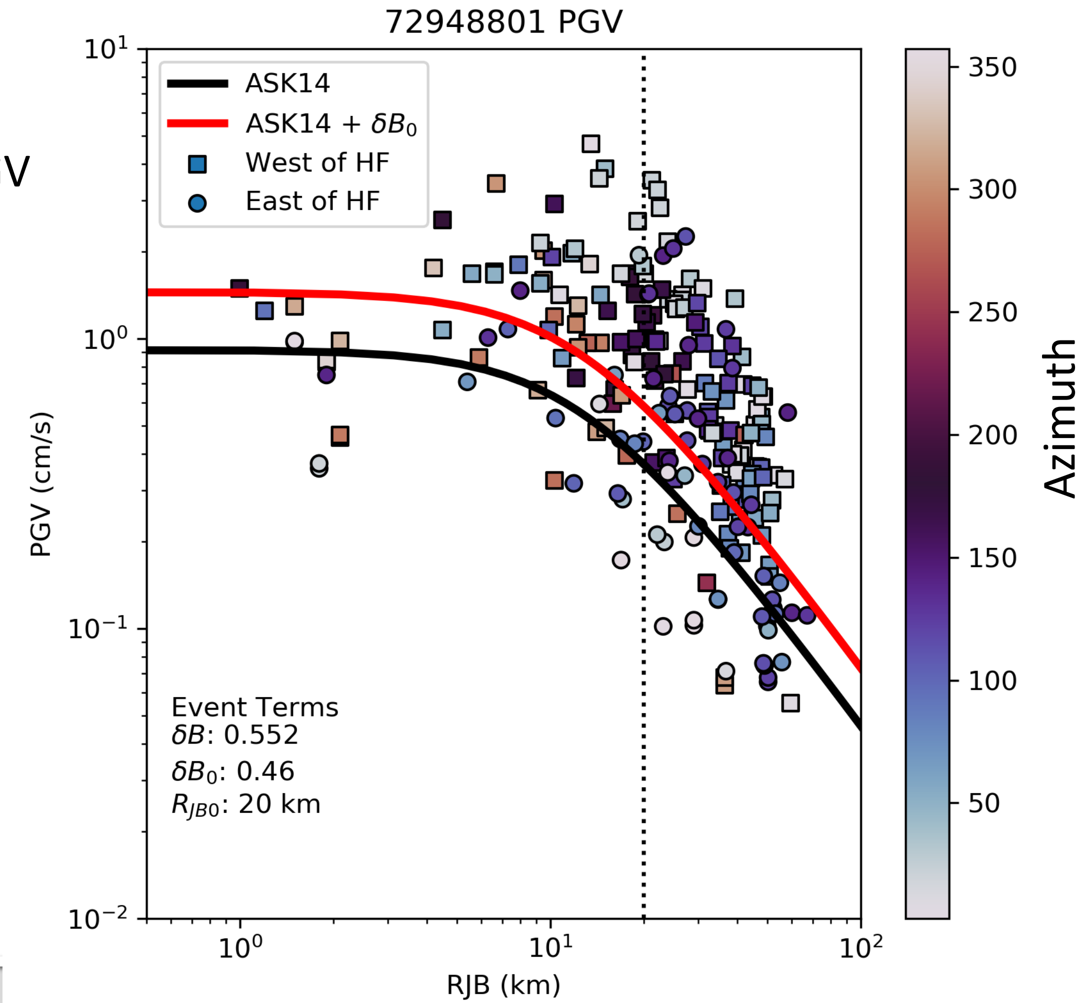
- West of HF: modest reduction of bias (1.06 – 0.61 = 0.45)
- East of HF: bias near zero for 3D model (0.705 – 0.04 = 0.701)

Peak ground velocity (PGV) versus R_{JB} Berkeley M_W 4.36 2018/01/04

This event had higher than average PGV
Possibly higher stress drop

Event term
δB = mean ln(PGV) for all distances
δB_0 = mean ln(PGV) $R_{JB} \leq 20$ km

No clear East-West difference in PGV



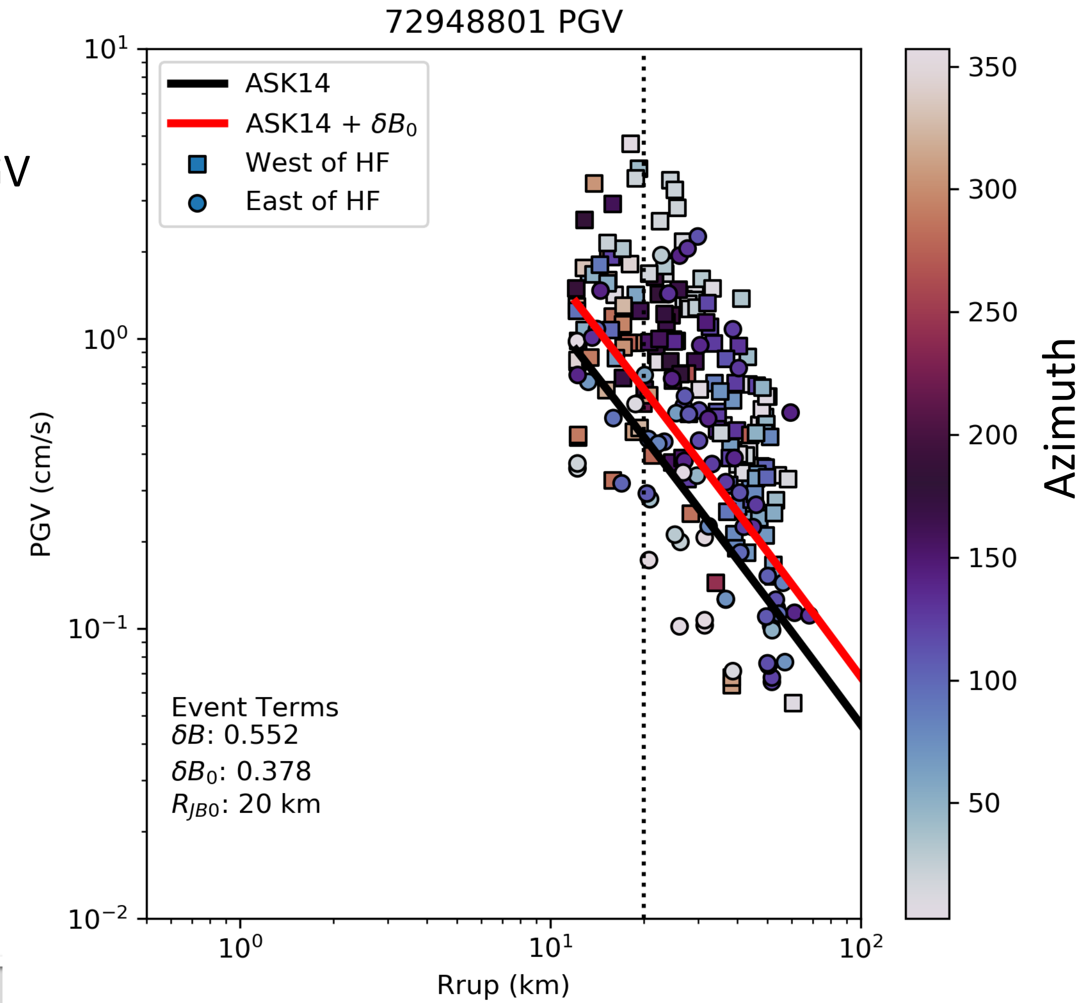
Peak ground velocity (PGV) versus R_{rup}
Berkeley M_W 4.36 2018/01/04

This event had higher than average PGV

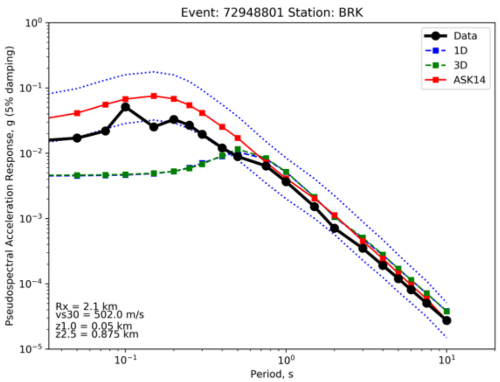
Event term

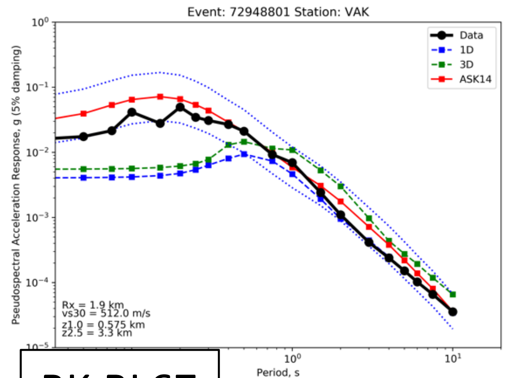
δB = mean ln(PGV) for all distances

δB_0 = mean ln(PGV) $R_{rup} \leq 20$ km

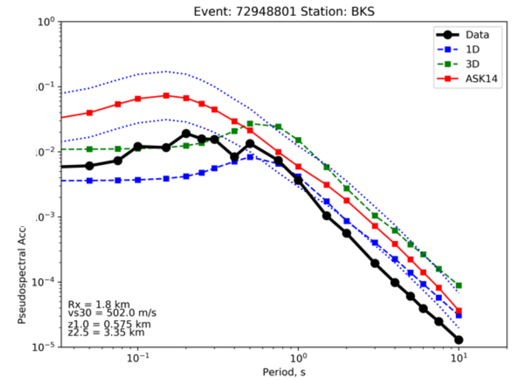


RotD50 response spectra (Data, ASK14, 1D, 3D) Berkeley M_W 4.36 2018/01/04

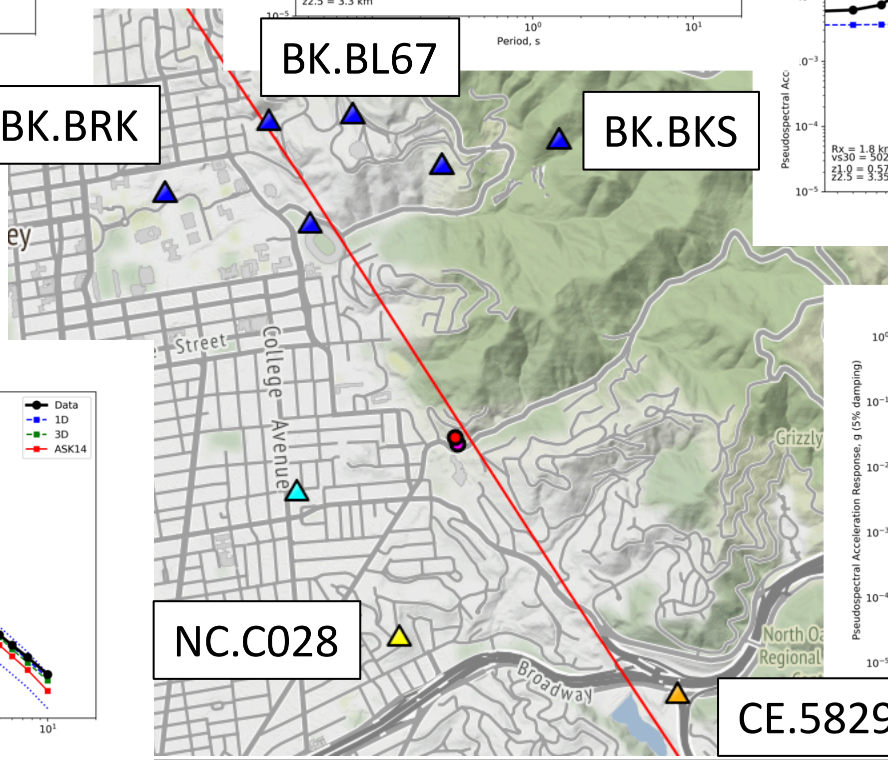


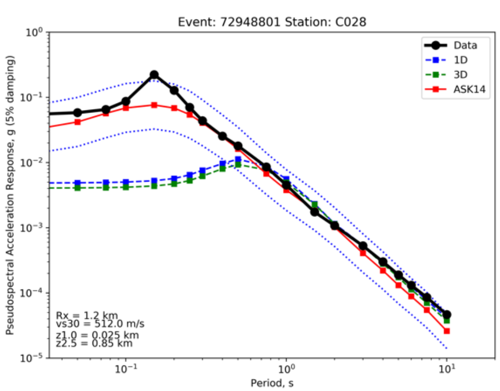


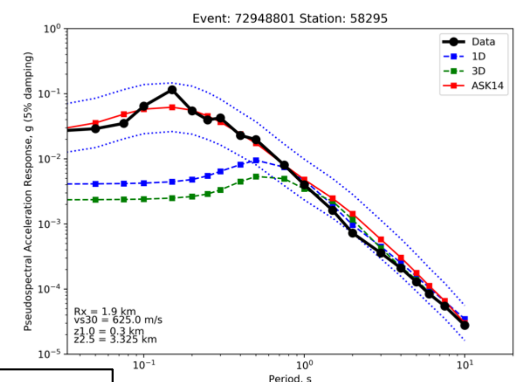
East of Hayward Fault
3D > 1D spectra



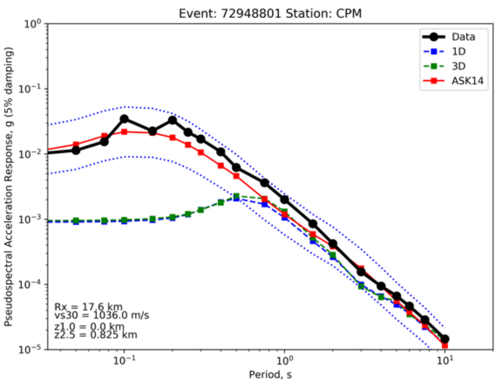
West of Hayward Fault very little difference between 1D and 3D

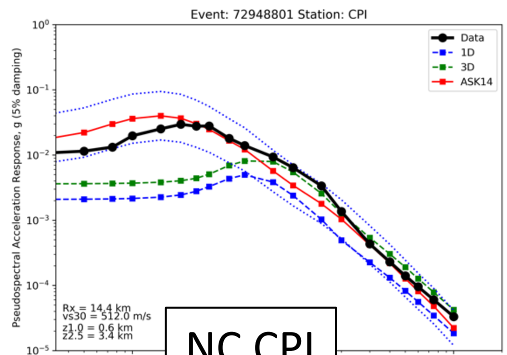


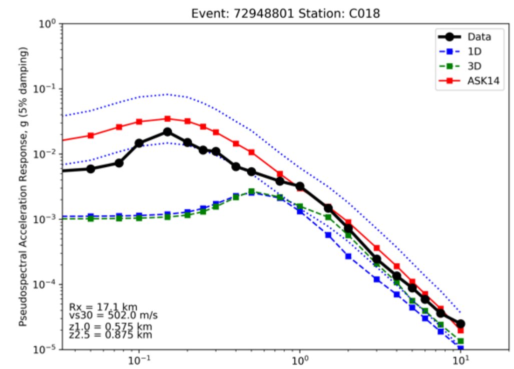




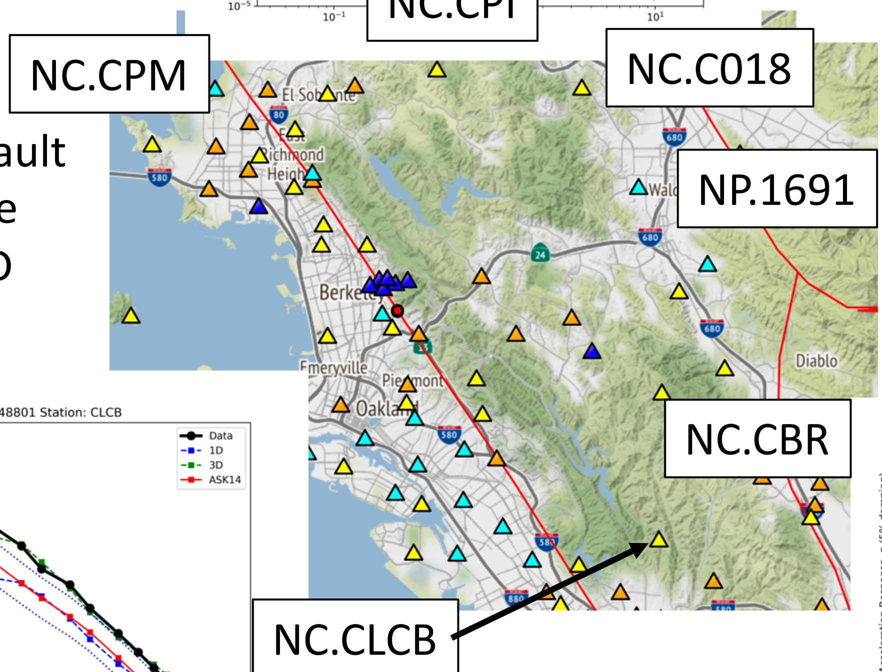
RotD50 response spectra (Data, ASK14, 1D, 3D)
Berkeley M_W 4.36 2018/01/04

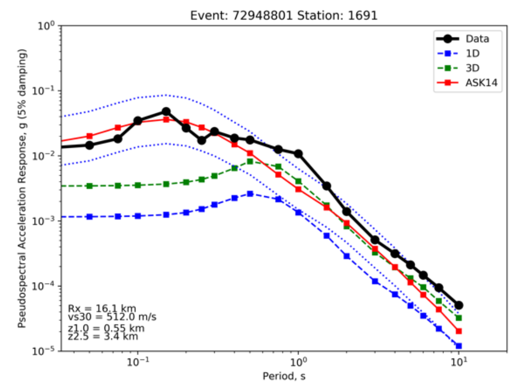


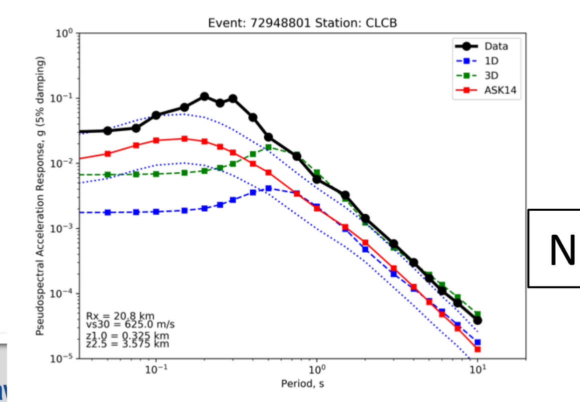


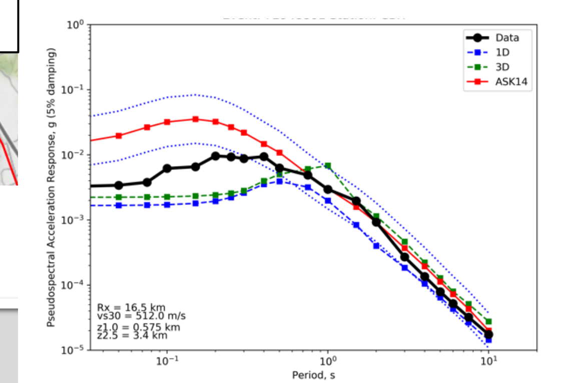


West of Hayward Fault very little difference between 1D and 3D



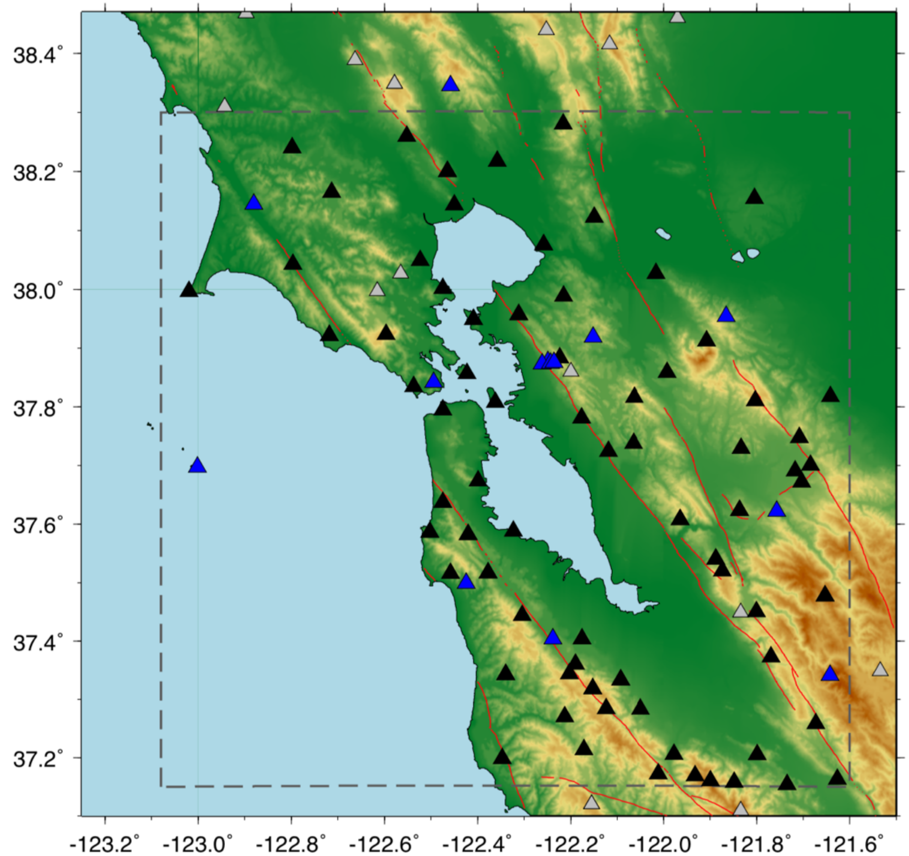


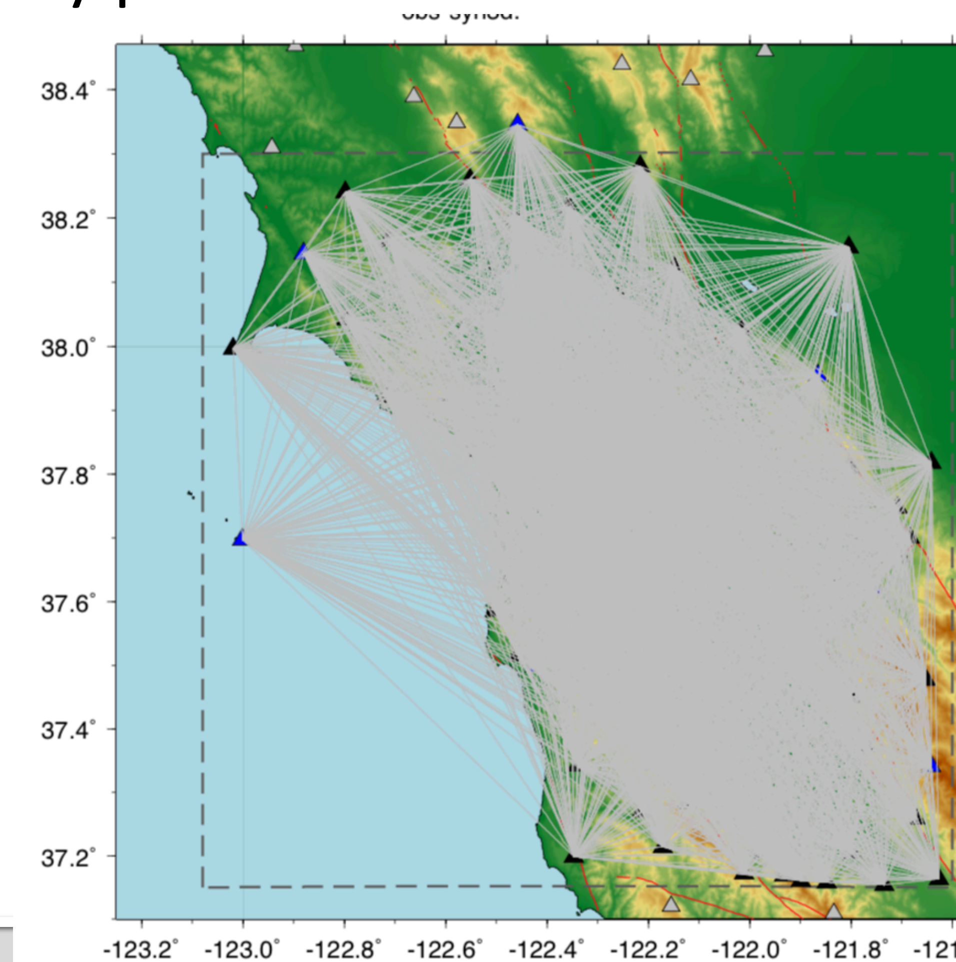




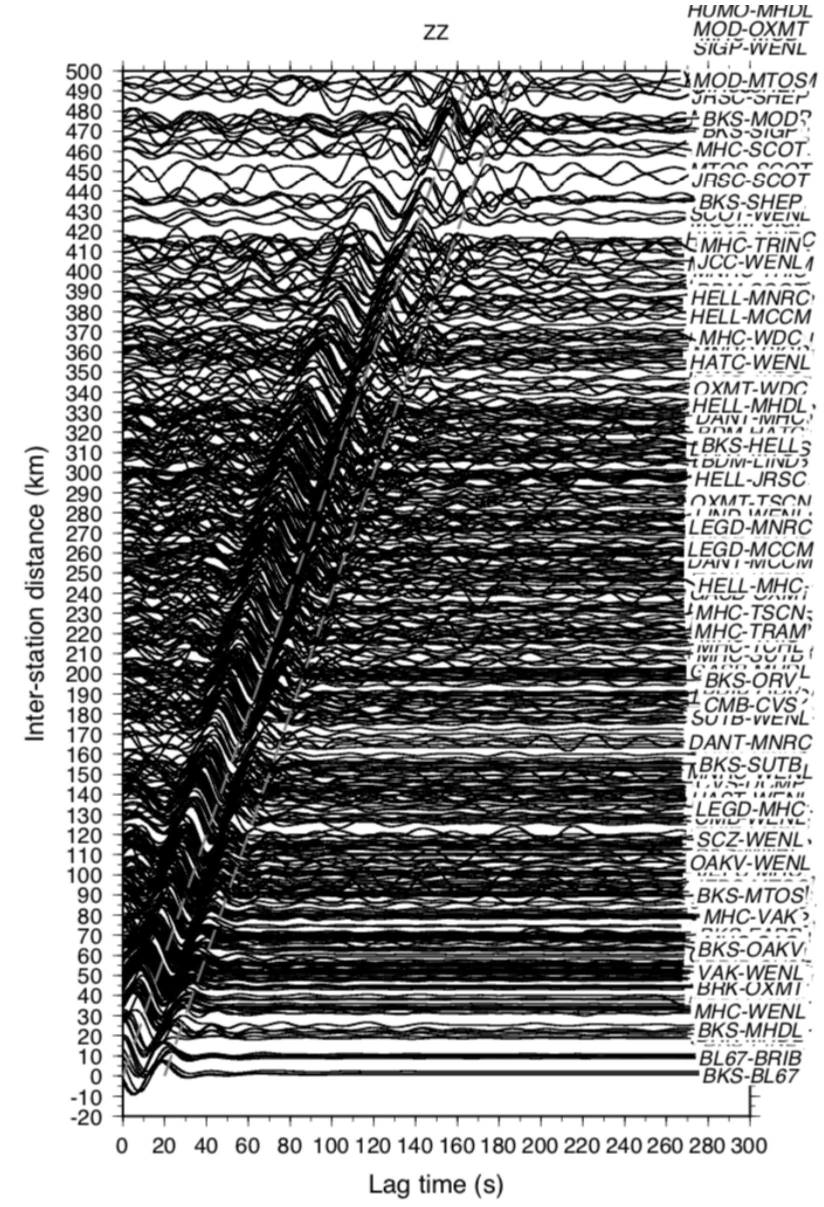
Stations for noise cross correlation. Blue is BDSN and black is USGS short-period (From Taira NEHRP Report 2019)

(left) map and (right) ray paths

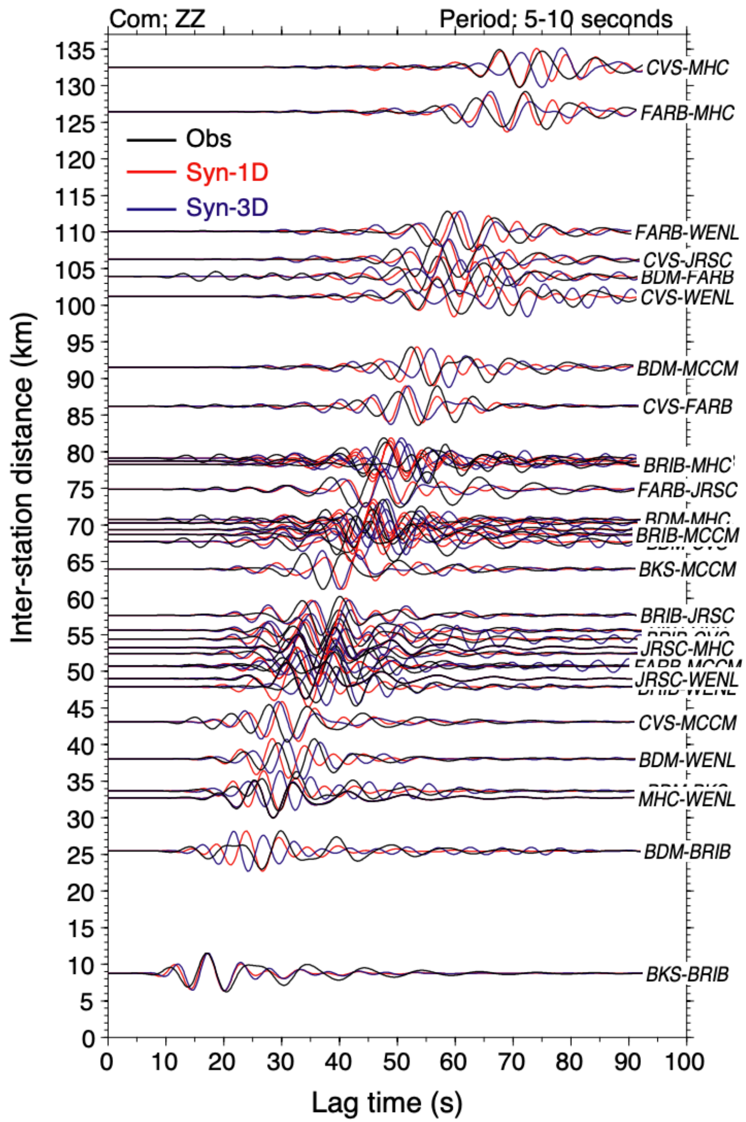




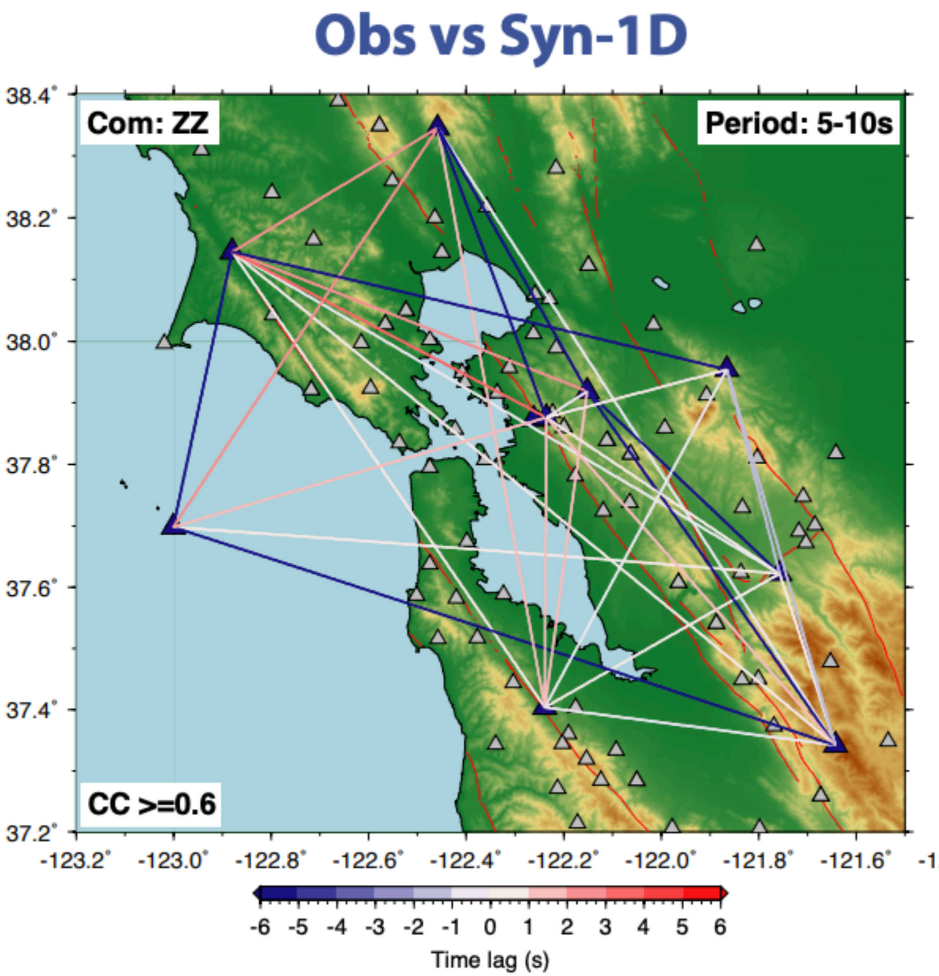
Noise GFs


ZZ
Inter-station distance (km)
Lag time (s)
MOD-OXMT
SIGP-WENL
BKS-MODO
MHC-SCOT
JRSC-SCOT
BKS-SHEP
MHC-TRIN
JCC-WENL
HELL-MNRC
HELL-MCCM
MHC-WDC
HATC-WENL
OXMT-WDC
HELL-MHDL
BKS-HELL
HELL-JRSC
LEGD-MNRC
LEGD-MCCM
HELL-MHC
MHC-TSCN
MHC-TRAM
BKS-ORV
CMB-CVS
DANT-MNRC
BKS-SUTB
LEGD-MHC
SCZ-WENL
OAKV-WENL
BKS-MTOS
MHC-VAK
BKS-OAKV
VAK-WENL
BRK-OXMT
MHC-WENL
BKS-MHDL
BL67-BRIB
BKS-BL67

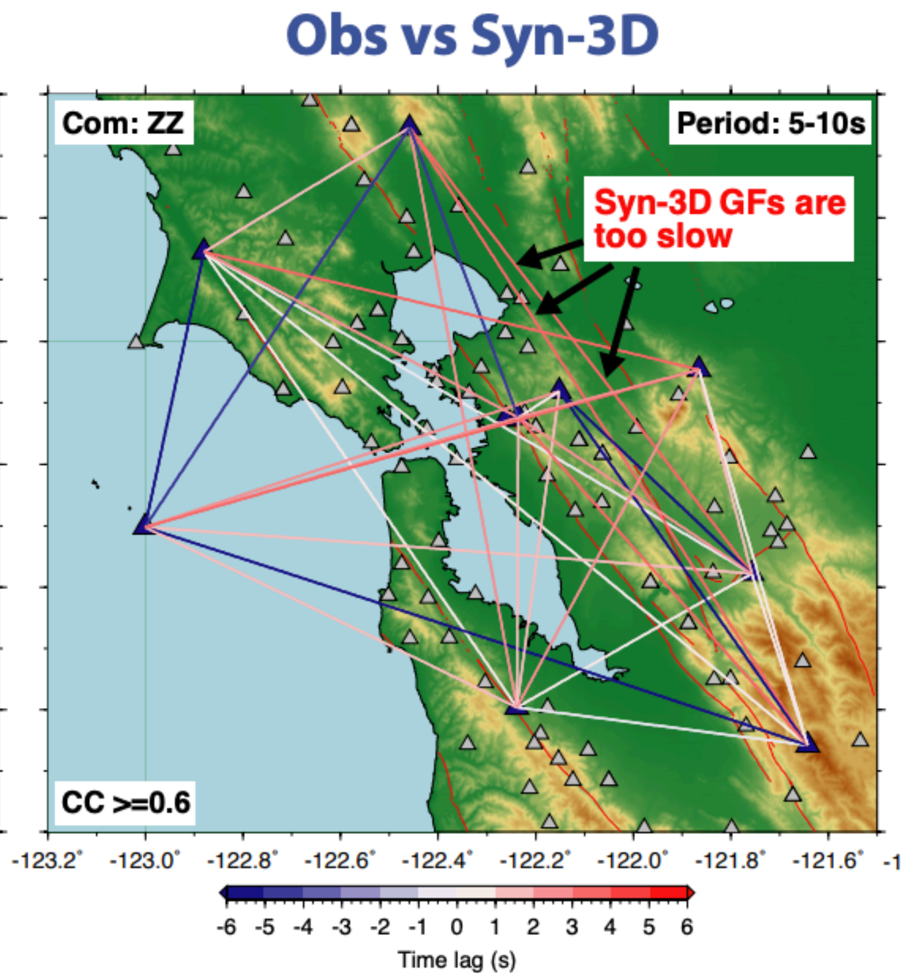
Noise GFs and synthetic data



Time lags



Obs vs Syn-1D
Com: ZZ
Period: 5-10s
CC >=0.6
Time lag (s)



Obs vs Syn-3D
Com: ZZ
Period: 5-10s
Syn-3D GFs are too slow
CC >=0.6
Time lag (s)

Conclusions …
based on just two nearby events on Hayward Fault

- First-motion double couple focal mechanisms (DC) provide better fits than regional moment tensors (MT)
- Satisfactory waveform fits to direct waves are achievable
  - Frequencies 0.1-0.5 Hz; CC $\geq$ 0.5; abs[ln(envelope ratio)] < 0.5
- West of the Hayward Fault in the Franciscan Complex
  - Little difference between synthetics and waveforms fits for 1D and 3D models
- East of the Hayward Fault in the Great Valley Sequence
  - Most paths are slower than 1D model
  - 3D model reduces delay time bias, however maybe too slow
  - 3D model produces large amplitudes and strong late scattered energy
    - This is the likely cause of large amplitudes in M 7.0 source-normalized GM maps

Further work is needed

- Consider other events and more paths
- Identify good quality events with well-constrained source parameters
  - Must fit waveforms at the close stations
- Higher frequencies, expose source-time function
  - Lower v_{Smin}
- Identify good quality waveform data set for testing path-specific waveform fits (delay time, CC, amplitudes, etc…)
  - Measure Fourier Amplitude spectra
- Look for systematic path and site effects
  - Address how USGS 3D model might be improved for specific regions & paths
  - Test future and/or alternative models?
- We need more stations sampling the Great Valley Sequence
  - Temporary deployment would provide such data
  - CGS/CSMIP stations reporting small events helps a lot

Acknowledgements

PG&E Corporation

Northern California Earthquake Data Center

University of California Berkeley Seismological Laboratory

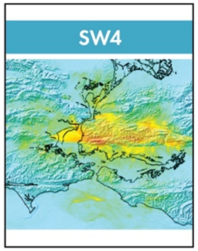
CGS California Geological Survey

USGS science for a changing world

LIVERMORE COMPUTING CENTER
HIGH PERFORMANCE COMPUTING

LLNL Computing Grand Challenge

SW4 is an open-source finite difference code developed by Anders Petersson & Bjorn Sjogreen at LLNL

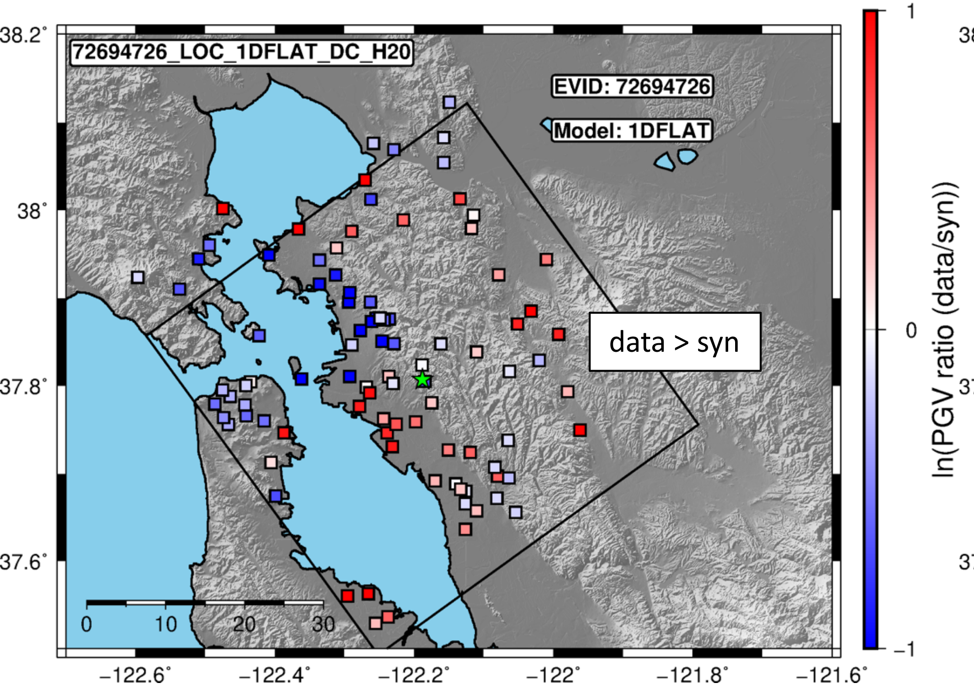


Earthquake waveform and metadata collected with ObsPy

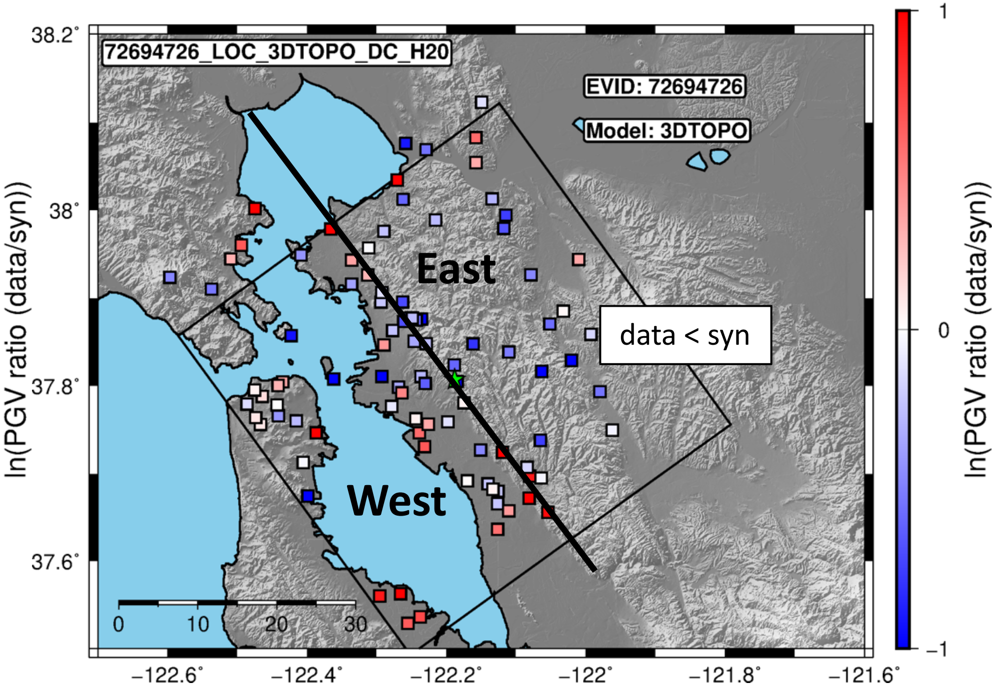
ObsPy
A Python Framework for Seismology

Band-limited (0.1-1 Hz) PGV comparison Piedmont M_W 3.54 2016/09/13

Piedmont 1DFLAT model

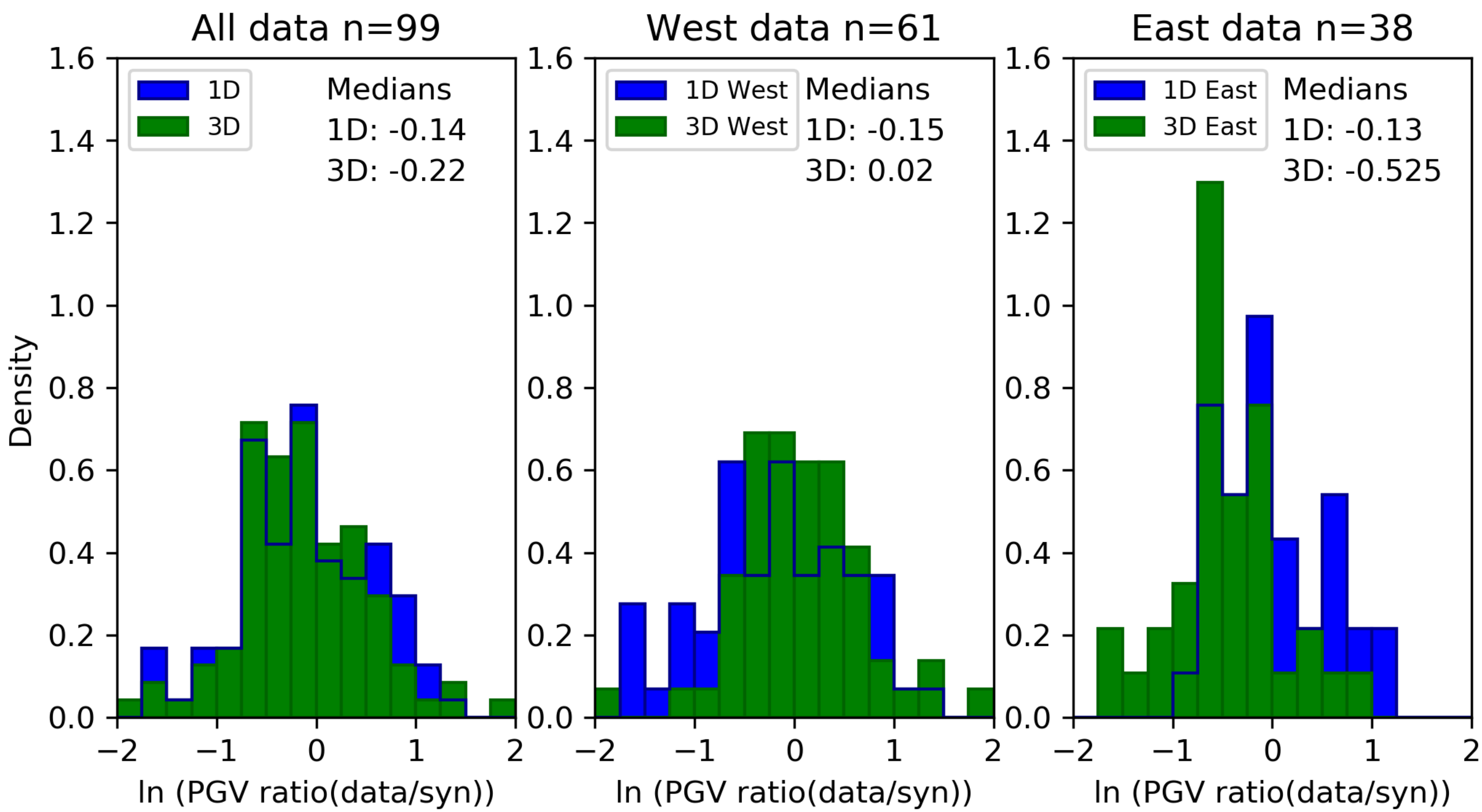


Piedmont 3DTOPO model



Filter data and synthetic 0.1 – 1.0 Hz (10 – 1 seconds)
Compute geometric mean of horizontal component PGVs
Form natural log PGV ratio (data/syn)
Subdivide by azimuth

Peak ground velocity (PGV) comparison Piedmont M_W 3.54 2016/09/13



PGV amplitude ratios for this event show less East/West bias compared with Berkeley
- PGV ratios east of the Hayward Fault become even smaller
  - too much path amplification by low wavespeed Great Valley Sequence?