

Accuracy of Synthetic Ground Motions for the 2014 M6.0 South Napa Earthquake and Moderate Earthquakes

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SFBA 3D Model Workshop

USGS, Menlo Park

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Arben Pitarka and N. Anders Petersson

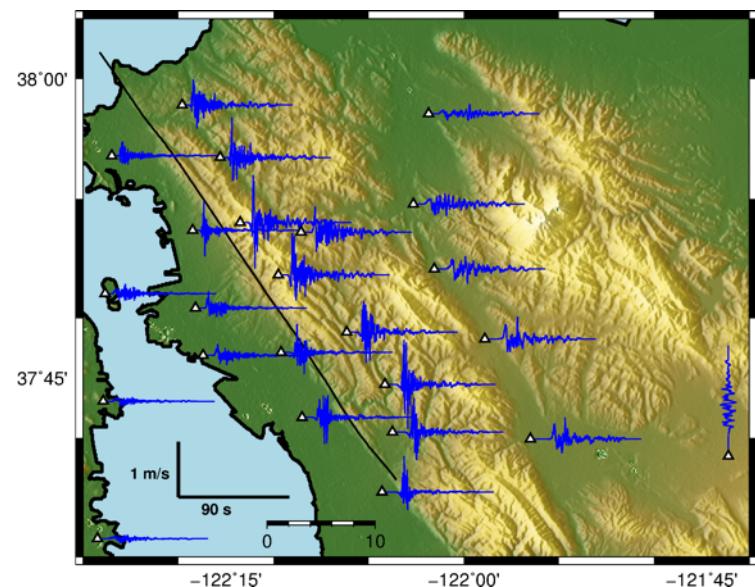
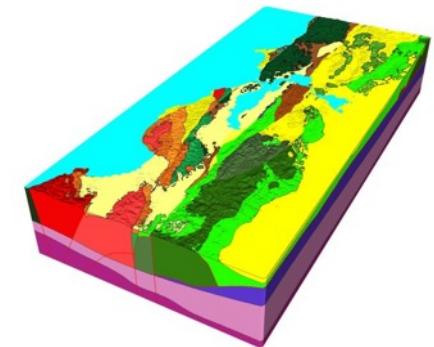
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What do we want?

- 3D model of sub-surface geologic material and seismic properties
 - v_p , v_s , ρ , Q_p , Q_s
 - Surface topography & bathymetry
 - Fault surfaces
- Fully 3D ground motion simulations for hazard and risk
 - Need to model frequencies of relevance to engineering analyses
 - Say, 5 Hz, wavelengths \sim 40 meters, $h \sim$ 5-10 m
 - Include geotechnical properties
- Earthquake locations, moment tensors and finite fault ruptures models from one fully 3D Earth model
 - Need self-consistency

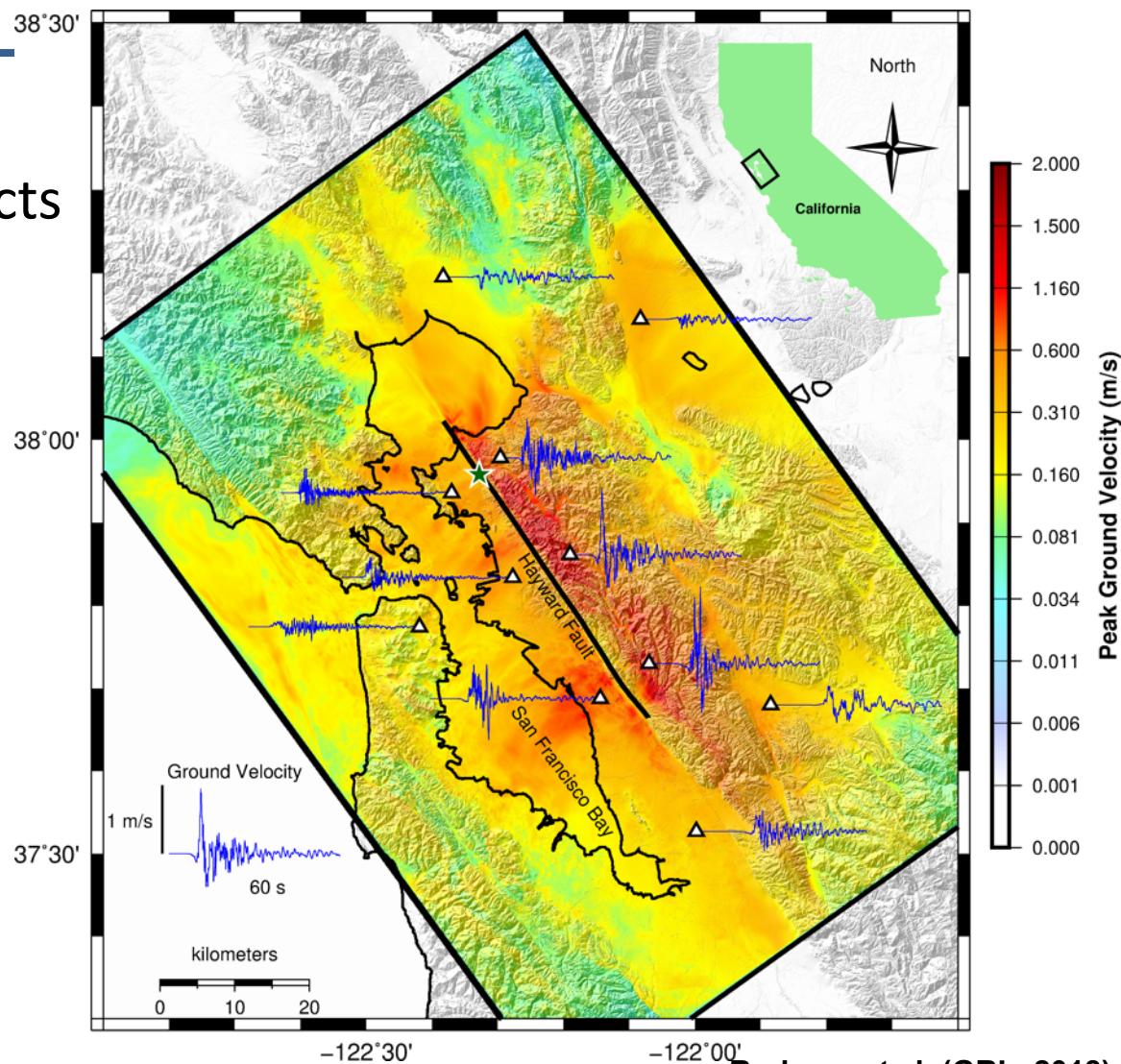
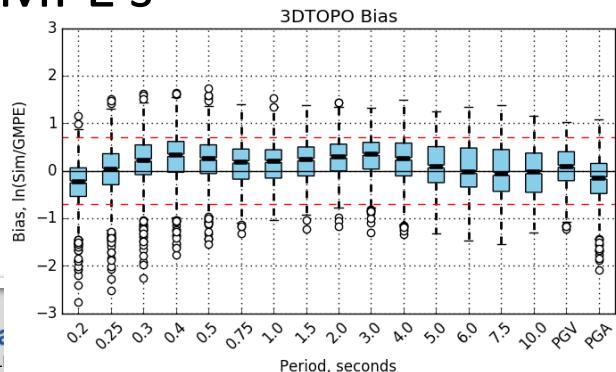


Some previous work on waveform simulations with the USGS SFBA 3D model(s)

- Early version of 3D model
 - Stidham et al. (1999)
- Bolinas eq. to East Bay
 - Baise et al. (2003)
- 1989 Loma Prieta
 - Aagaard et al. (2008)
- Southern Hayward & Calaveras,
Santa Clara Valley
 - Harmsen et al. (2008)
- Compared v. 5.1.0 & 8.3.0
 - Kim, Dreger and Larsen (2010)
- 2014 South Napa
 - Imperatori & Gallovic (2017)
- SF1906 modeling group
 - Aagaard et al. (BSSA, 2008)
- 12 M_W 4-5, BDSN stations
 - Model version 5.1.0
 - Rodgers et al. (BSSA, 2008)
 - SSA talk, NEHRP report
- 2014 M6.0 Napa eq.
 - Dreger et al. (SRL, 2015)
 - Rodgers et al. (SSA talk, 2015)
- M 7.0 Hayward Fault scenario
 - Johansen et al. (CiSE, 2017)
 - Rodgers et al. (GRL, 2018)

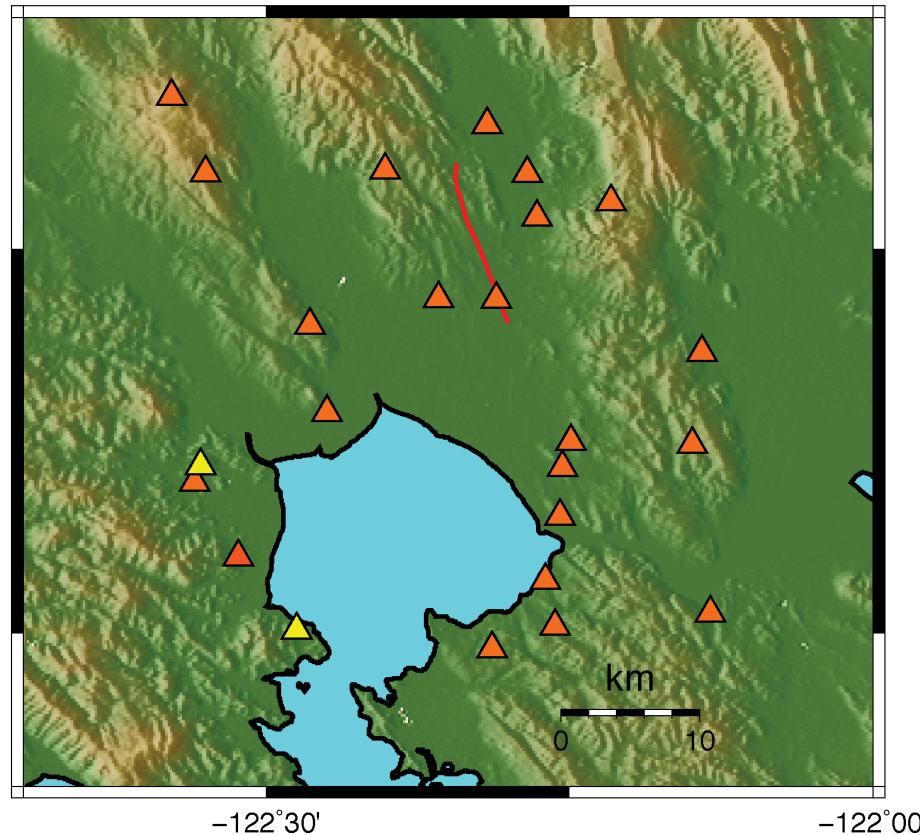
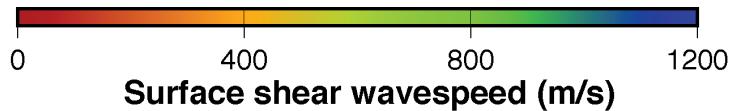
Recent M7.0 Hayward Fault simulation to 4 Hz with 3D model (v 8.3.0), topography & attenuation

- High amplitudes due to source, path and site effects
 - Peak motions are highly asymmetric across HF
- Motivates evaluation of USGS 3D model with moderate events
- Agrees on average with GMPE's

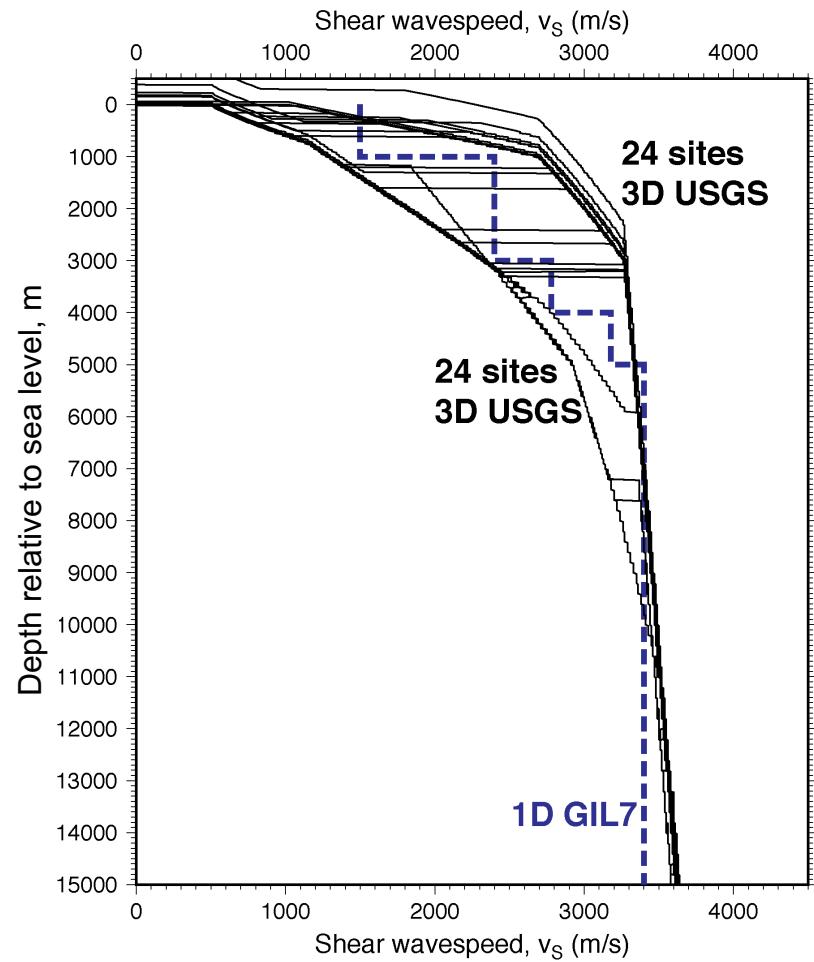


Rodgers et al. (GRL, 2018)

Strong motion sites for South Napa earthquake: Large variability in upper crust

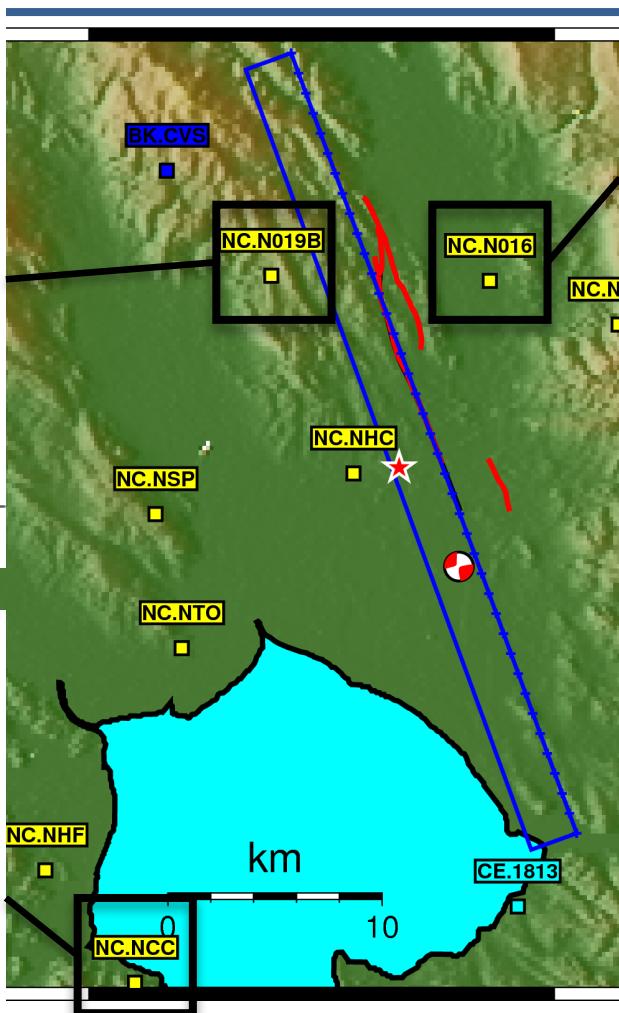
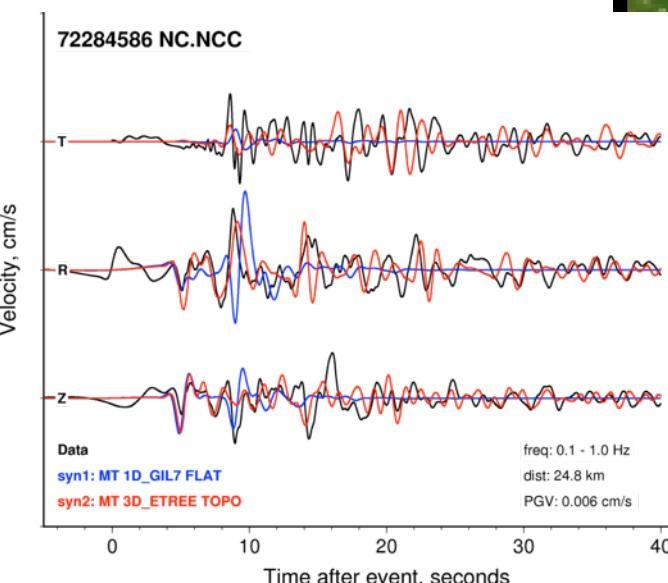
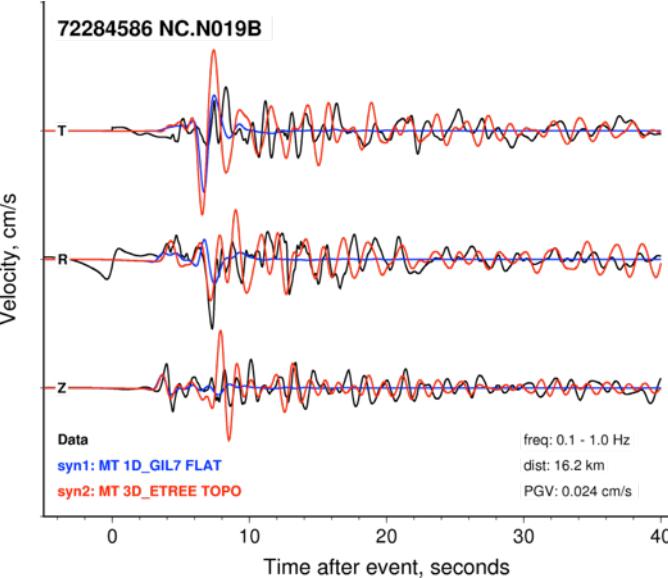


Surface v_S is generally low ~ 400-500 m/s



Large variability in v_S in upper 6 km

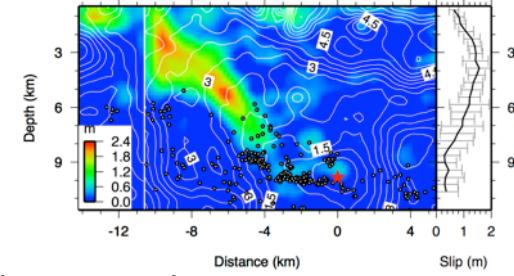
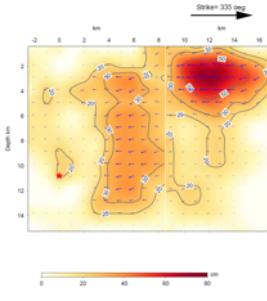
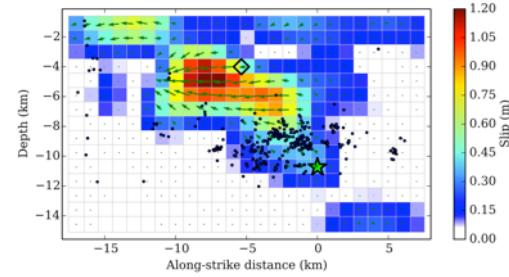
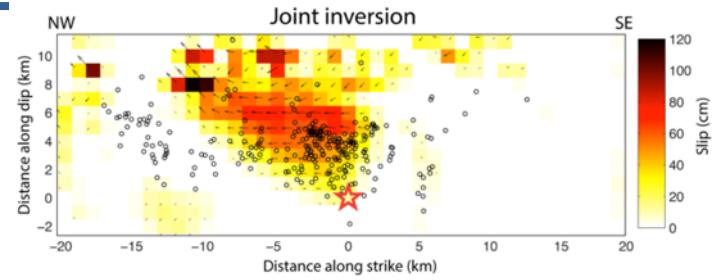
Aftershock (simpler source) shows clear evidence of 3D structure



Suggests that 3D effects are significant

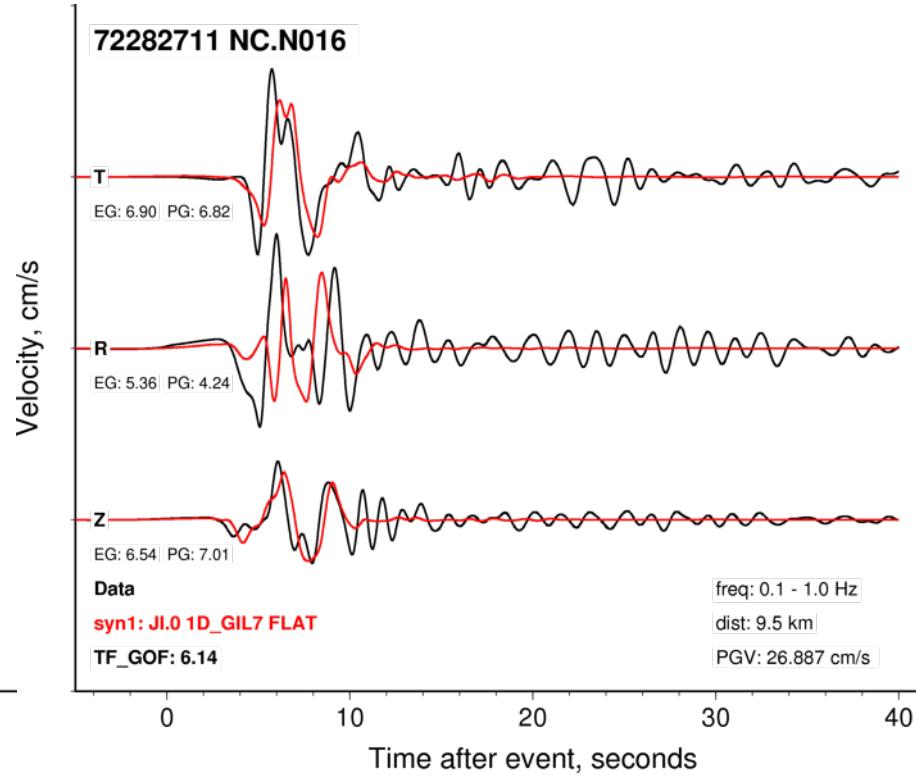
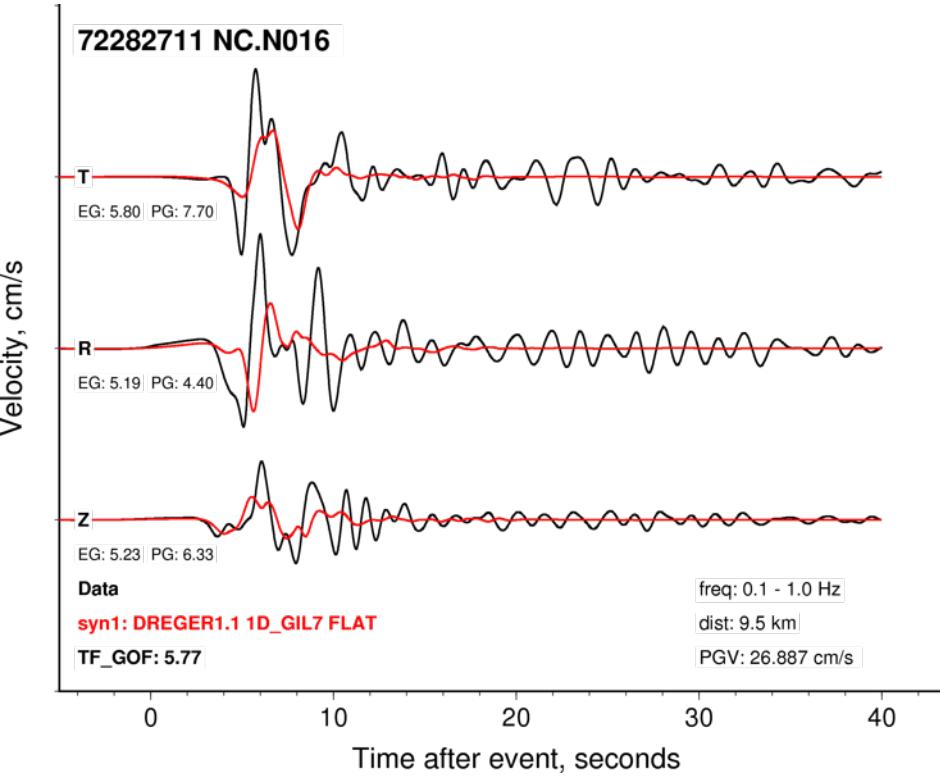
South Napa M_w 6.0 mainshock modeling: 4 source models considered in this study

- Dreger et al. (2015)
 - 1 segment, near-vertical, 80° west-dipping
 - Regional strong-motion, GPS, InSAR
- Melgar et al. (2015)
 - 1 segment, near-vertical, 76° west-dipping
 - cGPS, GPS vectors, local strong-motion
- Wei et al. (2015)
 - 2 segments, near vertical, east-dipping
 - Local strong-motion (3 Hz)
- Ji et al. (2015)
 - 2 segments, near vertical, 87° west-dipping
 - Local strong-motion, transverse (4 Hz) + vertical/radial (1.25 Hz)



Example waveform fits: 1D GIL7 model, Dreger & Ji source models, 0.1-1 Hz

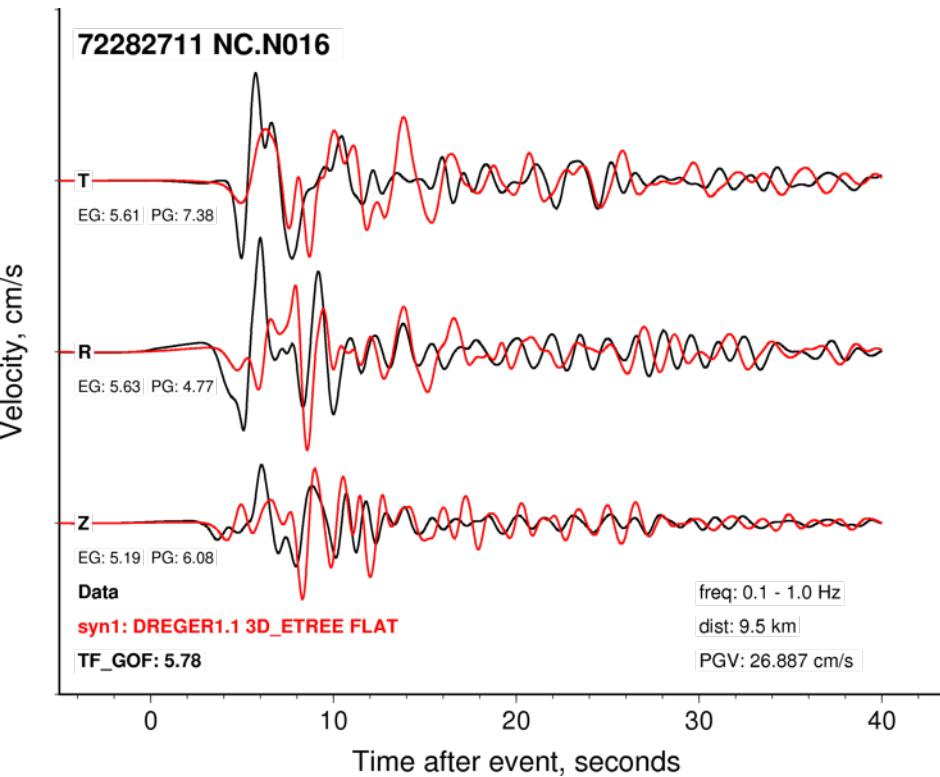
1D response goes flat after direct waves



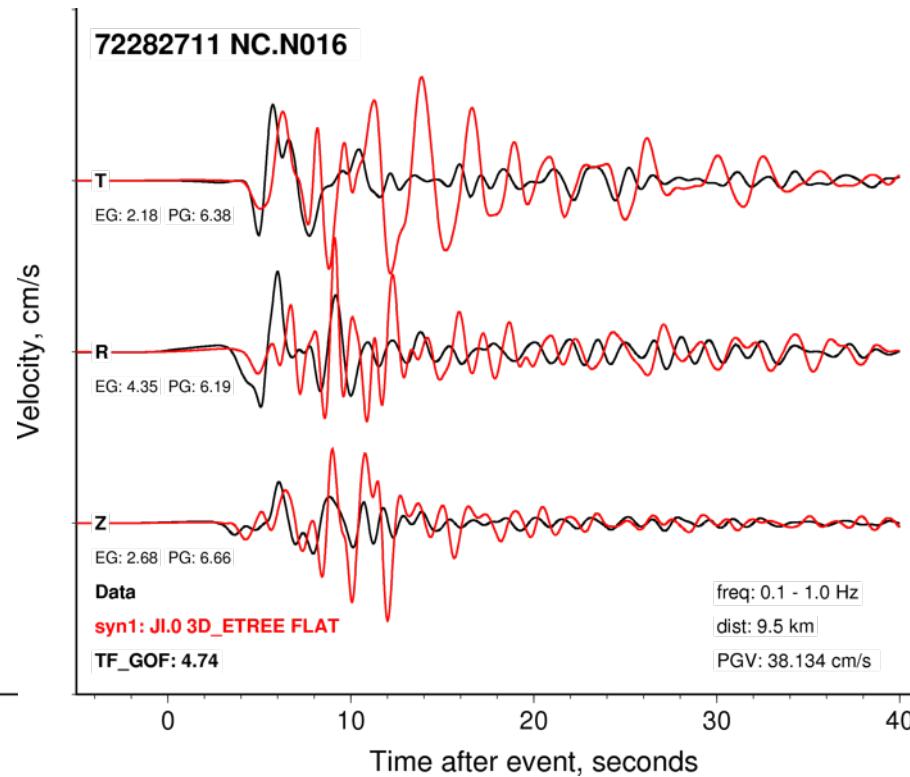
Ji source with 1D model has more complexity due to fine-scale rupture features

Example waveform fits: 3D USGS model, Dreger & Ji source models, 0.1-1 Hz

3D response has scattered waves

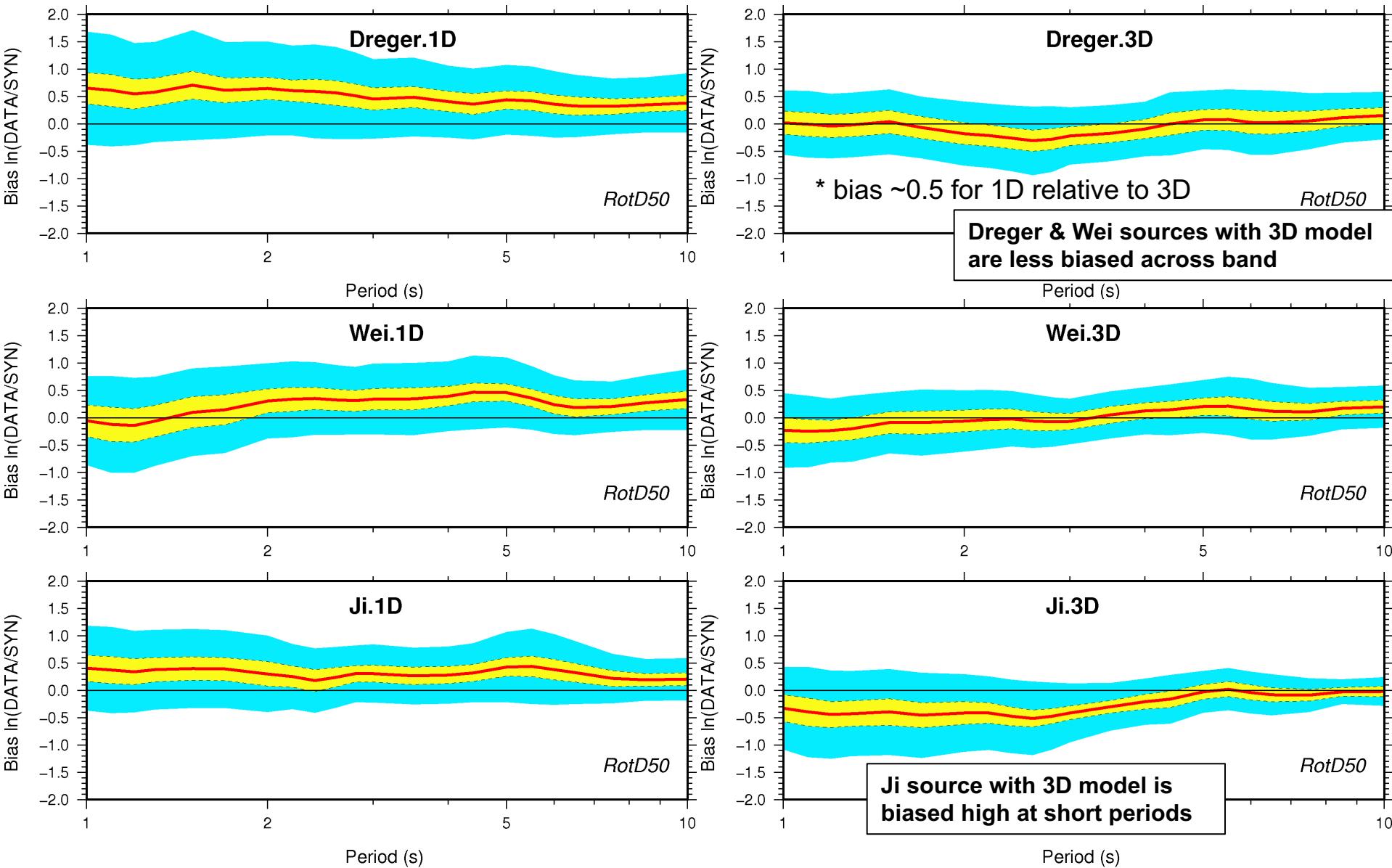


3D model has larger amplitude & coda waves



Ji source with 3D model tends to overpredict amplitudes

Response spectral ratios 1-10 seconds: 1D & 3D models, Dreger, Ji & Wei sources



Comparing waveforms from 12 moderate (M_w 5-4) earthquakes at BDSN broadband stations (v. 05.1.0)

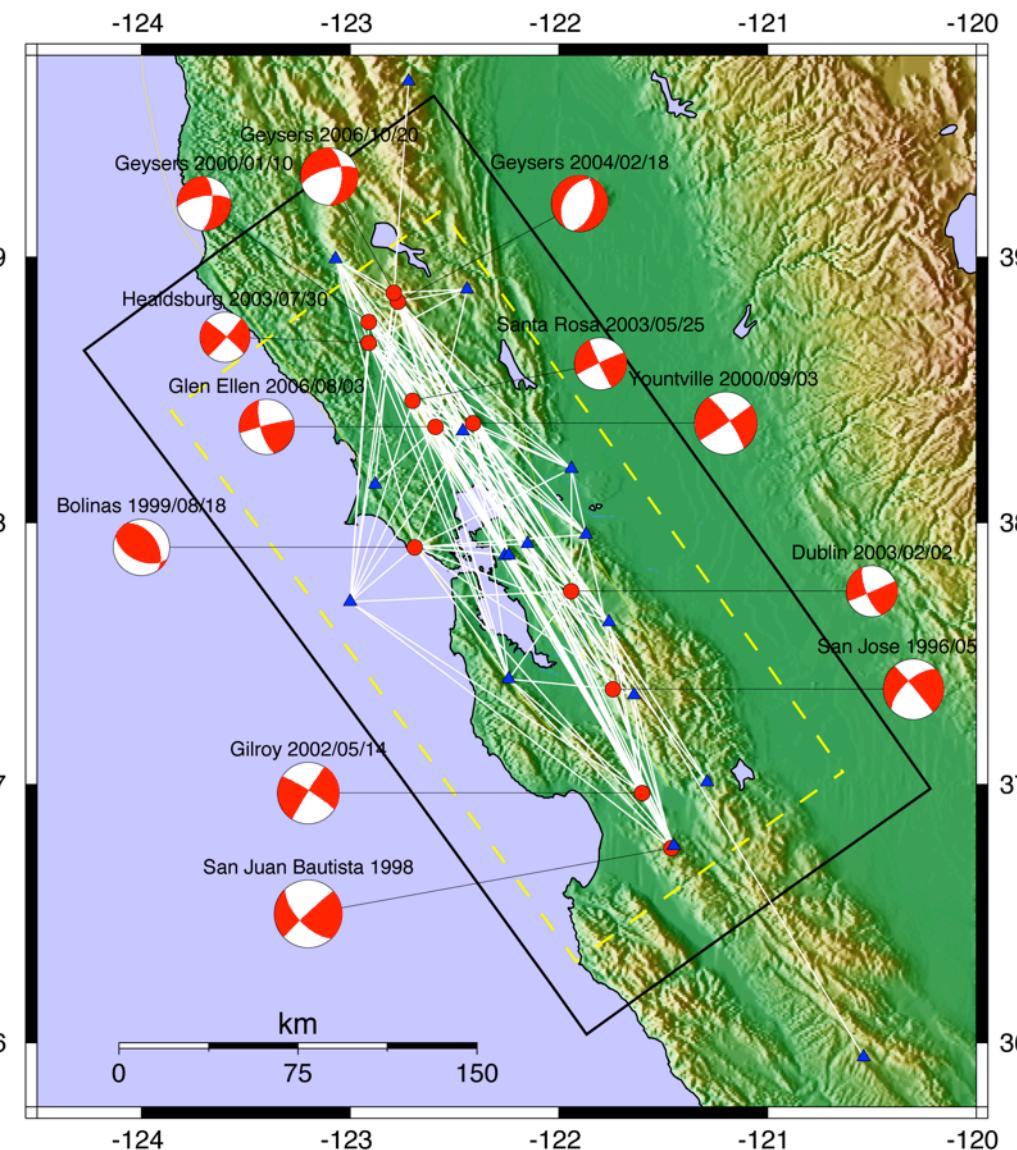
Events, BDSN Stations & Paths

Moderate (M_w 4-5) with BSL moment tensors

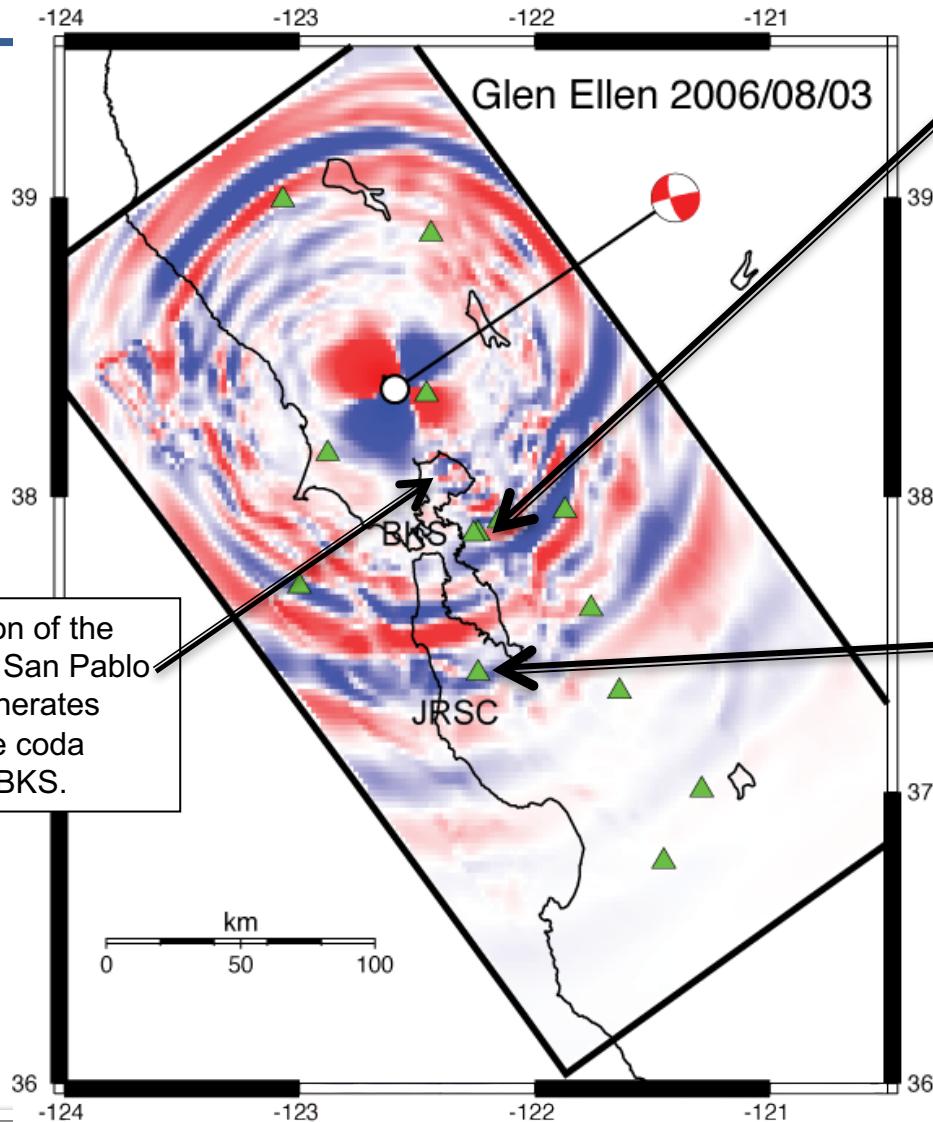
12 events (circles)
15 stations (triangles)

Coverage uneven

Rodgers et al. (BSSA, 2008)

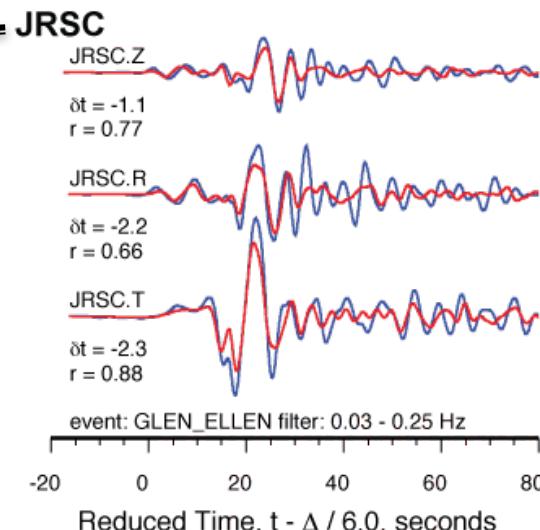
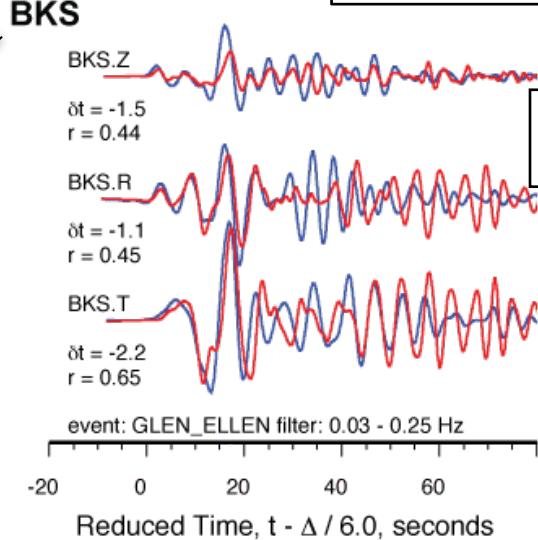


August 3 2006, Glen Ellen M_W 4.7 Earthquake (33-4 second periods)

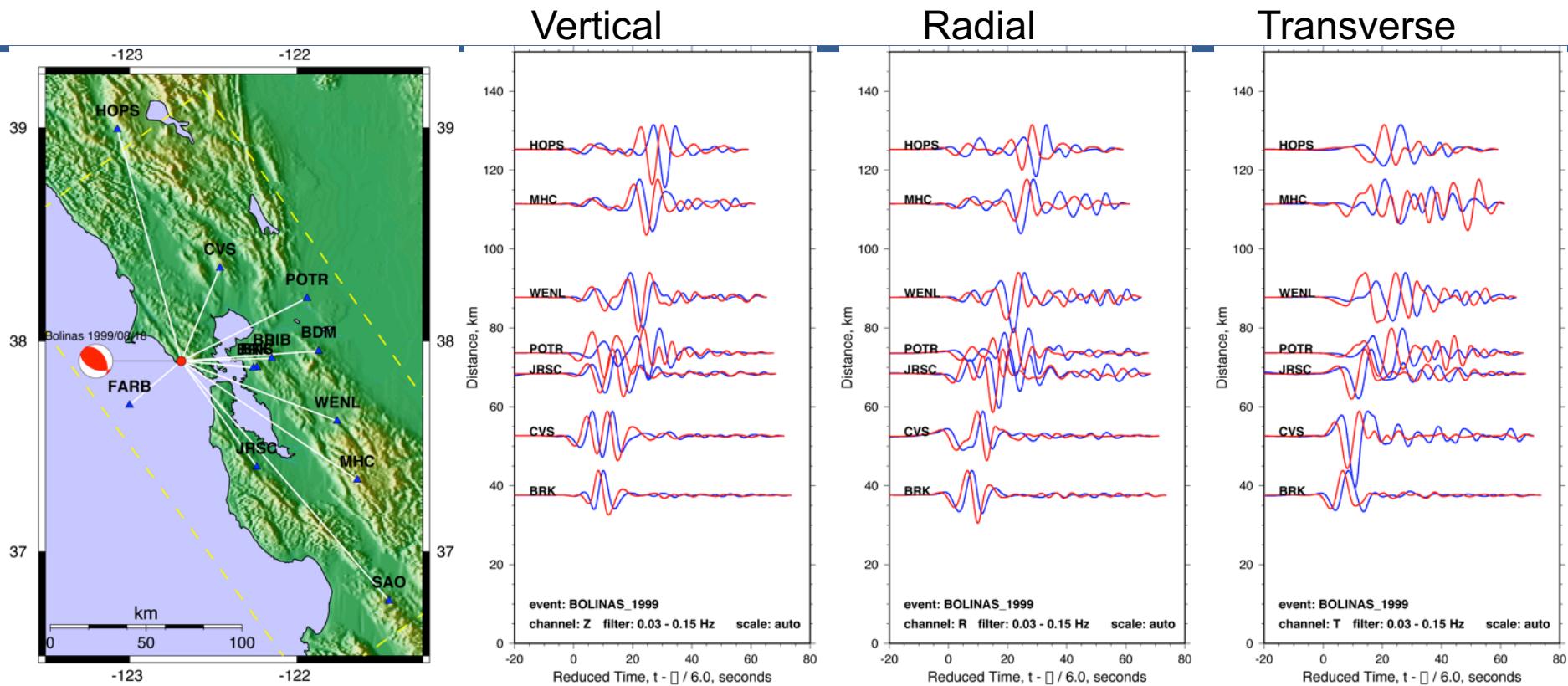


Note distortion of the wavefield by San Pablo Bay. This generates surface wave coda observed at BKS.

Absolute amplitudes,
time shifted and aligned
data & synthetic



Aug. 18 1999 M_w 4.6 Bolinas Earthquake (33-7 second periods)



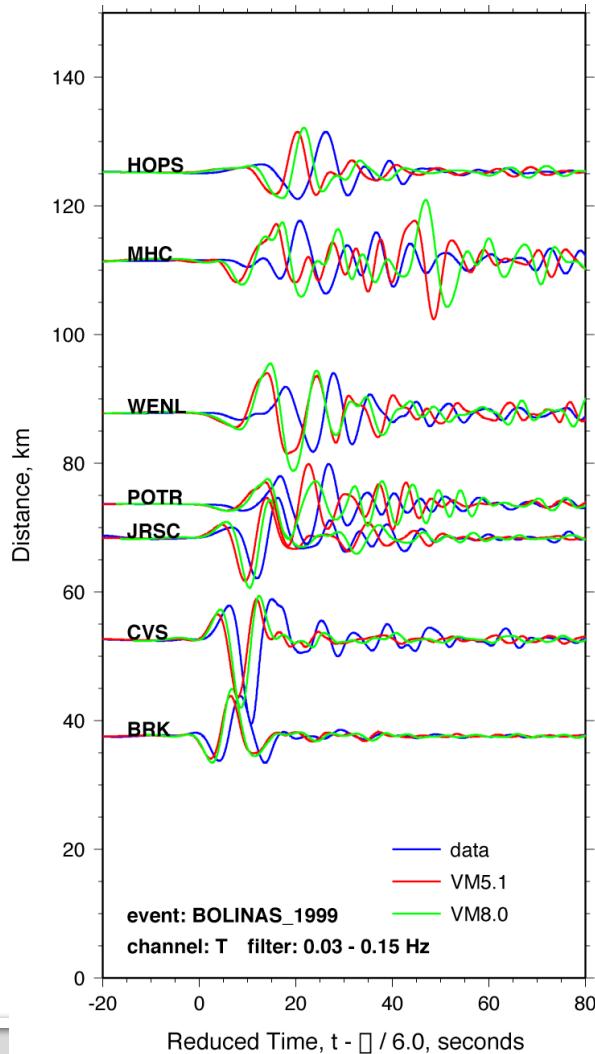
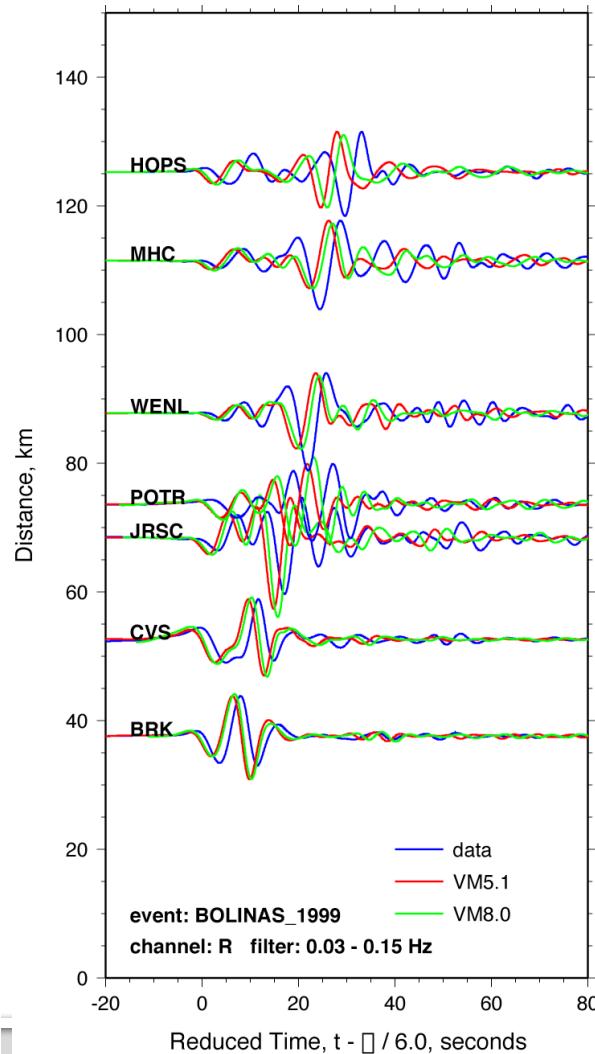
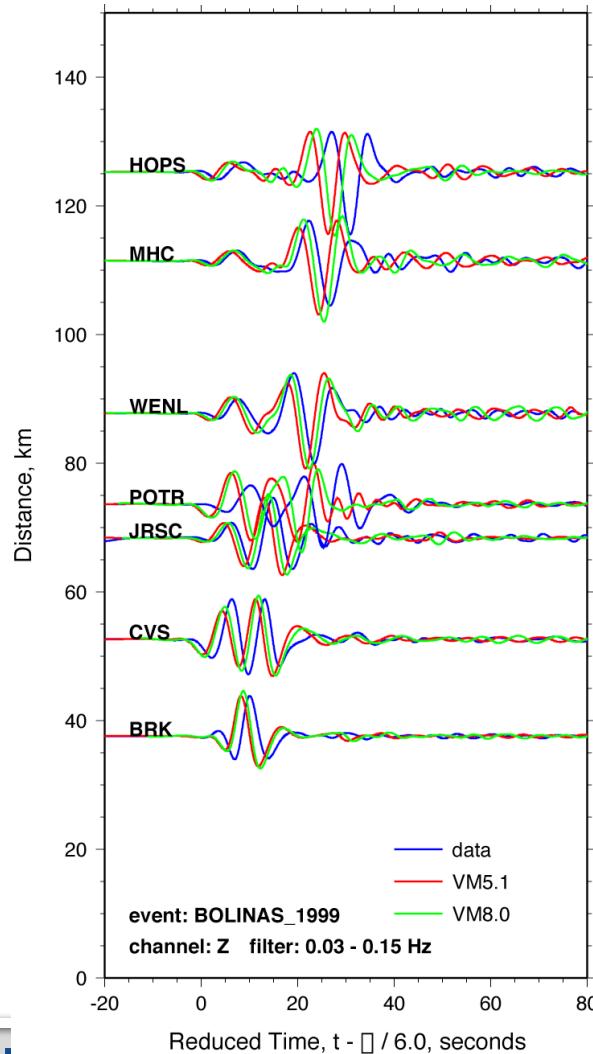
Frequencies = 0.03-0.15 Hz
Periods = 7-33 seconds

USGS model VM05.1

Delays increase with distance ...
suggests systematic bias
Note amplitudes are well matched
(see Kim, Dreger & Larsen, BSSA 2010)

Data and synthetics for two versions models for the Bolinas 1999 event

VM8.0 indeed slower than VM5.1, but slow enough?

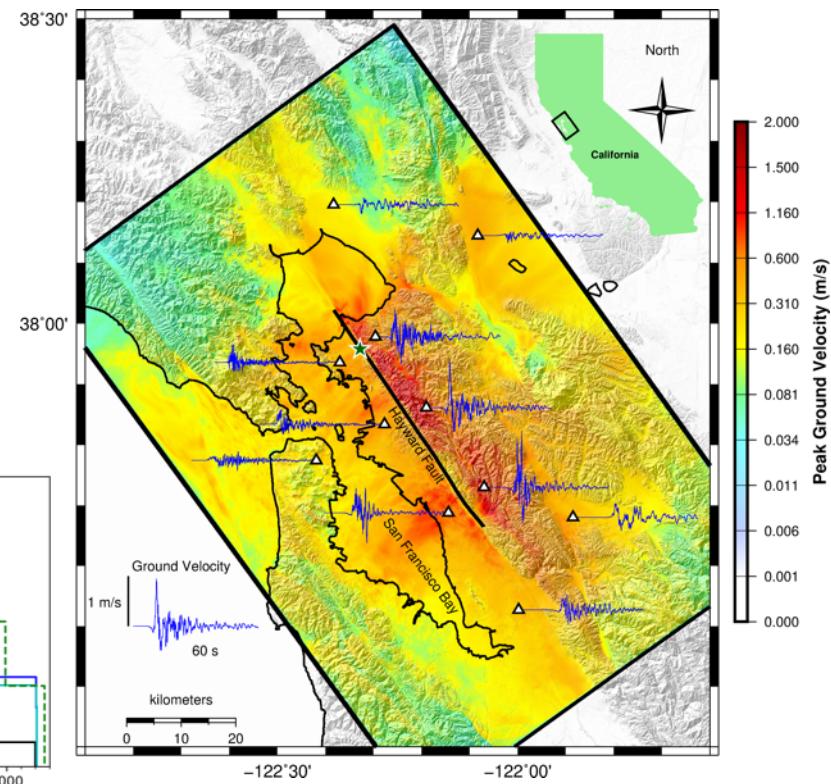
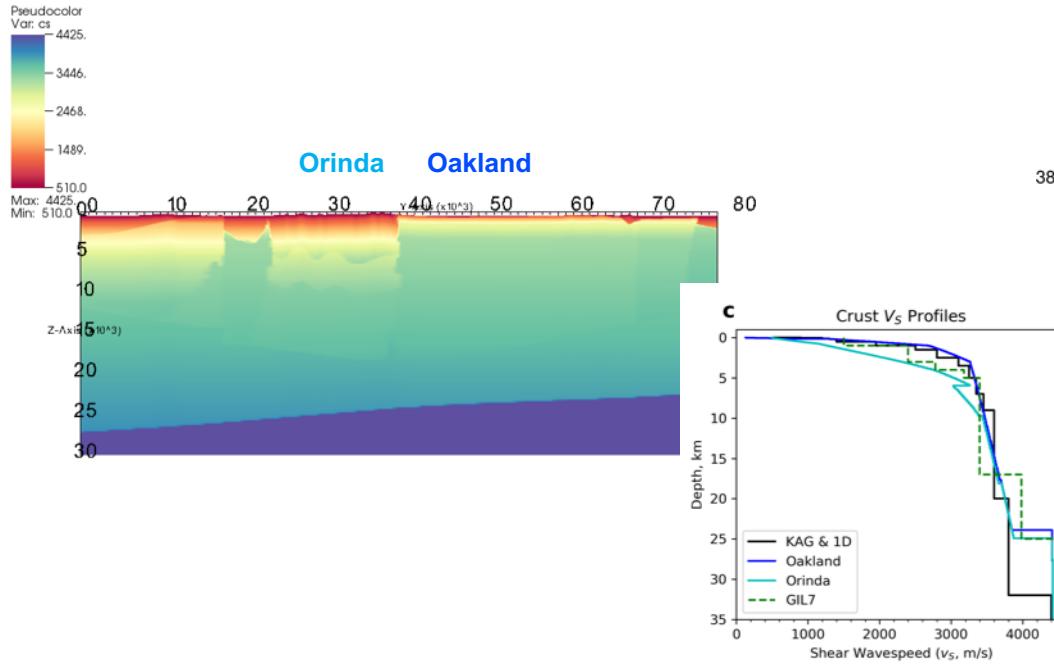


Summary of moderate earthquake waveform comparisons circa 2008

- Shear wavespeeds in the USGS 3D model are too fast
 - Based on complete waveforms 30-4 seconds
 - Surface wave delays increase with range
 - See BSSA 2008 paper
- With slight time shifts waveform comparisons and amplitudes are quite good
 - So maybe geometry of structure is OK, but volumetric wavespeeds must be improved
- Model version 8.0 slightly better than 5.1
 - Version 8.0 reduces delay time bias and improves waveform fit (slightly)
 - Presented at SSA 2008 talk & NEHRP report 08HQGR0022

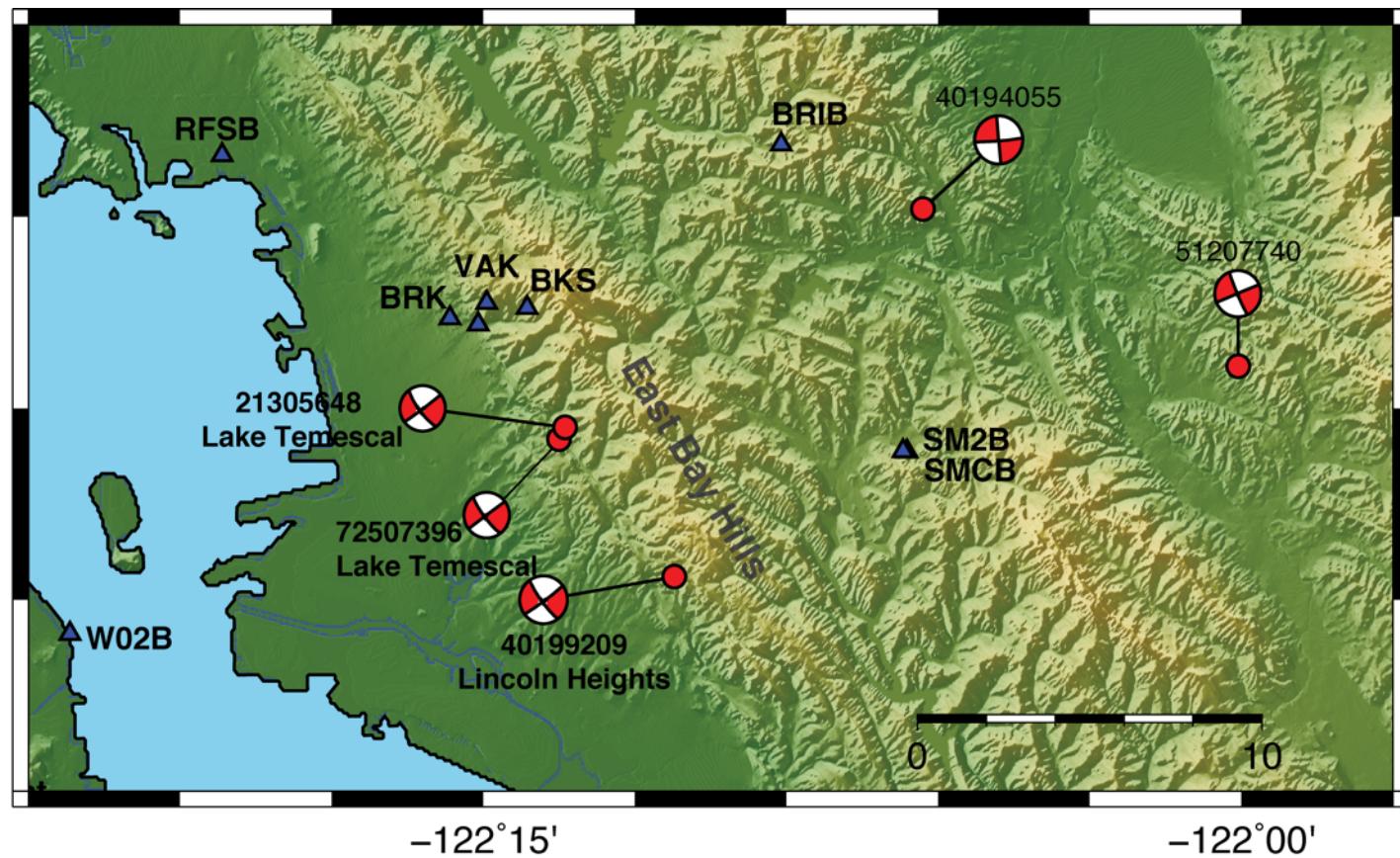
Recent work on Hayward Fault events, paths sampling East Bay Hills/Great Valley Sequence

- Why are motions so different across the HF in 4 Hz M 7.0 scenario?
 - $v_{S\min}$ (500 m/s) not accounting for geotech in Oakland?
 - v_s too low in EBH, amplifying motions
- Cross-section of v_s across HF, looking south:



v_s differences across HF persists to ~10 km

Recent consideration of 5 five events near Berkeley-Oakland-Orinda at BSL sites



Events

$M_W \sim 4.0$

BSL moment tensor

NCSS double-difference origins

Waveforms

Berkeley Digital Seismic Network (broadband)

Northern Hayward Fault Network (borehole)

Evaluate goodness-of-fit by cross-correlation on rotated, filtered waveforms

Plot shows 3-component wf's:

Observed waveform —————
Synthetic waveform -----
" shifted with optimal delay —————

Compute from peak of cross-

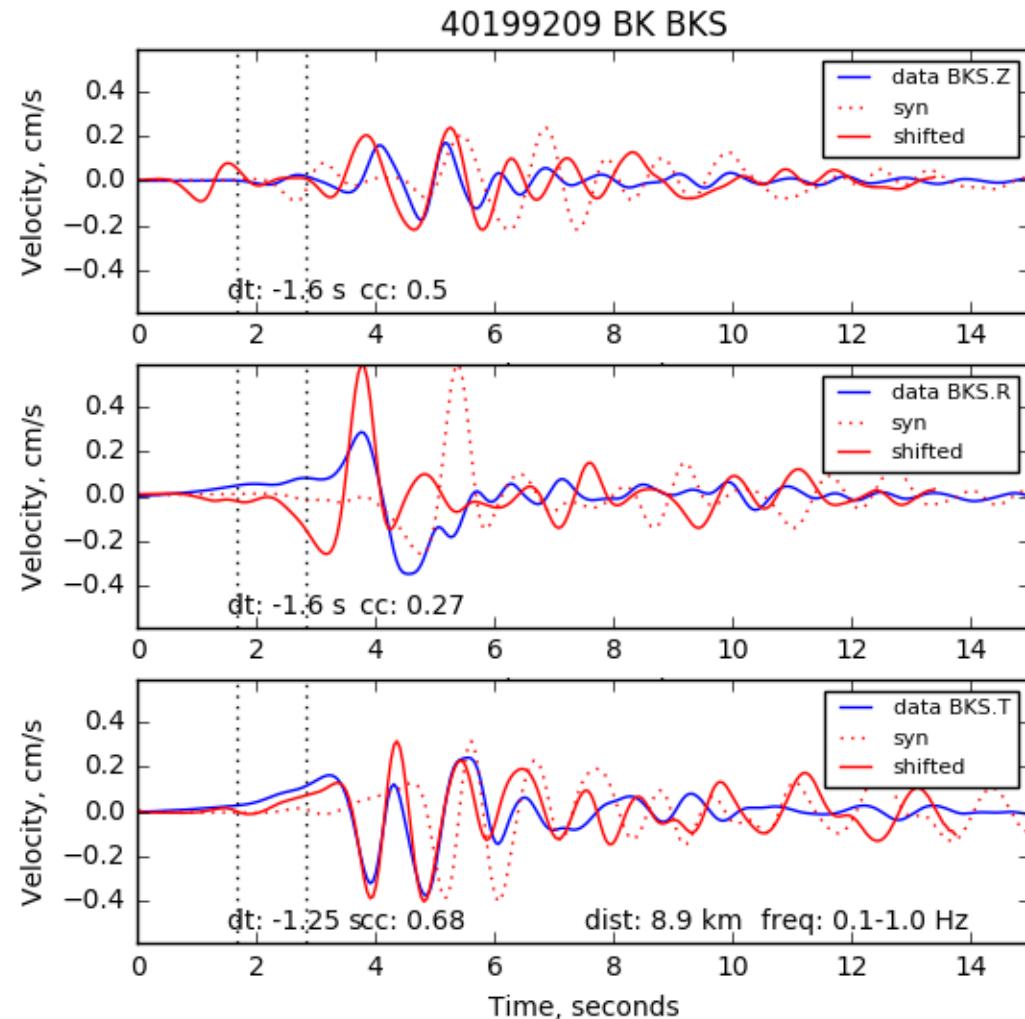
correlation:

- delay time
- correlation coefficient

Delay time indicates bias in Earth

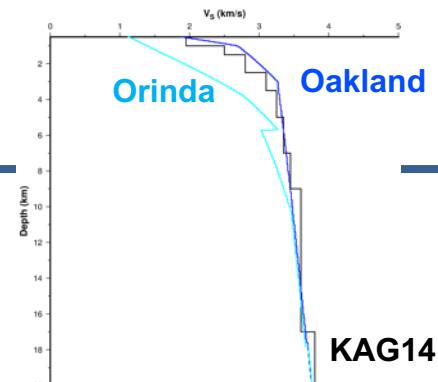
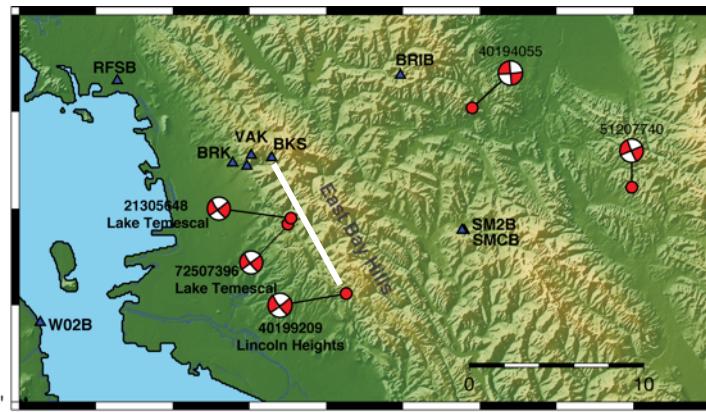
model

CC indicates accuracy of the
source & Earth models

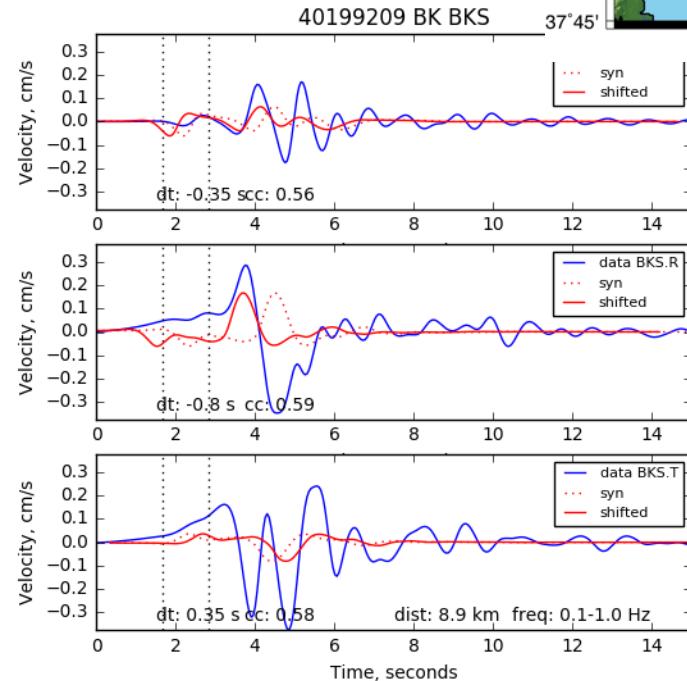


Lincoln Heights to BKS – East of HF

Velocity response
 Absolute amplitudes
 Filter 0.1-1 Hz
 Each data-syn pair x-correlated
 Shift by delay time, dt
 Compute cc



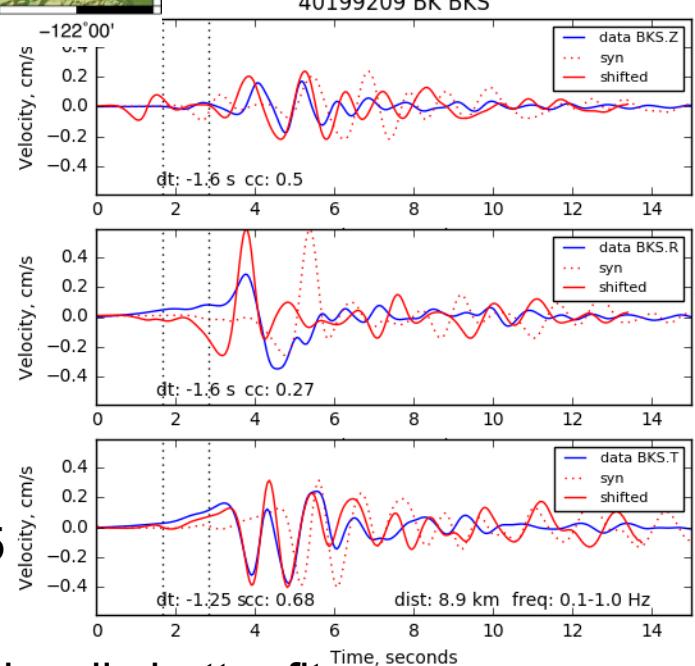
1D (KAG14)



USGS 3D model
east of the HF
appears to be
too slow?

$$\begin{array}{ll} dt = -0.35 & dt = -1.25 \\ cc = 0.58 & cc = 0.68 \end{array}$$

3D (USGS)



3D model gives visually better fit



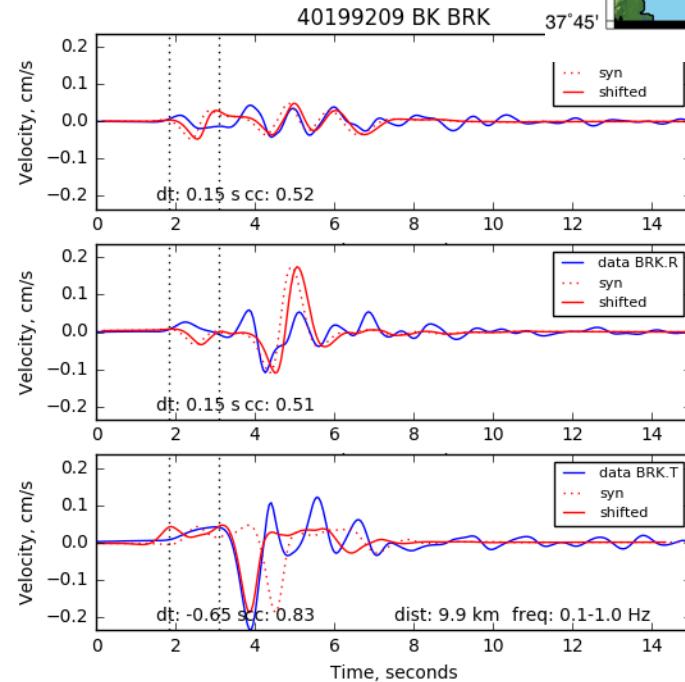
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LNNL-PRES-748020



Lincoln Heights to BRK – West of HF

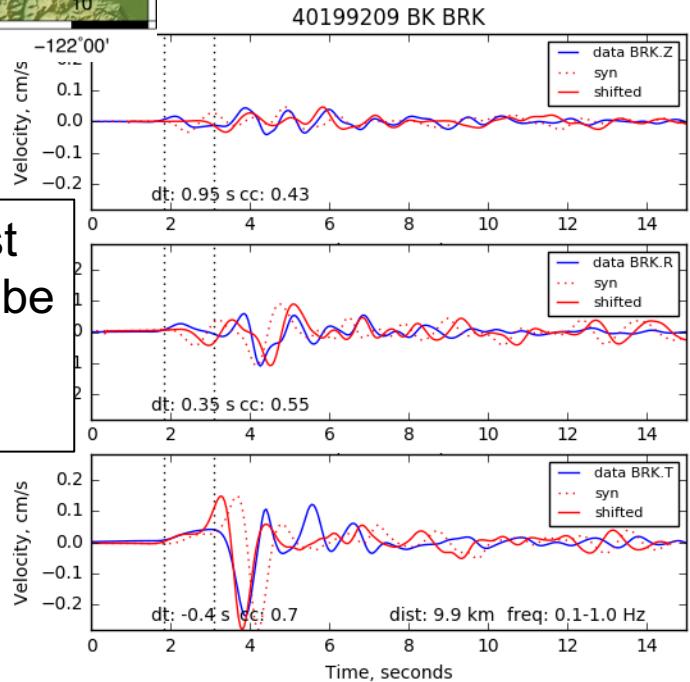
1D KAG2014



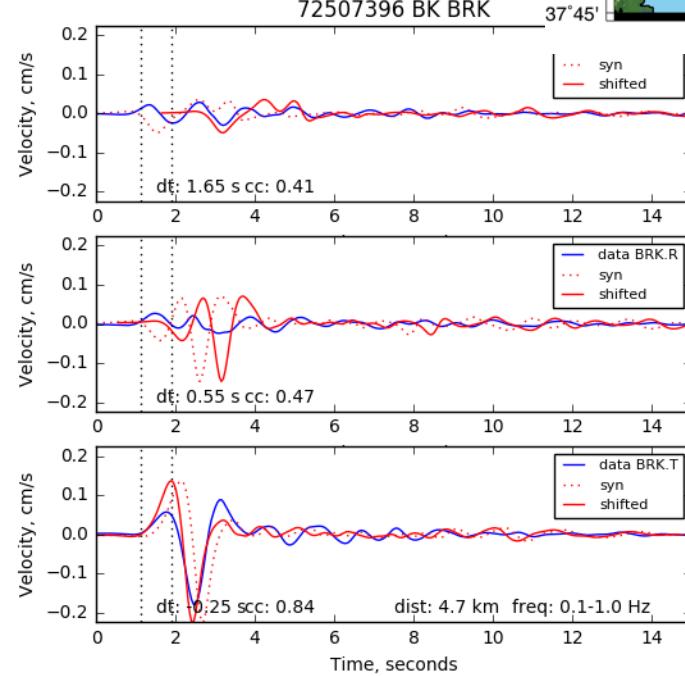
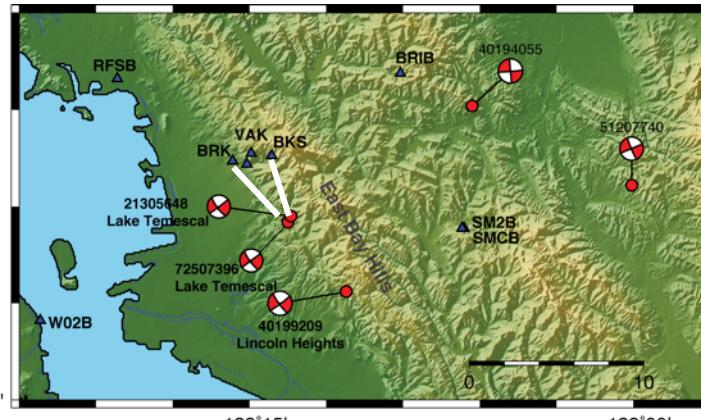
USGS 3D model west
of the HF appears to be
less biased than the
east side

$$\begin{aligned} dt &= -0.65 & dt &= -0.40 \\ cc &= 0.83 & cc &= 0.7 \end{aligned}$$

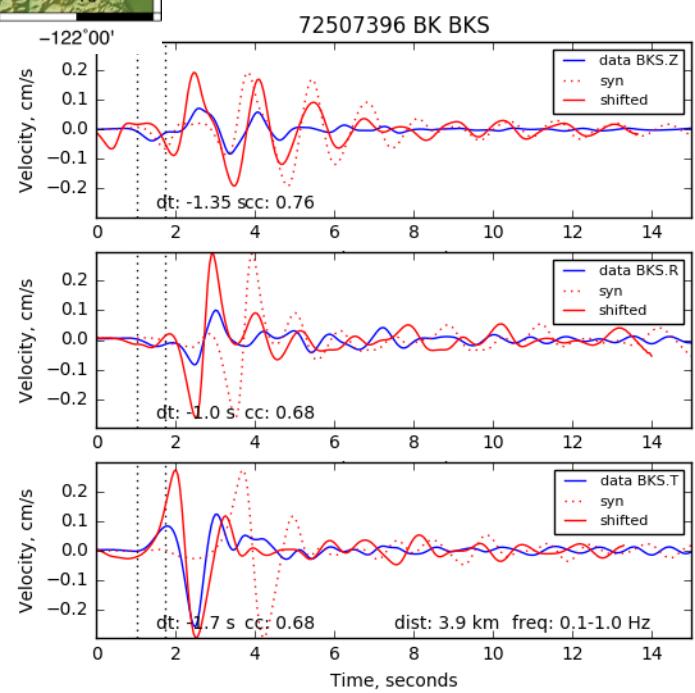
3D USGS



Lake Temescal to BRK (west) & BKS (east)

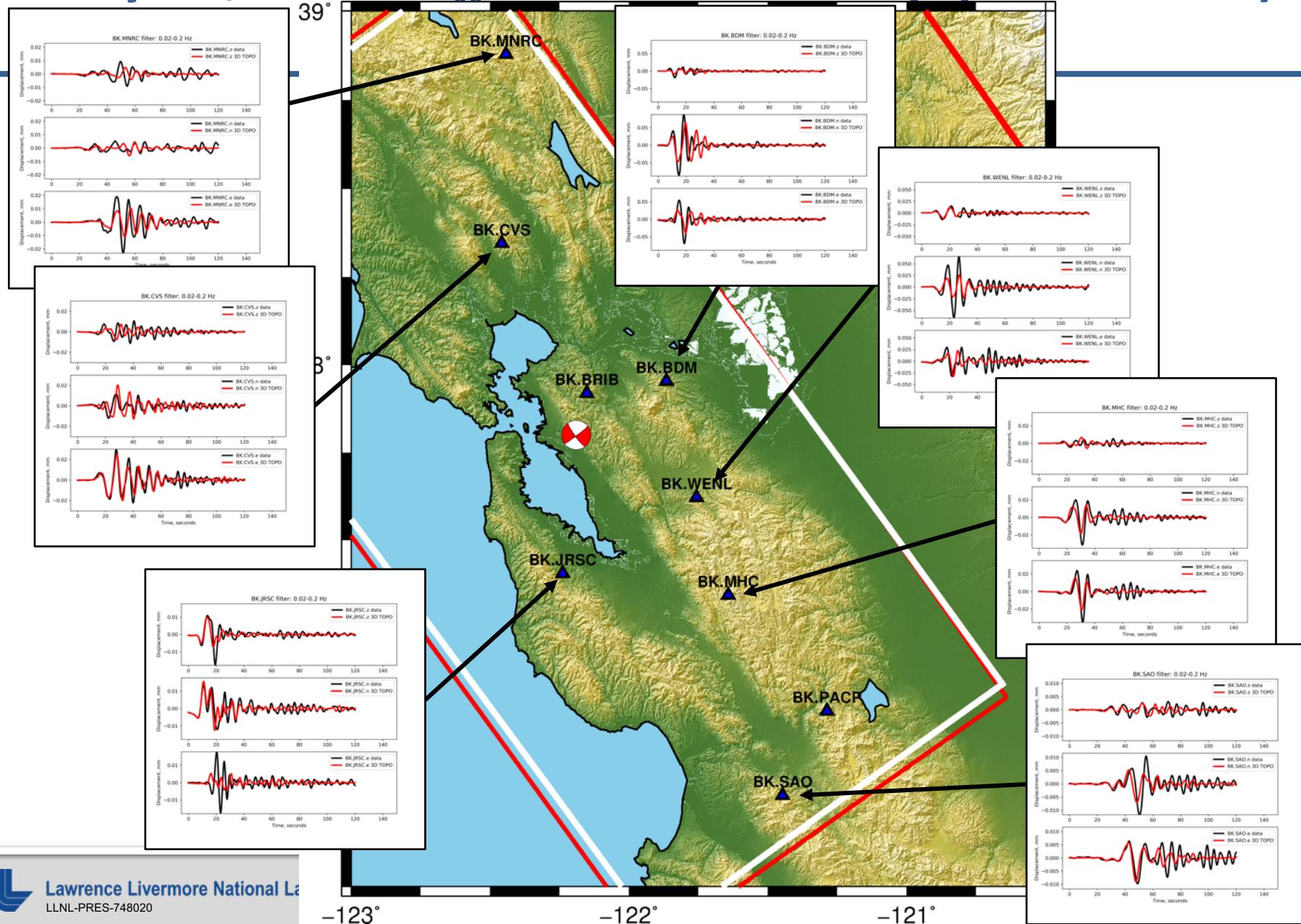


USGS 3D model
west of the HF
appears to be
less biased than
the east side



USGS 3D model east
of the HF appears to be
too slow?

Longer paths with USGS 3D Model version 8.3.0: July 20, 2007 M_w 4.2 Piedmont eq. (0.02-0.2 Hz)



Summary

- The current and previous versions of the USGS 3D model of the SFBA reproduce important features in observed seismograms from large (M_w 6.0 South Napa) and moderate (M_w 4-5) earthquakes
 - Direct waves at low frequencies ($f < 0.2$ Hz) look pretty
 - long-periods, $T > \sim 5$ seconds
- Significant differences in observed and simulated waveforms are exposed as we increase frequency content
 - especially clear at about 0.2 - 1 Hz
 - current long-wavelength 3D model likely does not cause scattering at higher frequencies
- The low wavespeeds in the East Bay Hills (Great Valley Sequence) and contrast across the Hayward Fault needs to be investigated more thoroughly
 - Source locations, mechanisms and 3D model are intertwined