Introduction

Utah Ground-Shaking Working Group

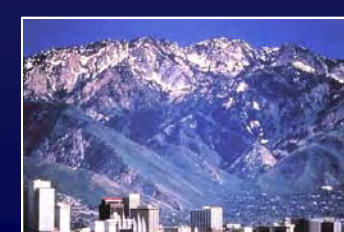
Ivan G. Wong
Seismic Hazards Group
URS Corporation
Oakland, CA 94612

Greg McDonald
Utah Geological Survey
Salt Lake City, UT

Annual Meeting #8   8 February 2010

2004 GSWG Plan

- Develop a community velocity model (CVM)
  - V_S30, R1, R2
- Evaluate seismic source and propagation path characteristics of Utah earthquakes, and site amplification and geotechnical characteristics of Utah soils
  - Stress drops, slip distributions, rupture processes
  - Hanging wall effects and directivity
  - Q and kappa
  - Non-linear dynamic soil properties



2004 GSWG Plan (cont.)

- Perform 3D modeling using CVM to evaluate the importance of basin structure on strong ground motions
  - Depth to R2, basin-edge/steep boundary effects
- Prepare large-scale Wasatch Front ground-shaking maps
  - Incorporate site conditions and basin effects

Results of 2009 Meeting: Priorities for 2010 Research

- Continue to test CVM with different dynamic and kinematic ground motion modeling approaches.
- Assess whether additional V_S data will improve CVM.
- Form working sub-groups to use the validated CVM to develop near-surface site-amplification and basin models.
- Provide a simple test case suggested by Mark Petersen with specific parameters to compare modeling results.

Goals of the 2010 Meeting

- Present results of 2009 research.
- Discuss progress on CVM refinement.
- Give updates on on-going projects summarized in previous meetings.

Goals of the 2010 Meeting (cont.)

- Finalize plans to prepare Wasatch Front urban seismic hazard maps
  - Characterize earthquake sources
  - Develop site-amplification and basin models
  - Prepare maps
- Identify 2011 research priorities

Agenda

7:00 – 7:30	Continental Breakfast	
7:30 – 7:45	Introduction Overview of Meeting Review of Last Year's Priorities	Ivan Wong
7:45 – 8:00	Analysis of ANSS Data for Stress Drop and Kappa	Ivan Wong
8:00 – 8:15	Sonic Log Analyses for the Wasatch Front CVM	Jim Pechmann
8:15 – 8:30	Update on Modifications to Community Velocity Model (CVM)	Harold Magistrale
8:30 – 9:00	Wasatch Front CVM - Versions in Use by Modelers/Effects on Results - Distribution of Model - Future Updates	Greg McDonald
9:00 – 11:00	Presentation/Discussion of Different Wasatch Front Ground Motion Models	
9:00 – 9:10	- USGS Plans for Analysis of the CVM	Morgan Moschetti/ Mark Petersen
9:10 – 9:20	- 3D Nonlinear Earthquake Ground Motion Simulation in the Salt Lake Basin Using the Wasatch Front CVM	Jacobo Bielak
9:20 – 9:50	- Ground Motions in Salt Lake Basin from Dynamic Modeling of a **M** 7 Earthquake on the Wasatch Fault	Ralph Archuleta/ Bob Smith
9:50 – 10:00	Break	
10:00 – 10:45	- 3D Nonlinear Broadband Ground Motion Predictions for **M** 7 Earthquakes on the Salt Lake City Segment of the Wasatch Fault Using Dynamic Source Models	Kim Olsen/Daniel Roten
10:45 – 11:00	- Modeling Near-Surface Effects	Ivan Wong
11:00 – 12:00	USGS perspective - Comparison of Models/Differences - Applicability for Urban Hazard Maps, Direction of Modeling, and Priorities for Future Research	Mark Petersen
12:00	Adjourn	

Analysis of ANSS Data for Stress Drop, Q(f), and Kappa

Utah Ground Motion Working Group

Ivan Wong
Seismic Hazards Group
URS Corporation
Oakland, CA

Jim Pechmann
Dept. of Geology and Geophysics
University of Utah
Salt Lake City, UT

Bob Darragh and Walt Silva
Pacific Engineering & Analysis
El Cerrito, CA

Danielle Lowenthal-Savy and Fabia Terra
Seismic Hazards Group
URS Corporation
Oakland, CA

Salt Lake City, UT
8 February 2010

Introduction

- Objective: To evaluate the critical factors that control ground shaking hazard along the Wasatch Front: stress drop, kappa, and crustal attenuation.
- Some previous studies have suggested that ground motions in an extensional regime such as the Basin and Range Province may be lower than in California for the same magnitude and distance.
- The inference was that this difference may be due to the lower stress drops of extensional earthquakes compared to compressional earthquakes as first suggested by McGarr (1984).

Background

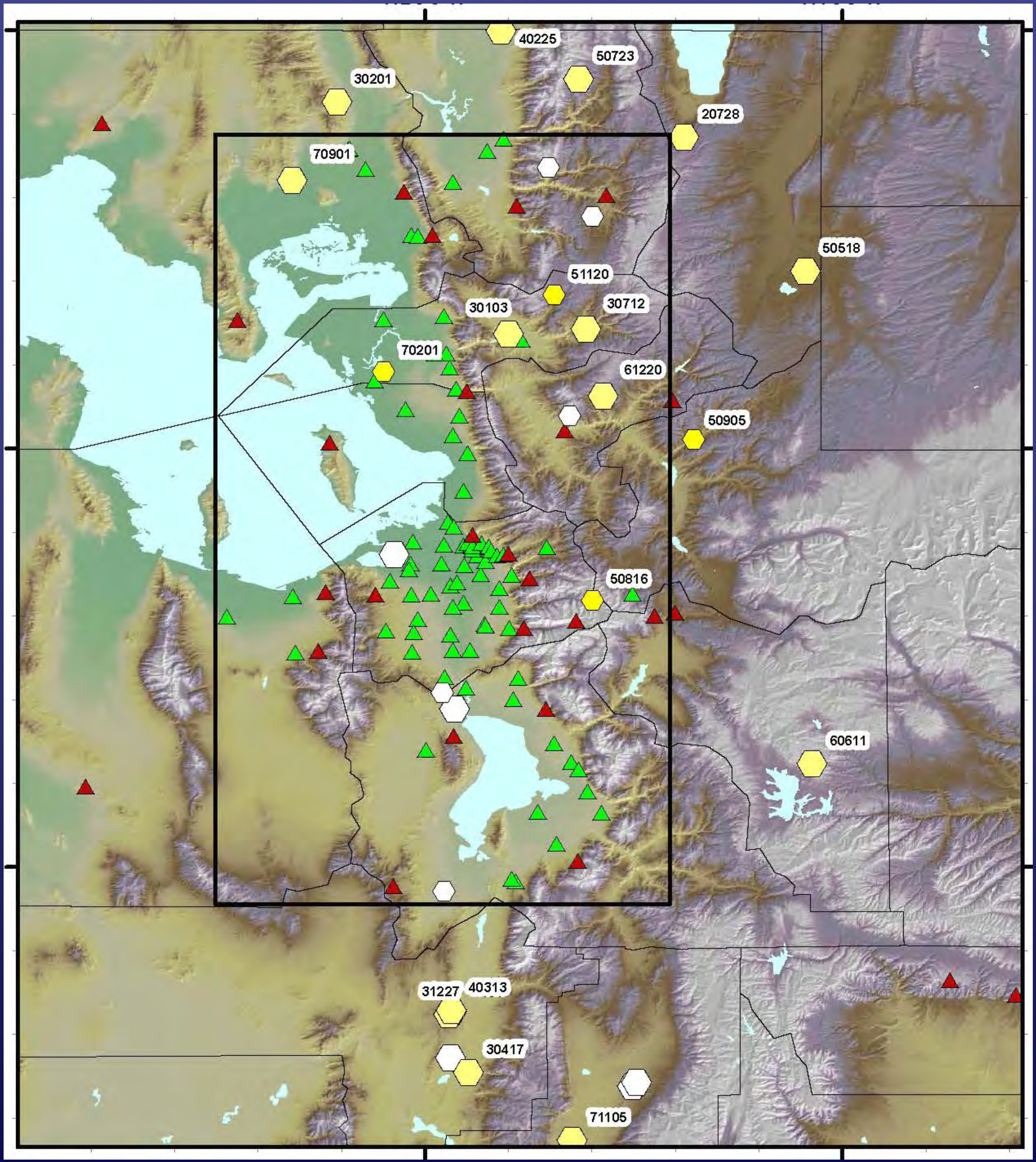
- No systematic evaluation of earthquake stress drops has been performed for earthquakes along the Wasatch Front.
- No studies have been performed to evaluate the variability in kappa in the central Wasatch Front. Kappa can have a very significant effect on high-frequency ground motions with lower values of kappa resulting in larger high-frequency ground motions.
- Only a few studies to estimate Q(f) for the Wasatch Front (Brockman and Bollinger, 1992; Jeon and Herrmann, 2004) have been performed.

Scope of Work

- To analyze the available strong motion and broadband data from ANSS stations in the central Wasatch Front region for stress drop, kappa, and Q(f).

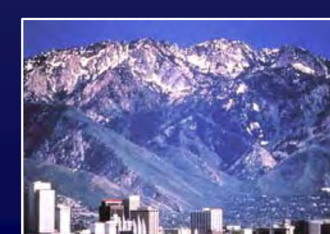
- The approach uses an inversion scheme developed by Walt Silva. In the inversion scheme, earthquake source, path and site parameters are obtained by using a nonlinear least-squares inversion of Fourier amplitude spectra.

Earthquakes Being Evaluated



Earthquakes to be Analyzed

- Total of 17 events
- Period: May 2001 to November 2007
- Magnitude Range: **M** 3.0 to 4.2
- Number of stations recording events: 18 to 68



Scope of Work

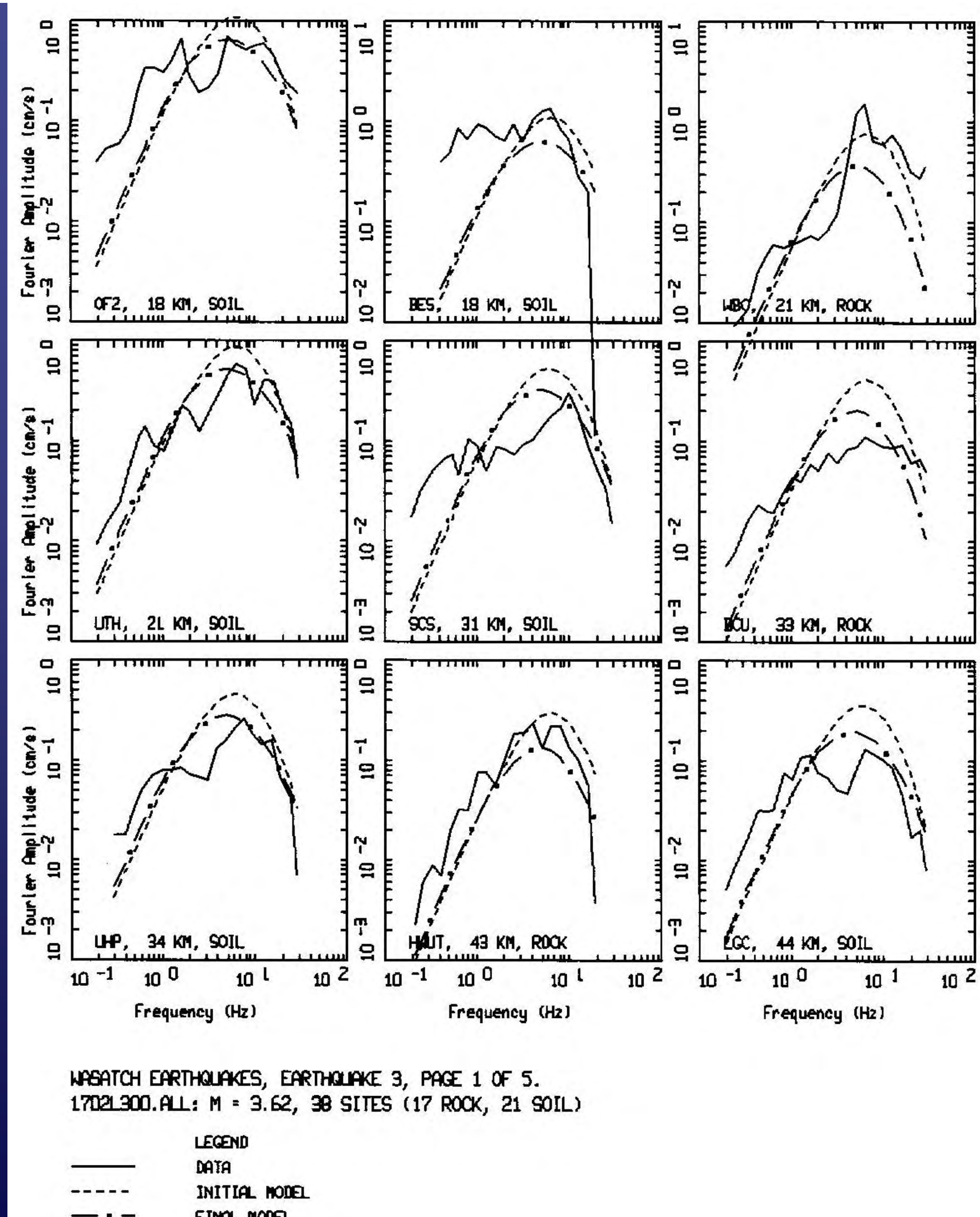
- Steps involved in analyses are:

  1) windowing and calculation of Fourier amplitude spectra of each of the recordings;

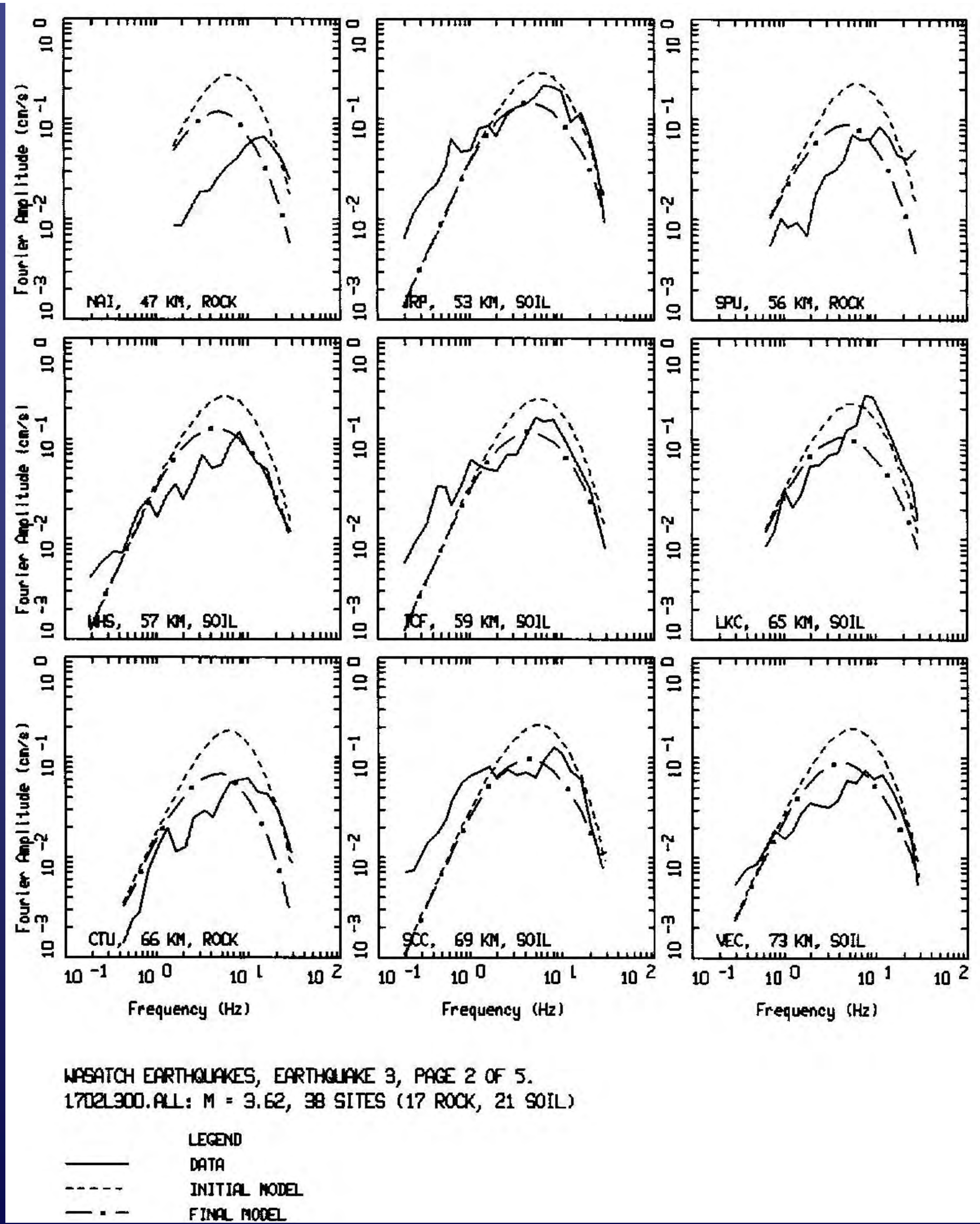
  2) inversion of the recordings for each earthquake for stress drop, kappa plus a frequency-independent amplification factor, and Q(f); and

  3) evaluation of the results.

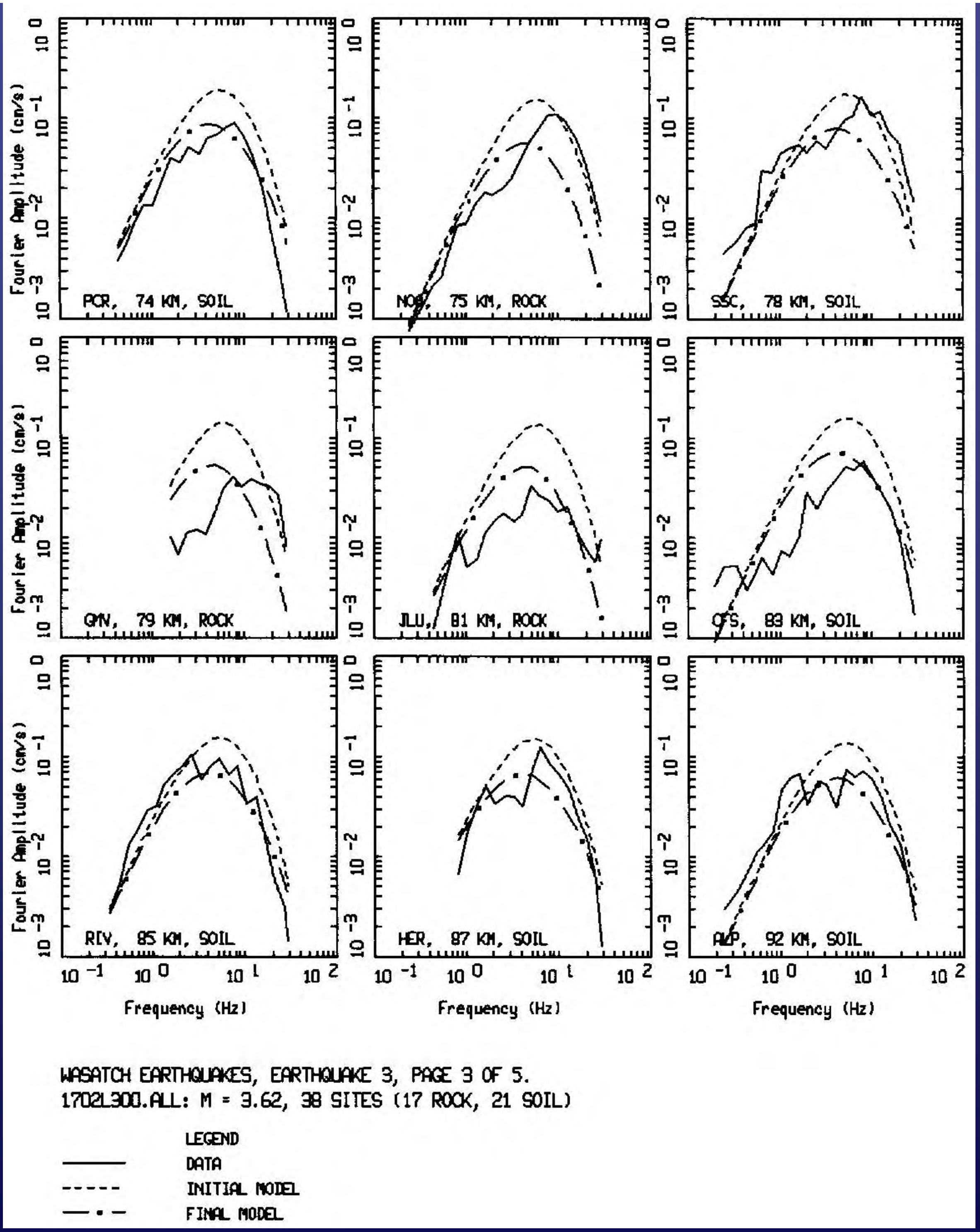
Preliminary Inversion Results



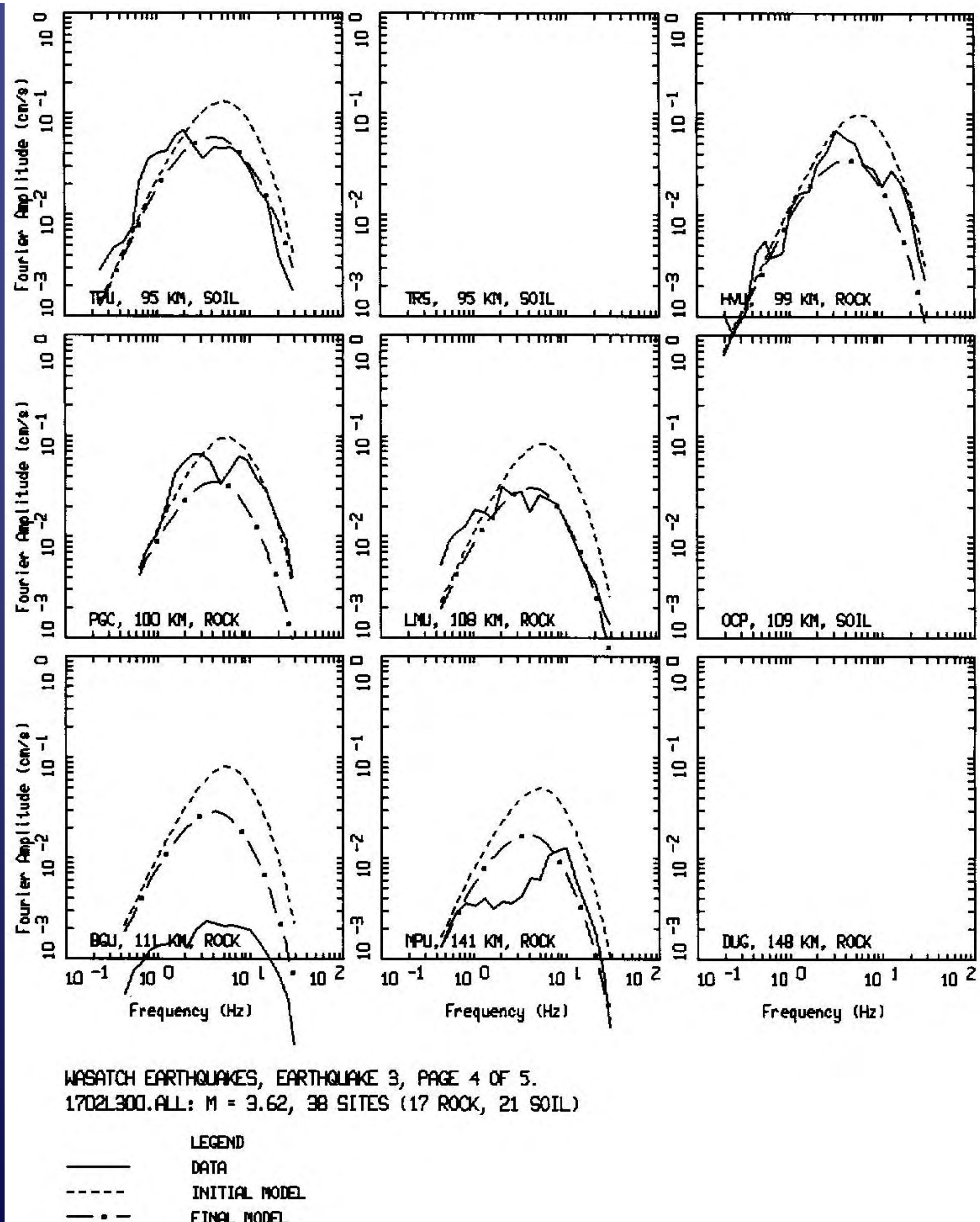
Preliminary Inversion Results



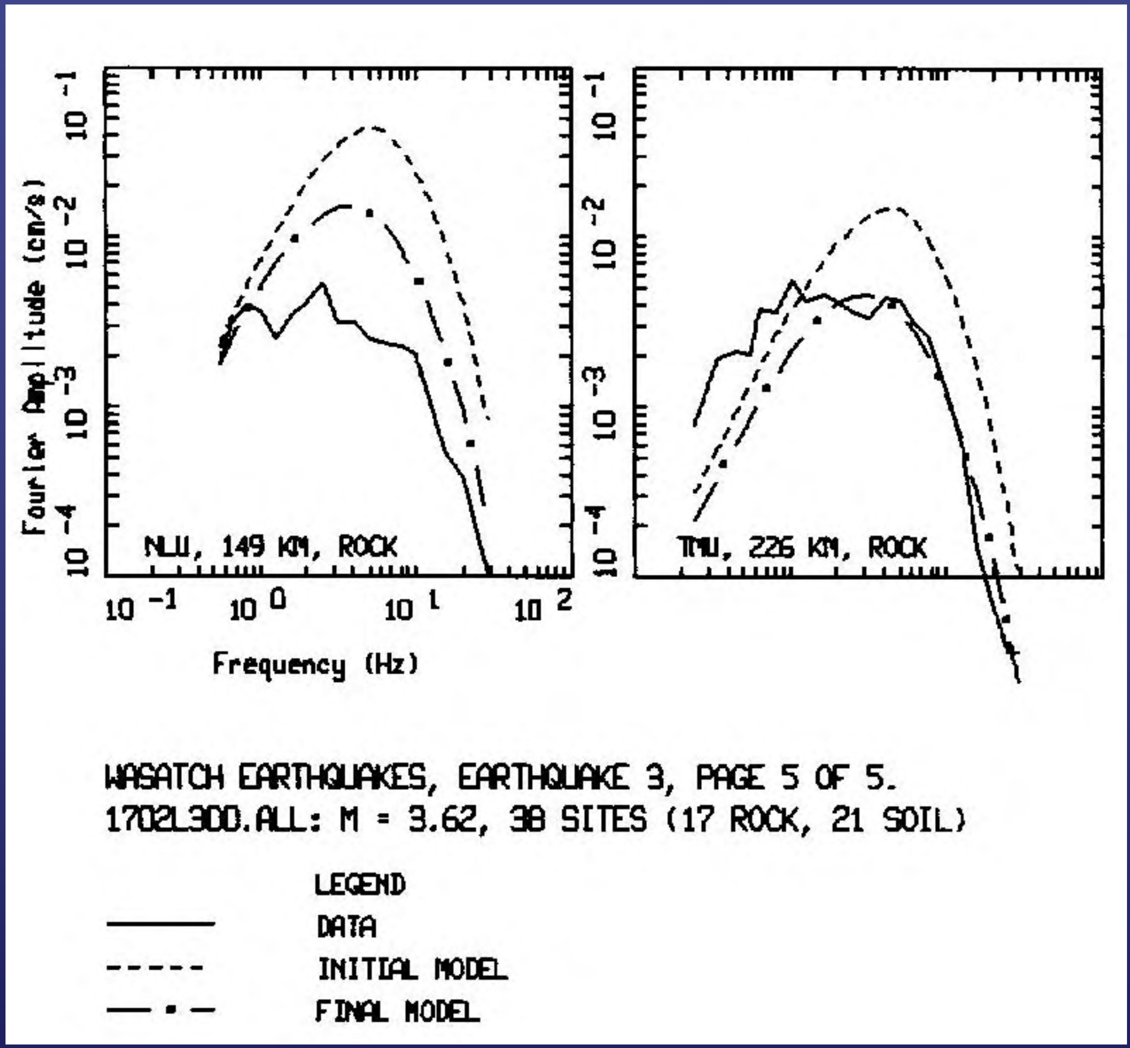
Preliminary Inversion Results



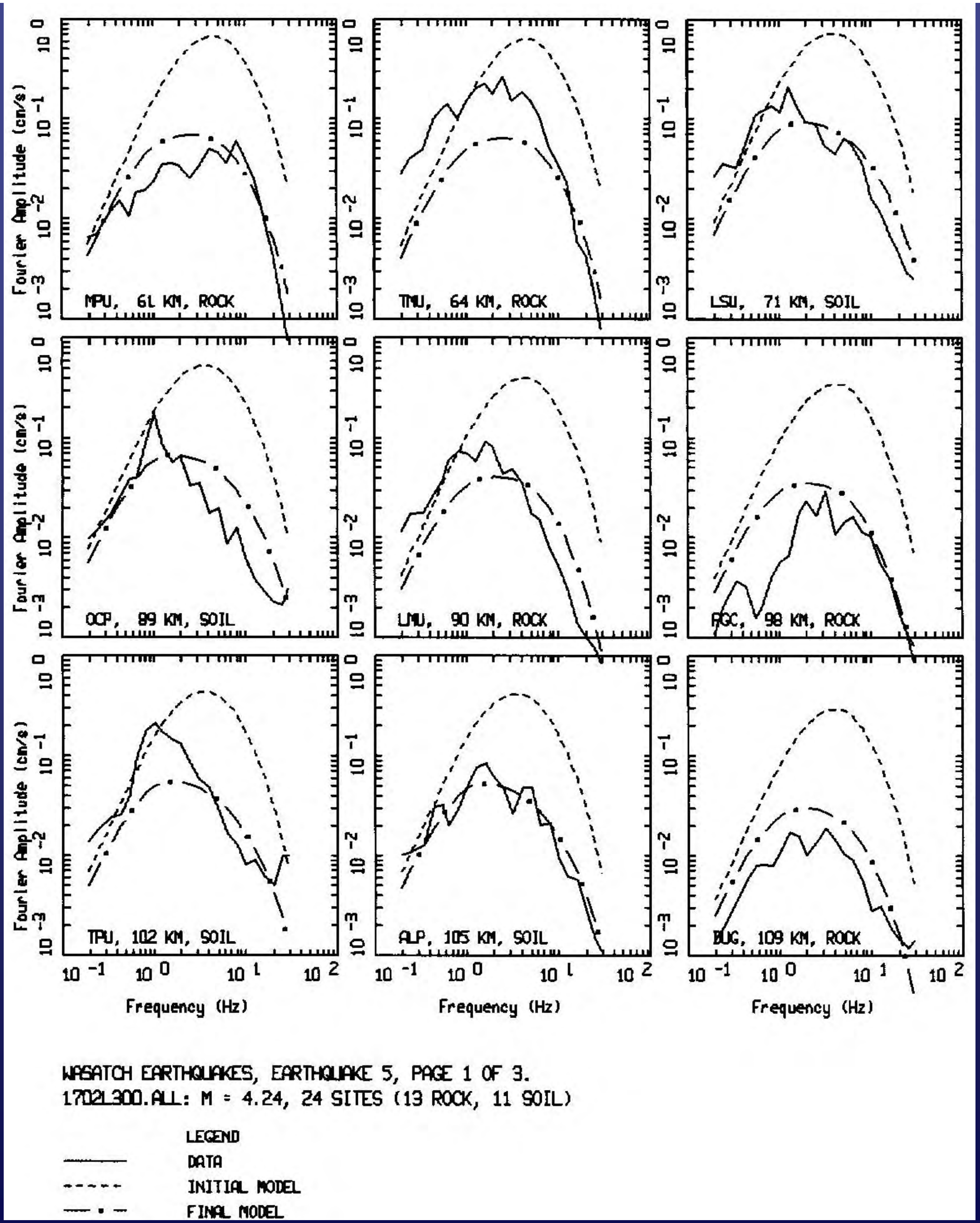
Preliminary Inversion Results



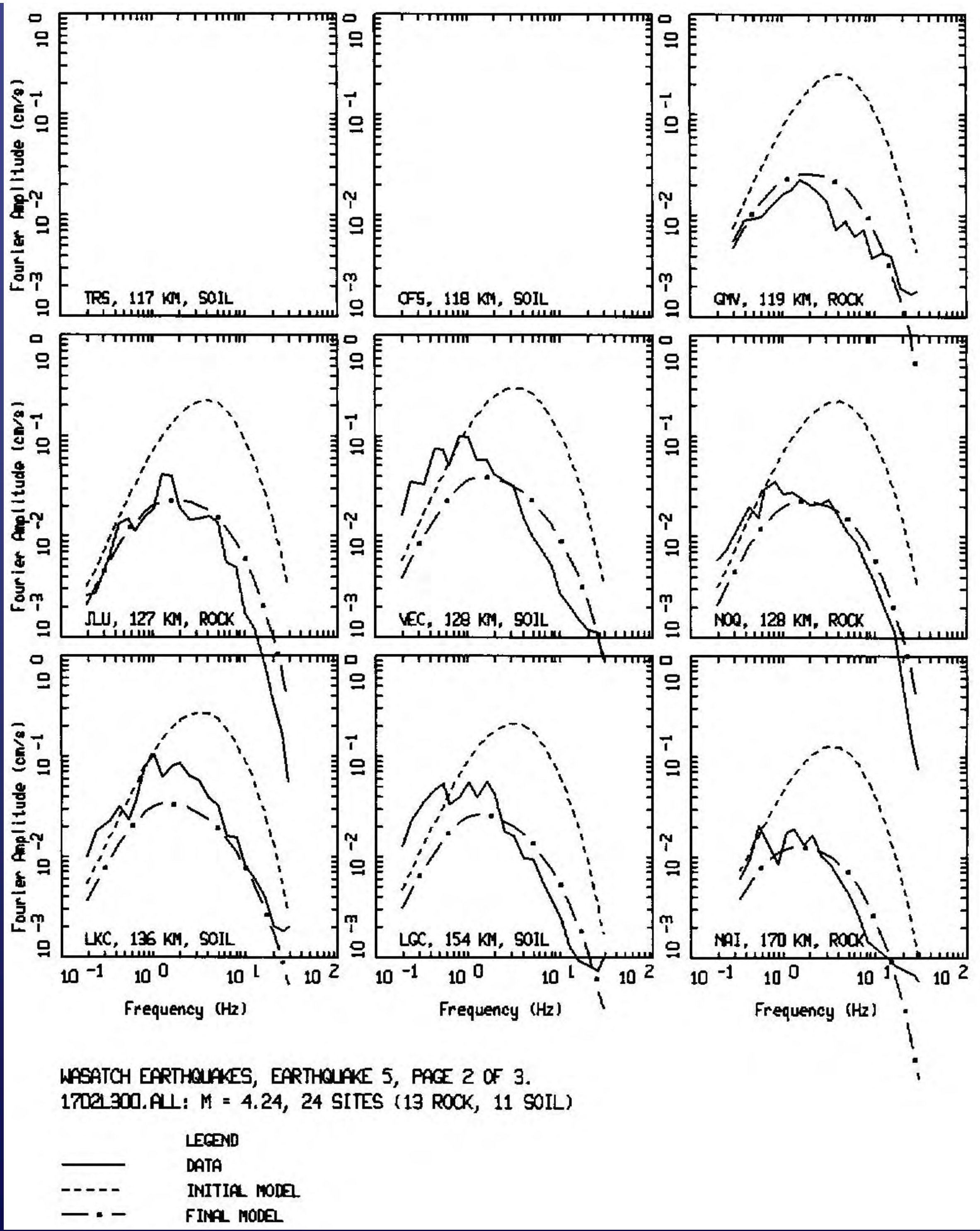
Preliminary Inversion Results



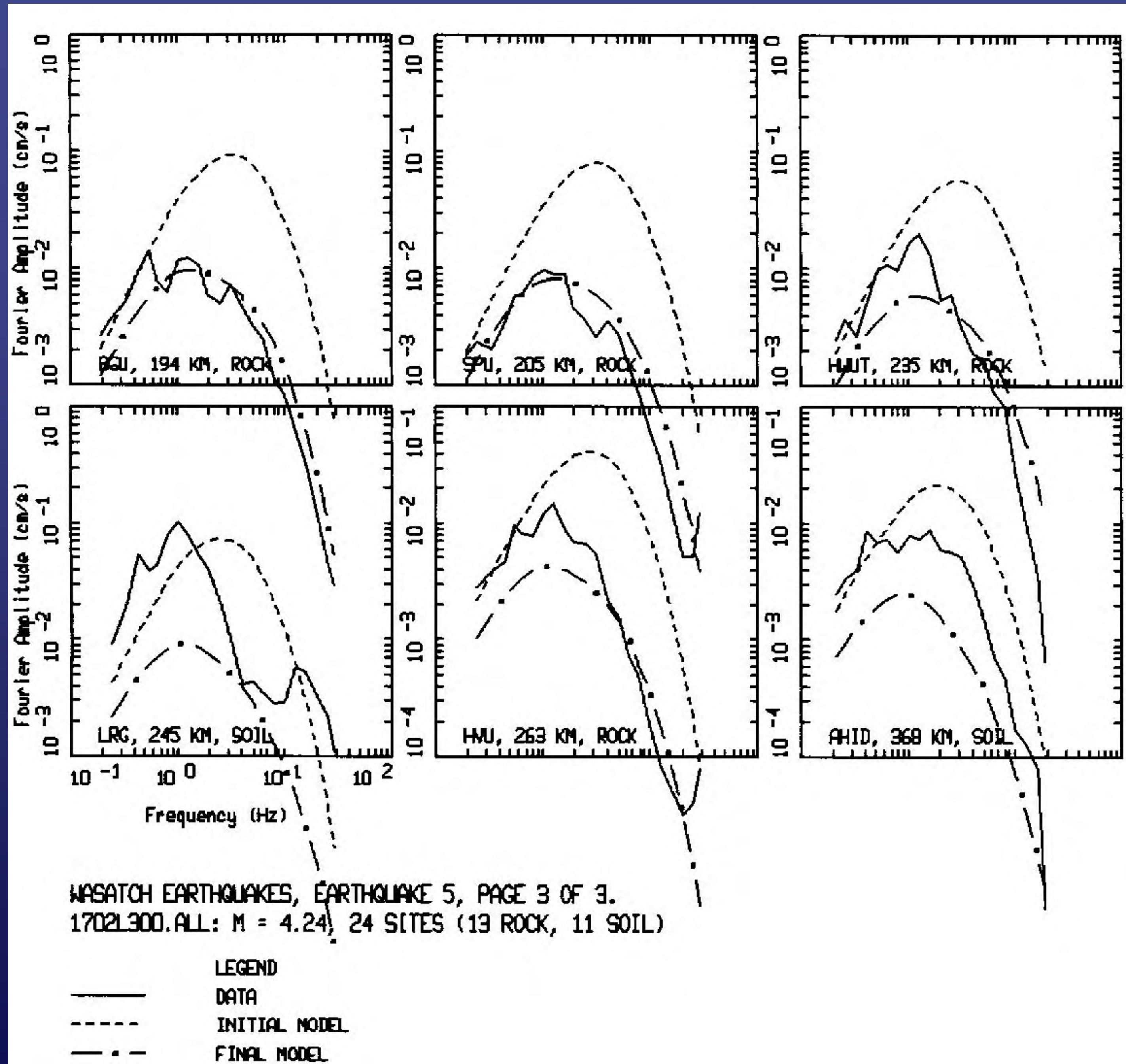
Preliminary Inversion Results



Preliminary Inversion Results



Preliminary Inversion Results



Preliminary Results

Event	Date	Event ID	Magnitude	Depth (km)	$\Delta\sigma$ (bars)
1	20010524	10524024041	3.30	5.86	4.47
2	20020728	20728193840	3.59	9.25	2.54
3	20030103	30103050212	3.62	11.7	12.5
4	20030201	30201203731	3.15	0.22	2.78
5	20030417	30417010419	4.24	0.08	2.69
6	20030712	30712015440	3.50	8.97	12.95
7	20031227	31227003924	3.64	0.88	7.12
8	20040225	40225004104	3.38	1.68	14.36
9	20040313	40313130447	3.17	1.77	3.78
10	20050518	50518192147	3.29	1.56	3.39
11	20050723	50723053748	3.30	11.07	35.25
12	20050905	50905093155	3.00	7.41	5.88
13	20051120	51120102429	2.62	2.77	14.26
14	20060611	60611100150	3.41	10.37	6.43
15	20061220	61220181536	3.35	7.94	32.56
16	20070901	70901183202	3.92	5.61	3.50
17	20071105	71105214801	3.91	5.5	7.36

Q_o = 103.44
η = 0.69
κ (sec) = 0.039 rock, 0.028 soil; $\bar{\kappa}$(sec) = 0.033
$\overline{\Delta\sigma}$ (bars) = 7.09, σ_{ln} = 0.83

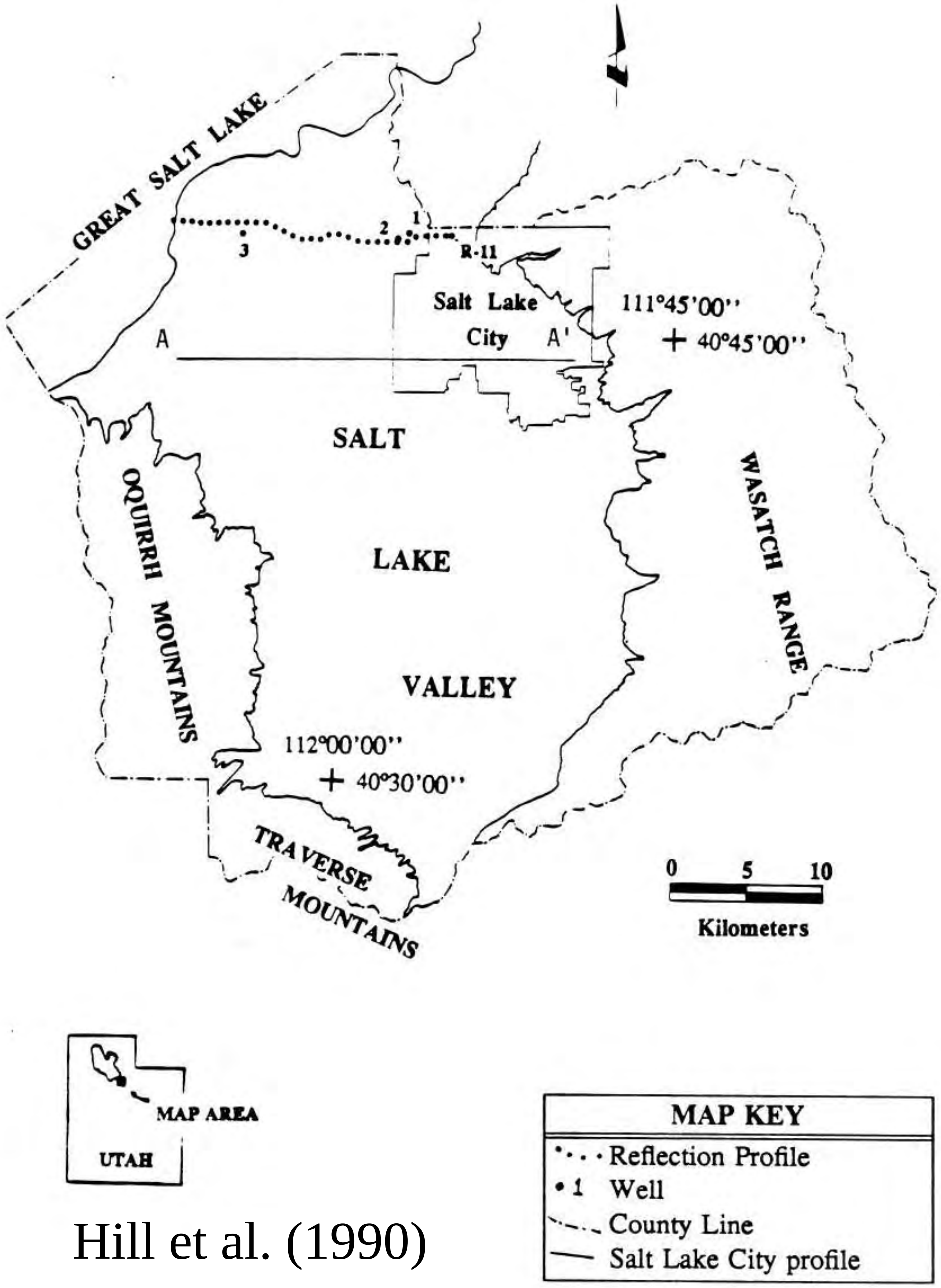
Sonic Log Analyses for the Wasatch Front Community Velocity Model

by

James C. Pechmann, Kevin J. Jensen
University of Utah, Salt Lake City, Utah

and Harold Magistrale
FM Global, Norwood, MA

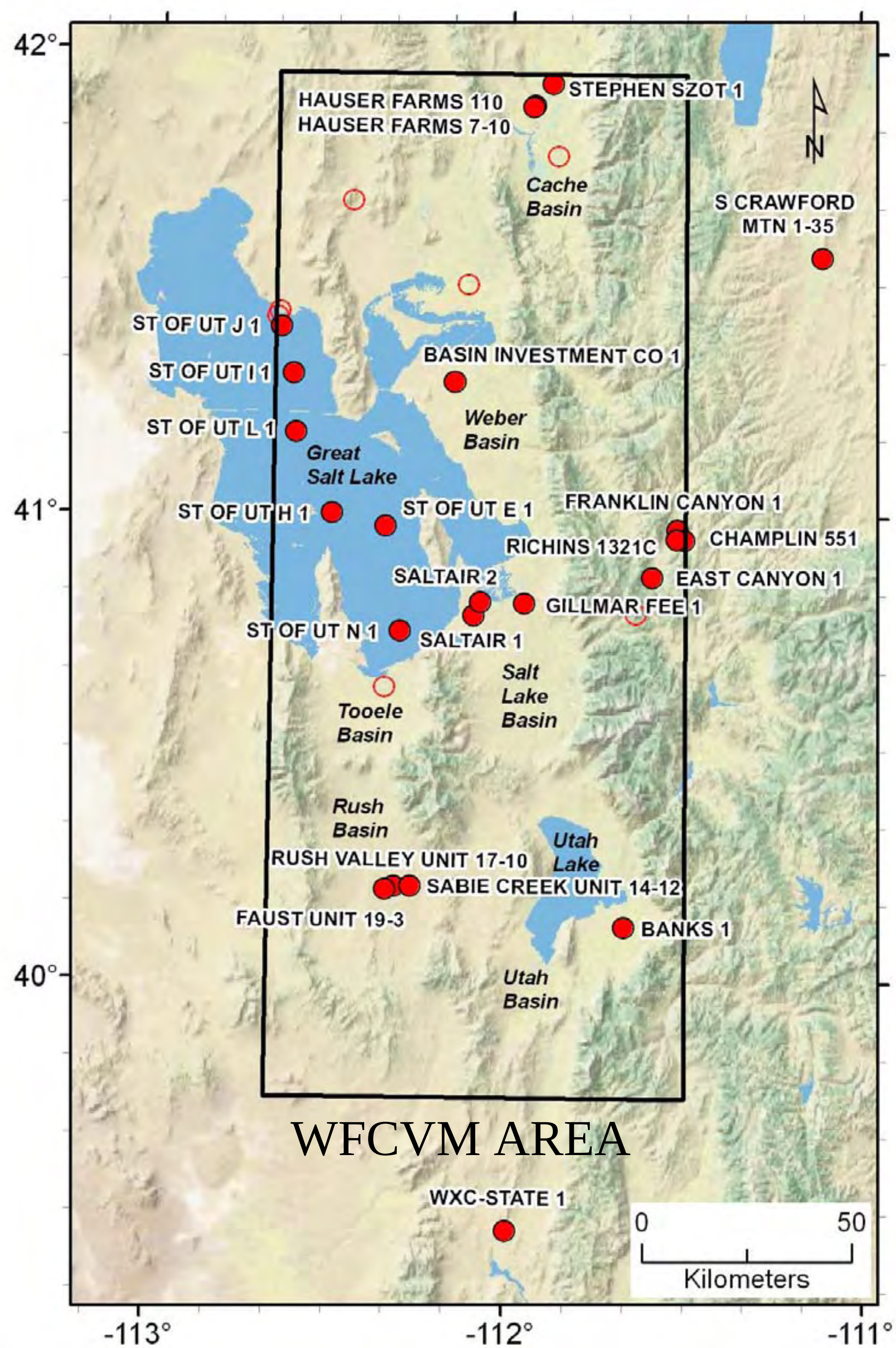
SALT LAKE BASIN MODEL (Hill et al., 1990)
Unconsolidated Quaternary Sediments R1
Semiconsolidated Tertiary Sediments R2
Tertiary Sedimentary Rocks R3
Basement



Hill et al. (1990)

Hill et al. (1990) model based on:

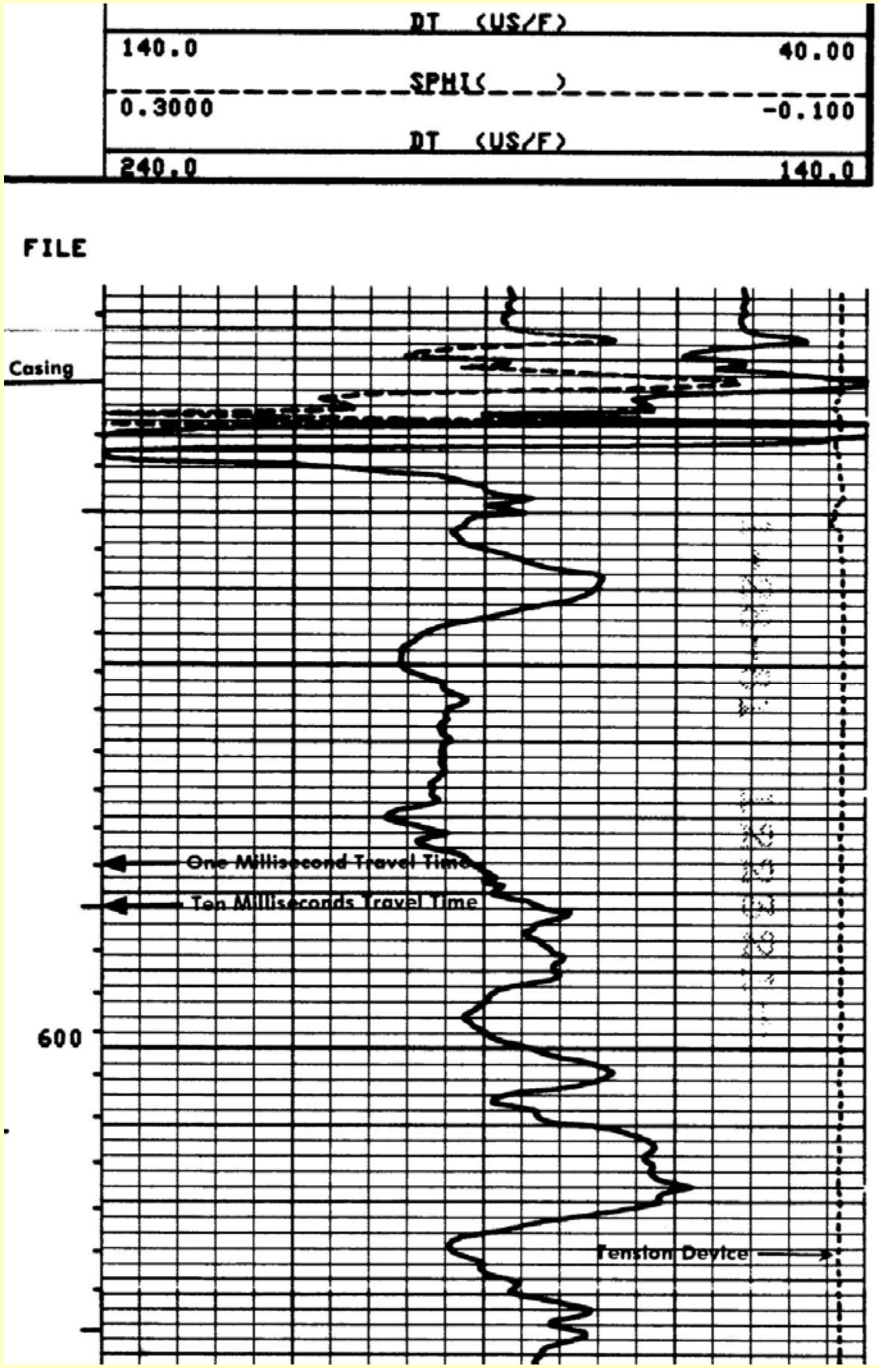
- **Two sonic logs (2 and 3)**
- **Three density logs (1-3)**
- **One seismic reflection profile (dotted line)**

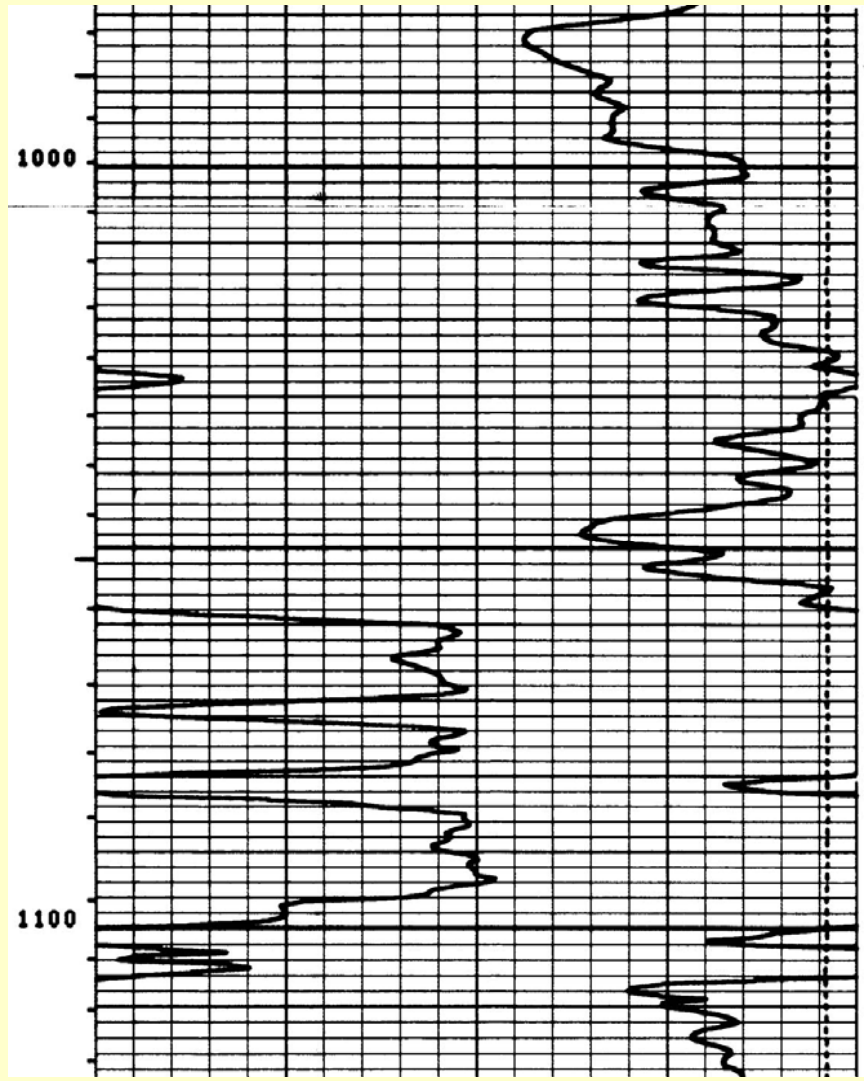


Sonic Logs Used in This Study

- 17 from wells in Quaternary basins in WFCVM area
- 7 from wells on bedrock (3 outside WFCVM area)
- Maximum depths of 0.9 to 5.3 km; median of ~2 km.

Samples of Sonic Logs
Stephen Szot 1 Well:
API No. 4300530009

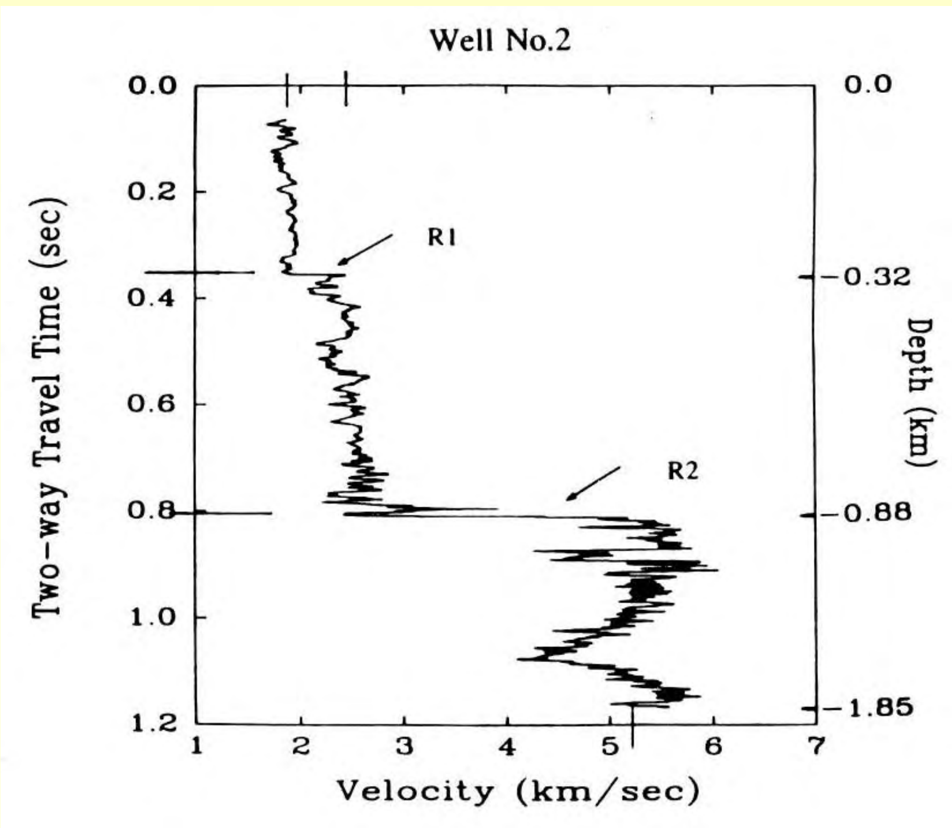


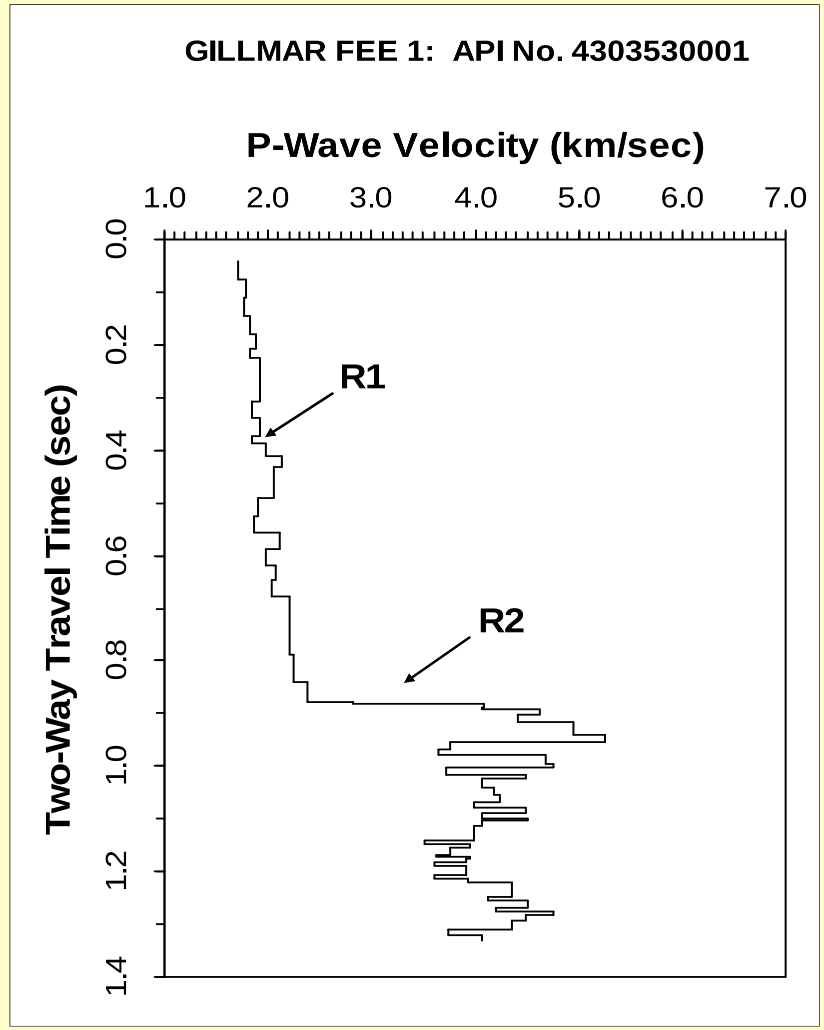


Gillmar Fee 1 Well: Sonic Log Profiles

This Study

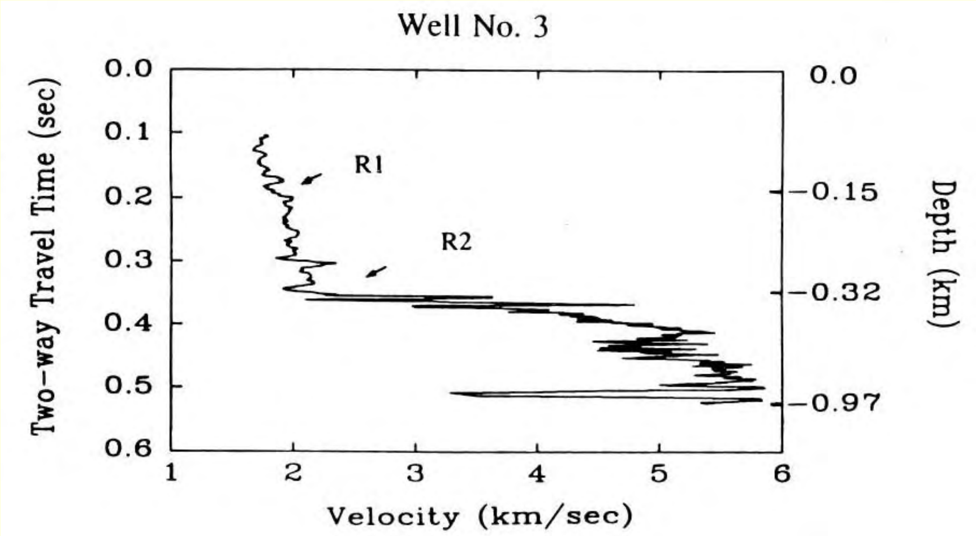
Hill et al. (1990)



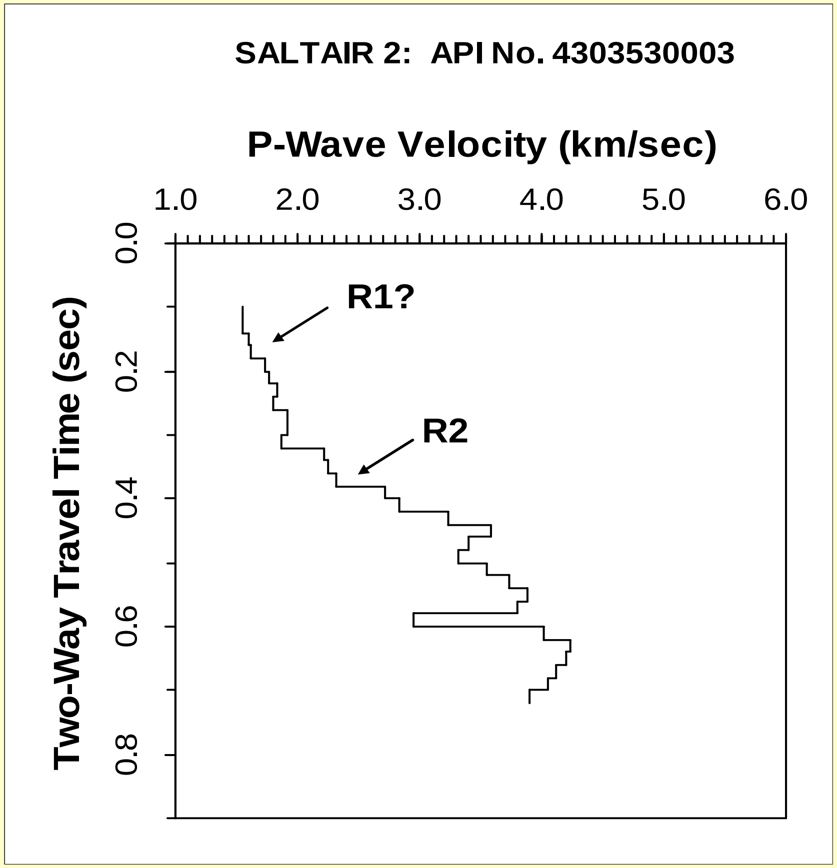


Saltair 2 Well: Sonic Log Profiles

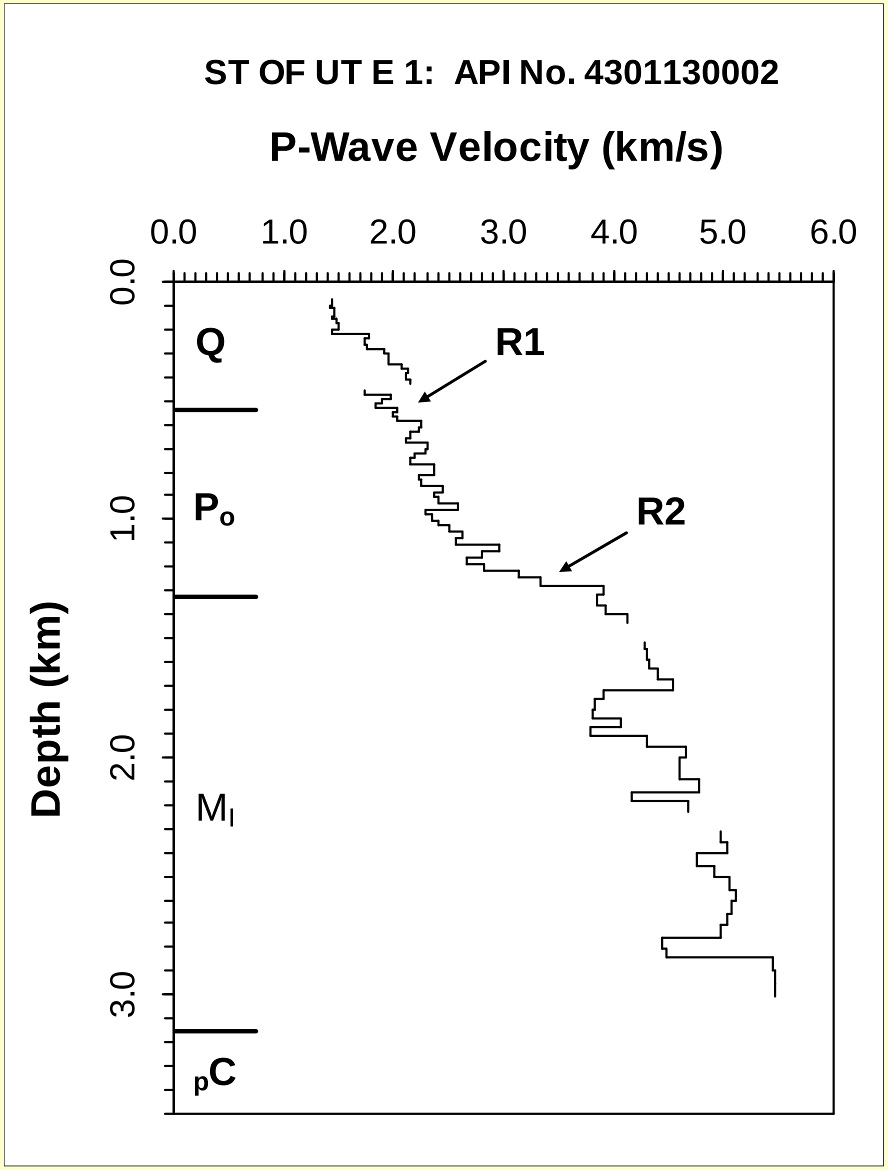
Hill et al. (1990)

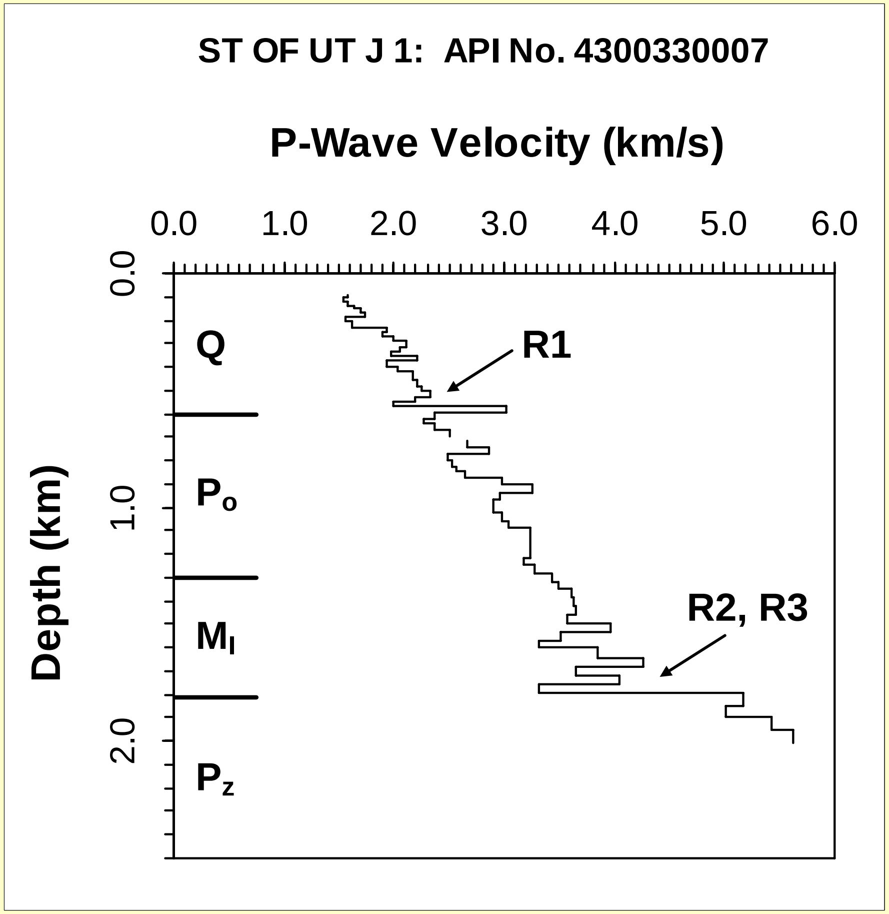


This Study



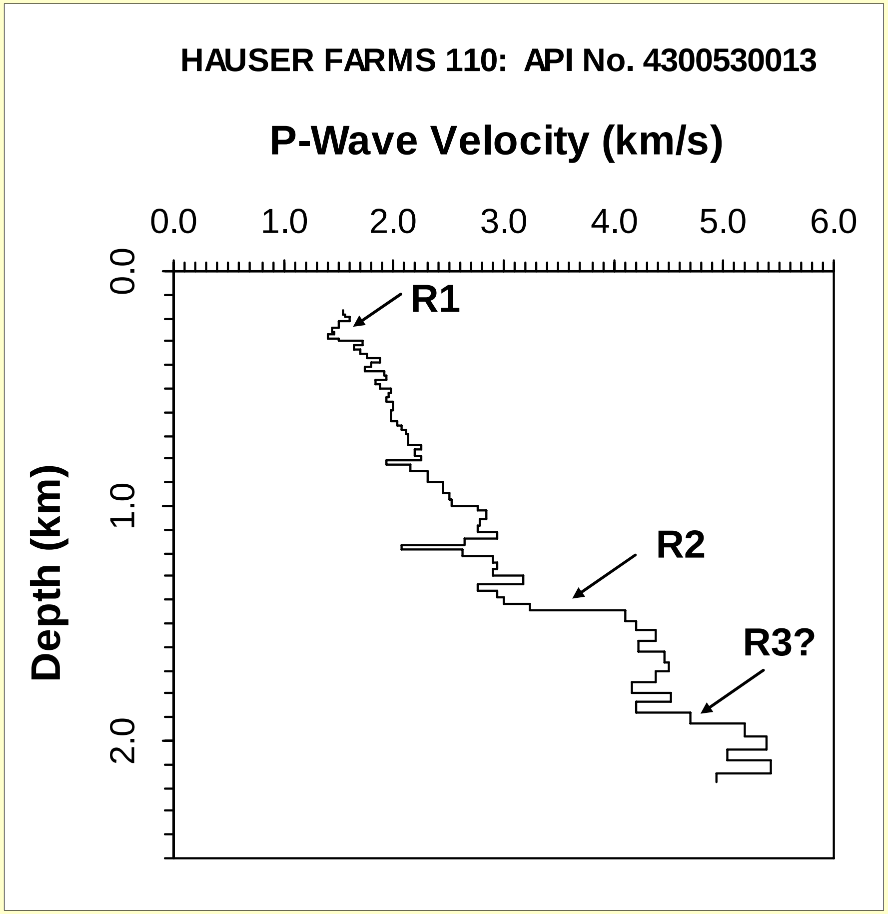
Sample Sonic Log Profiles: Great Salt Lake

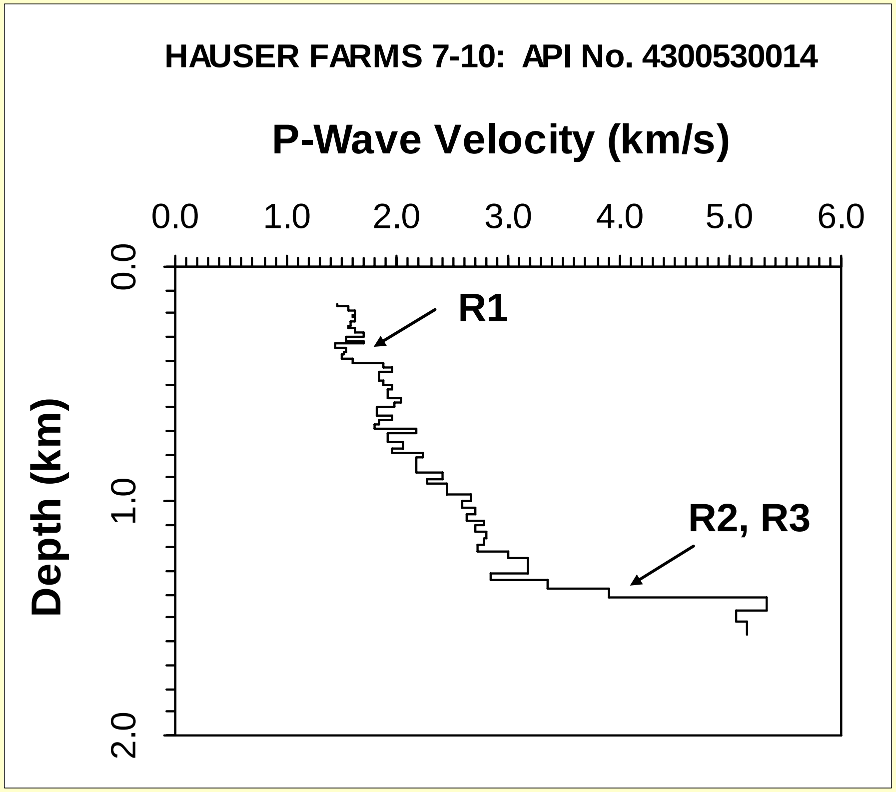


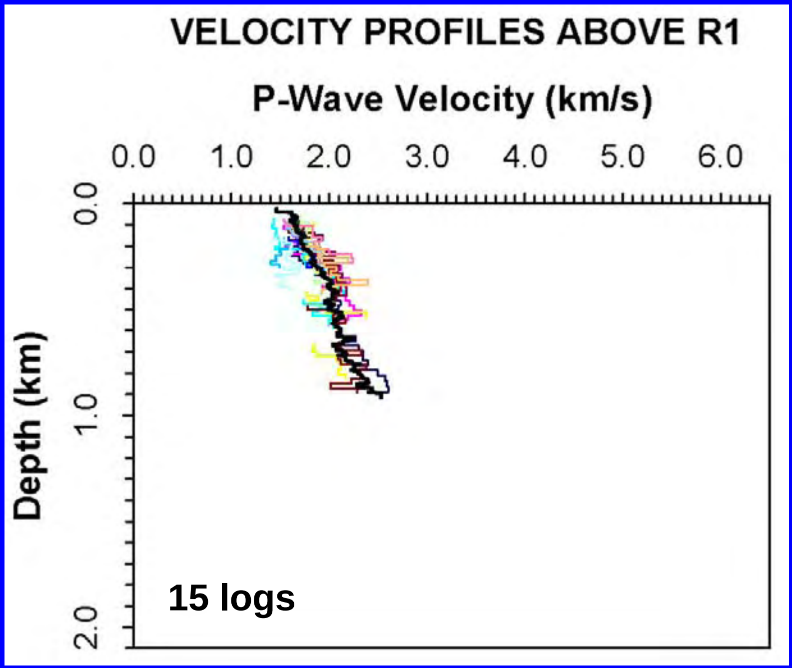


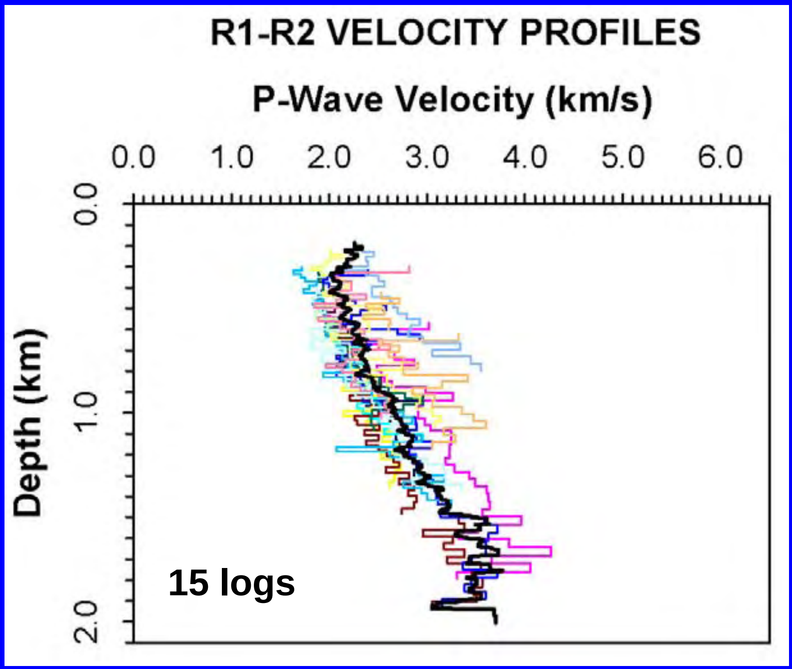
Stratigraphic boundaries from Amoco palynology studies (Viveiros, 1986)

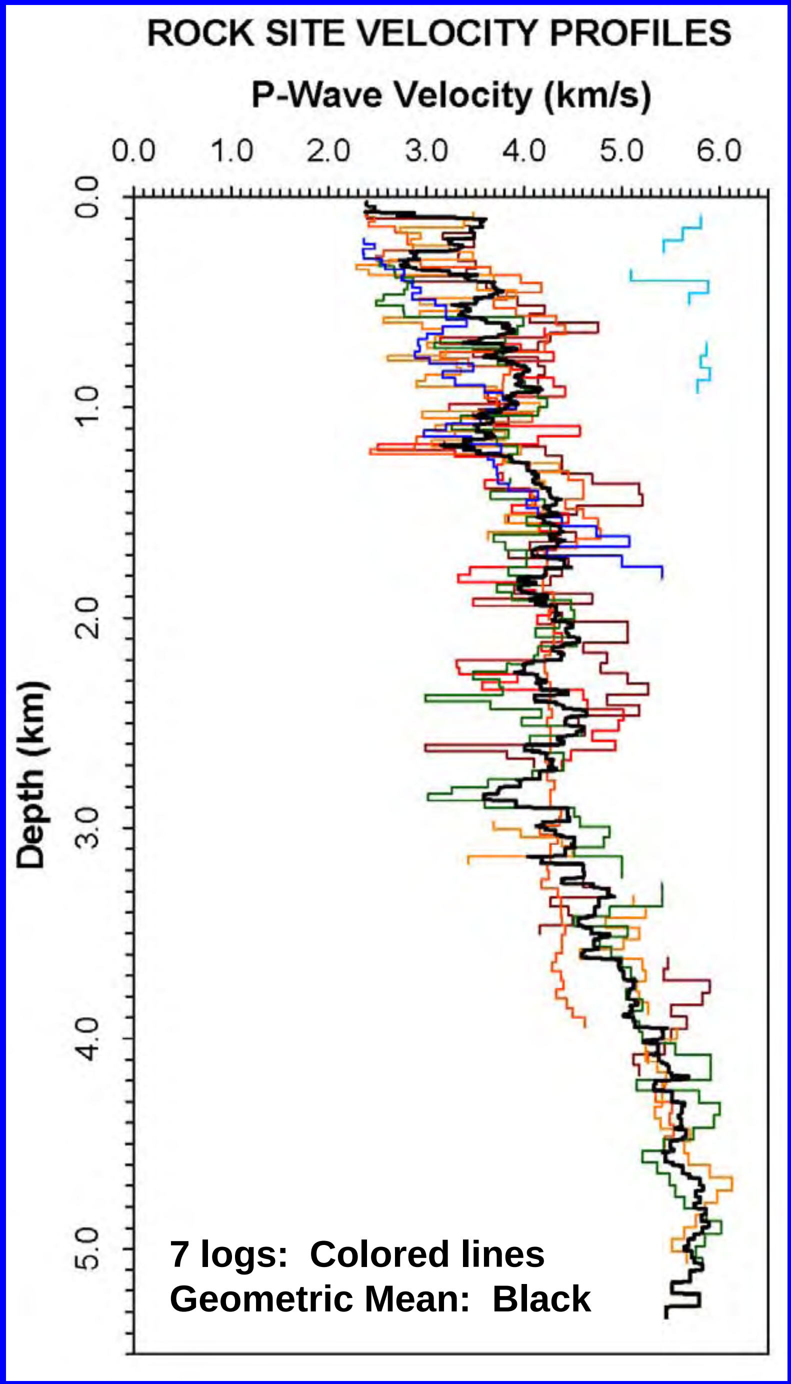
Sample Sonic Log Profiles: Cache Valley

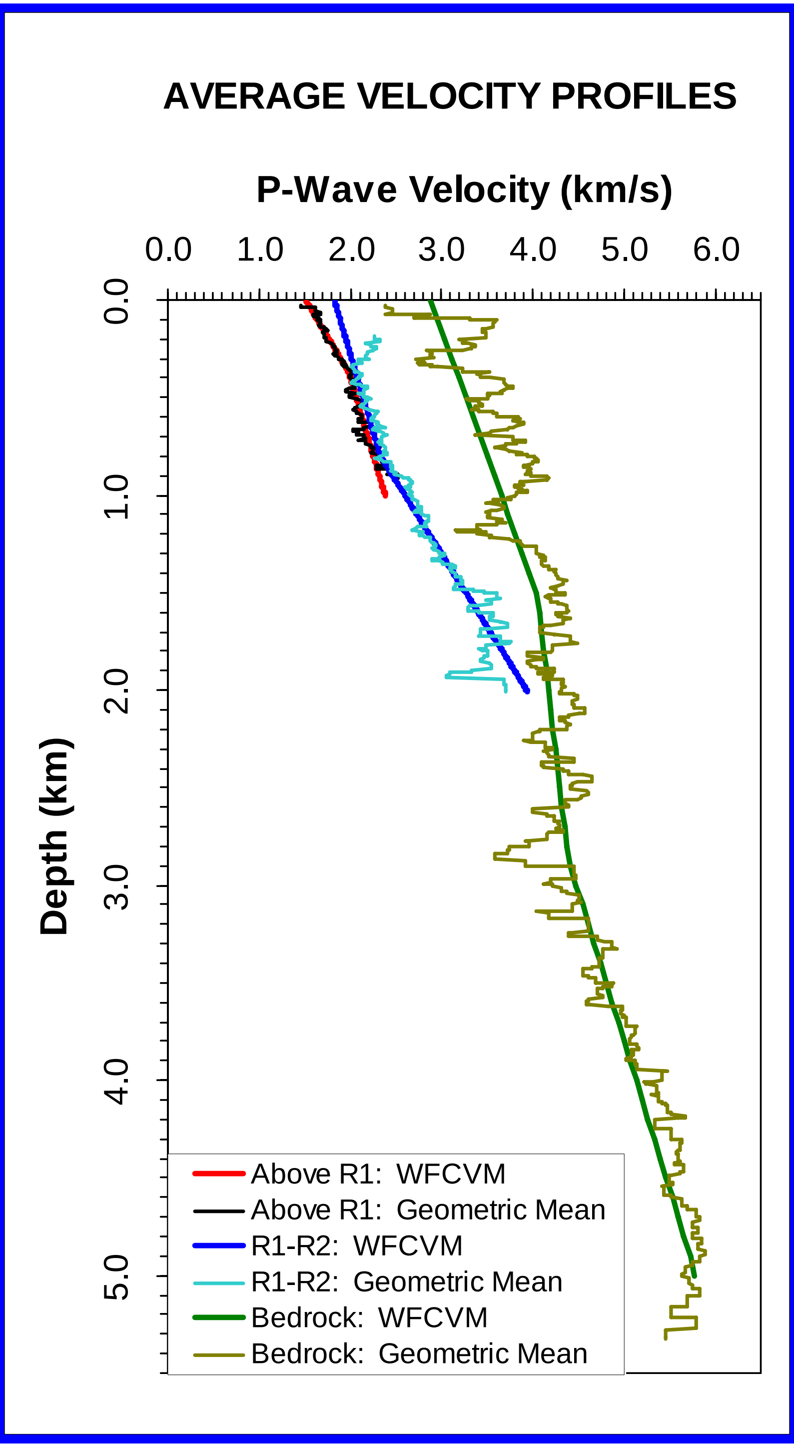





VELOCITY PROFILES ABOVE R1
P-Wave Velocity (km/s)
0.0 1.0 2.0 3.0 4.0 5.0 6.0
Depth (km)
0.0 1.0 2.0
15 logs

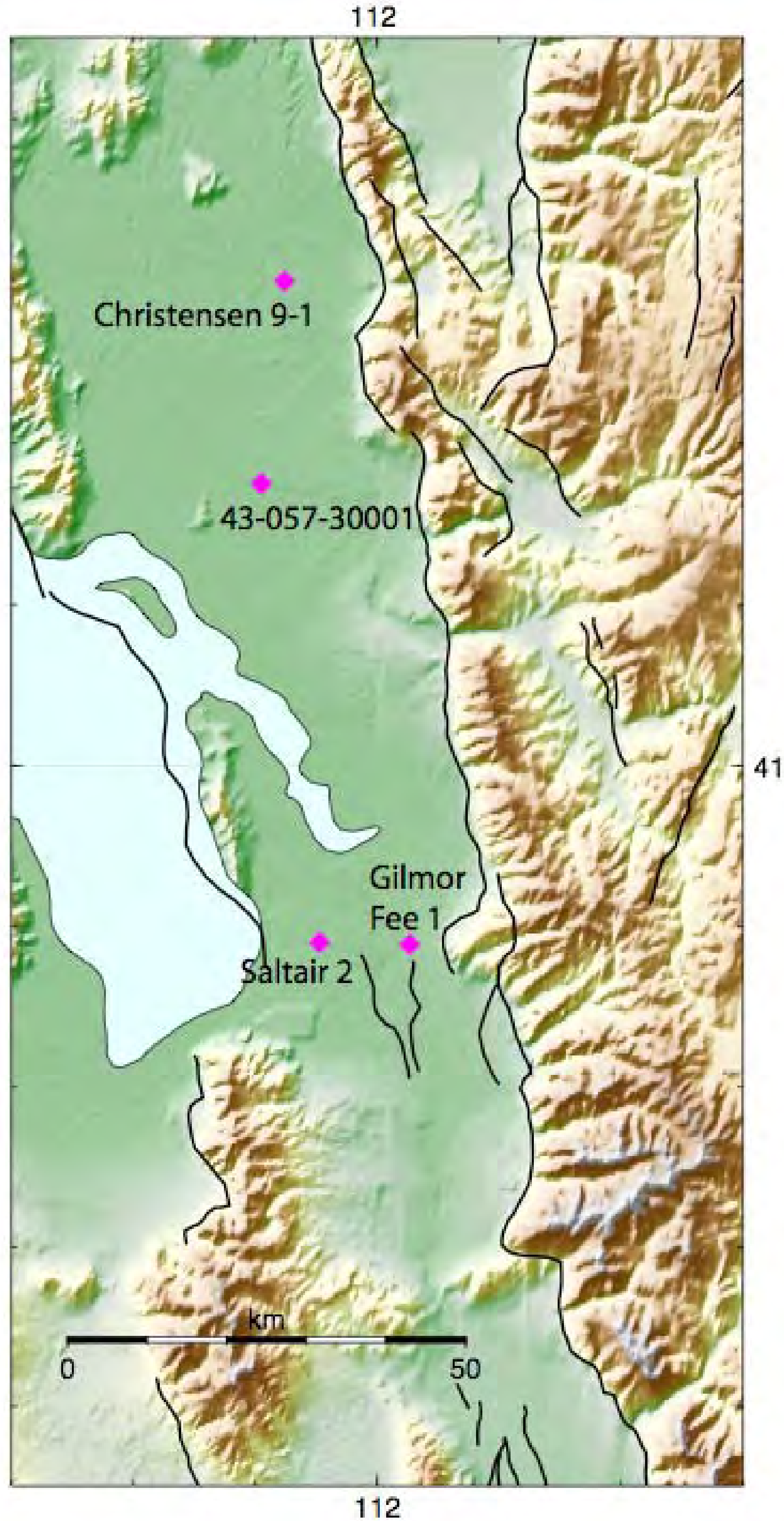

R1-R2 VELOCITY PROFILES
P-Wave Velocity (km/s)
0.0 1.0 2.0 3.0 4.0 5.0 6.0
Depth (km)
0.0 1.0 2.0
15 logs

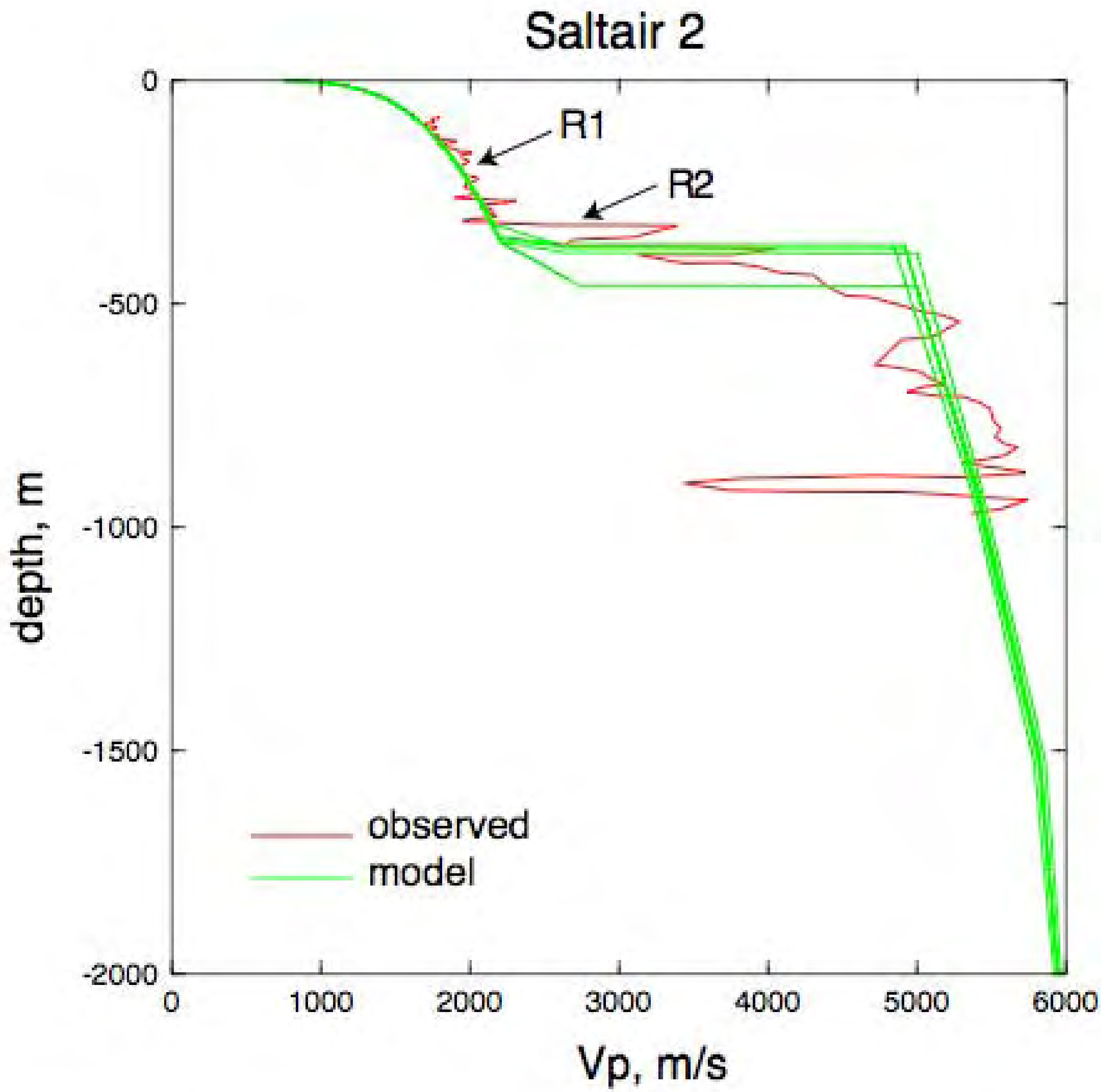

ROCK SITE VELOCITY PROFILES
P-Wave Velocity (km/s)
0.0 1.0 2.0 3.0 4.0 5.0 6.0
Depth (km)
0.0 1.0 2.0 3.0 4.0 5.0
7 logs: Colored lines
Geometric Mean: Black


AVERAGE VELOCITY PROFILES
P-Wave Velocity (km/s)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Depth (km)
0.0
1.0
2.0
3.0
4.0
5.0
Above R1: WFCVM
Above R1: Geometric Mean
R1-R2: WFCVM
R1-R2: Geometric Mean
Bedrock: WFCVM
Bedrock: Geometric Mean

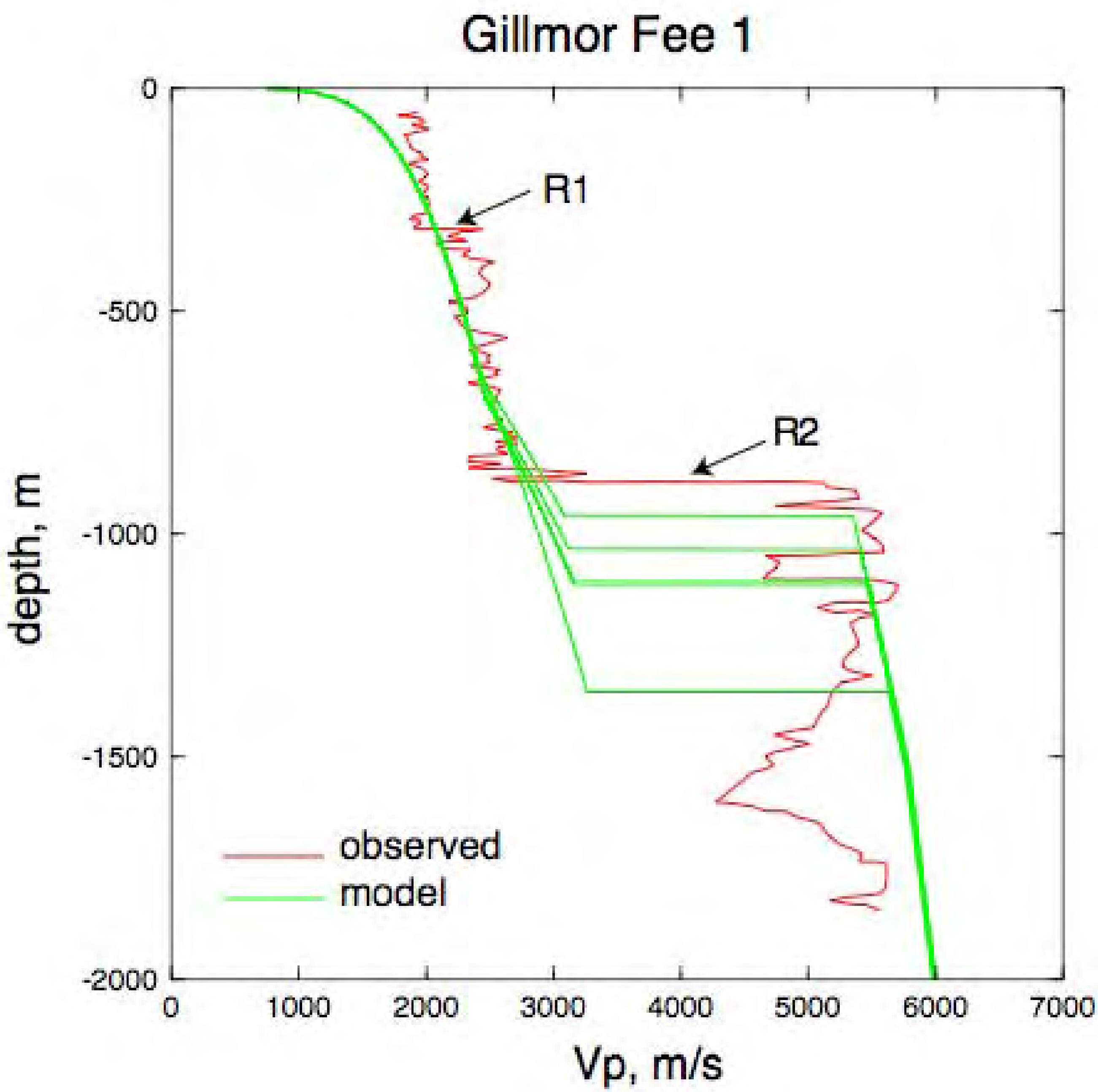
Conclusions

- **The sonic logs from the basins are generally consistent with the basic basin model developed by Hill et al. (1990).**
- **Our results confirm that R2, interpreted as the boundary between semiconsolidated sediments and Tertiary sedimentary rocks, is the largest velocity contrast in the basins.**
- **The basin P-wave velocities that we determined just below R2 are typically ~1 km/s lower than those reported by Hill et al. (1990).**
- **The geometric mean P-wave velocity in the bedrock increases from ~3.0 km/s near the surface to ~5.8 km/s at 5 km depth.**
- **The lateral variability of the measured P-wave velocities in the bedrock is comparable to that in the basins.**

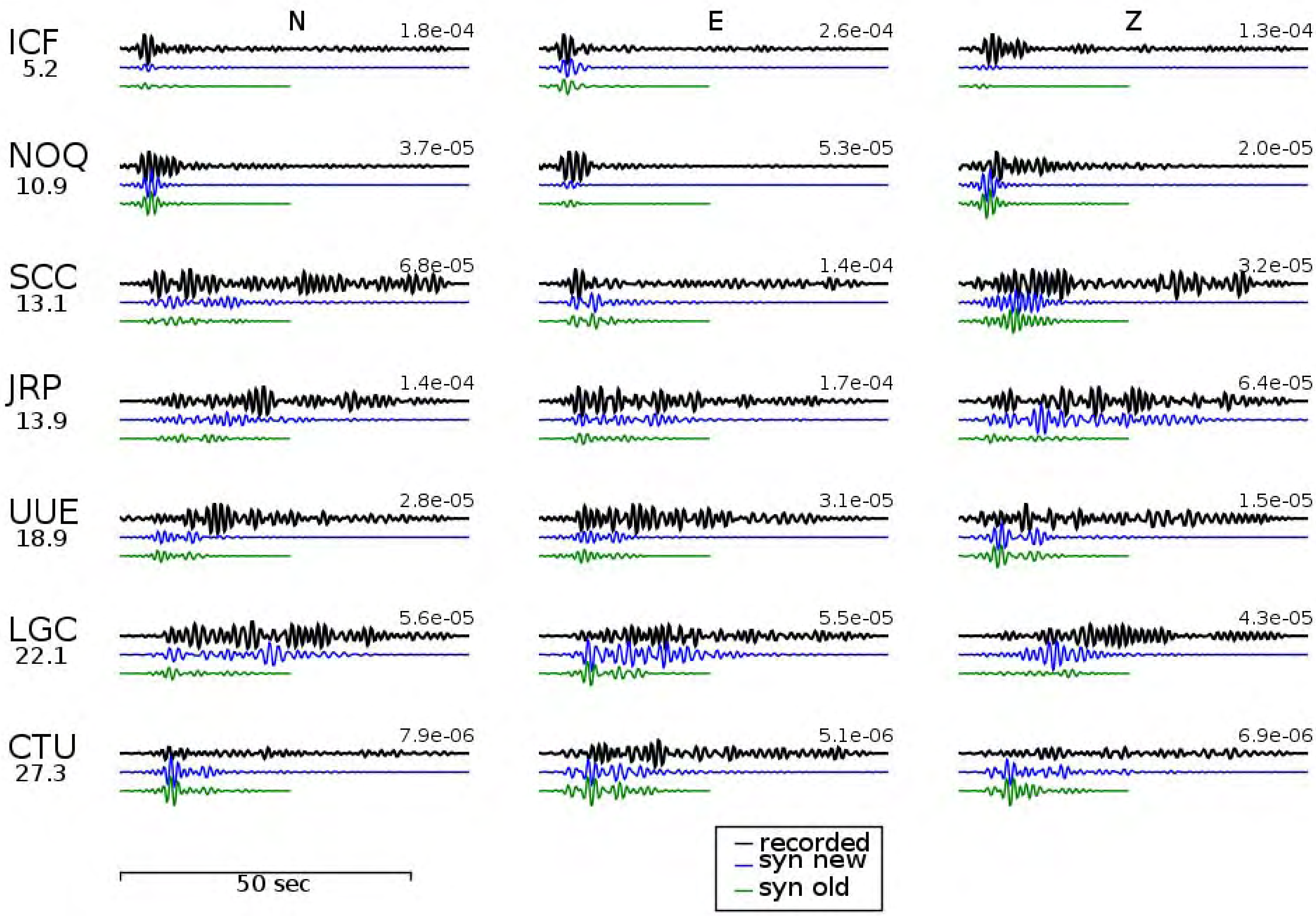

112
Christensen 9-1
43-057-30001
41
Gilmor
Fee 1
Saltair 2
km
0
50
112



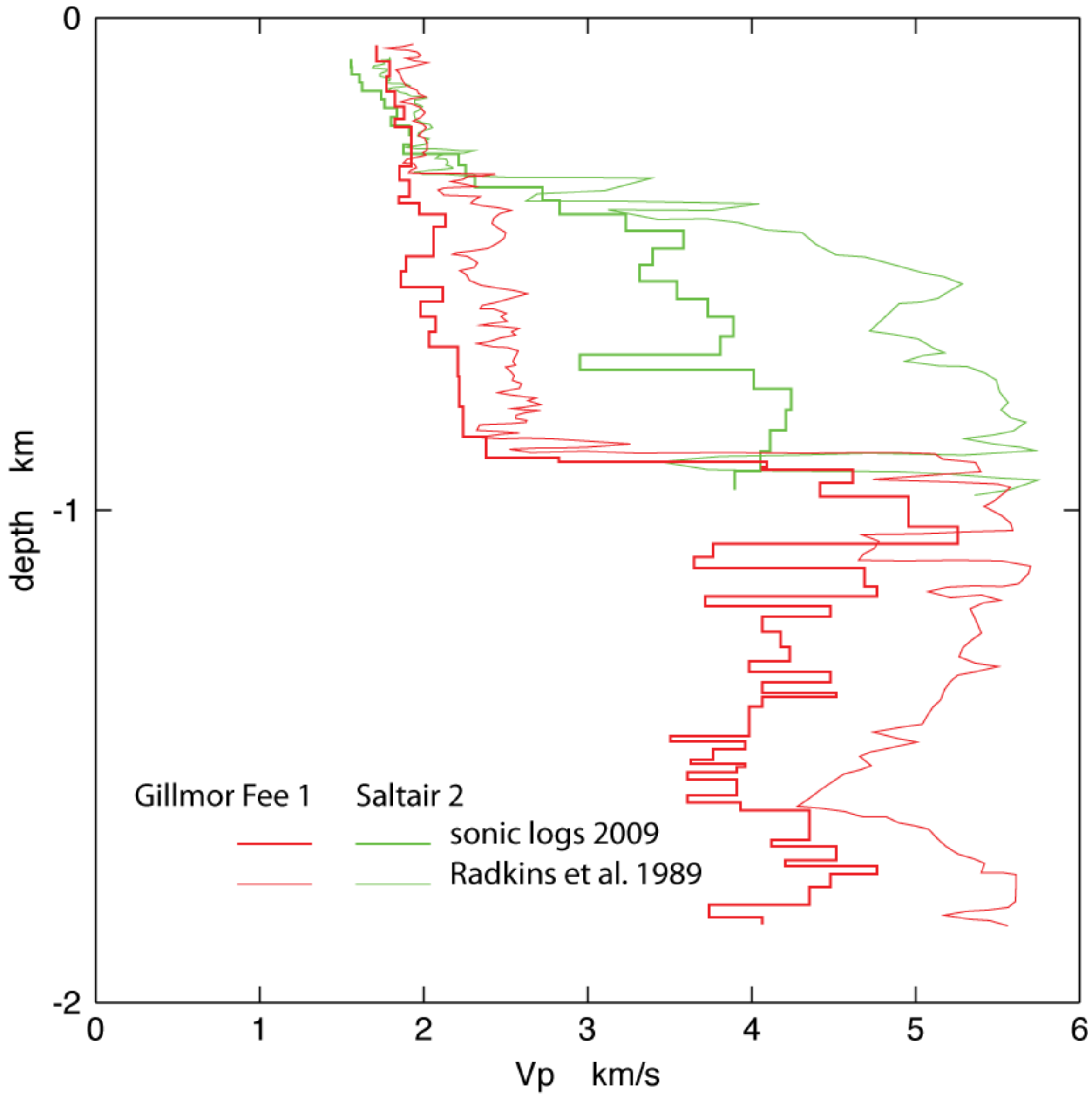
from Radkins et al. 1989



from Radkins et al. 1989



N
E
Z
ICF
5.2
1.8e-04
2.6e-04
1.3e-04
NOQ
10.9
3.7e-05
5.3e-05
2.0e-05
SCC
13.1
6.8e-05
1.4e-04
3.2e-05
JRP
13.9
1.4e-04
1.7e-04
6.4e-05
UUE
18.9
2.8e-05
3.1e-05
1.5e-05
LGC
22.1
5.6e-05
5.5e-05
4.3e-05
CTU
27.3
7.9e-06
5.1e-06
6.9e-06
50 sec
recorded
syn new
syn old



0
-1
-2
depth km
0
1
2
3
4
5
6
Vp km/s
Gillmor Fee 1
Saltair 2
sonic logs 2009
Radkins et al. 1989

Version 3c

Above R1

- Vp from piecewise linear fits to geometric mean sonic log profiles
- If Vs geotech, get Vp from modified mudline

R1-R2

- Vp from piecewise linear fits to geometric mean sonic log profiles
- If Vs geotech, get Vp from original sigma

R2-R3

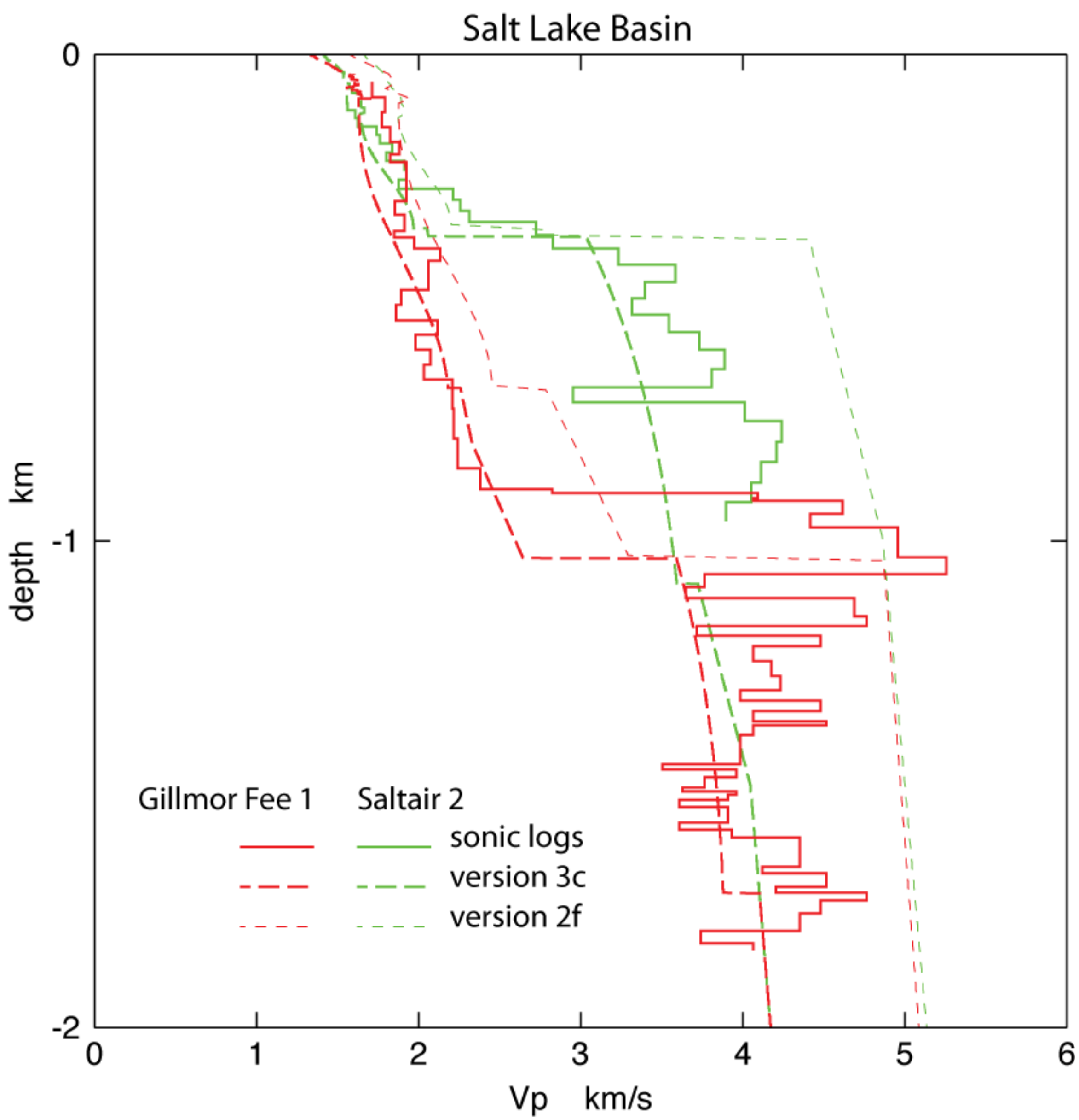
- Basement now at R3
- R2 to R3 Vp from Faust

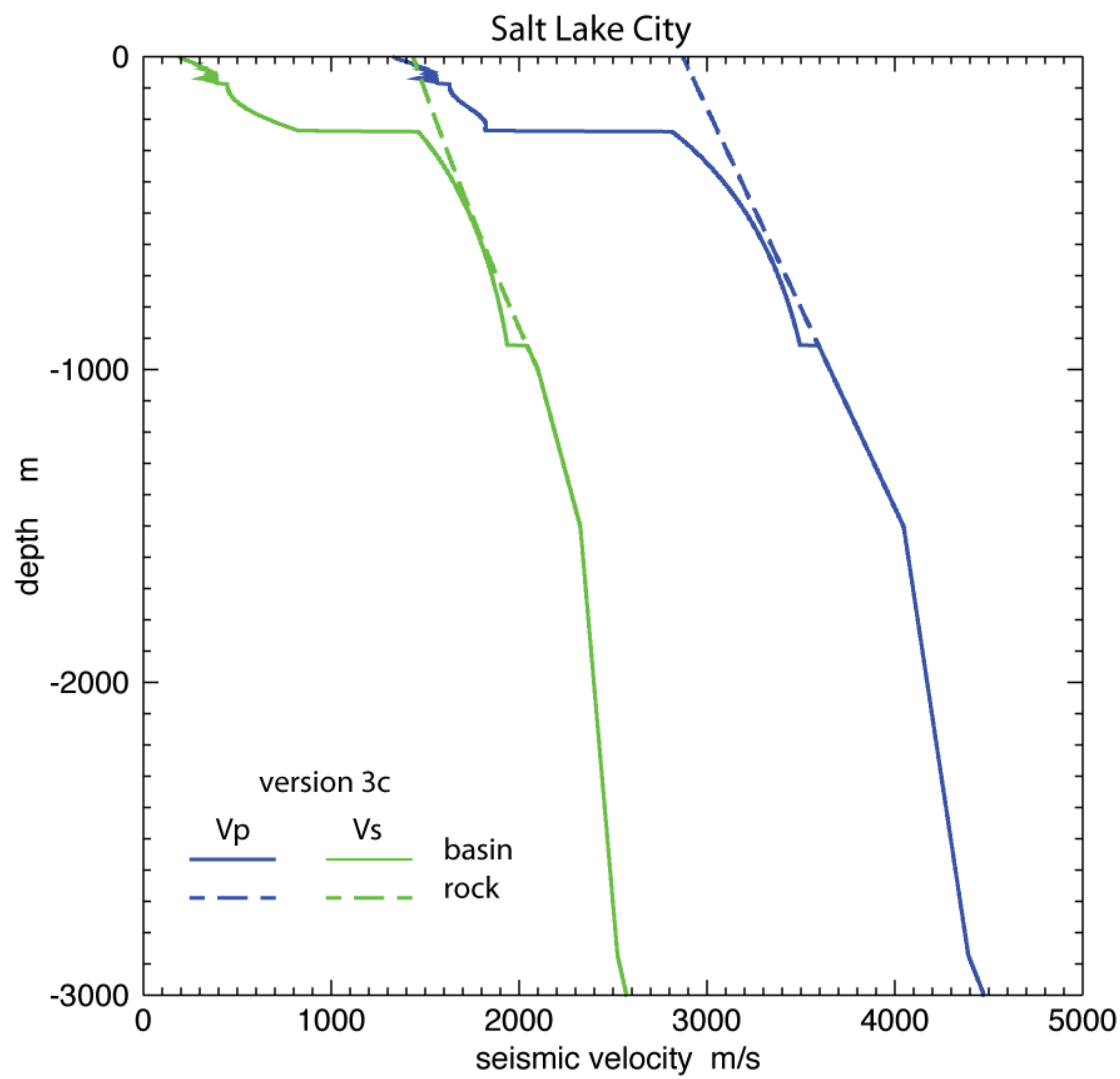
Basement:

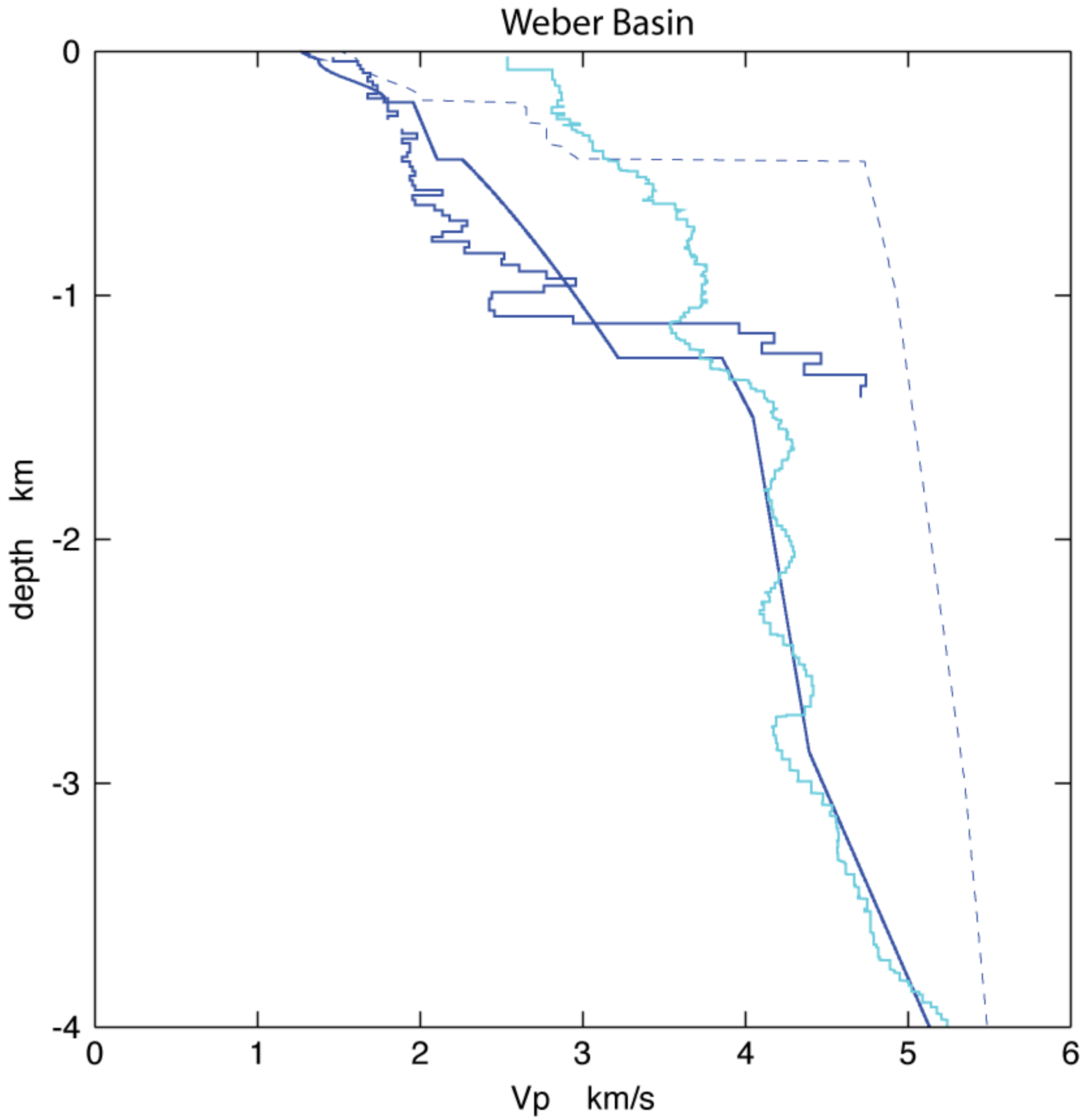
- Use Vp from sonic logs 0 to 4 km depth, taper to tomographic Vp between 4 and 5 km depth
- Vp/Vs gradient 2.0 to 1.74 from 0 to 1 km depth
- Correct bug 47,000 feet to 47,000 meter

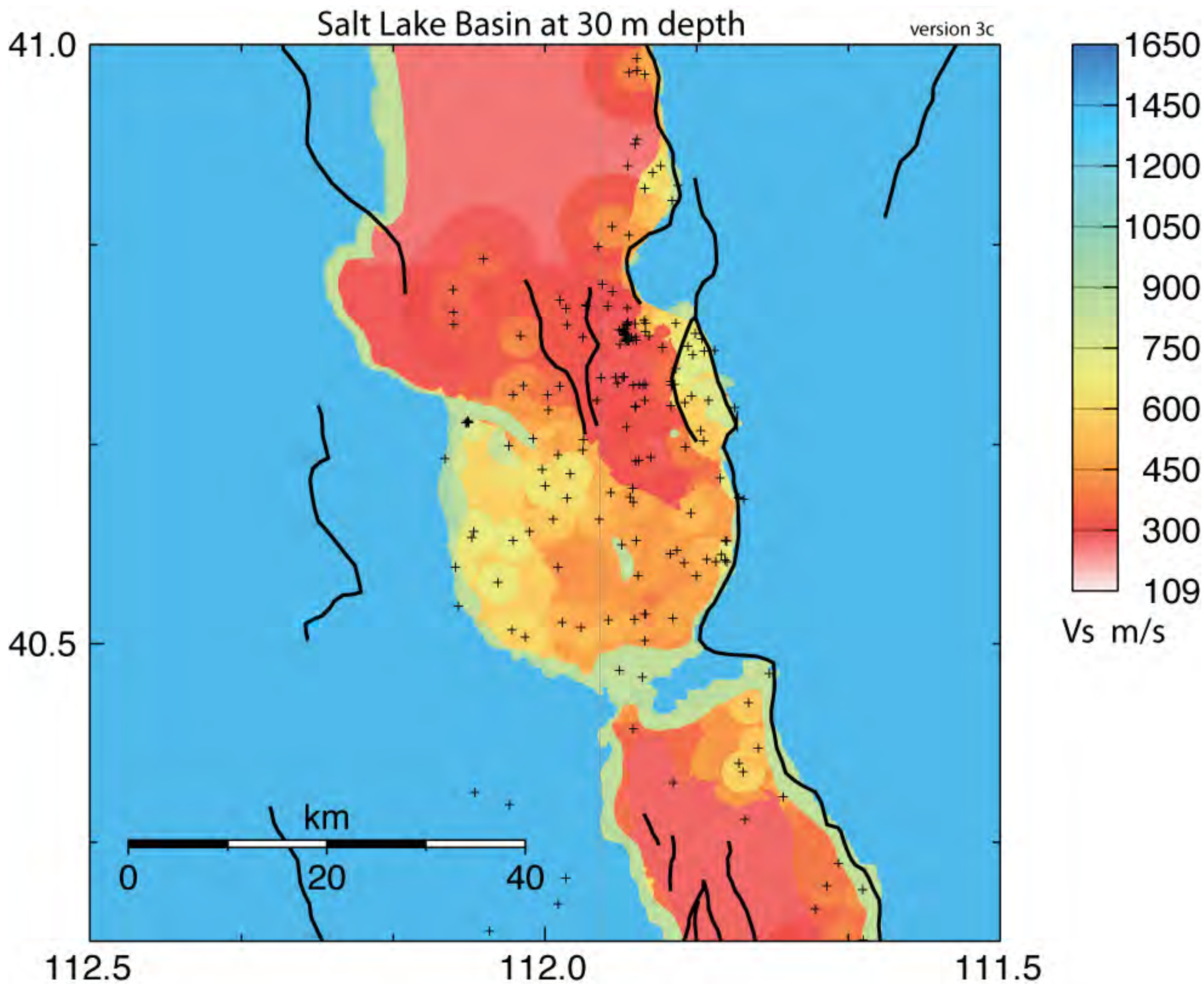
Other

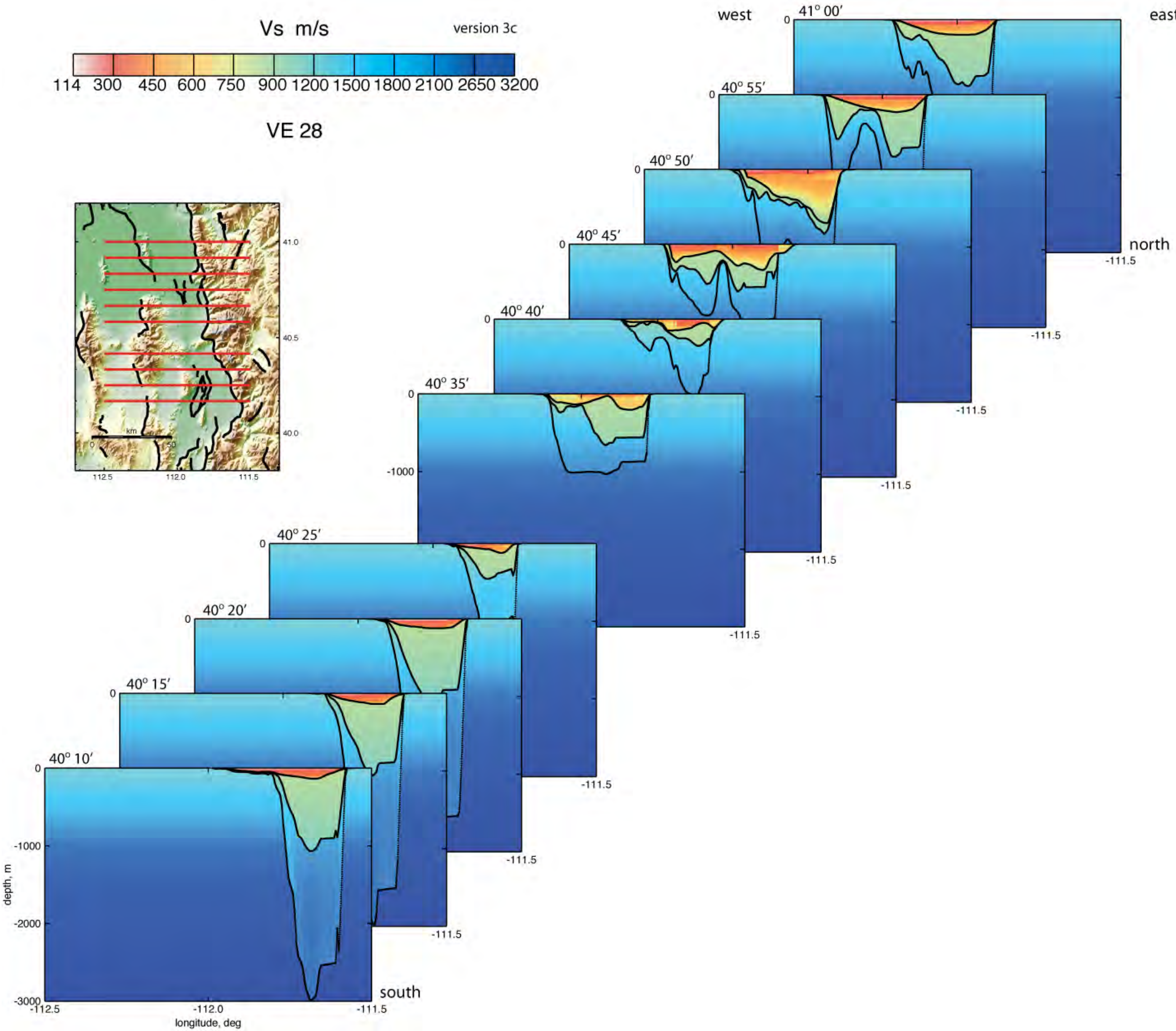
- Faust constants set in new subroutine getkay
- Constants re-calibrated
- Fixed subroutine taperp call
- Verbose comments


Salt Lake Basin
0
-1
-2
depth km
0
1
2
3
4
5
6
Vp km/s
Gillmor Fee 1
Saltair 2
sonic logs
version 3c
version 2f

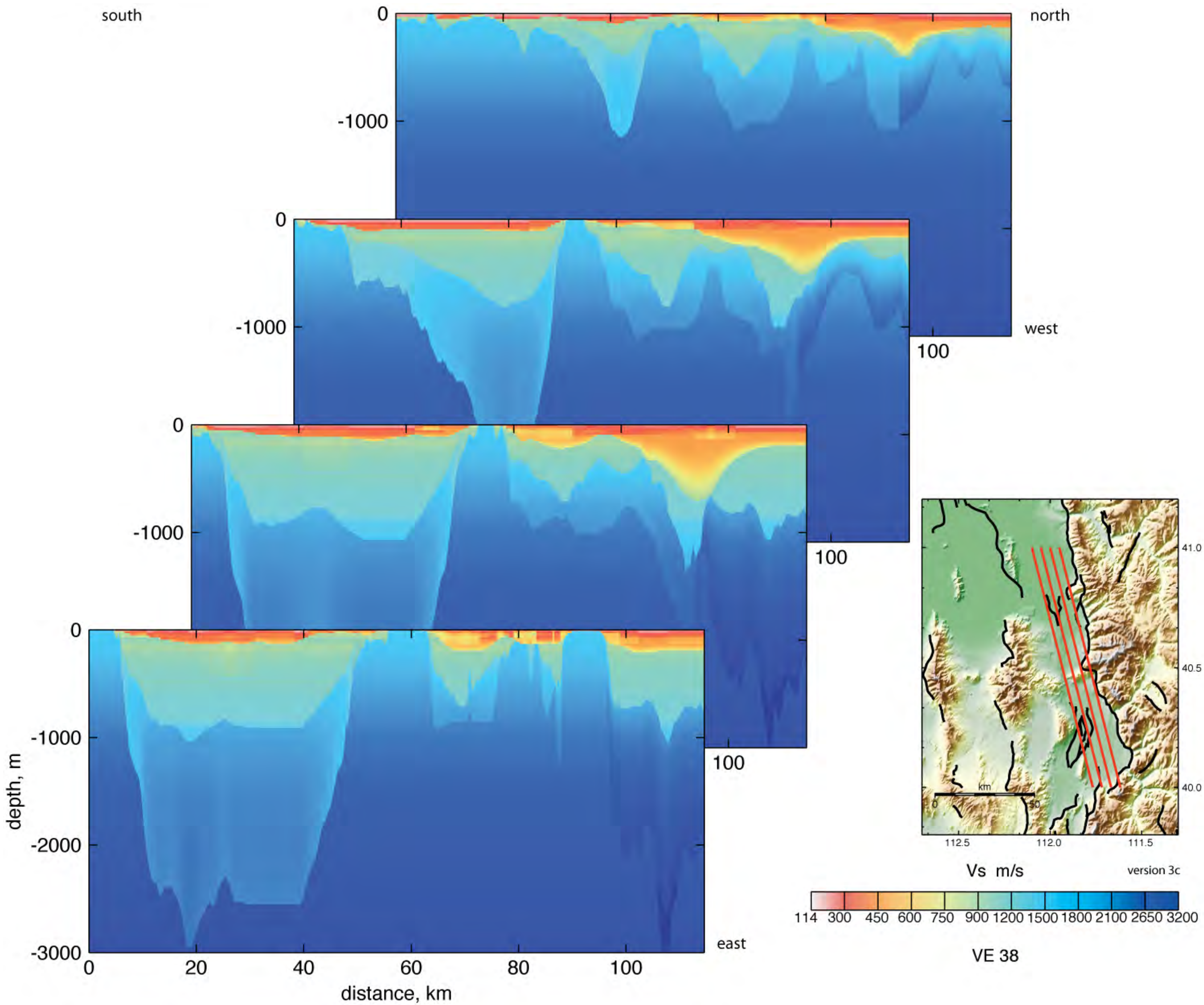

Salt Lake City
0
-1000
-2000
-3000
depth m
0
1000
2000
3000
4000
5000
seismic velocity m/s
version 3c
Vp
Vs
basin
rock


Weber Basin
0
-1
-2
-3
-4
depth km
0
1
2
3
4
5
6
Vp km/s

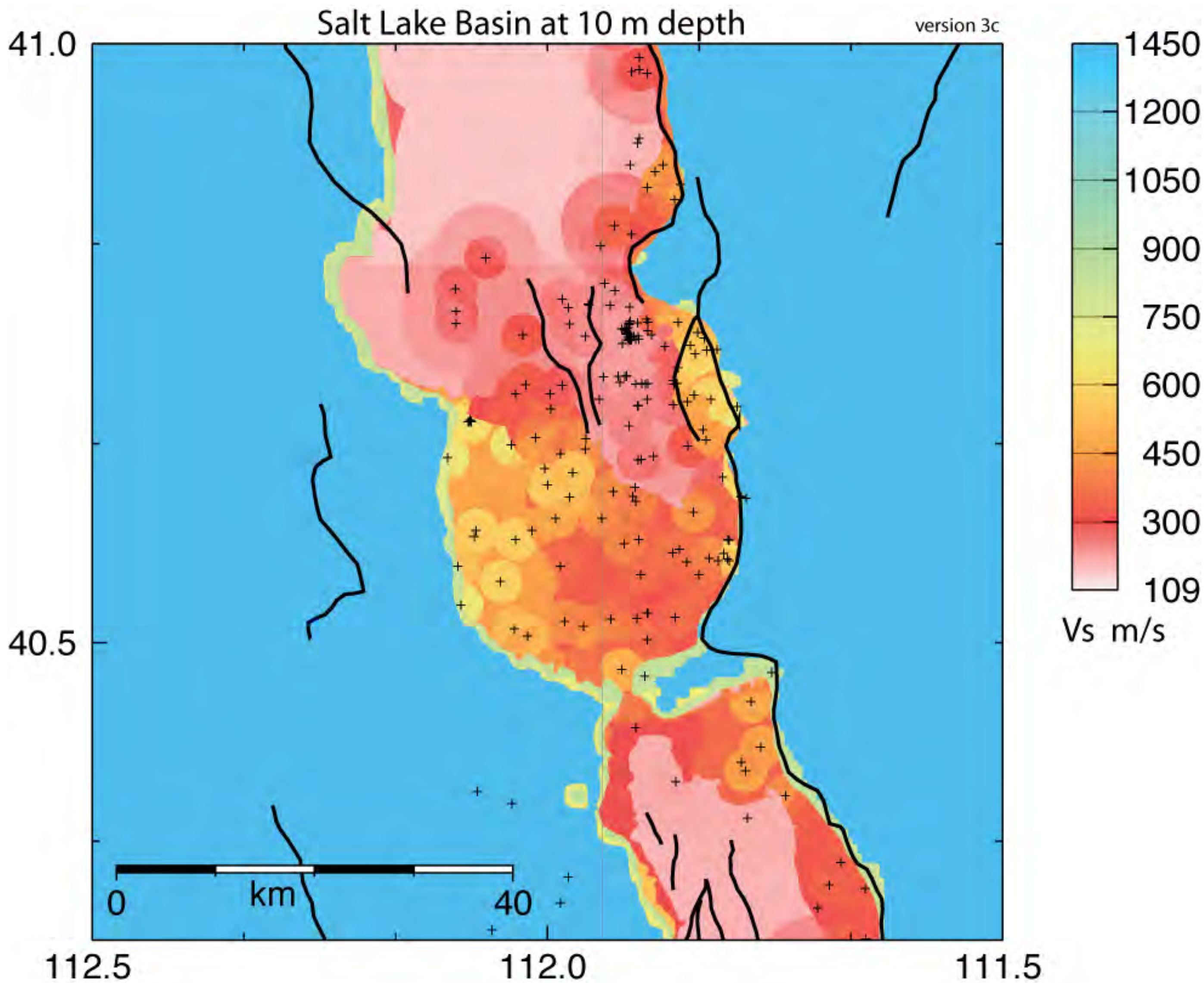

Salt Lake Basin at 30 m depth
version 3c
41.0
40.5
112.5
112.0
111.5
km
0
20
40
1650
1450
1200
1050
900
750
600
450
300
109
Vs m/s



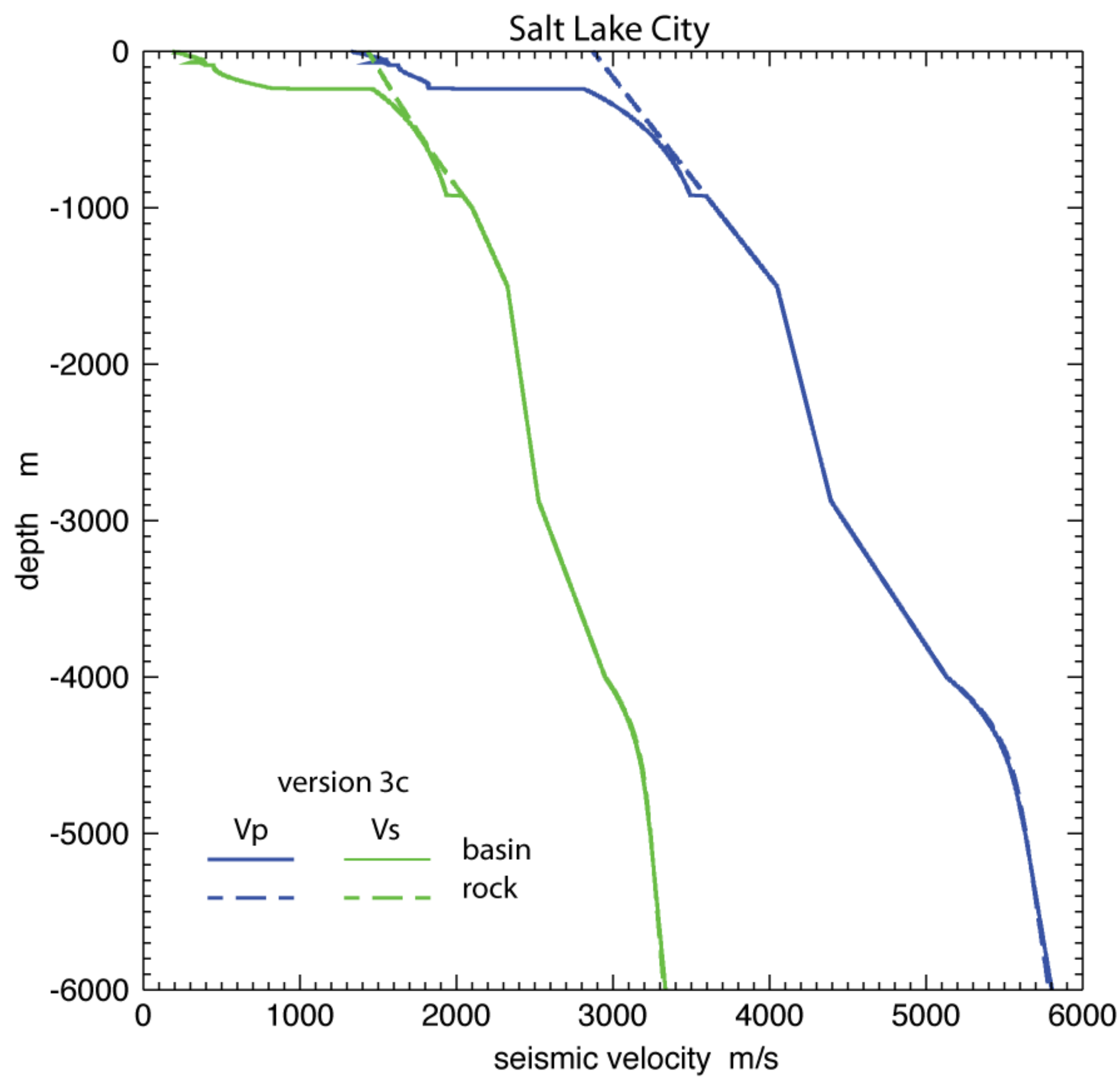
Vs m/s
version 3c
114 300 450 600 750 900 1200 1500 1800 2100 2650 3200
VE 28
west
east
north
south
41° 00′
40° 55′
40° 50′
40° 45′
40° 40′
40° 35′
40° 25′
40° 20′
40° 15′
40° 10′
depth, m
longitude, deg
-112.5
-112.0
-111.5
0
-1000
-2000
-3000
km



south
north
west
east
0
-1000
-2000
-3000
100
depth, m
0
20
40
60
80
100
distance, km
41.0
40.5
40.0
km
0
50
112.5
112.0
111.5
Vs m/s
version 3c
114 300 450 600 750 900 1200 1500 1800 2100 2650 3200
VE 38



Salt Lake Basin at 10 m depth
version 3c
41.0
40.5
112.5
112.0
111.5
0
km
40
1450
1200
1050
900
750
600
450
300
109
Vs m/s


Salt Lake City
0
-1000
-2000
-3000
-4000
-5000
-6000
depth m
0
1000
2000
3000
4000
5000
6000
seismic velocity m/s
version 3c
Vp
Vs
basin
rock

USGS Wasatch Front ground motion modeling efforts

M. Moschetti, M. Petersen, L. Ramirez Guzman

USGS, NEIC, Golden, CO

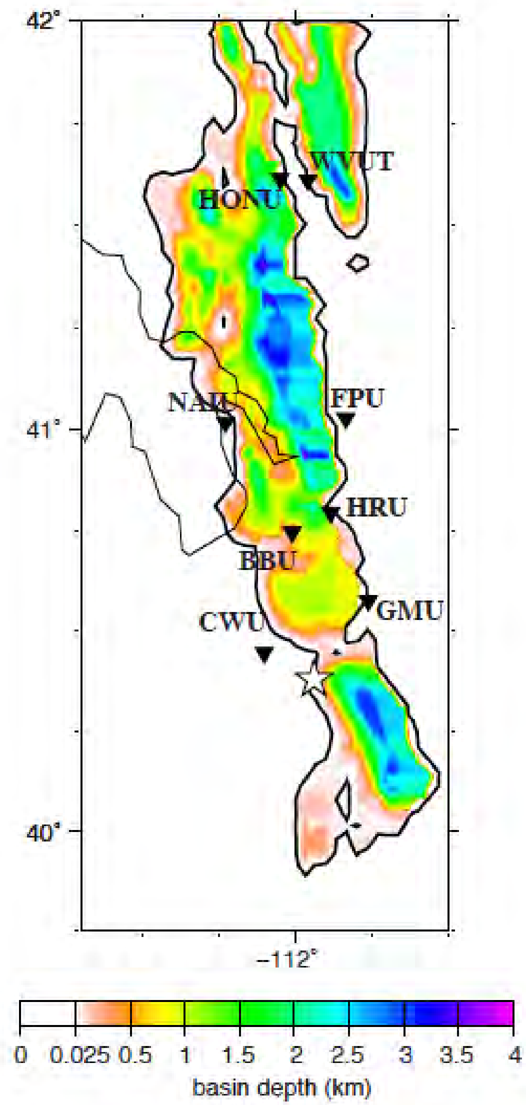
USGS efforts in calculating ground motions in Wasatch Front

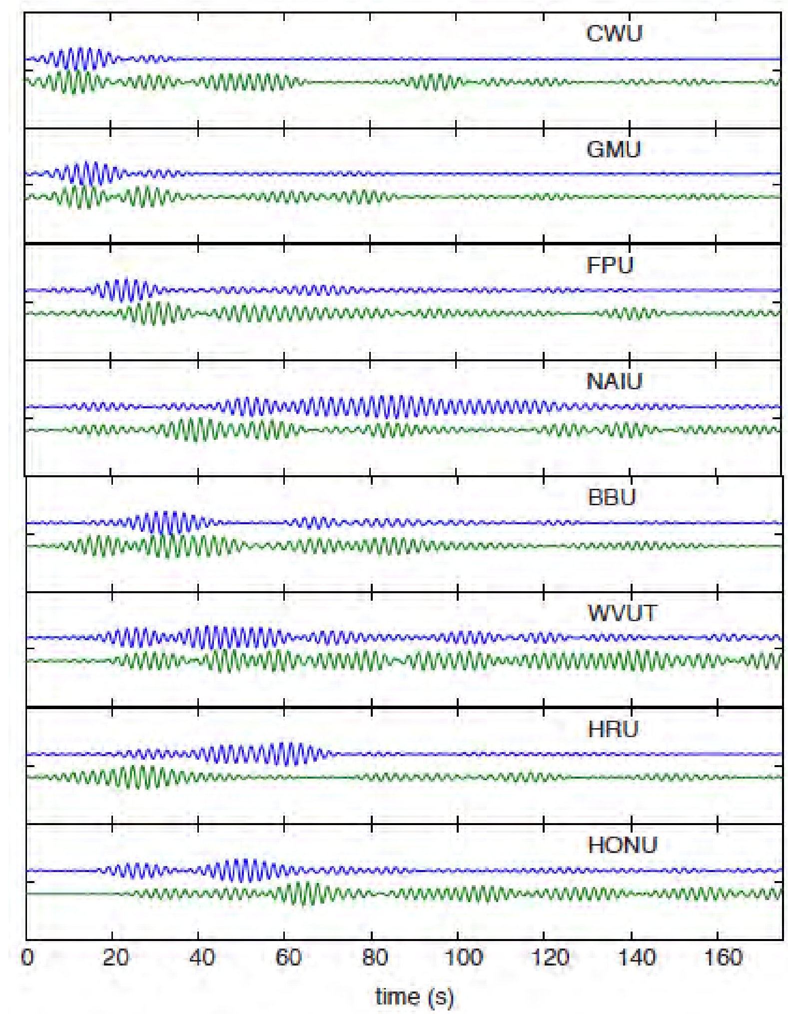
- Two distinct efforts related to calculation of ground motions in Wasatch Front
  - Modeling ground motions for existing Wasatch CVM
  - Evaluating Wasatch CVM – improvements to regional S-wave velocity model.

Current modeling efforts

- Wasatch Front CVM, version 3c
- Hercules, finite element code (Carnegie Mellon University)
- Linear, kinematic modeling
- “Validation” seismic events – Lehi and Magna earthquakes
- Current runs up to 0.5 Hz on desktop machines

Preliminary ground motion calculations: Lehi EQ





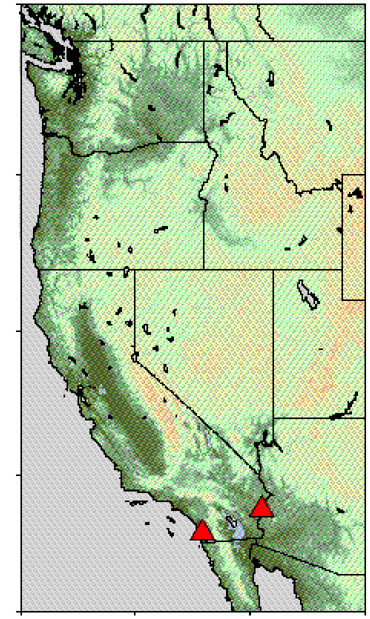
Future modeling efforts

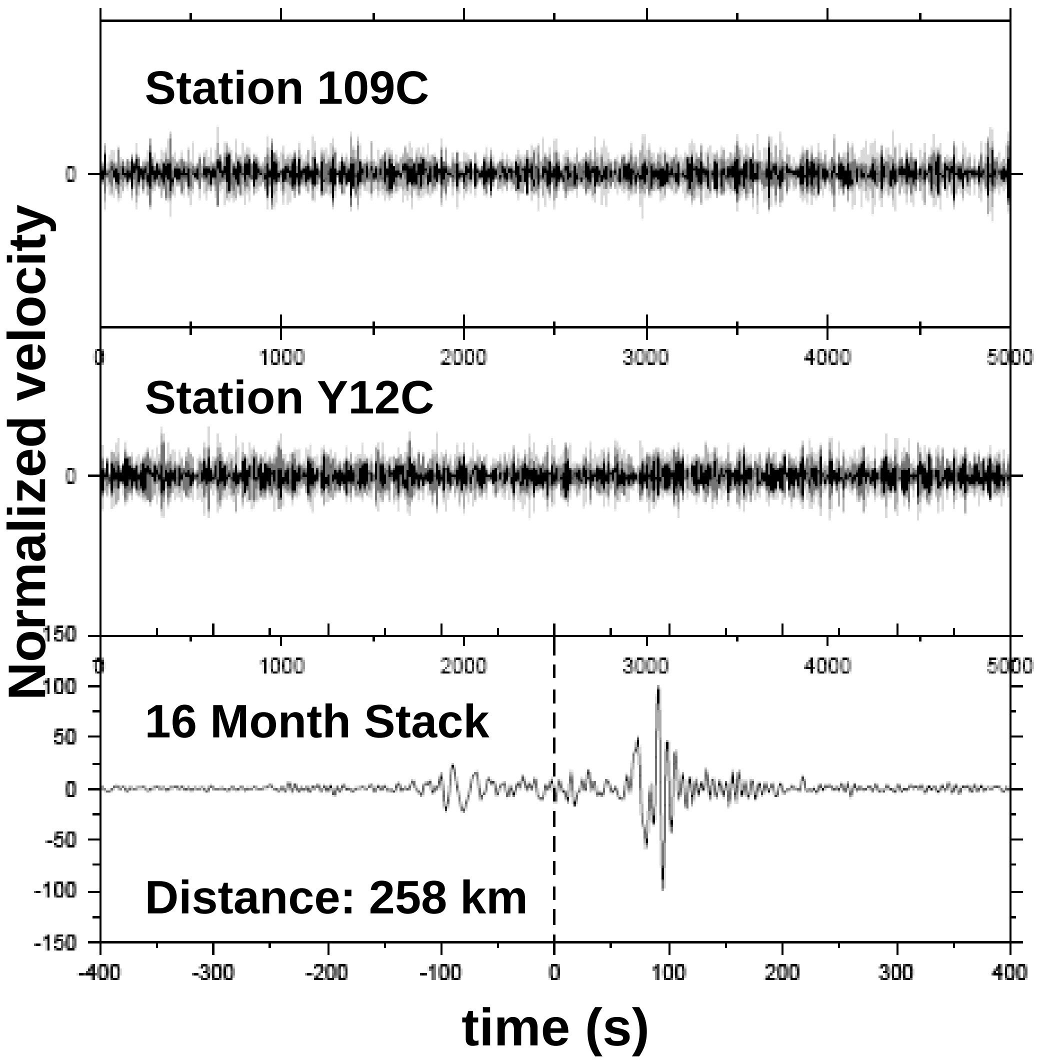
- “Validation” runs on USGS or Teragrid clusters for Lehi and Magna events to ~ 2 Hz
- Scenario earthquake (SL segment Wasatch Fault) ground motion modeling for comparison with other UGSWG results.
- Effects of slip history, fault geometry on earthquake ground motions in Wasatch Front.

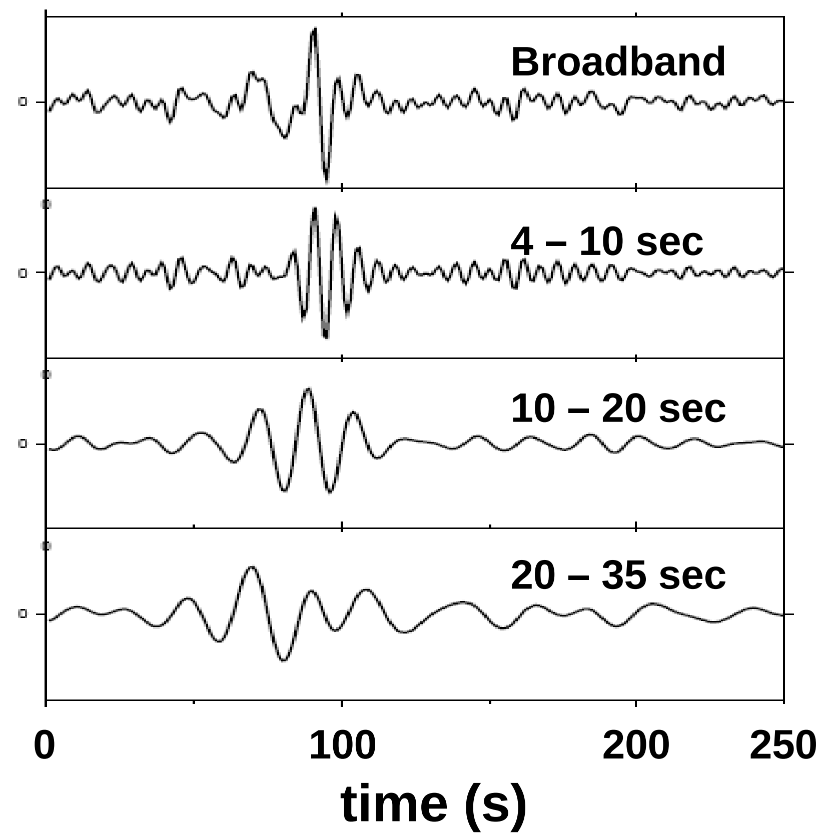
Modifying regional V_S model

- Motivated by absence of regional-scale crustal Vs model for the region
- Ambient noise tomography (ANT) – combine existing USArray Transportable Array data with additional (shorter inter-station pair) measurements in region of Wasatch Front.
- Inversion of dispersion maps from ambient seismic noise can incorporate some sedimentary velocity structure and reduce velocity trade-offs.

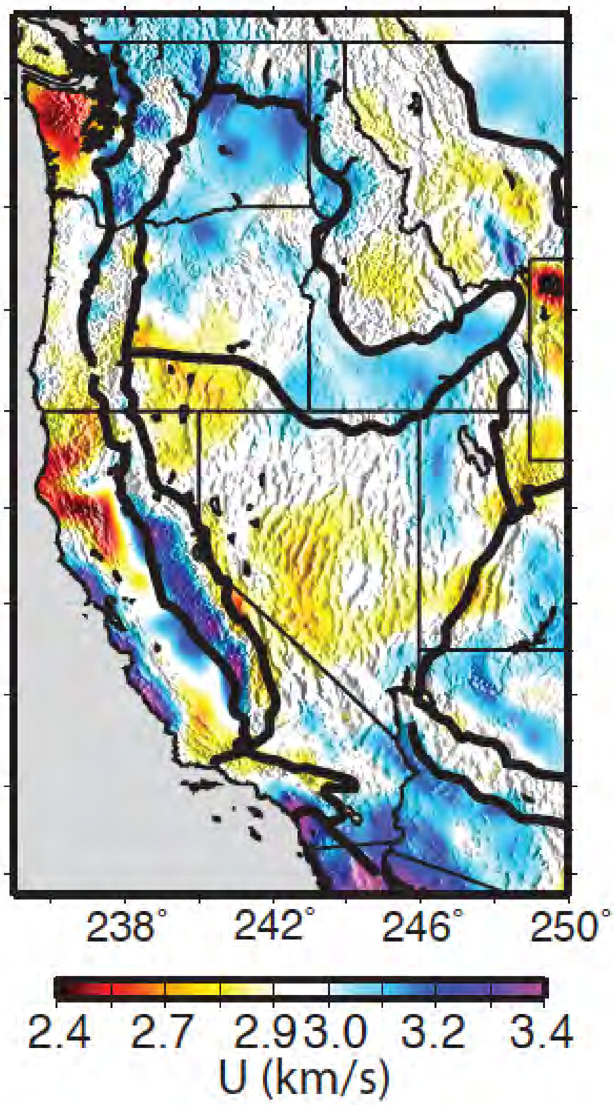
Surface wave measurements from ambient seismic noise





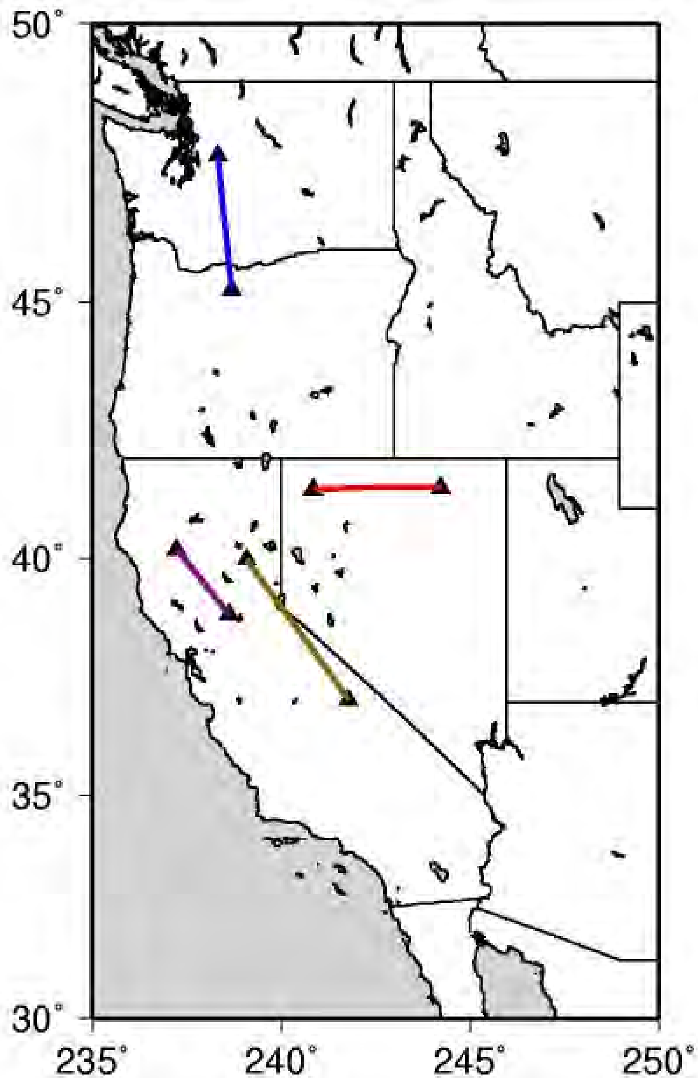


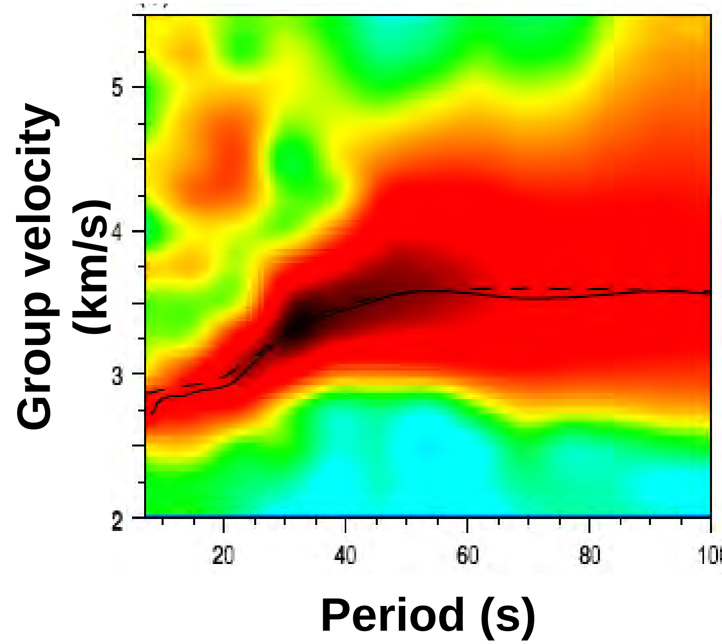
Dispersion maps from ambient seismic noise

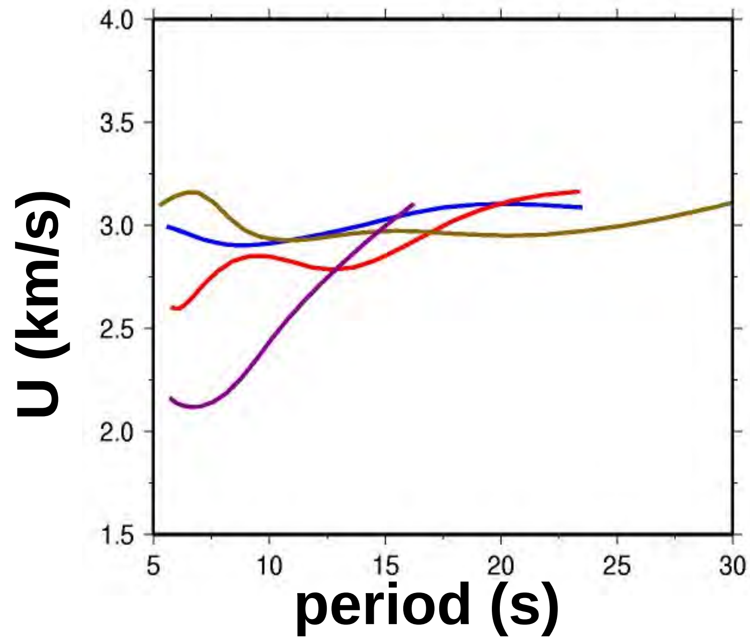


- Ambient noise tomography – maps in 6 – 40 s period band
- Earthquake surface wave tomography maps to 100 s
- Combined inversion for shear-wave velocity structure – regional model
- Current resolution ~ 50 km using TA. Improvements from incorporation of local data.
- Invert dispersion maps for 3-D Vs structure

Surface wave dispersion measurements







Three-dimensional nonlinear earthquake ground motion simulation in the Salt Lake Basin using the Wasatch Front Community Velocity Model

Ricardo Taborda and Jacobo Bielak

Computational Seismology Laboratory
Department of Civil & Environmental Engineering

THE QUAKE Group AT **Carnegie Mellon University**

Overall Objective

The main objective is to examine:

- how nonlinear soil behavior,

- in combination with other factors, such as the depth of the sedimentary deposits, edge effects, and focusing, that influence ground shaking in large basins,

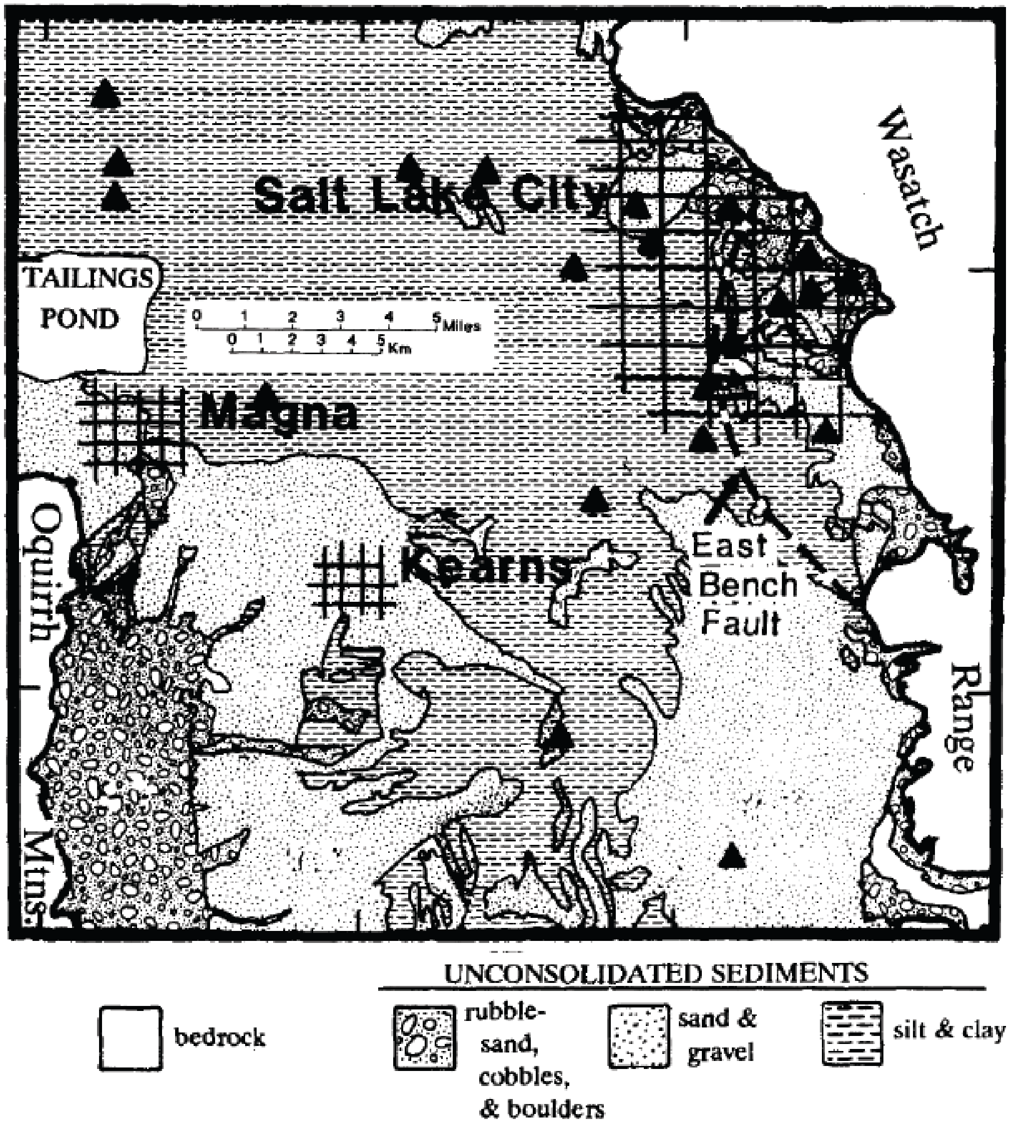
- affects the earthquake ground motion in the Salt Lake Basin (WFCVM).

Overall Objective

- The proposed simulations will be limited to 'low' frequencies: (< 1.5 - 2 Hz*). From direct ob-*servations of site amplification in the Salt Lake Basin, this range encompasses several resonant frequencies of the basin. Thus, we can expect significant amplifications in simulations of the linear case.

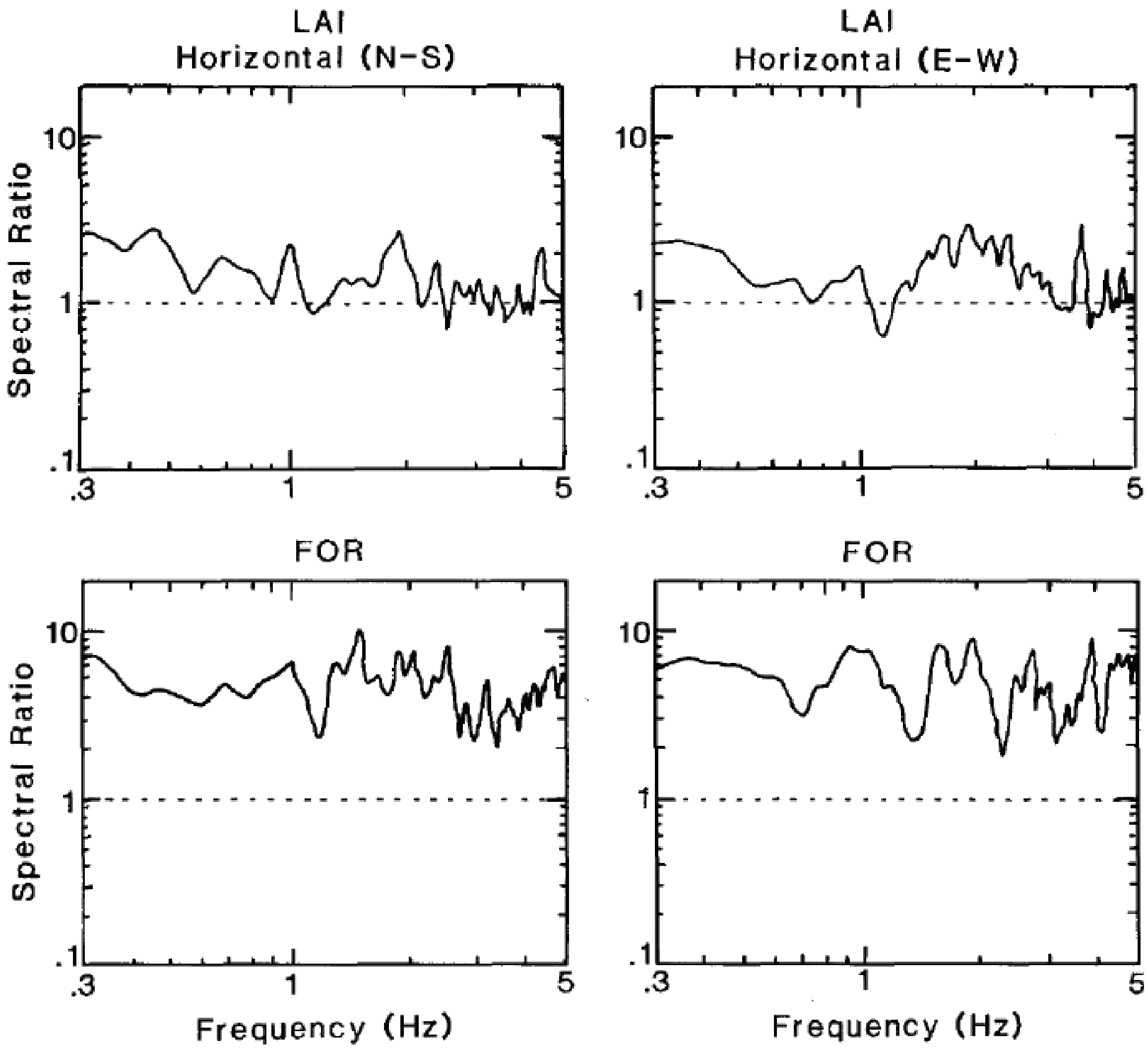
- Determining what happens to the ground motion as the soil becomes increasingly nonlinear will be one of our main objectives.

Generalized surficial geology of the SLV area
Site locations are shown by triangles



After Rodgers et al., 1984

Spectral ratios of ground motion at two sites

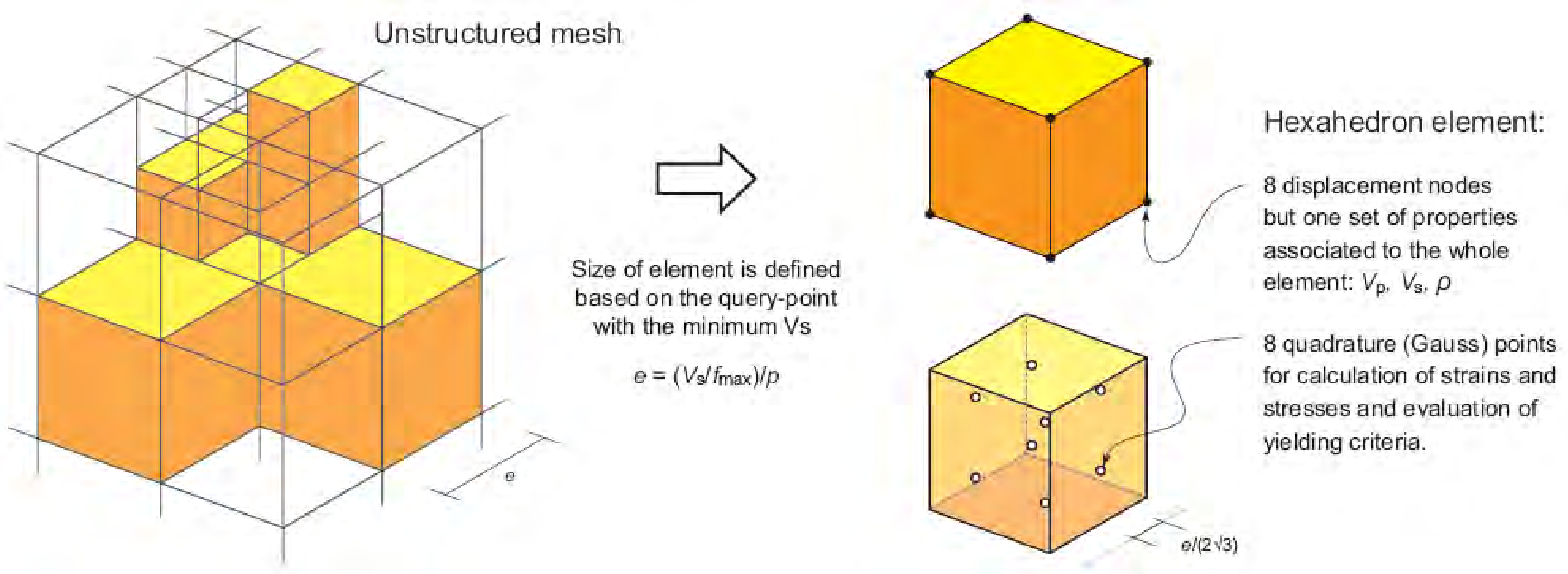


Sand/gravel

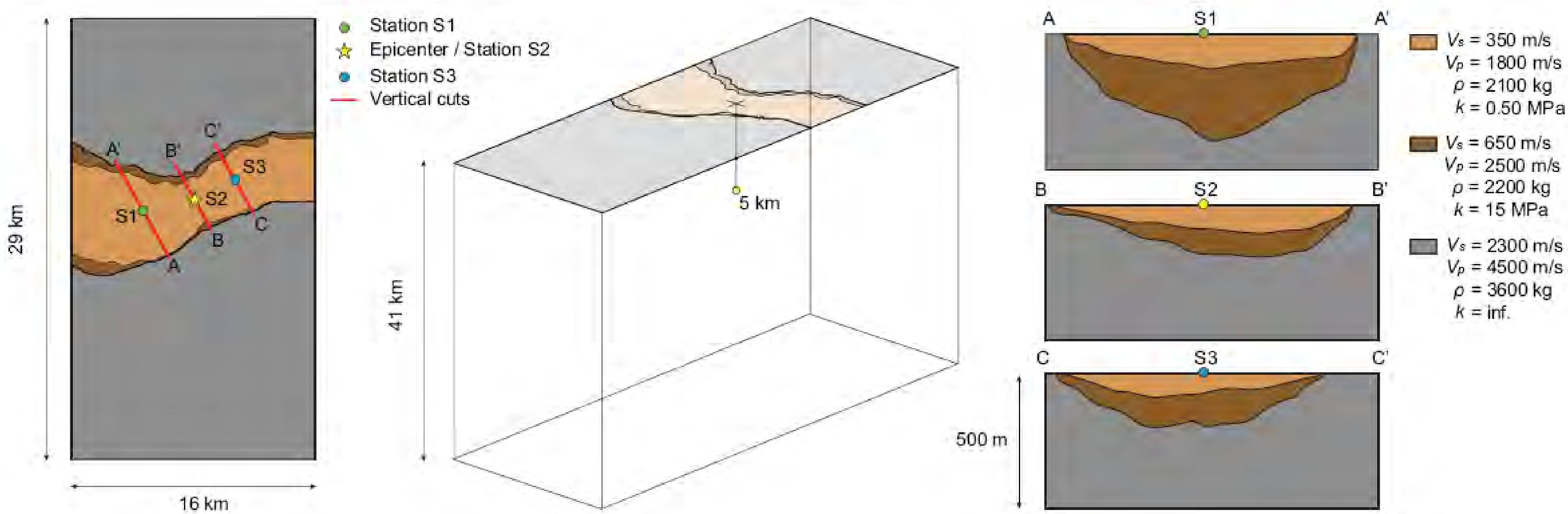
Silt/clay

(After King et al., 1987)

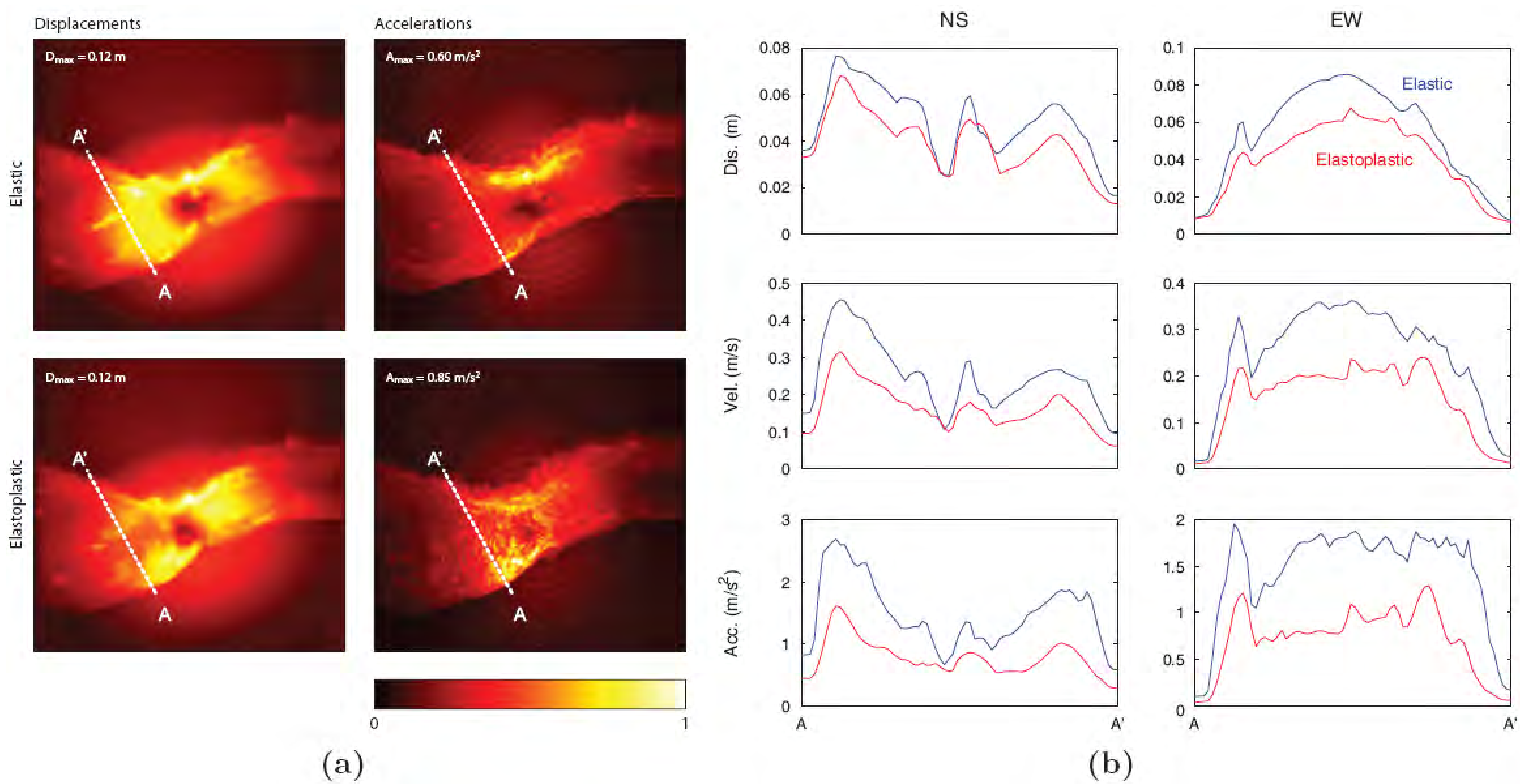
Hercules unstructured mesh and typical hexahedron element



Basin structure for Volvi Euroseistest verification exercise



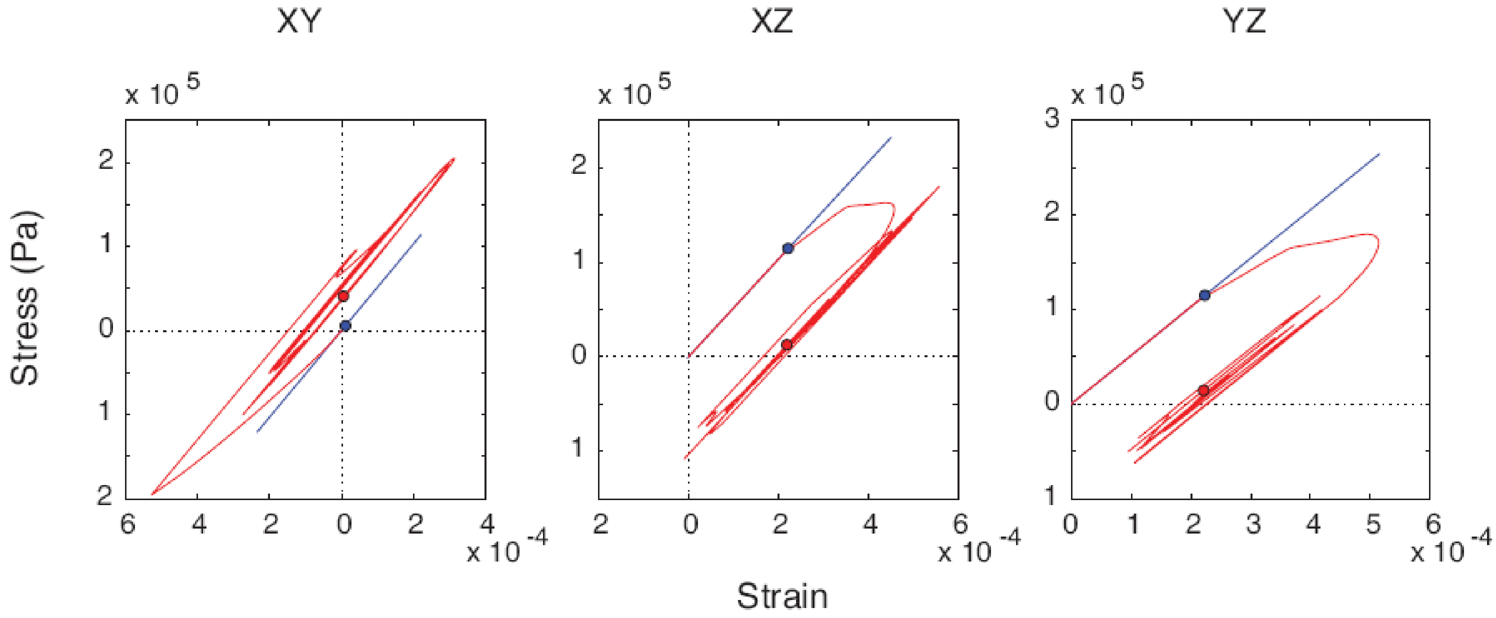
Ground motion due to point source below center of valley



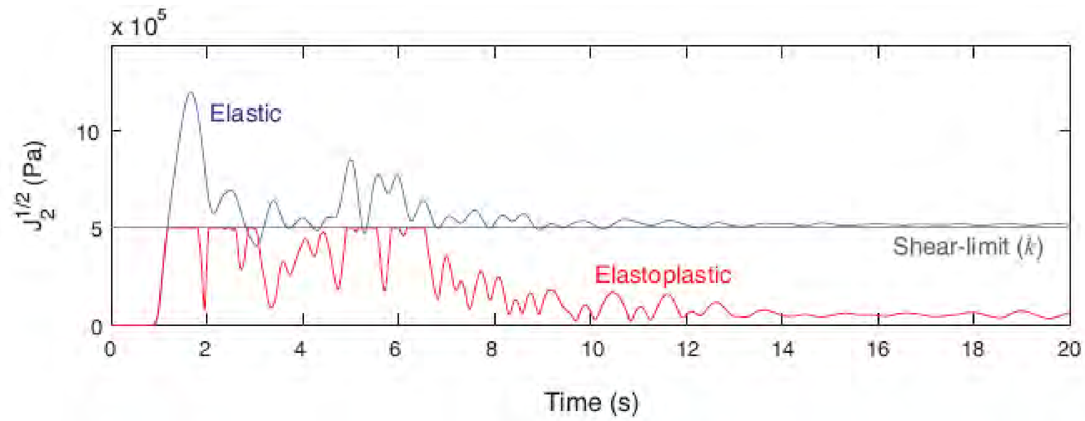
Distribution of peak response

Peak response along line AA'

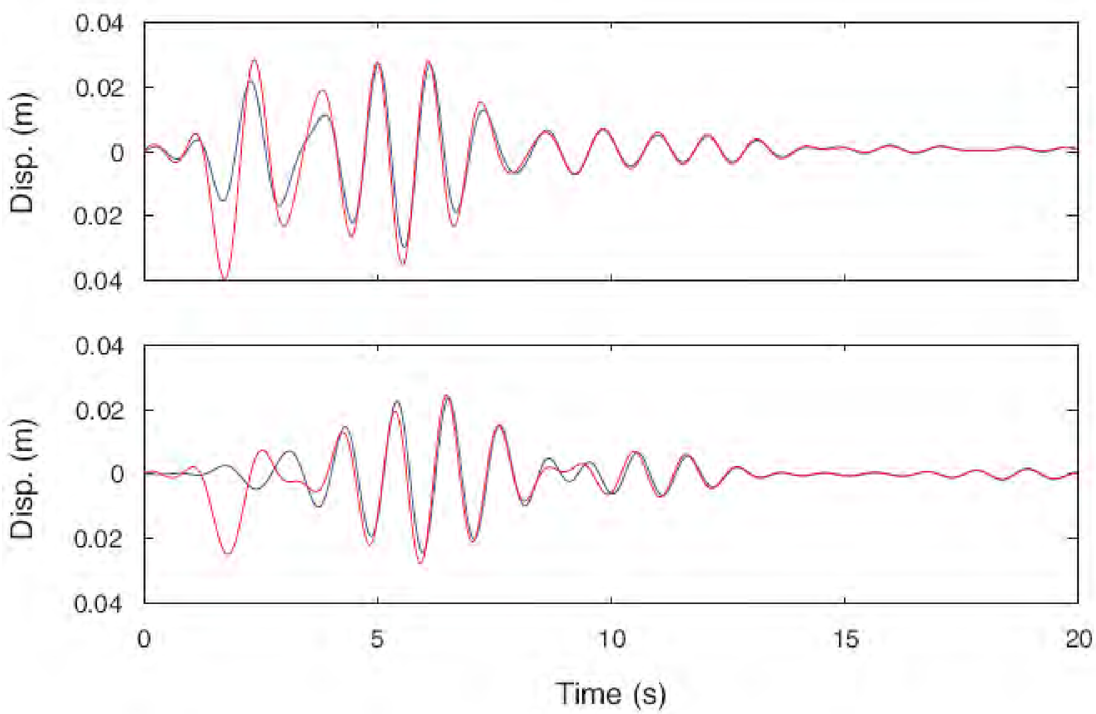
Elastic (blue) and elastoplastic (red) shear stress-strain relationships at station S2



Elastic and elastoplastic stress invariant J_2

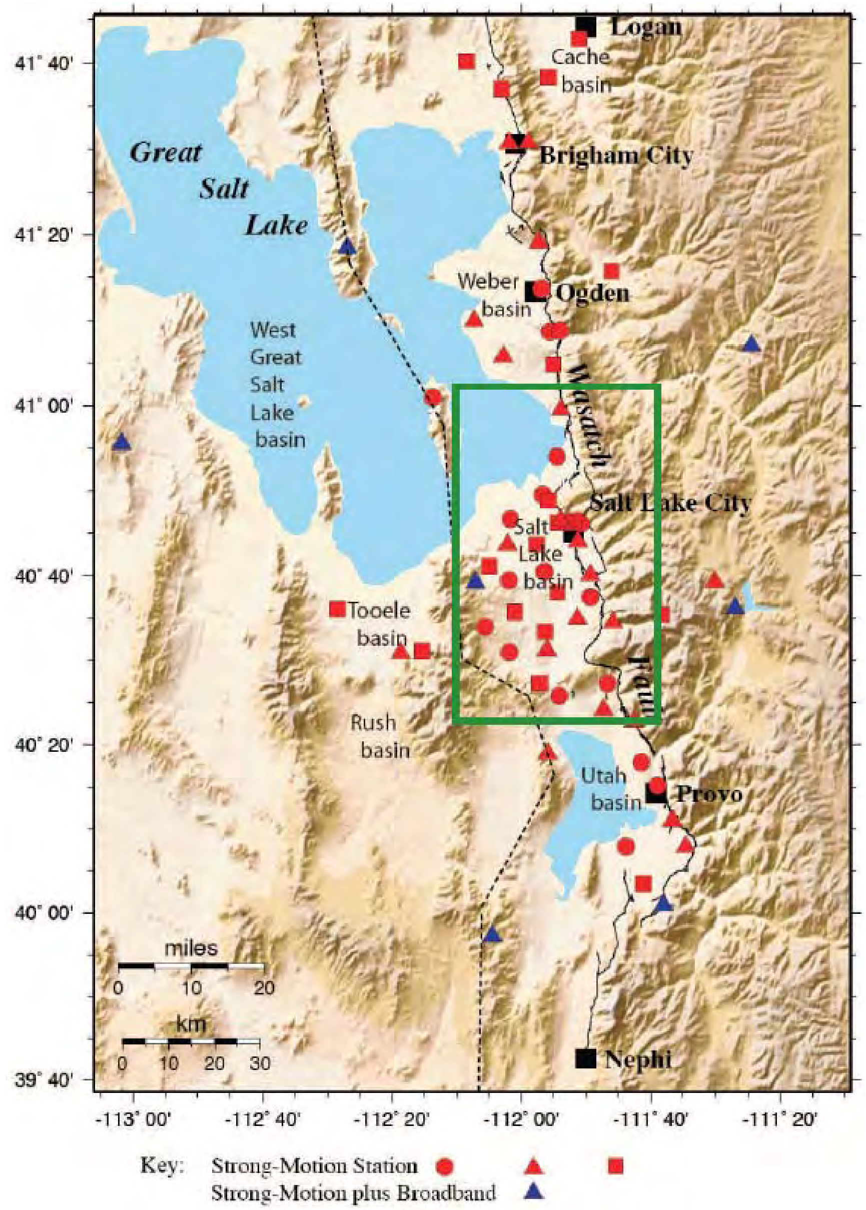


(a)



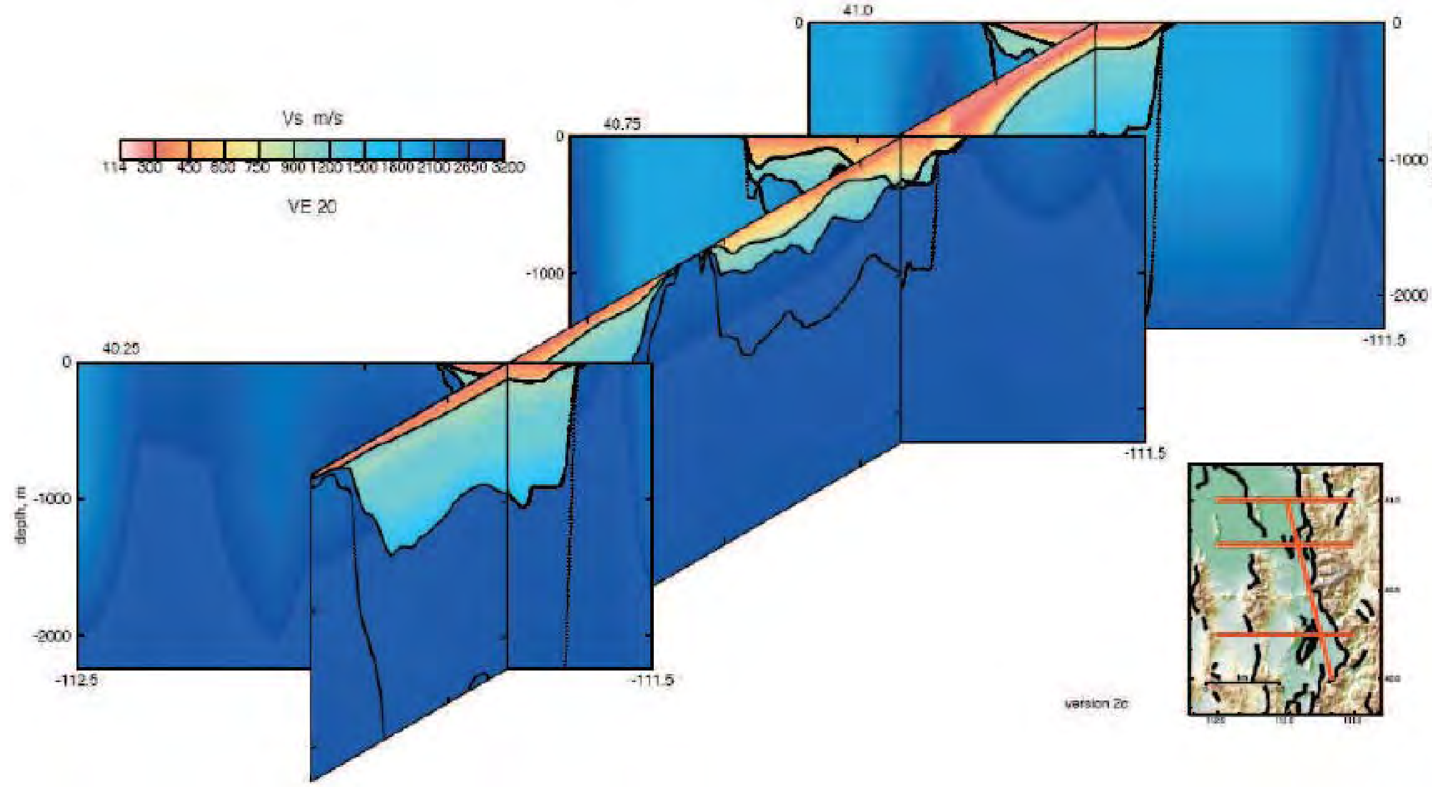
(b)

The Wasatch Front CVM region



After Magistrale et al, 2006

Fence diagram of V_S from WFCVM



Key questions

The key research question to be examined from a physical point of view is:

- under what conditions, and
- to what extent
- does the basin structure and the non-linear behavior of the soil affect earthquake ground motion in the Salt Lake Basin?
- Methodologically: use elastoplastic constitutive laws; need to incorporate geostatic stresses and extend model to more realistic constitutive relations.

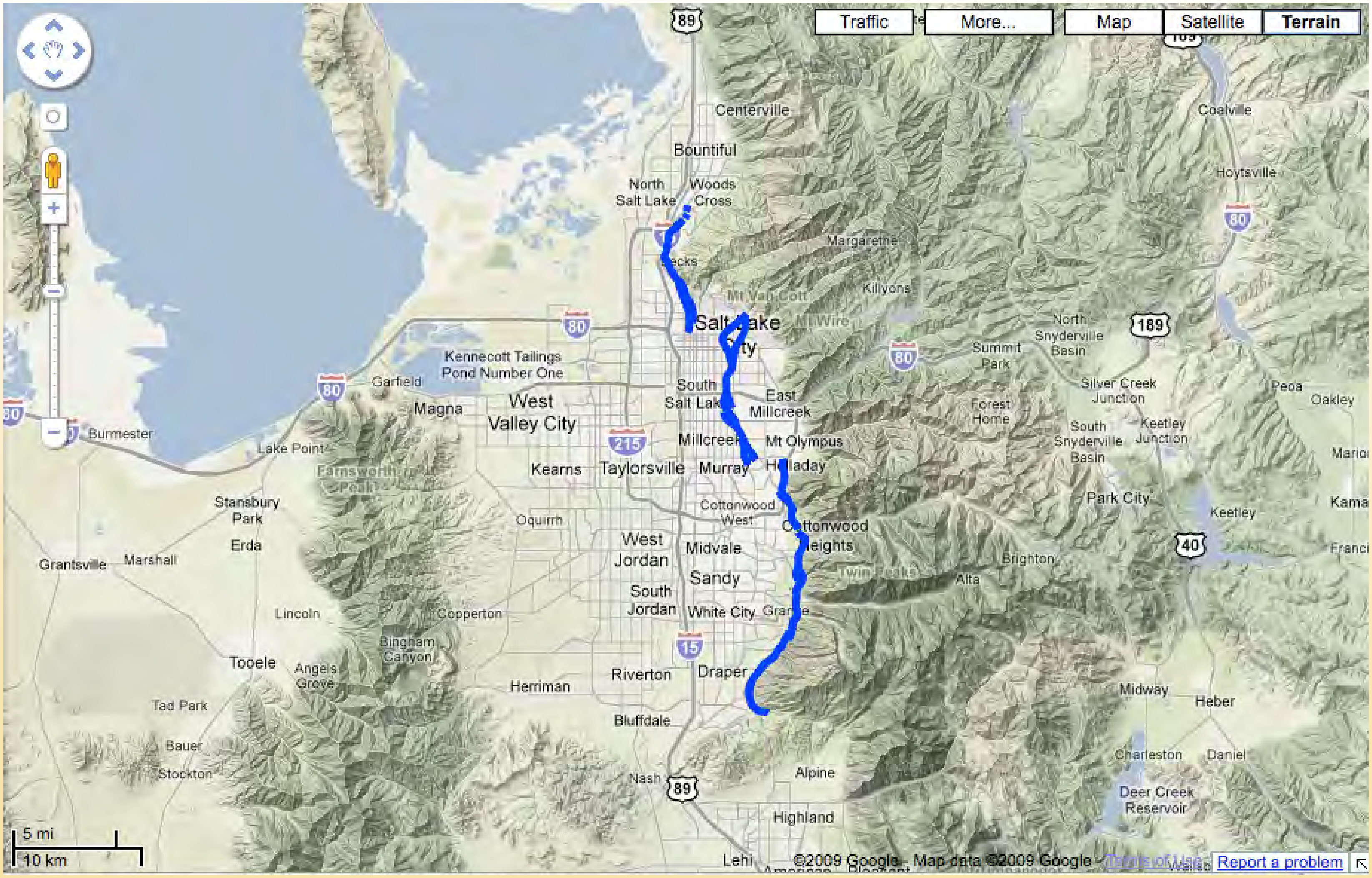
Wasatch Fault: Salt Lake City Segment Ground-Motion Simulation

Ralph Archuleta
Qiming Liu
University of California, Santa Barbara

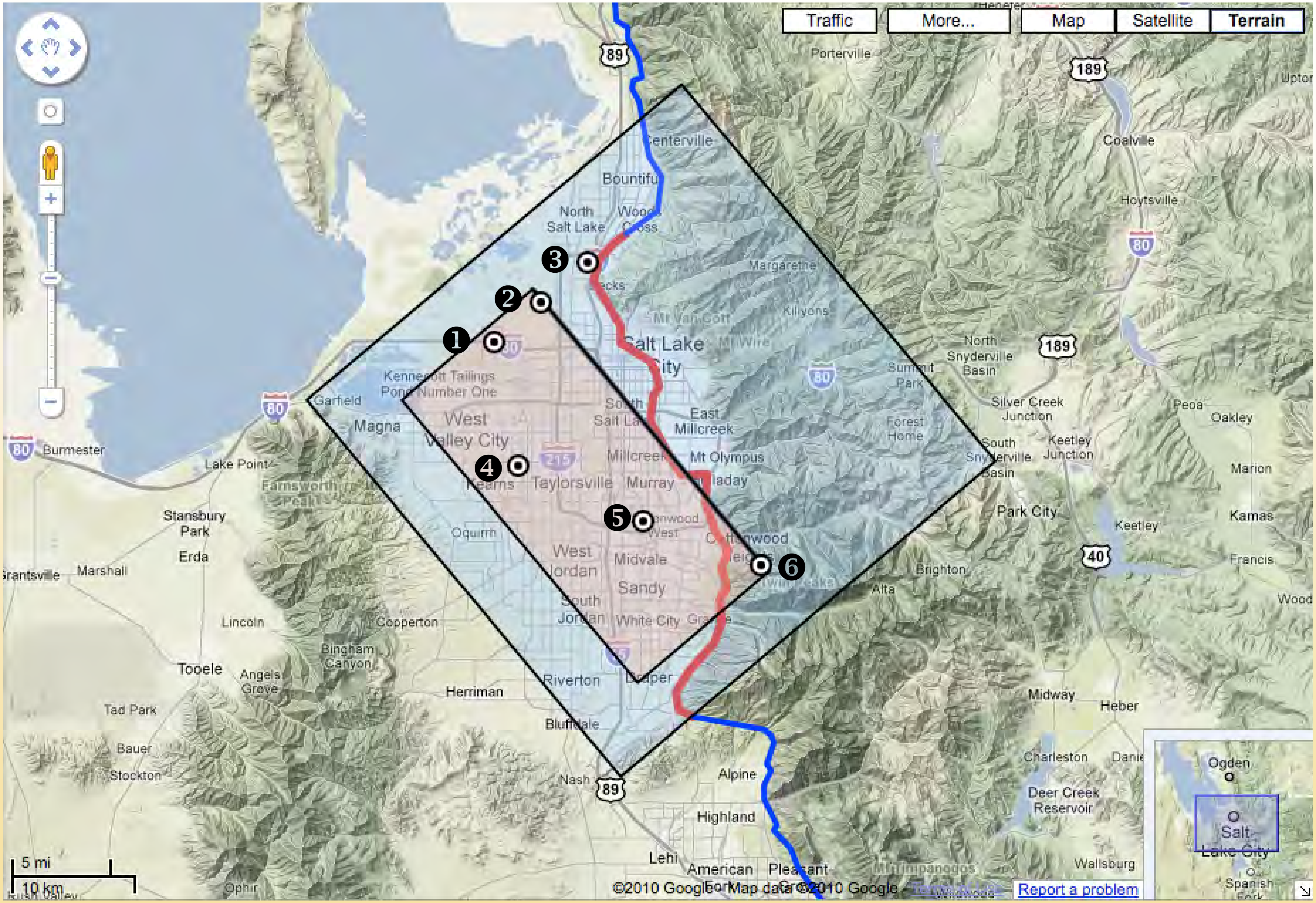
Robert Smith
Christine Puskas
University of Utah

Overview Map

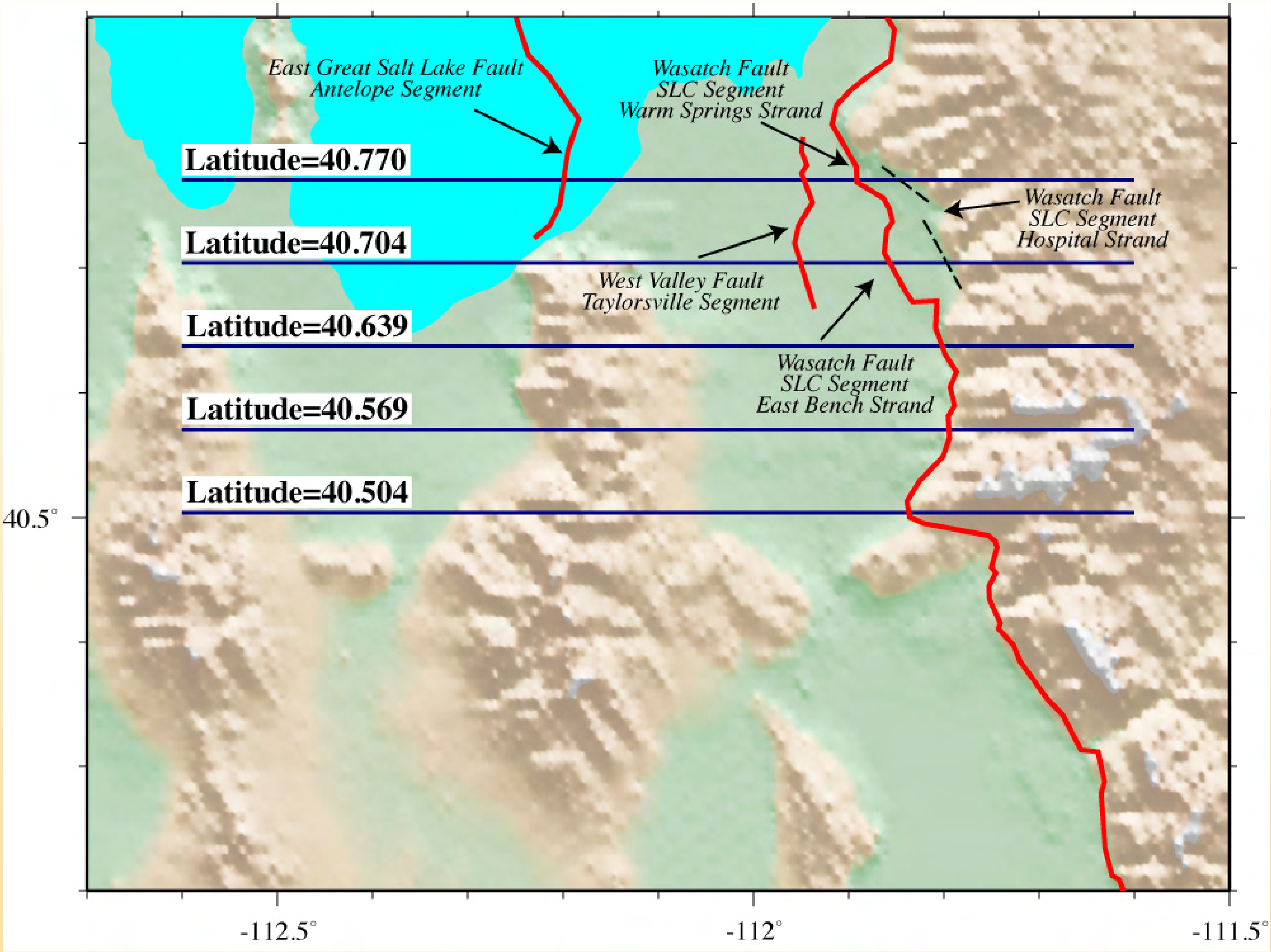
Fault Map
(Wasatch Fault SLC Segment)



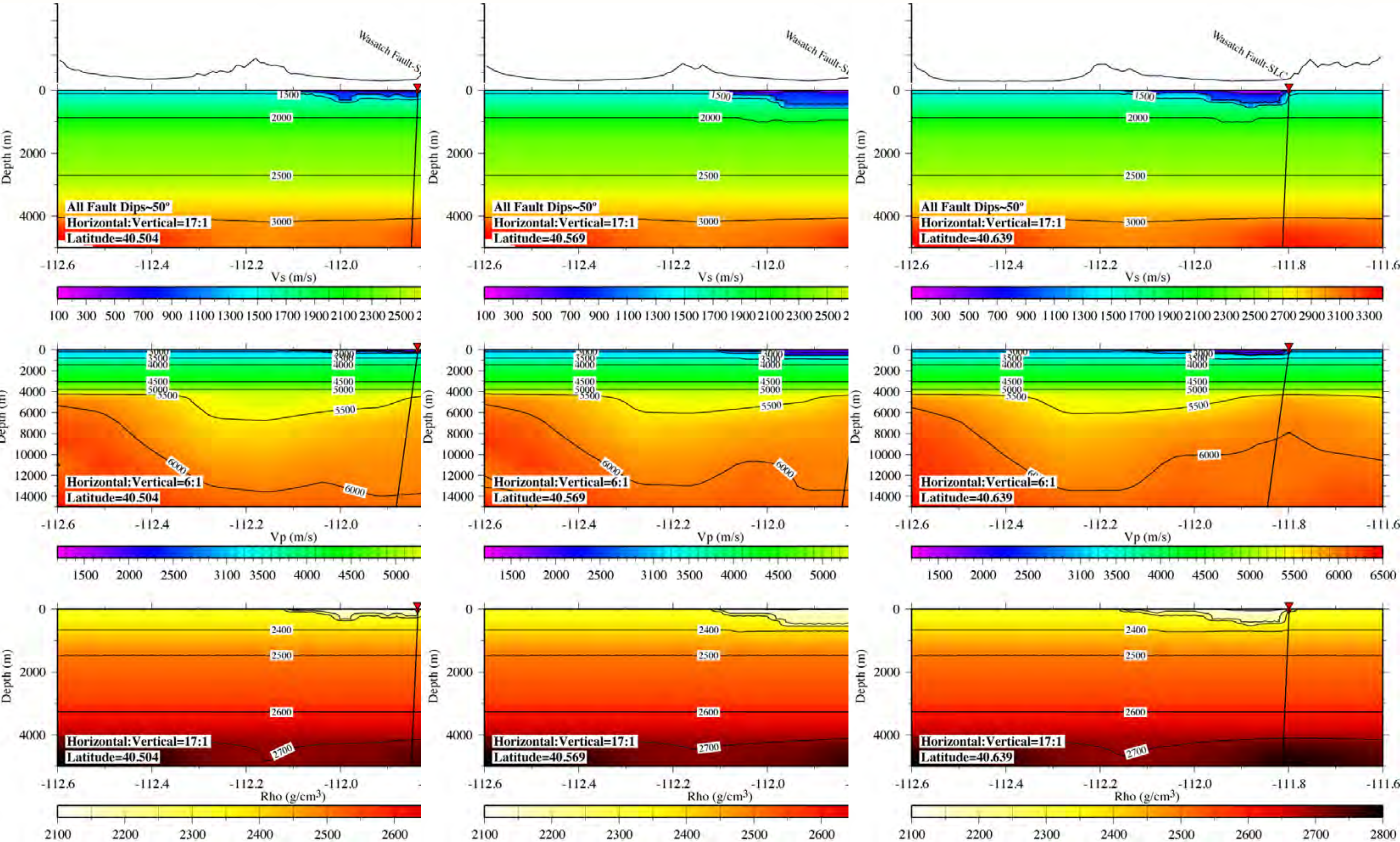
Modeling Area



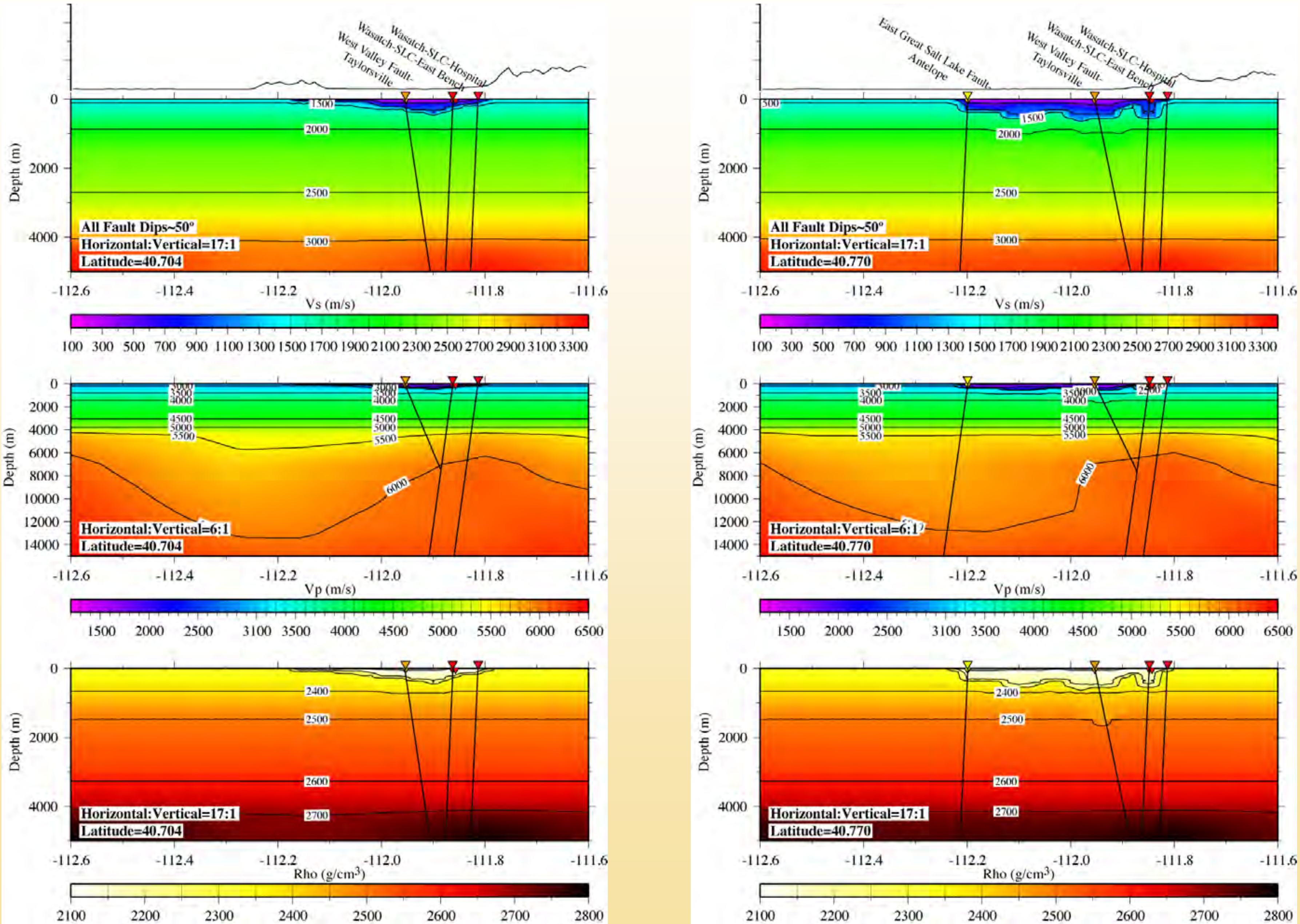
Velocity Structure Profiles



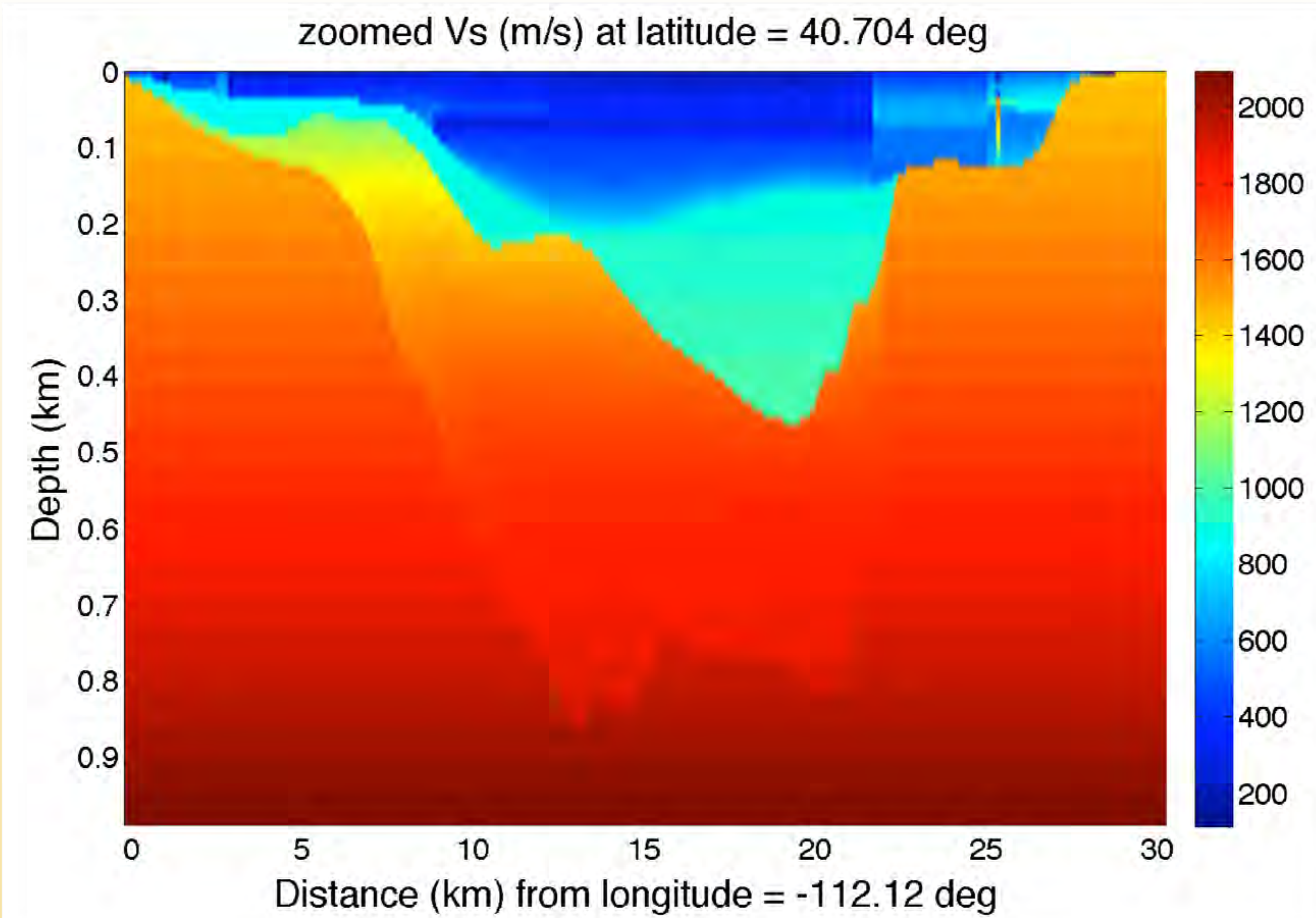
Velocity Structure Profiles (1)



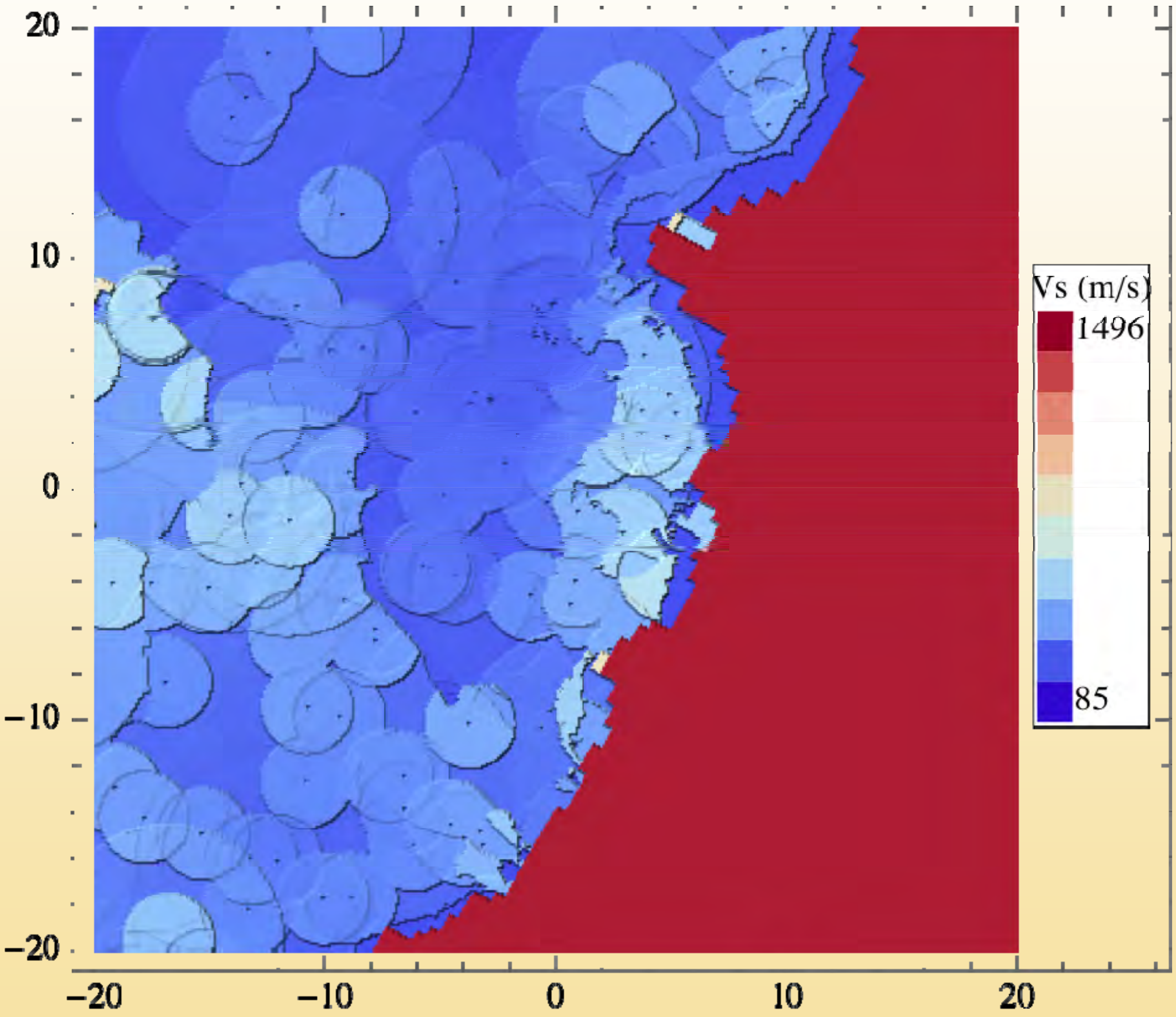
Velocity Structure Profiles (2)



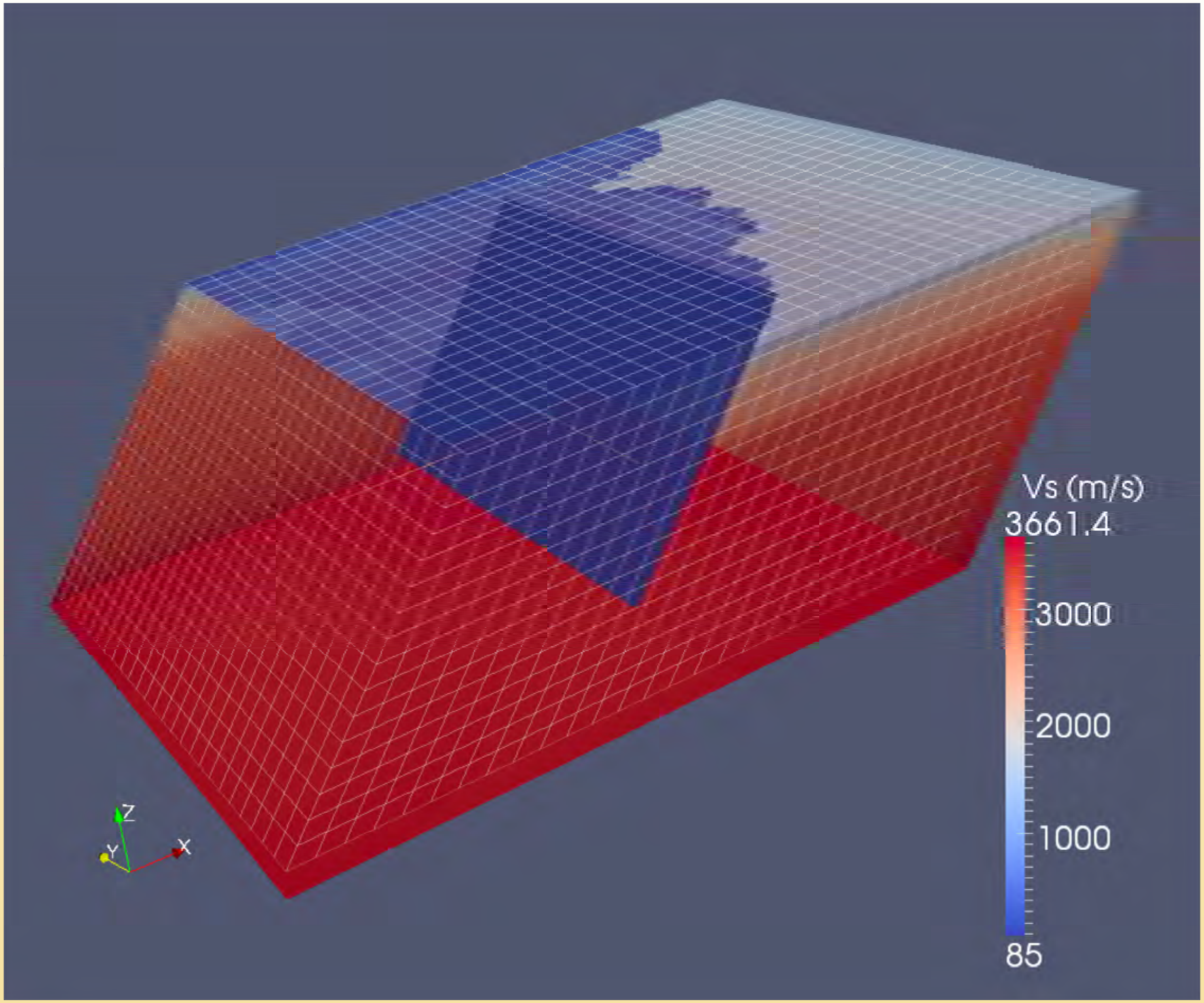
Velocity Structure Zoomed



Plan View of the Velocity Structure on Free Surface



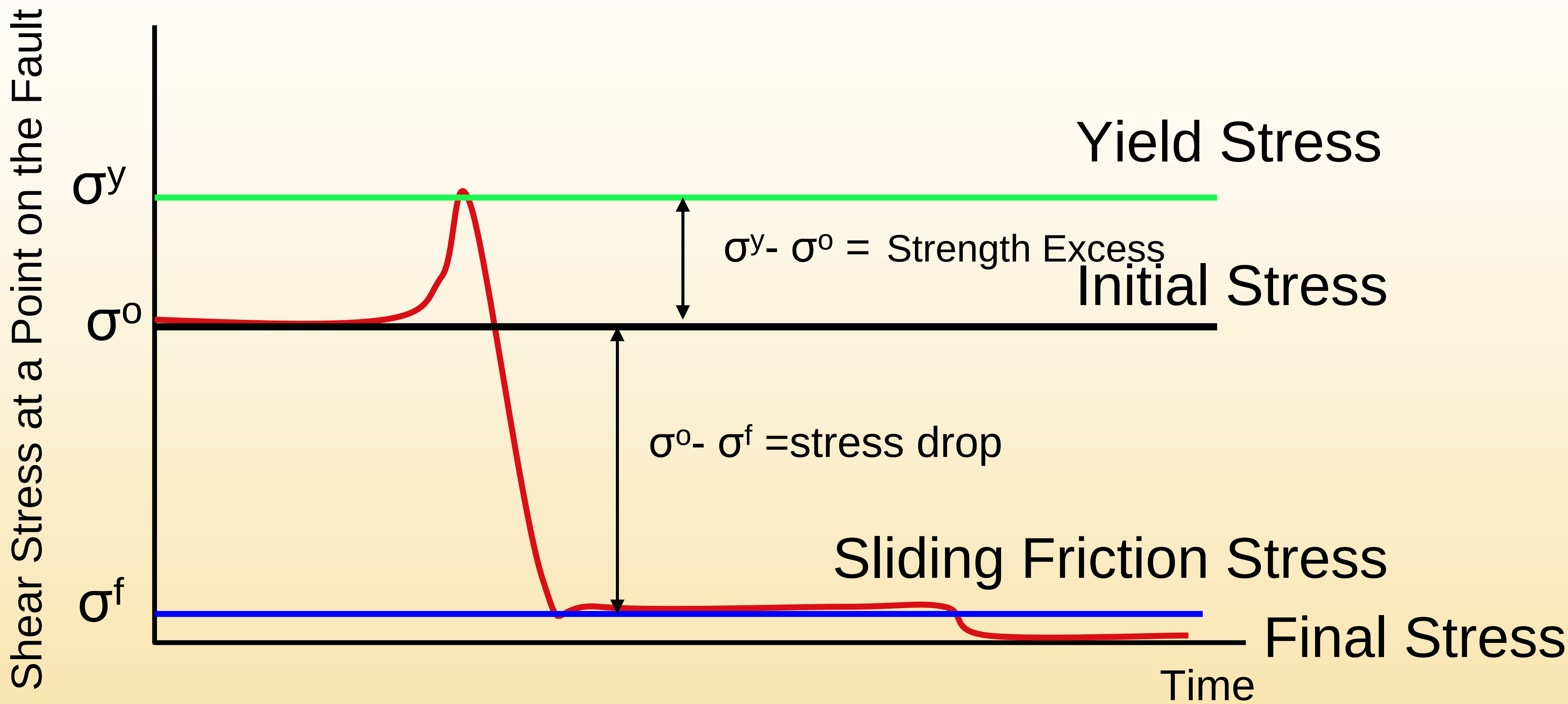
Meshing



Basic Parameters

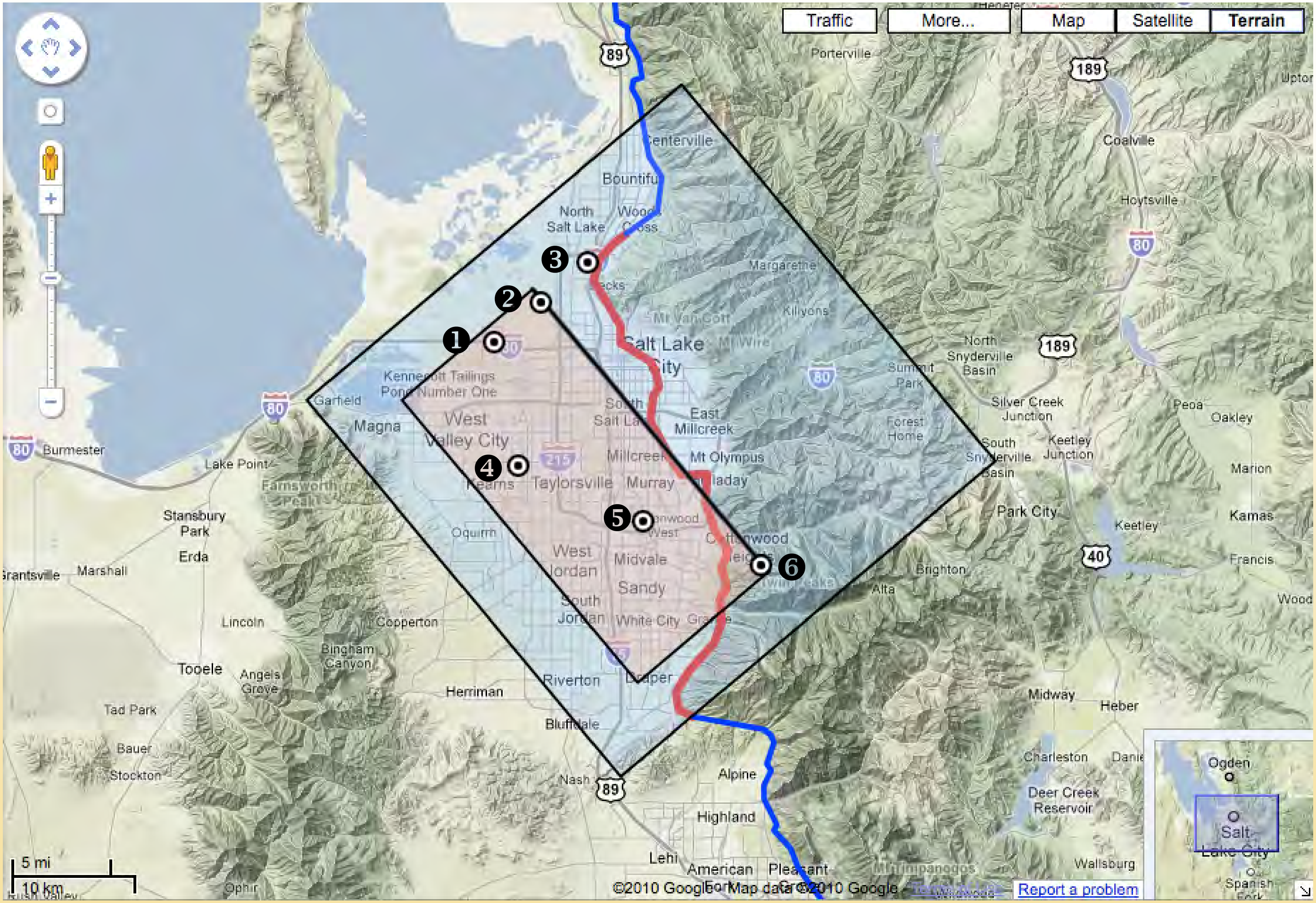
Lx, Ly, Lz	40 km, 40 km,17 km
dx, dy, dz	50 m, 50 m ,50 m
strike, dip angle	150˚, 50˚
Friction law	Slip-weakening
initial normal stress	36 MPa
µ0, µd , µs, S	0.55, 0.448, 0.66, 1.1
Dc	0.25 m
tmax	30 s
Vs minimum	500 m/s
Maximum Freq	1 Hz

Behavior of Shear Stress at a Point on the Fault

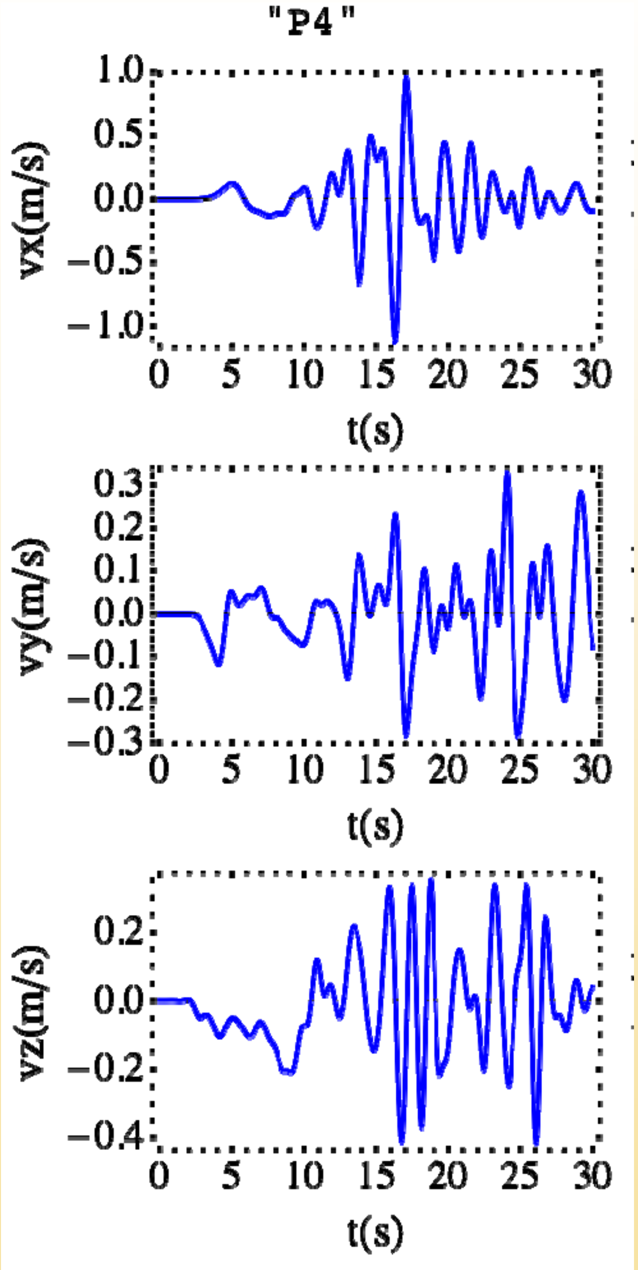


S= Strength Excess/Stress Drop

Modeling Area



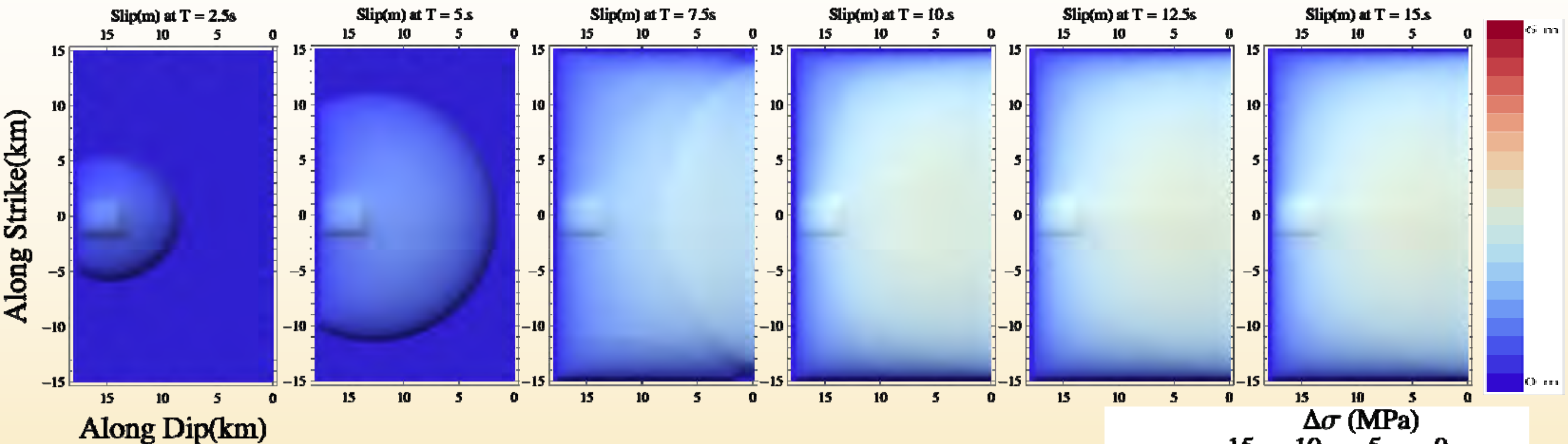
Ground Motion Parameters



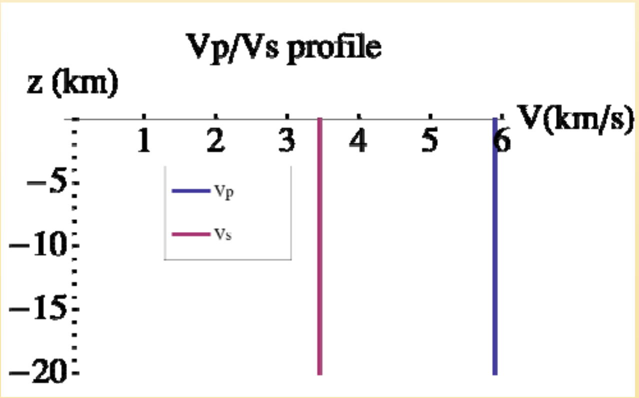
$$PHV = \sqrt{V_x(\max)^2 + V_y(\max)^2}$$

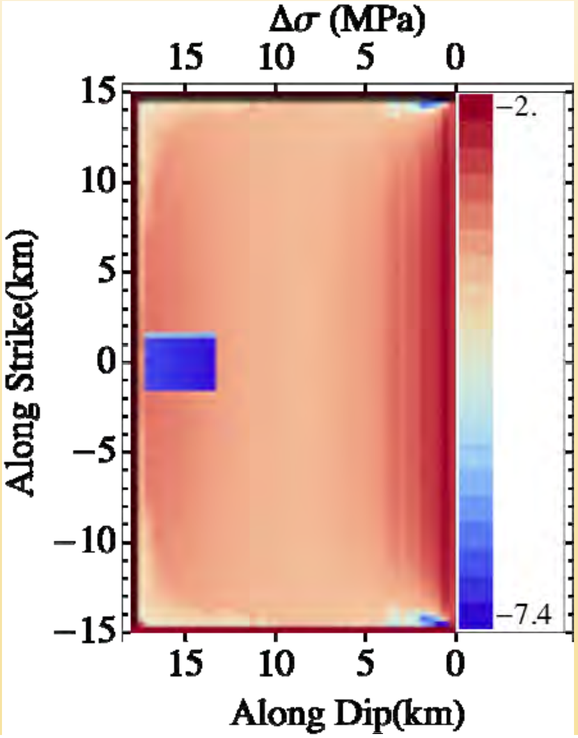
$$CAV = \int_0^{t\max} |a(t)|\, dt$$

Case 1: Homogeneous space

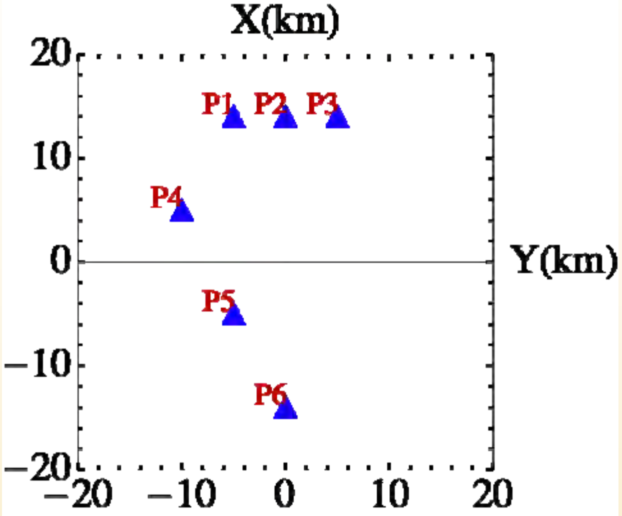


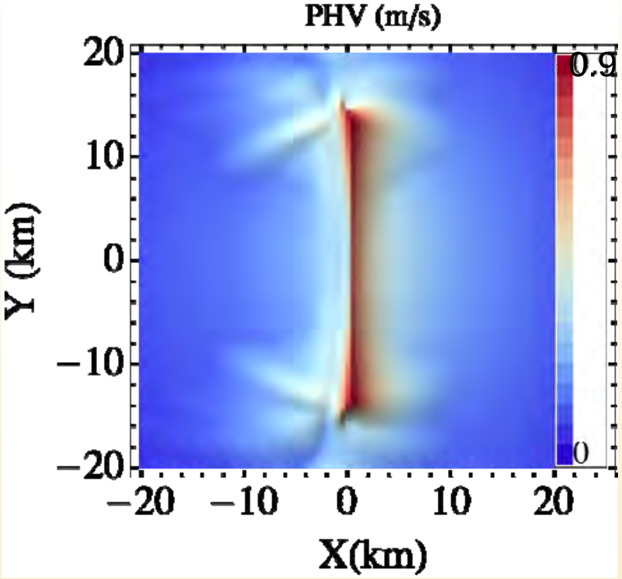
Simulation result from Model B, half space model, top row is the rupture snapshot.
Figure on the right is the shear stress drop due to the rupture.

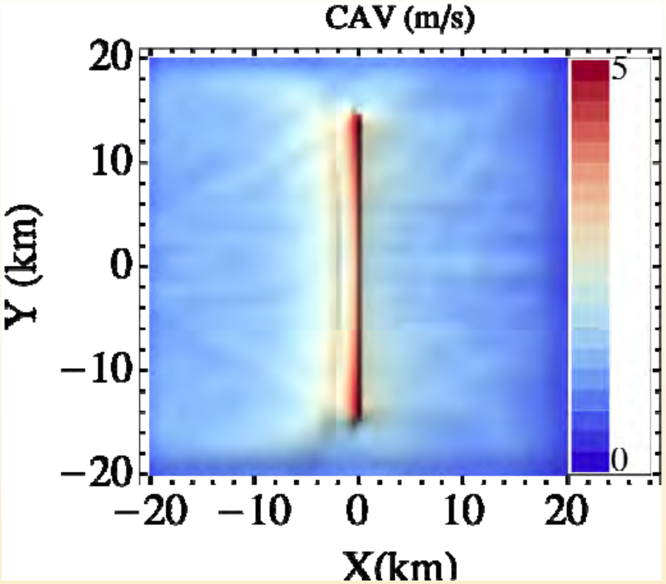


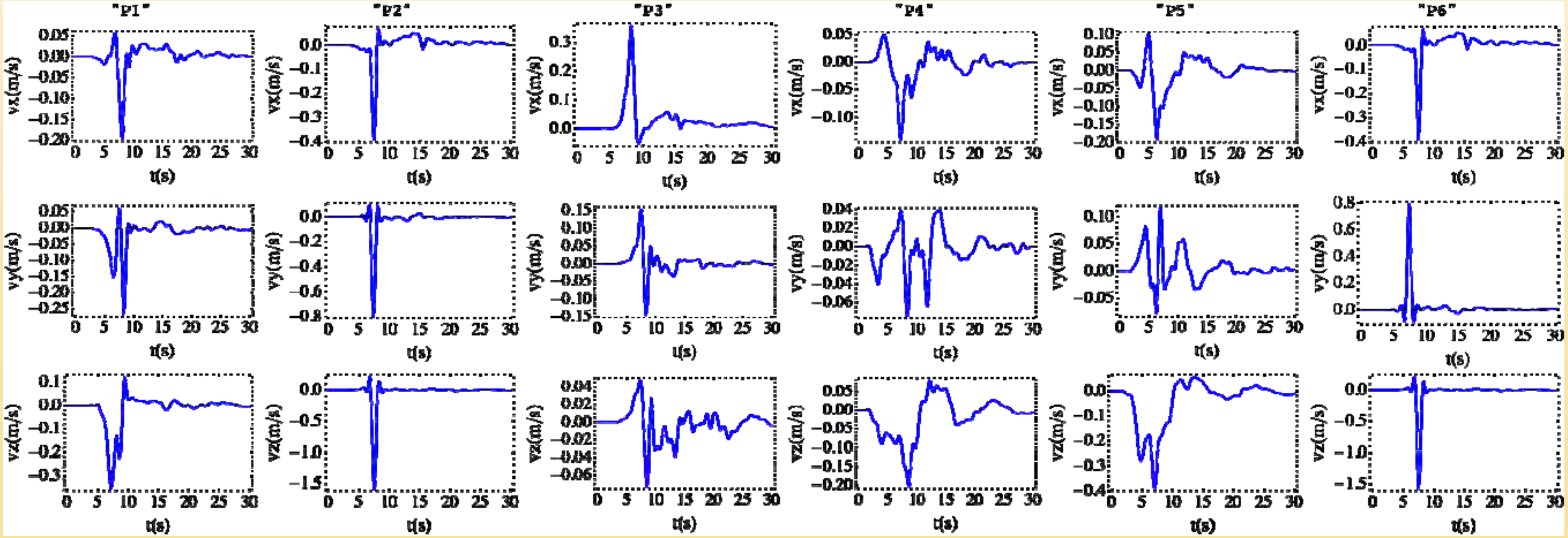


Case 1 : Ground Motion

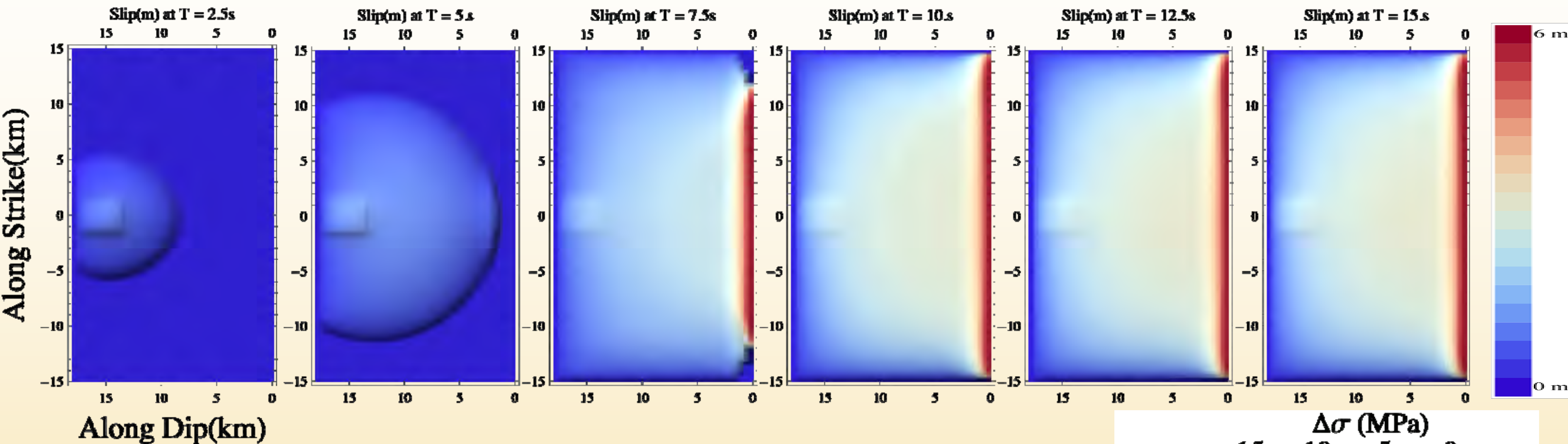




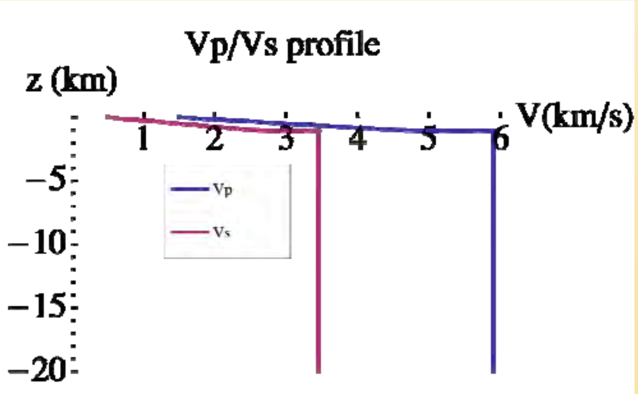


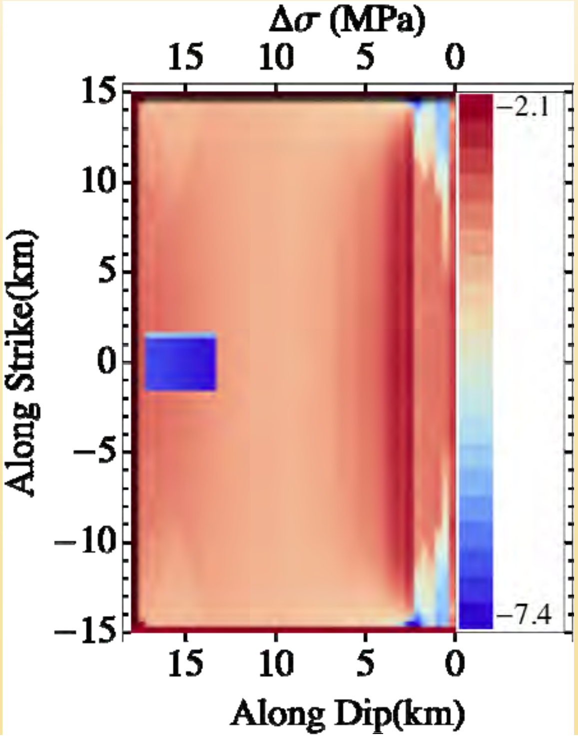


Case 2: Layered Model

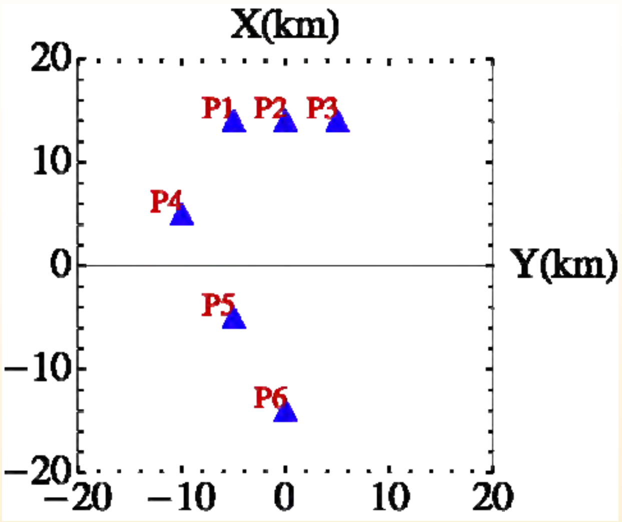


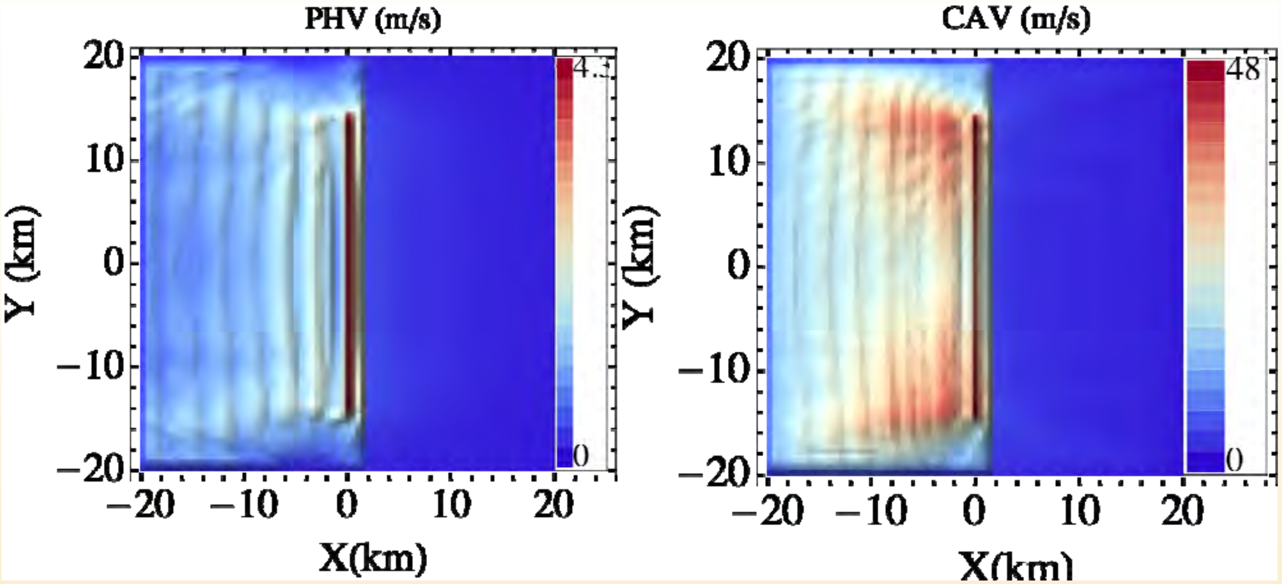
Simulation result from Model C, simplified layered model (velocity increase from free surface to 1km depth on the hanging wall side), top row is the rupture snapshot. Figure on the right is the shear stress drop due to the rupture.

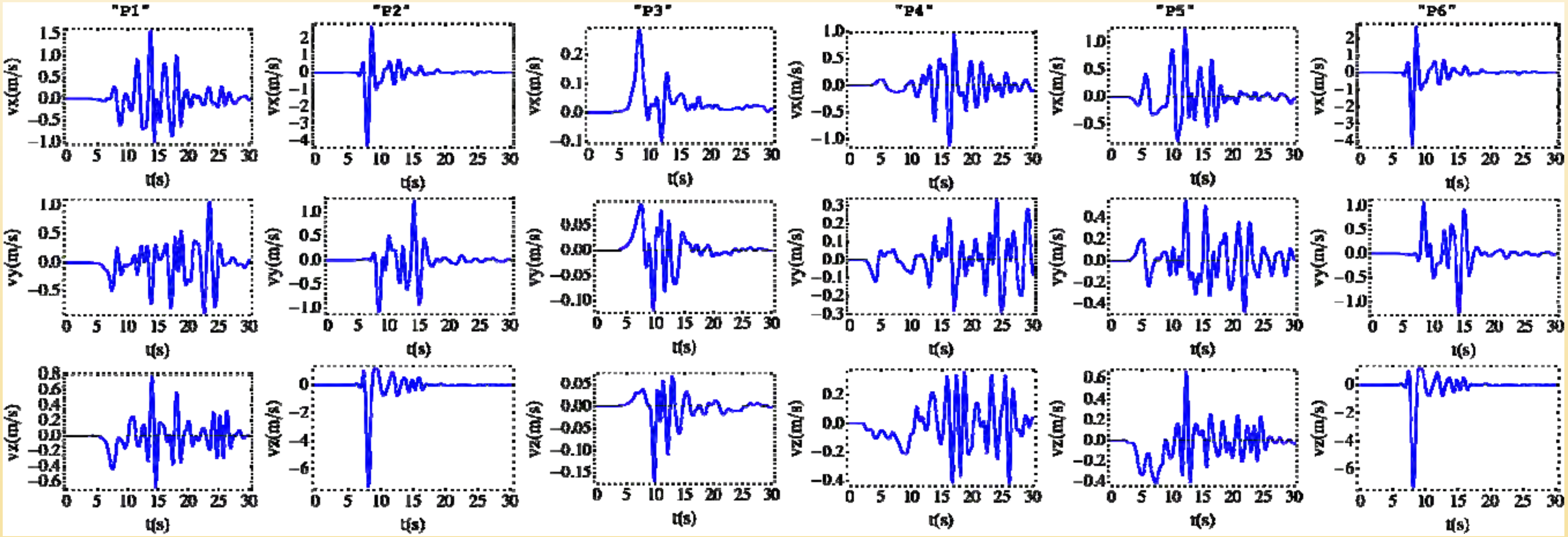




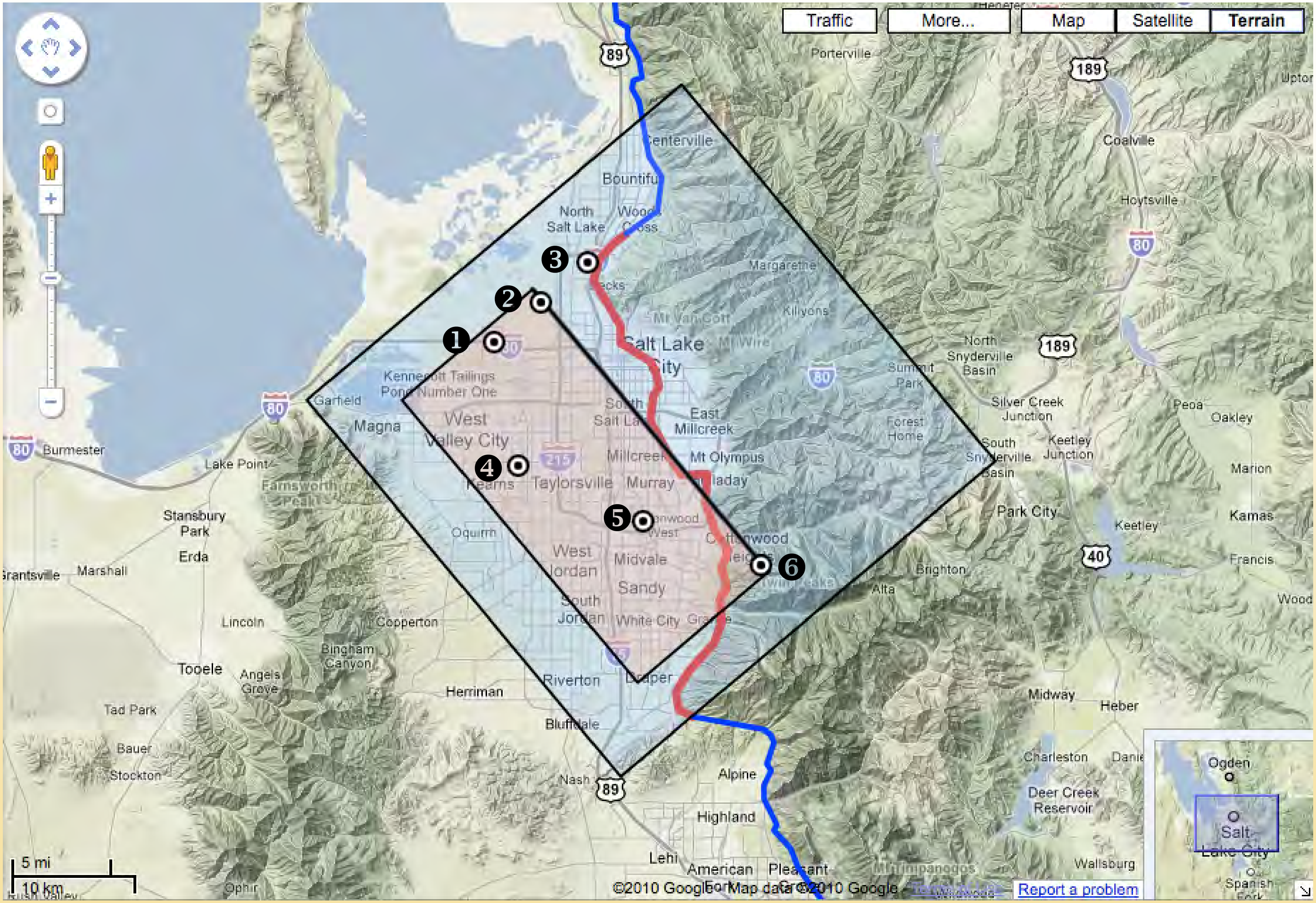
Case 2: Ground Motion



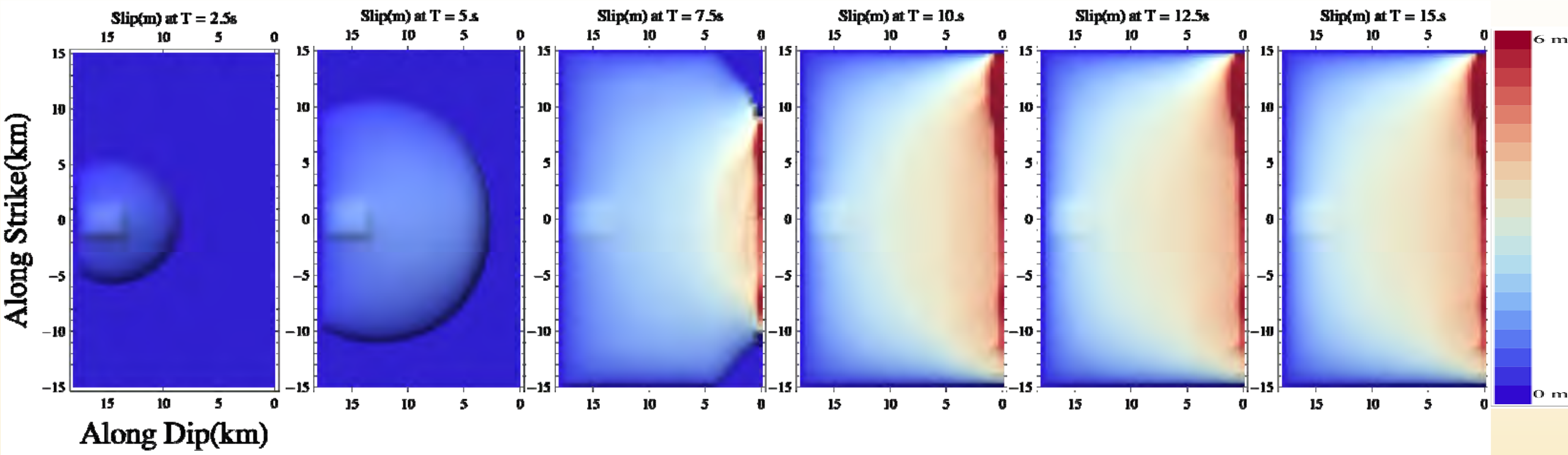




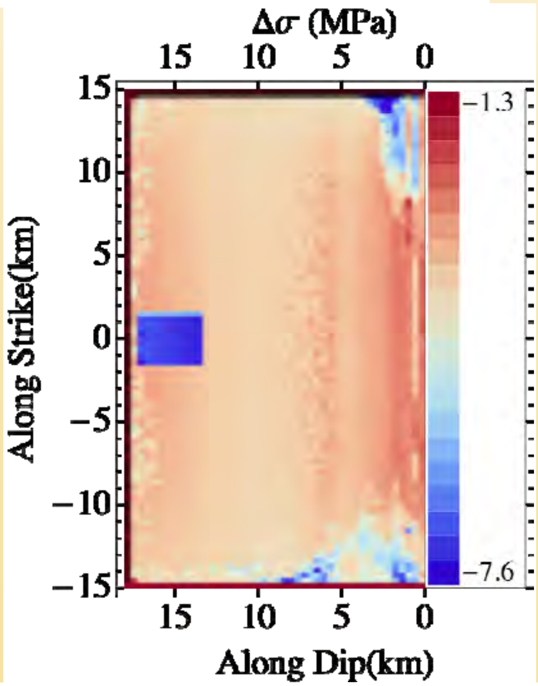
Modeling Area



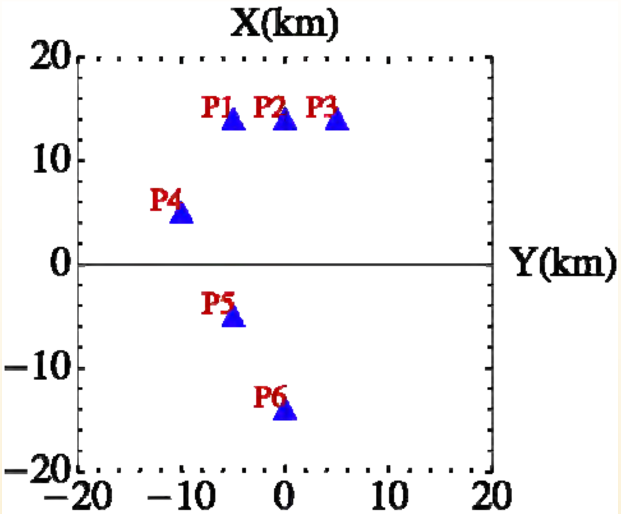
Case 3: Community Velocity Model

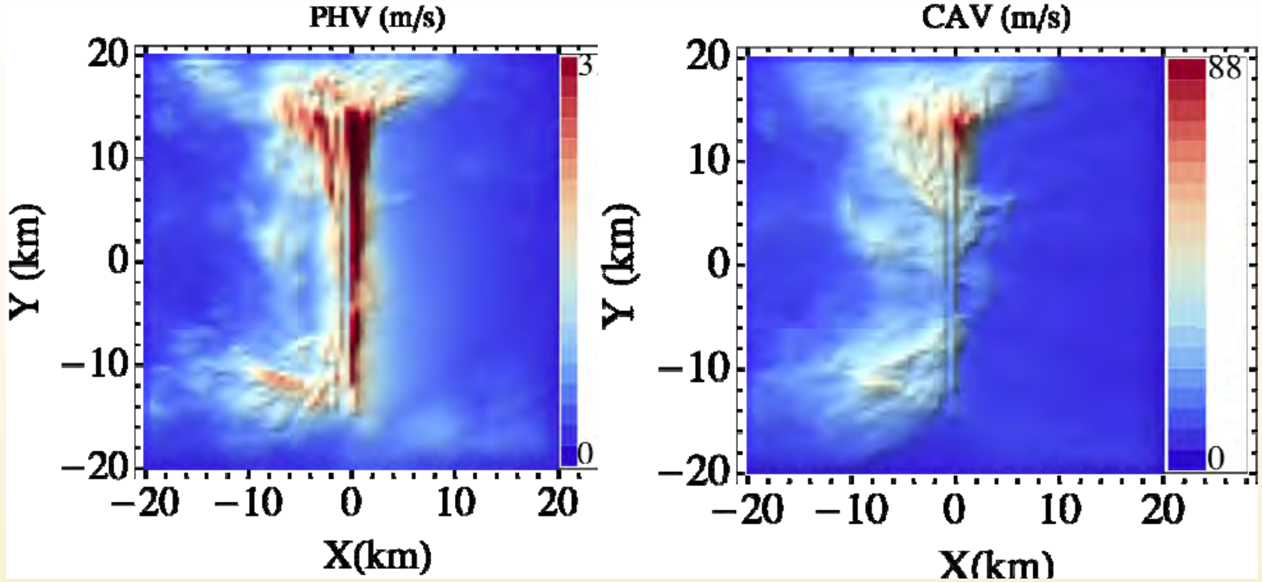


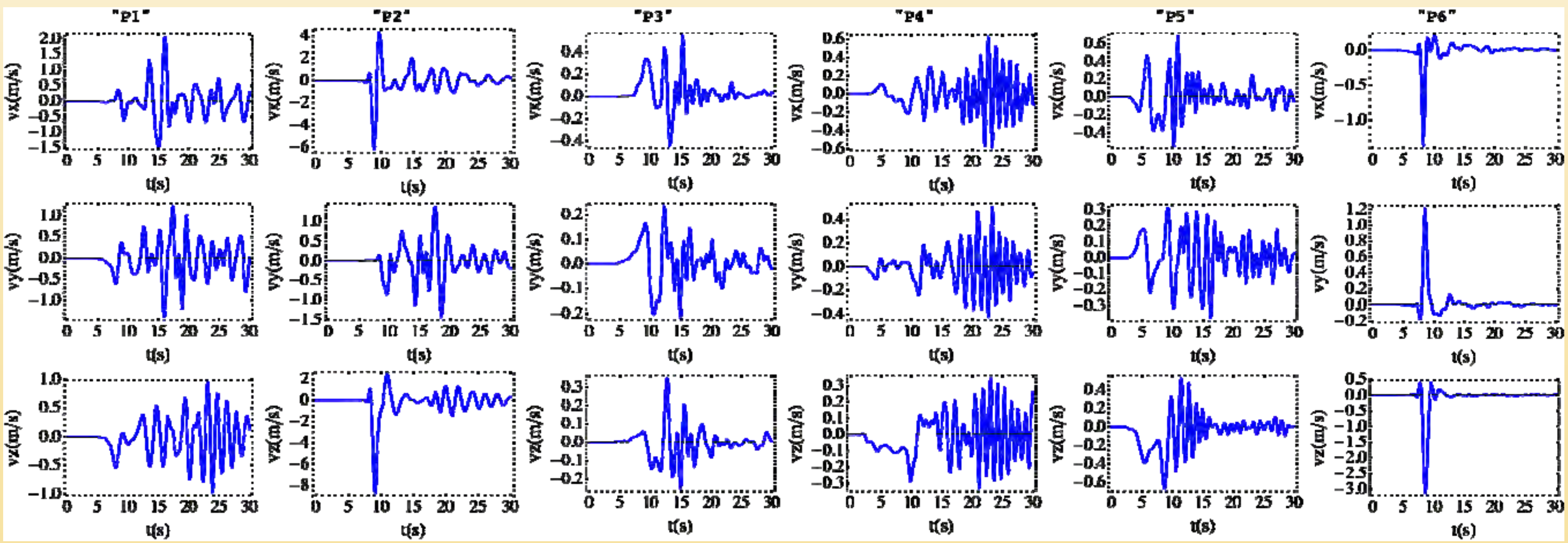
Simulation result from Model A, with WFCVM model, top row is the rupture snapshot. Figure on the right is the shear stress drop due to the rupture.



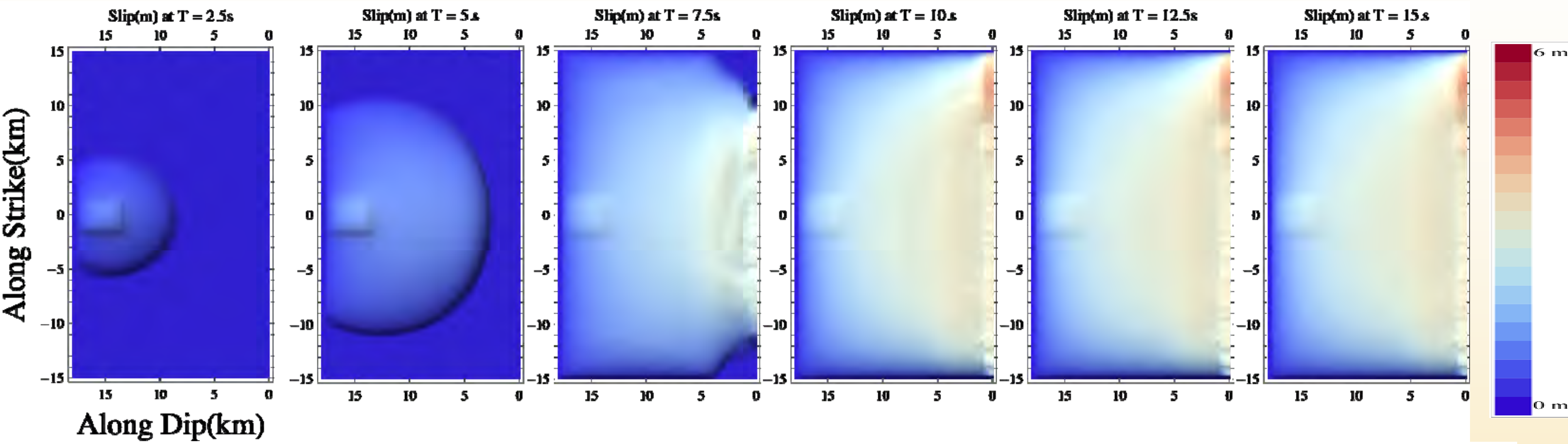
Case 3: Ground Motion



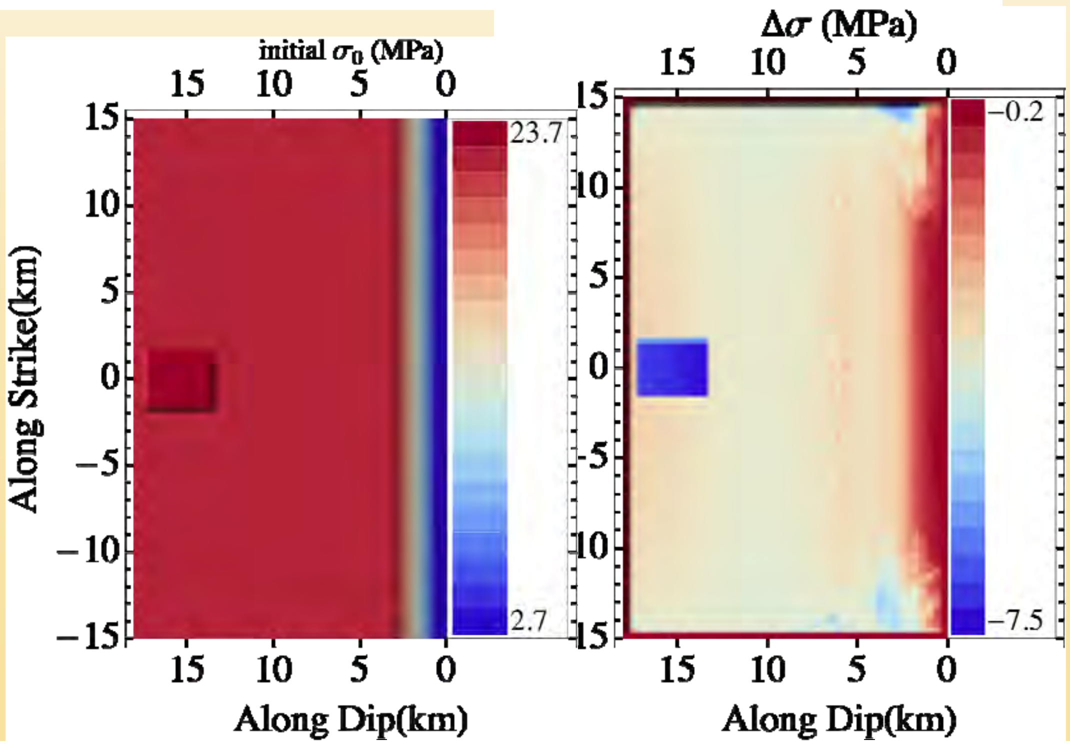




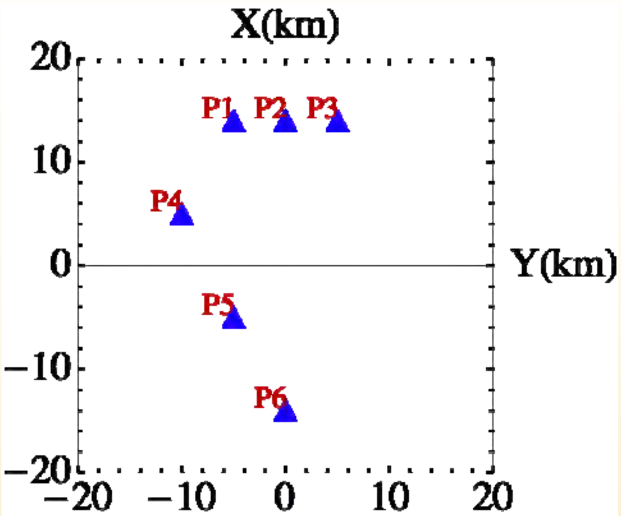
Case 4: Depth Dependent Initial Stress

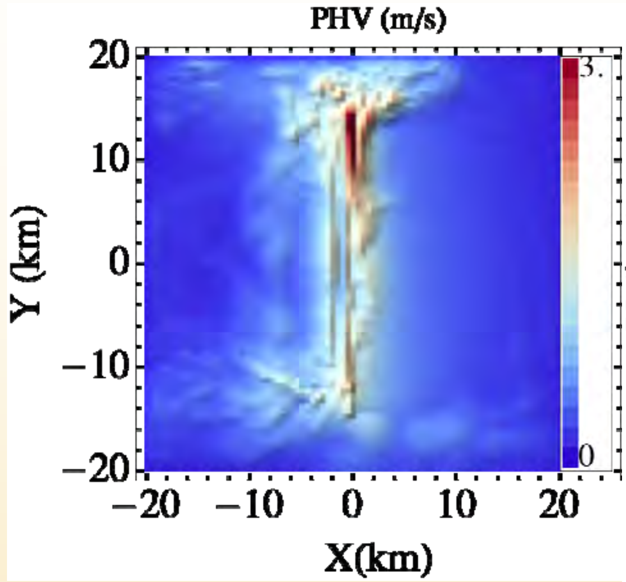


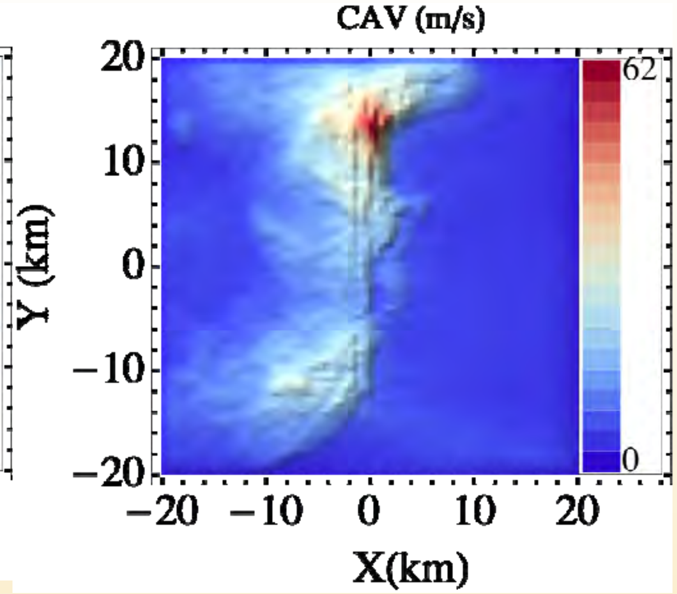
Simulation result from Model E, WFCVM velocity structure with increasing initial stress from free surface to 2km depth, top row is the rupture snapshot.
Figure on the right is the shear stress drop due to the rupture.

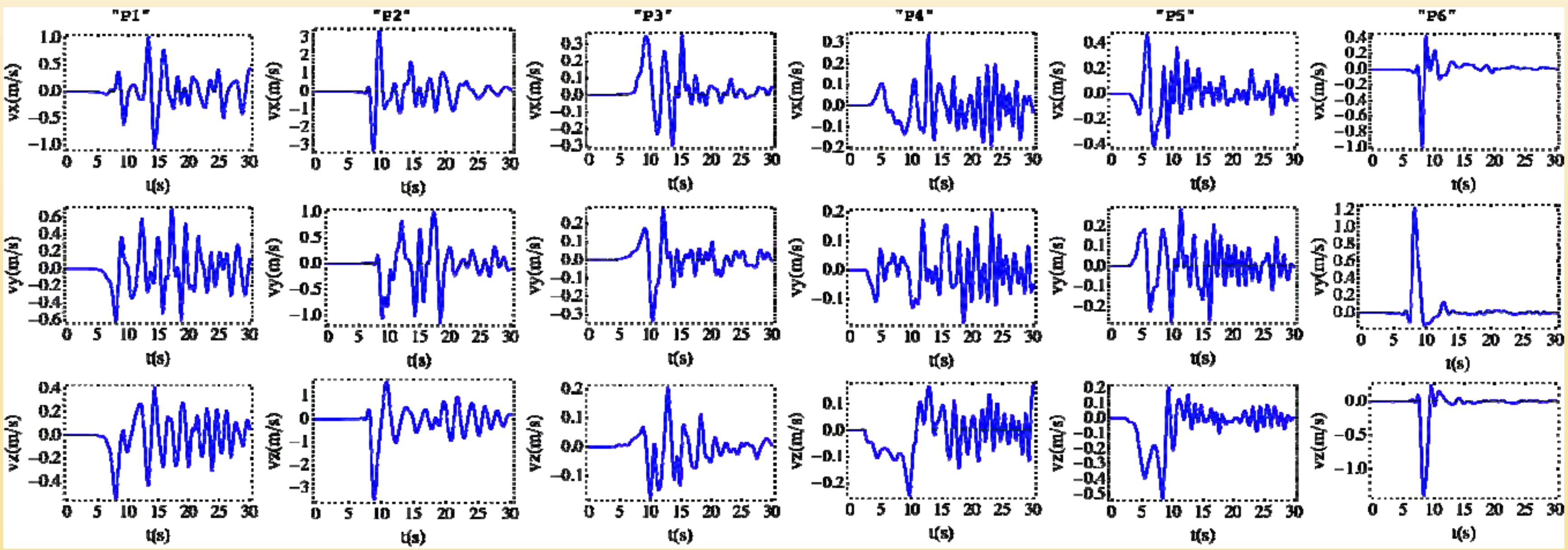


Case 4: Ground Motion

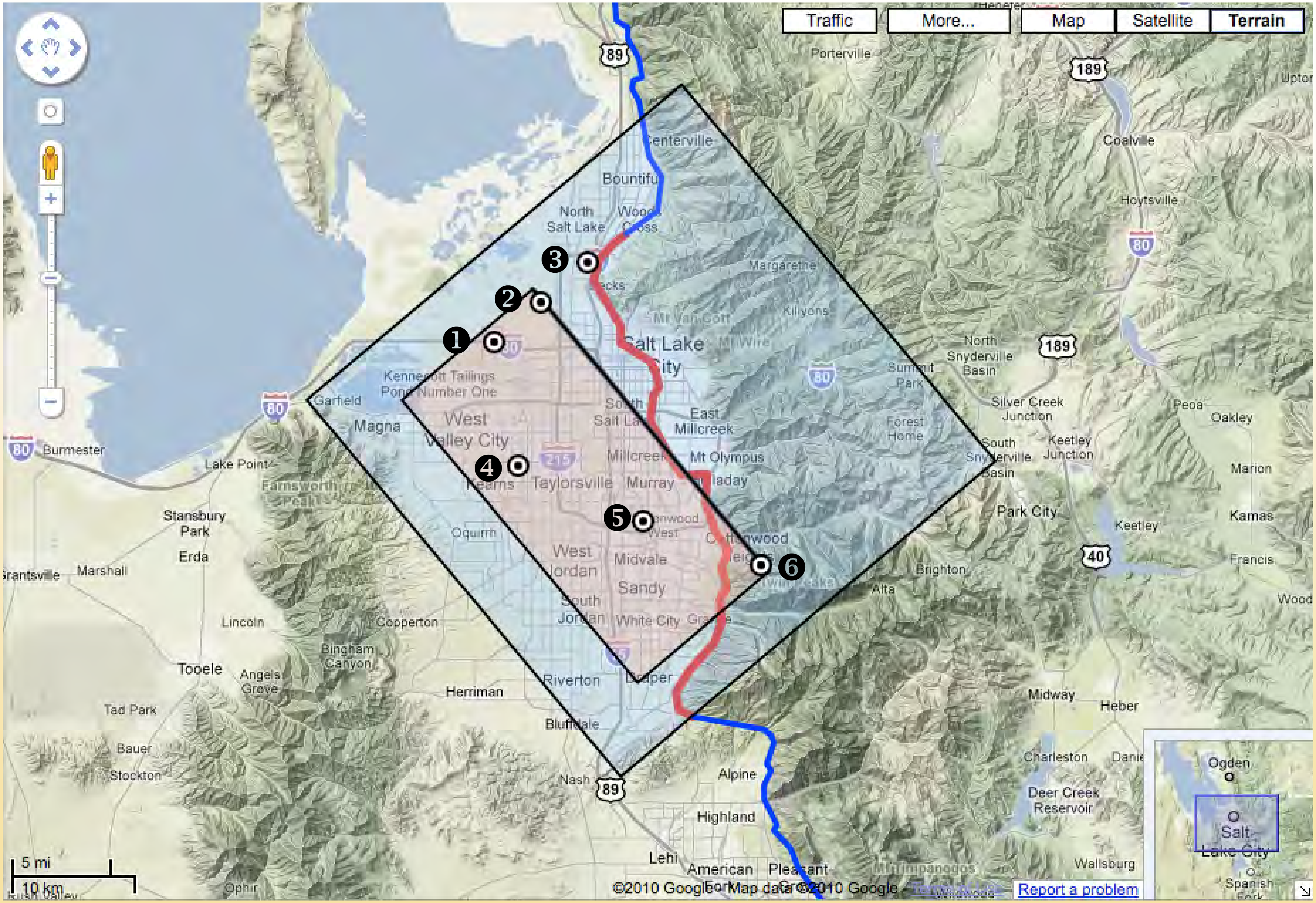




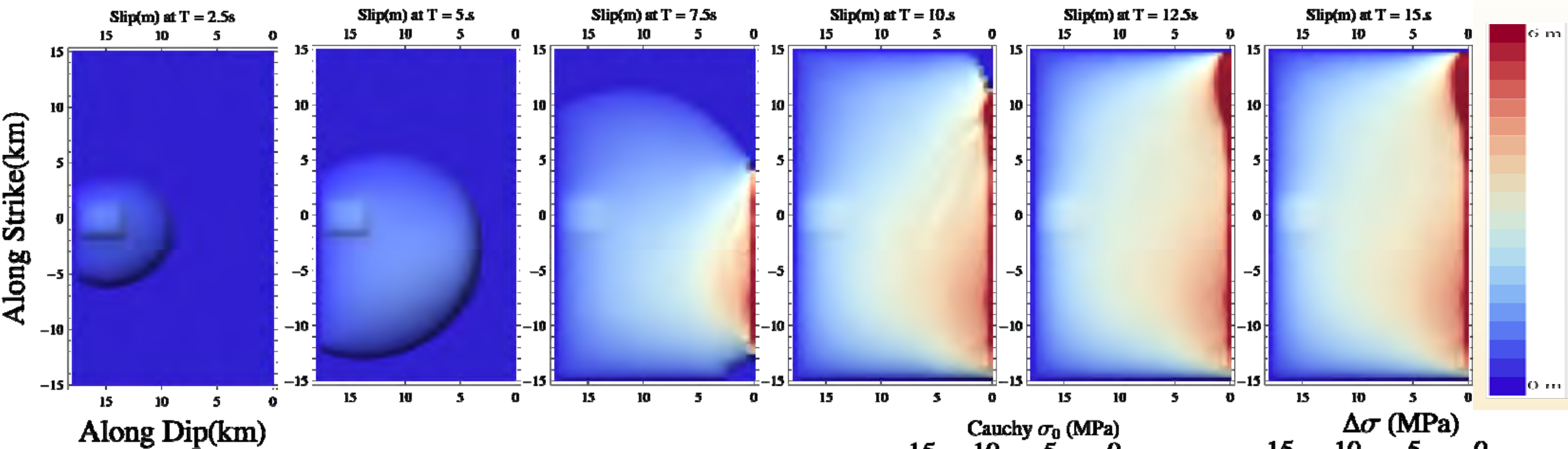


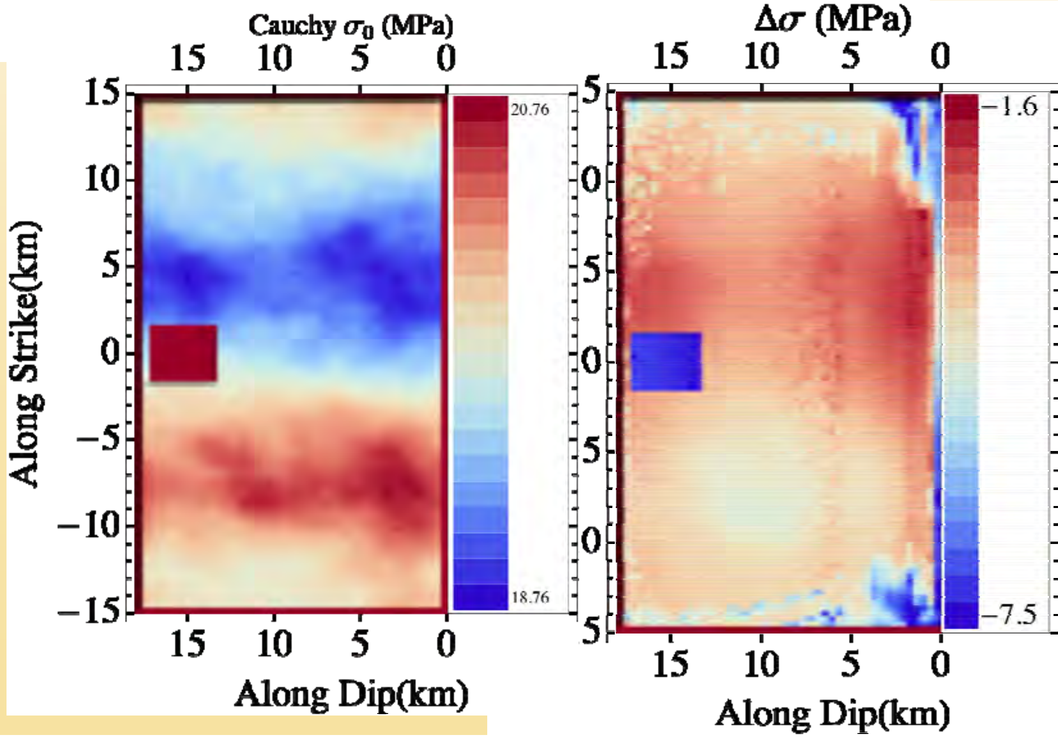


Modeling Area



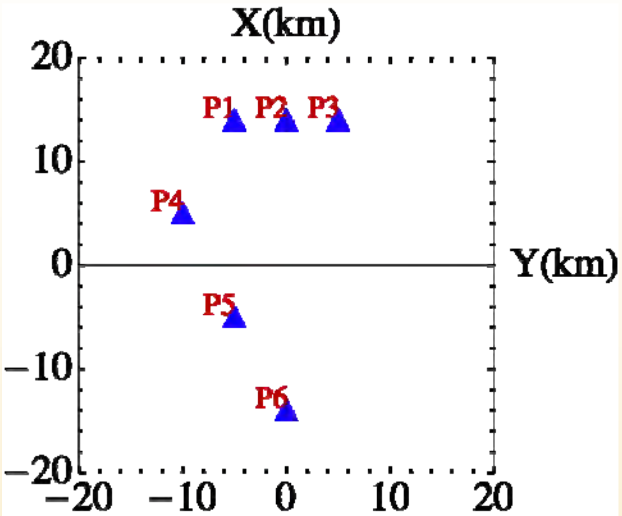
Case 5: Random Initial Stress

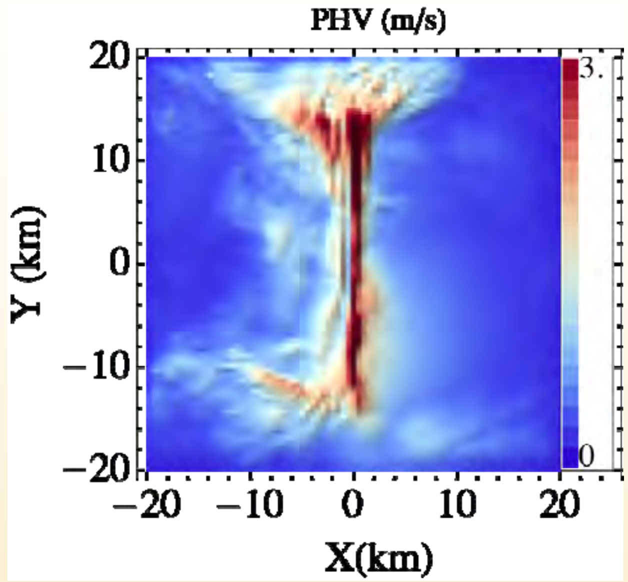


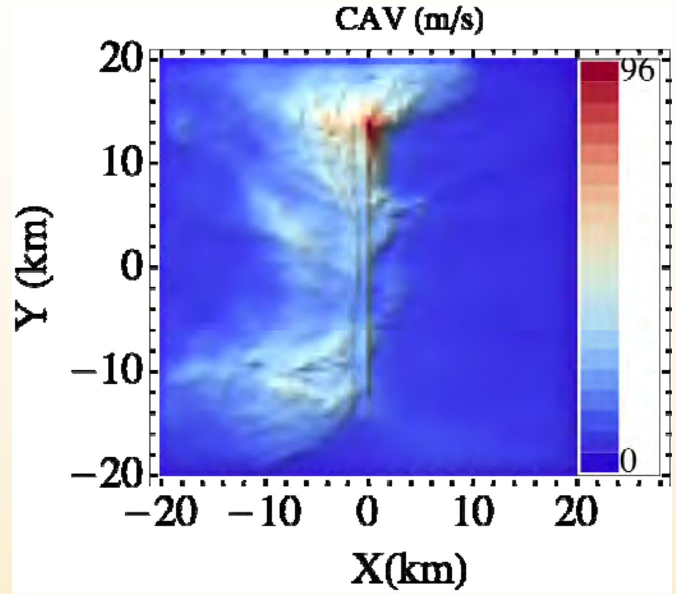


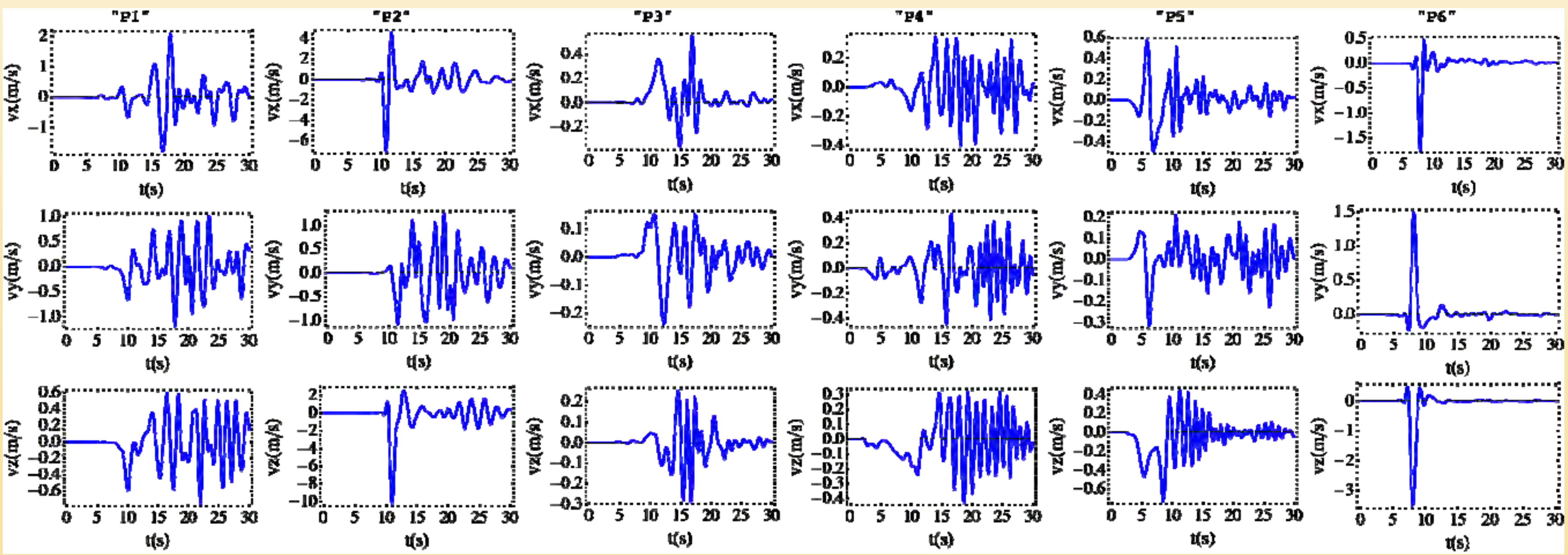
Simulation result from Model D, WFCVM velocity structure with random initial stress, top row is the rupture snapshot.
Figures on the right are the initial shear stress distribution and shear stress drop due to the rupture.

Case 5 : Ground Motion

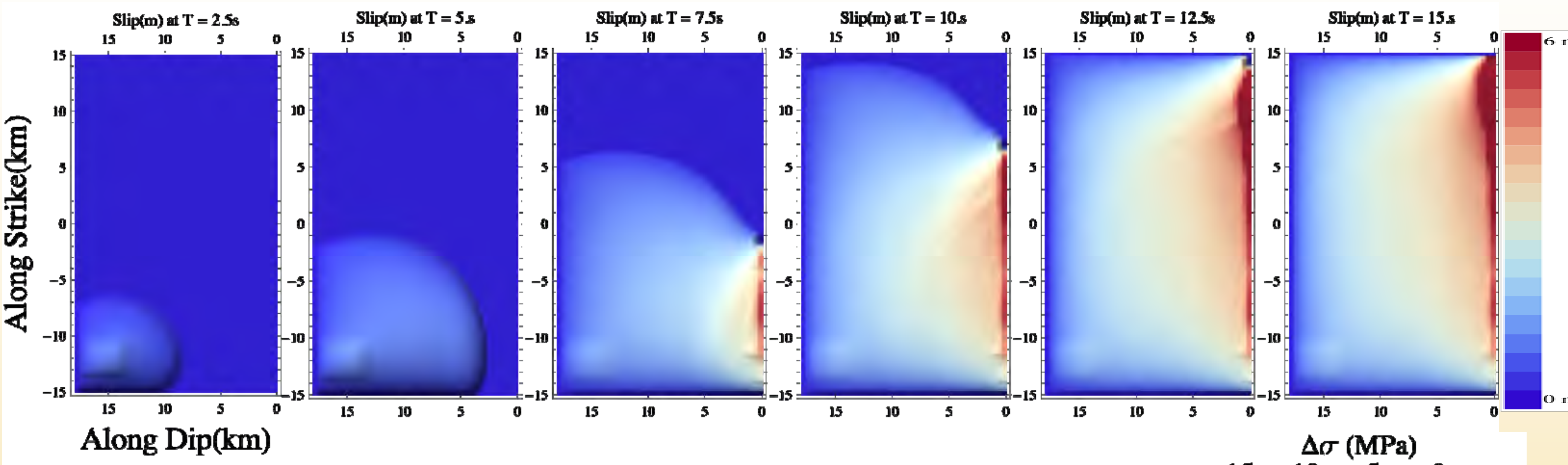




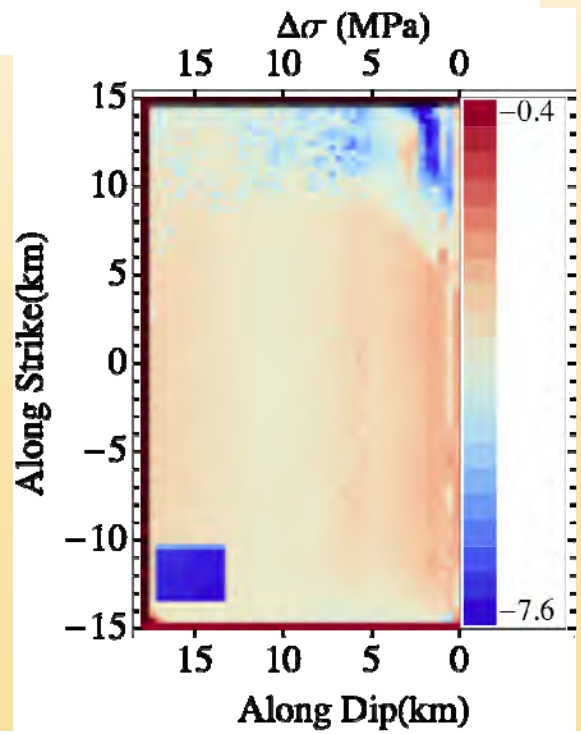




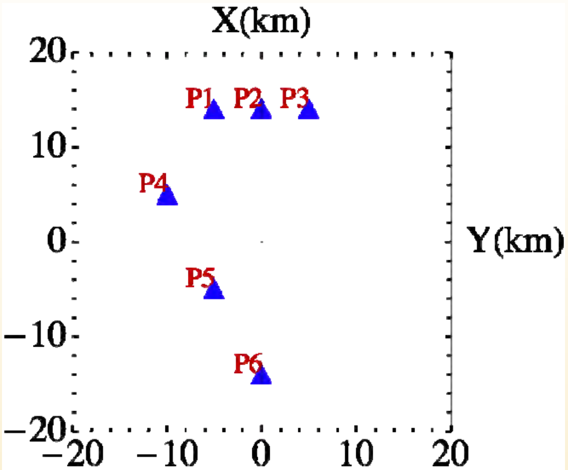
Case 6: Different Hypocenter

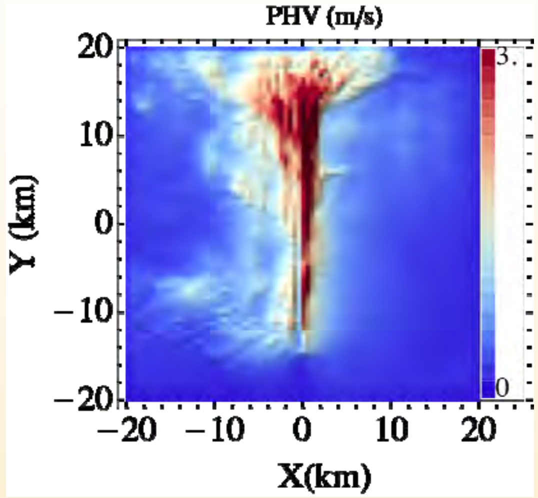


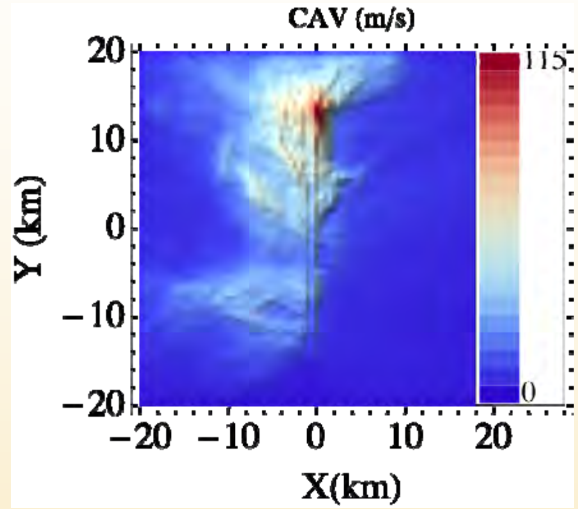
Simulation result from Model F, WFCVM velocity structure with hypocenter at bottom south corner, top row is the rupture snapshot.
Figure on the right is the shear stress drop due to the rupture.

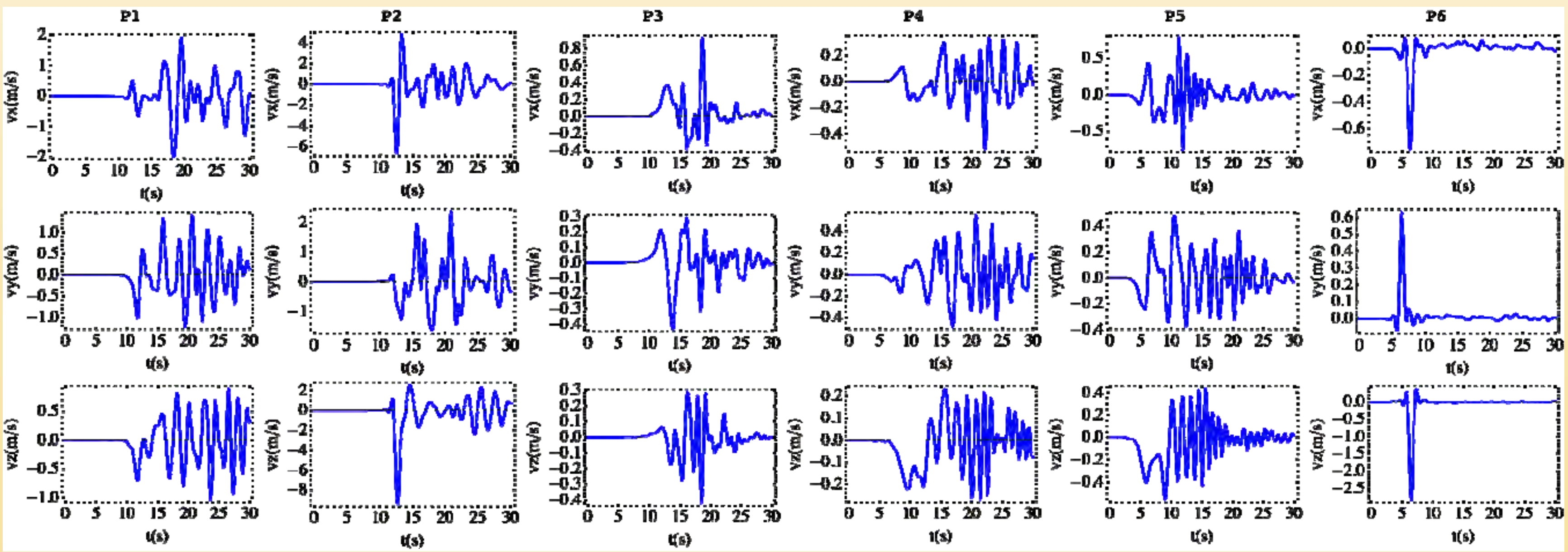


Case 6 : Ground Motion

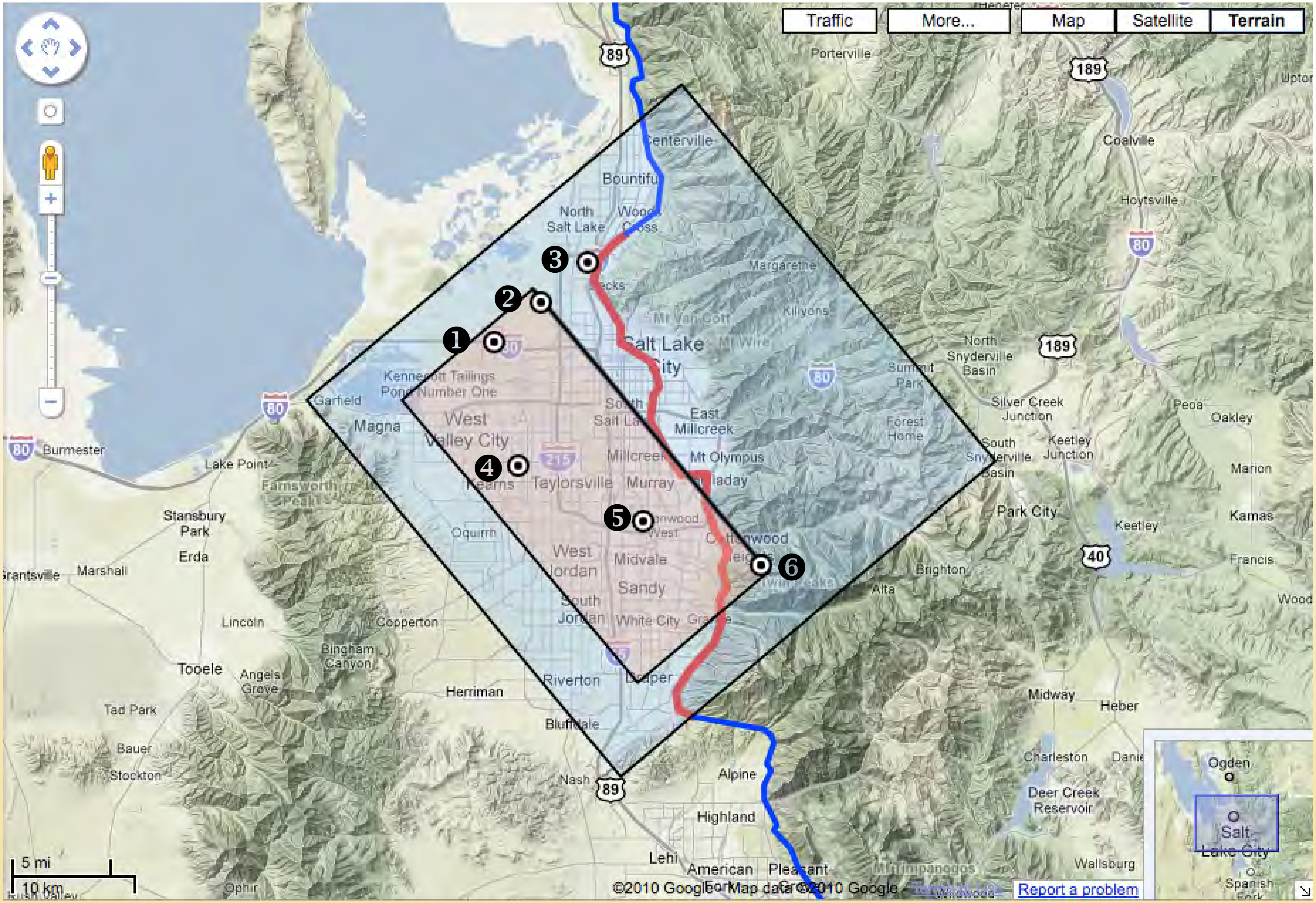








Modeling Area



Summary

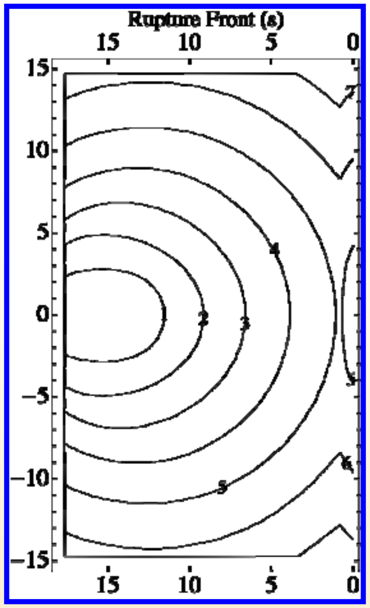
• There is a strong concentration energy near the crack tip leading to peak horizontal velocities that exceed 3 m/s.

• Hanging wall, sediments, have a primary effect.

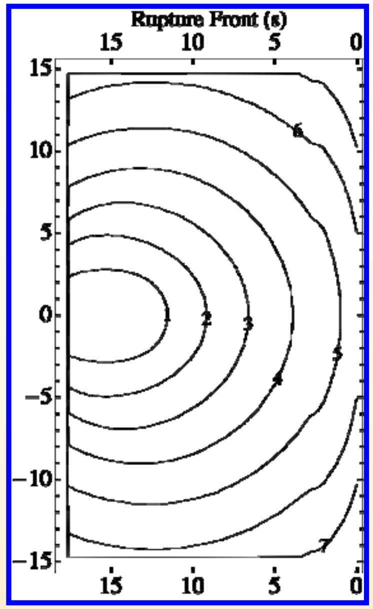
• Basin leads to longer duration; amplitudes ~0.2-0.5 m/s far from the fault.

Rupture Front Contours

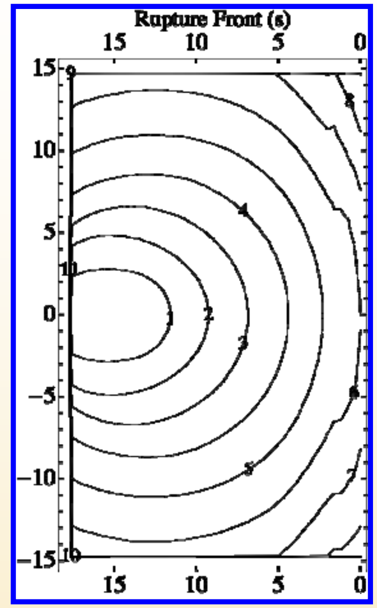
Homogeneous



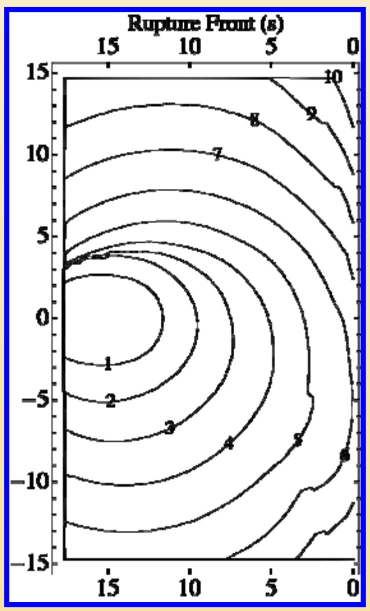
Layered Model



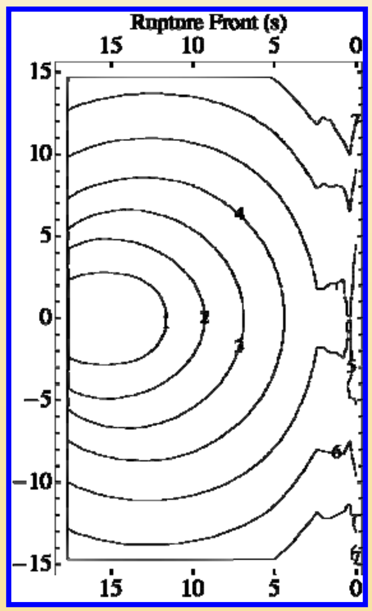
CVM



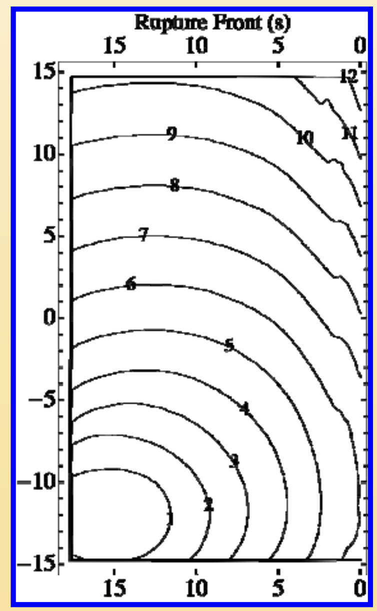
Random Initial stress



Depth Dep Initial Stress



Diff hyp=6

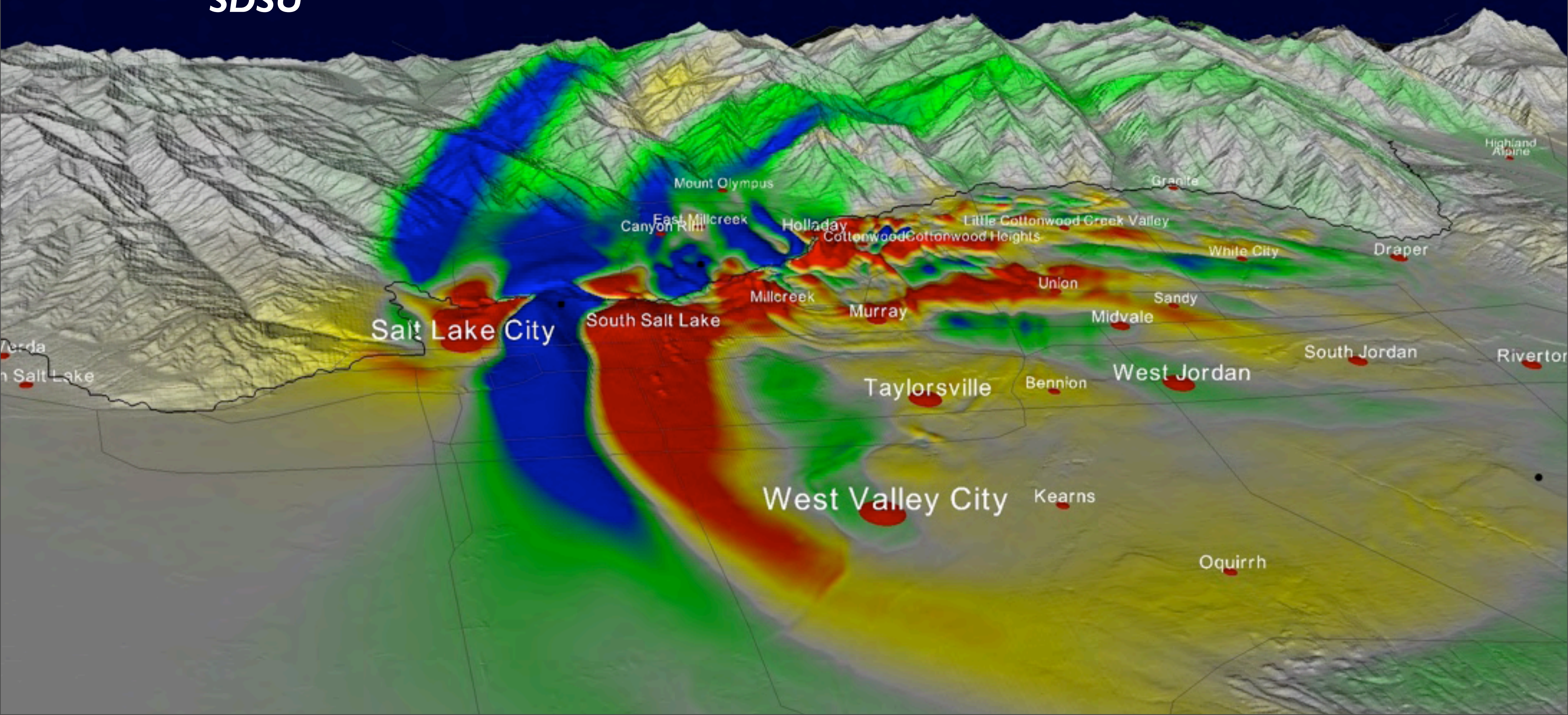


3D Nonlinear Broadband Ground Motion Predictions for M7 Earthquakes on the Salt Lake City Segment of the Wasatch Fault Using Dynamic Source Models

Daniel Roten
Kim B. Olsen
Harold W. Magistrale
SDSU

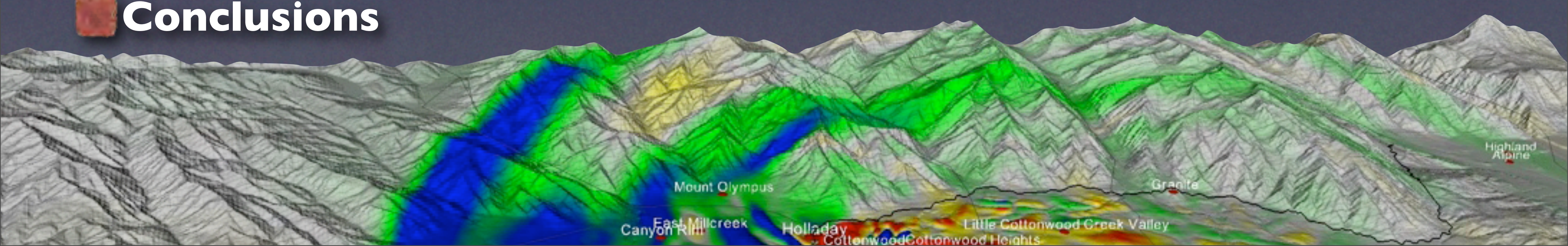
James C. Pechmann
University of Utah

Victor M. Cruz Atienza
UNAM



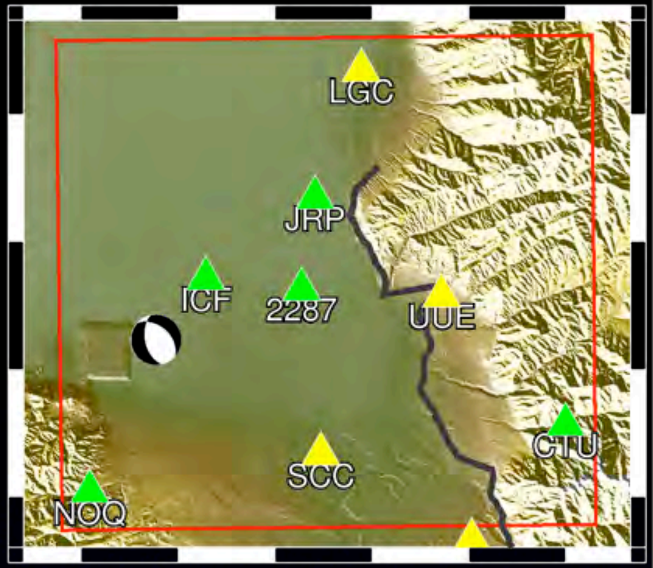
Outline

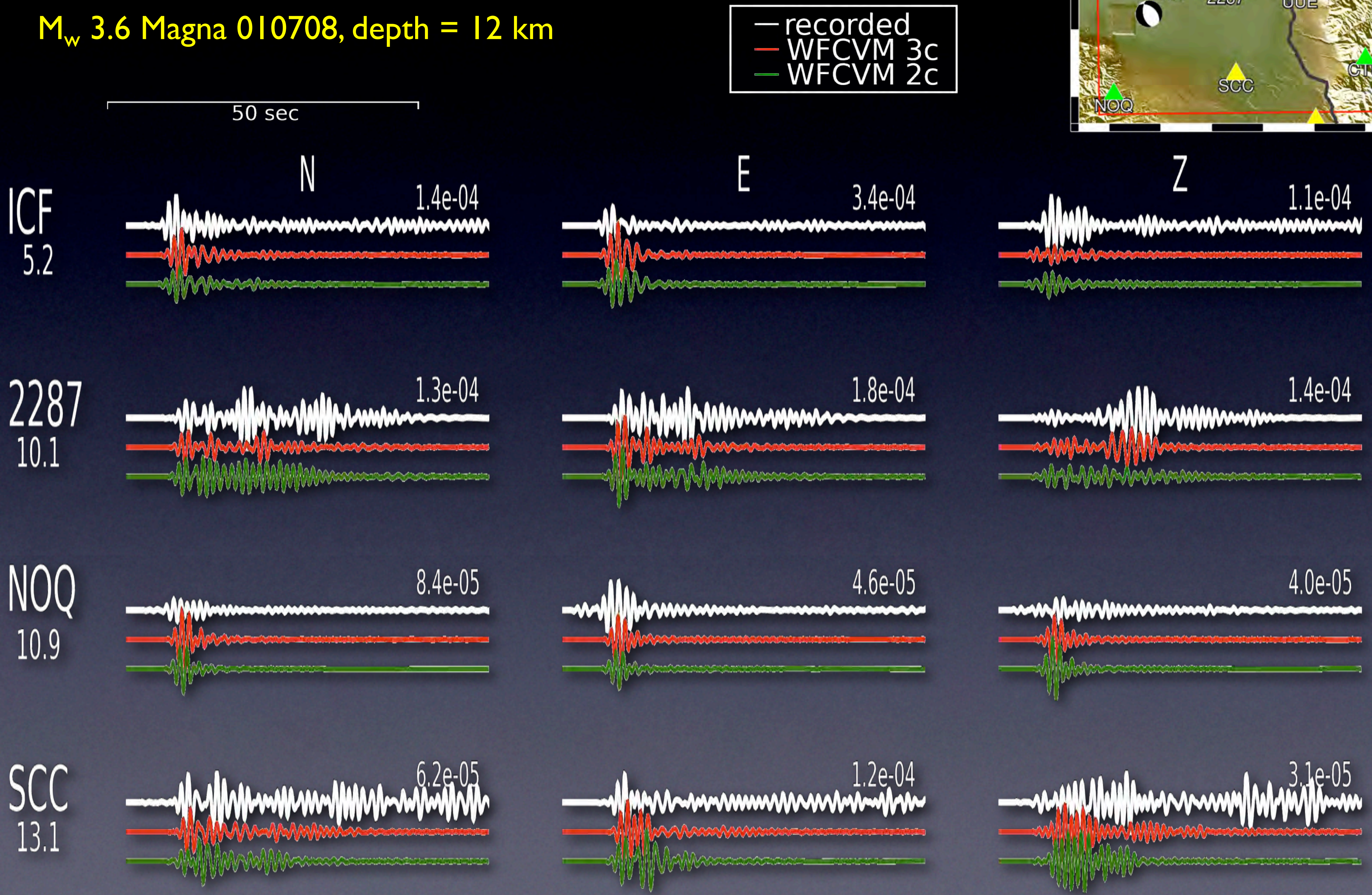
- **Revalidation of the WFCVM version 3c**
- **Dynamic M7 rupture models**
  - depth-dependent normal stress (Dalguer & Mai, 2008)
- **Long-period (0-1 Hz) 3D FD simulations for 6 scenario EQs**
  - 2s-SAs obtained from individual scenarios
  - importance of source directivity effects
  - average 2s/1s-SAs compared to Solomon et al. (2004) and NGA models
  - analysis of wave propagation effects causing large amplification
- **Broadband (BB) synthetics (0-10 Hz)**
  - maps of SAs and PGAs derived from BB time series
  - comparison of BB SAs and PGAs along 3 profiles with NGA predictions
- **1-D simulations of nonlinear soil behavior**
  - estimation of nonlinear soil parameters
  - impact of nonlinearity on PGAs and SAs, compared to NGA models
- **Conclusions**



Validation of WFCVM (3c)

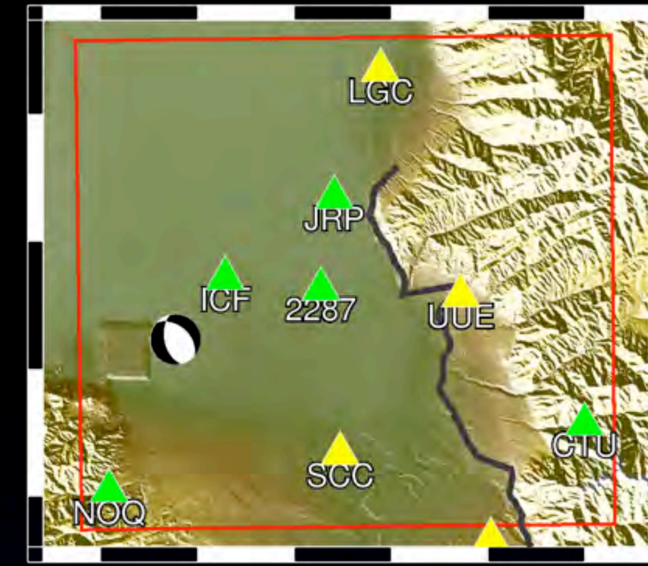
M_w 3.6 Magna 010708, depth = 12 km

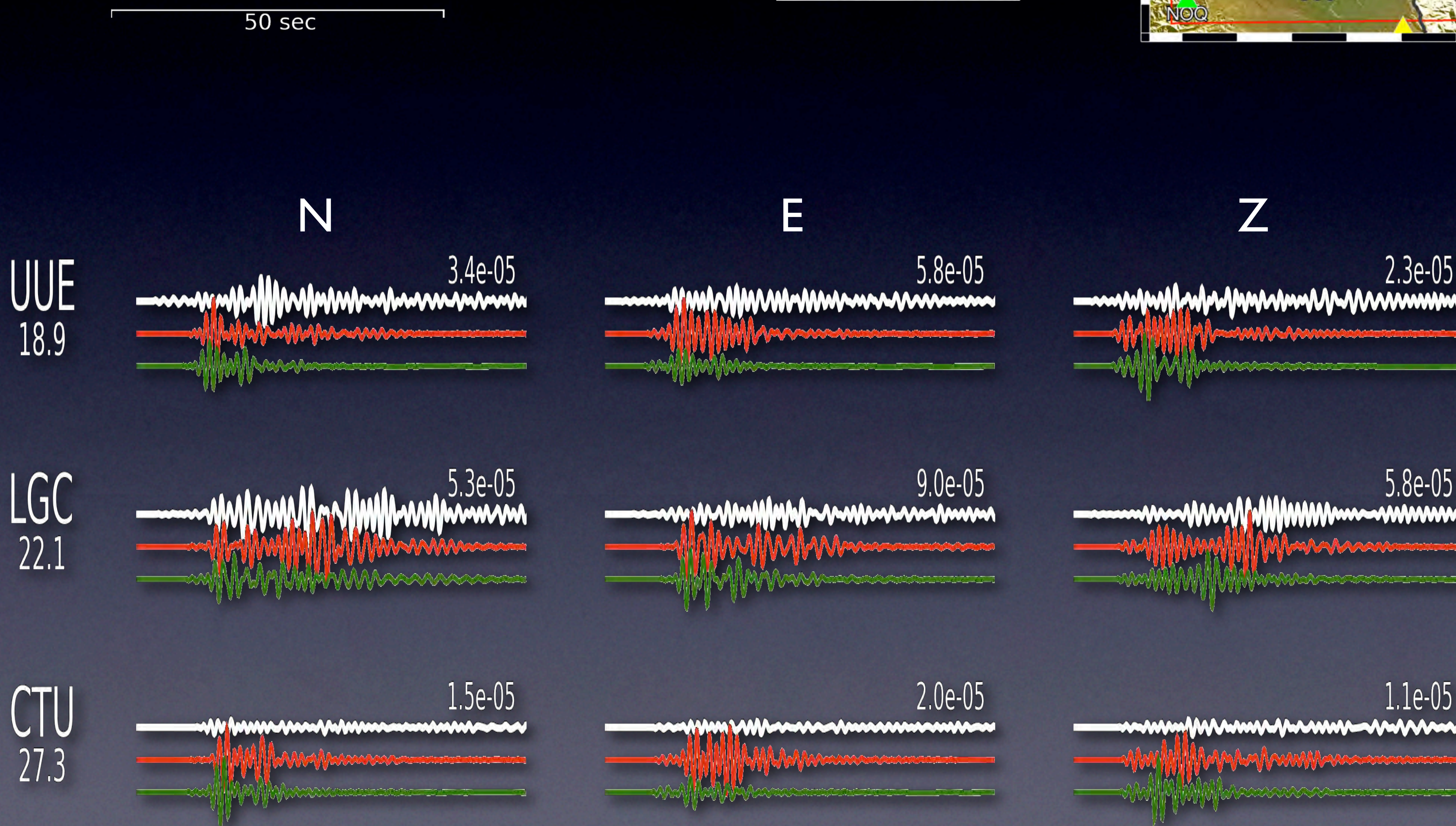




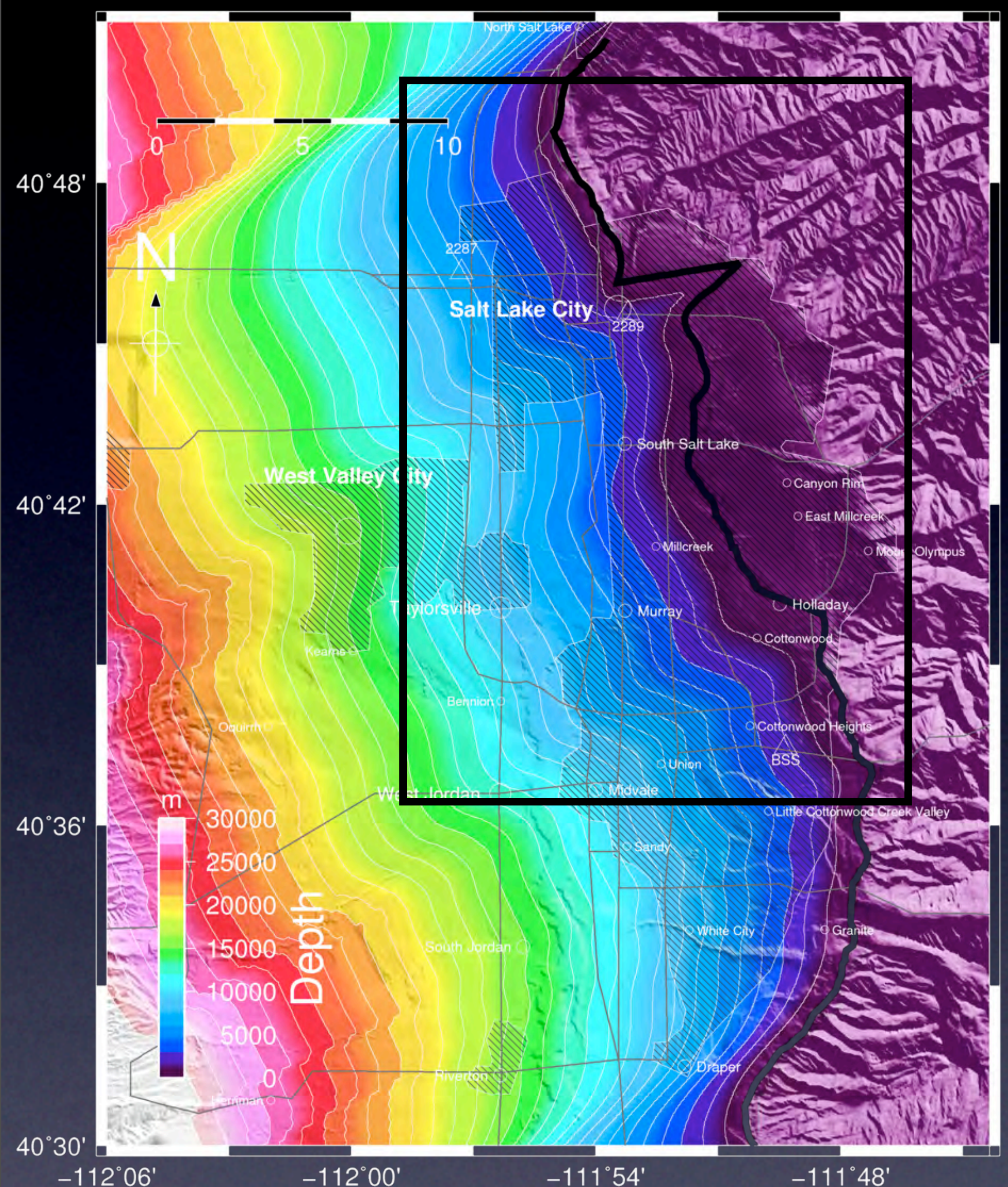
Validation of WFCVM (3c)

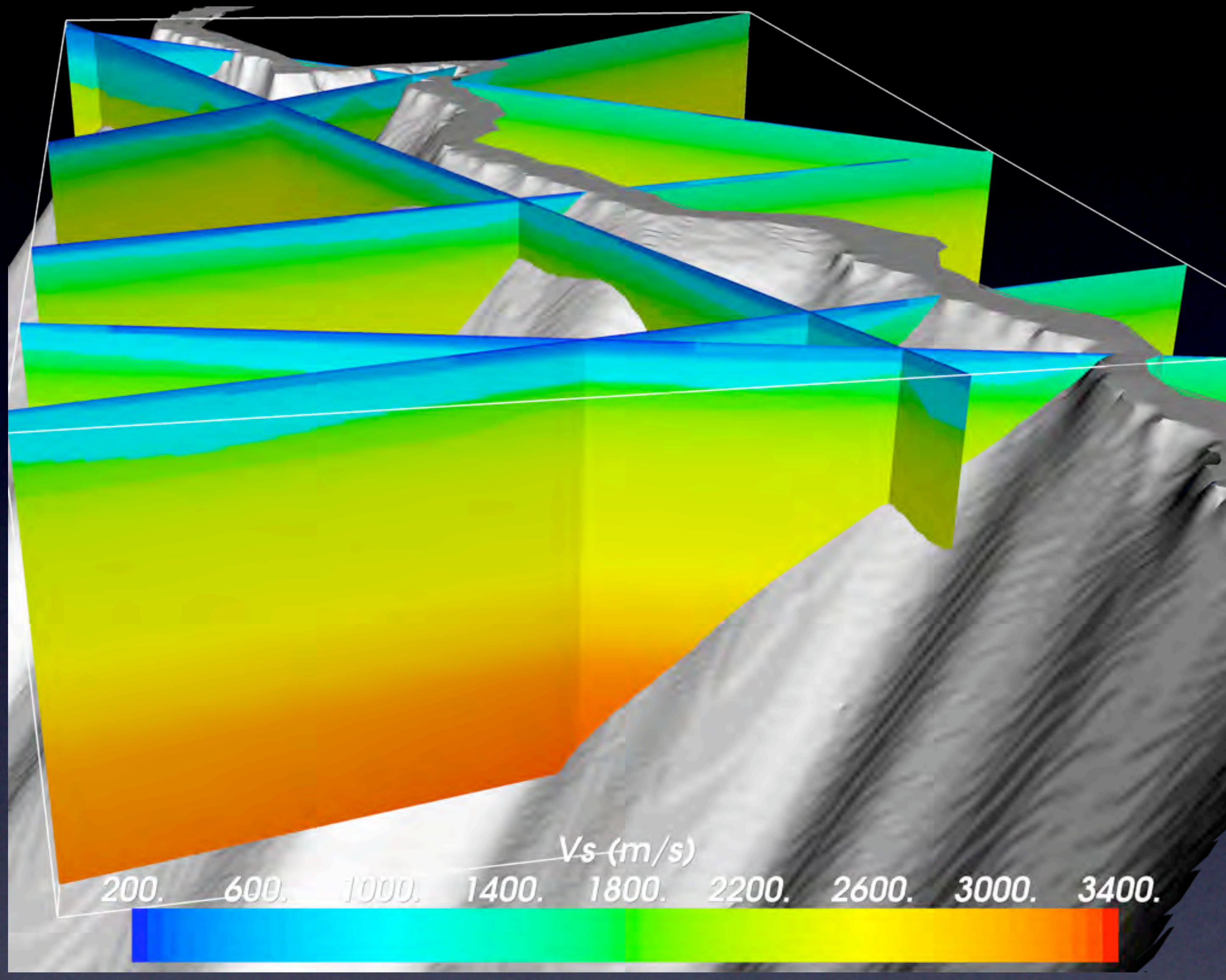
M_w 3.6 Magna 010708, depth = 12 km





3D model of the WF SLC segment

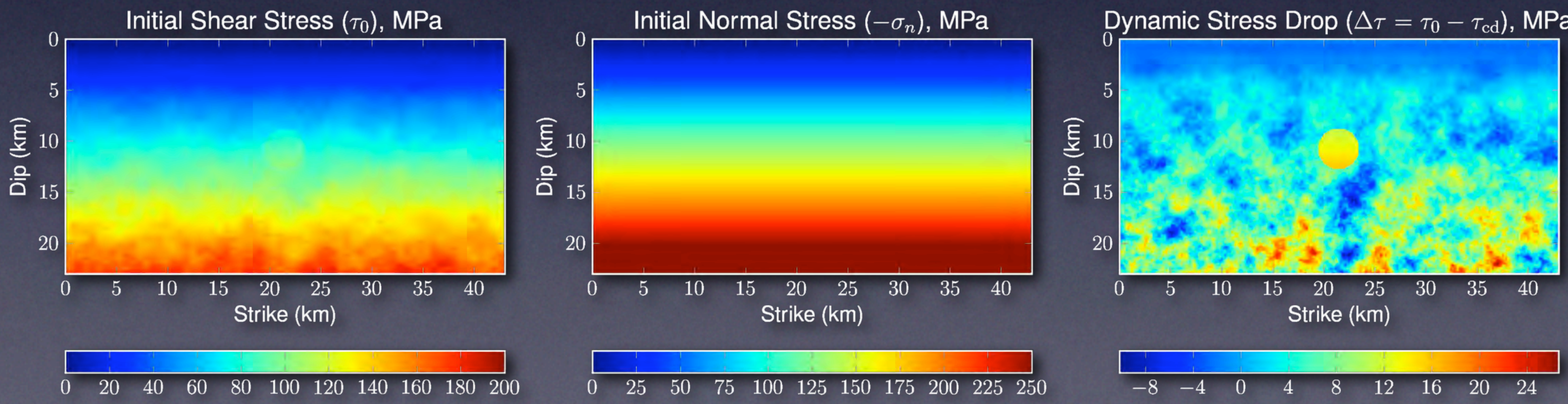




- Final model of the SLC segment of the WF used for M7 scenario simulations
- Fault geometry mostly consistent with eastern boundaries of the Salt Lake Valley basin

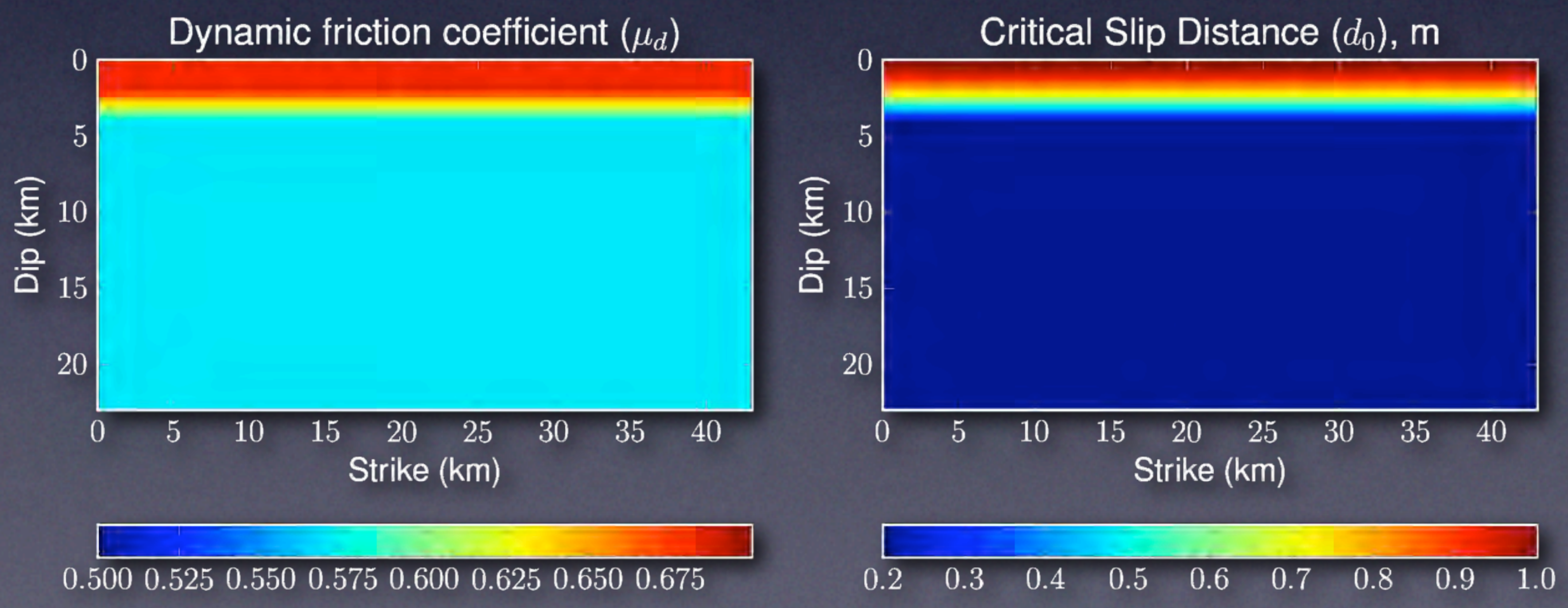
Spontaneous Rupture Models

- Simulation of dynamic rupture process on a planar vertical fault
- Staggered-grid split node finite difference method (Dalguer & Day, 2007)
- Depth-dependent normal stress (Dalguer & Mai, 2008)
- Simulated velocity strengthening near the free surface (reduce τ_0, increase d_0, $\mu_d > \mu_s$)
- Four rupture models with different hypocenter locations



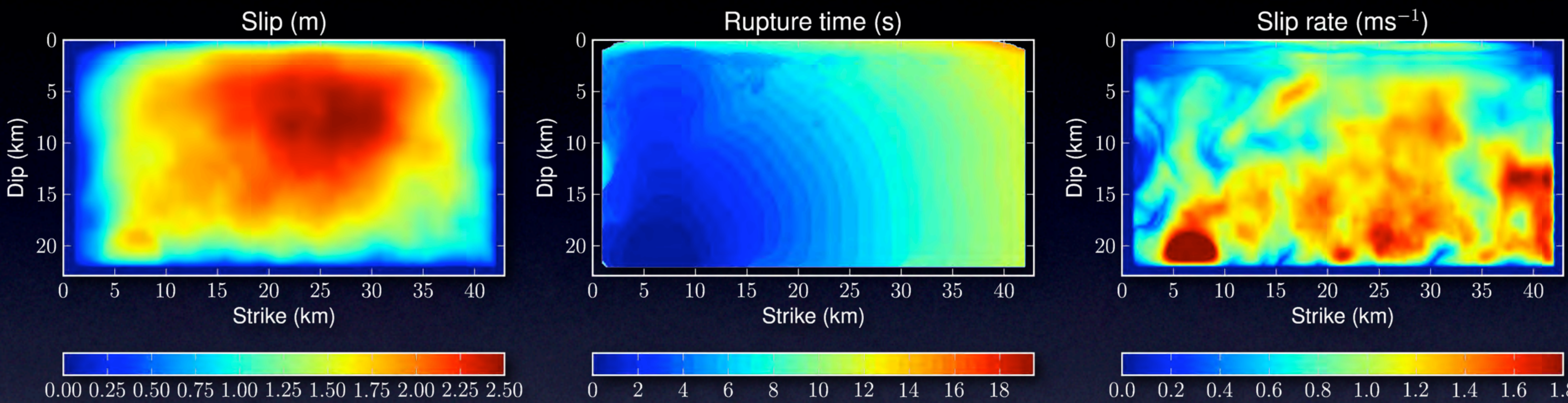
Spontaneous Rupture Models

- Simulation of dynamic rupture process on a planar vertical fault
- Staggered-grid split node finite difference method (Dalguer & Day, 2007)
- Depth-dependent normal stress (Dalguer & Mai, 2008)
- Simulated velocity strengthening near the free surface (reduce τ_0, increase d_0, $\mu_d > \mu_s$)
- Four rupture models with different hypocenter locations

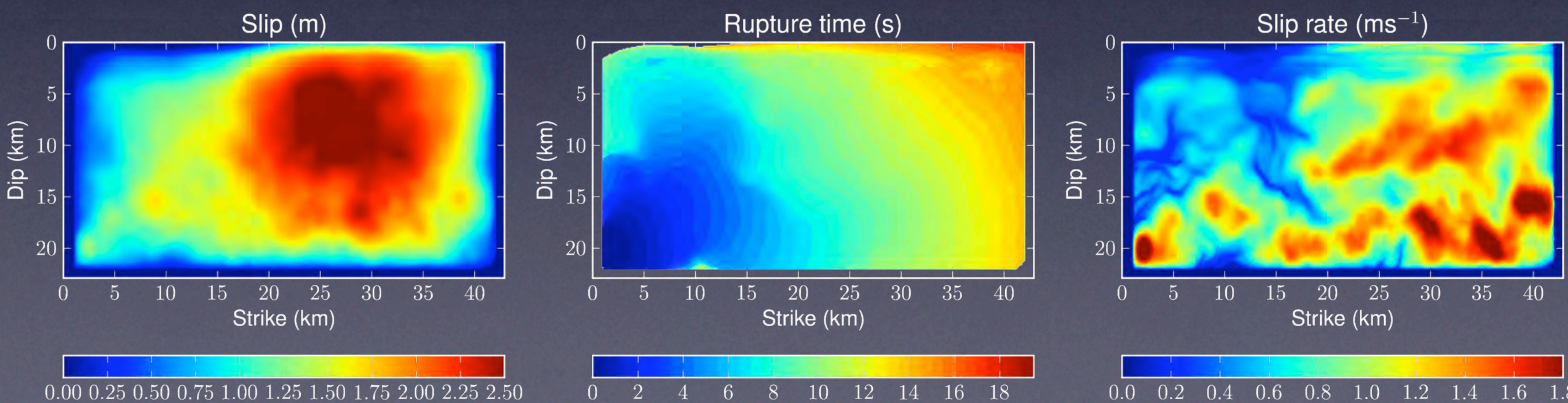


Spontaneous Rupture Models

Scenario 2a

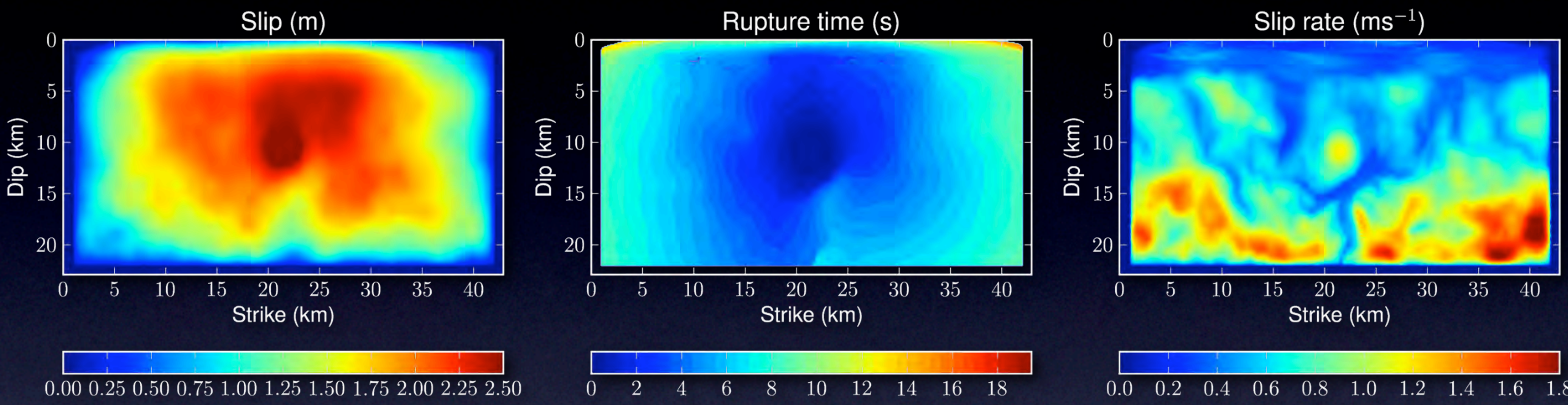


Scenario 5a

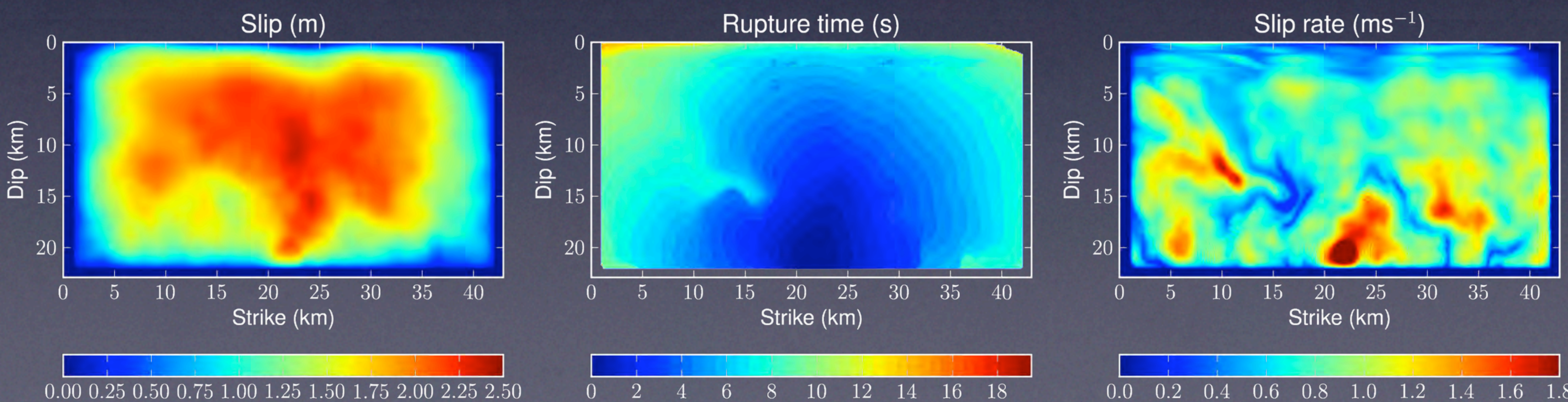


Spontaneous Rupture Models

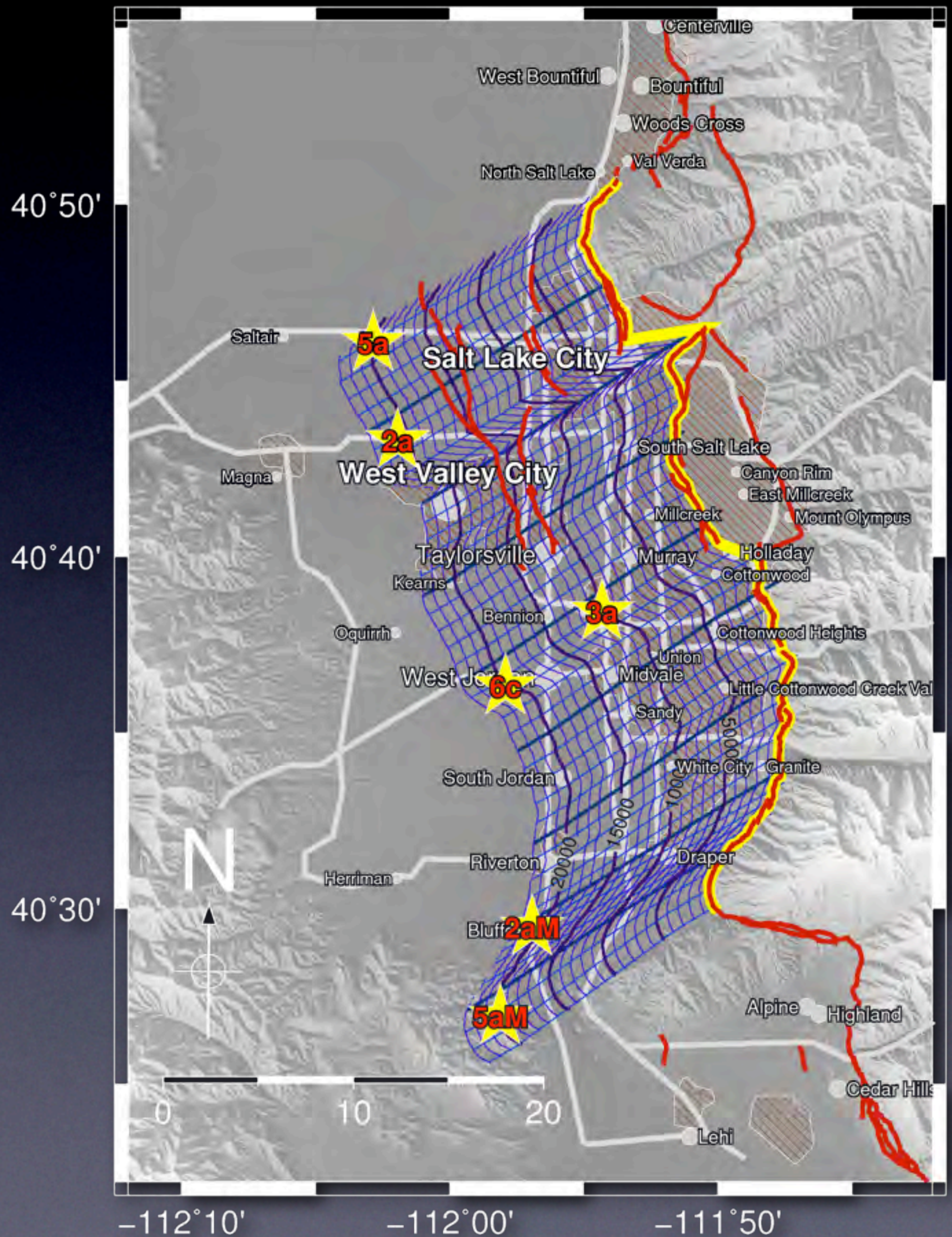
Scenario 3a



Scenario 6c



Six scenario EQs



Representative distribution of hypocenter locations:

Normal faulting EQs tend to originate near brittle-ductile transition zone (~15 km depth):

- 5 deep hypocenters (20 km down-dip)
- 1 shallower hypocenter (10 km down-dip)

Rupture tends to start near non-conservative barriers:

- near northern end (2a, 5a)
- near southern end (2aM, 5aM)
- near bifurcation near Holladay stepover (3a, 6c)

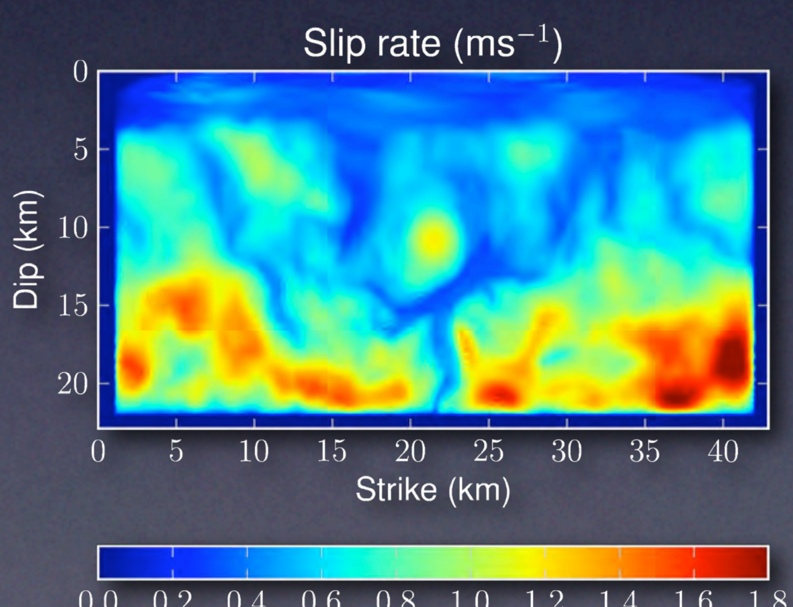
(Bruhn et al. ,1992)

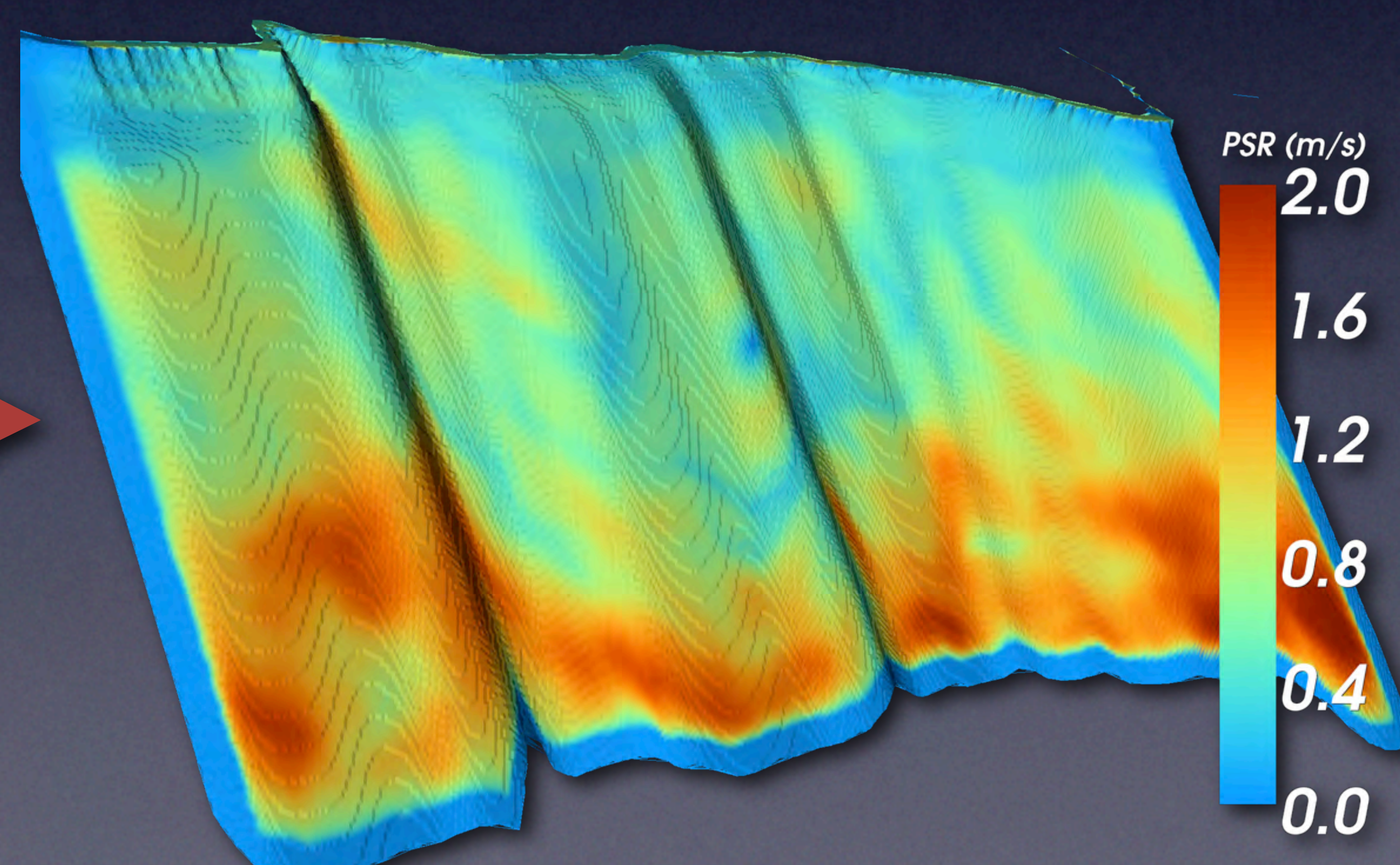
FD Simulation of Wave Propagation

- Planar rupture model is projected onto irregular 3-D model of the WF and the moment rate time histories are inserted into grid nodes

- Wave propagation of this source model is simulated with velocity-stress staggered-grid finite difference method (Olsen, 1994):

FD3D parameters	
Model dimensions	1500 x 1125 x 500
Simulation length	60s (24,000 iter.)
Discretization	40m / 0.0025 s
Minimum V_S	200 ms^{-1}
Highest frequency	1 Hz
# of CPU cores	1875
Wall-clock runtime	2.5 hrs (NICS Kraken)



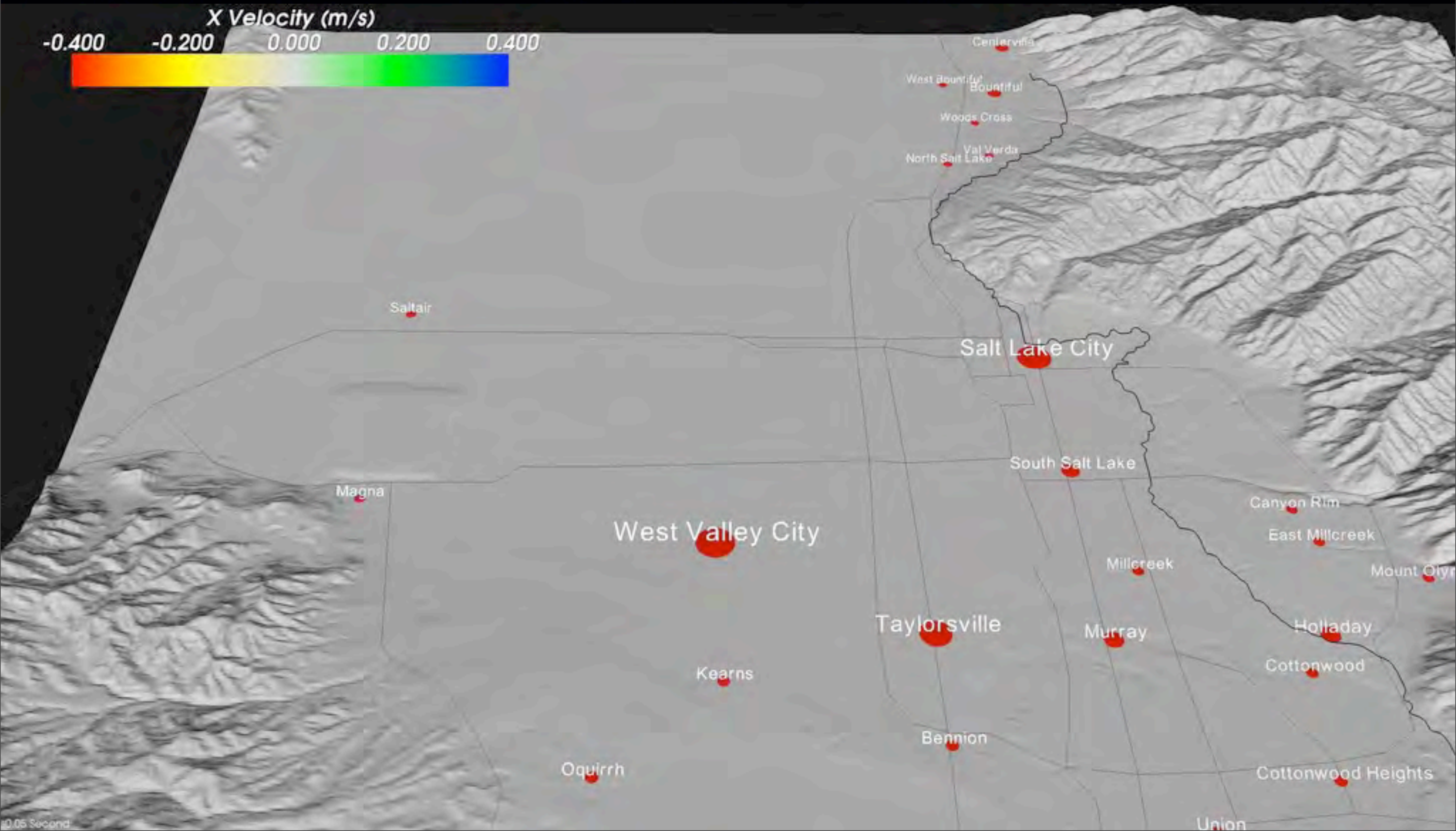


3-D Simulation of Wave Propagation

Scenario 2a

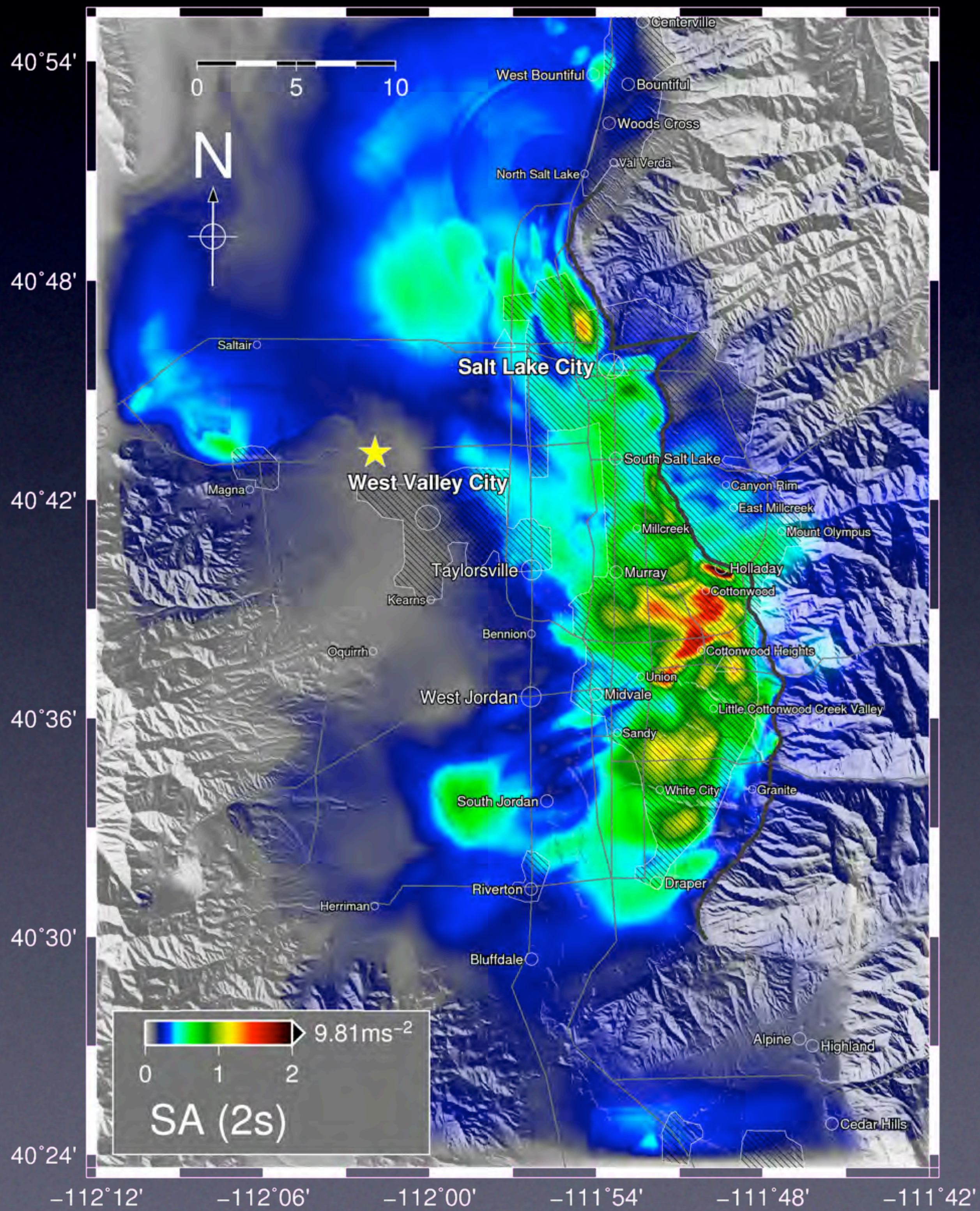
3-D Simulation of Wave Propagation

Scenario 2a

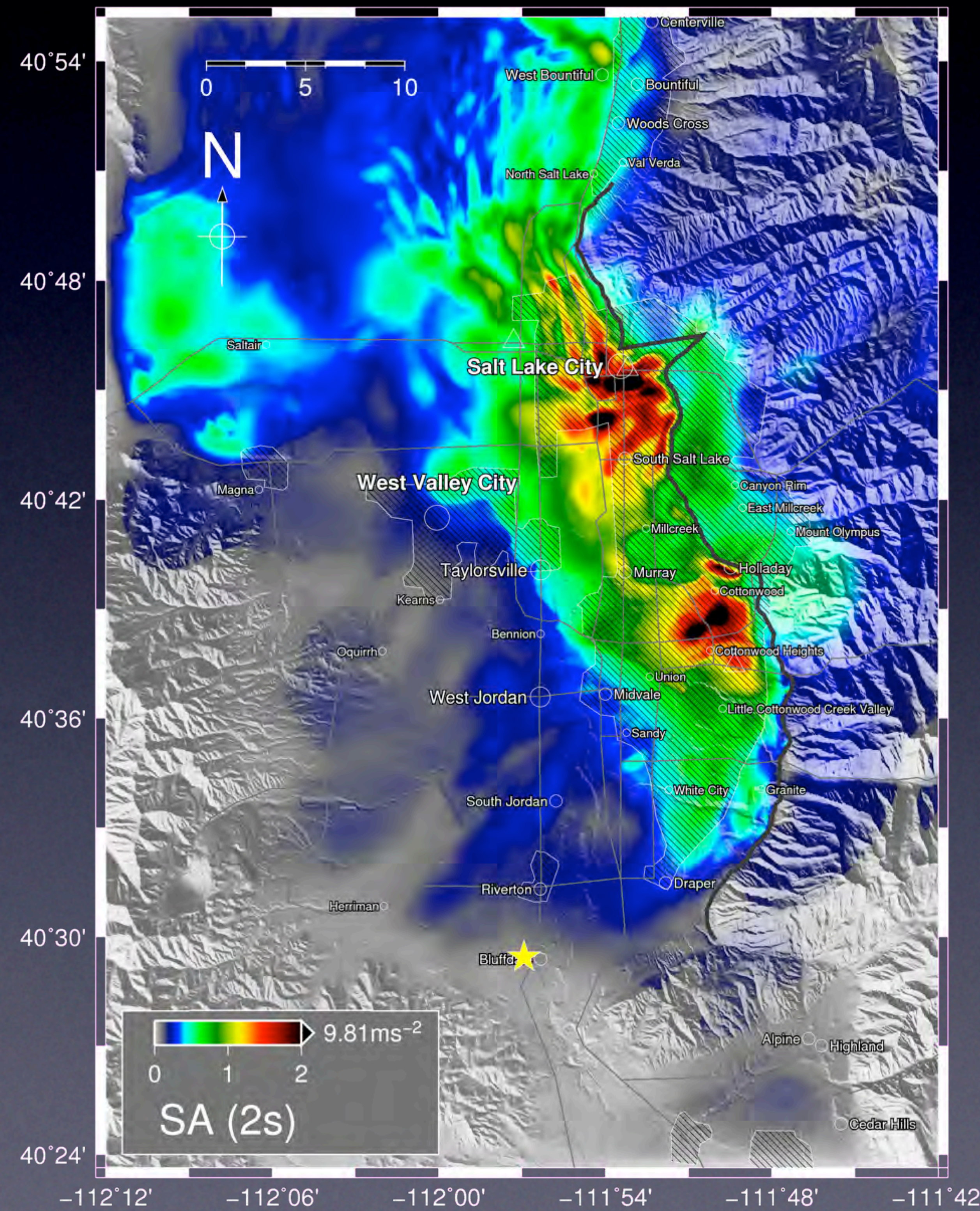


Spectral Accelerations at 2s (2s-SAs)

Scenario 2a

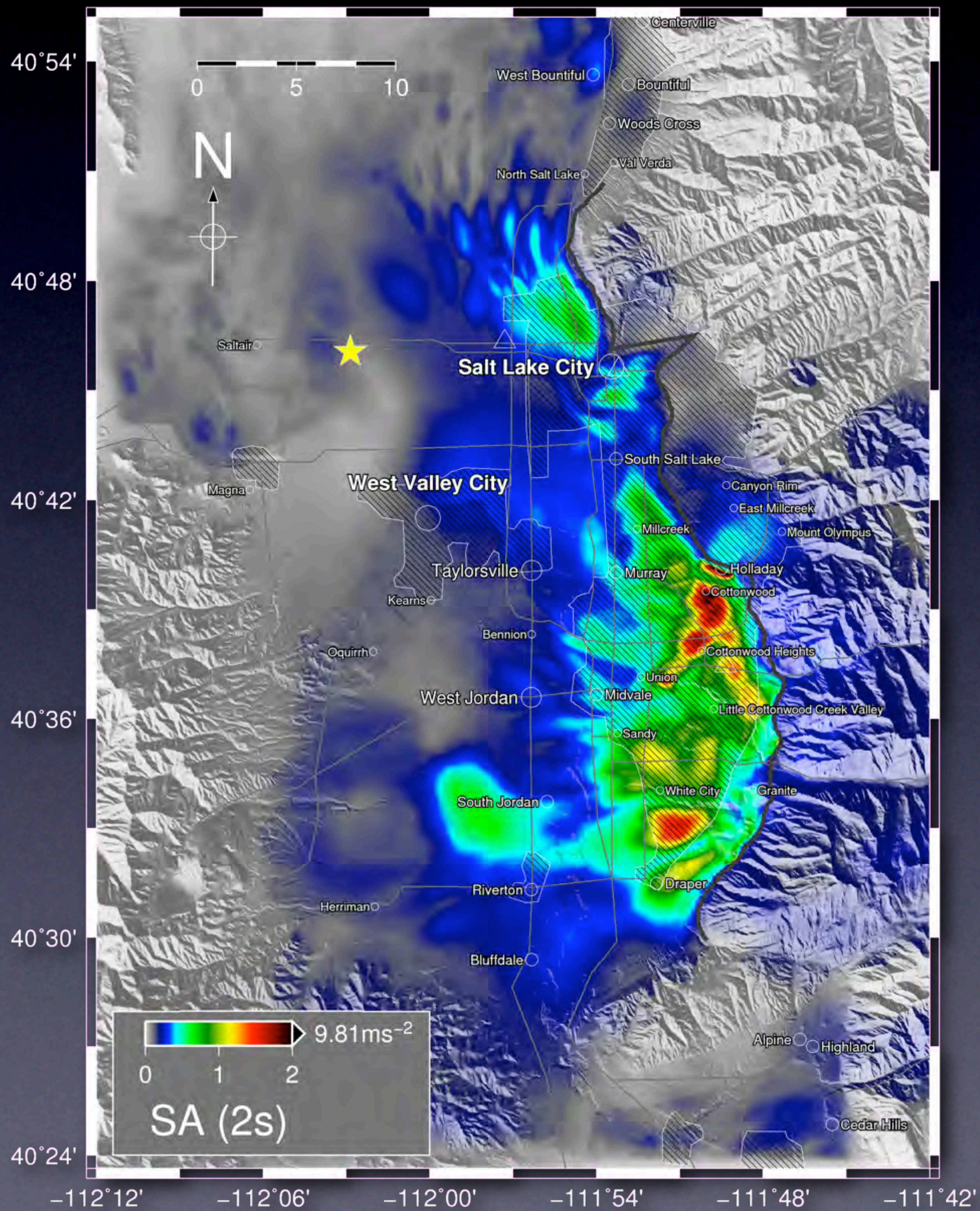


Scenario 2aM

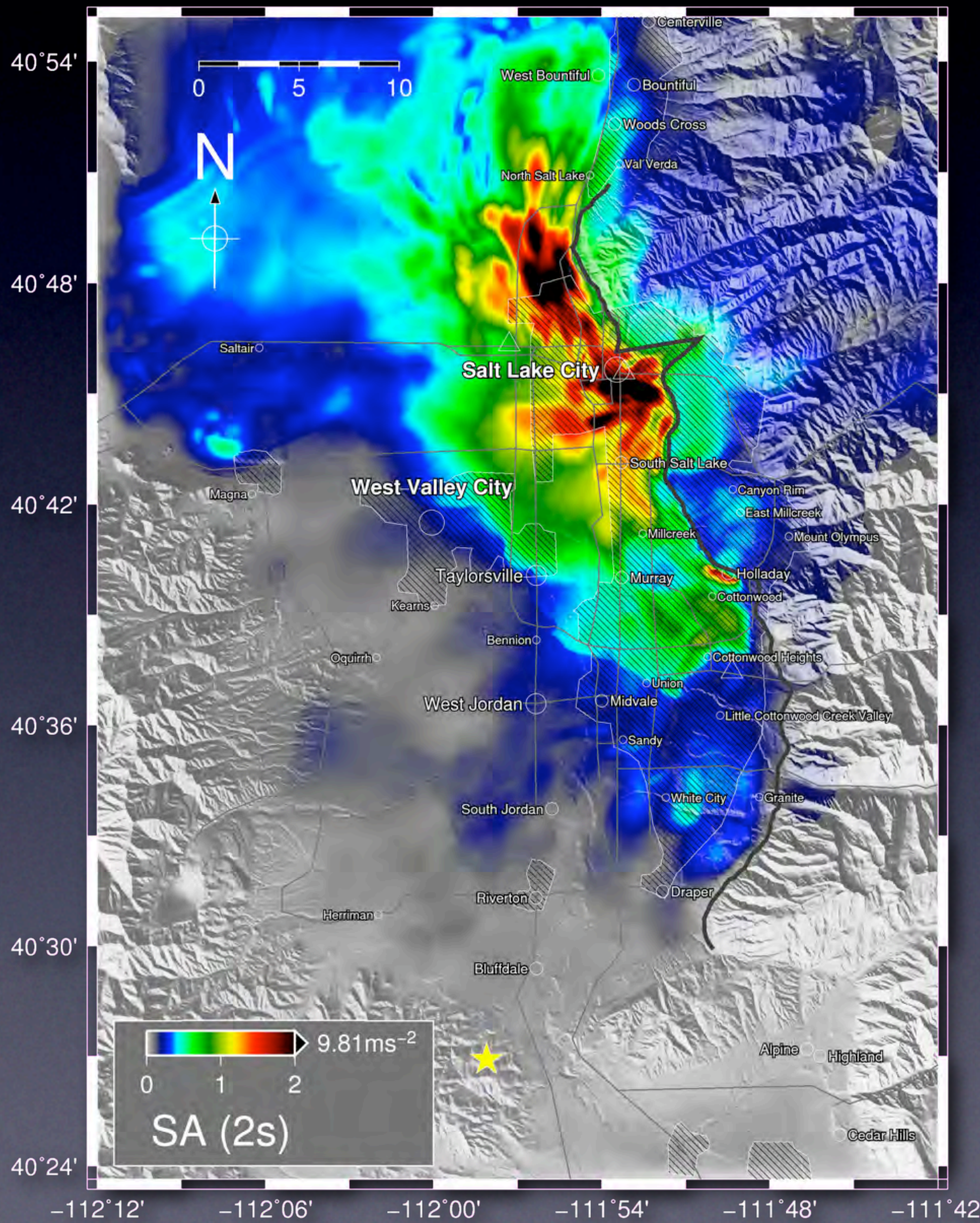


Spectral Accelerations at 2s (2s-SAs)

Scenario 5a

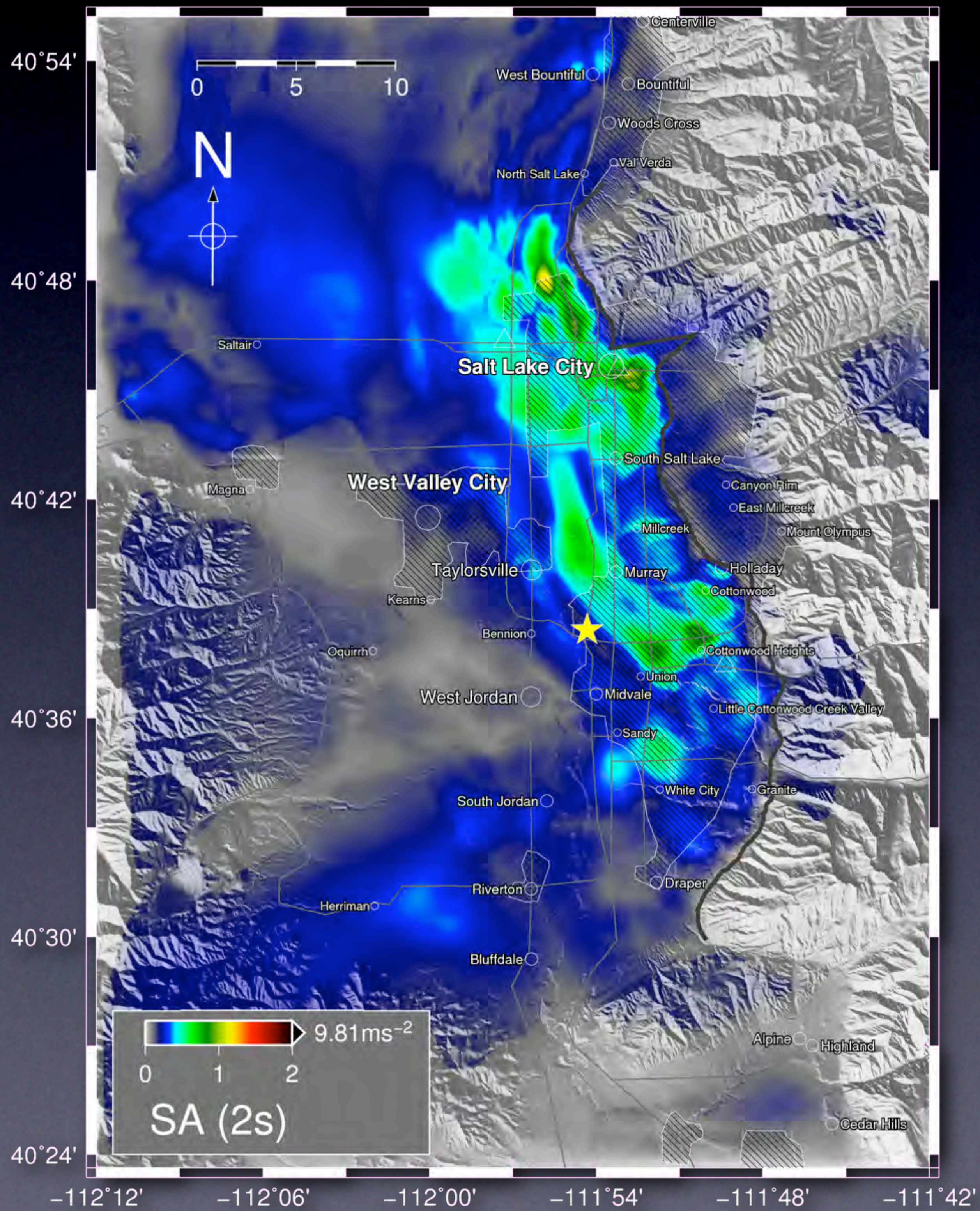


Scenario 5aM

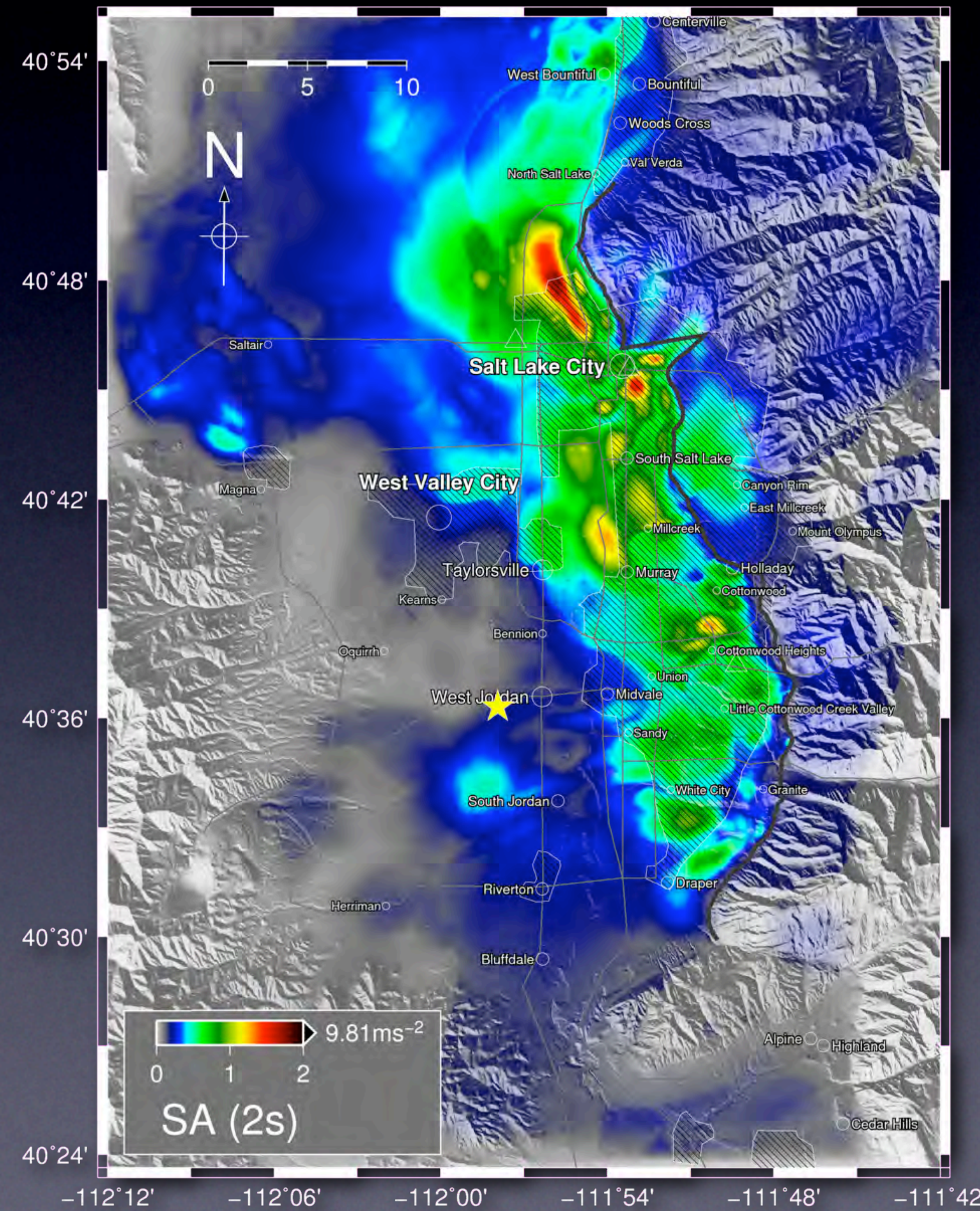


Spectral Accelerations at 2s (2s-SAs)

Scenario 3a

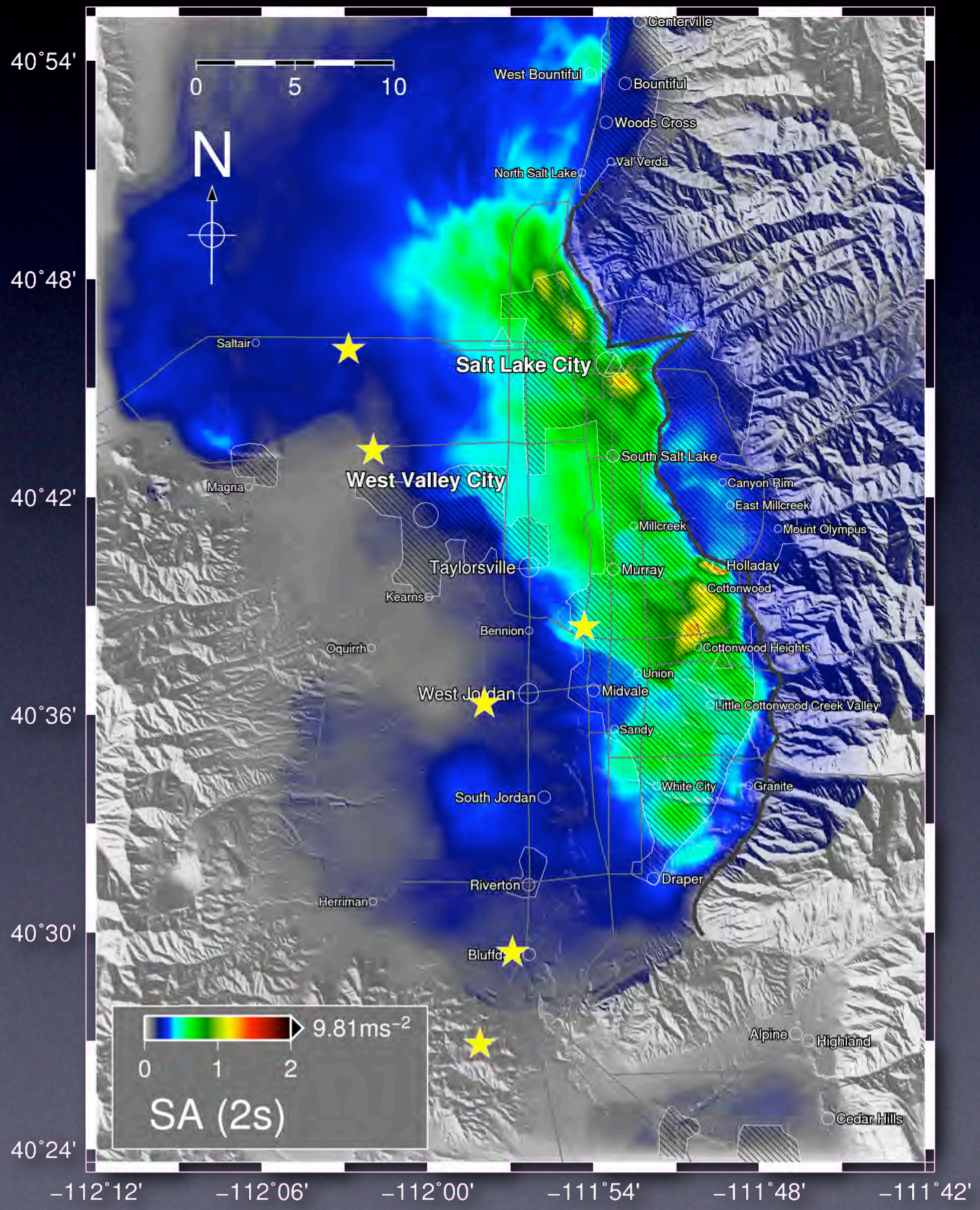


Scenario 6c



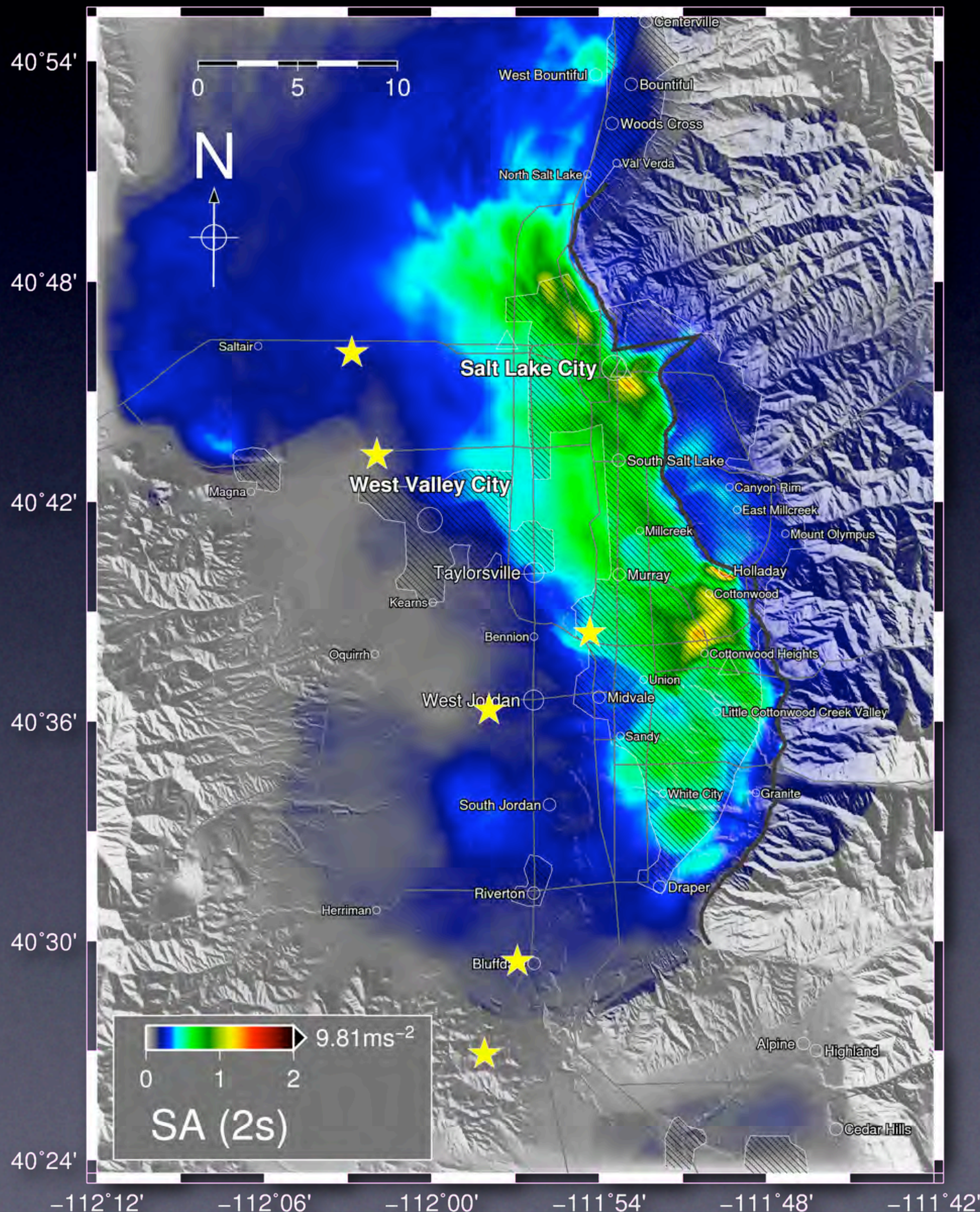
Average SAs

Average 2s-SAs

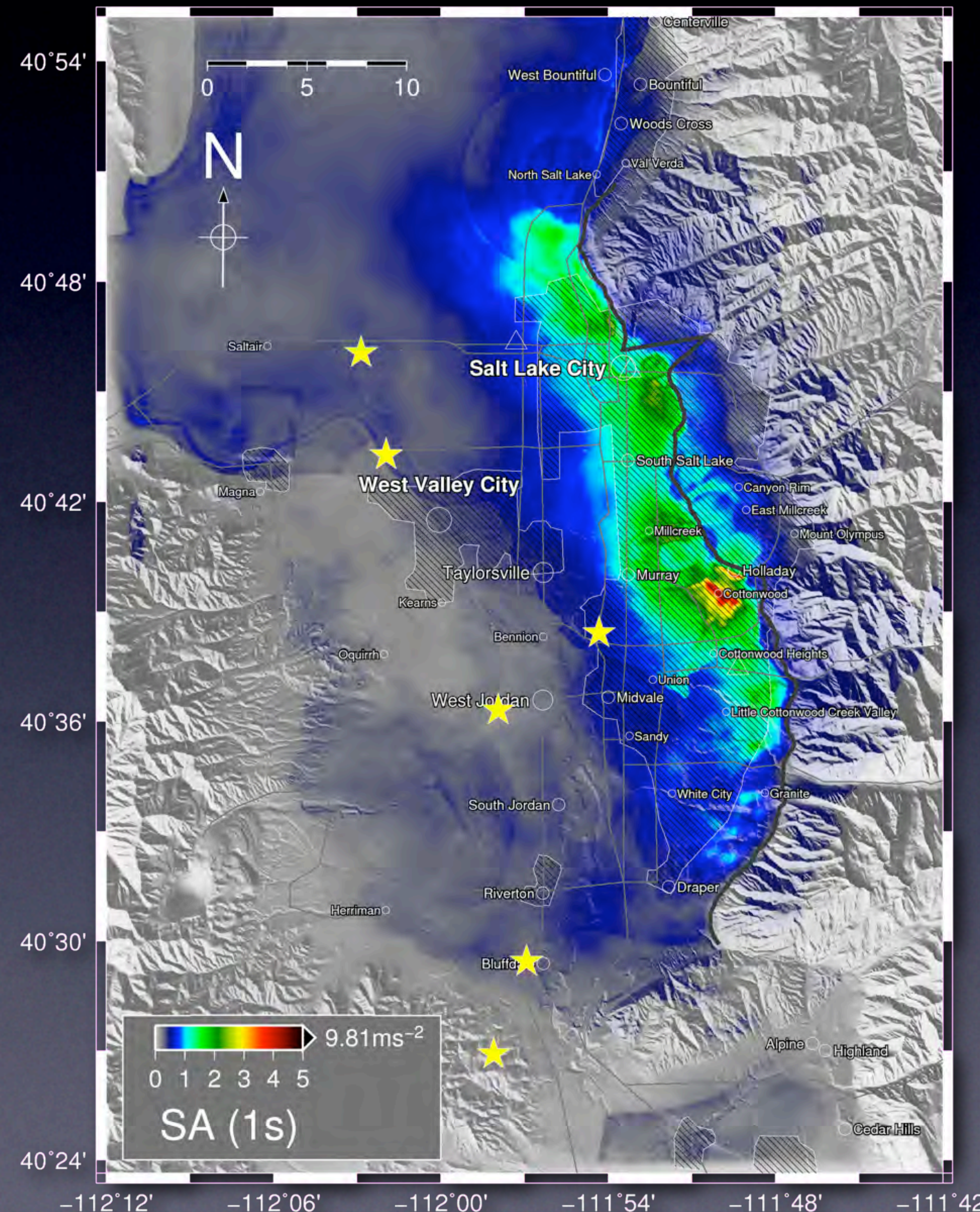


Average SAs

Average 2s-SAs

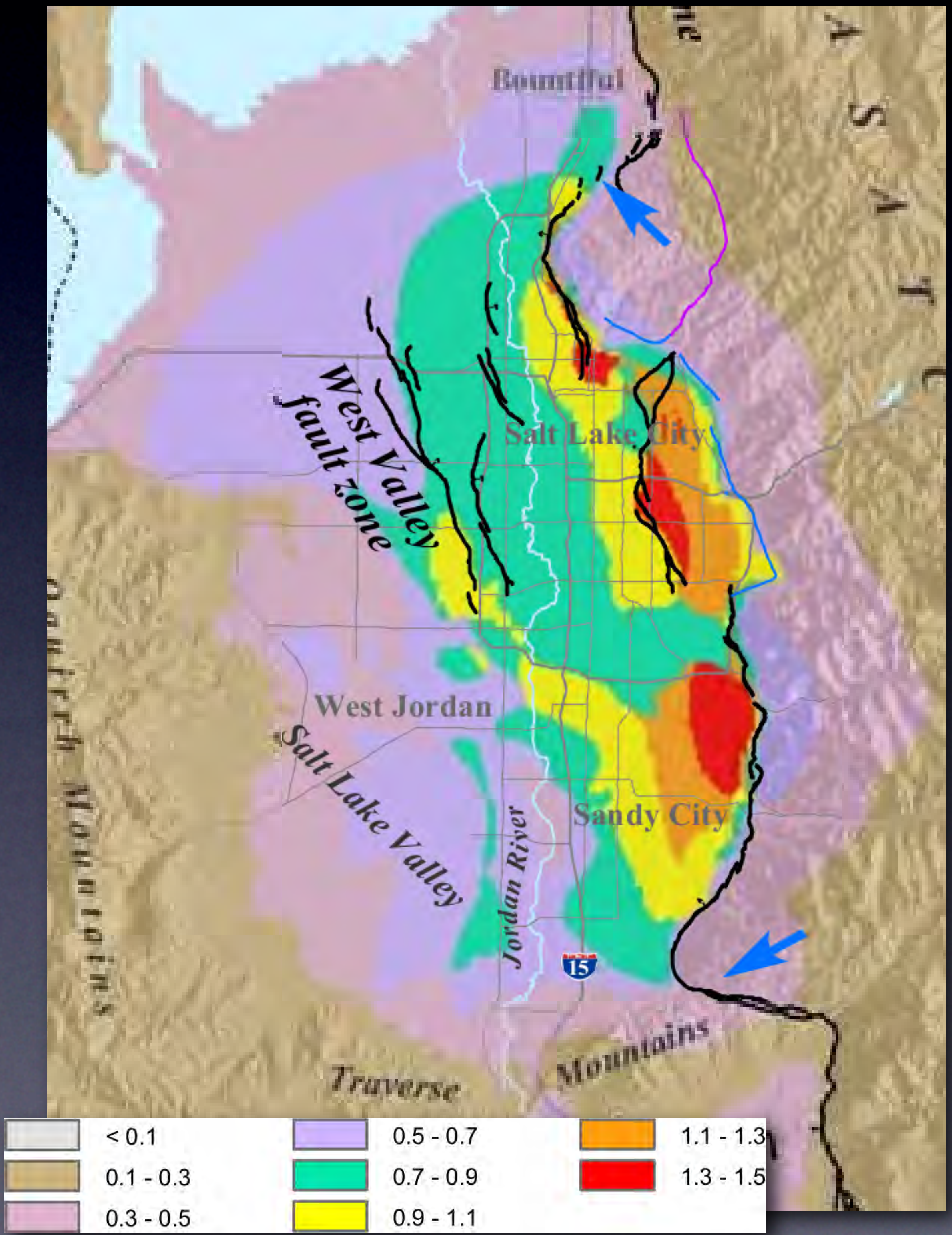


Average 1s-SAs

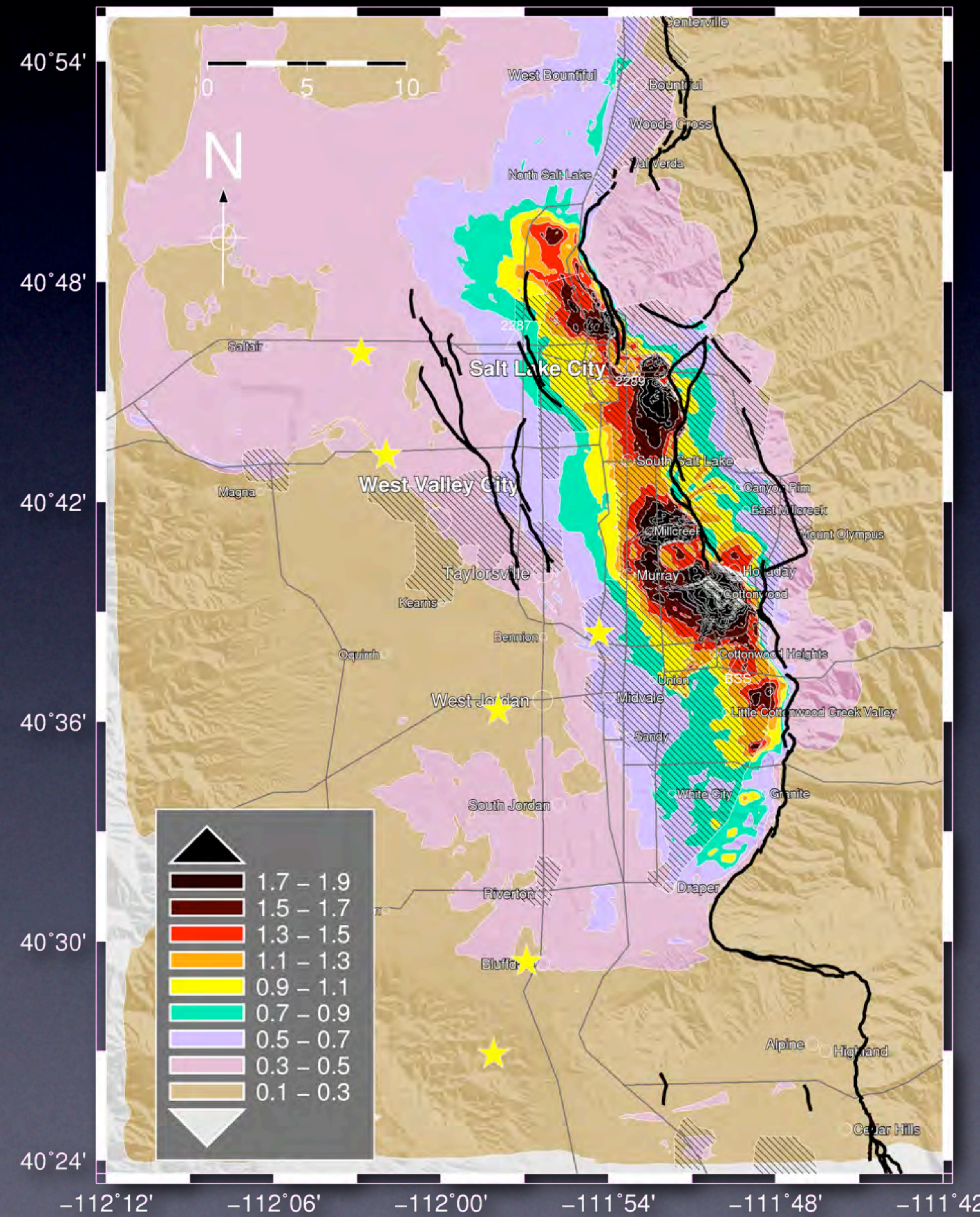


Average 1s-SAs

Solomon et al. (2004)

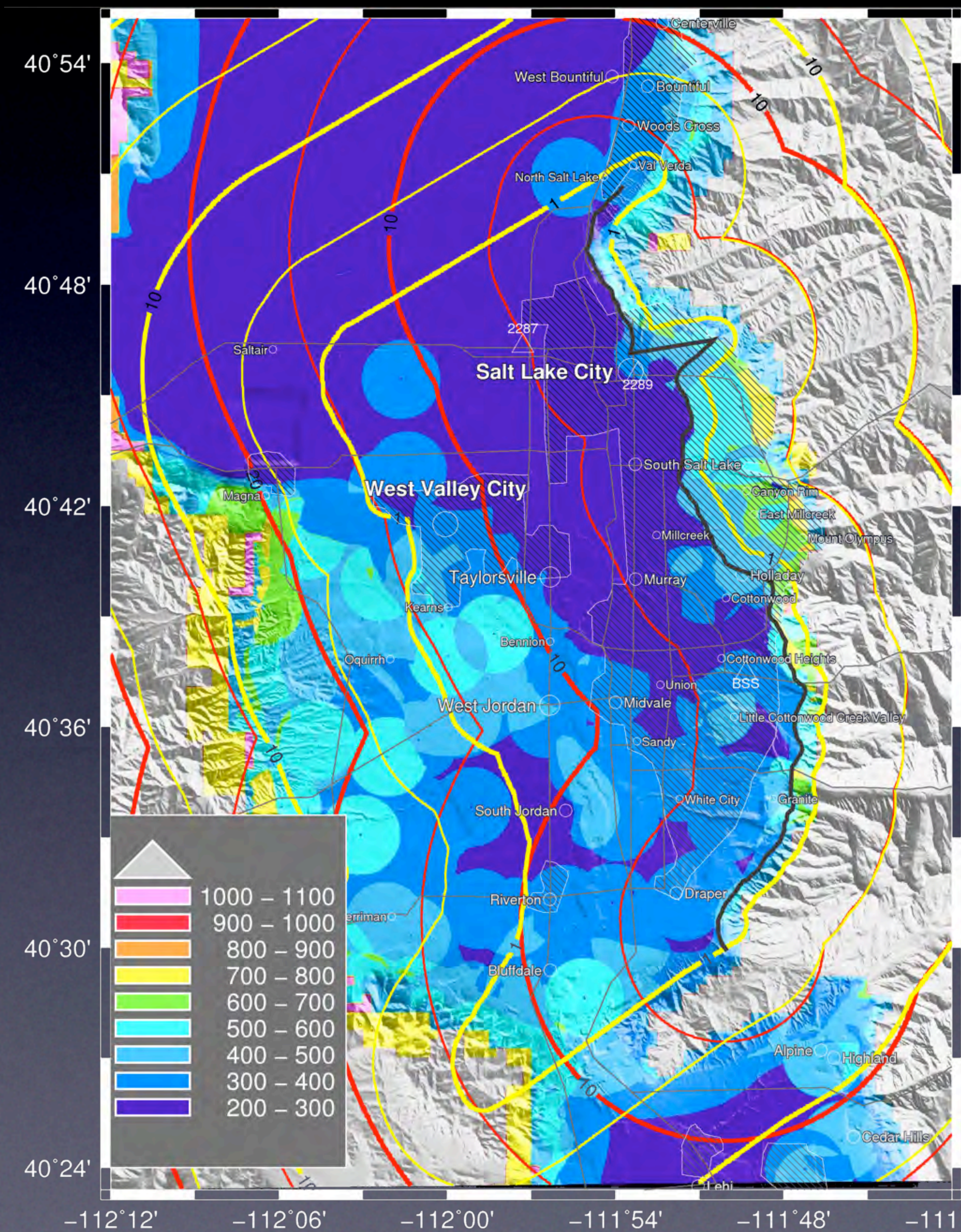


3-D FD simulations

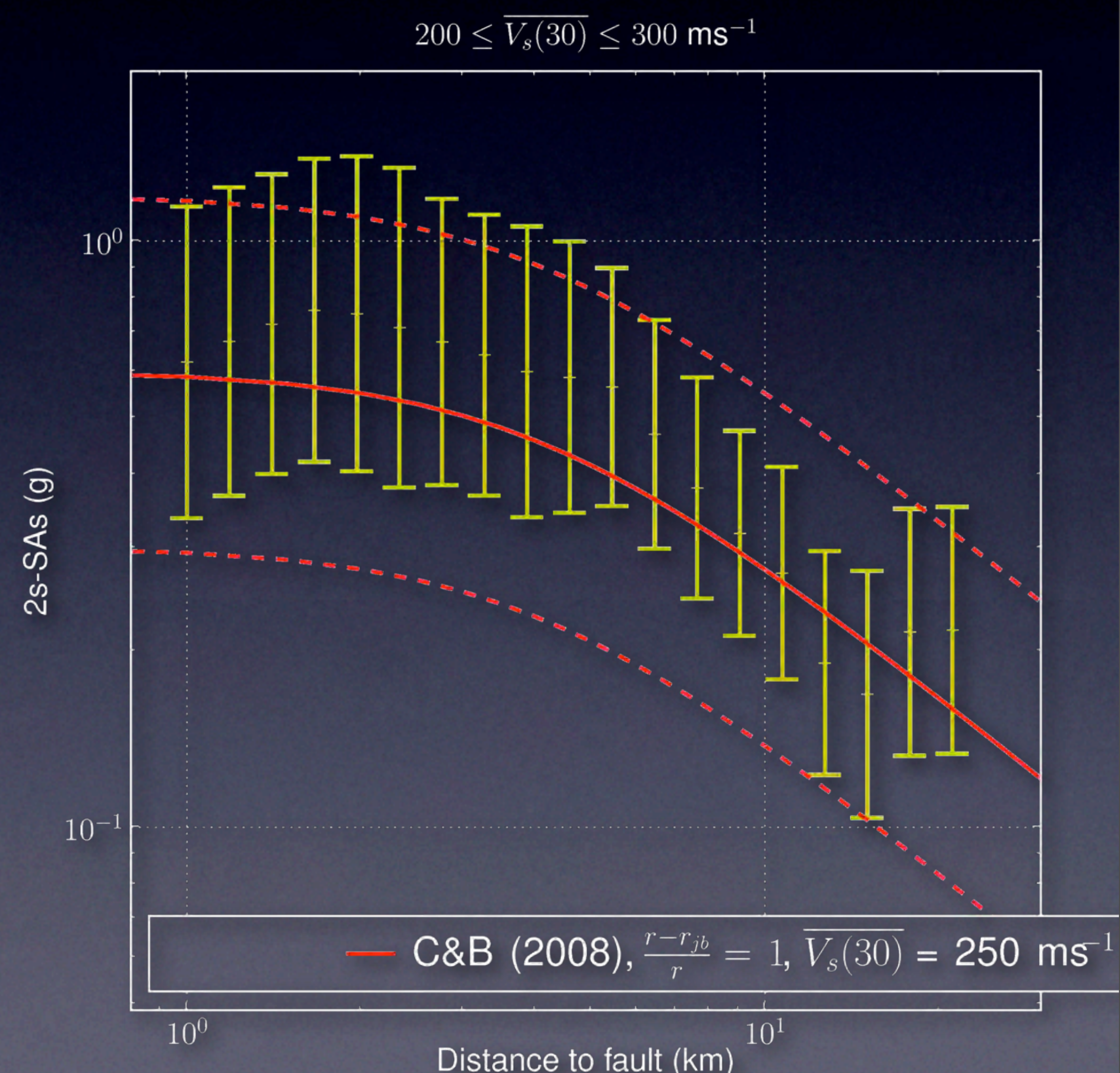


Comparison to NGA

$V_s(30)$ ms^{-1}

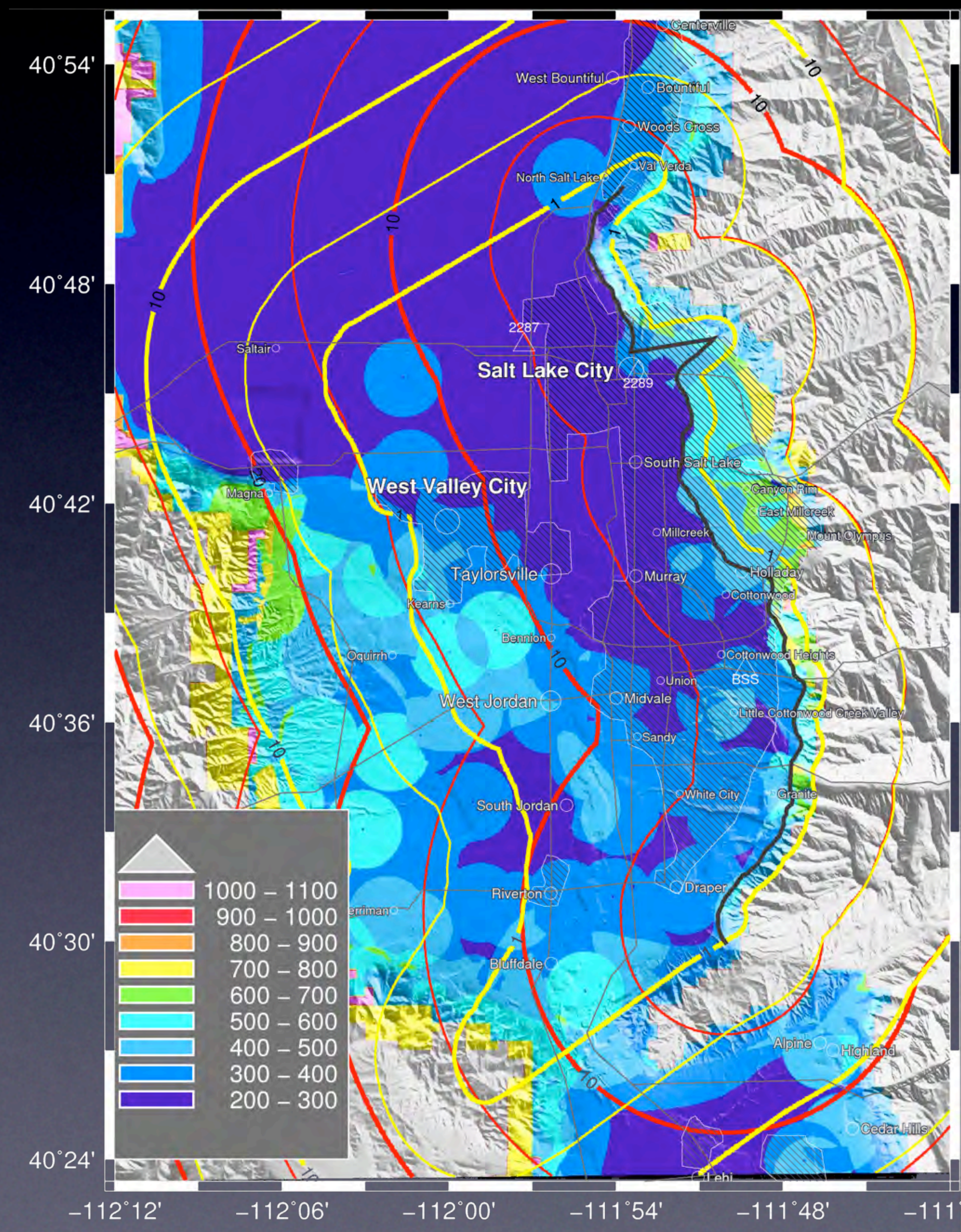


2s-SAs

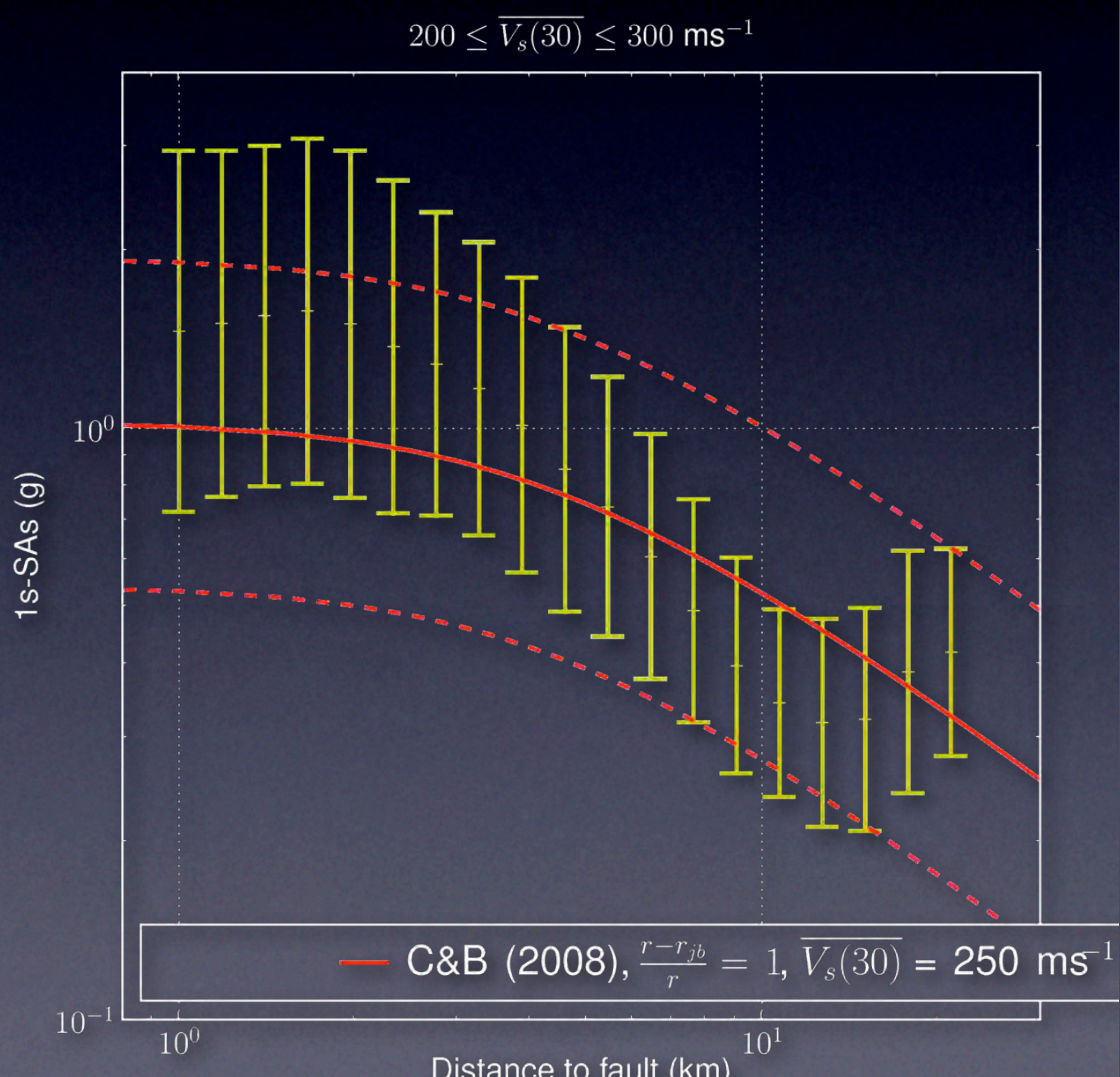


Comparison to NGA

$V_s(30)$ ms^{-1}

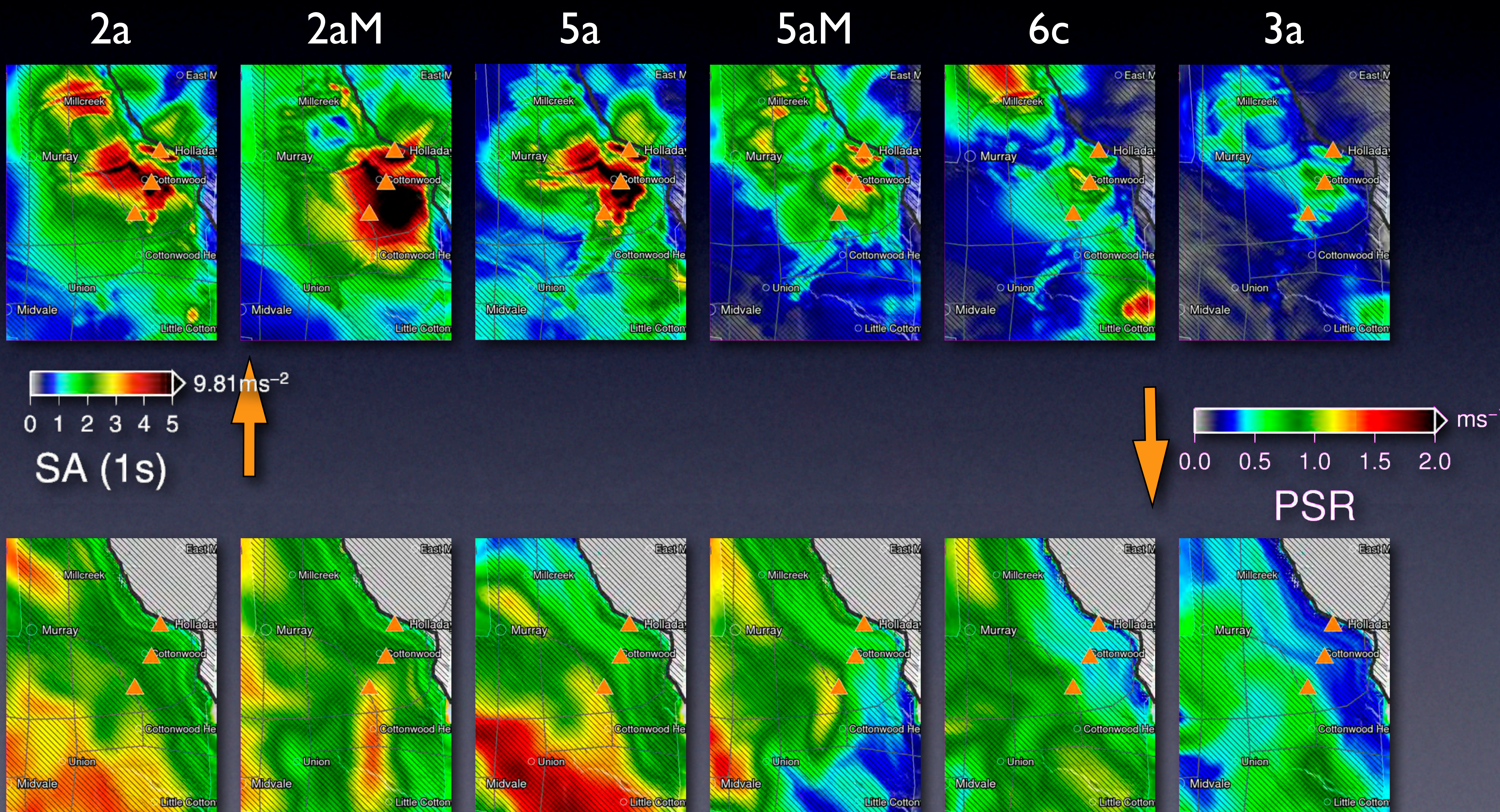


1s-SAs



1s-SAs SW of Holladay stepover

What causes the up to 5g 1s-SAs near Cottonwood?

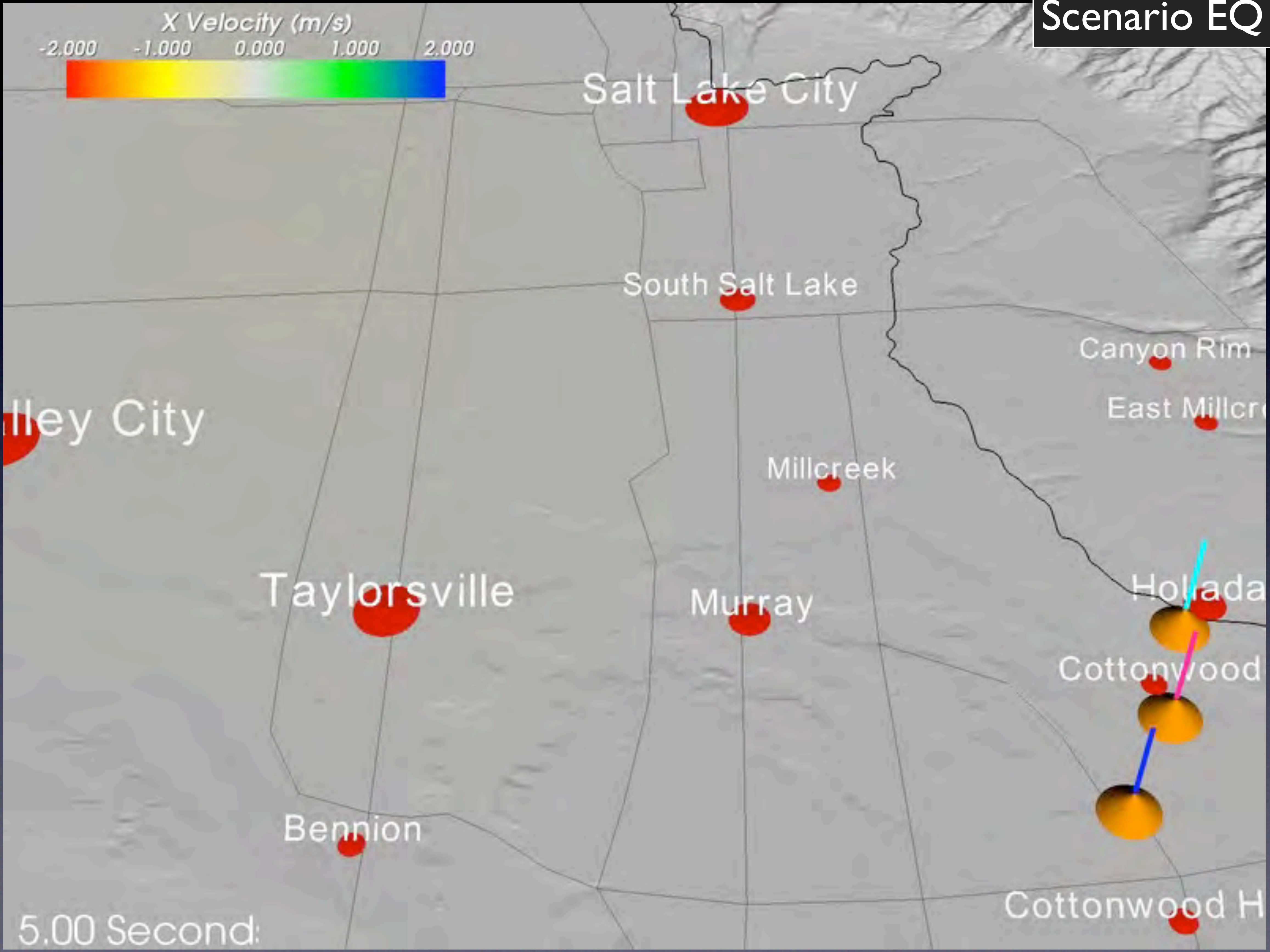


1s-SAs SW of Holladay stepover

Scenario EQ 5a:

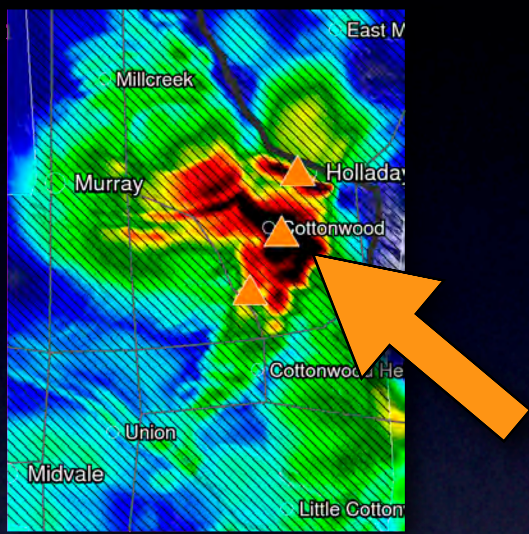
1s-SAs SW of Holladay stepover

Scenario EQ 5a:

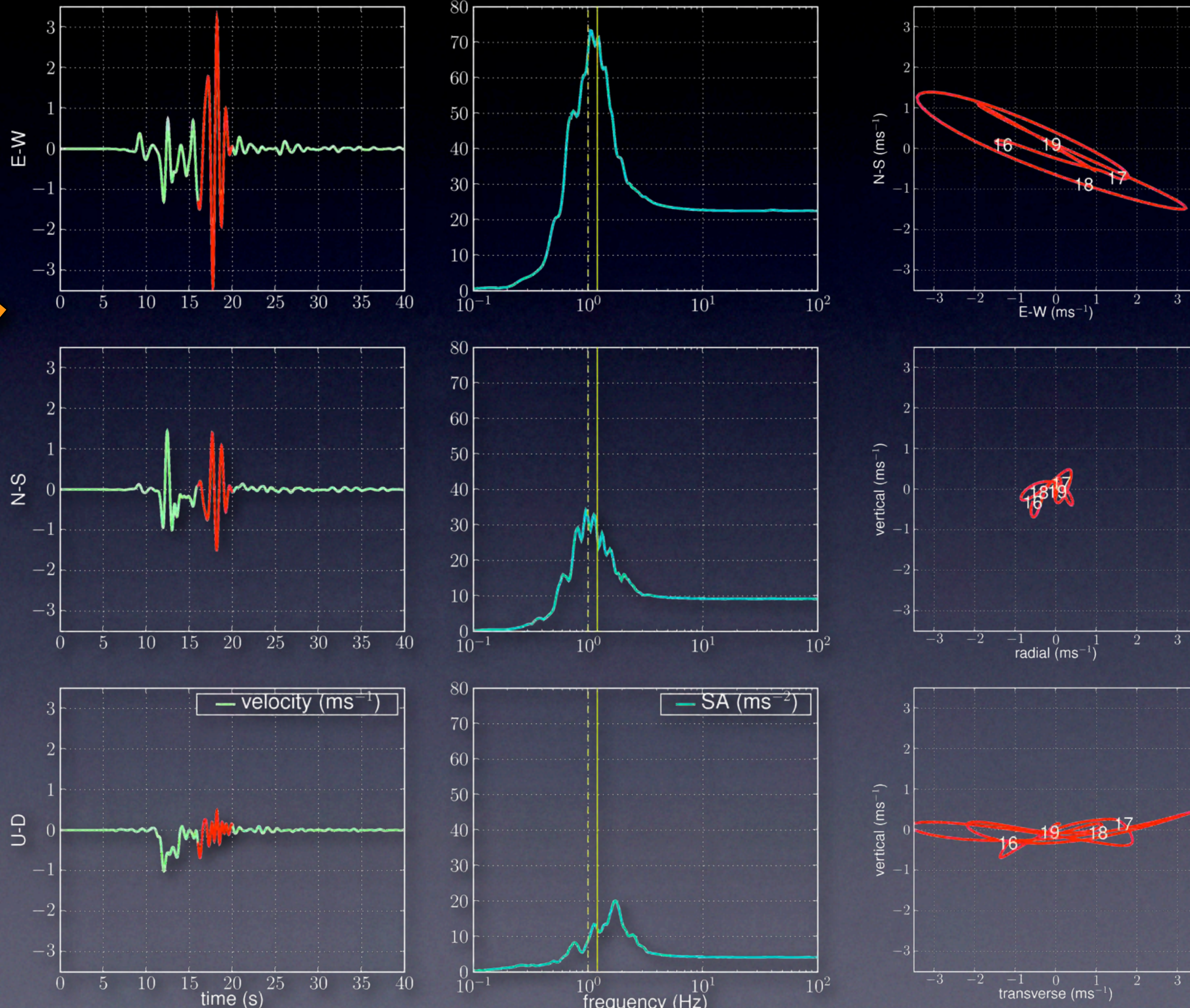


1s-SAs SW of Holladay stepover

5a



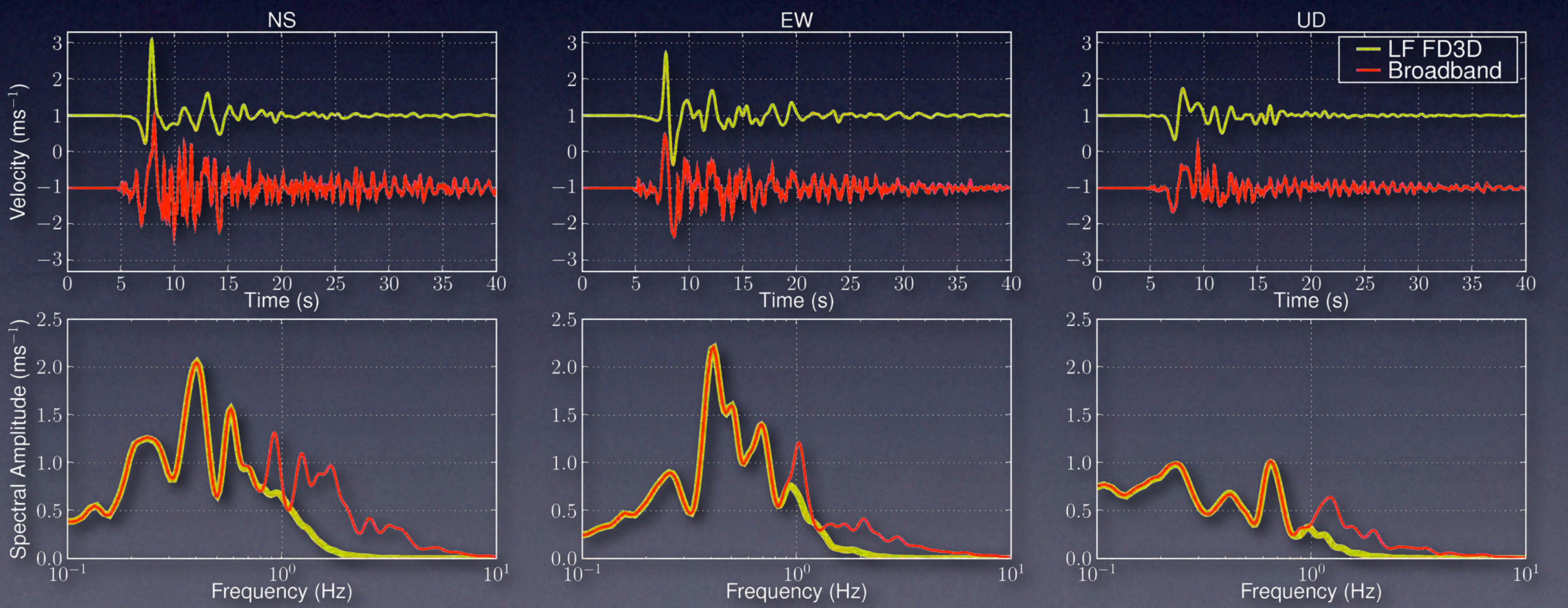
Velocity | Response spectra | Particle motion



Synthetic Broadband Seismograms

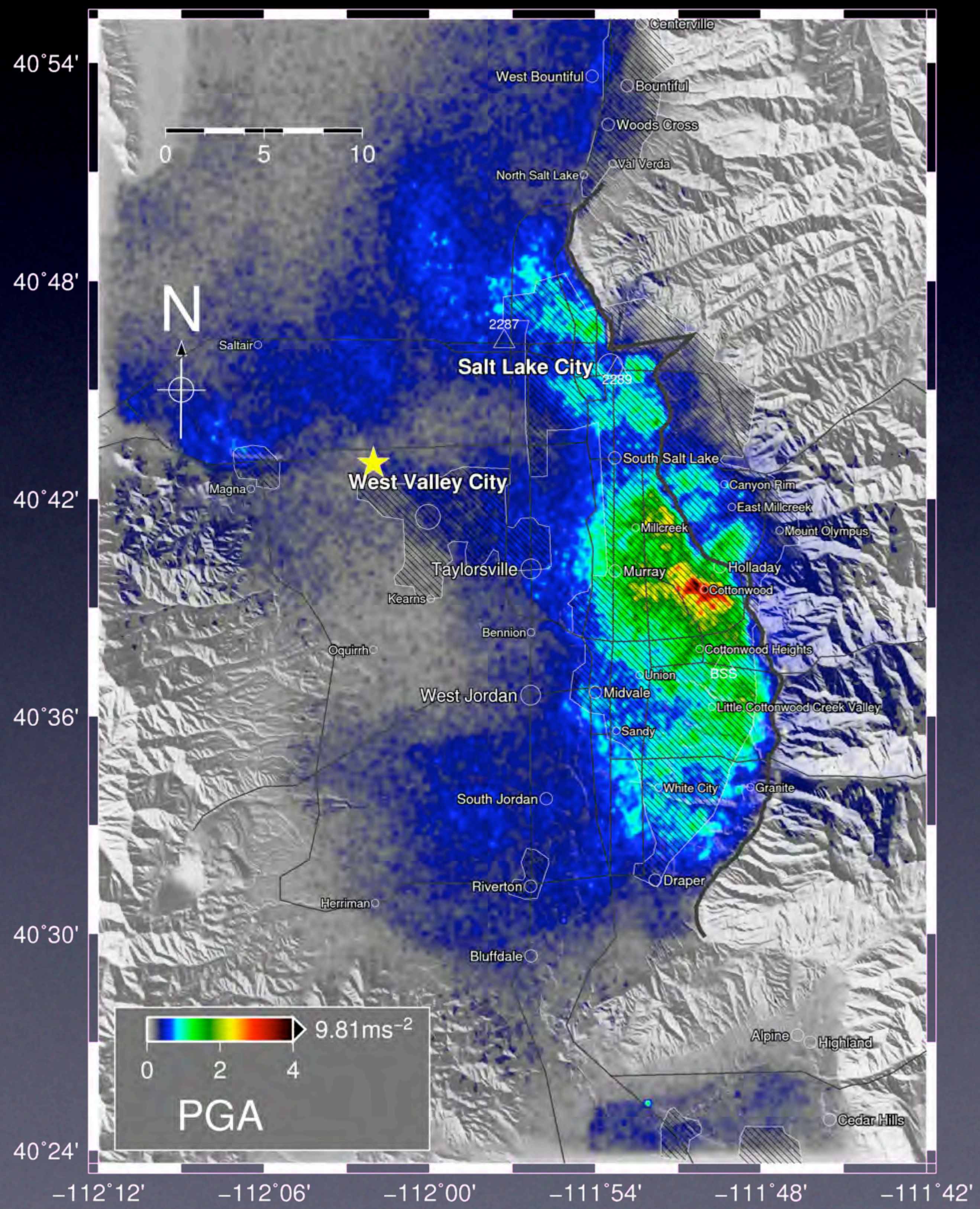
Combining low-frequency FD synthetics with high-frequency scattering operators:

- Scatterograms are computed using multiple scattering theory with scattering parameters based on site-specific velocity structure
- Scatterograms are convolved with dynamically consistent source time function
- LF and HF synthetics are combined into broadband seismograms in the frequency domain using a simultaneous amplitude and phase matching algorithm (Mai & Olsen, 2009)



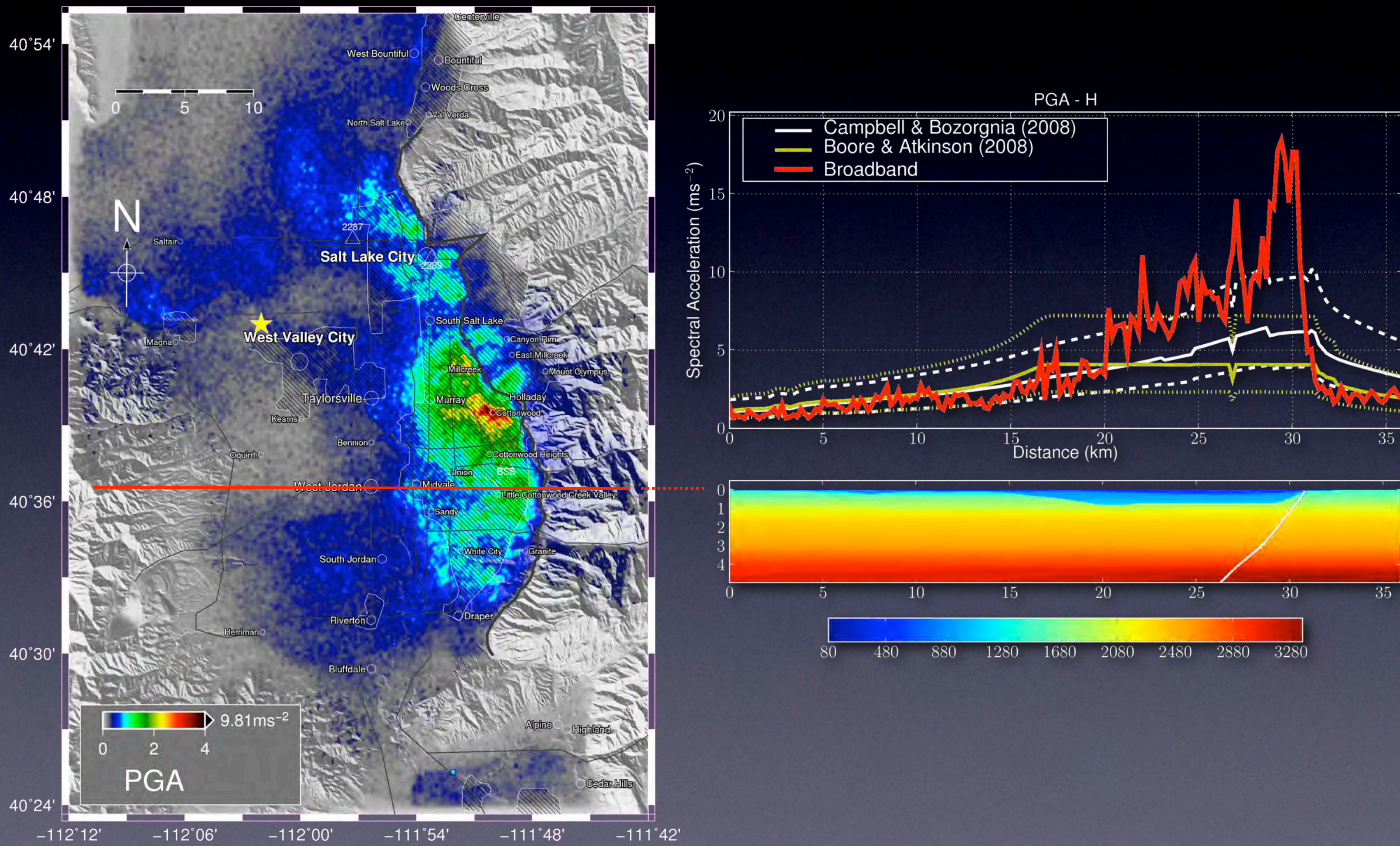
Synthetic Broadband Seismograms

Broadband PGA (Scenario 2a)



Synthetic Broadband Seismograms

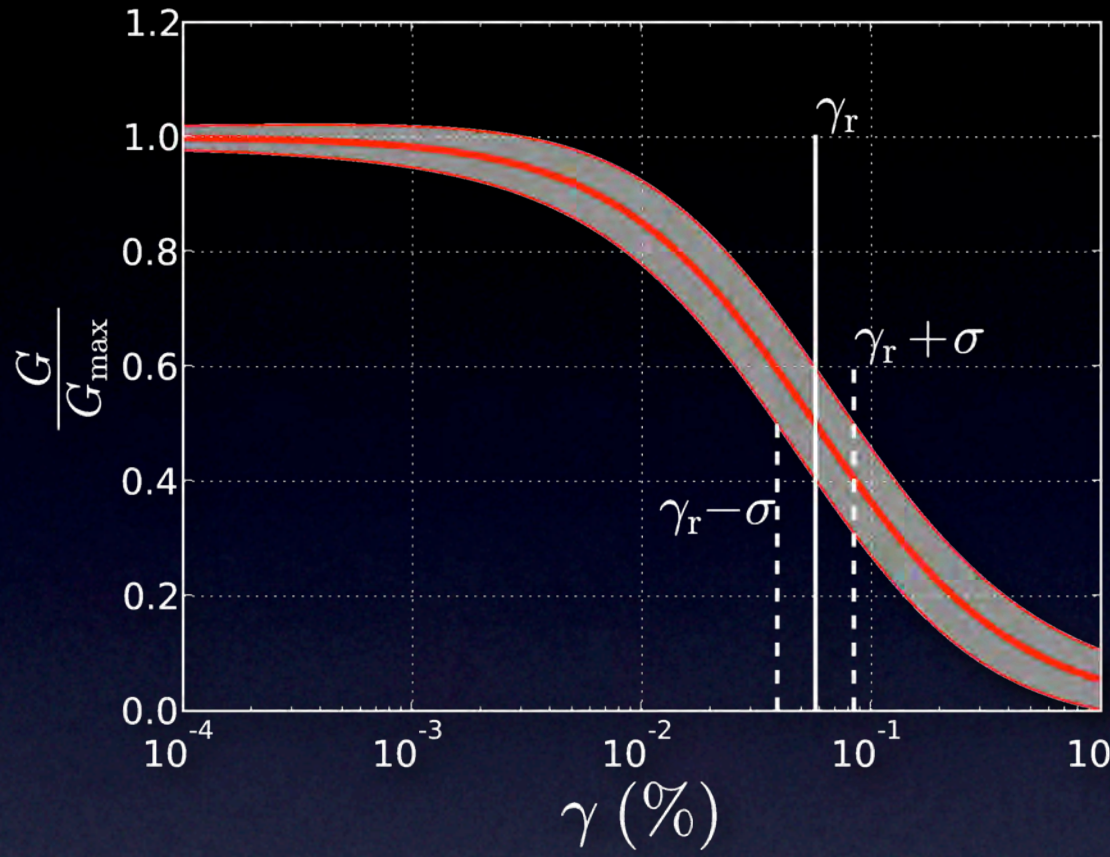
Broadband PGA (Scenario 2a)



Simulation of Nonlinear Soil Response

- Nonlinear 1-D propagator *NOAH* (Bonilla et al., 2005) to model SH propagation in top 240m
- Not modeling pore water pressure or soil dilatancy (parameters are not available)
- Shear modulus reduction is controlled by reference strain γ_r:

$$\frac{G}{G_{\max}} = \frac{1}{1 + \frac{\gamma}{\gamma_r}}$$



- *Reference strain* γ_r is derived from an empirical relationship (Darendelli, 2001), modified to take results of recent laboratory test of Bonneville clays into account (Bay & Sasanakul, 2005):

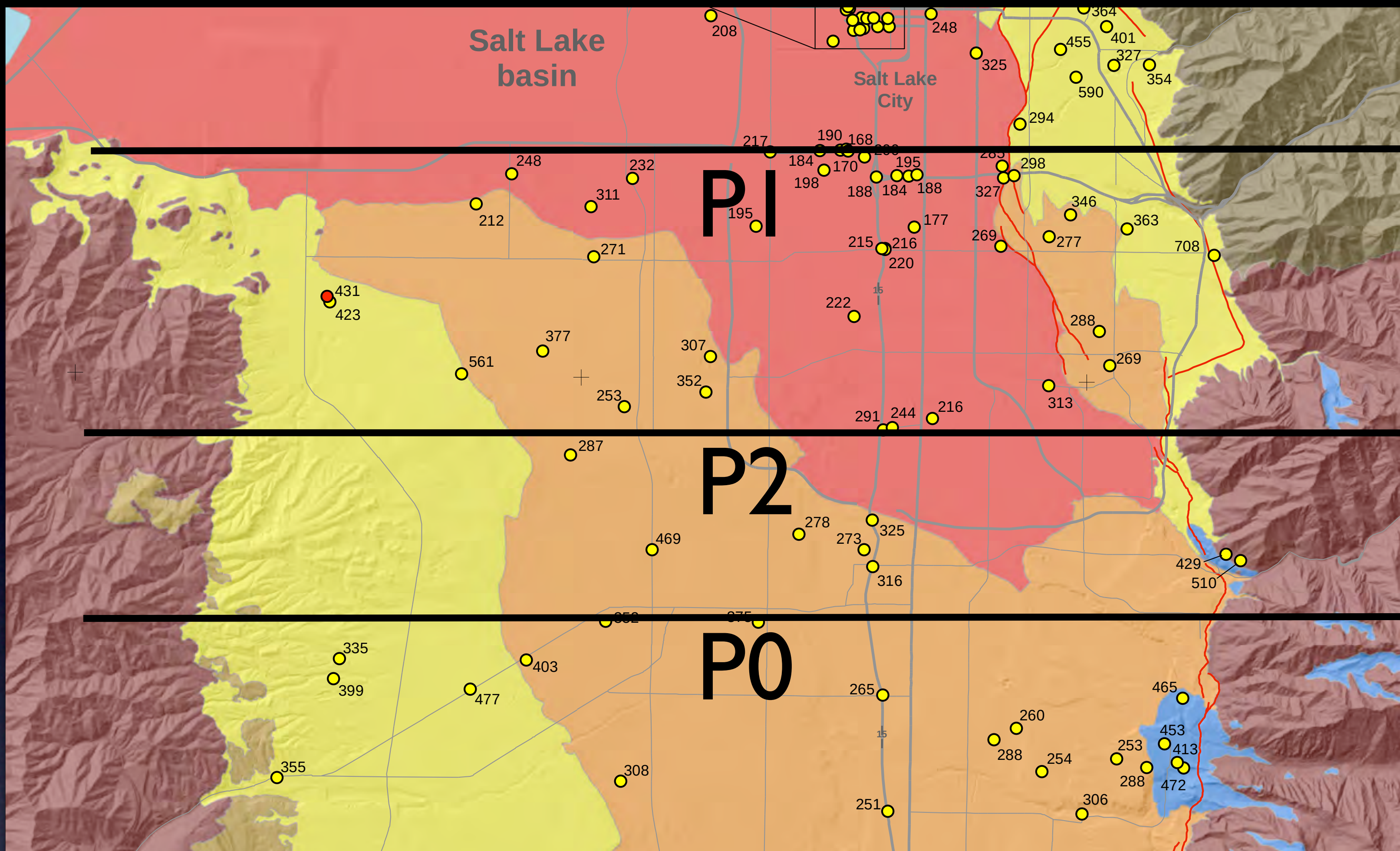
$$\gamma_r(\mathrm{PI}, \mathrm{OCR}, \sigma_v)$$

- Hysteresis dissipation is controlled by maximum damping ratio at large strains ξ_{max}, which we also estimate from Darandelli (2001):

$$\xi_{\max}(\mathrm{PI}, \mathrm{OCR}, \sigma_v, N, f)$$

	Parameter	Value
PI	Plasticity Index	0 - 40
OCR	Overconsolidation ratio	1
σ_v	Confining pressure	f(z)
N	Number of cycles	10
f	Frequency	1 Hz

Nonlinear soil parameters



Q01 (PI=40%)

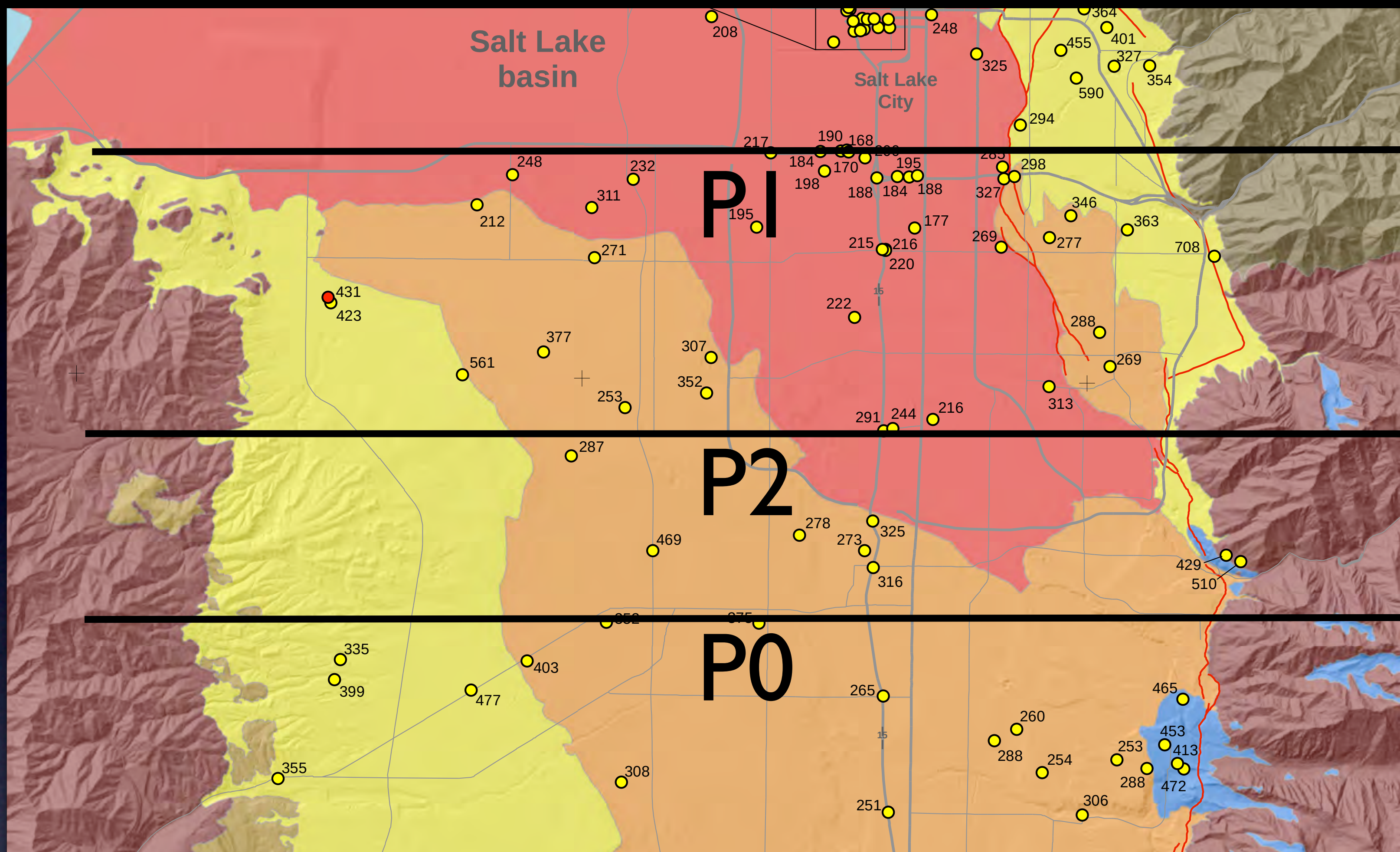
Q02 (PI=30%)

Q03 (PI=0%)

Rock (linear)

McDonald and Ashland (2008)

Nonlinear soil parameters



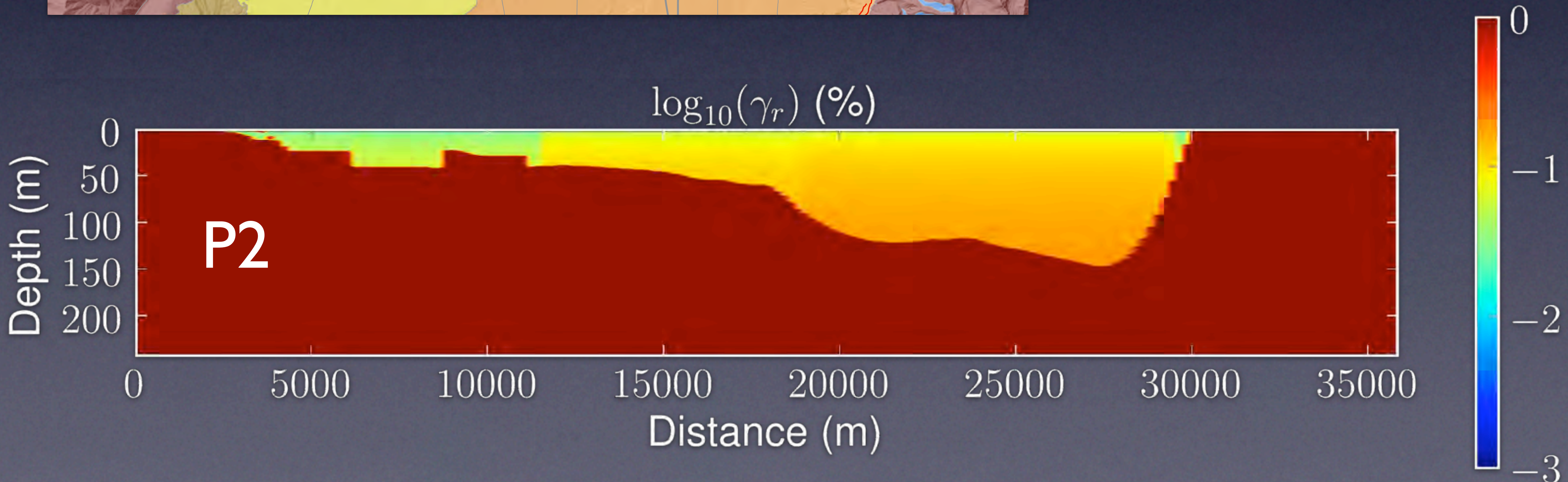
Q01 (PI=40%)

Q02 (PI=30%)

Q03 (PI=0%)

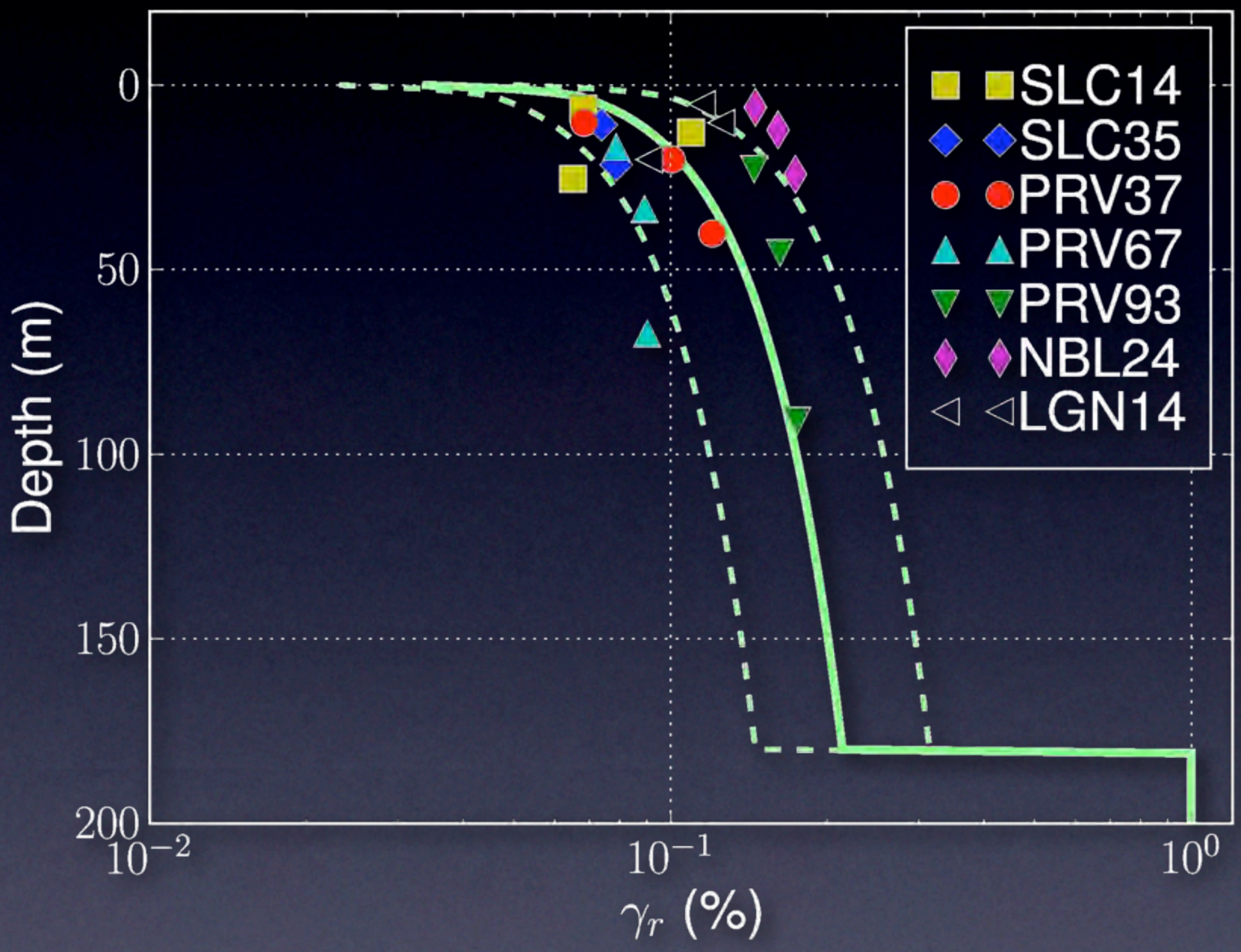
Rock (linear)

McDonald and Ashland (2008)



Nonlinear soil parameters

Example site on P1 (5 km south of airport):



reference strain γ_r

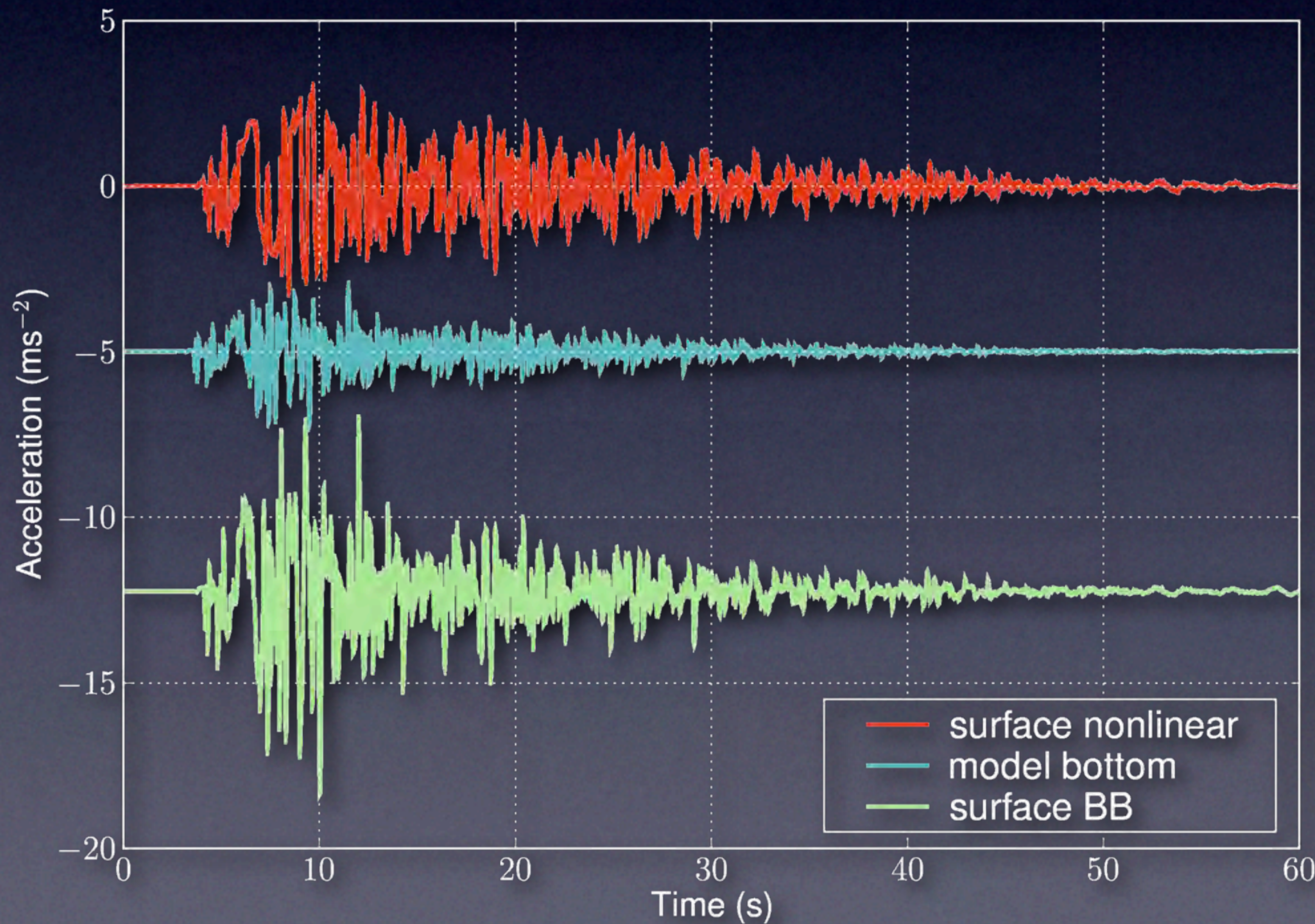
γ_r ± std

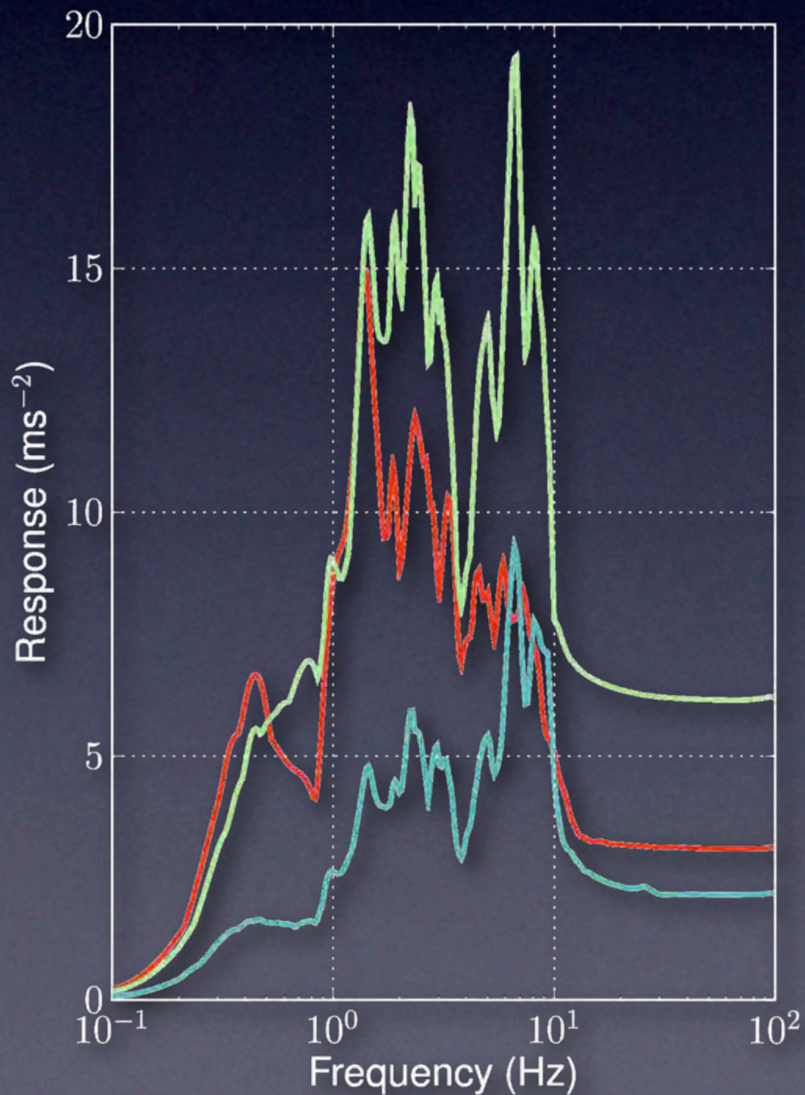
Three 1D models for each site:

Model	Reference strain	Damping ratio
Nonlinear	γ_r	ξ
More nonlinear	γ_r - std	ξ + std
Less nonlinear	γ_r + std	ξ - std

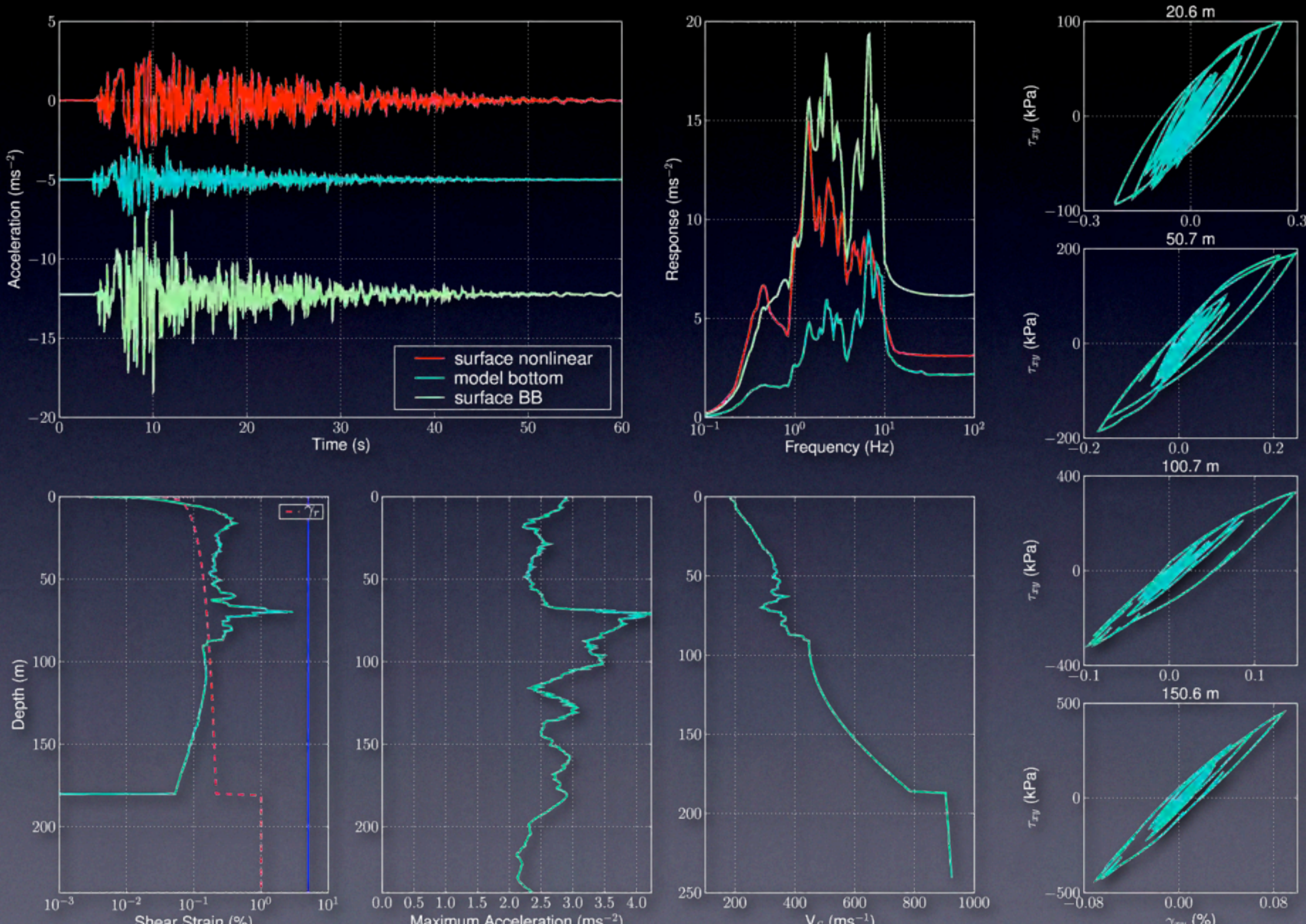
Simulation of Nonlinear Soil Response

- **Broadband synthetics at free surface** are deconvolved to remove response of upper 240m
- Resulting signal represents **incoming wavefield at depth** and serves as input for nonlinear simulation
- Nonlinear 1-D simulation yields ground motion on the **surface of the nonlinear layer**



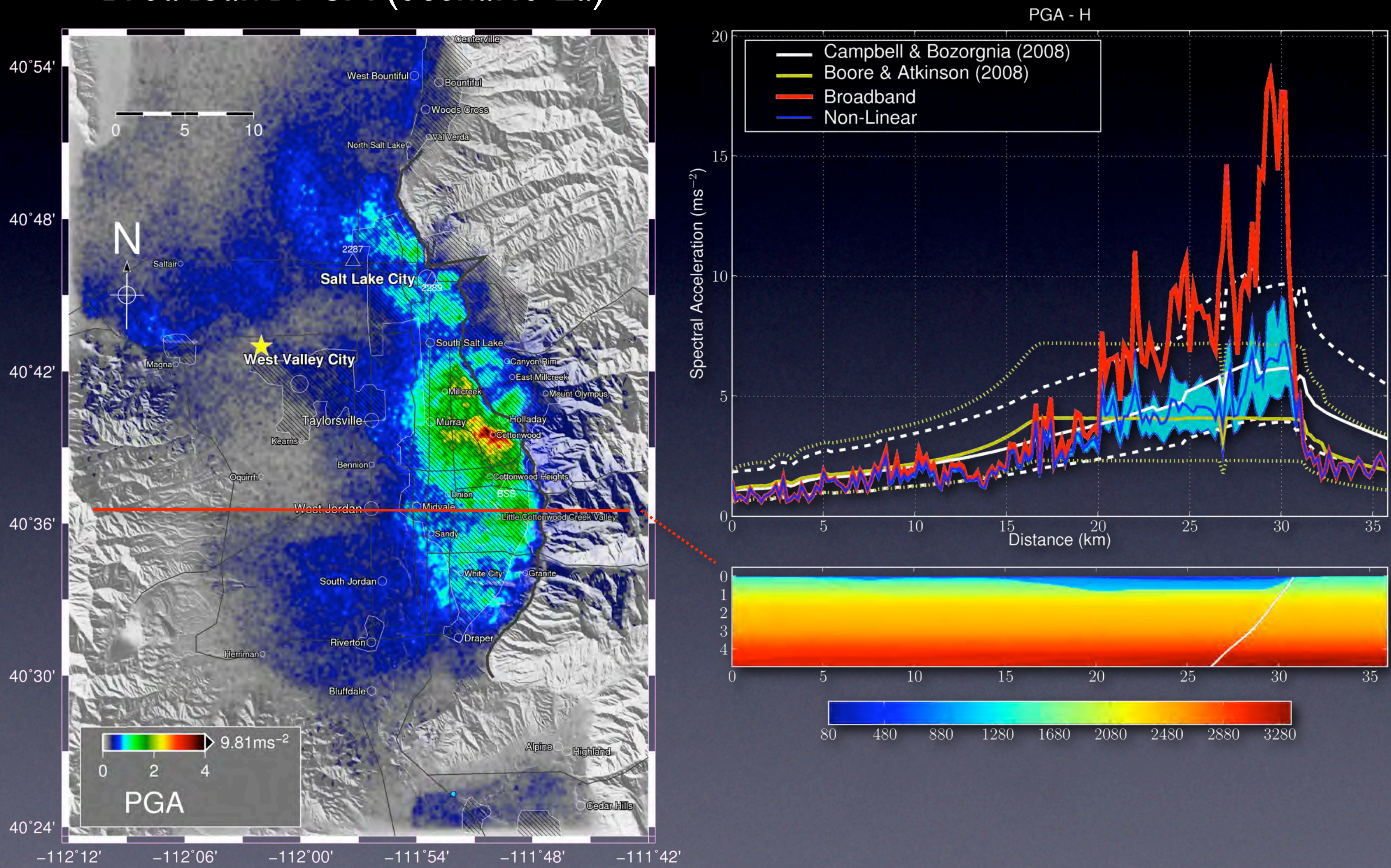


Simulation of Nonlinear Soil Response



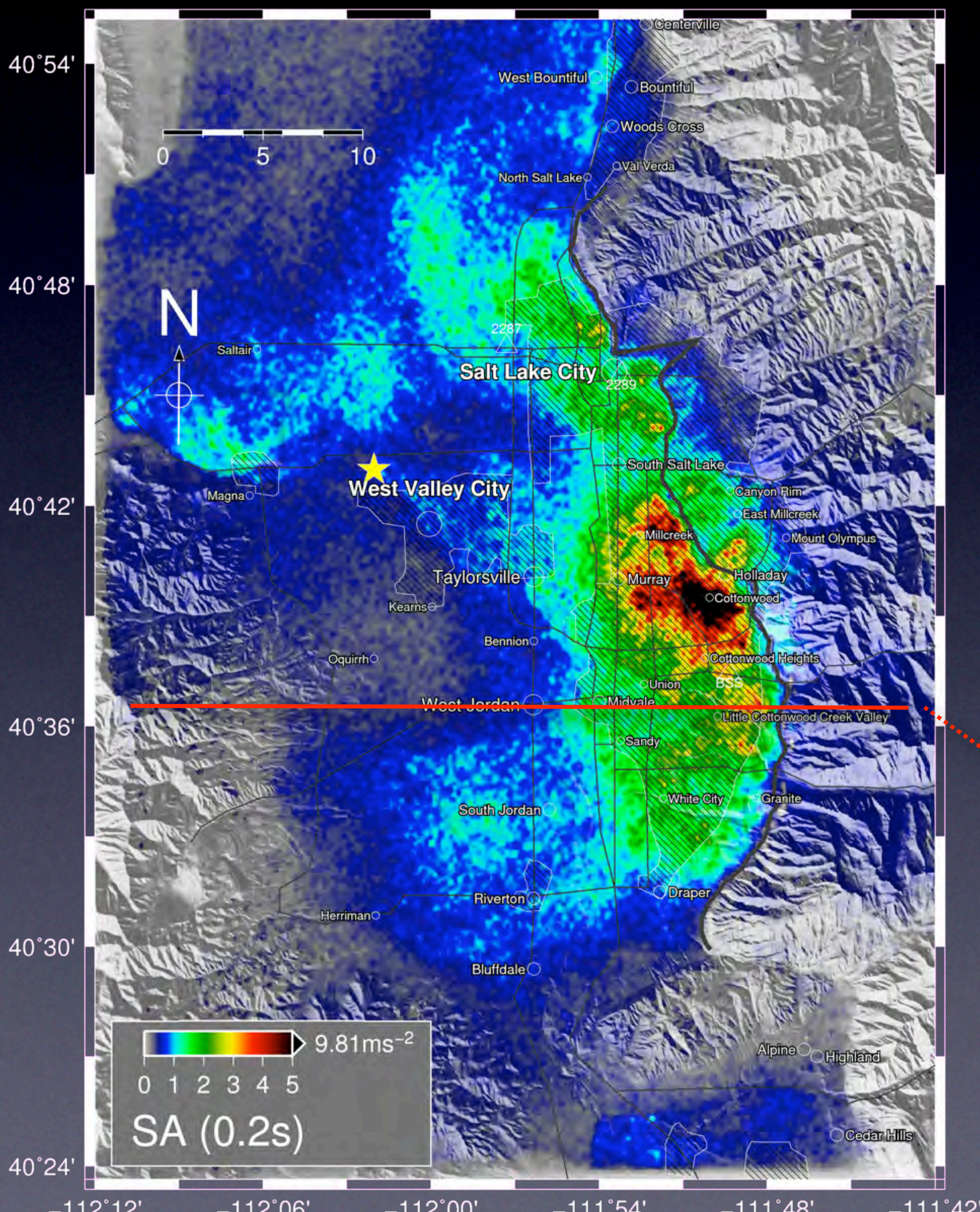
Linear (Broadband) vs. Nonlinear

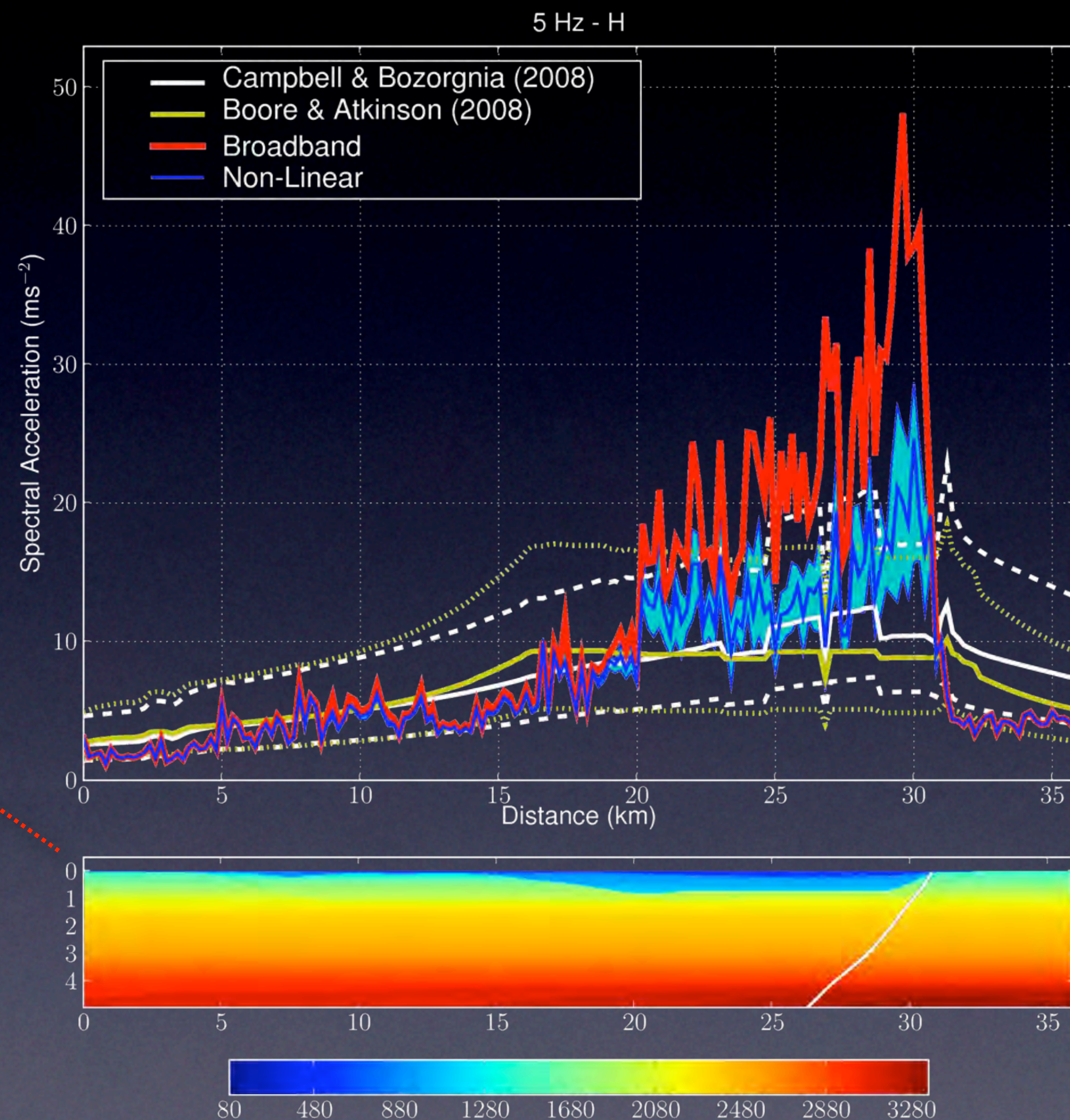
Broadband PGA (Scenario 2a)



Linear (Broadband) vs. Nonlinear

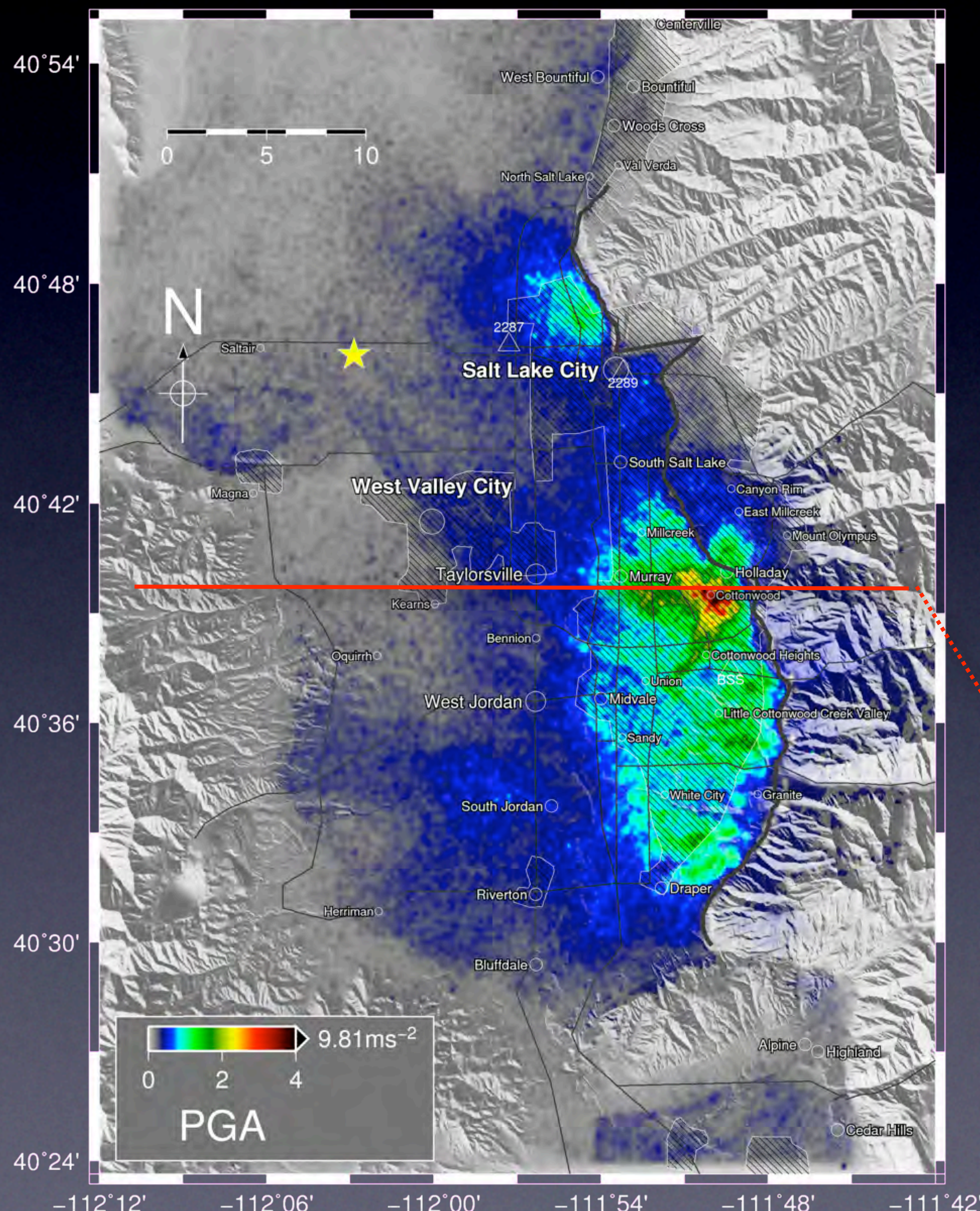
Broadband 0.2s-SAs (Scenario 2a)

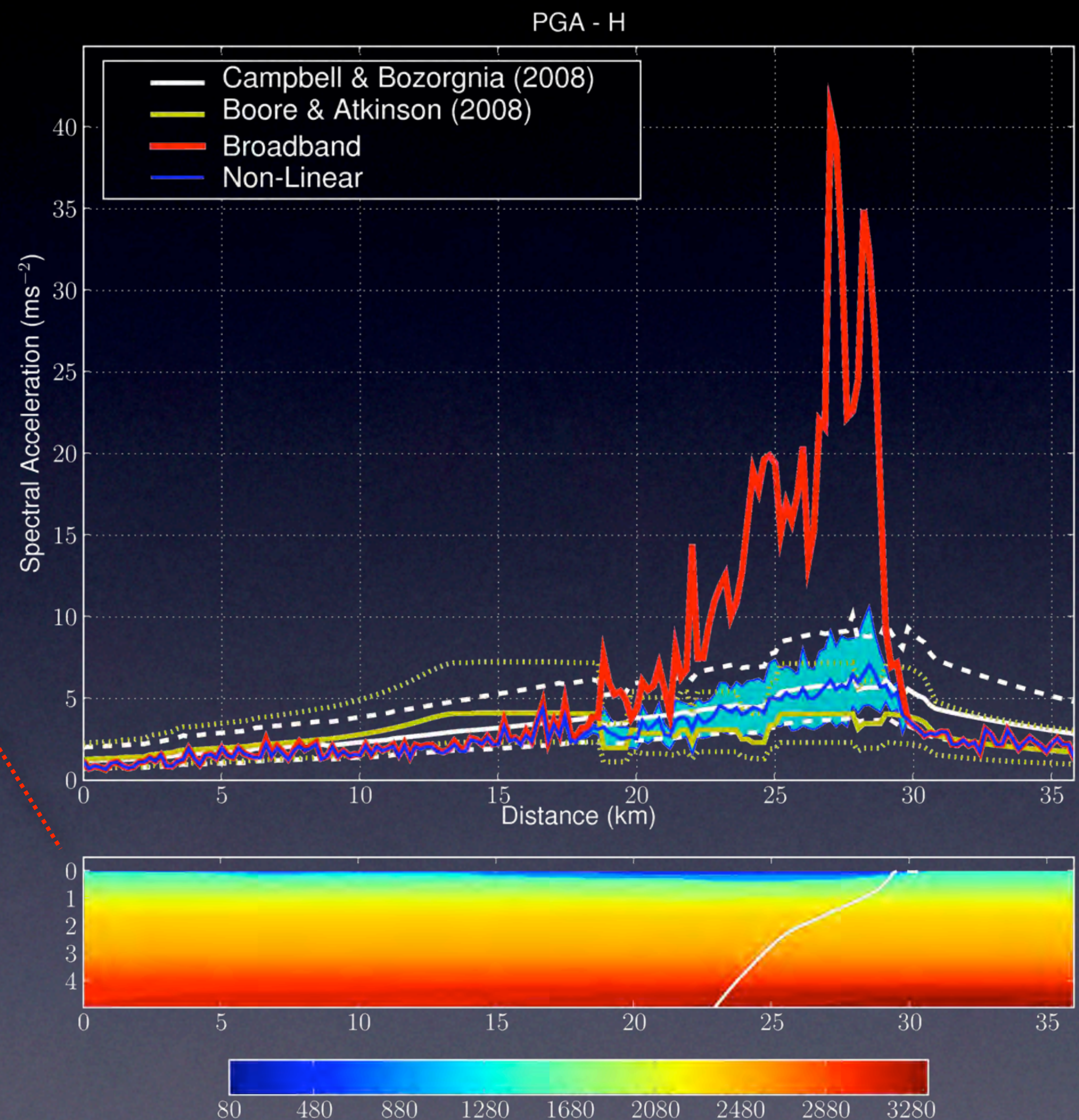




Linear (Broadband) vs. Nonlinear

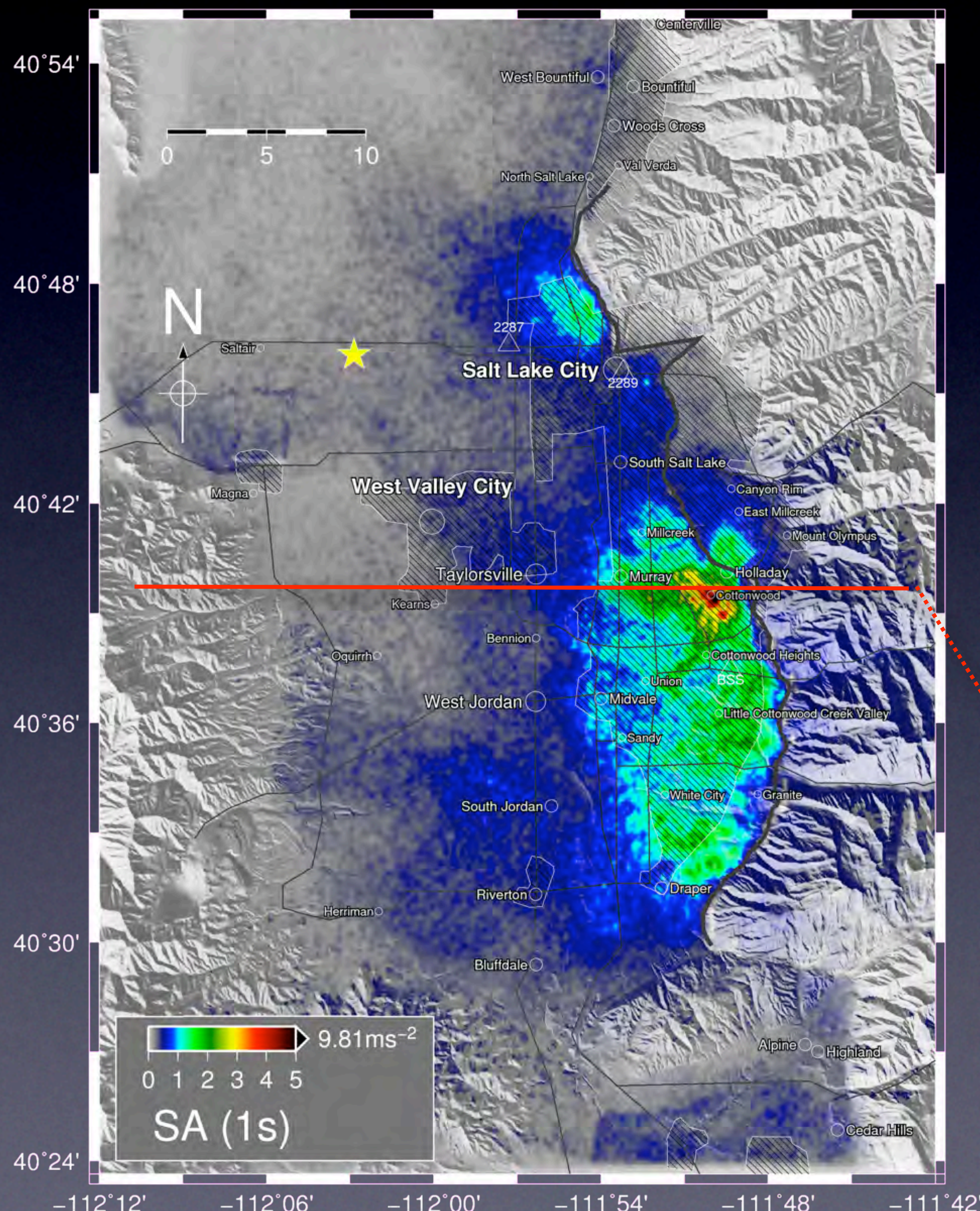
Broadband PGA (Scenario 5a)

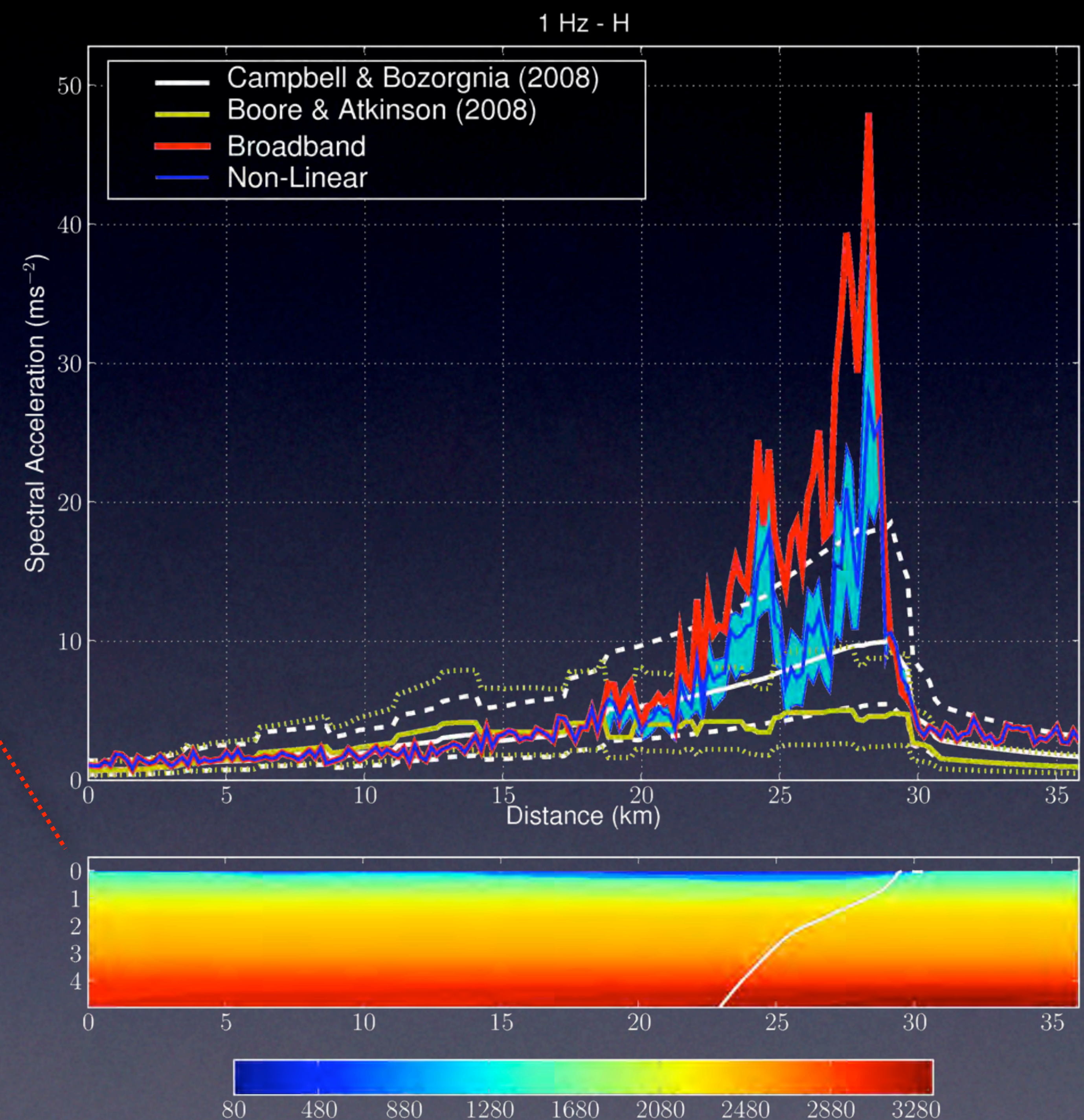




Linear (Broadband) vs. Nonlinear

Broadband 1s-SAs (Scenario 5a)

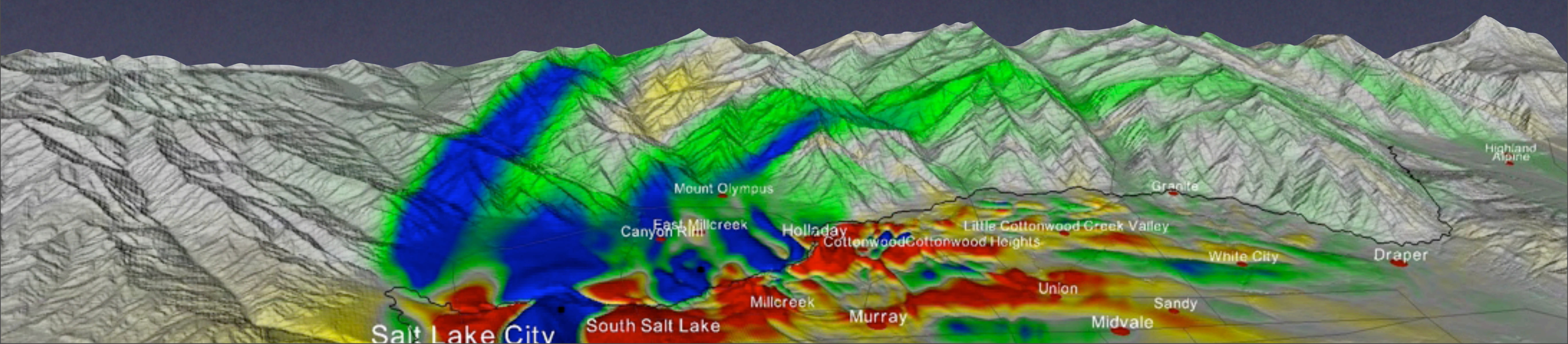




Conclusions I

0-1 Hz 3-D FD simulations of scenario earthquakes

- Ground motion tends to be larger on the low-velocity sediments on the hanging wall side of the fault than on outcropping rock on the footwall side, confirming results of previous studies on normal faulting EQs (O'Connell et al., 2007)
- The simulated ground motions reveal strong along-strike and along-dip directivity effects
- Compared to Solomon et al. (2004), our 3-D FD simulations predict larger ground motion on the hanging wall side of the fault, but lower values on the footwall side
- Our simulations suggest that the highest average 2s-SAs and 1s-SAs occur at ~2 km distance from the surface trace of the fault, where they exceed NGA predictions by up to 75%.
- Extreme 1s-SAs of up to 5g are caused by Love waves generated near the Holladay stepover



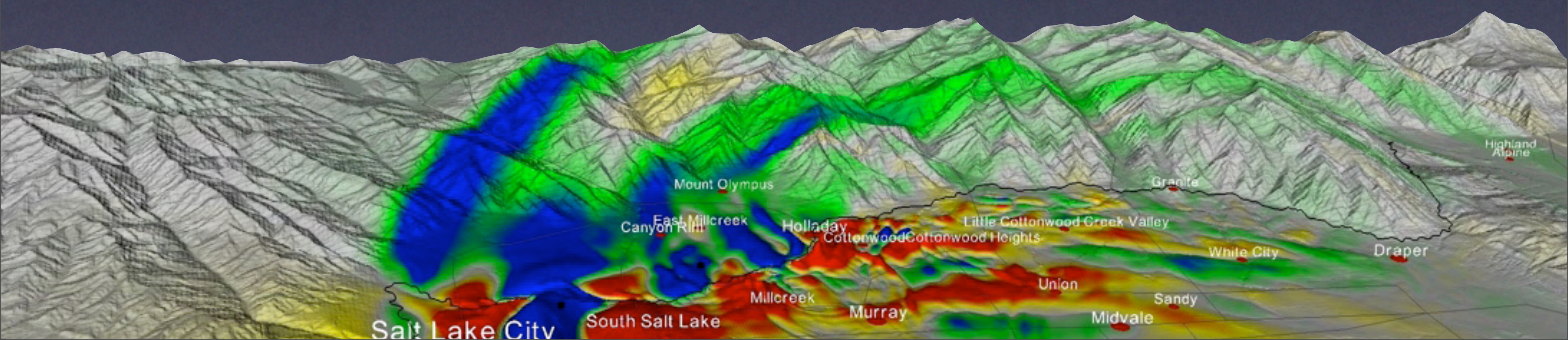
Conclusions II

Broadband (0-10Hz) synthetics:

- PGAs derived from broadband synthetic seismograms are exceeding those predicted by NGA models by more than one standard deviation at near-fault locations on the hanging wall side, but agree well at some distance from the fault

Nonlinear soil response:

- Synthetic ground motions obtained from a fully nonlinear 1-D propagator exhibit PGAs and SAs that are more consistent with values predicted by NGA models, even when taking into account the uncertainty in the nonlinear soil parameters



Discussion of USGS Wasatch Front Urban Seismic Hazard Maps

Optimal Products

- Based on 3D simulations and empirical ground motion models
- Broad band
  - 10 Hz-1Hz (0.2 s?)- fully non-linear analysis
  - 1-10s (possibly 2 Hz) – simulations with CVM
- Scenario ground motion models for M 7 SLC segment rupture
- Probabilistic maps of SL County Urban hazard

Groups

- Olsen and Pechmann (O&P)– completed, finite difference dynamic and kinematic models
- Archuleta and Smith – in progress, finite-element dynamic and kinematic models
- Bielak – in progress, finite element code with non-linear effects
- USGS – in progress, Bielak linear code, maybe others (e.g., Liu’s code)

Phase I – Methodology for long-period simulations

- Test models – validation by comparison between groups and observations (for both high frequency and long-period, dynamic vs kinematic)
  - Use CVM (version 3C)
  - Prescribe source – one of O&P's validation events
  - Prescribe damping model, slip history, and frequency band (0.1-1Hz; O&P model)
  - Prescribe resolution of mesh and minimum shear-wave velocity (O&P model)

General Methodology

- Finite fault geometry (SLC segment Wasatch fault, O&P model?)
- Prescribe same damping model and CVM as were used in the validation test
- Allow for variable slip functions (super-shear, etc) Do we need to consider other variability (e.g., CVM, dip, input parameters)? How many slip models can each group deliver?
- Prescribe output grid and format (XYZ g.m., grid ~100 m)

Phase I - Long-period Methodology

- Compute Spectral accelerations at each site in grid
- Compare ground motions, calculate statistics, every site will have an uncertainty
- Use statistics to modify ground motion prediction equations for the site class used in CVM.

Phase II - High Frequency Methodology

- Calculate high frequency using stochastic methods and non-linear models (Wong)
- Compute Spectral accelerations at each site in grid
- Compare ground motions, calculate statistics
- Use statistics to modify ground motion prediction equations for the Vs30 site class defined in CVM.

Phase III - Use results in calculations to estimate ground motion from other faults – may be other alternatives

- USGS conducts modeling for multiple faults with multiple slip distributions and for a grid of background point sources (i.e., “gridded seismicity”).
- Add uncertainty from Phase I and Phase II.
- Calculate the hazard for the urban hazard maps