The August 24, 2014 South Napa Earthquake: What Is Known So Far, Accessing Open Information And Preliminary Ground Motion Simulations

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Lawrence Livermore National Laboratory

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Co-workers & acknowledgements

- LLNL
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  - Arben Pitarka – spectral acceleration comparisons
  - Rob Mellors – geodetic data
  - LC, Comp – access to HPC
- UC Berkeley
  - Prof. Doug Dreger and students – source model
  - Doug Neuhauser – access to NCEDC data
  - Ingrid Johanson & Mong-Han Huang – geodetic data
- United States Geological Survey
  - Brad Aagaard, Jack Boatwright (Menlo Park)
  - Rob Graves (Pasadena)

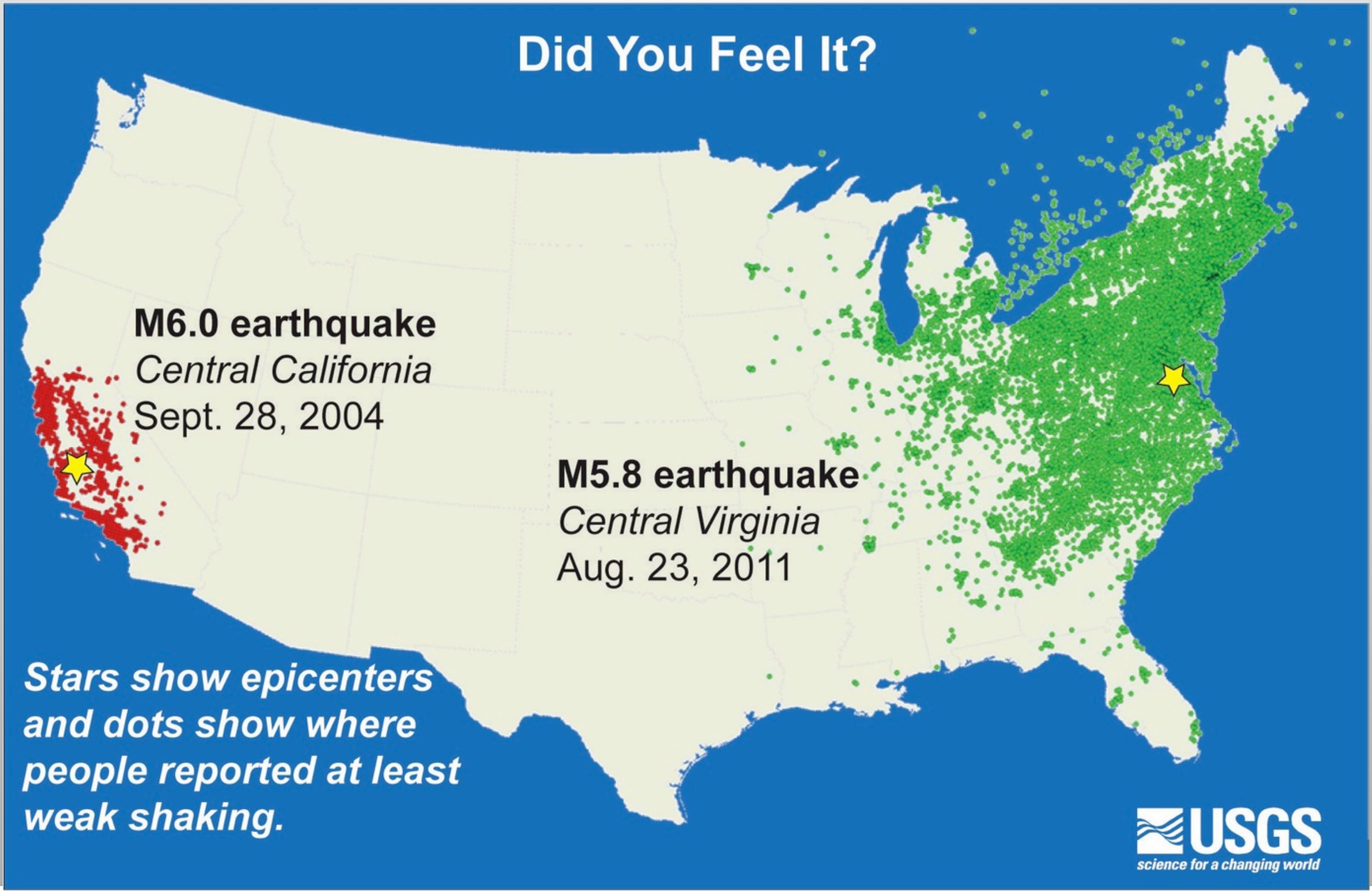
Outline

- Background
  - South Napa earthquake fact sheet
  - Overview of seismic hazard in the San Francisco Bay Area
- Overview of the South Napa earthquake
  - Accessing openly available information after an earthquake
  - Seismological details emerge …
- Simulations of ground motions using *SW4* on LLNL's HPC

South Napa Earthquake Fact Sheet

- August 24, 2014 3:20:44 local (10:20:44 UTC)
- Ruptured surface ~12 km along West Napa Fault
  - Hypocenter southwest of Napa
- Caused (much) greater than $100M damage
  - More than 50 buildings red-tagged, 100 yellow-tagged
- 1 fatality, over 100 injuries
- Tested current systems for real-time monitoring and rapid response
- Large enough to cause wide-spread damage
  - But no where near the devastation expected for an M ~ 7 Hayward, Rodgers Creek or San Andreas earthquake

Geology matters … east vs. west US



Damage

Engineering, building design and construction practice matter …

Compares recent M ~ 6 earthquakes in the US and China

So. Napa M 6.0
Yunnan, China M 6.1

http://www.vox.com/2014/8/26/6069921/watch-what-a-6-magnitude-earthquake-does-in-china-vs-the-us

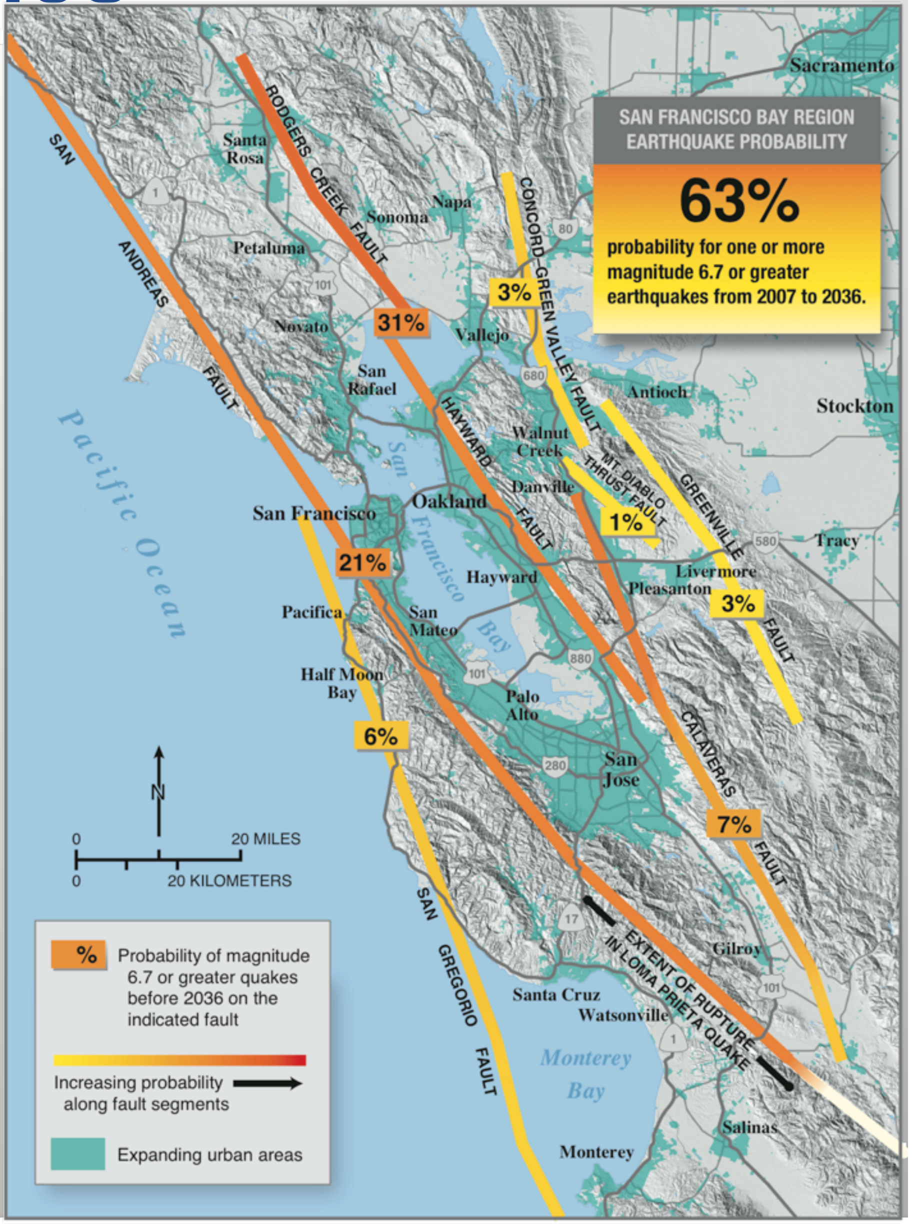
Earthquake Probabilities in SF Bay Area

63% chance for one or more M_W 6.7 or greater events between 2007 and 2036

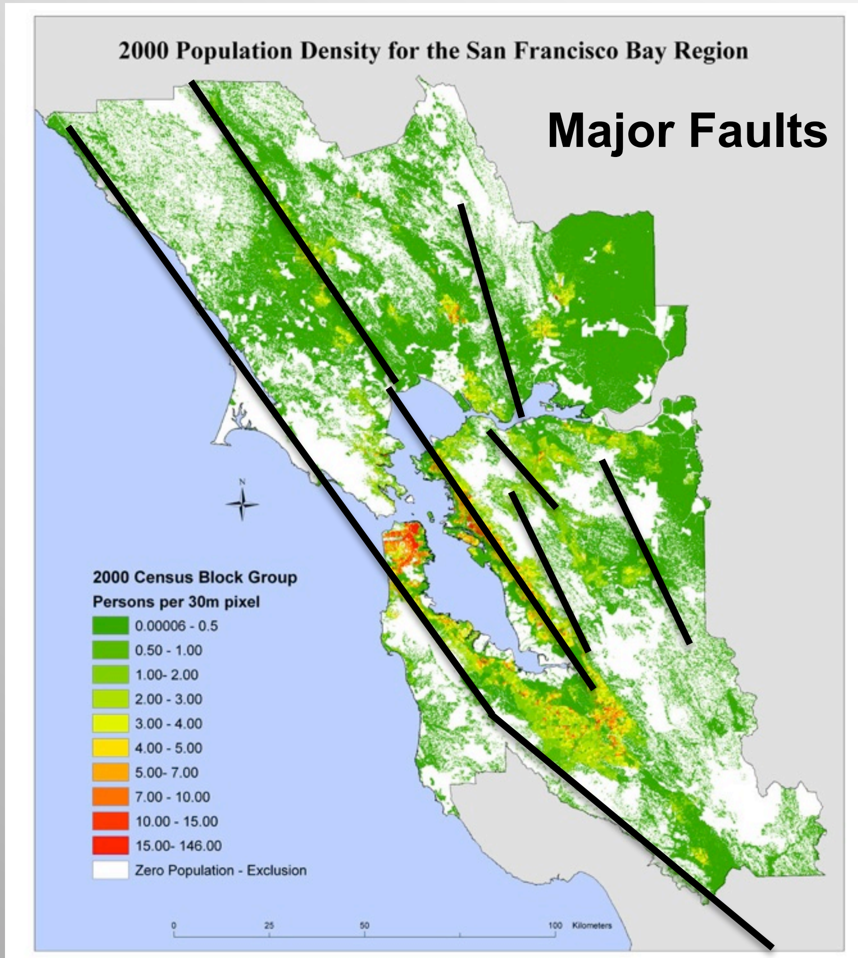
Hayward & Rodgers Creek Faults are the most likely (31%)

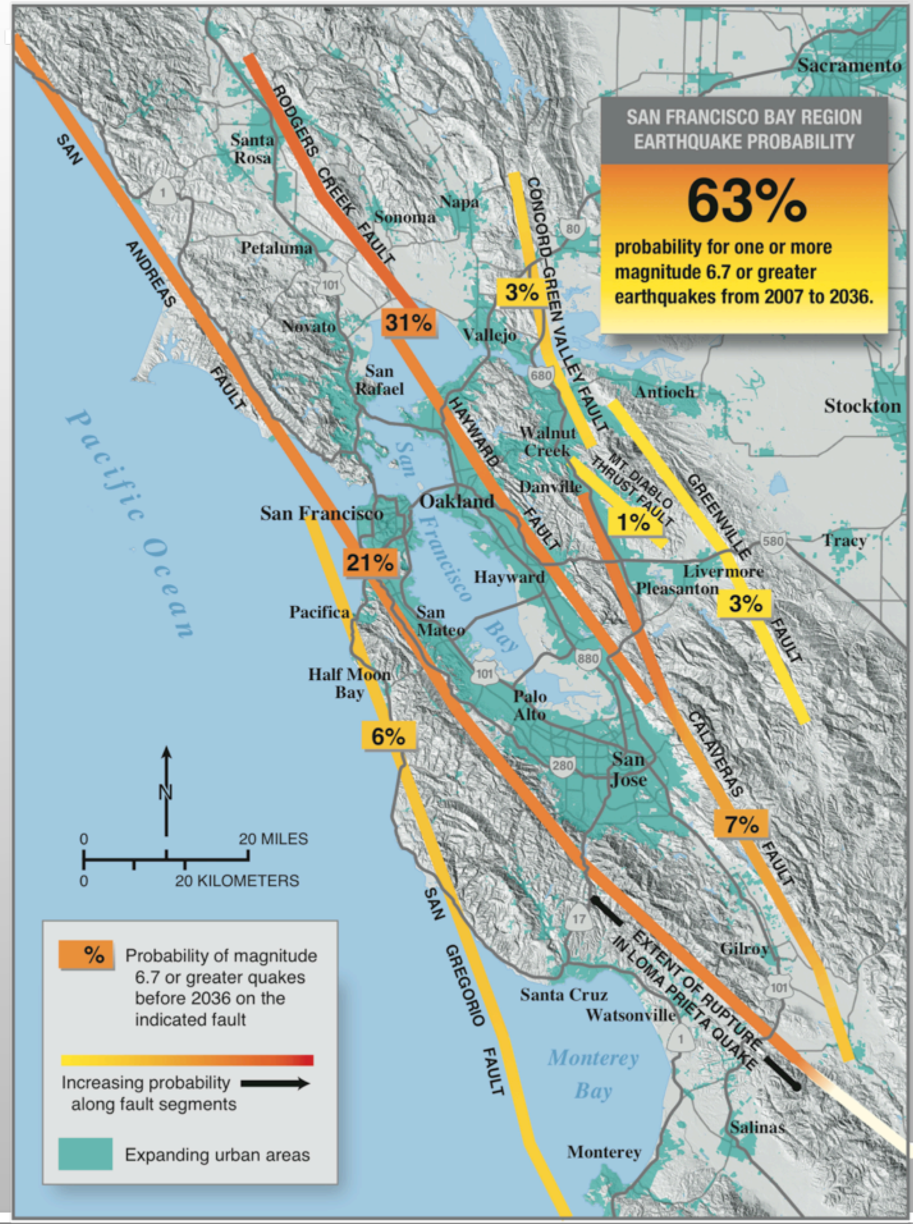
Citation:
The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2)

2007 Working Group on California Earthquake Probabilities
USGS Open File Report 2007-1437



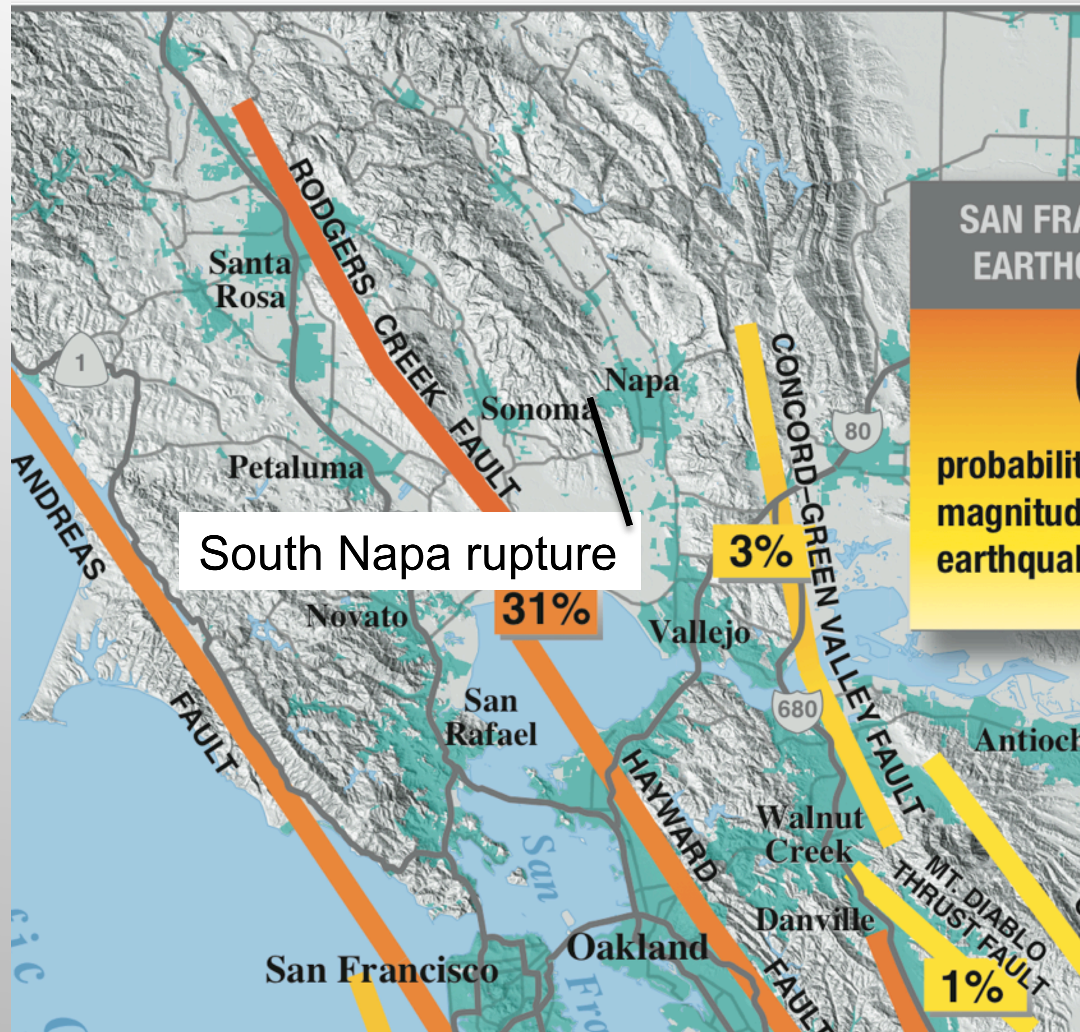
Population is exposed to hazard



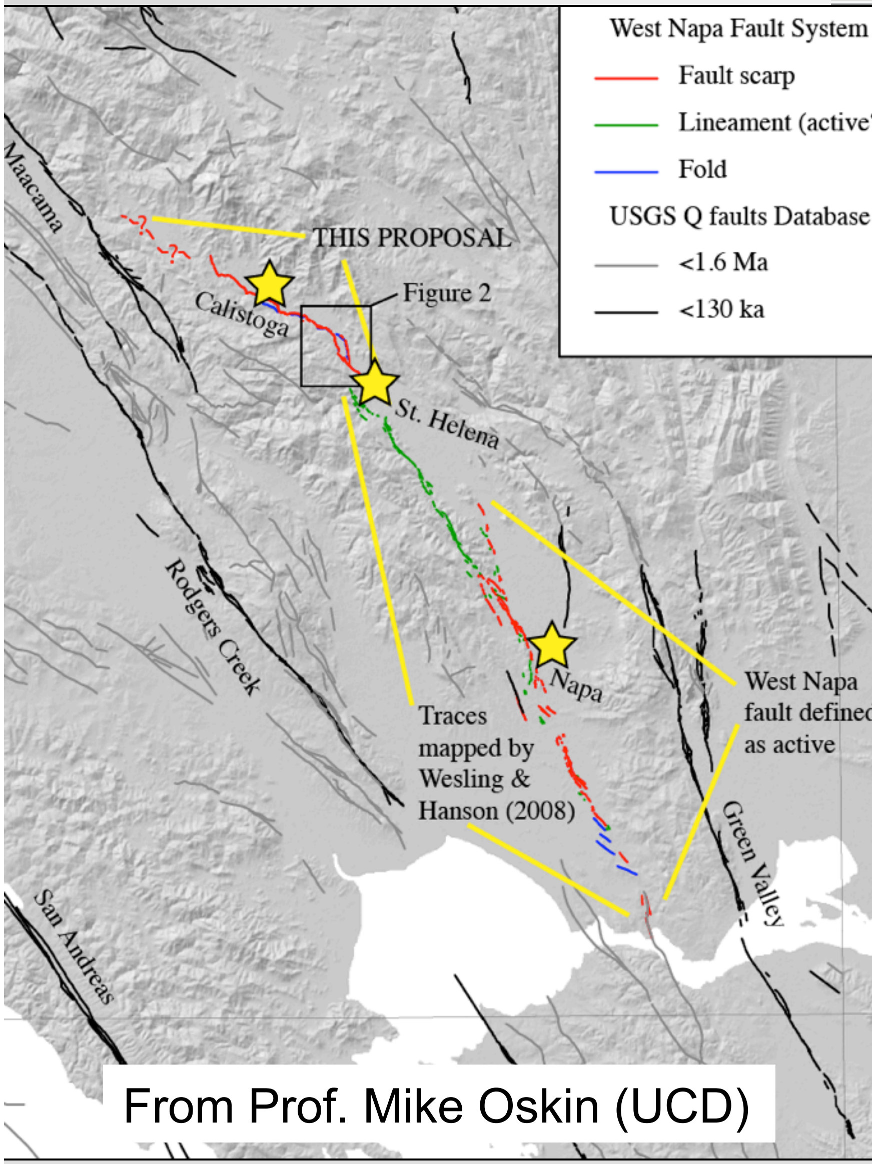


Focusing on SF North Bay

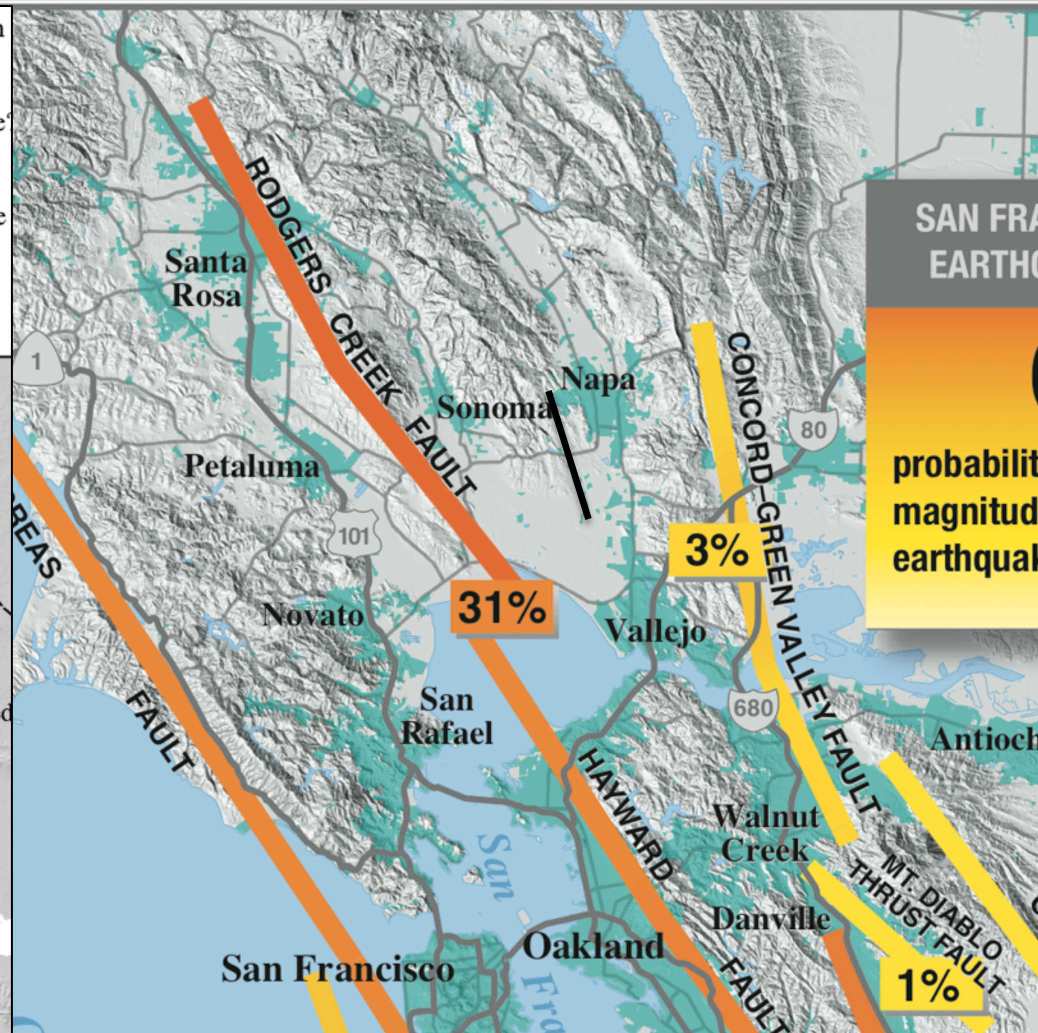
West Napa Fault not on this map of “major” faults



The West Napa Fault was identified as active, capable of M 6 event



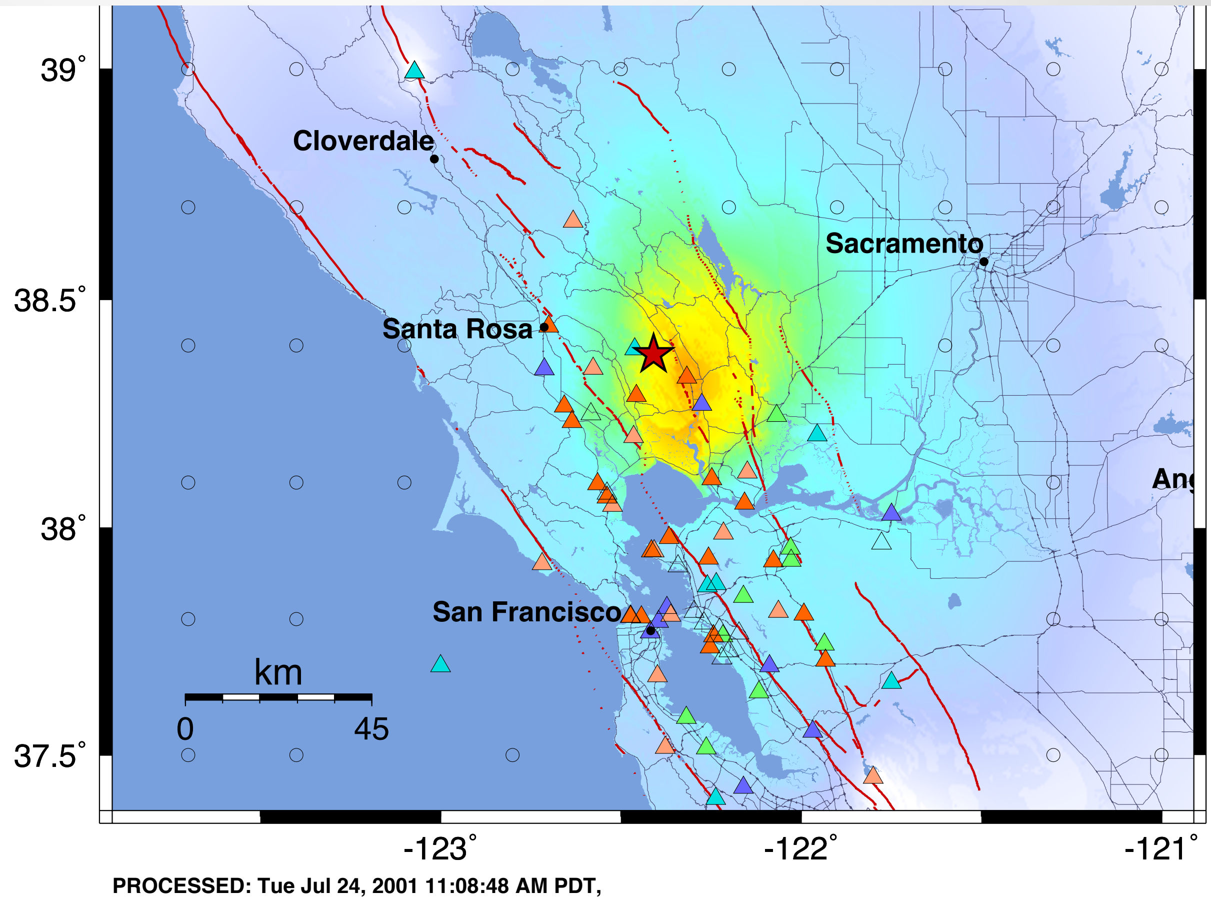
From Prof. Mike Oskin (UCD)



The Sep. 3, 2000 M 5.1 Yountville Earthquake

Produced strong shaking in Napa Valley, especially in sediment-filled alluvium geologies

ShakeMap – provides rapid broadcast of ground shaking everywhere near the event, based on recorded data, expected behavior and some geologic structure

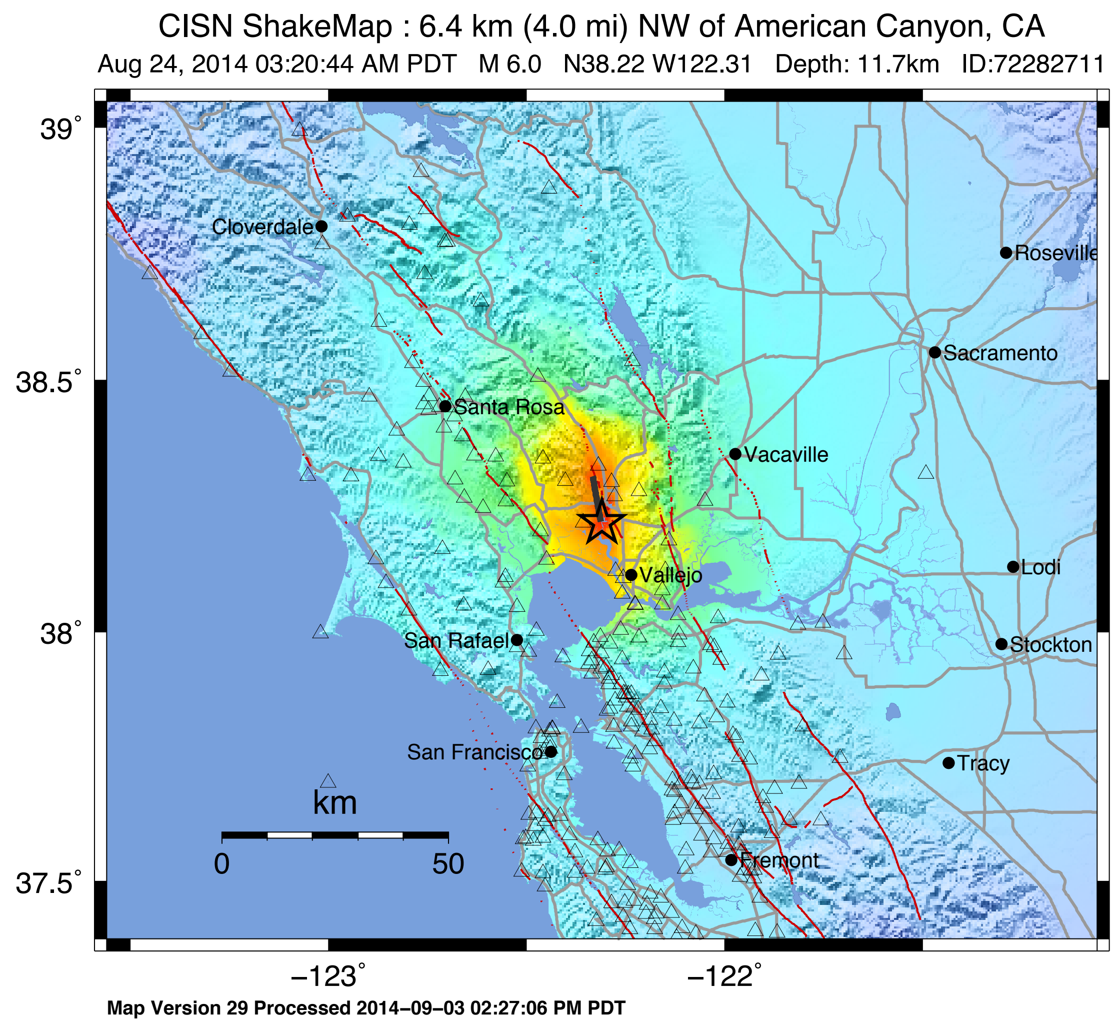


PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

The Aug. 24 2014 M 6.0 South Napa Earthquake

Produced strong shaking in Napa Valley, especially in sediment-filled alluium geologies

ShakeMap evolves over time as details emerge



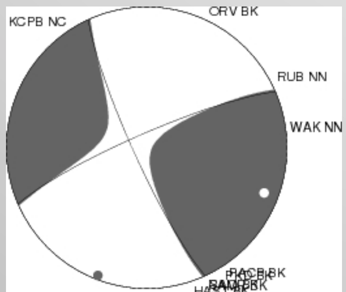
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<0.1*	*0.5*	*2.4*	*6.7*	*13*	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	*11*	*22*	*43*	*83*	*>160*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

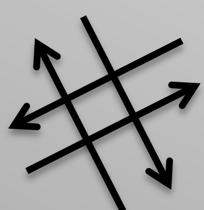
Mainshock location, mechanism and surface rupture

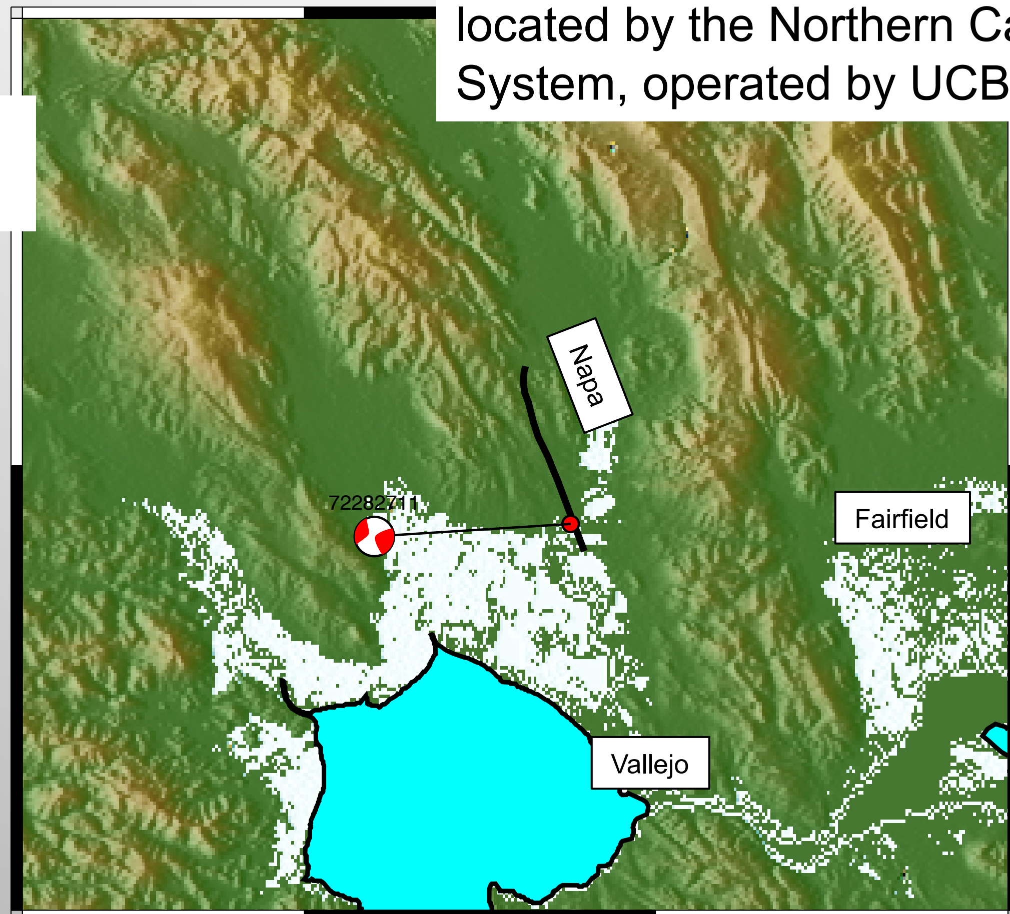
Events are routinely and automatically located by the Northern California Seismic System, operated by UCB and USGS

Mechanism from BSL, Prof. Doug Dreger



Possible directions of slip

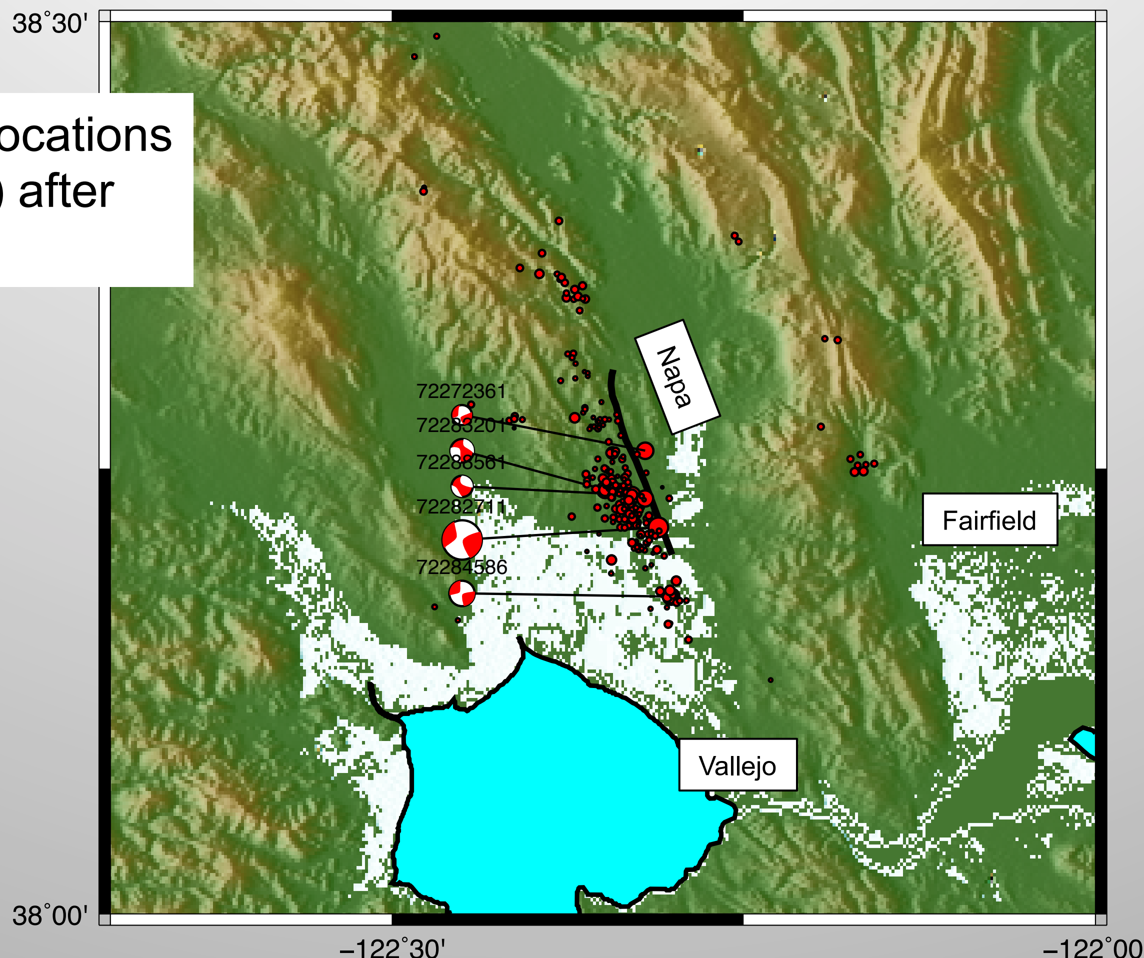




Surface rupture mapped by Prof. Mike Oskin (UCD)

Mainshock and aftershock locations and mechanisms with surface rupture

Routine event locations (USGS, NCSN) after two weeks



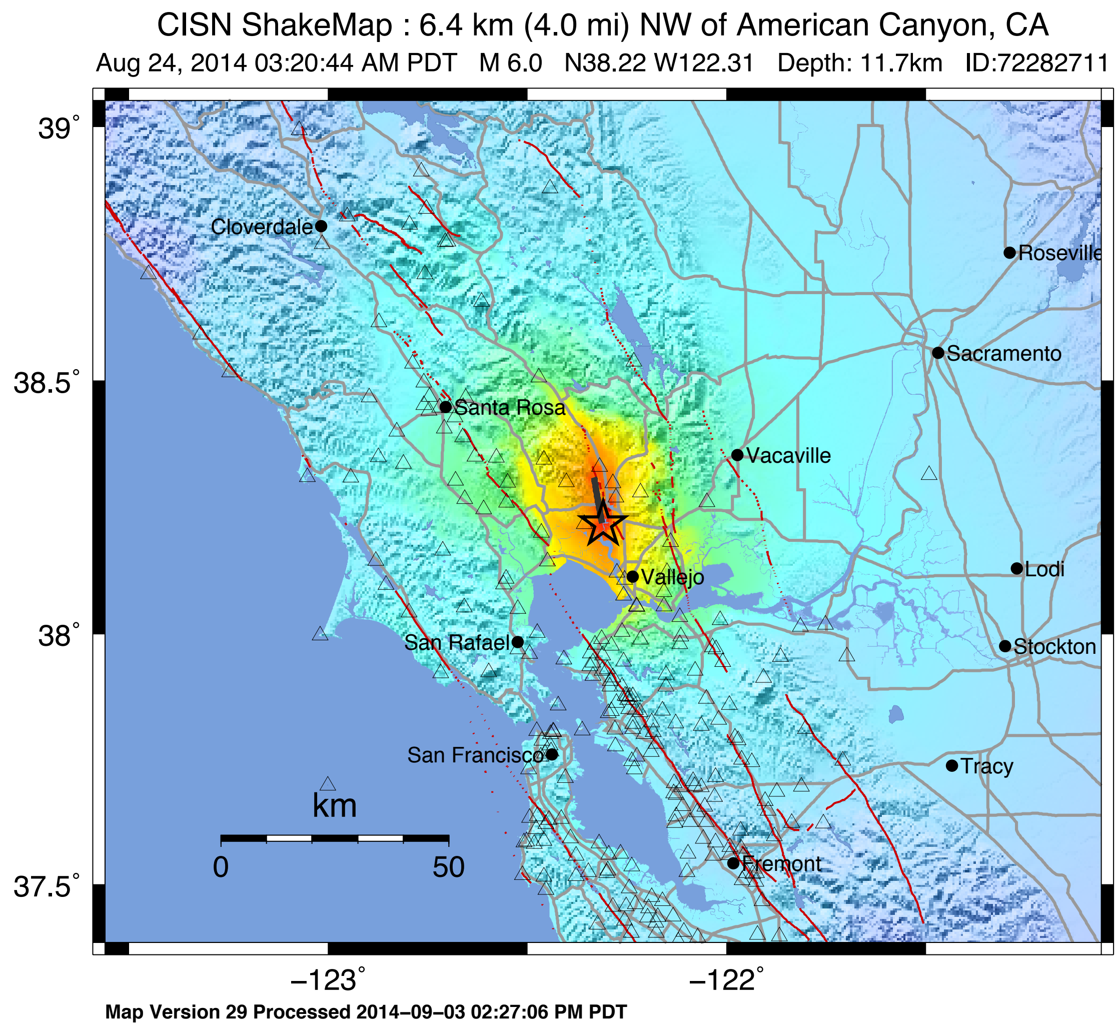
Openly available, rapid information from USGS web pages

- USGS National Earthquake Information Center
  - http://earthquake.usgs.gov/earthquakes/map/
- Event page
  - Summary information about events
    - When, where, how big …
  - ShakeMap – intensity of shaking
    - http://earthquake.usgs.gov/earthquakes/shakemap/
  - PAGER - Prompt Assessment of Global Earthquakes for Response
    - http://earthquake.usgs.gov/earthquakes/pager/
  - DYFI - “Did You Feel It?”
    - http://earthquake.usgs.gov/earthquakes/dyfi/

ShakeMap

Produced strong shaking in Napa Valley, especially in sediment-filled alluvium geologies

ShakeMap – provides rapid broadcast of ground shaking everywhere near the event, based on recorded data, expected behavior and some geologic structure



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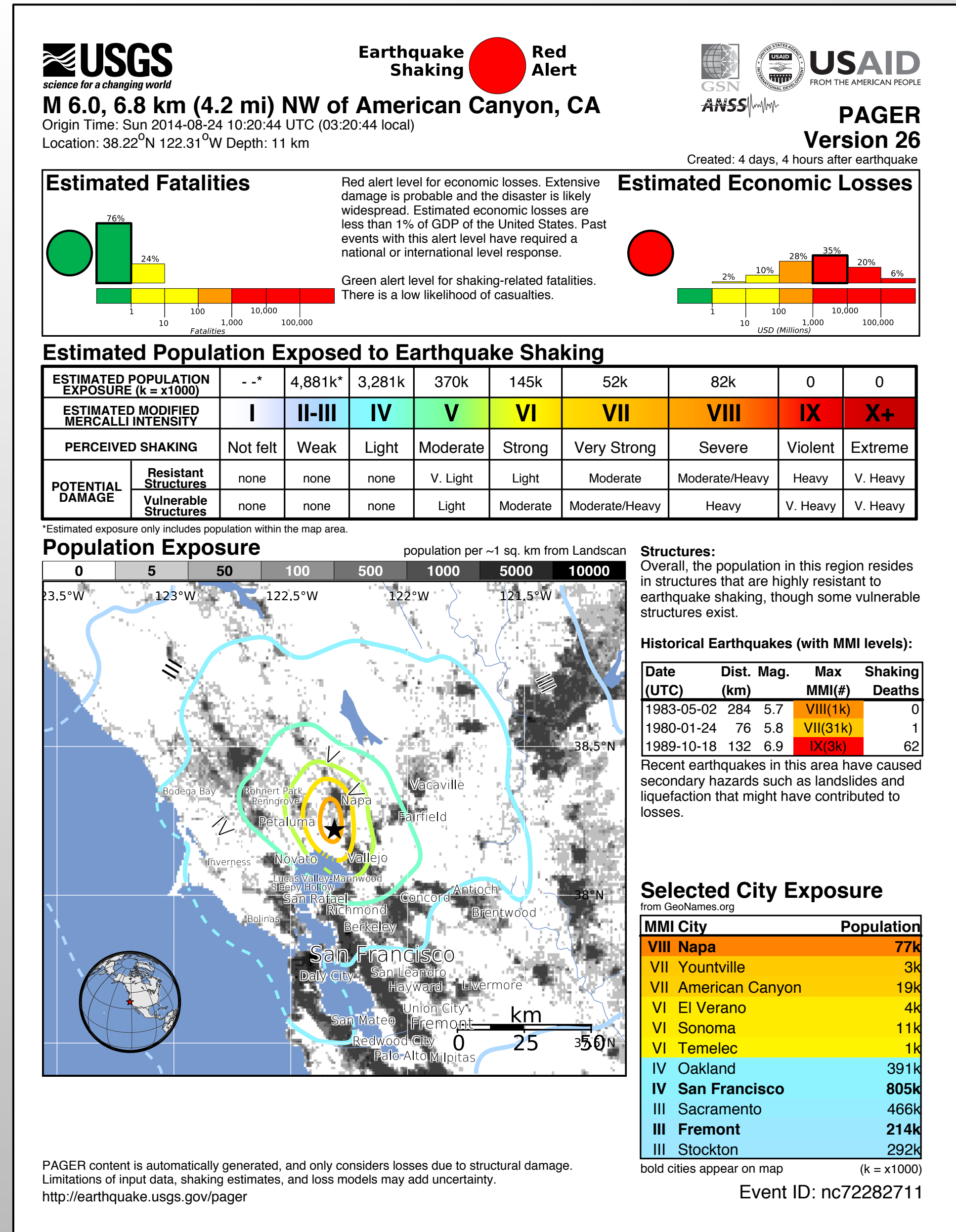
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

PAGER

Combines ShakeMap ground motion estimates with population exposure

Provides estimate of fatalities and economic losses



USGS
science for a changing world

Earthquake Shaking — Red Alert

USAID FROM THE AMERICAN PEOPLE

GSN ANSS

M 6.0, 6.8 km (4.2 mi) NW of American Canyon, CA

Origin Time: Sun 2014-08-24 10:20:44 UTC (03:20:44 local)

Location: 38.22°N 122.31°W Depth: 11 km

PAGER Version 26

Created: 4 days, 4 hours after earthquake

Estimated Fatalities

Red alert level for economic losses. Extensive damage is probable and the disaster is likely widespread. Estimated economic losses are less than 1% of GDP of the United States. Past events with this alert level have required a national or international level response.

Green alert level for shaking-related fatalities. There is a low likelihood of casualties.

Estimated Economic Losses

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	4,881k*	3,281k	370k	145k	52k	82k	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per ~1 sq. km from Landscan

0	5	50	100	500	1000	5000	10000

Structures:
Overall, the population in this region resides in structures that are highly resistant to earthquake shaking, though some vulnerable structures exist.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1983-05-02	284	5.7	VIII(1k)	0
1980-01-24	76	5.8	VII(31k)	1
1989-10-18	132	6.9	IX(3k)	62

Recent earthquakes in this area have caused secondary hazards such as landslides and liquefaction that might have contributed to losses.

Selected City Exposure

from GeoNames.org

MMI	City	Population
VIII	**Napa**	**77k**
VII	Yountville	3k
VII	American Canyon	19k
VI	El Verano	4k
VI	Sonoma	11k
VI	Temelec	1k
IV	Oakland	391k
IV	**San Francisco**	**805k**
III	Sacramento	466k
III	**Fremont**	**214k**
III	Stockton	292k

bold cities appear on map (k = x1000)

PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/pager

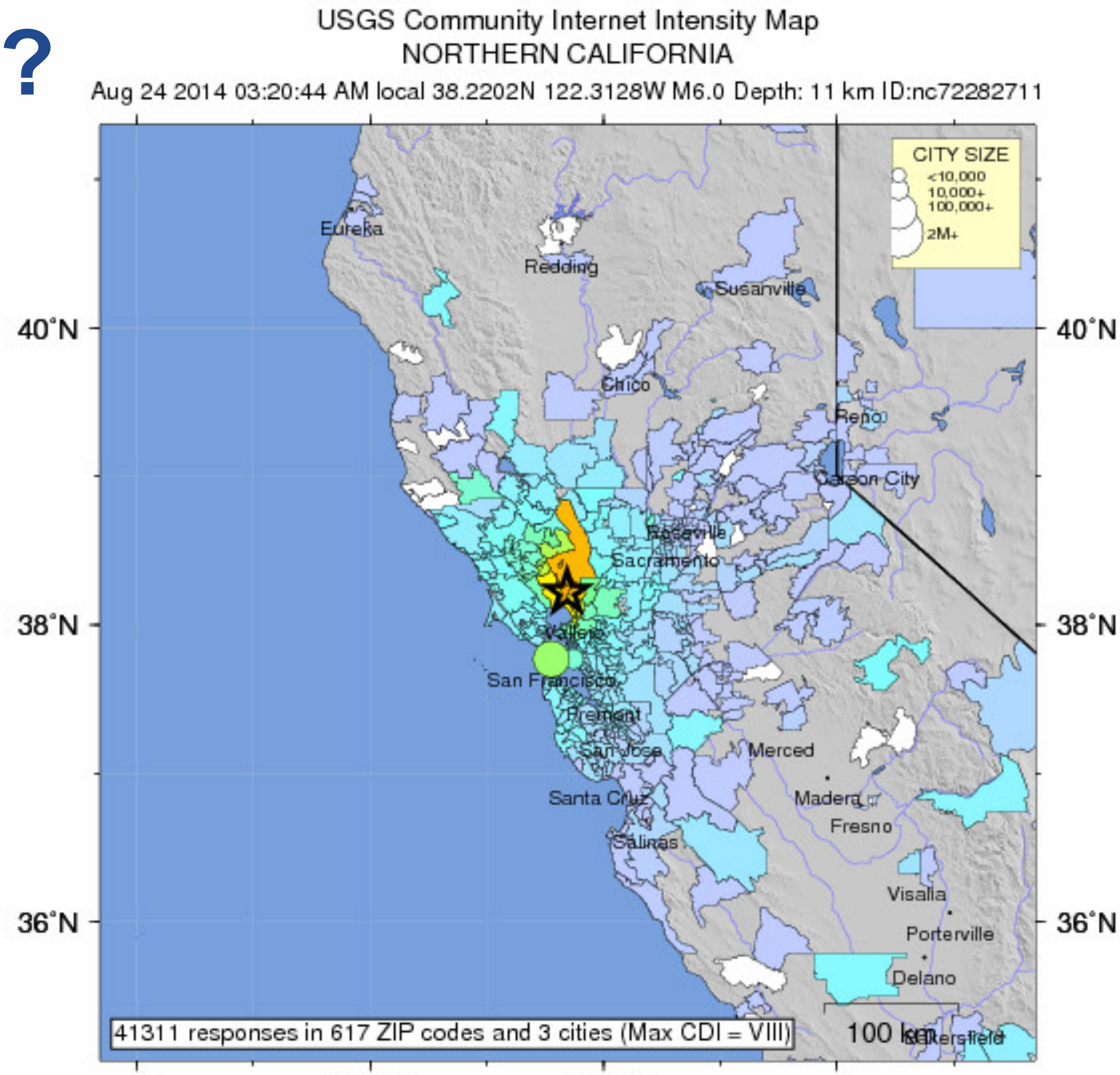
Event ID: nc72282711

Did You Feel it? DYFI

Based on internet reports at DYFI website

Estimates Modified Mercalli Intensity (MMI) based on reported shaking intensity

Geo-coded by ZIP code

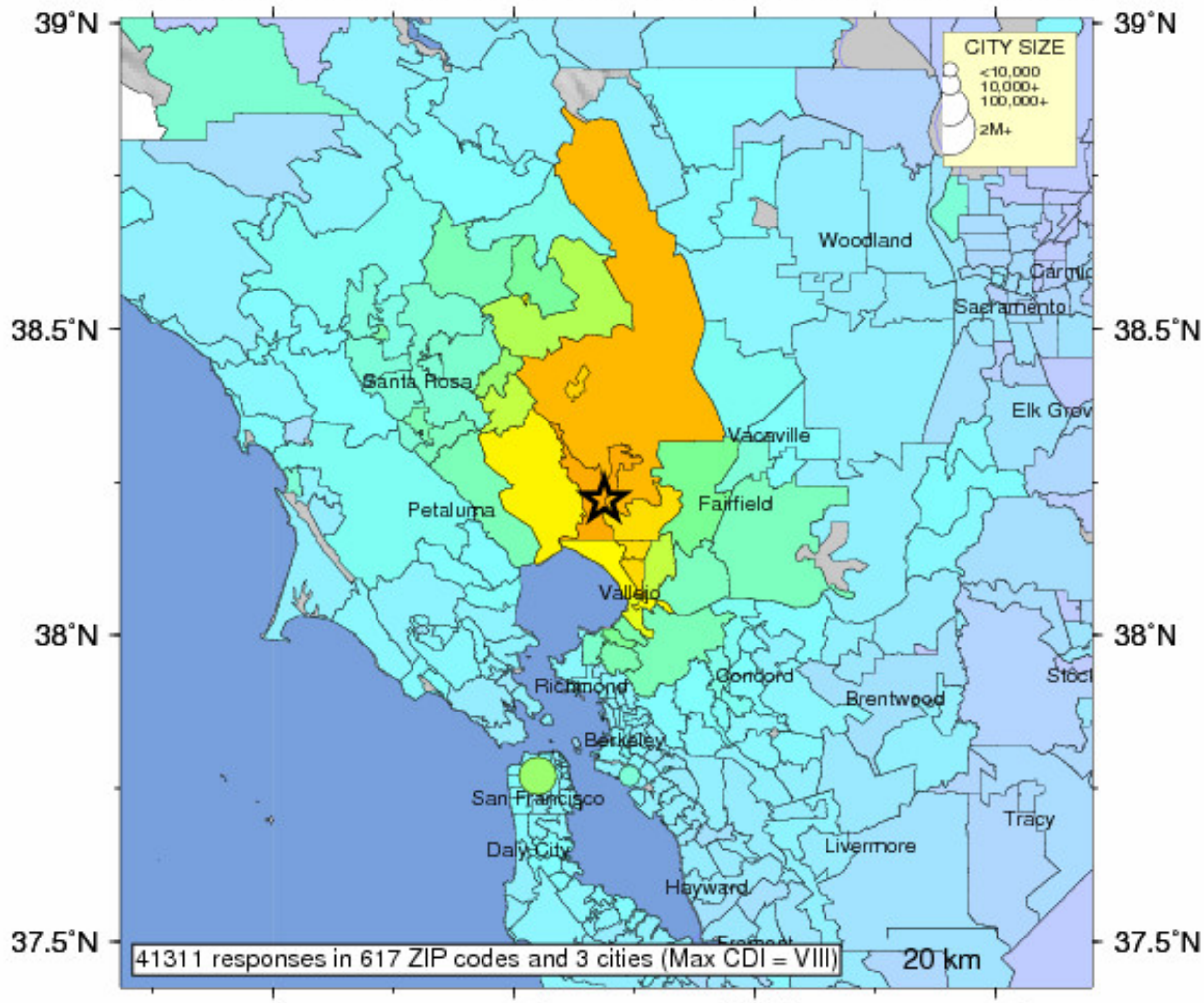


INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy

Processed: Tue Sep 16 18:07:11 2014

Did You Feel it? DYFI (zoom)

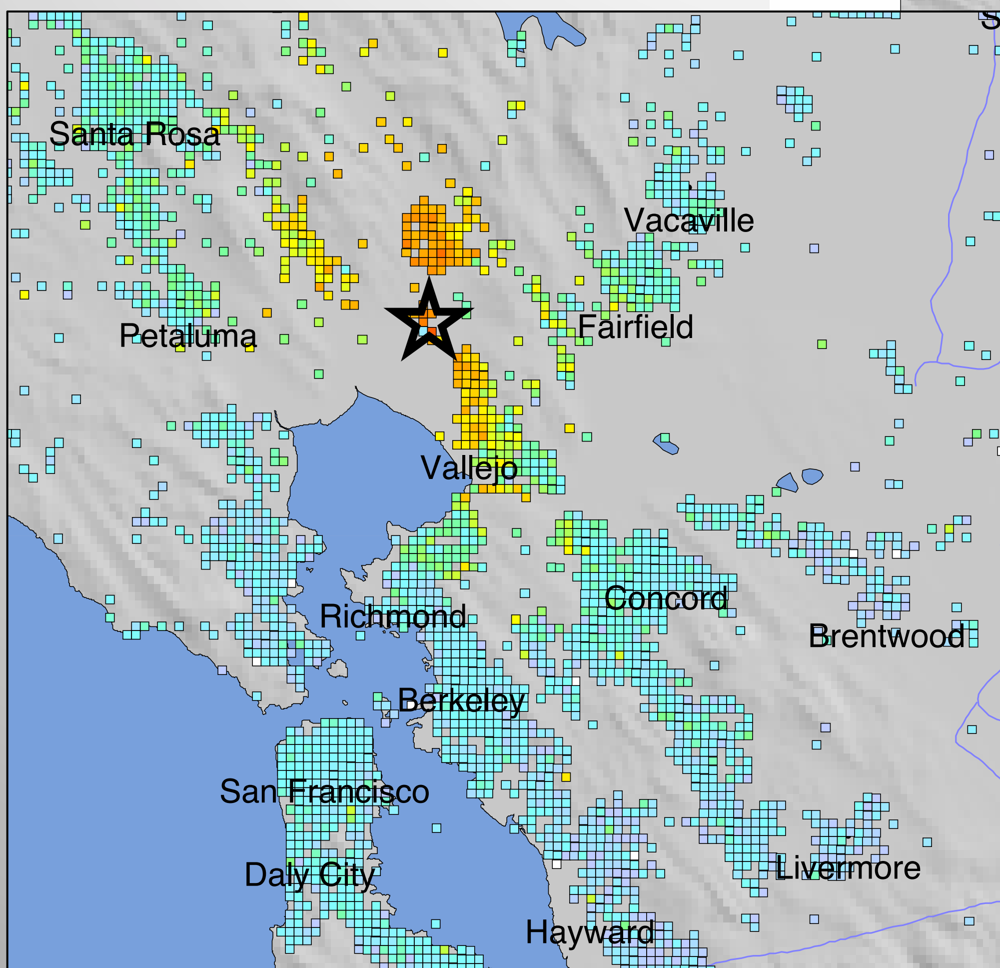
Some ZIP codes provide strange results …

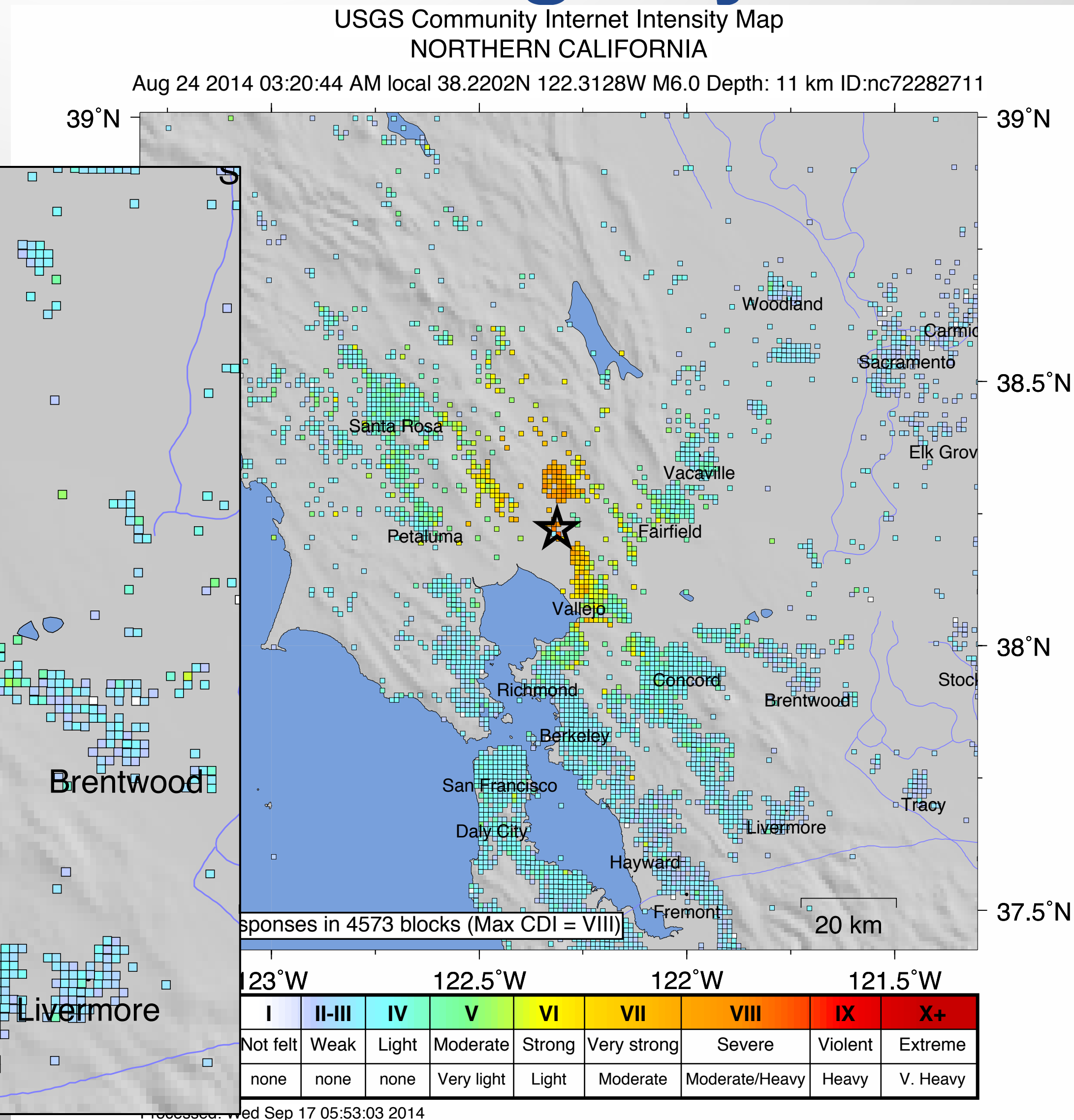


INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy

Processed: Tue Sep 16 18:07:42 2014

Did You Feel it? DYFI: looking at your neighborhood

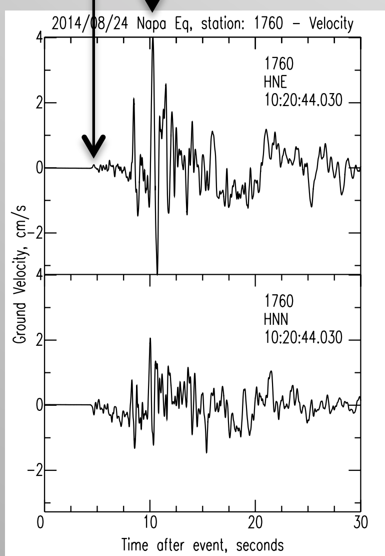


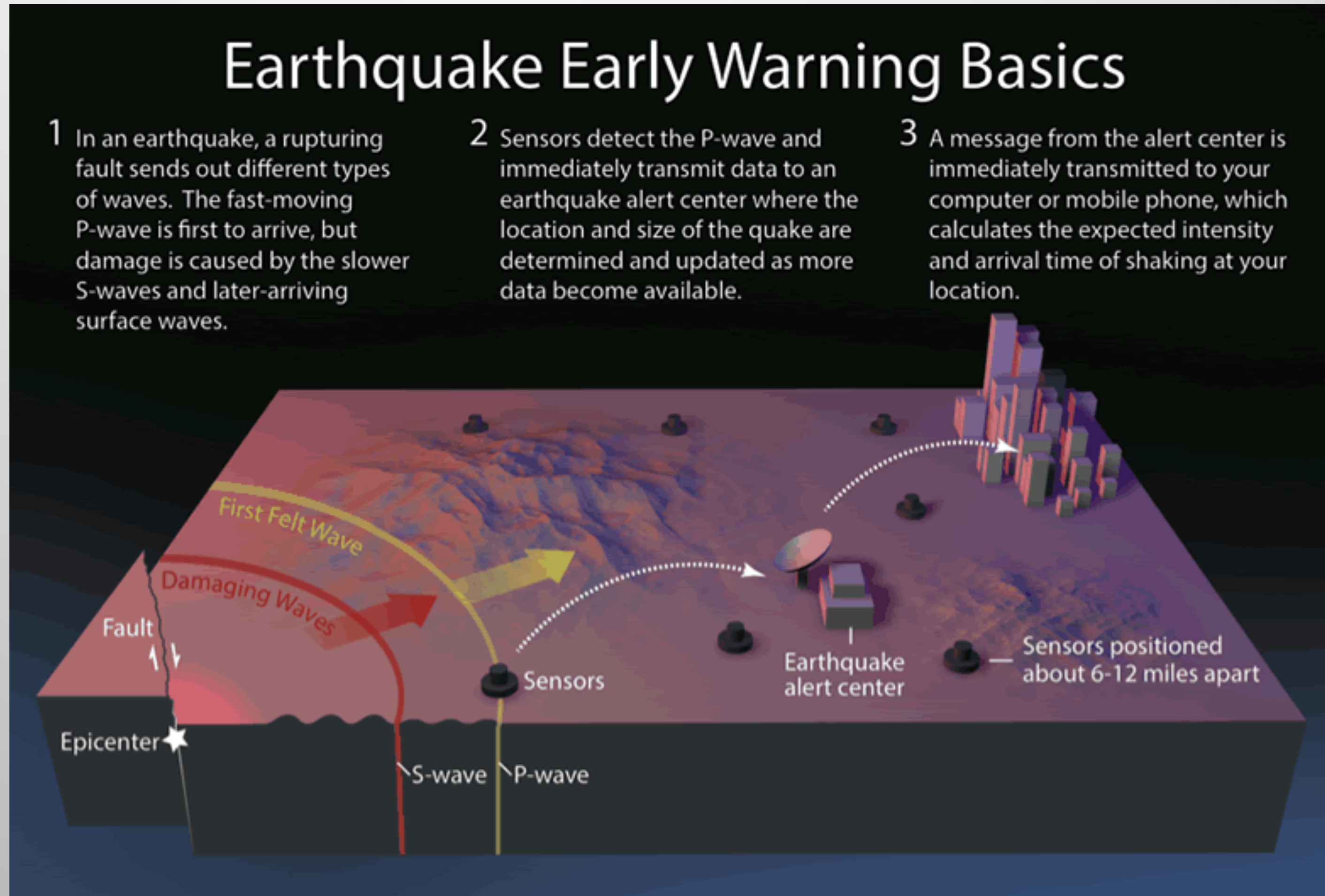


Earthquake Early Warning (EEW): How it works (1)

P-wave
(first felt)

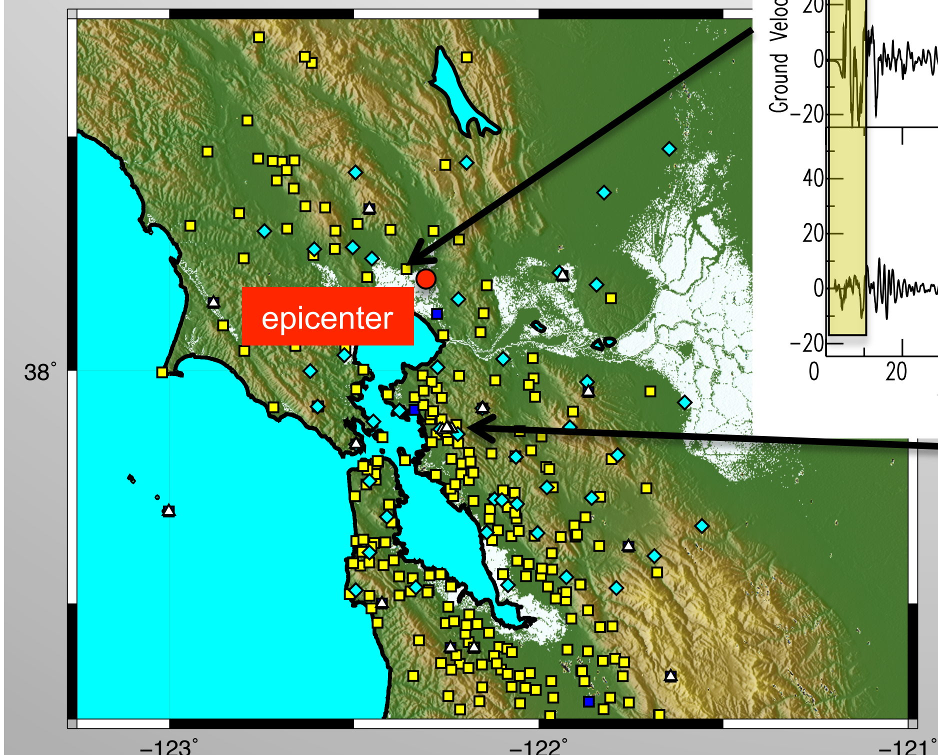
S-wave
(damaging)

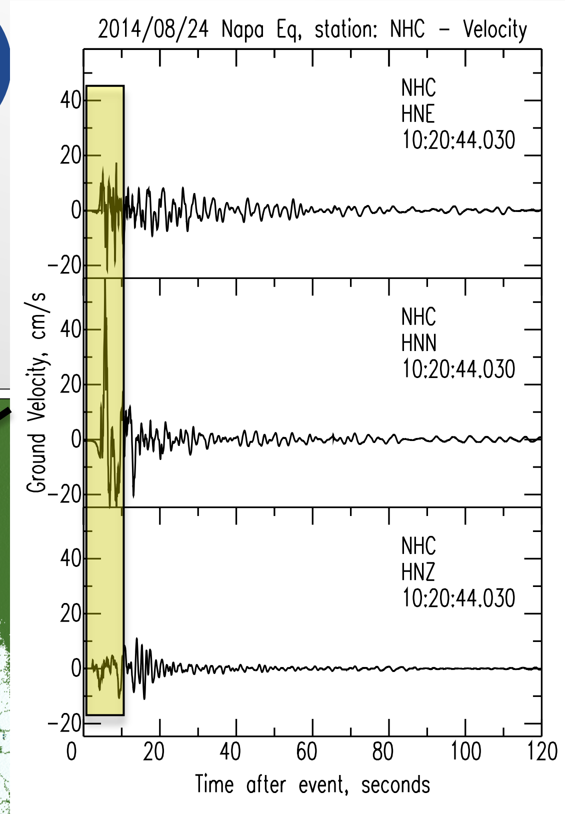




Earthquake Early Warning (EEW): How it works (2)

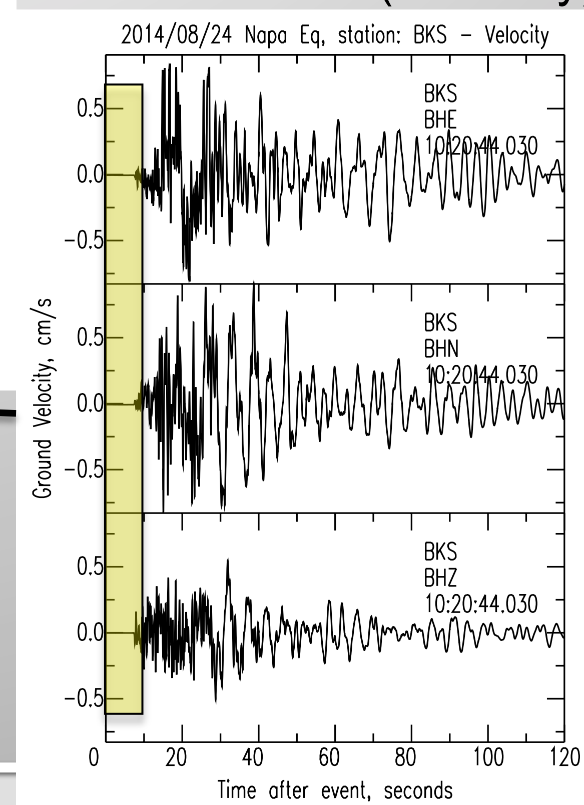
Nearby station 3 km from hypocenter



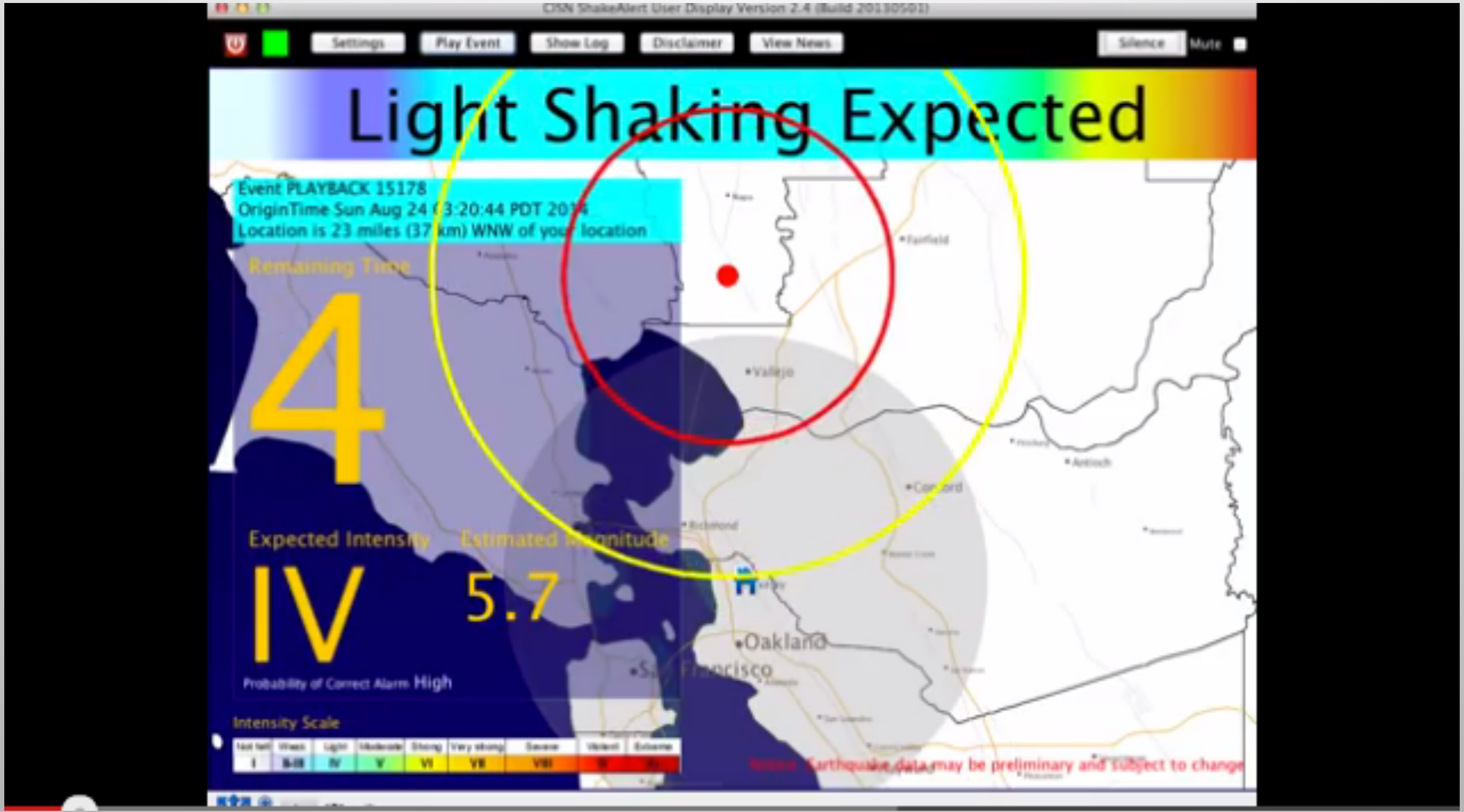


Detection, location, magnitude estimated from ≥ 4 nearby stations in 5-10 seconds

Distant station (Berkeley)

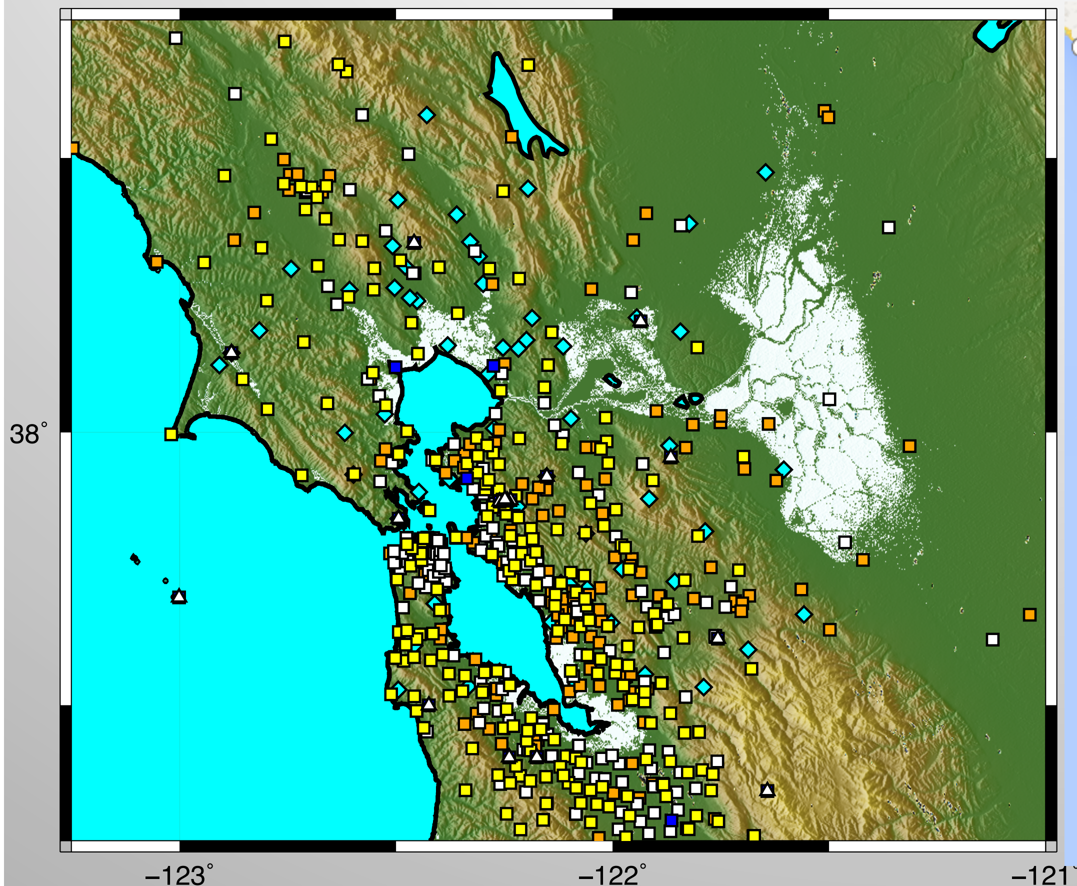


EEW worked well for the South Napa earthquake

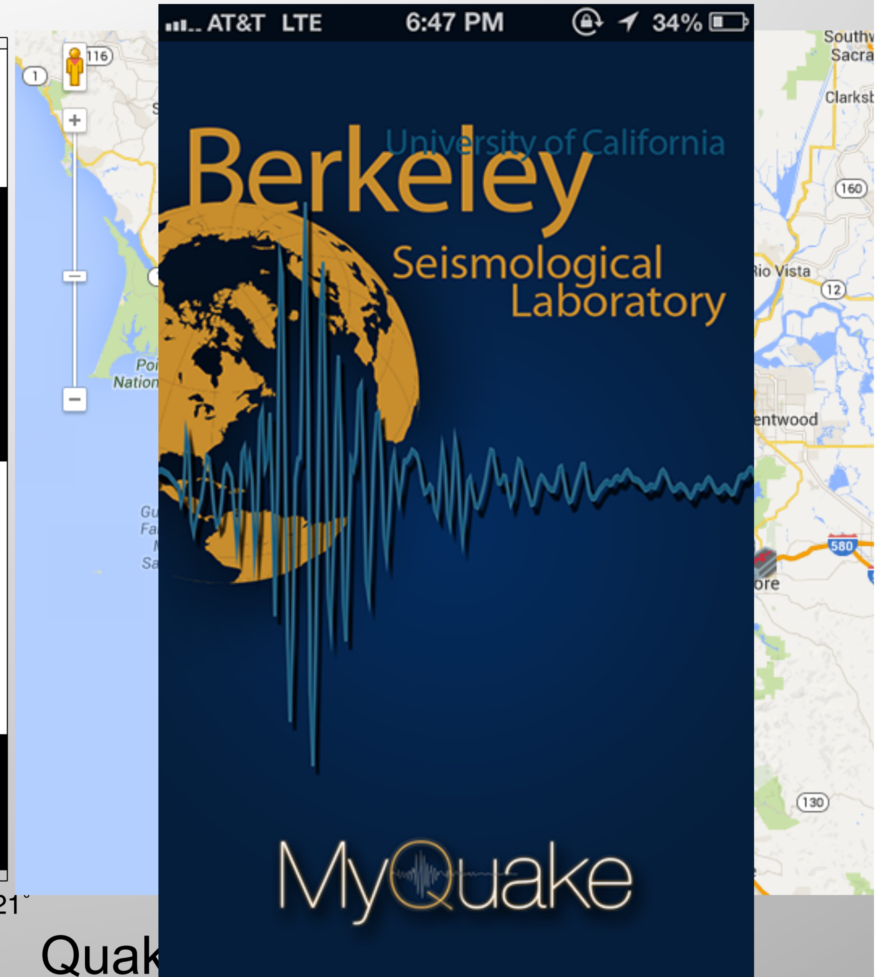


http://www.youtube.com/watch?v=muXhT3FTrJI
http://newscenter.berkeley.edu/2014/09/04/time-for-statewide-earthquake-early-warning-system-is-now/

More distributed sensors will help EEW



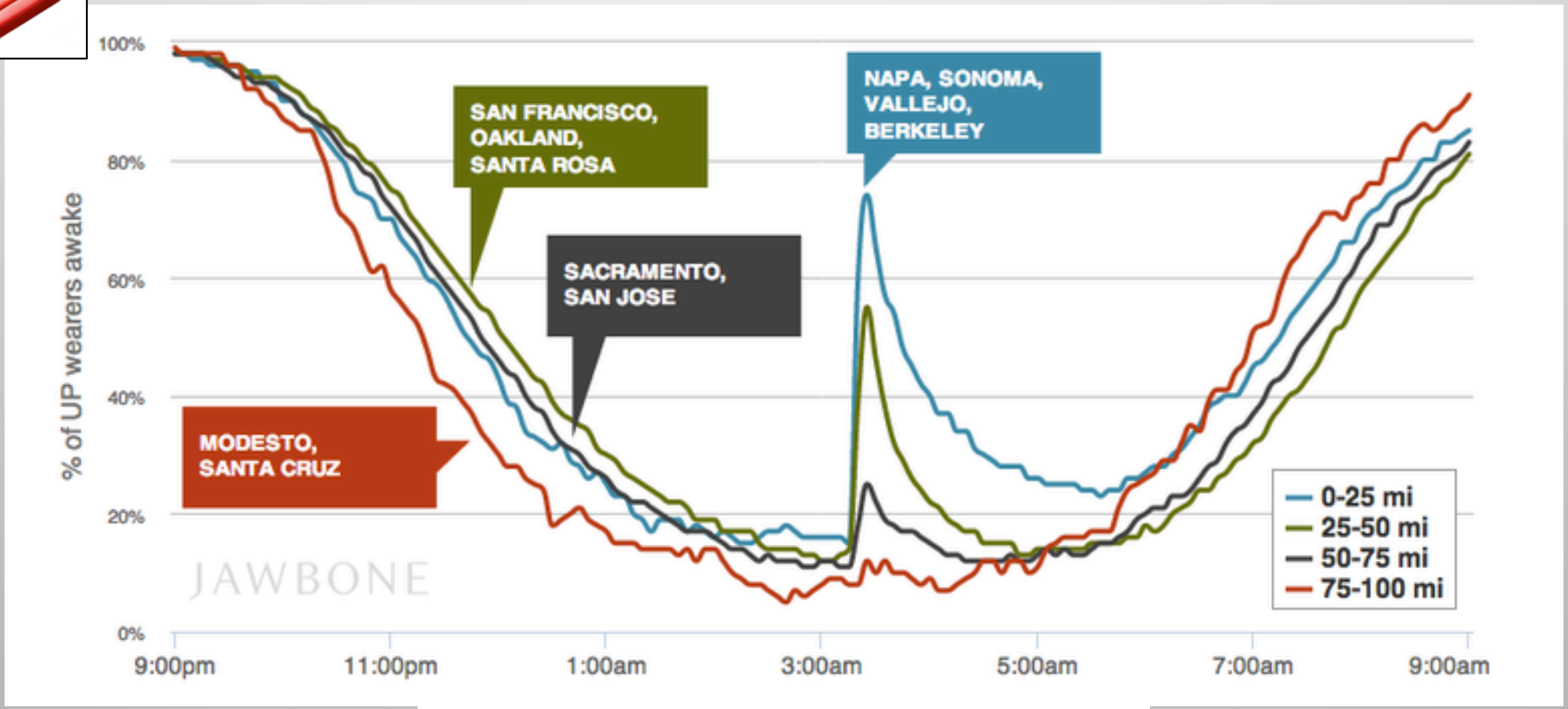
USGS, Existing seismic stations
(not all real-time)



Quak
(US

Mobile phones are ubiquitous!

Jawbone® activity monitor data show how quake woke up SF Bay Area

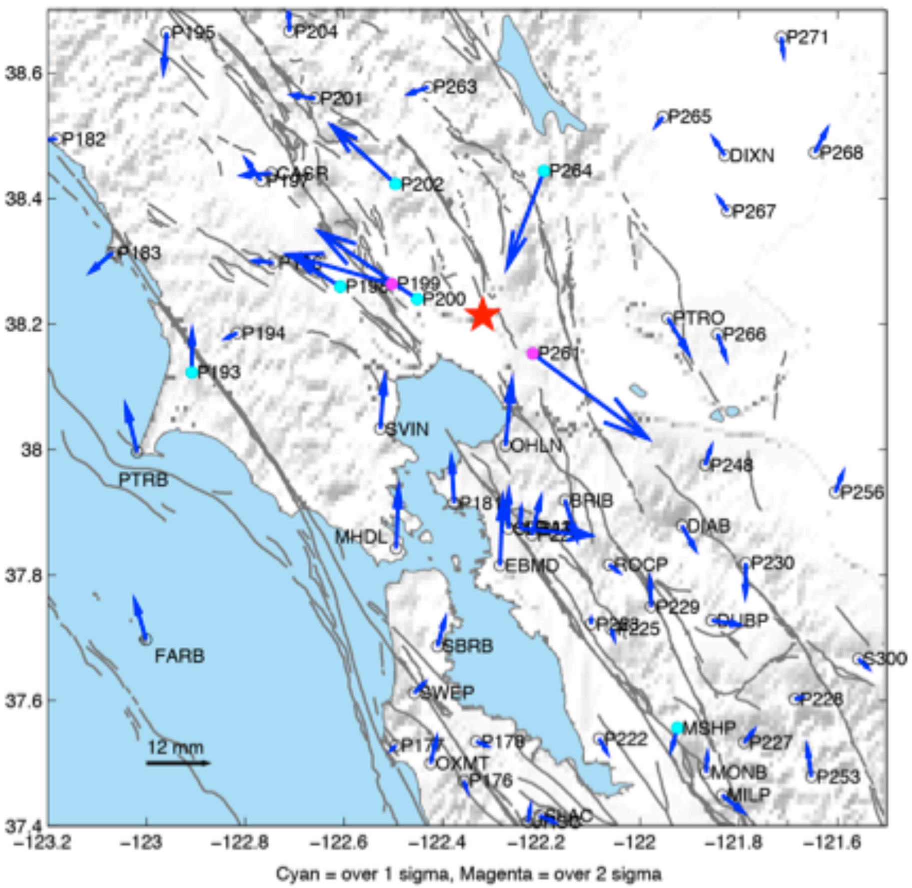


Local time Sunday August 24, 2014

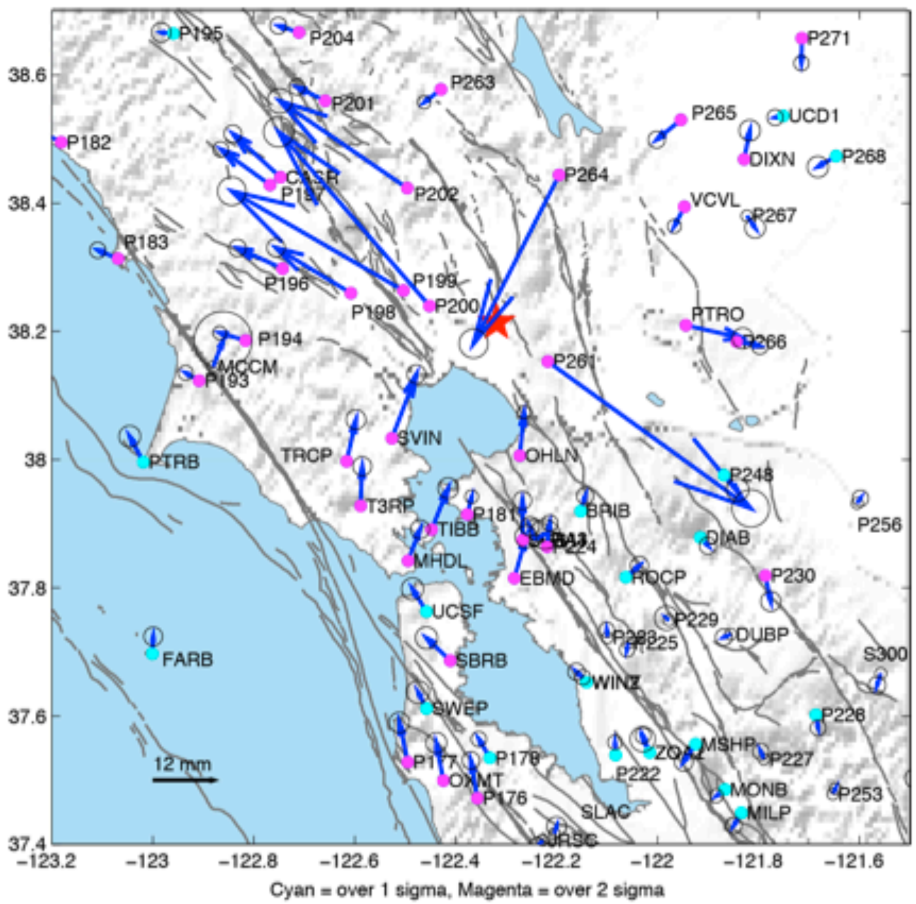
Further geologic, seismological & geophysical data and models emerged …

Geodetic displacements observed by permanent GPS stations

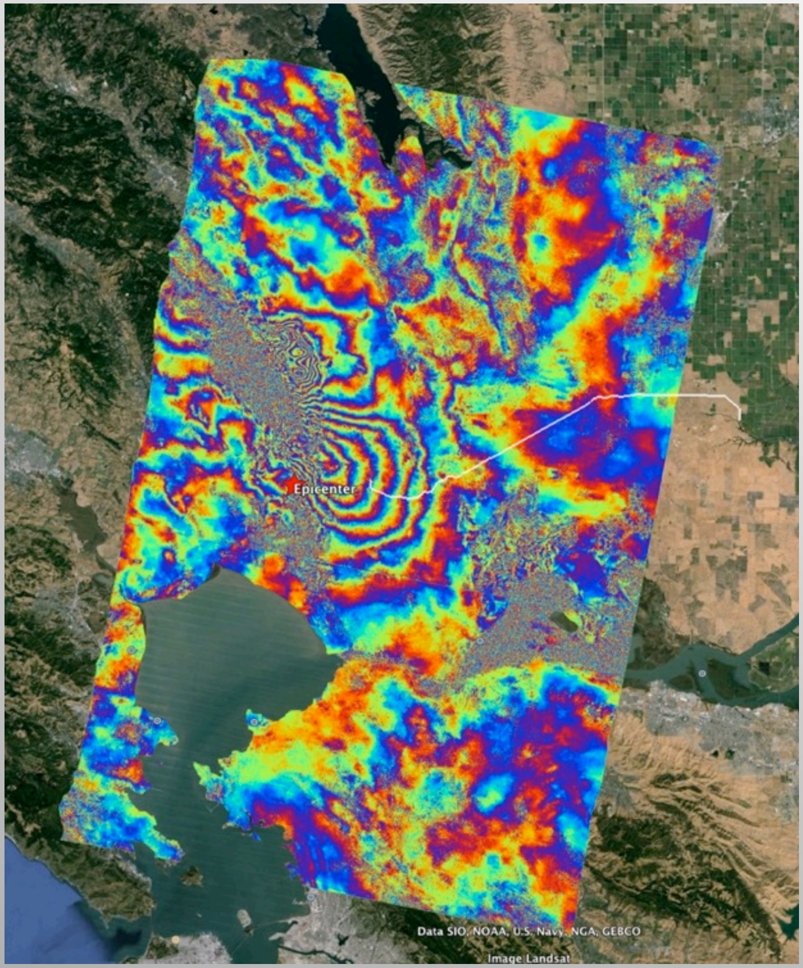
Solutions from 5 Minute Sample Rate Time Series
Available Day After Earthquake

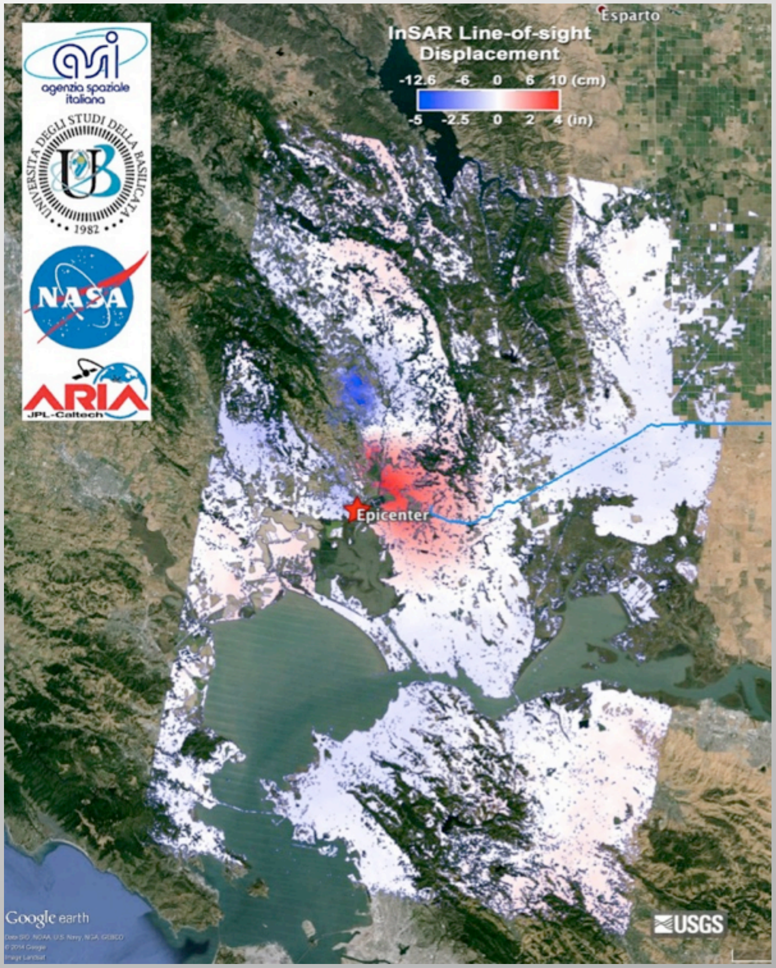


Solutions from 24 Hour Sample Rate Time Series
Available 2 Days After Earthquake

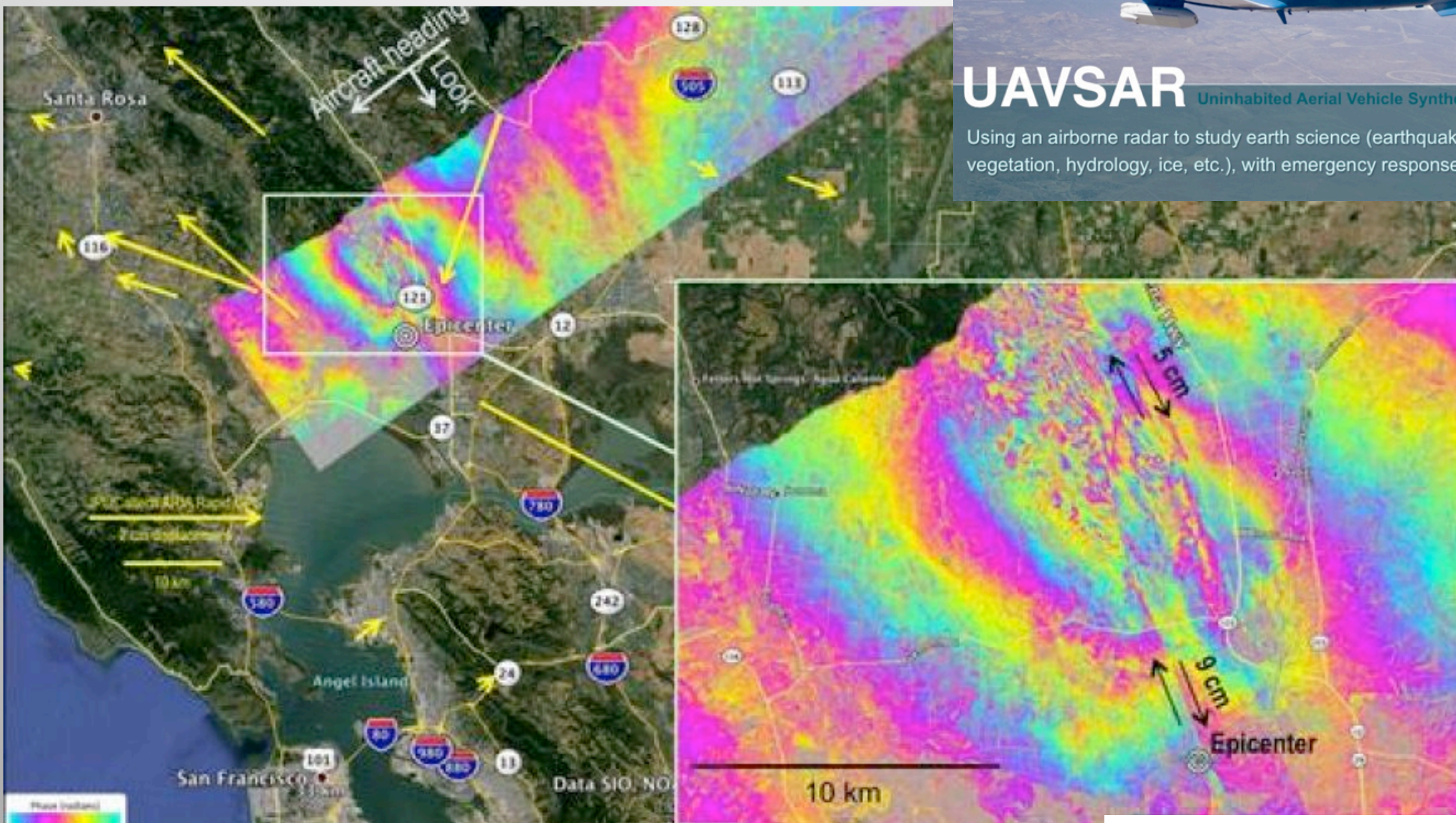


Satellite geodesy: InSAR (Interferometric Synthetic Aperture Radar) – big picture





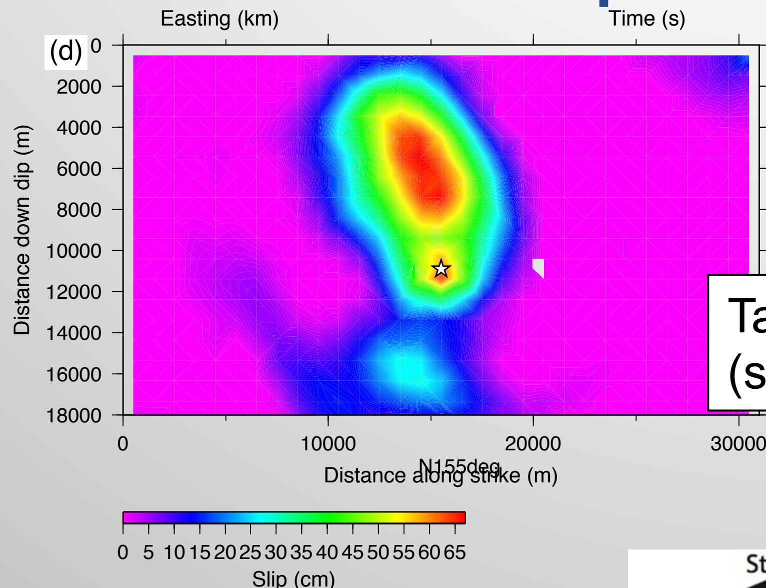
UAVSAR system - allows timely, detailed view

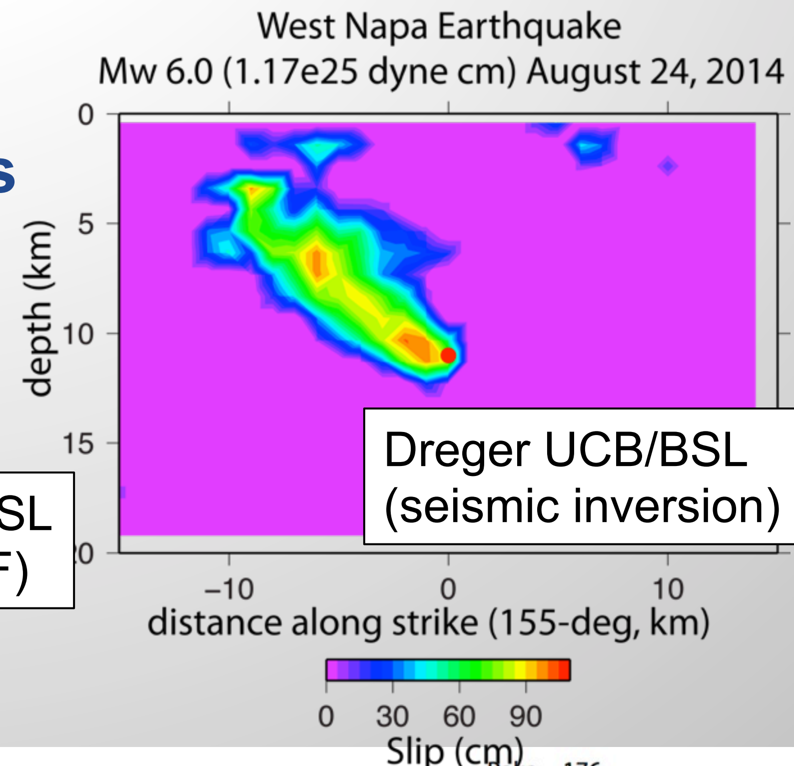


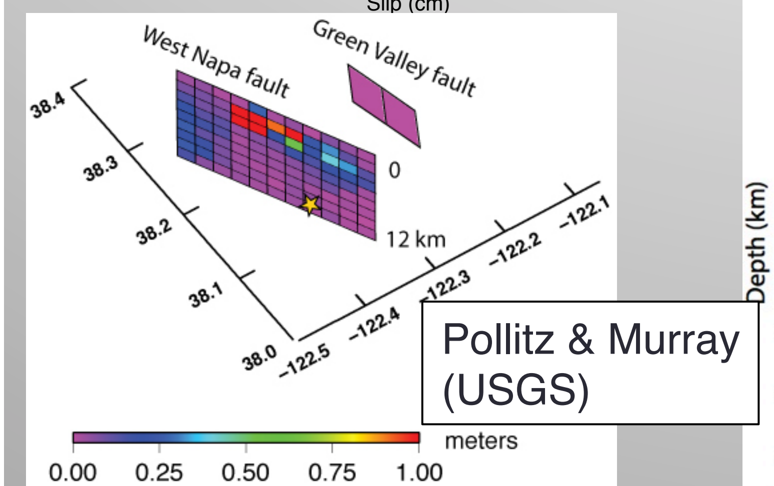
Jet Propulsion Laboratory

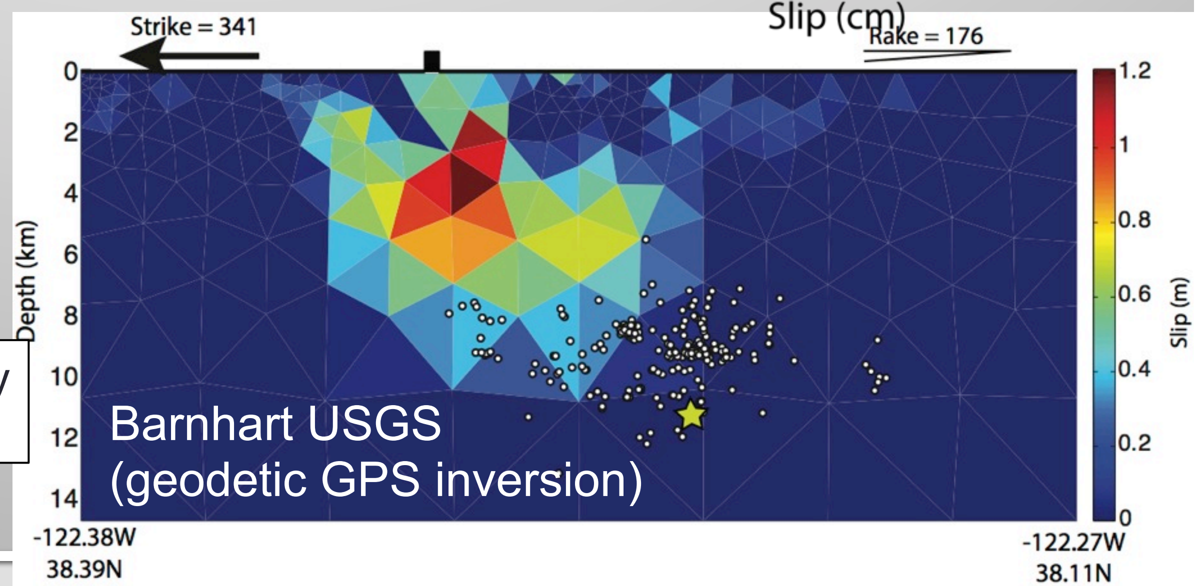
Finite fault models:

events of this size not point sources





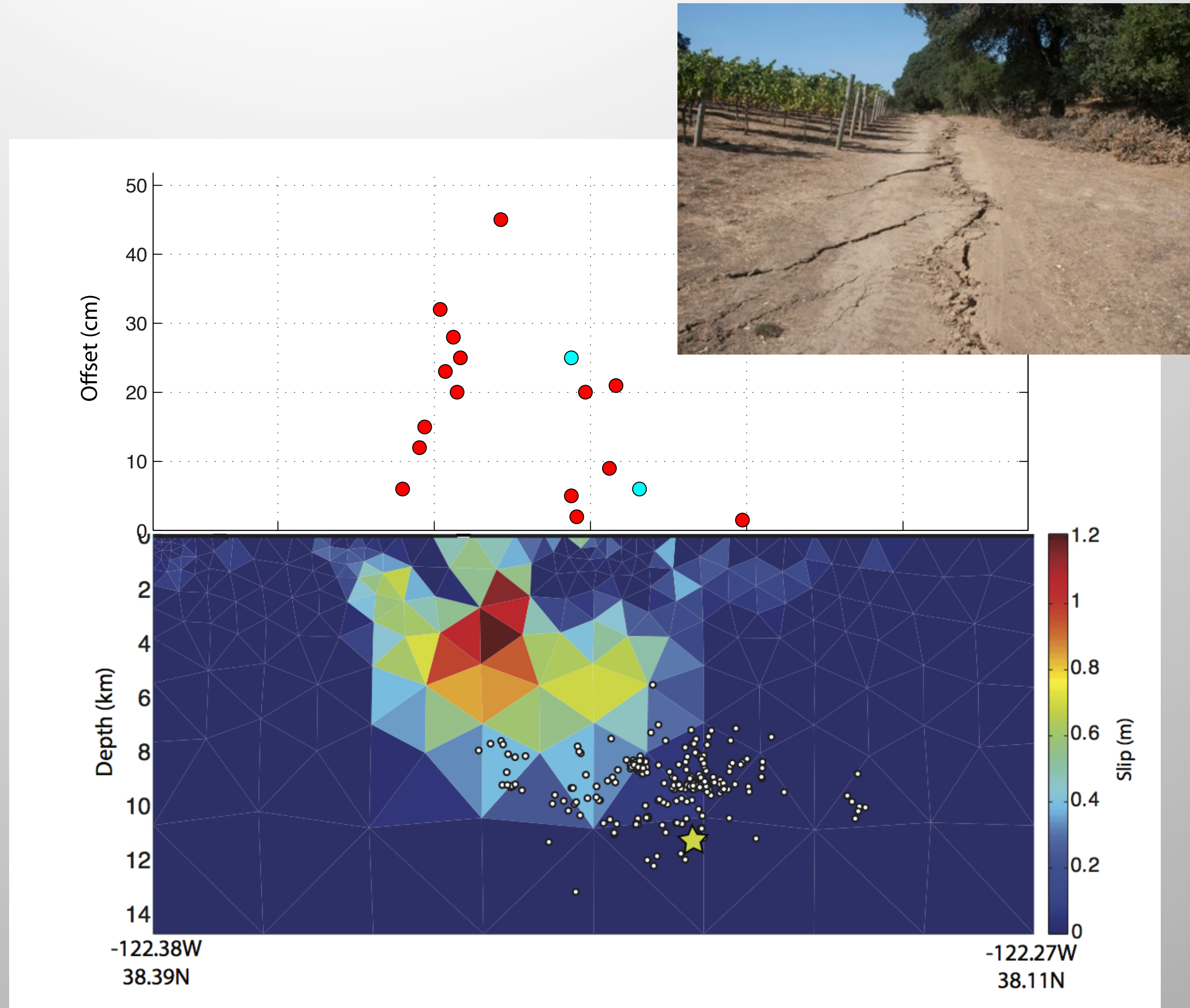




Comparison of surface and sub-surface slip

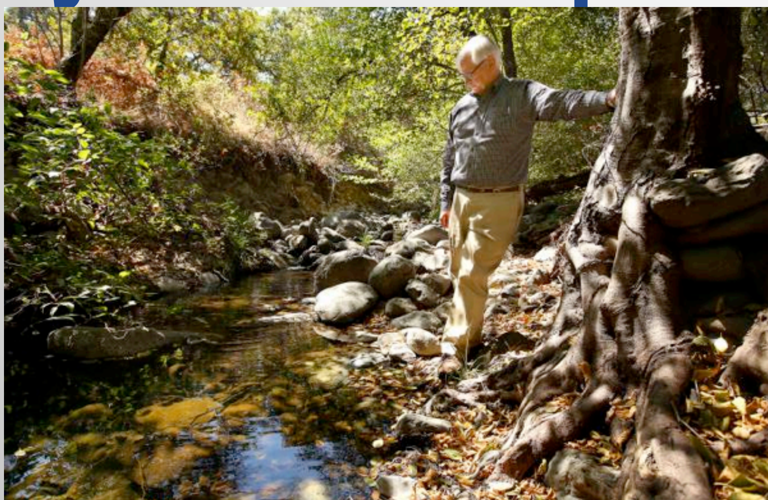
Observed surface slip
(several researchers)

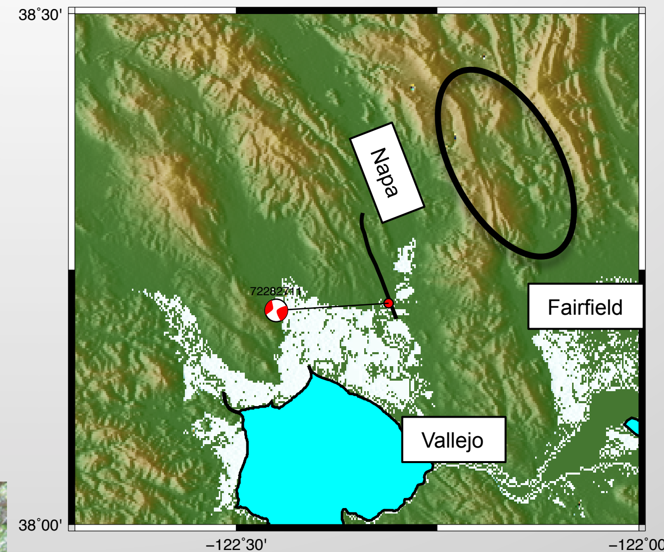
Inferred sub-surface slip
From GPS geodetic data
(Bill Barnhart, USGS)



Slip measurements: Morelan, Trexler, Brooks, Hudnut, Lienkamper. Model: Barnhart

Springs near Green Valley Fault activated by the earthquake





Green Valley

Prof. Chi Wang (UCB) at Tuteur Ranch, Napa

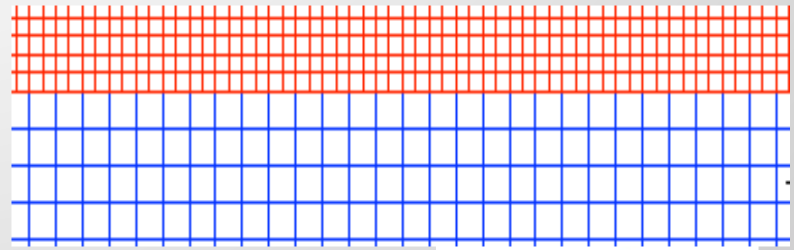
Computer Simulations of Ground Motion using LLNL's SW4 code on LC HPC

The pieces for 3D ground motion simulation

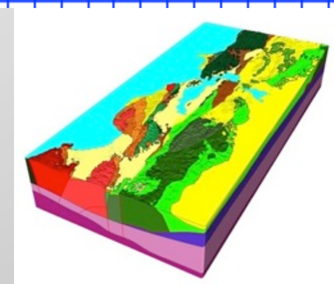
- Wave propagation method & code
- 3D Earth model
- Source model
- High-performance computers
- Data to evaluate and validate the numerical method and the 3D model

WPP & SW4

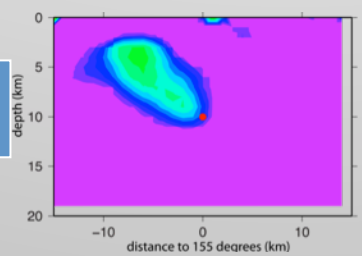
$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \mathbf{T} + \mathbf{F}(\mathbf{t})$$



3D model

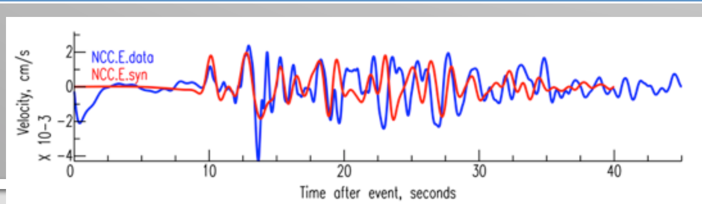


Source model



Parallel Computer

Validate method & models



We use SW4 – LLNL's anelastic finite difference code for seismic simulations

- SW4 is based on summation-by-parts algorithm
  - displacement formulation, proven energy stability, parallel
- Uses 4th order scheme in space and time
  - WPP used a 2nd order scheme
  - Improved behavior with higher v_P/v_S (< 5) ratios
- Verified against canonical problems
- Includes
  - Anelastic attenuation (Q_P & Q_S)
  - Surface topography
  - Various ways to specify sources & 3D material model

Computational Domain

EVENT: 72282711 2014/08/24 10:20:44.03 M_w = 6.02
Domain X: 50000 Y: 50000 Z: 30000 h: 50 (meters)
v_{Smin} = 400 m/s ; PPW: 8 ; f_{max} = 1 Hz

Dimensions: 50 km x 50 km x 30 km
centered on event hypocenter

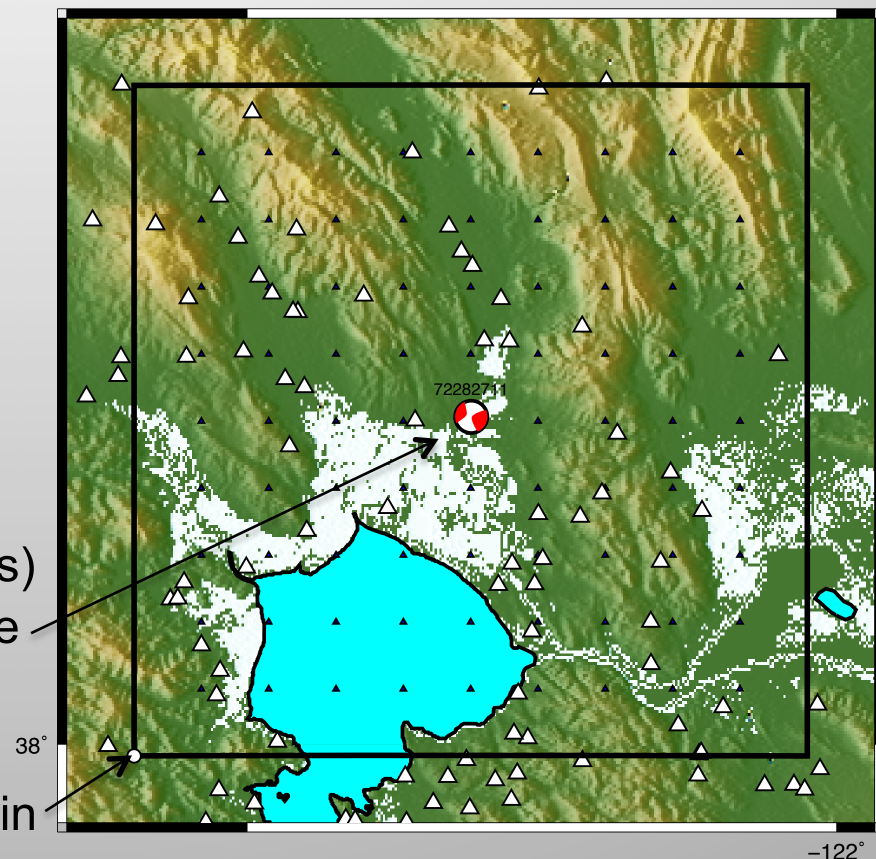
Grid spacing, h = 50 m
Number of grid points: ~ 0.5 billion
Miminum wavespeed, vsmin = 400 m/s
Maximum frequency = 1 Hz (8 PPW)

Stations:

BK, NC, GPS network sites (white triangles)
grid w/ 5 km spacing (black triangles)

Source

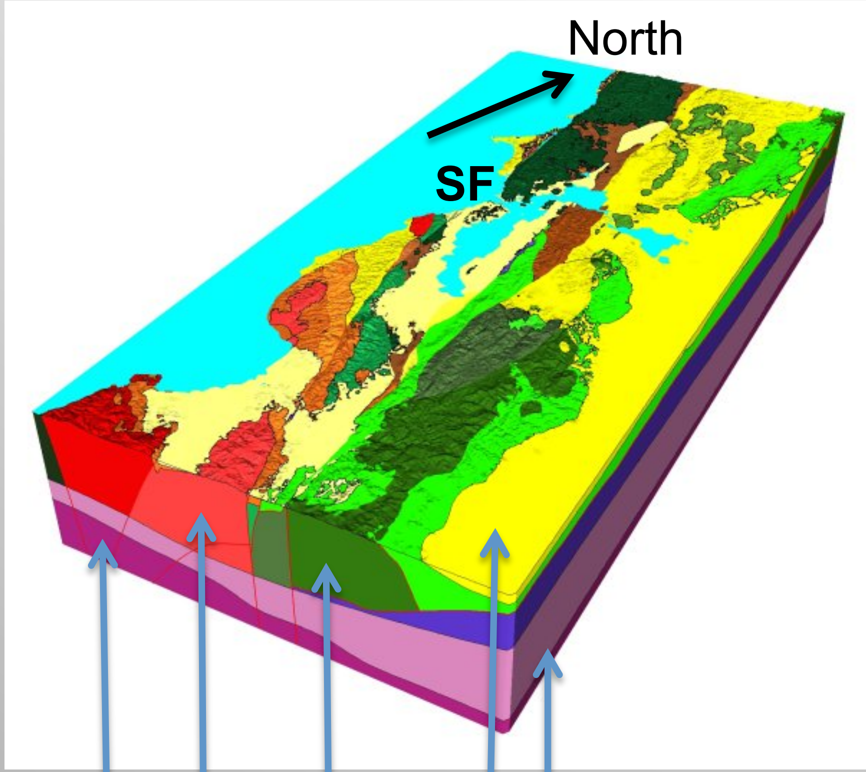
Domain

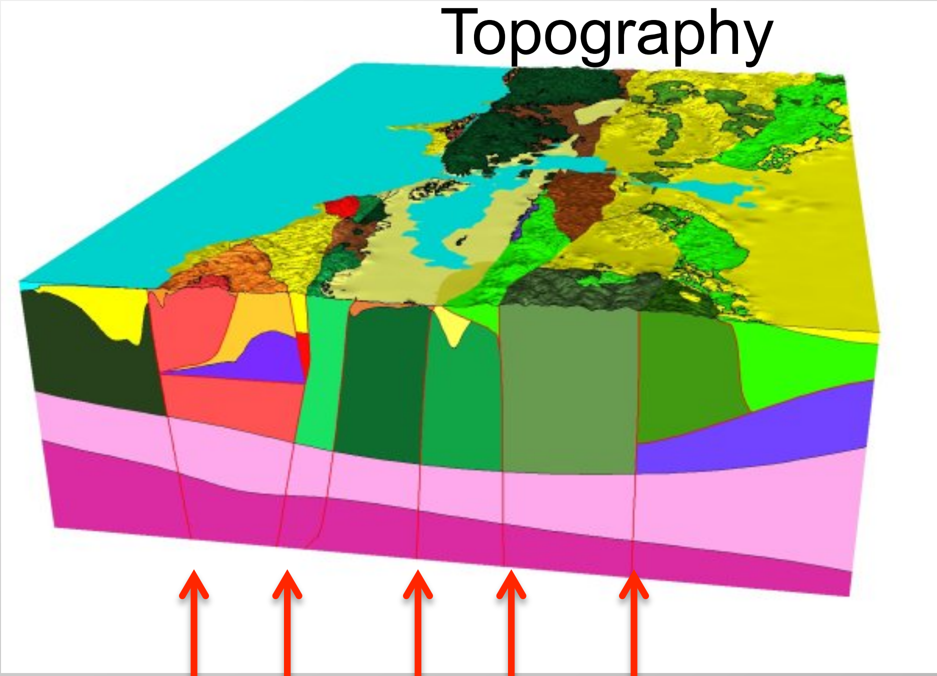


Simulations investigate how various factors impact the ground motion

- Source model
  - Point source, BSL moment tensor (Dreger et al.)
    - Full moment tensor or double couple (strike, dip, rake)
  - Finite slip model (Dreger)
- Material model
  - 1D (average GIL7 model of Dreger, Pasyanos et al.)
  - 3D Etree model (USGS, Brocher, Aagaard, Jachens et al.)
- Attenuation is included in these simulations
  - 3D Q from USGS ETREE model (version 08)
- Topography

Sub-surface material model: USGS 3D etree-formatted model

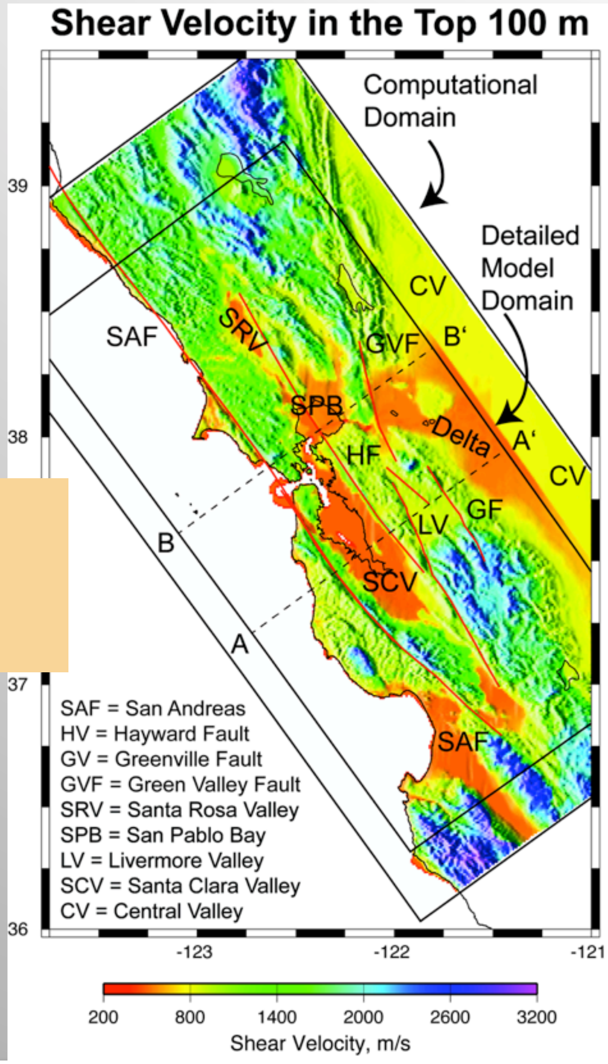




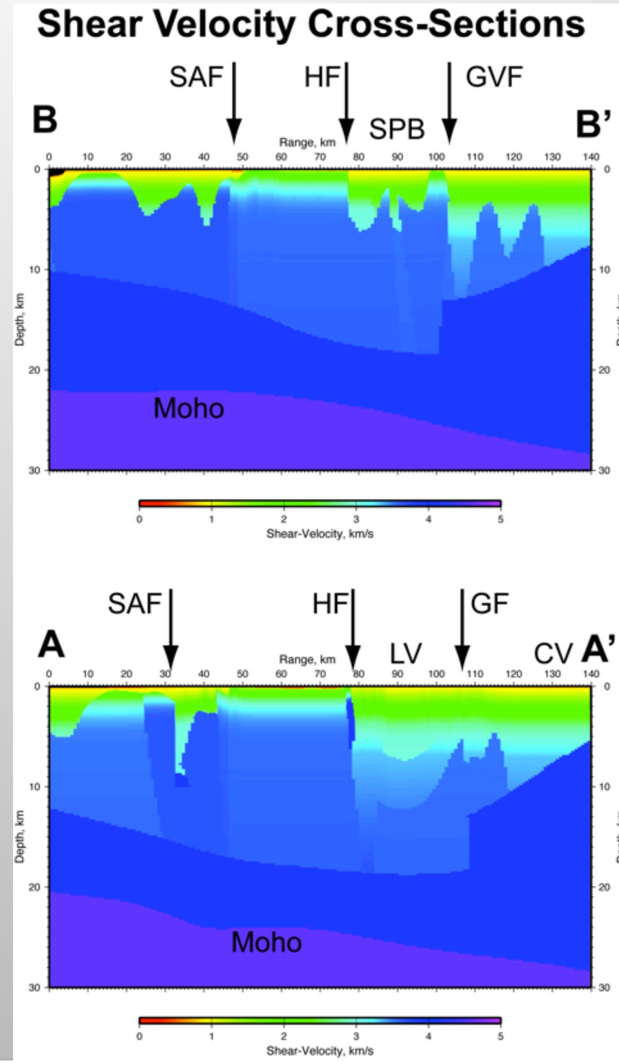
Different rock types

Faults

USGS 3D sub-surface material model: shear velocities at surface and depth

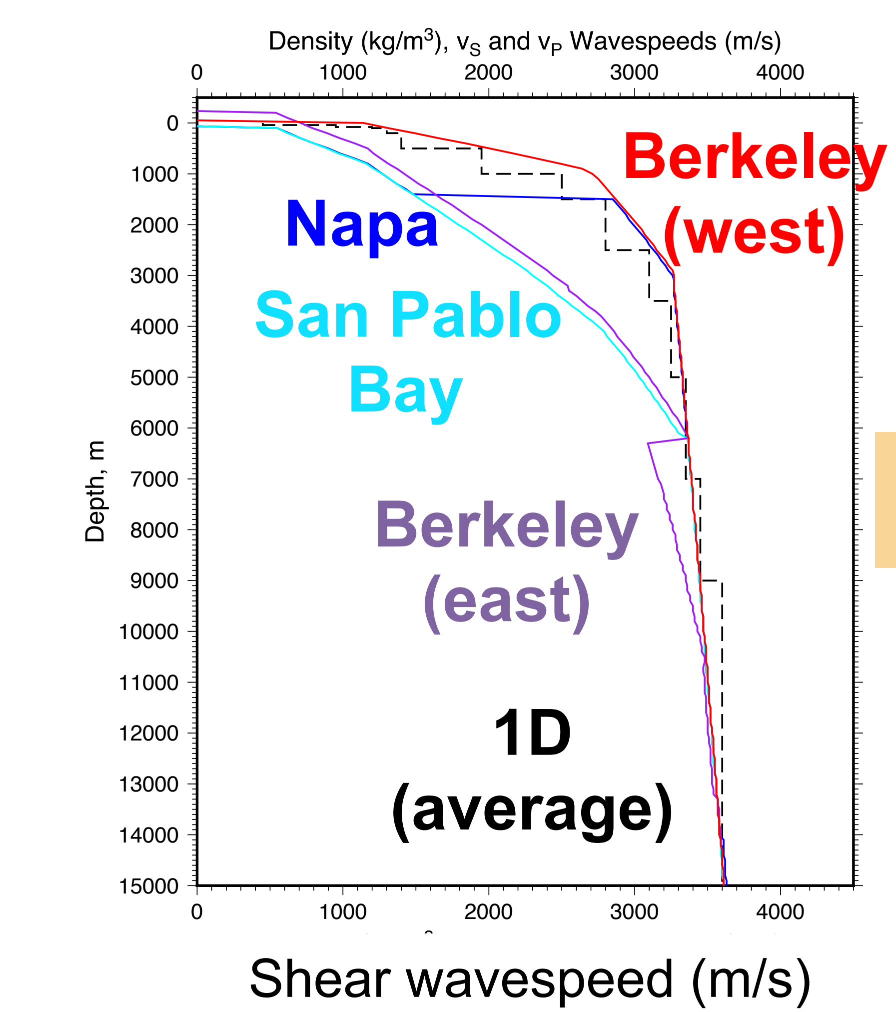


Up to 12x variation at surface



Up to 2x variation at depth

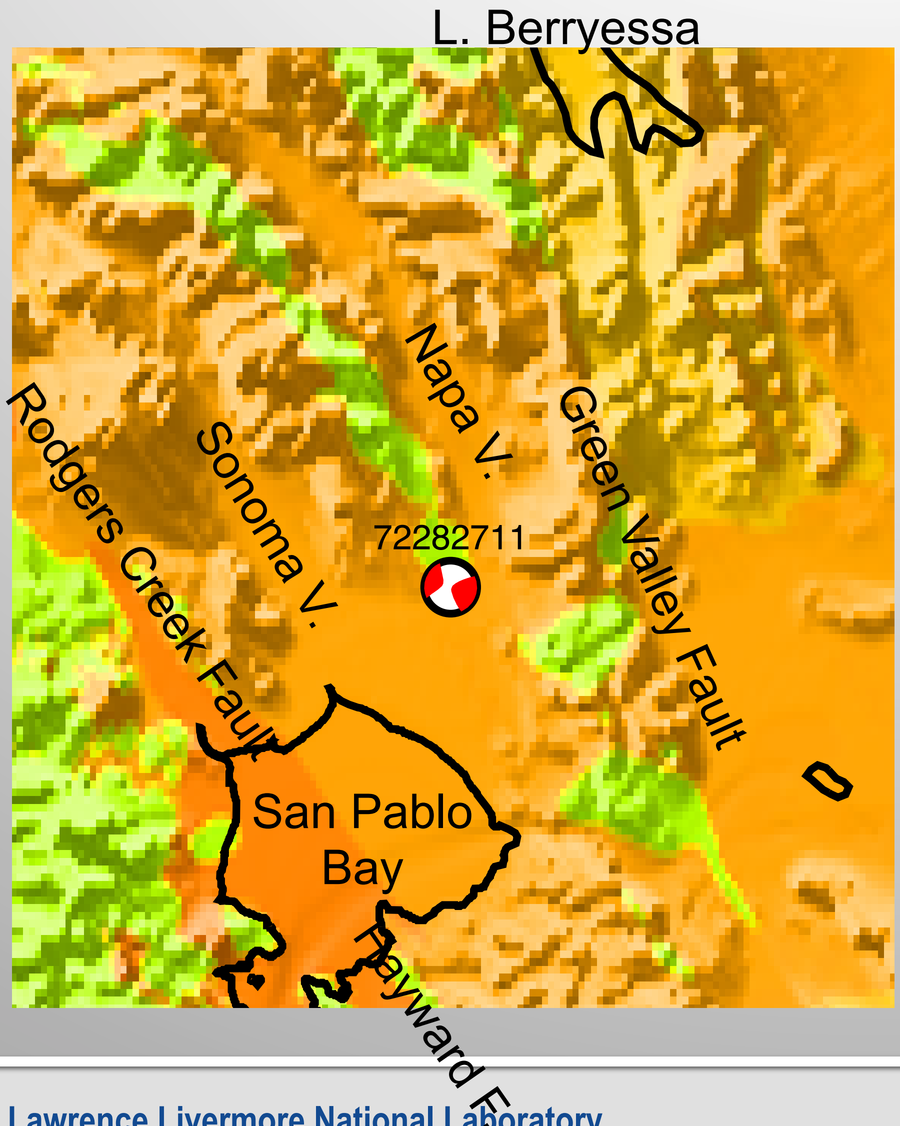
Sub-surface material model: comparison of depth profiles from USGS 3D & 1D (BBP)

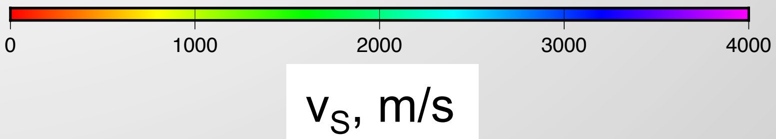


Napa Valley sediments are ~1000 m deep

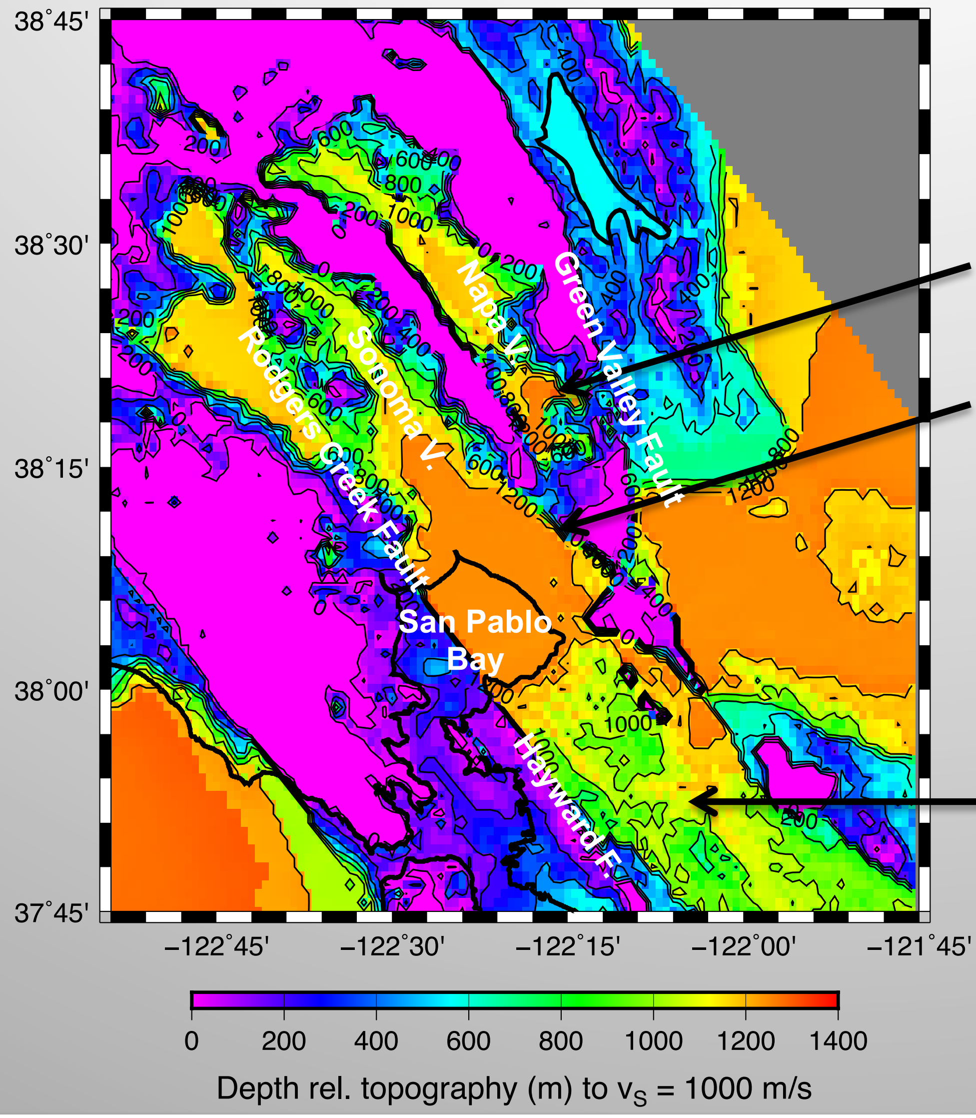
1D model from PEER Broadband Platform (BBP)

Geography near the event, with topography and vs at surface





"Basin" depth (depth to v_S = 1000 m/s)



Basin depth in Napa Valley approaches 1000 m

Note sharp drop in basement depth near South Napa earthquake rupture

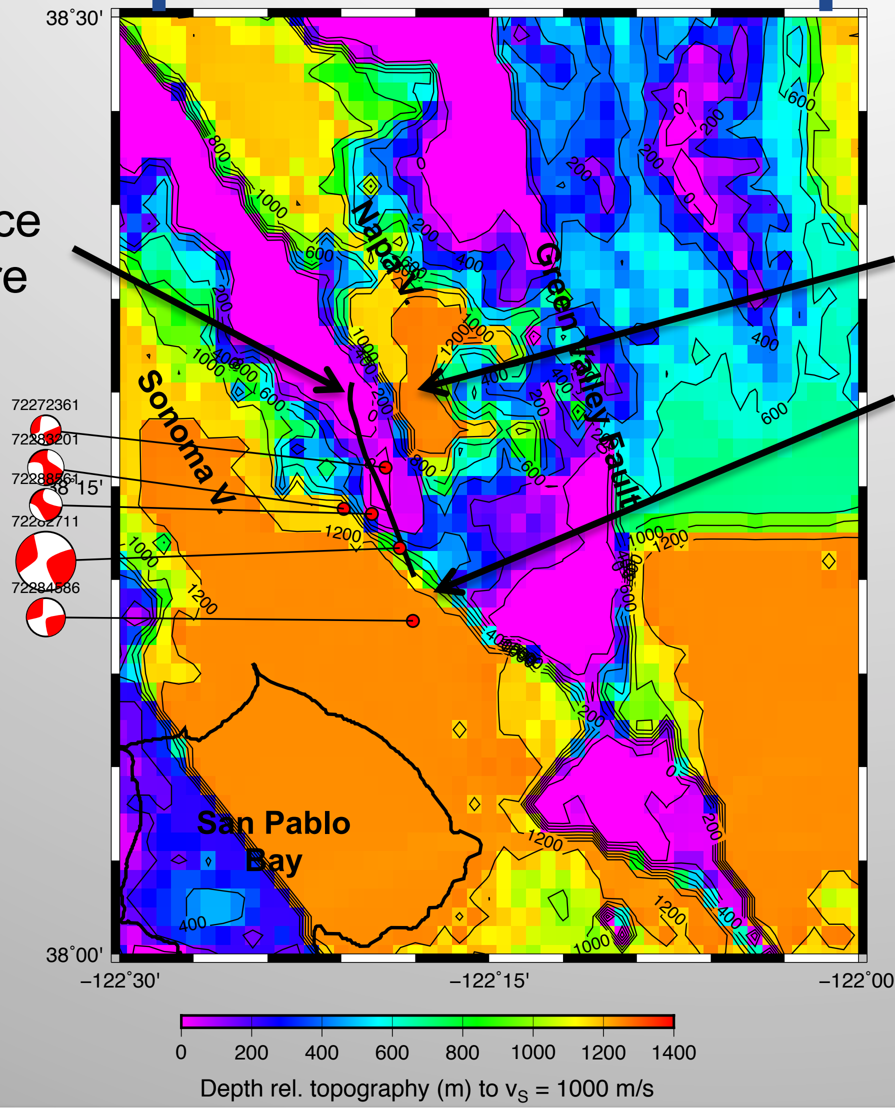
Sediment thickness > 1000 m under San Pablo Bay

East Bay Hills (east of Hayward Fault) has low wavespeed

Basin depth (v_S = 1000 m/s) close-up near Napa shows sharp features

Surface rupture

BSL MT's

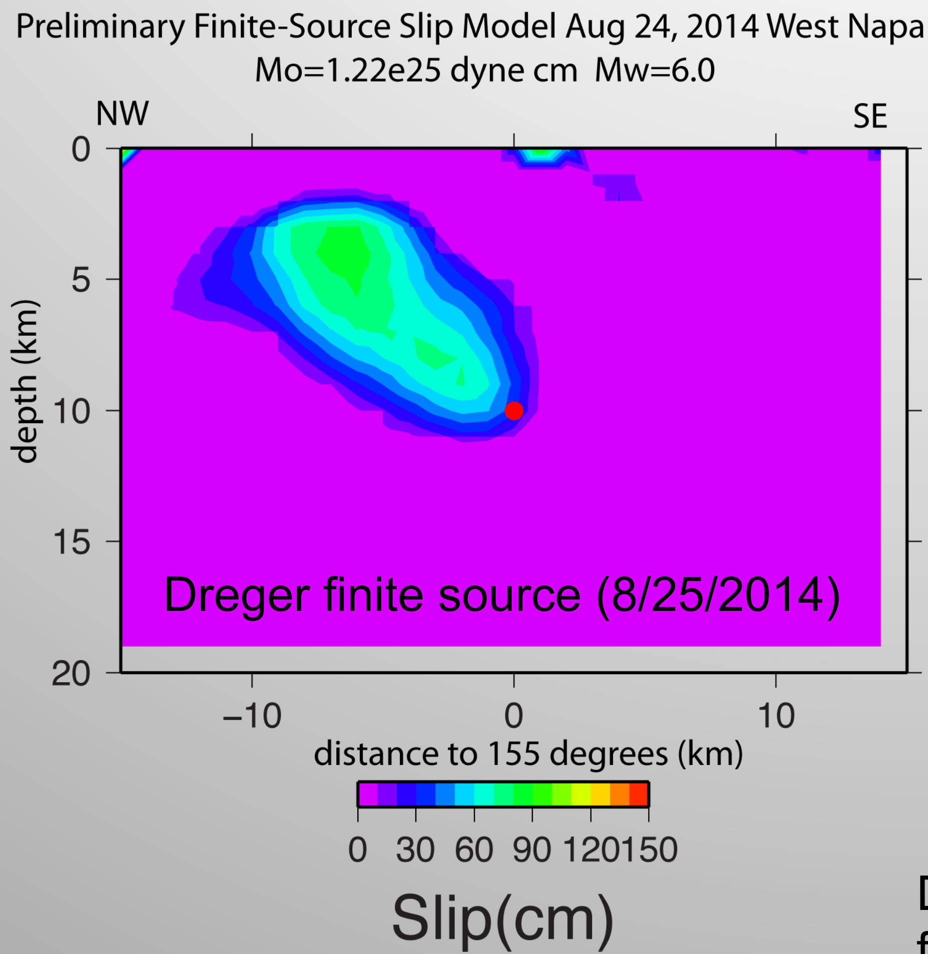


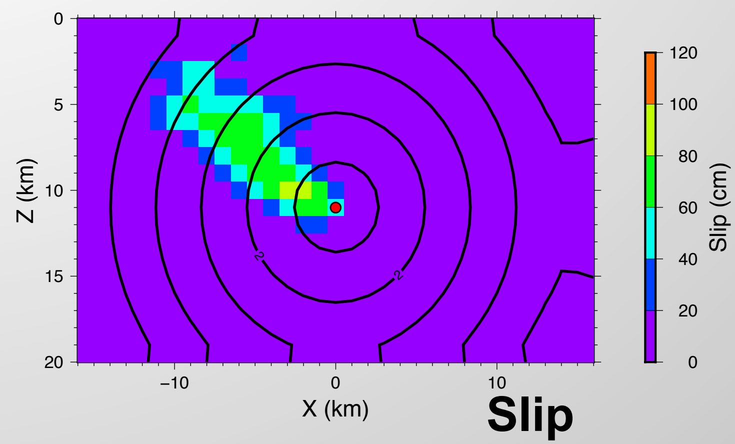
Basin depth in Napa Valley is greater than 1000 m

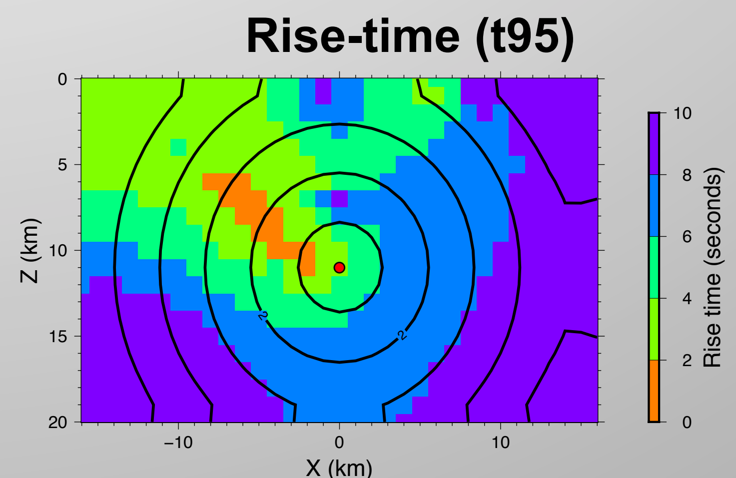
Note sharp drop in basement depth near southern end of South Napa earthquake rupture

Sediment thickness > 1000 m under San Pablo Bay

Mainshock: Doug Dreger's finite source model



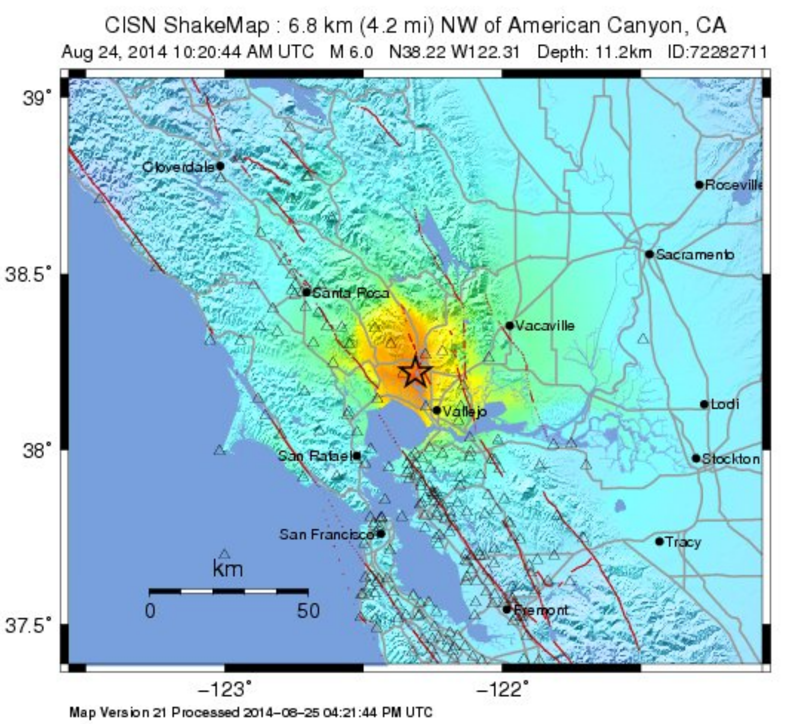




Dreger source rendered onto 1 km sub-faults, assume Liu-type source-time function

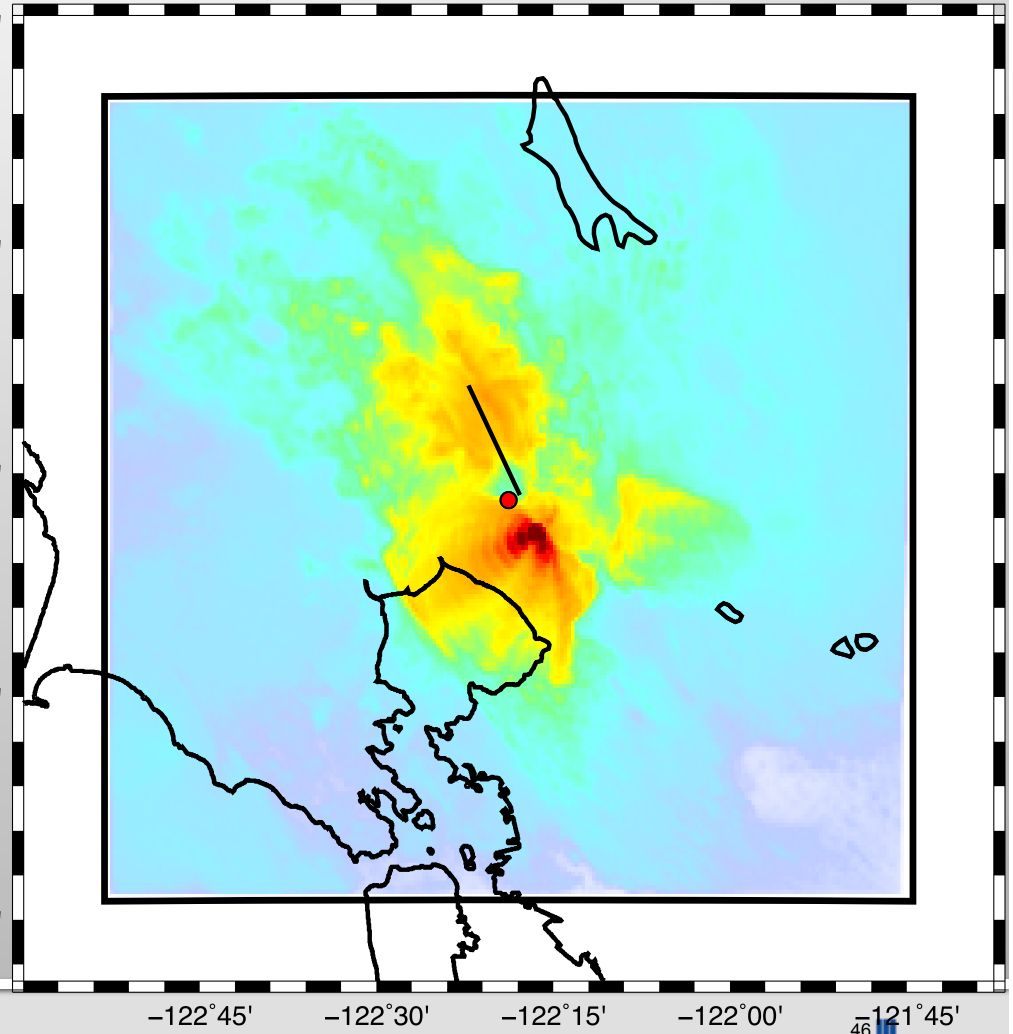
ShakeMap (Peak Ground Velocity) reported (left) and simulated (right)

RUN: 72282711.SLIP.3D_ETREE.TOPO.Q.400.100.SW4



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

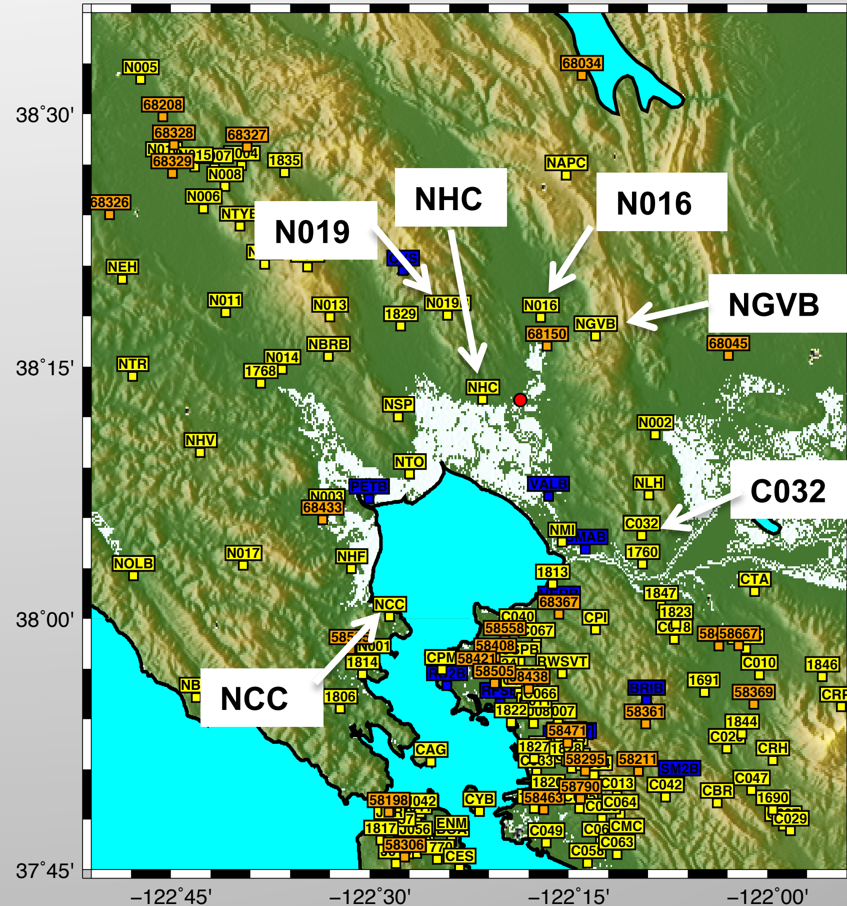


Mainshock waveform comparisons: station by station

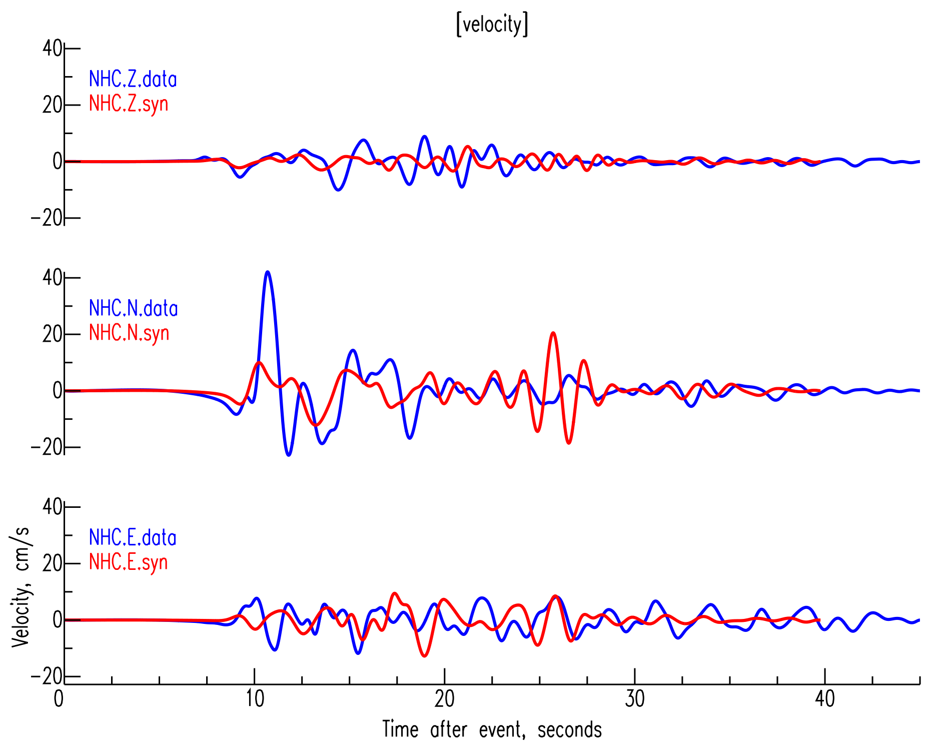
Source model is Dreger (2014) finite slip model from BK strong motion

Data & **Synthetic**
Both filtered 0.1-1.0 Hz
Plotted vertical, north & east

Stations shown in following clockwise from NHC



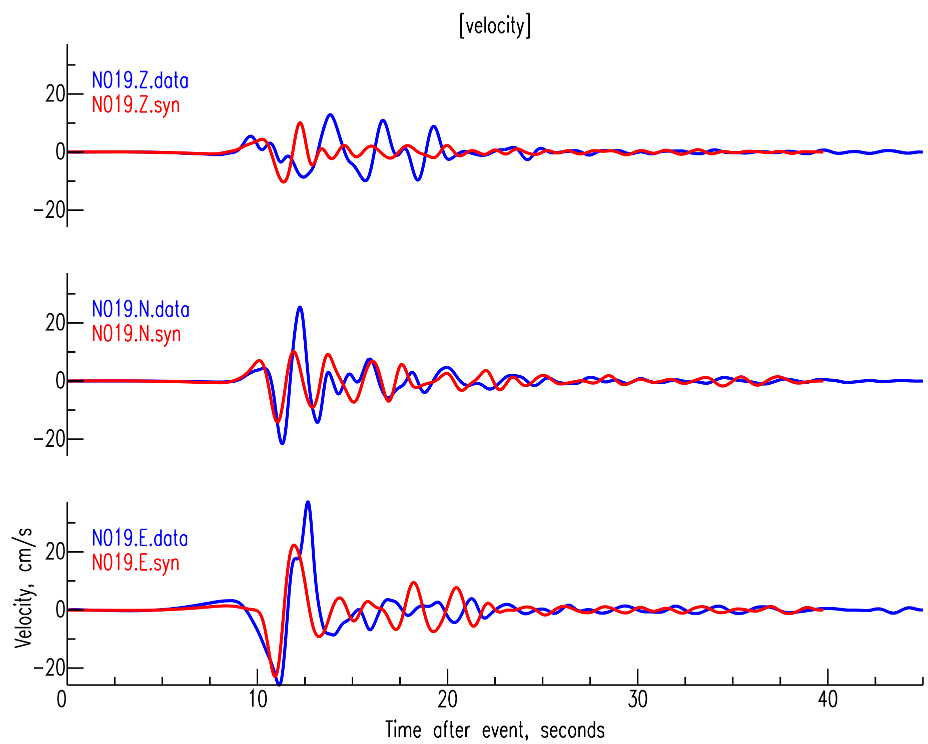
Mainshock waveform comparisons



Amplitudes underpredicted for both 1D and 3D models, but 3D fits better

Station NC.NHC 4 km

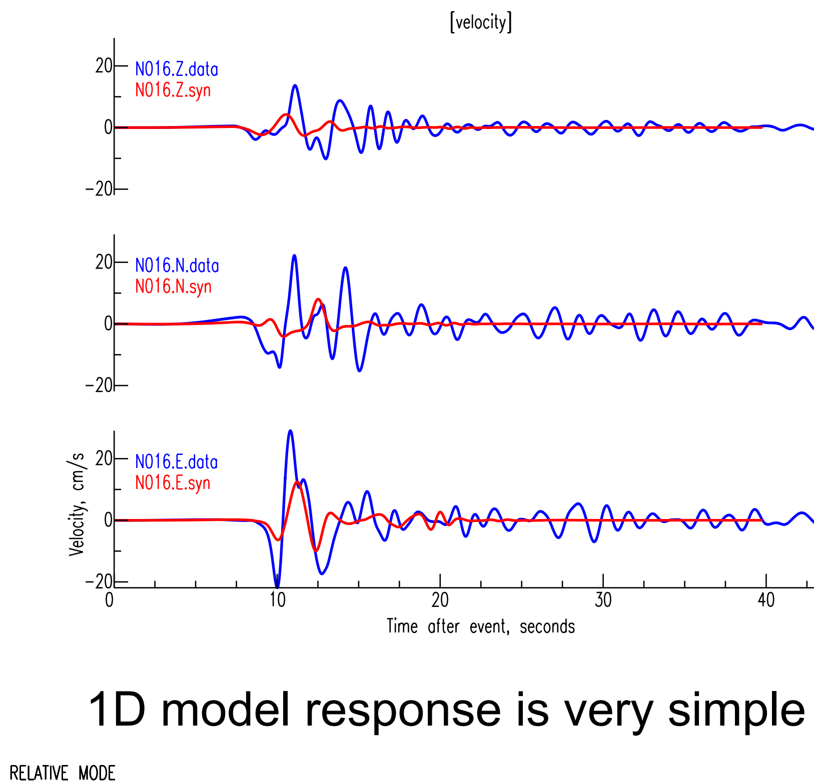
Mainshock waveform comparisons



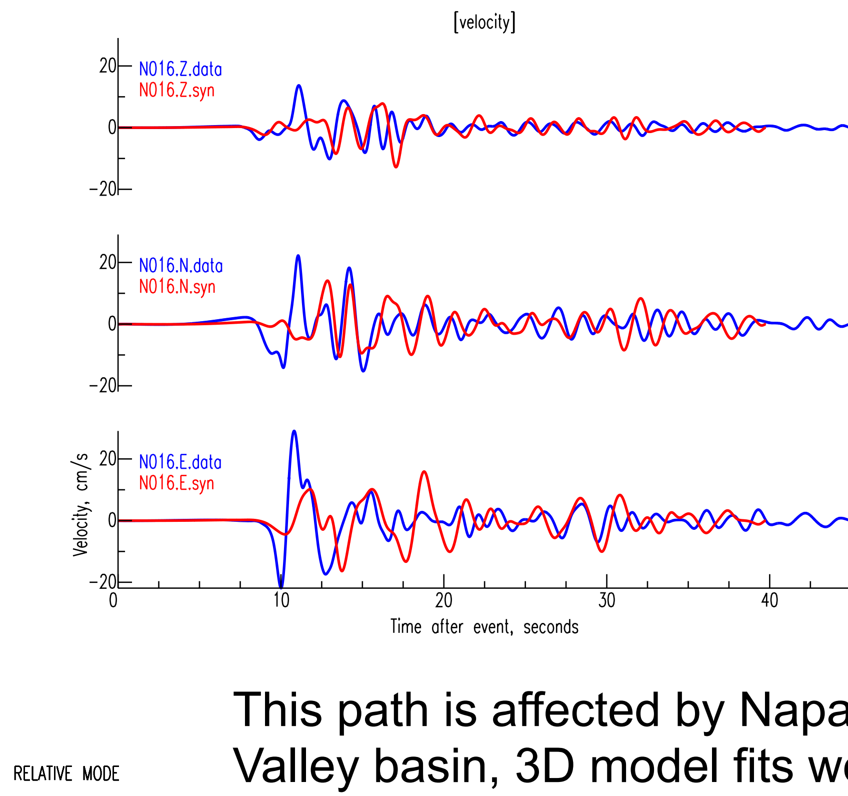
3D model fits amplitude better and later energy on North comp.

Station NC.N019 6 km

Mainshock waveform comparisons Model: 1D_BBP (left) & 3D_ETREE (right)



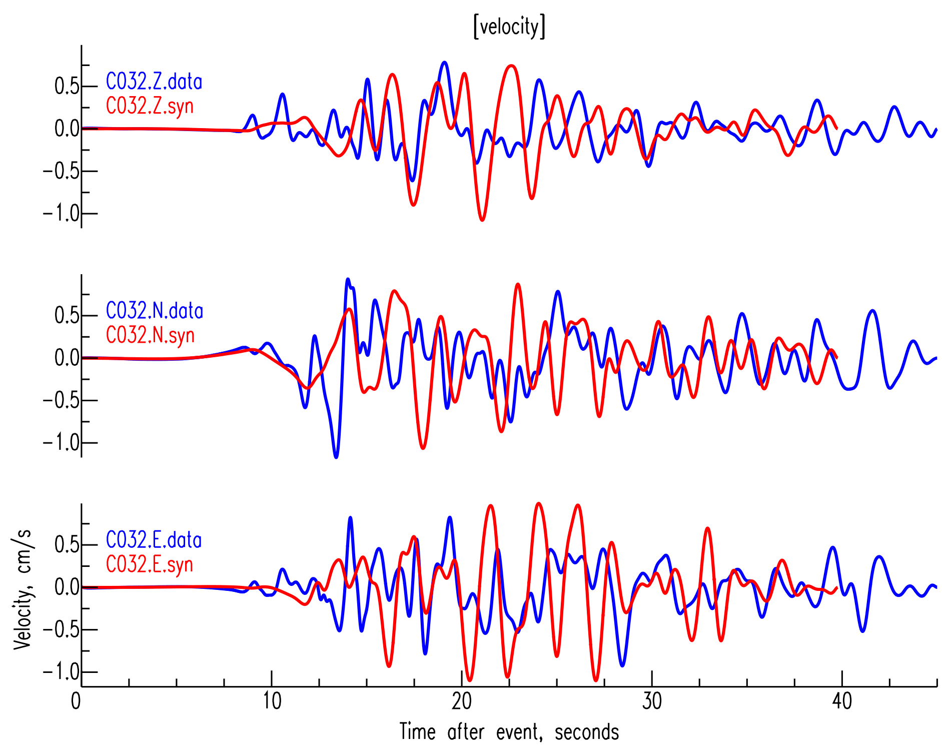
1D model response is very simple



This path is affected by Napa Valley basin, 3D model fits well

Station NC.N016 4 km

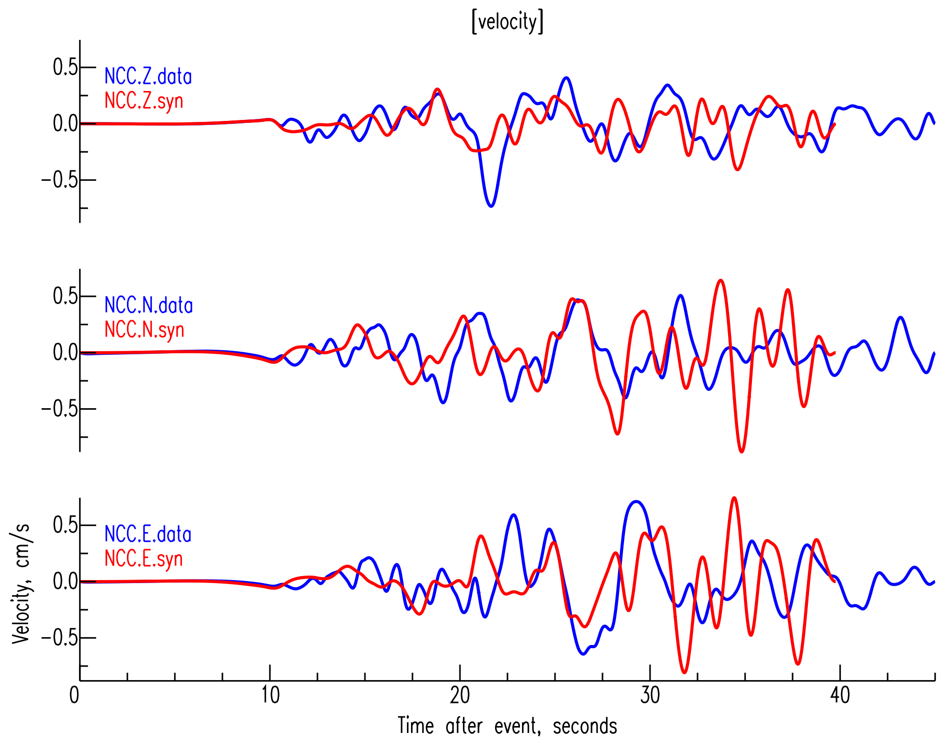
Mainshock waveform comparisons



3D model fits duration and late arriving energy better than 1D

Station NC.C032 21 km

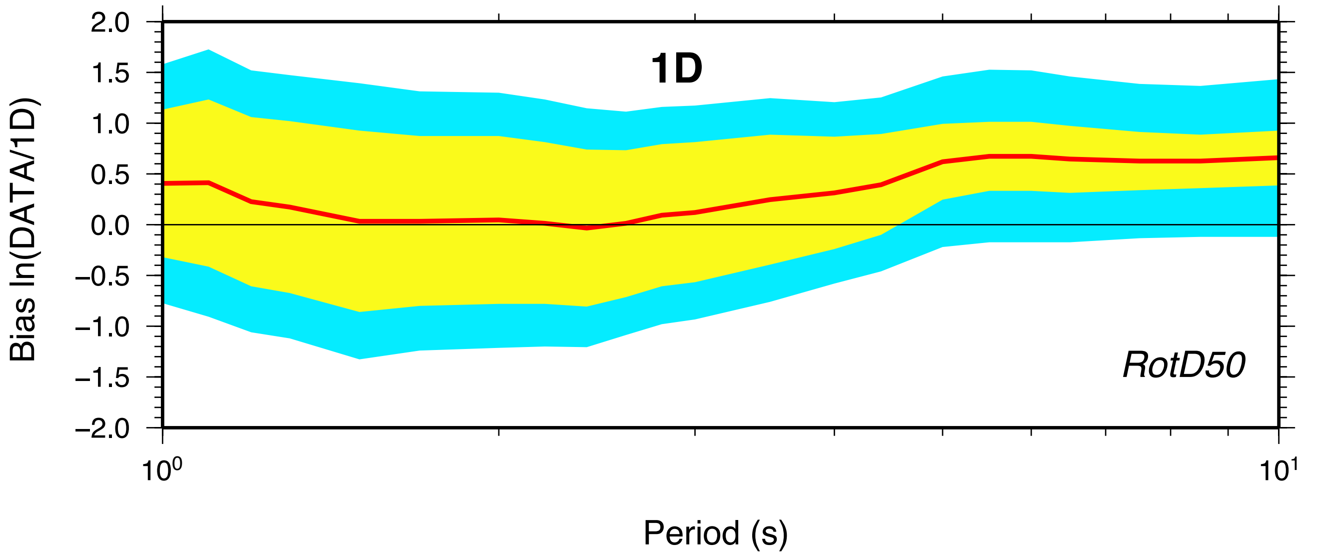
Mainshock waveform comparisons

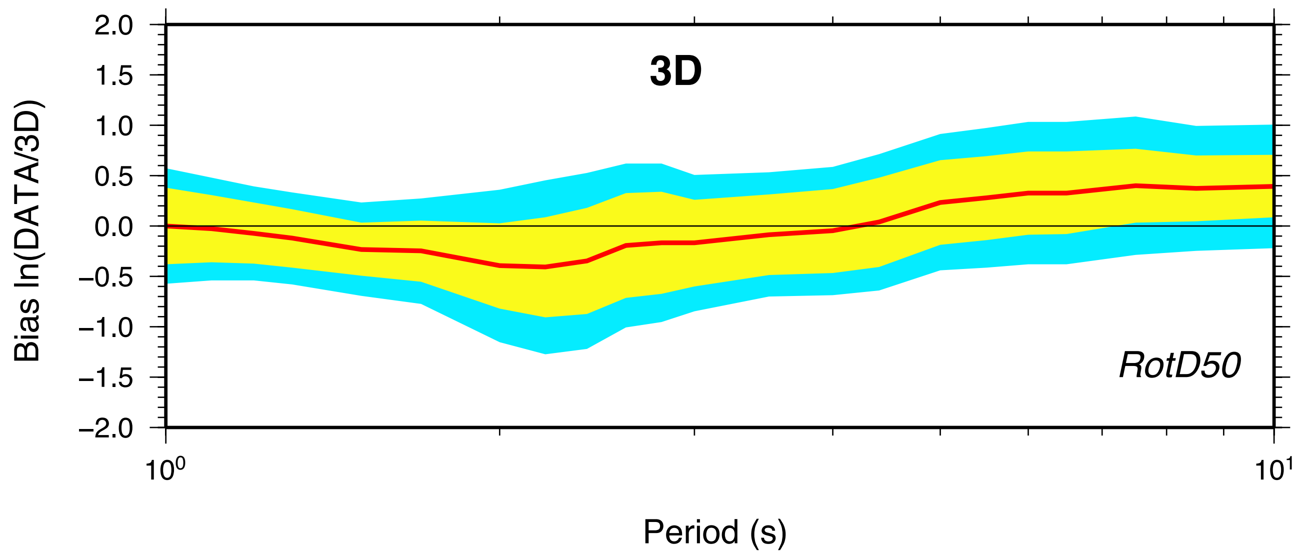


Path across San Pablo Bay is well fit by 3D model!

Station NC.NCC 28 km

Quantitative comparison of data and synthetics for 1D and 3D models





Spectral acceleration periods: 1-10 s

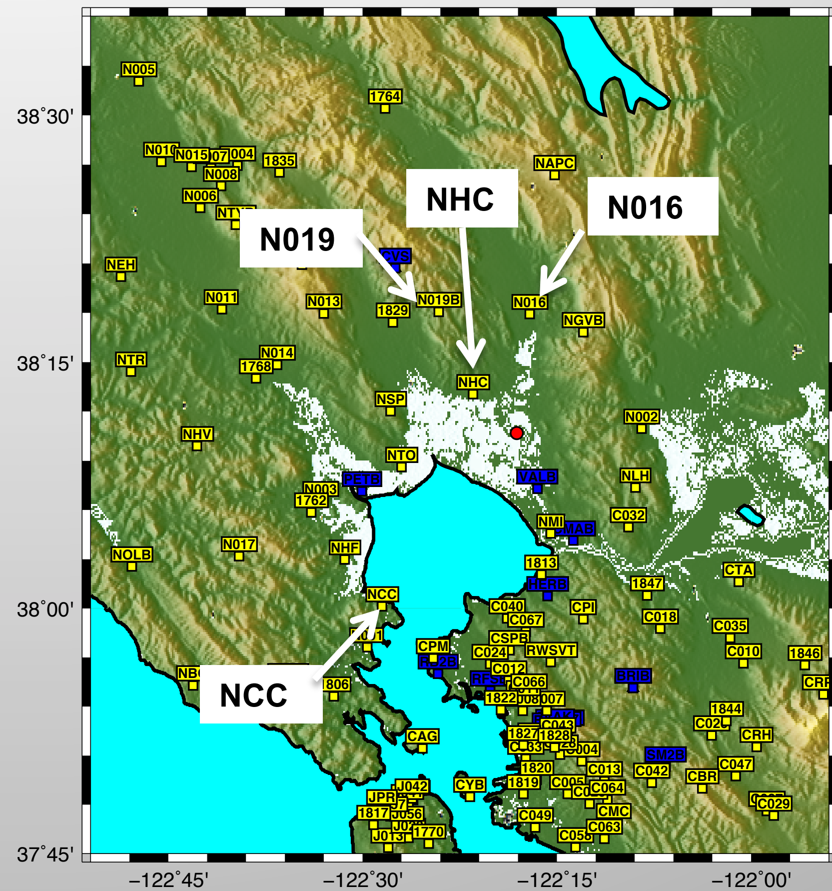
Thanks to Arben Pitarka!

Aftershock Aug. 26, 2014 12:33:16 GMT (Evid = 72284586, M_W 3.9)

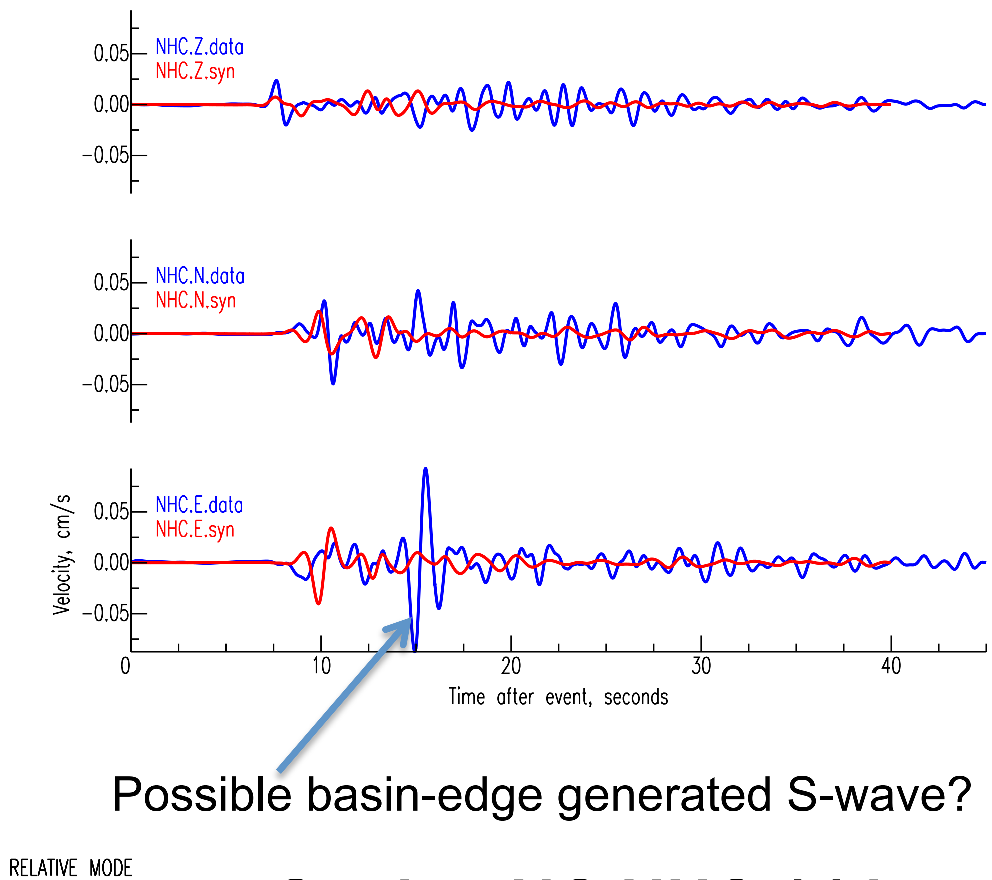
Source model is BSL moment tensor

Data & **Synthetic**
Both filtered 0.1-1.0 Hz
Plotted vertical, north & east

Stations shown in following clockwise from NHC

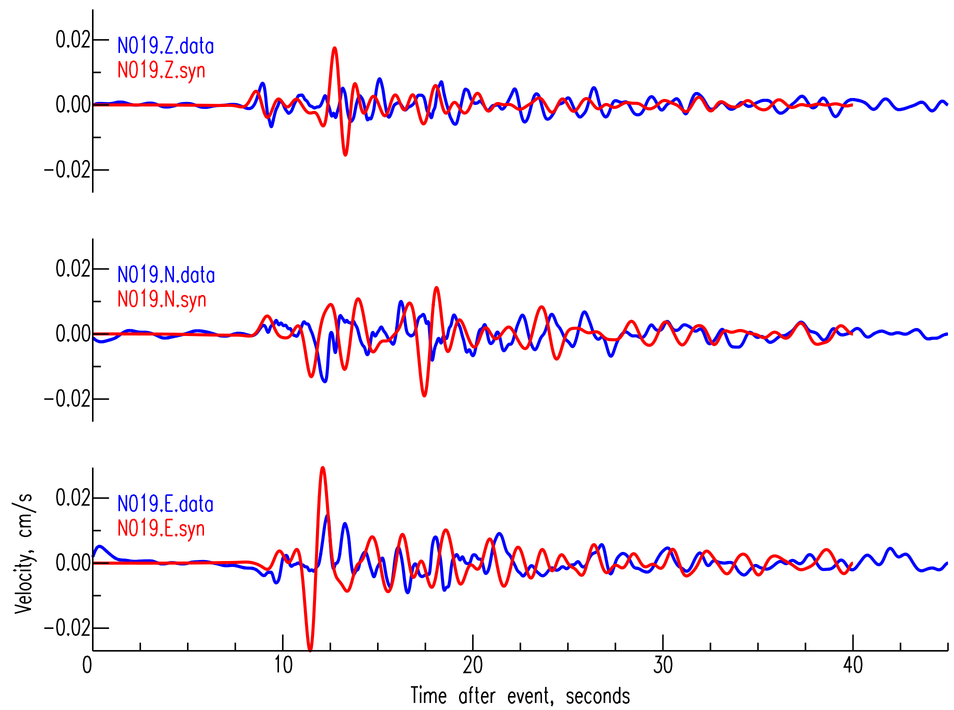


Aftershock waveform comparisons



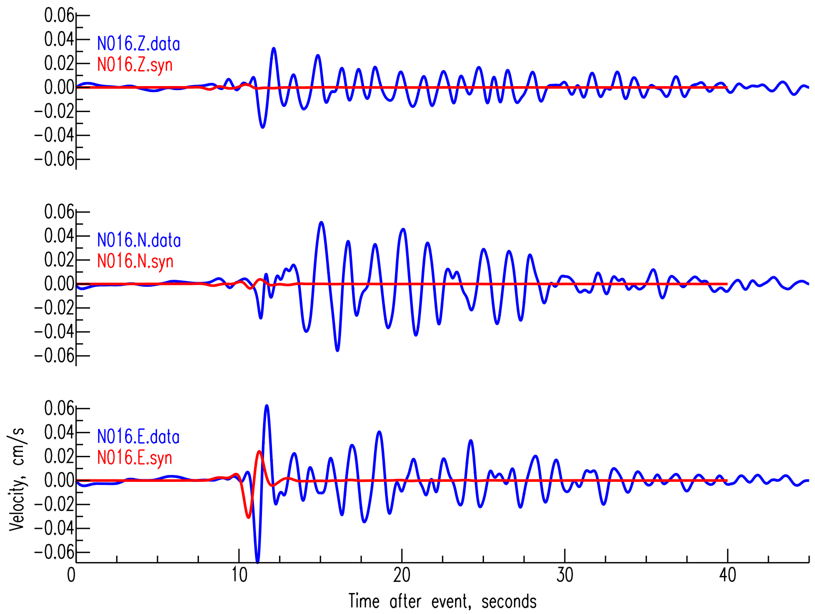
Station NC.NHC 14 km

Aftershock waveform comparisons



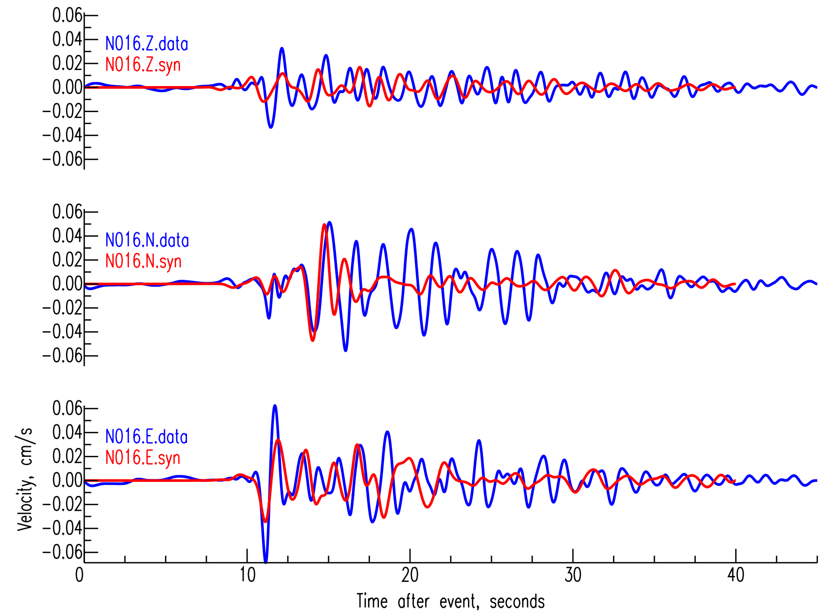
Station NC.N019 20 km

Aftershock waveform comparisons
Model: 1D_BBP (left) & 3D_ETREE (right)



RELATIVE MODE

1D model cannot predict ringing basin surface waves

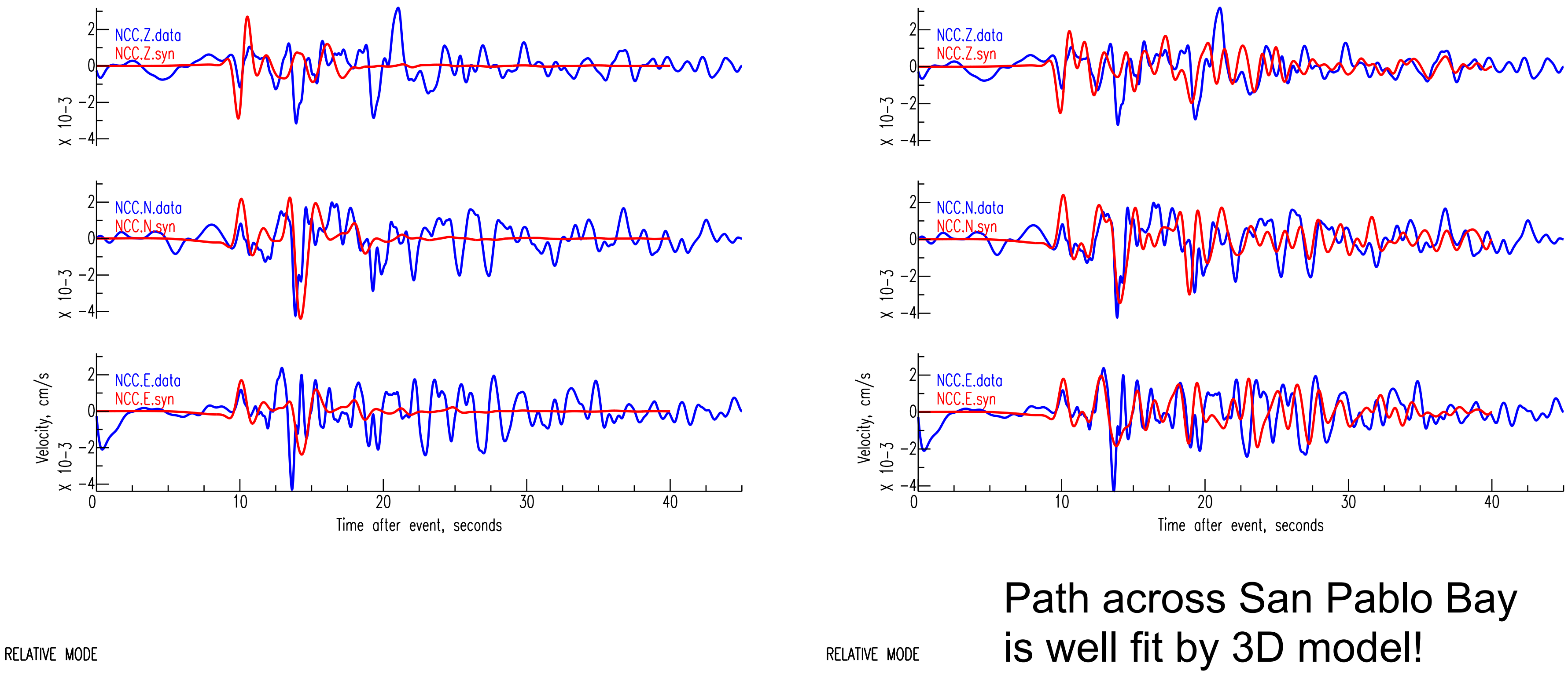


RELATIVE MODE

3D model can predict some basin surface waves, good timing & amplitude predictions

Station NC.N016 18 km

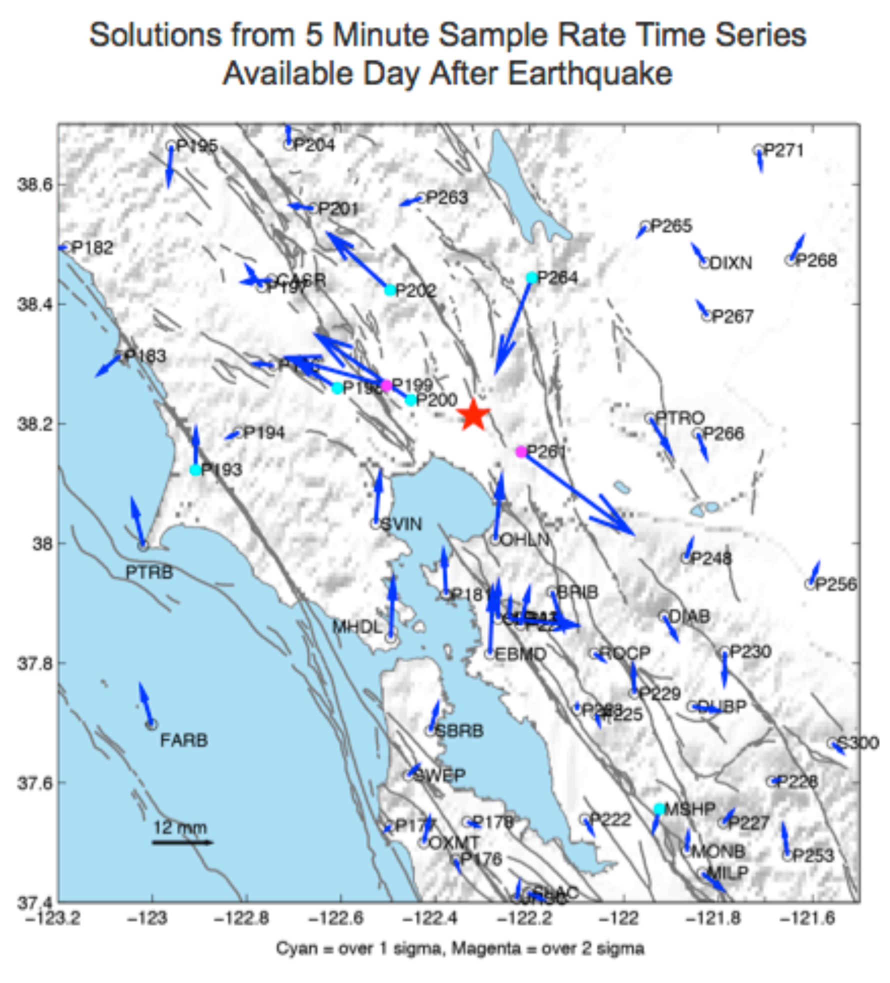
Aftershock waveform comparisons
Model: 1D_BBP (left) & 3D_ETREE (right)

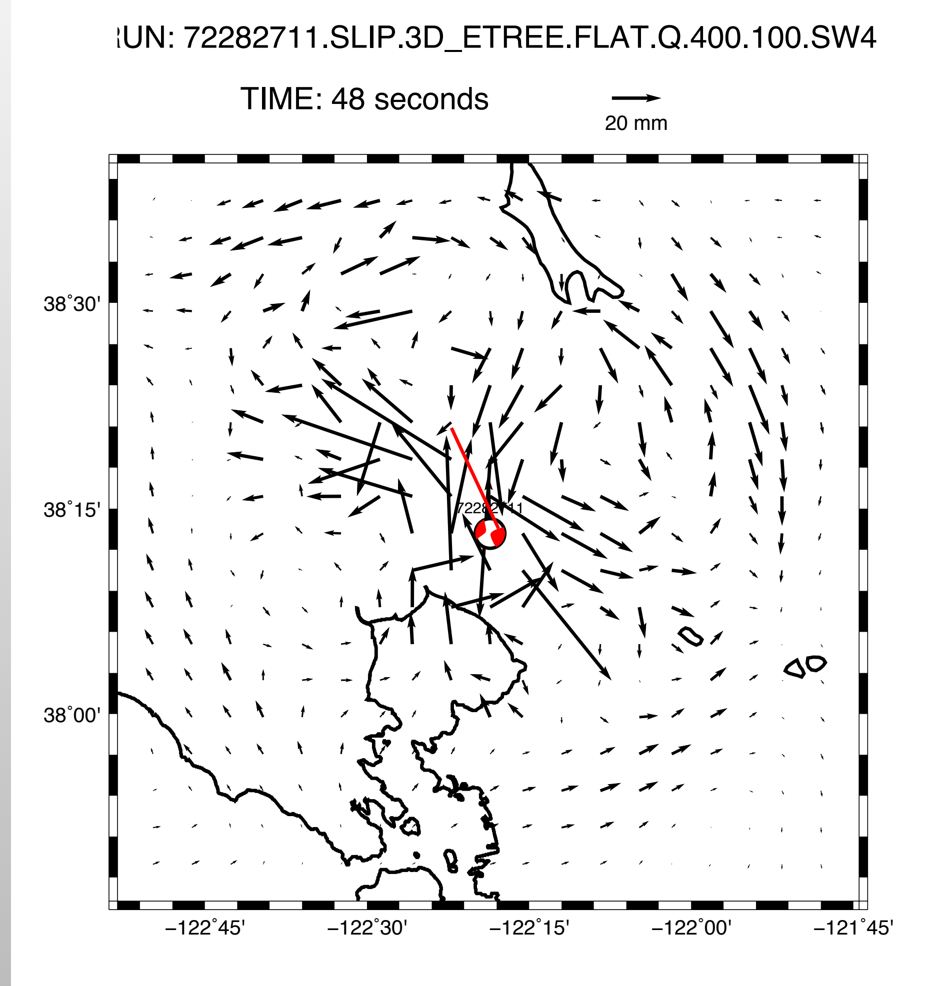


Path across San Pablo Bay
is well fit by 3D model!

Station NC.NCC

Observed (GPS, left) & simulated (right) horizontal displacements





Conclusions on simulations of recent South Napa earthquakes

- Initial comparison of observed and simulated seismograms looks very encouraging
  - Dreger source model looks good for frequencies < 1 Hz
  - 3D paths effects are important
  - Paths to the south are not well fit by 3D model, possibly due to basin-edge effect
- Modeling M_W 3.9 aftershock shows that the 3D model can fit quite well, but may need adjustments
- Fits for paths crossing San Pablo Bay are well fit for both mainshock and aftershock

Further work is needed …

- Investigate different rupture models, including variations/ perturbations of Doug's model
  - Are there other rupture models to consider?
    - e.g. from strong motion, geodetic, teleseismic data?
- Simulate more aftershocks to evaluate 3D model
  - Re-visit aftershock mechanisms
- Make more quantitative measures of goodness-of-fit
  - e.g. waveform misfit, PGV, Sa, etc…
- Compare geodetic displacements (obs. & sim.)
- Consider computing 3D Greens functions for source inversion for local strong motion and static displacements
- Improve USGS 3D model through waveform tomography

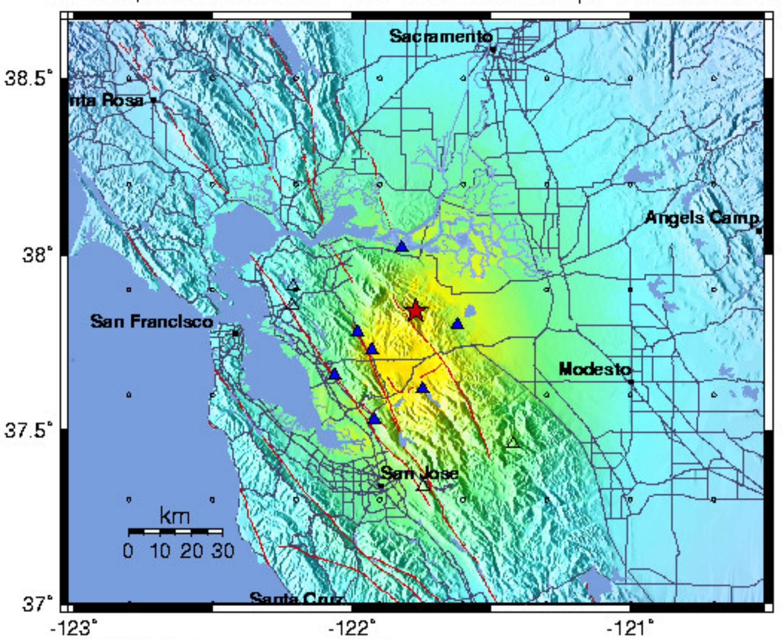
What about seismic hazard at LLNL …

- "Livermore earthquakes" on Greenville Fault caused $10M damage ($11 M total)
  - January 1980 M 5.8 and 5.6 earthquakes
  - Simulations of these events with modern tools, validation would be very interesting
- Could LLNL benefit from EEW?
  - How could warning time be reduced?
    - Seismic network improvements
    - Notification alert through cell phones

Jan. 24 1980 Livermore ruptured toward LLNL

CISN Rapid Instrumental Intensity Map for Livermore Earthquake

Thu Jan 24, 1980 11:00:08 AM PST M 5.6 N37.84 W121.77 Depth: 10.5km ID:Livermore



PROCESSED: Mon Jun 23, 2003 11:15:52 AM PDT,

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+