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Final Report for USGS NEHRP Project 08HQGR0022

A. J. Rodgers

September 29, 2015

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Final Report for USGS NEHRP Project 08HQGR0022

USGS Award number: 08HQGR0022
Project Title: "Quantifying Uncertainties in Ground Motion Simulations for Scenario Earthquakes on the Hayward-Rodgers Creek Fault System Using the USGS 3D Seismic Velocity Model and Realistic Pseudodynamic Ruptures"
Term of Award: December 2007 – August 2009.

Principal Investigator: Dr. Arthur J. Rodgers
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Date of Report: September 30, 2015

Abstract

This is the final report for United States Geological Survey (USGS) National Earthquake Hazard Reduction Program (NEHRP) Project 08HQGR0022, entitled "Quantifying Uncertainties in Ground Motion Simulations for Scenario Earthquakes on the Hayward-Rodgers Creek Fault System Using the USGS 3D Seismic Velocity Model and Realistic Pseudodynamics Ruptures". Work for this project involved three-dimensional (3D) simulations of ground motions for Hayward Fault (HF) earthquakes. We modeled moderate events on the HF and used them to evaluate the USGS 3D model of the San Francisco Bay Area. We also contributed to ground motions modeling effort for a large suite of scenario earthquakes on the HF. Results were presented at conferences (see appendix) and in one peer-reviewed publication (Aagaard et al., 2010).

Report

This project was awarded to the PI (Dr. Arthur Rodgers) at the University of California, Santa Cruz and work was performed at Lawrence Livermore National Laboratory (LLNL) as intercampus transfer in the period December 2007 – August 2009. The work performed for this project was cooperative with the USGS Menlo Park. After funding was received, the PI was invited to collaborate with Dr. Brad Aagaard at USGS-MP. Dr. Aagaard was leading a multi-institutional project to simulate ground motions for possible large scenario earthquakes on the Hayward Fault. This work was strongly aligned with the work proposed in my NEHRP project and effort was directed toward this project. The work in the original proposal was not performed, but rather the PI worked with Dr. Aagaard and co-workers on a large suite of scenario earthquakes on the Hayward-Rodgers Creek Fault system.

During the course of the project, research results and progress were reported at several conferences. Presentation details are provided below. For presentations given by the author, the material is described and included in the Appendix.

- 2007 American Geophysical Union (AGU) Fall Meeting, Dec. 10-14, 2007, San Francisco
    - Rodgers et al., (2007). This poster described two efforts: 1) modeling of two moderate earthquakes and large scenario earthquakes on the Hayward Fault. The two moderate earthquakes (20 July, 2007 Piedmont and 31 October 2007 Alum Rock) were modeled using the Berkeley Seismological Laboratory moment tensor. Waveforms at local distance stations (< 50 km) were shown. The 3D model reproduces the complex response seen for paths crossing sedimentary basins, especially the Santa Clara and Livermore Basins. The scenario earthquakes on the Hayward Fault used finite fault models from a database maintained by Martin Mai (http://equake-rc.info/SRCMOD/). We used four source models for the 17 January 1995 Kobe and one for the 6 October, 2000 Tottori earthquake. These strike slip earthquakes are similar to the expected behavior of the Hayward Fault. Results show how asperities near sedimentary basins can lead to large ground motions.

- 2008 Seismological Society of America Annual Meeting, Apr. 16–18, 2008, Santa Fe, New Mexico, USA
    - Aagaard et al. (2008)
    - Rodgers et al. (2008). This oral presentation describes further work on modeling scenario earthquakes on the Hayward Fault and quantitative comparison of two versions of the USGS 3D model: versions 5.1 and 8.0. In an earlier study by Rodgers et al. (2008) we showed that the shear wavespeeds in model version 5.1 were fast by about 5%. Following this work the USGS (Dr. Thomas Brocher) made changes to the rules governing the assignment of material properties to lithologic units. The USGS-MP created 3D model version 8.0 and we compared the waveform fits for 6 moderate earthquakes recorded at Berkeley Digital Seismic Network broadband stations. Results showed that the perturbed model (version 8.0) provided better fits to the waveforms, where fit is quantified by the delay time of the main surface wave and linear correlation taking the delay into account.

- 2008 American Geophysical Union (AGU) Fall Meeting, Dec. 15-19, 2008, San Francisco
    - Aagaard et al. (2008)

Work for this project culminated in a published paper in the Bulletin of the Seismological Society of America (Aagaard et al., 2010). This paper should have been cited the NEHRP project in question in the acknowledgements, but was not due to my oversight. This paper describes simulated ground motions for a large suite (39 scenarios) of possible earthquakes on the Hayward-Rodgers Creek Fault System and is very much in the spirit of the original proposal.

Bibliography - publications resulting from the work performed under the award

Aagaard, B., Brocher, T., Boatwright, J., Dreger, D., Graves, R. Graymer, R. Harris, R., Larsen, S., Lienkaemper, J., Ma, S., Ponce, D., Rodgers, A., Schwartz, D., Simpson, R., and Spudich, P. (2008). Scenario Earthquake Ruptures of the Hayward Fault. Seismological Research Letters, Volume 79, Number 2, March/April 2008, presented at Seismological Society of America Annual Meeting, Apr. 16–18, 2008, Santa Fe, New Mexico, USA

Aagaard, B., R. Graves, S. Larsen, S. Ma, T. Brocher, R. Graymer, R. Harris, J. Lienkaemper, D. Ponce, D. Schwartz, R. Simpson, P. Spudich, D. Dreger, N. A. Petersson and J. Boatwright (2008). Ground Motion Simulations of Scenario Earthquake Ruptures of the Hayward Fault, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract S14B-08, presented at American Geophysical Union (AGU) Fall Meeting, Dec. 15-19, 2008, San Francisco

Aagaard, B. T., R. W. Graves, A. J. Rodgers, T. M. Brocher, R. W. Simpson, D. S. Dreger, N. A. Petersson, S. C. Larsen, S. Ma and R. C. Jachens (2010). Ground-Motion Modeling of Hayward Fault Scenario Earthquakes, Part II: Simulation of Long-Period and Broadband Ground Motions, *Bull. Seismol. Soc. Am.*, 100, 2945-2977, doi: 10.1785/0120090379

Rodgers, A., X.-B. Xie and N. A. Petersson. (2007). Bounding Ground Motions for Hayward Fault Scenario Earthquakes Using Suites of Stochastic Rupture Models, *Eos Trans. AGU, 88*(52), Fall Meet. Suppl., Abstract S21A-0232**,** 2007 American Geophysical Union (AGU) Fall Meeting, Dec. 15-19, 2007, San Francisco

Rodgers, A., Xiao-Bi Xie (2008). Ground Motion Modeling of Recent Moderate (M4–5) and Large (M>6.5) Scenario Earthquakes on the Hayward Fault. Seismological Research Letters, Volume 79, Number 2, March/April 2008, Seismological Society of America Annual Meeting, Apr. 16–18, 2008, Santa Fe, New Mexico, USA

Acknowledgements

This work benefitted from collaboration with the USGS-Menlo Park with Brad Aagaard, Tom Brocher and Jack Boatwright. Anders Petersson and Bjorn Sjogreen developed the WPP 3D finite difference code used in simulations. Xiao-Bi Xie and UC Santa Cruz helped develop the original proposal. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-TR-677660.

Appendix

Presentations: Rodgers et al., (2007) and Rodgers et al. (2008).

Rodgers et al. AGU 2007

Two Recent Moderate Earthquakes and Hypothetical Large Scenario Earthquakes on the Hayward Fault

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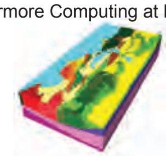
also at Center for the Study of Imaging and Dynamics of the Earth, University of California at Santa Cruz, Santa Cruz, CA
Xiao-Bi Xie, Institute of Geophysics and Planetary Physics, University of California at Santa Cruz, Santa Cruz, CA USA,
xie@es.ucsc.edu
Anders Petersson, Center for Applied Scientific Computing, Lawrence Livermore National Laboratory, Livermore, CA USA,
andersp@llnl.gov

Lawrence Livermore National Laboratory

Simulations were performed using LLNL-developed WPP code, the USGS 3D seismic velocity model for the San Francisco Bay Area (Brocher et al., 2006) and parallel computers operated by Livermore Computing at LLNL.



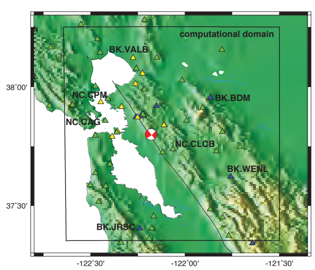
The WPP code is supported by LLNL LDRD project 05-ERD-079. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Hayward Fault scenario earthquake simulations are supported by USGS/NEHRP Project 08HQGR0022 to the University of California, Santa Cruz.

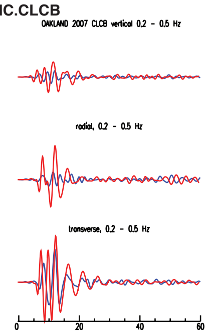
Piedmont 2007/07/20 Earthquake

Simulation of the 2007 July 20 Piedmont earthquake was done with our new WPP code for 100 km x 100 km x 30 km volume with 100 m grid spacing for accurate synthetics to 0.5 Hz. Seismograms were obtained from the NCEDC for the Berkeley Digital Seismic Network (BDSN, blue triangles), Northern Hayward Fault Network (NHFN, yellow) and strong-motion instruments of the USGS Northern CA Network (green).

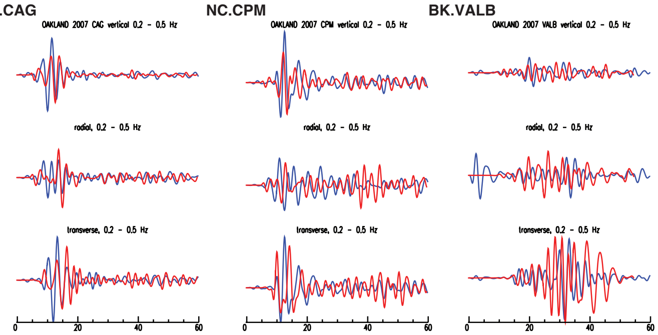
Comparison of observed and synthstic seismograms shows good agreement in general with satisfactory prediction of amplitudes and waveform complexity. Longer paths (> 10 km) often show the synthetics arriving ahead of the data, consistent with an earlier study (Rodgers et al., *BSSA* in press).



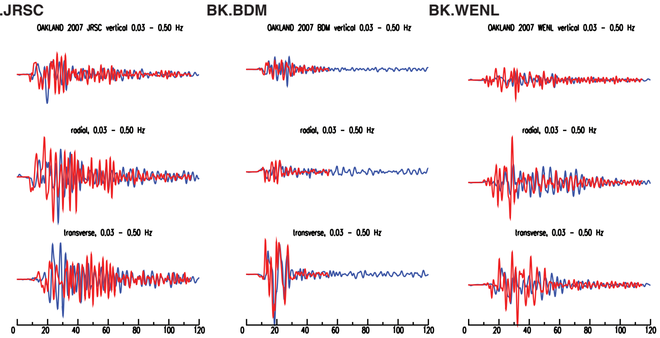
NC.CLCB



NC.CAG NC.CPM BK.VALB

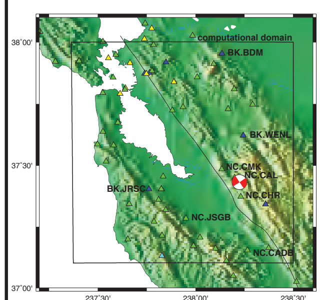


BK.JRSC BK.BDM BK.WENL



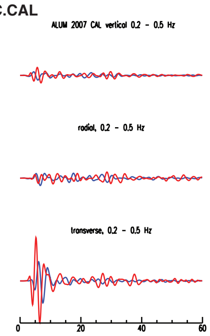
Absolute time and amplitude scaling

Alum 2007/10/31 Earthquake

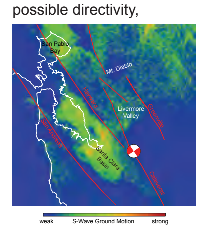


Simulation of the 2007 October 31 Alum earthquake was done for 100 km x 100 km x 30 km volume with 100 m grid spacing for accurate synthetics to 0.5 Hz. Observed and predicted waveforms are compared below. Seismograms were obtained from the NCEDC for the Berkeley Digital Seismic Network (BDSN, blue), Northern Hayward Fault Network (NHFN, yellow) and strong-motion instruments of the USGS Northern CA Network (green). This event is larger and appears to have a more complex source-time function and possible directivity,

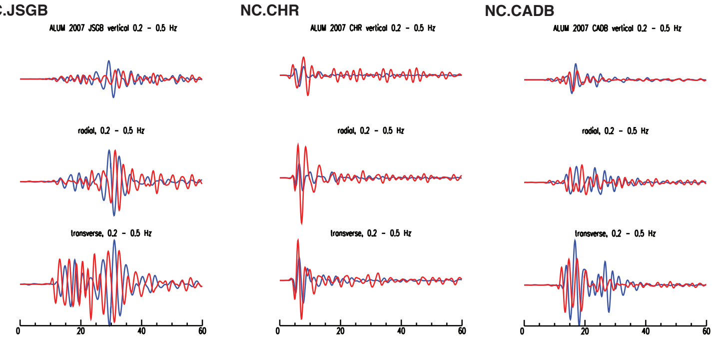
NC.CAL



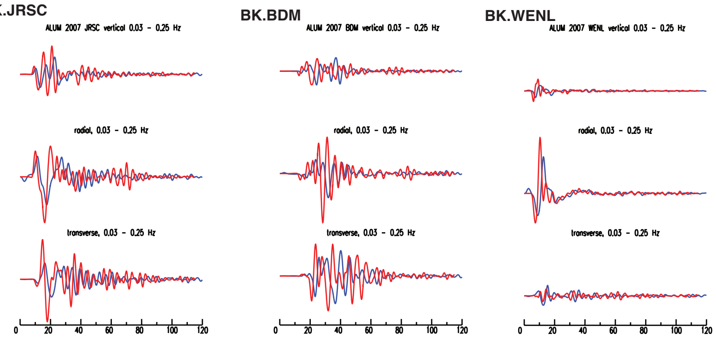
3D simulation allows us to output the wavefield. The plot to the right shows the curl of the velocity field, responsible for S-wave motion at a time after the direct energy has passed through most of the region. The largest amplitude shaking is seen in the sedimentary structures as expected, e.g. Santa Clara Valley, Livermore Valley, San Pablo Bay.



NC.JSGB NC.CHR NC.CADB



BK.JRSC BK.BDM BK.WENL



Absolute time and amplitude scaling

Rodgers et al. AGU 2007

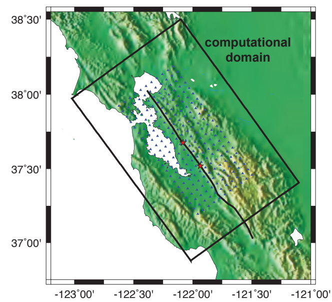
Hayward Scenario Earthquakes

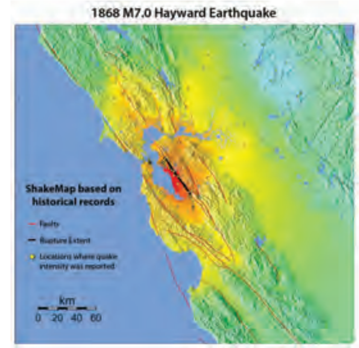
We performed simulations of scenario earthquakes on the Hayward Fault using reported finite rupture models from large strike-slip earthquakes. These included the following two events:

1995/01/17 **Kobe, Japan** using source models from:
- Wald (1996) Mw = 6.92
- Sekiguchi et al. (2000) Mw = 7.02
- Zeng and Anderson (2000) Mw = 6.90

2000/10/06 **Tottori, Japan** using source model from:
- Iwata and Sekiguchi (2001) Mw = 6.86

Finite source models were obtained from the database maintained by Martin Mai (http://www.seismo.ethz.ch/srcmod). Simulations were performed using WPP with a 150 km x 100 km x 50 km volume with 100 m grid spacing and minimum shear velocity of 500 m/s for accurate synthetics to 0.5 Hz. Seismograms were computed on the grid of stations surrounding the fault, shown on the right. We were interested in predicting the character of the inferred ShakeMap for the 1868 M ~7.0 Hayward earthquake (shown further to the right).



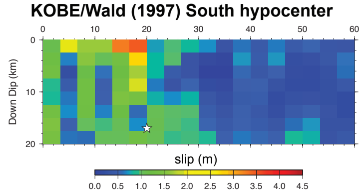


Summary of Results

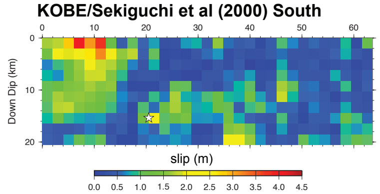
Simulations of scenario earthquakes on the Hayward Fault using reported finite rupture models for the M ~7 Kobe and Tottori earthquakes show large damaging ground motion levels near the asperities along the fault. Strong and/or long-duration shaking is also predicted in the sedimentary basins, particularly the Evergreen, Cupertino, San Leandro, Livermore basins and San Pablo Bay.

Future Work will focus on increasing the bandwidth of scenario earthquake simulations (possibly with other reported rupture models) and investigating pseudodynamic rupture models following the method of Liu et al (BSSA, 2006).

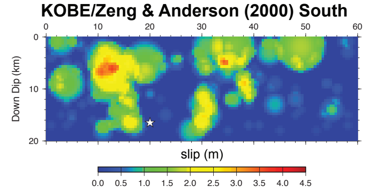
KOBE/Wald (1997) South hypocenter



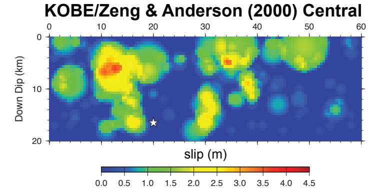
KOBE/Sekiguchi et al (2000) South



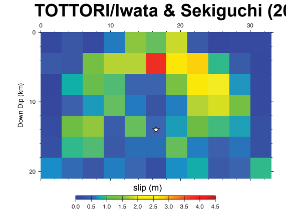
KOBE/Zeng & Anderson (2000) South

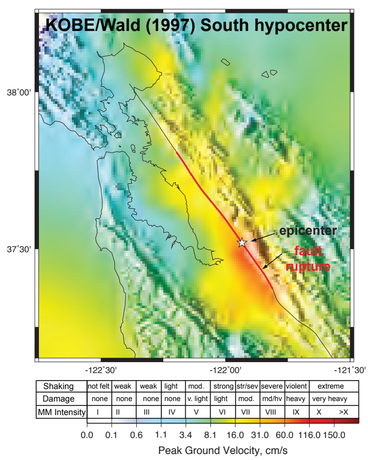


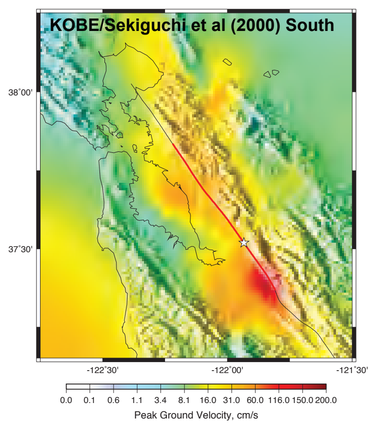
KOBE/Zeng & Anderson (2000) Central

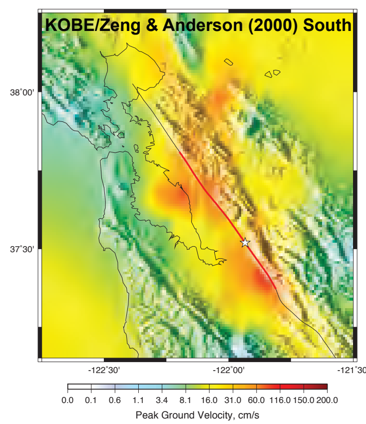


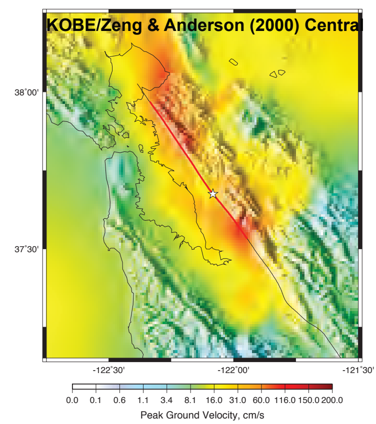
TOTTORI/Iwata & Sekiguchi (2001) South

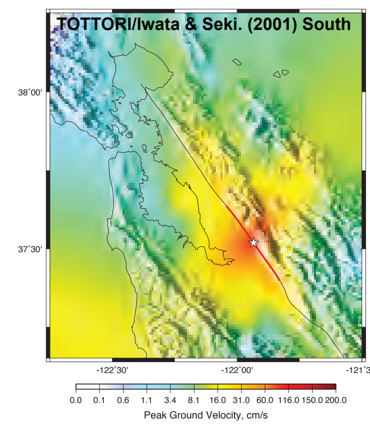






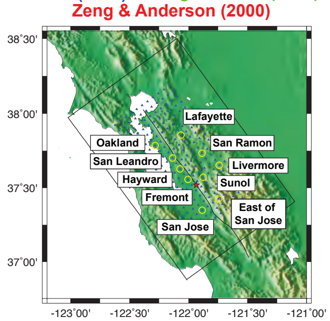


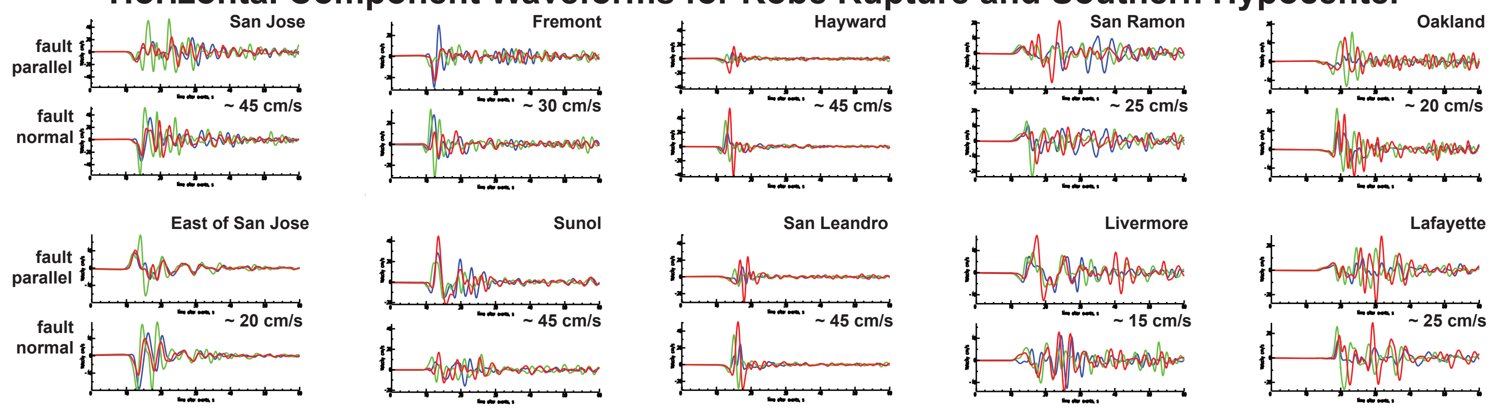




Horizontal Component Waveforms for Kobe Rupture and Southern Hypocenter

Horizontal component ground velocity seismograms for three rupture models with a Southern hypocenter at several locations. Records are color-coded by rupture model: **Wald (1996)** , **Sekiguchi et al (2000)** **Zeng & Anderson (2000)**





Ground Motion Modeling of Recent Moderate (M 4-5) and Large (M > 6.5) Scenario Earthquakes on the Hayward Fault

Arthur Rodgers[1,2] and Xiao-Bi Xie[1]

[1] *Center for the Study of Imaging and Dynamics of the Earth (CSIDE)*
University of California, Santa Cruz
Santa Cruz, CA
and
[2] *Lawrence Livermore National Laboratory*
Livermore, CA

Ground motion modeling depends critically on 3D seismic model

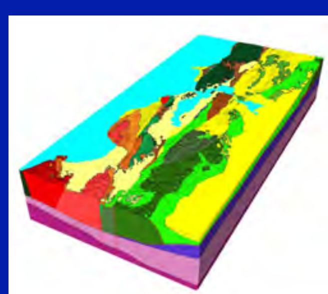
- Hayward Fault scenario earthquake calculations currently underway
- These use the USGS 3D seismic model(s)
- **Scenario earthquake simulations are only as accurate as the 3D model**
- Moderate earthquakes are ideal for testing ground motion predictions by 3D models
  - Recorded on-scale by broadband and strong-motion sensors
  - Generally, have simple source-time functions and focal mechanisms

Outline

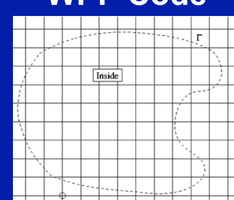
- Performance USGS 3D models
  - Compare observed and synthetic waveforms
    - Three-component broadband waveforms
    - Moderate (M_W 4-5) earthquakes
- Synthetics computed for 2 models
  - VM5.1
  - VM8.0
- Model performance measured by
  - Waveform delays and correlations
    - Rodgers et al. (2008)
  - Time-frequency misfits with wavelet method
    - Kristekova et al. (BSSA, 2006)

Ground motion modeling made possible with 3D model, code and computers

USGS Model(s)



WPP Code



Livermore Computing

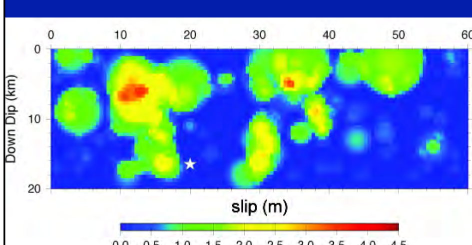
WPP code

- Open-source anelastic wave propagation code
  - 2nd order, node-centered code
  - Runs serial or parallel
  - Download at:
    - https://computation.llnl.gov/casc/serpentine/software.html
- Recent release includes
  - Mesh refinement
  - Attenuation

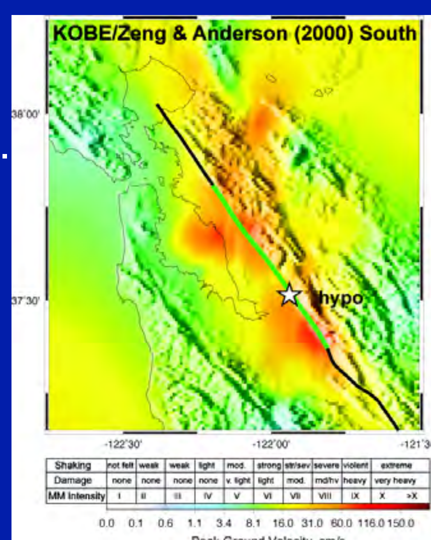
Hayward Scenario Earthquakes

ShakeMap for M_W 7.02 event derived from PGV

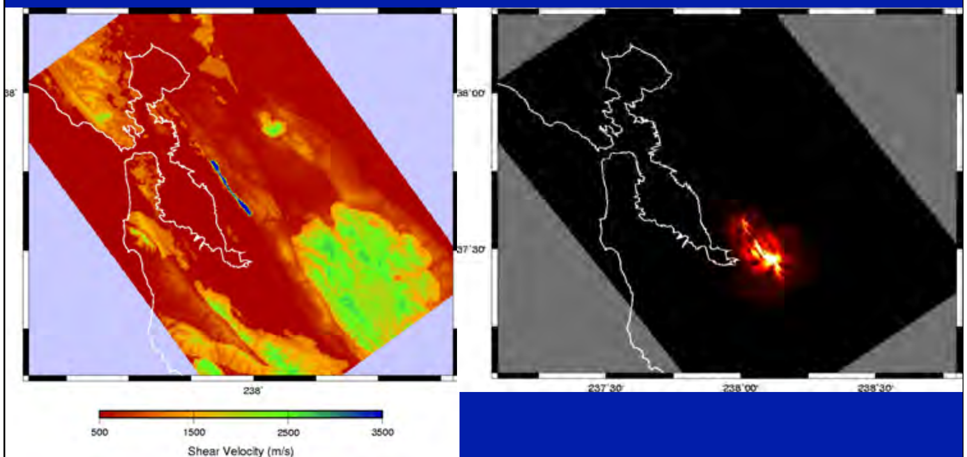
WPP synthetics valid to 1 Hz.

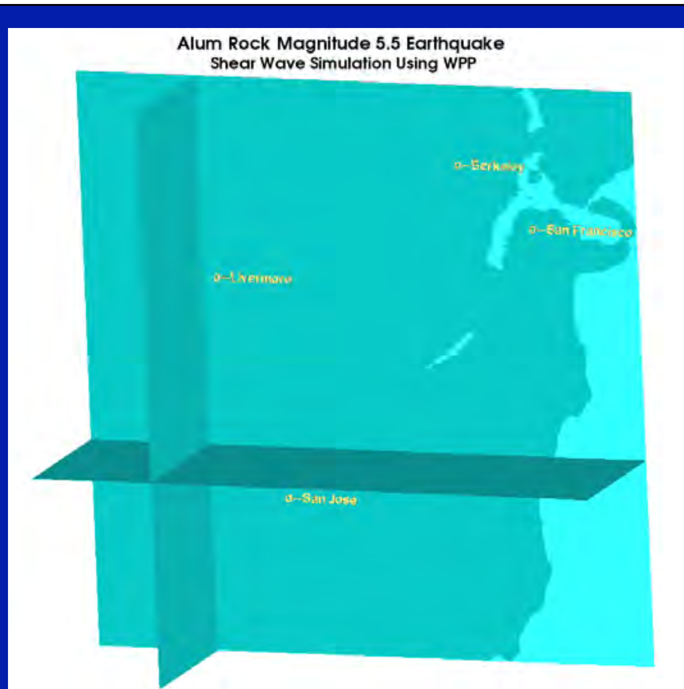


Slip model from Zeng and Anderson (2000)



Kobe slip model (Zeng and Anderson 2000) on the Hayward Fault



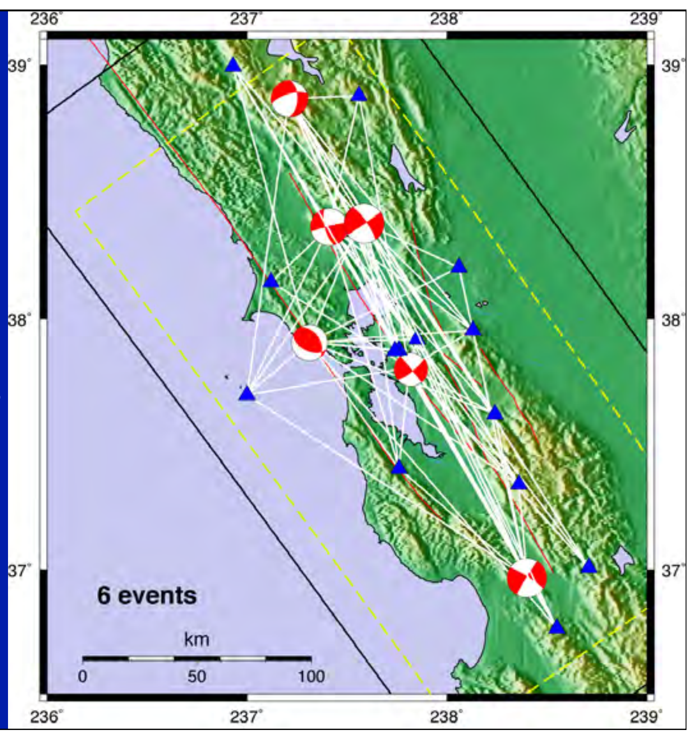


We compare the performance of two 3D models created by the USGS

- VM5.1
  - Developed for modeling 1906 SF earthquake
    - *A priori* model, based on geology and geophysics
    - Used by various researchers
    - Found to have fast velocities, ~5%
- VM8.0
  - Perturbation of VM5.1
    - Reduces shear velocities

6 Events

Bolinas 1999
Yountville 2000
Gilroy 2002
Geysers 2006
Glen Ellen 2006
Oakland 2007

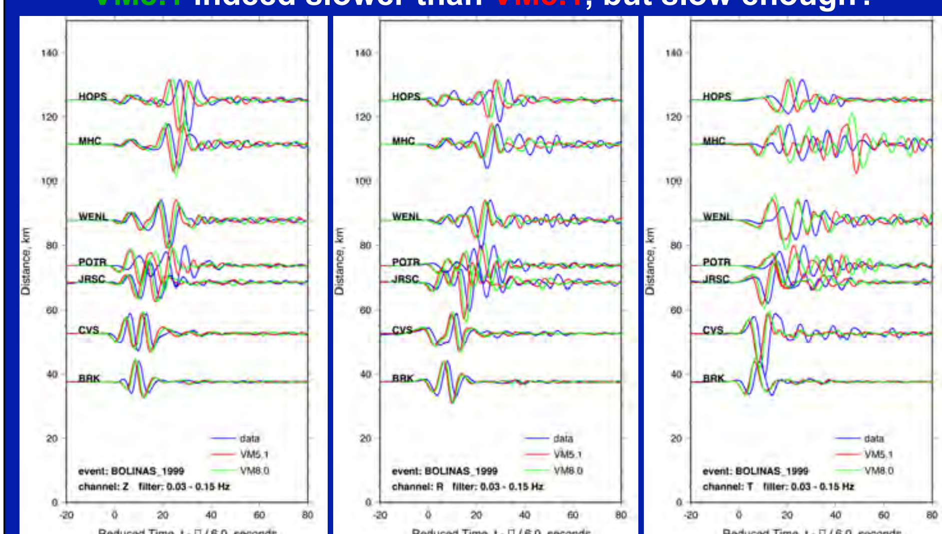


WPP synthetics for each event

- USGS Bay Area 3D Model
  - grid spacing with mesh refinement
    - 125 m 0-5 km depth
    - 250 m 5-50 km depth
  - minimum velocity: 500 m/s
  - Allows resolution of frequencies ≤ 0.25 Hz (4 seconds)
  - Domain: 360 km x 180 km x 50 km
  - Run time:
    - ~ 3 hours on 984 CPU's on Thunder LINUX cluster
- Source Parameters
  - USGS locations
  - UC Berkeley (Dreger et al.) mechanisms
    - M_0 and depth from waveform modeling
    - Double couple focal mechanisms

Data and synthetics for both models for the Bolinas 1999 event

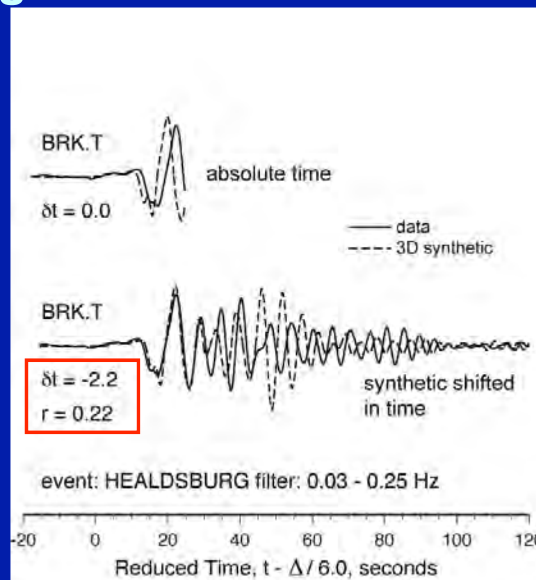
VM8.1 indeed slower than VM5.1, but slow enough?



Quantifying waveform misfit

Observed and synthetic waveforms are windowed and cross-correlated to find optimal alignment of direct waves. Determine time shift, δt

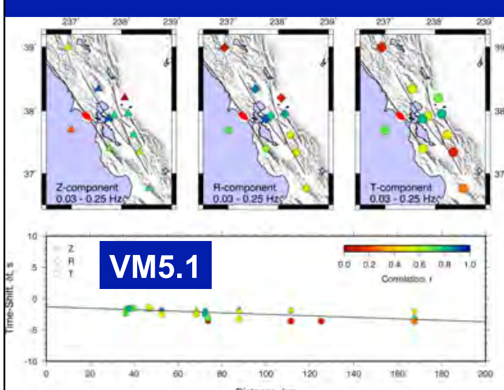
Linear correlation computed for a longer window, with δt from above



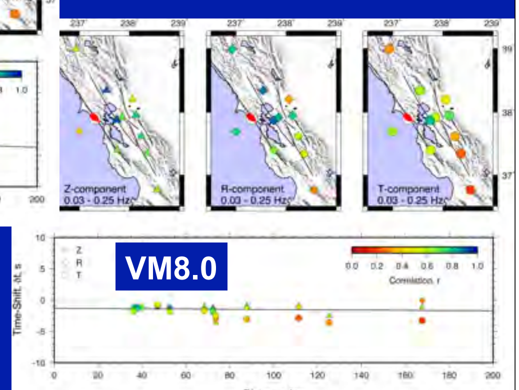
Delays and fits for Bolinas 1999

linear correlation, r, plotted at site

delay time, δt, plotted vs. distance

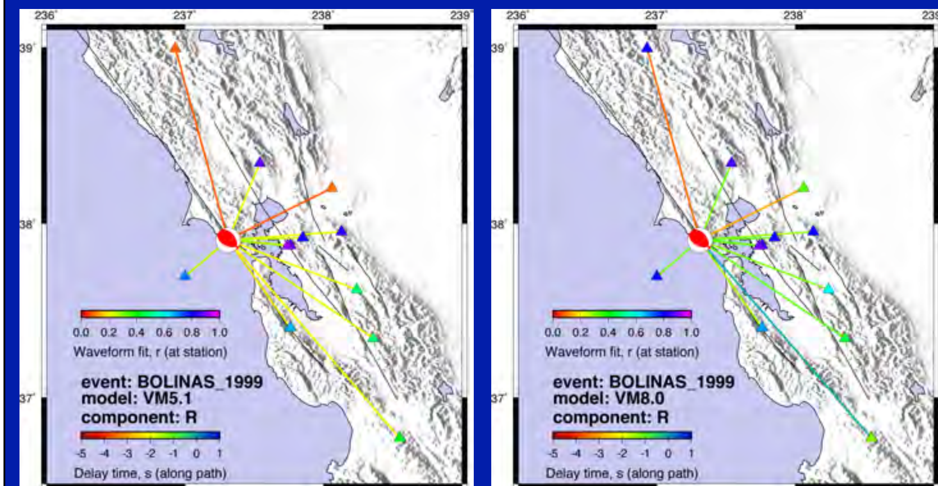


VM8.0 reduces δt trend relative to VM5.1



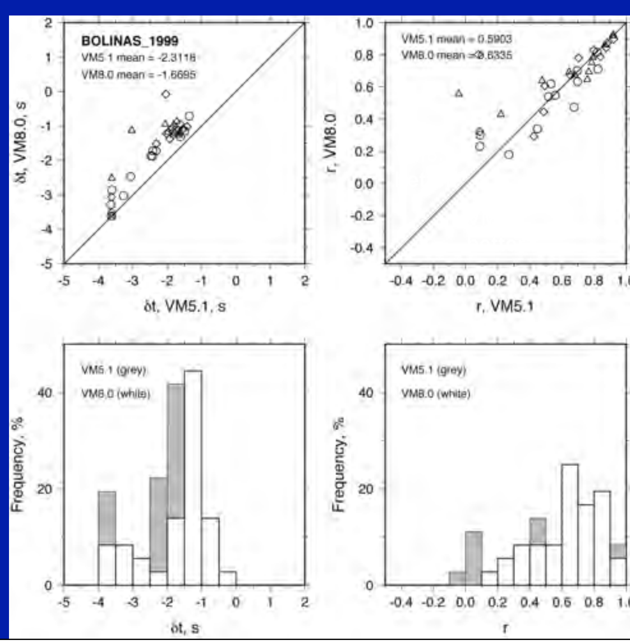
Map of delay time and misfit: Bolinas

VM8.0 shows measurable improvement over VM5.1

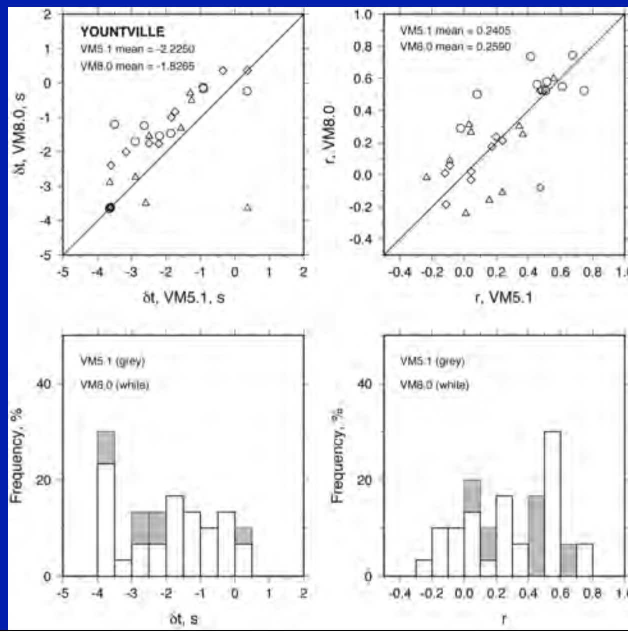


Delays and fits improved in the East and North Bay

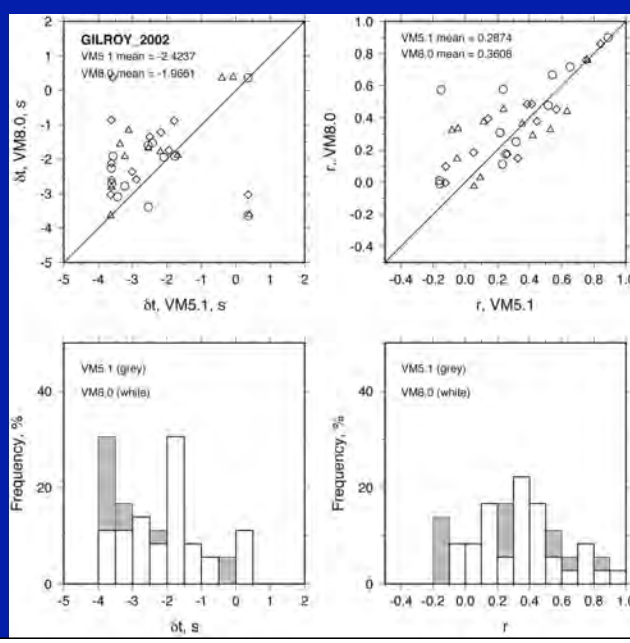
Waveform misfit measures: Bolinas



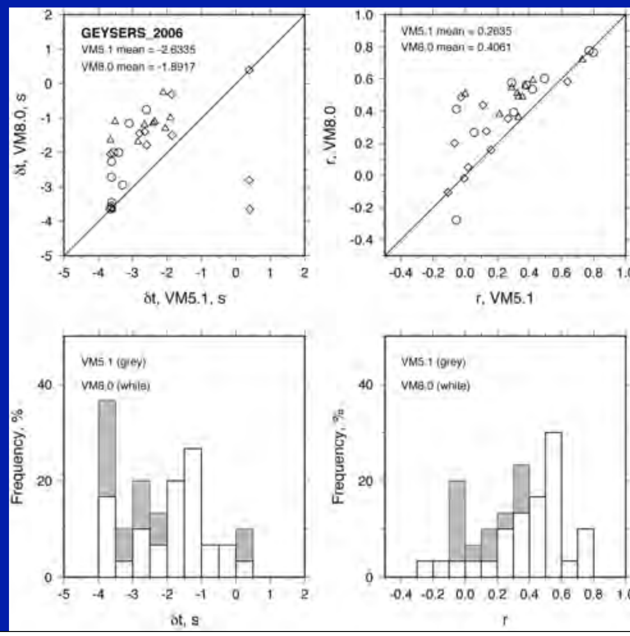
Waveform misfit measures: Yountville



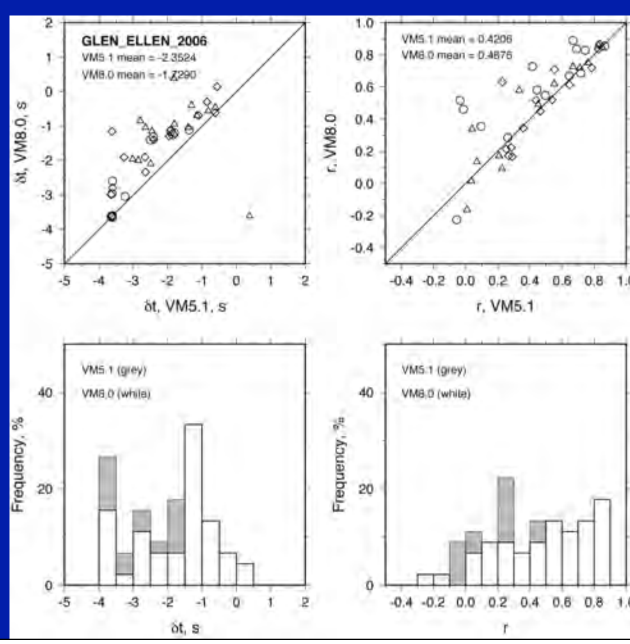
Waveform misfit measures: Gilroy



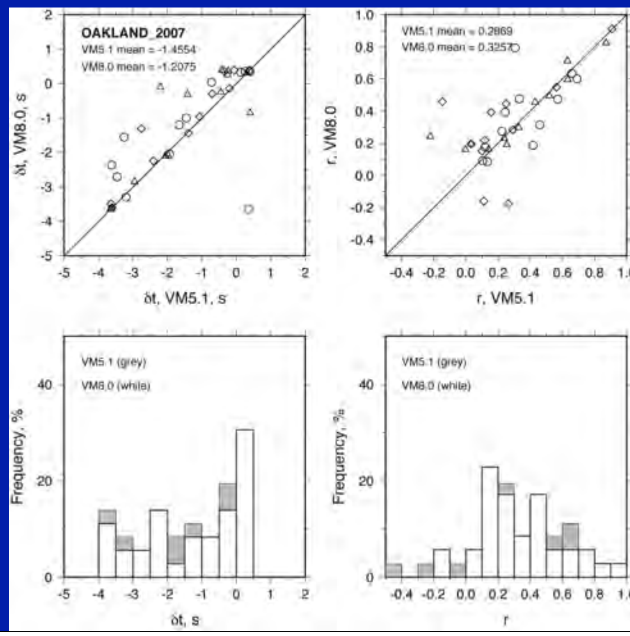
Waveform misfit measures: Geysers



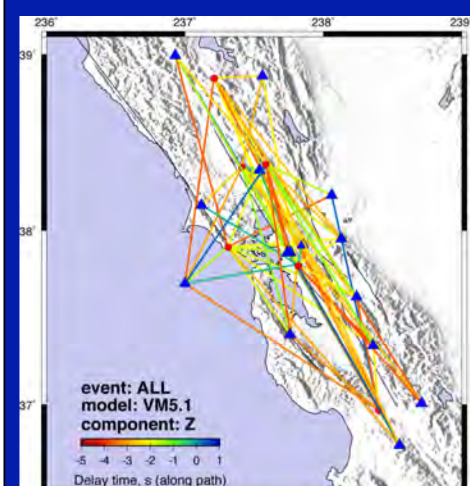
Waveform misfit measures: Glen Ellen

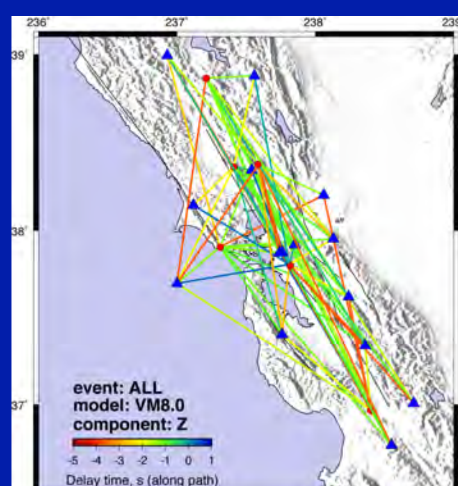


Waveform misfit measures: Oakland



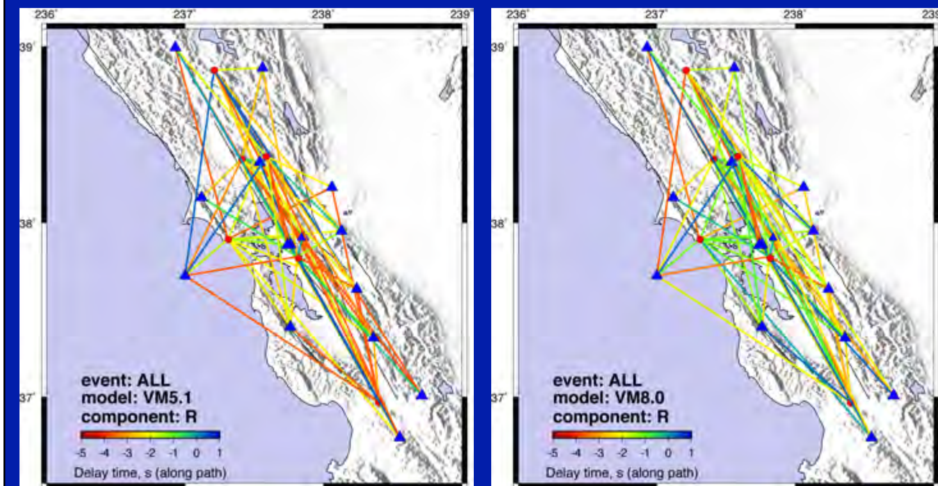
Summary maps of delays: Vertical





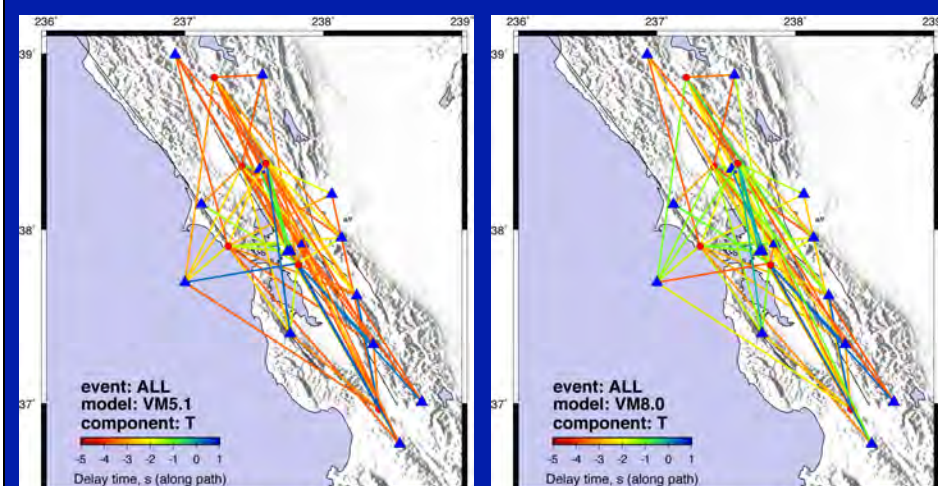
VM8.0 reduces δt bias

Summary maps of delays: Radial



VM8.0 reduces δt bias

Summary maps of delays: Transverse



VM8.0 reduces δt bias

Summary statistics of misfit measures

Event	VM5.1 δt (s)	VM8.0 δt (s)	difference	VM5.1 r	VM8.0 r	difference
Bolinas	-2.31	-1.67	-28%	0.59	0.63	+6.8%
Yountville	-2.23	-1.83	-18%	0.24	0.26	+8.3%
Gilroy	-2.42	-1.97	-19%	0.29	0.36	+24.1%
Geysers	-2.63	-1.89	-28%	0.26	0.41	+57.7%
Glen Ellen	-2.35	-1.73	-26%	0.42	0.49	+16.7%
Oakland	-1.46	-1.21	-17%	0.29	0.33	+13.8%

In all cases:

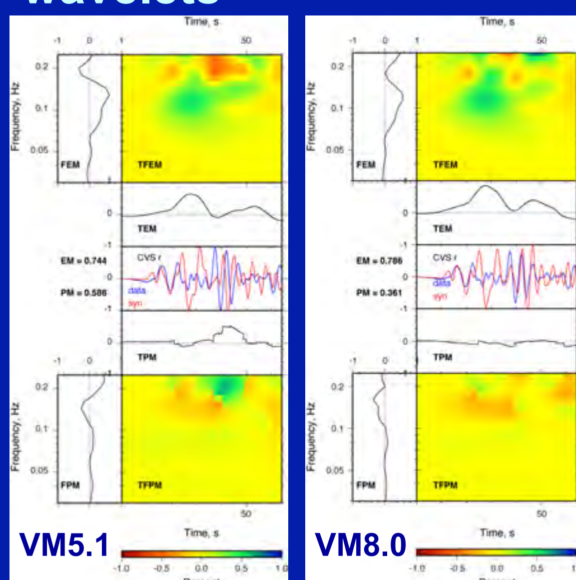
- **delay times are reduced and**
- **waveform fits are improved**

Time-frequency misfits based on wavelets

Oakland event
CVS radial

TF misfits describe misfit as a function of time and frequency

Quantitatively describes misfit for different parts of the seismogram



Conclusions

- On average, VM8.0 provides measurable improvement in waveform fit over VM5.1
  - Reduces arrival time bias
  - Reduces waveform misfit
- However, VM8.0 still shows delay time bias
- These data and the USGS 3D model (VM8.0) is an appropriate:
  - model for scenario earthquake modeling
  - starting model for waveform tomography