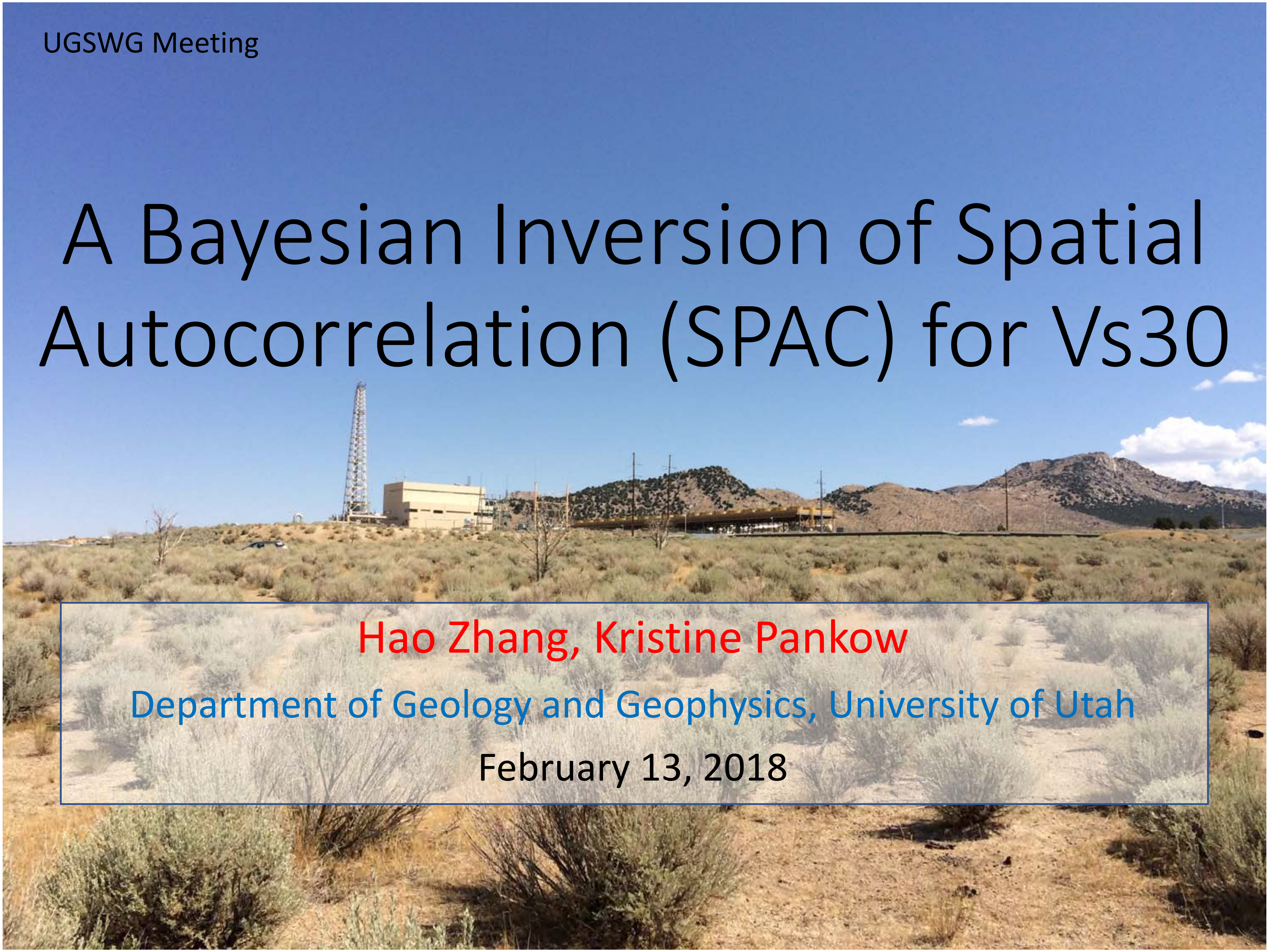
UGSWG Meeting

A Bayesian Inversion of Spatial Autocorrelation (SPAC) for Vs30



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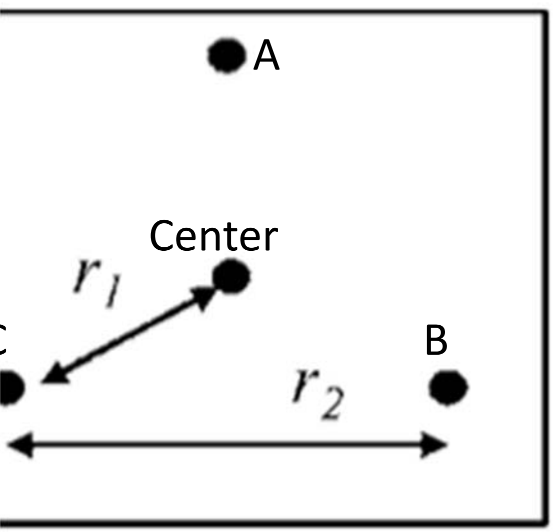
Department of Geology and Geophysics, University of Utah

February 13, 2018

Spatial Autocorrelation (SPAC)



Theoretical:

$$c(f) = \frac{1}{2\pi}\int_0^{2\pi} \exp\{irk\cos(\theta - \phi)\}d\theta$$

$$= J_0(rk) = J_0\left(\frac{2\pi f r}{v(f)}\right),$$

Observation:

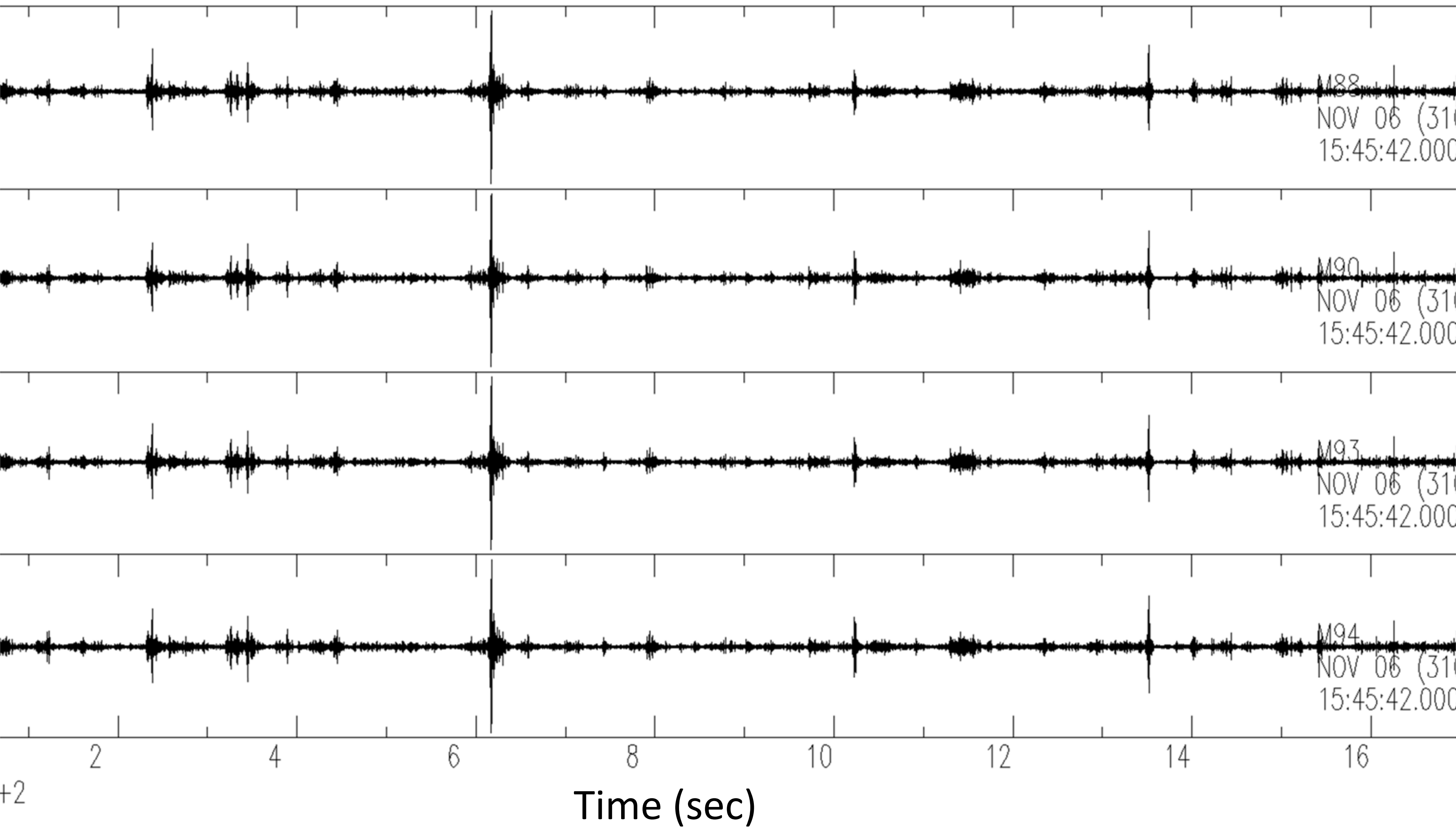
$$c(f) = \frac{1}{2\pi}\int_0^{2\pi} \frac{C(f,r,\theta)}{\sqrt{P(f,0)P(f,\theta)}}d\theta$$

$$= \frac{1}{N}\sum_{i=1}^{N} \frac{C(f,0,r_i)}{\sqrt{C(f,0,0)C(f,r_i,r_i)}}$$

0: the average shear velocity of
ne layer within the top 30 meters

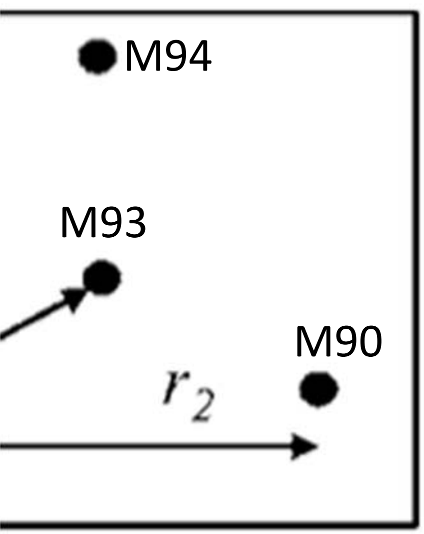
(Aki, 1957; Okad

Data

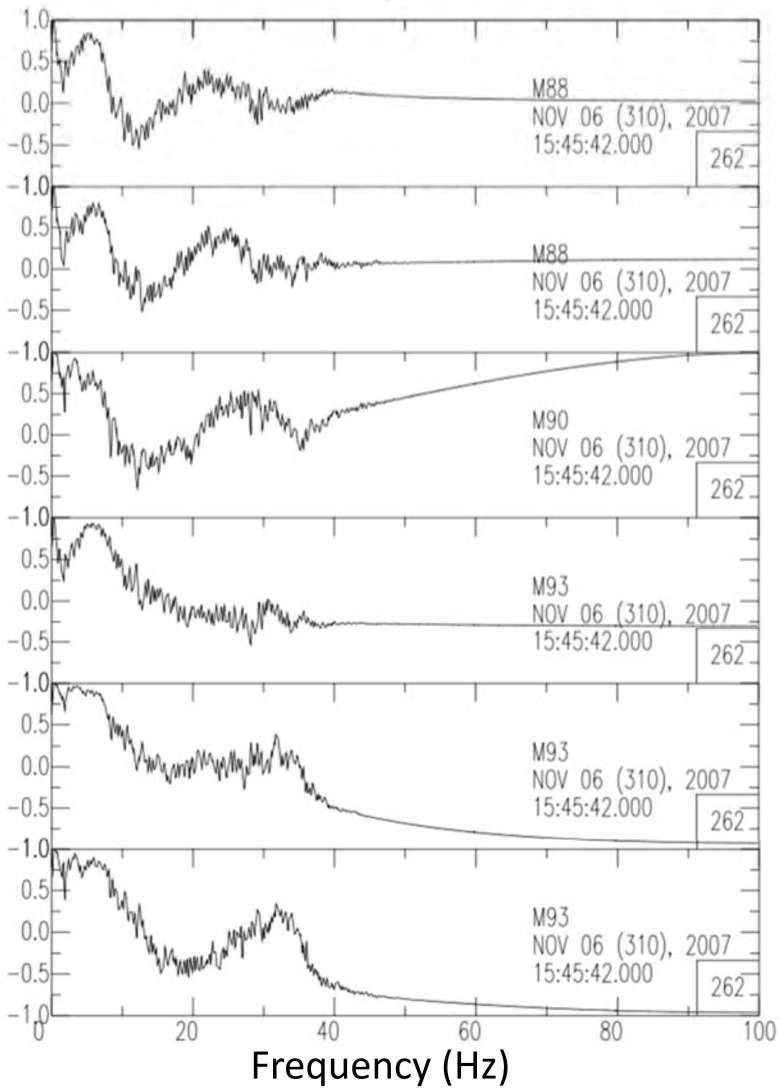

M88
NOV 06 (31
15:45:42.000
M90
NOV 06 (31
15:45:42.000
M93
NOV 06 (31
15:45:42.000
M94
NOV 06 (31
15:45:42.000
2
4
6
8
10
12
14
16
+2
Time (sec)

Coherency function for each station pair

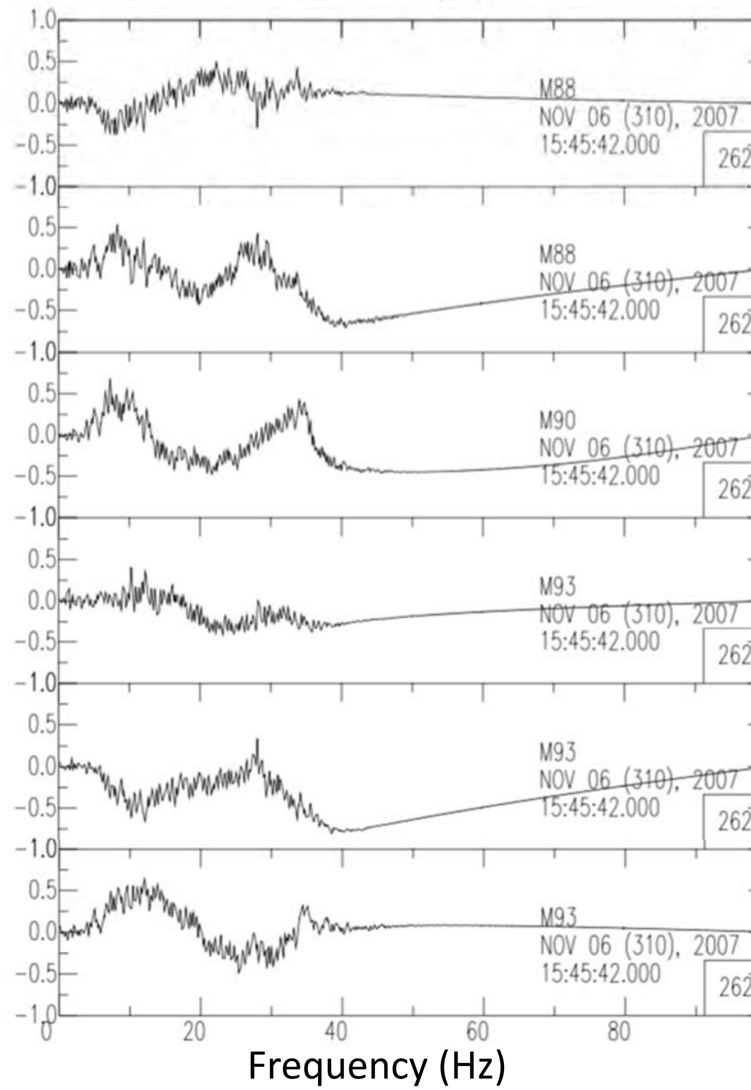
cohM88_M90_rl.sm cohM88_M94_rl.sm cohM90_M94_rl.sm cohM93_M88_rl.sm cohM93_M90_rl.sm cohM93_M94_rl.



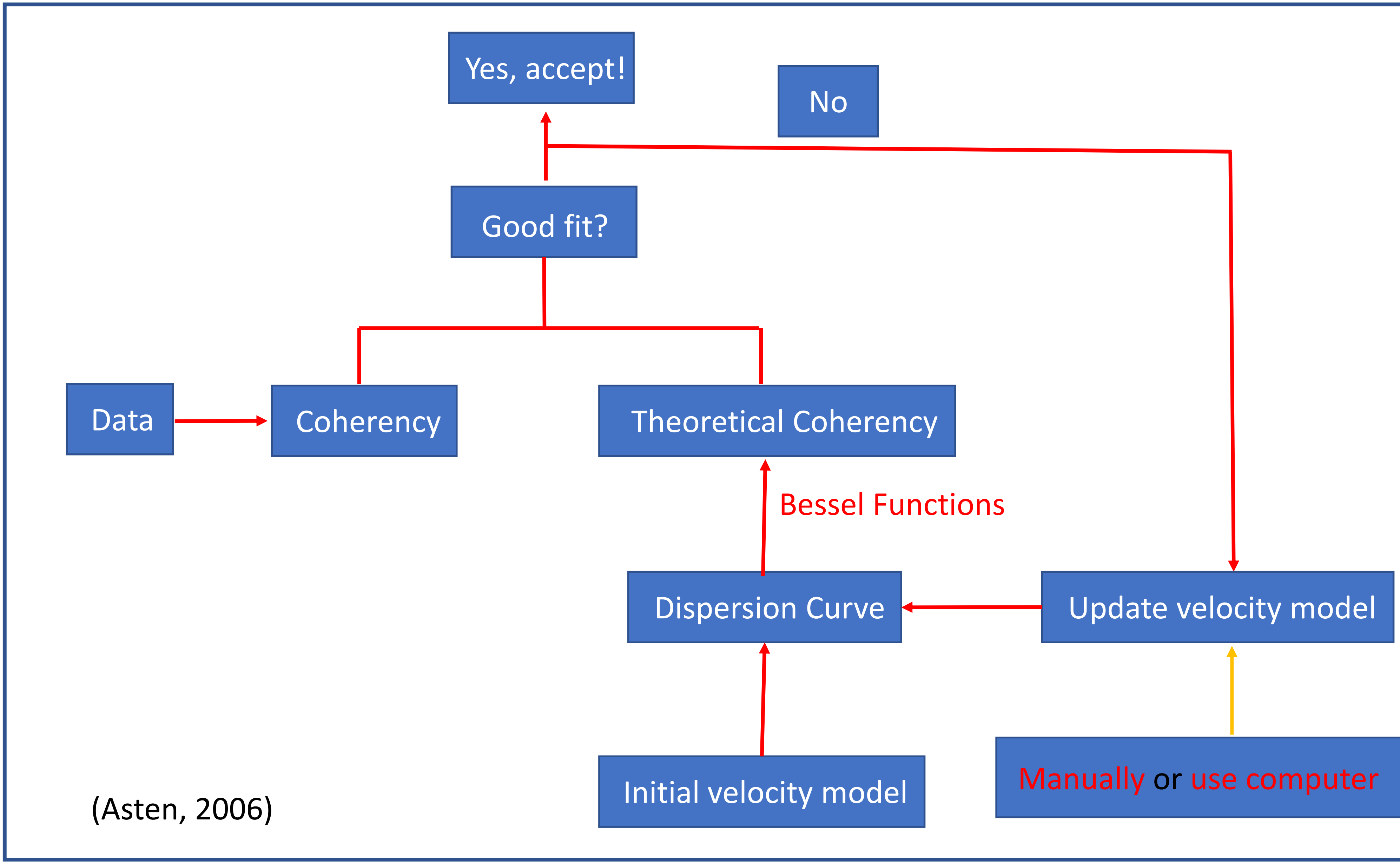
Real part



Imaginary part



Workflow of MMSPAC



Bayesian Method

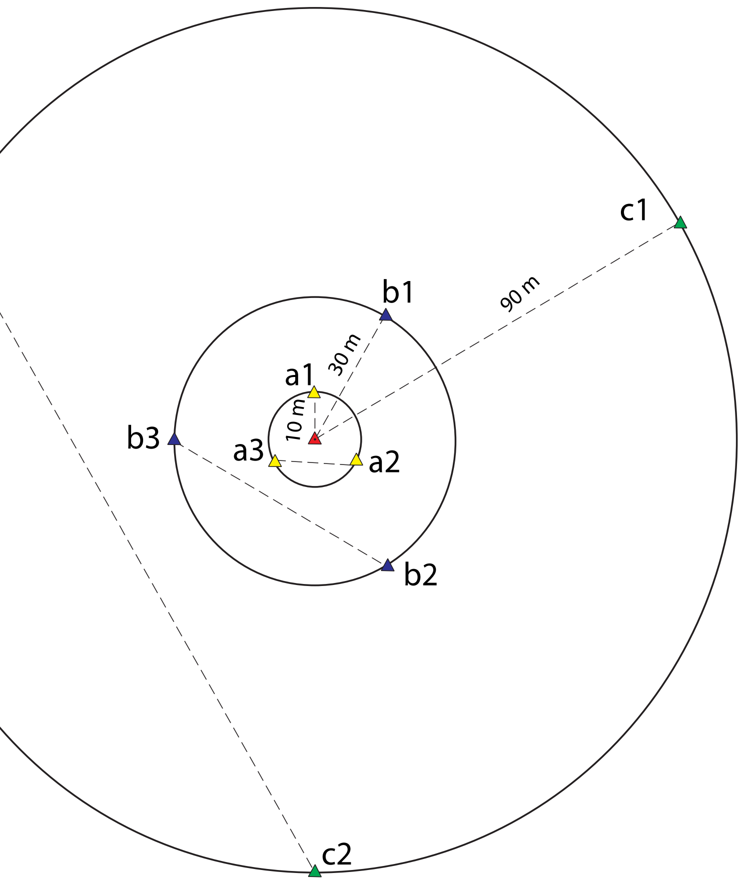
The Bayesian method is based on Bayes' theorem and is implemented in a Markov Chain Monte Carlo (MCMC) – Metropolis Hasting scheme

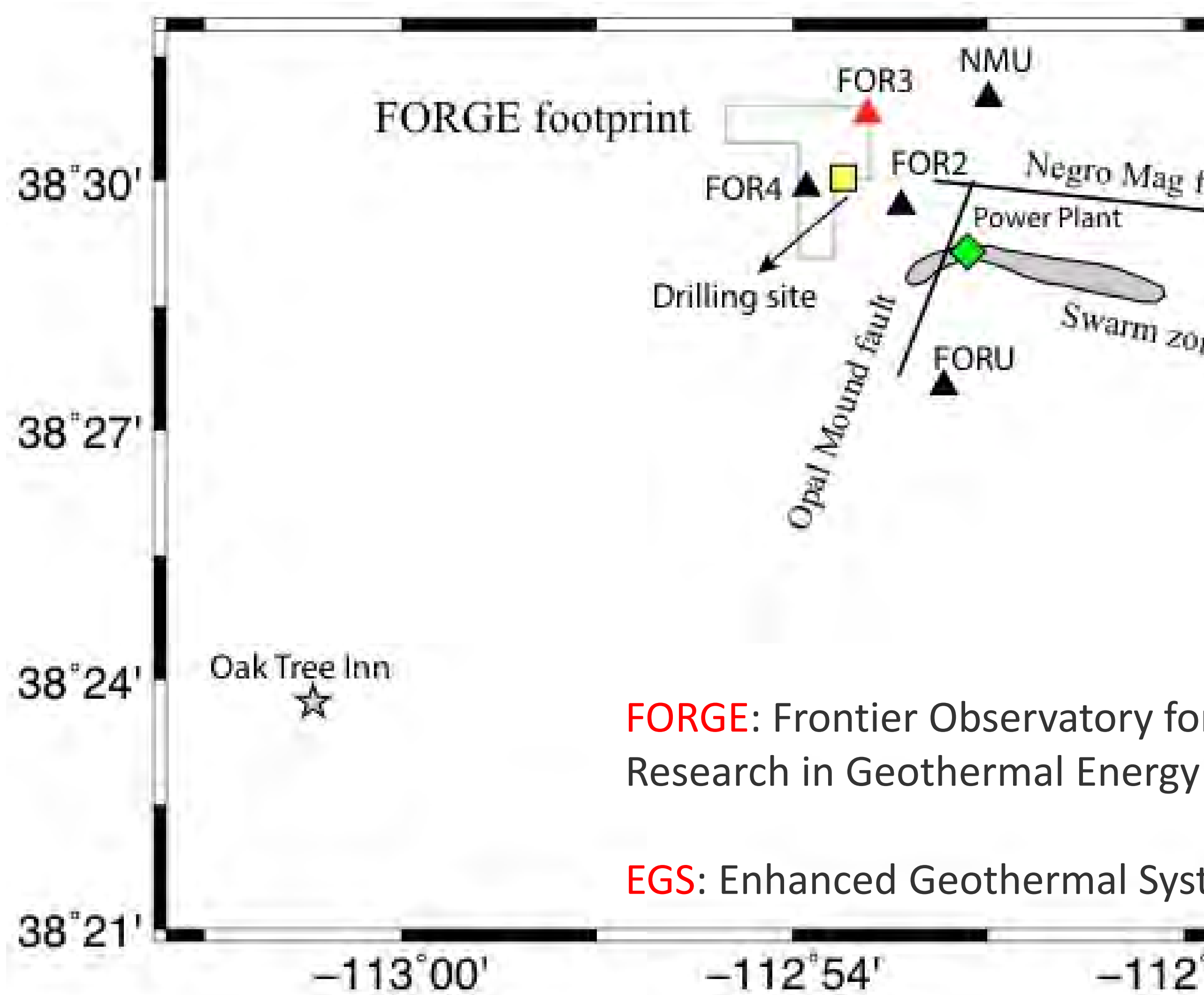
3000 models are randomly generated and for each model shear velocities and thicknesses of the top five layers are the variables to be modifed

For the resultant 3000 models, a burning point of 1500 best models is used

Application to the FOR3 array

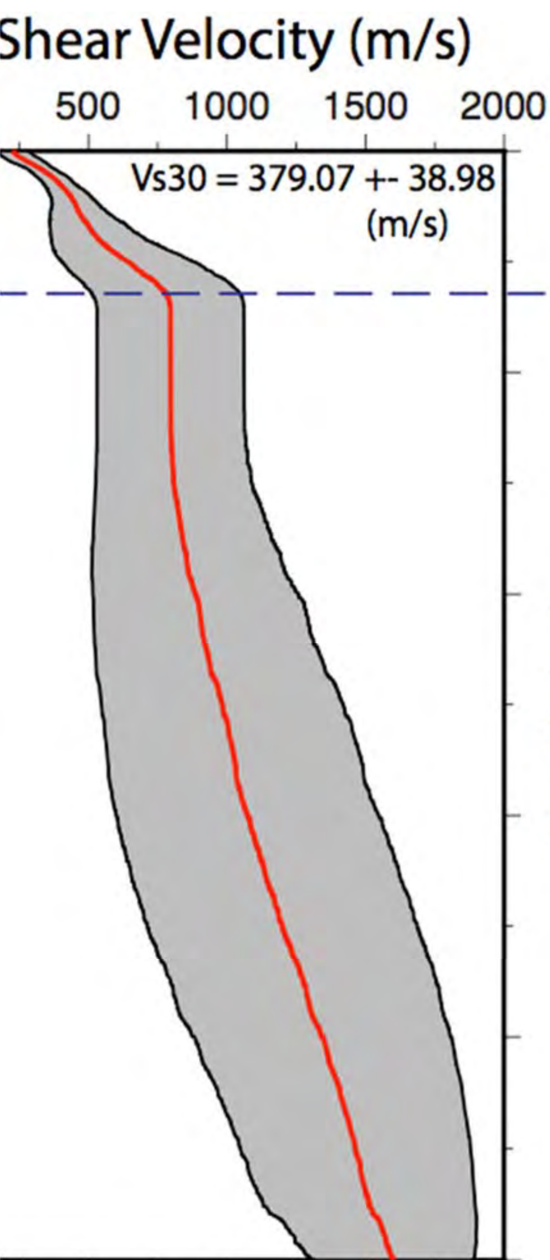
Array configuration at station FOR3



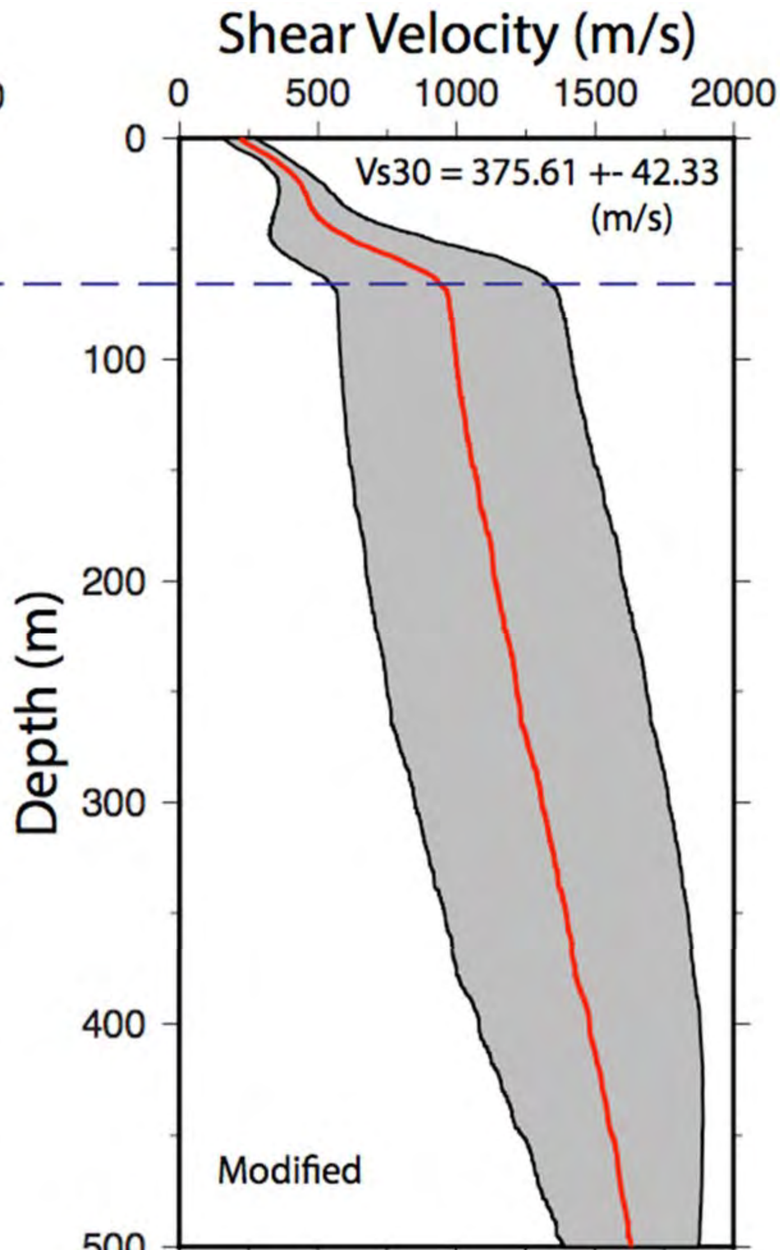


FORGE: Frontier Observatory fo
Research in Geothermal Energy

EGS: Enhanced Geothermal Syst



Model 1



Model 2

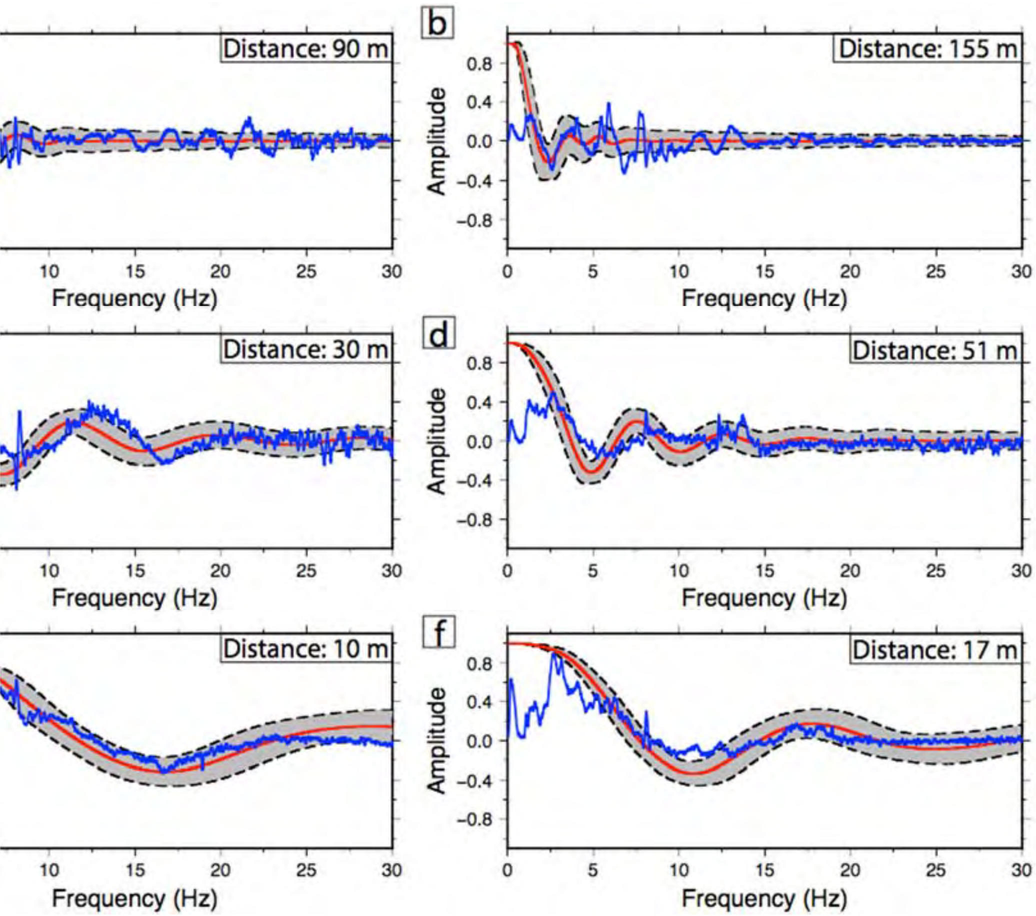
Parameter Table

	Thickness (m)	Vs (m
Layer 1	h1 ∈ $[0,10]$	Vs1∈ $[100$
Layer 2	h2 ∈ $[0,10]$	Vs2∈ $[Vs1$
Layer 3	h3 ∈ $[0,10]$	Vs3∈ $[Vs2$
Layer 4	H4 ∈ $[0,50]$	Vs4∈ $[Vs3$
Layer 5	h5	Vs5
Layer 6	1000	2000
Layer 7	0.0	3490

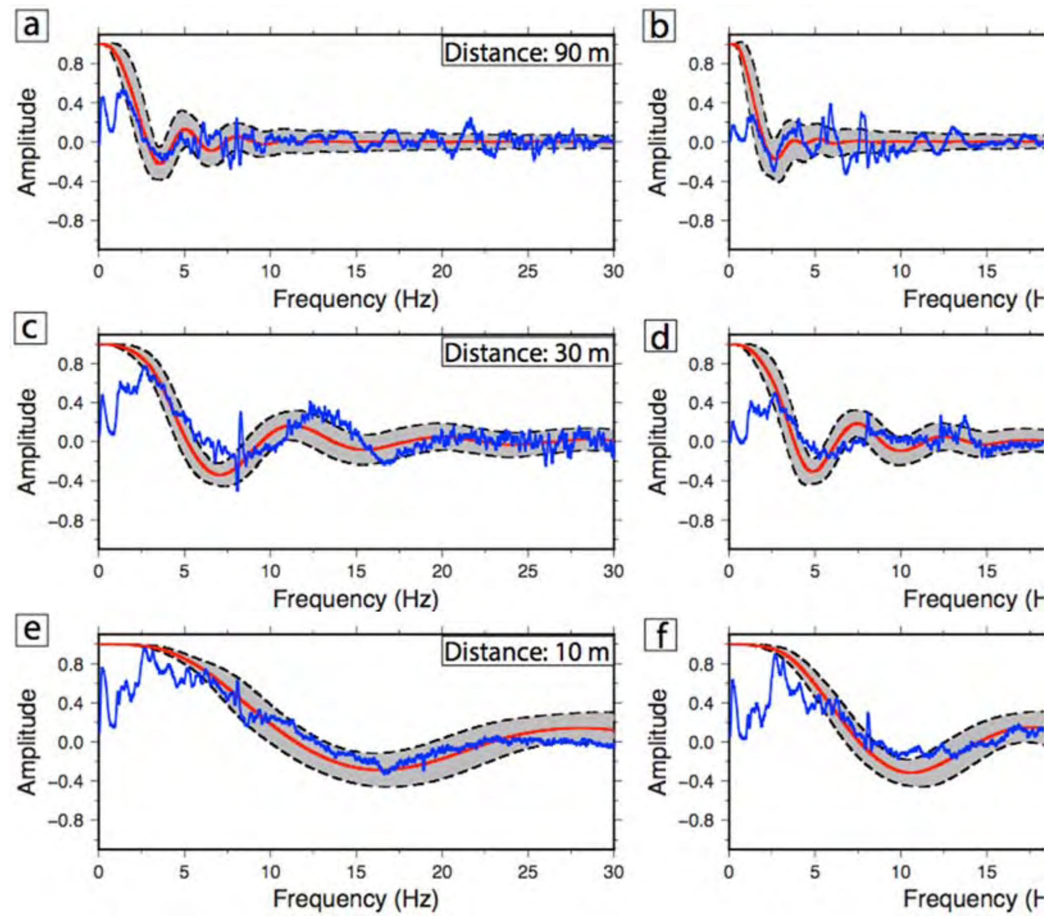
Model 1 : h5 ∈ $[100,500]$, Vs5 ∈ $[Vs$

Model 2 : h5 ∈ $[0,500]$, Vs5 ∈ $[Vs4,$

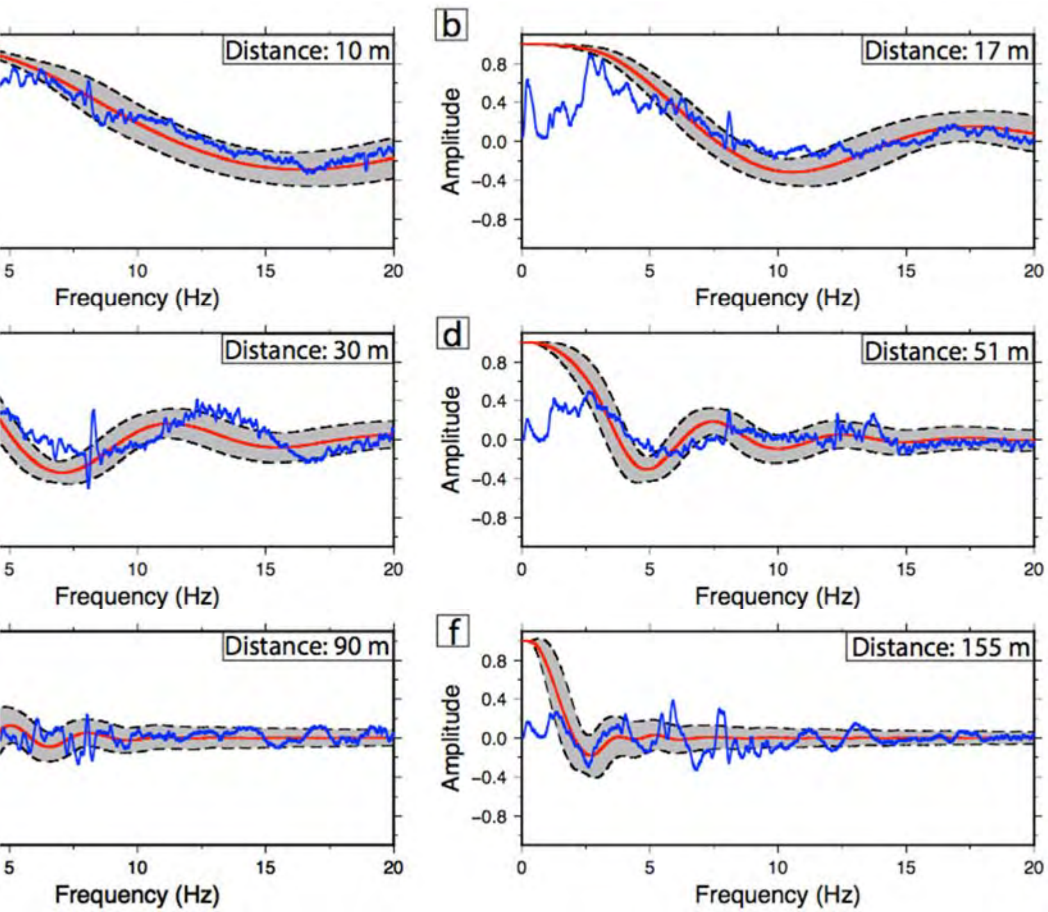
Model 1



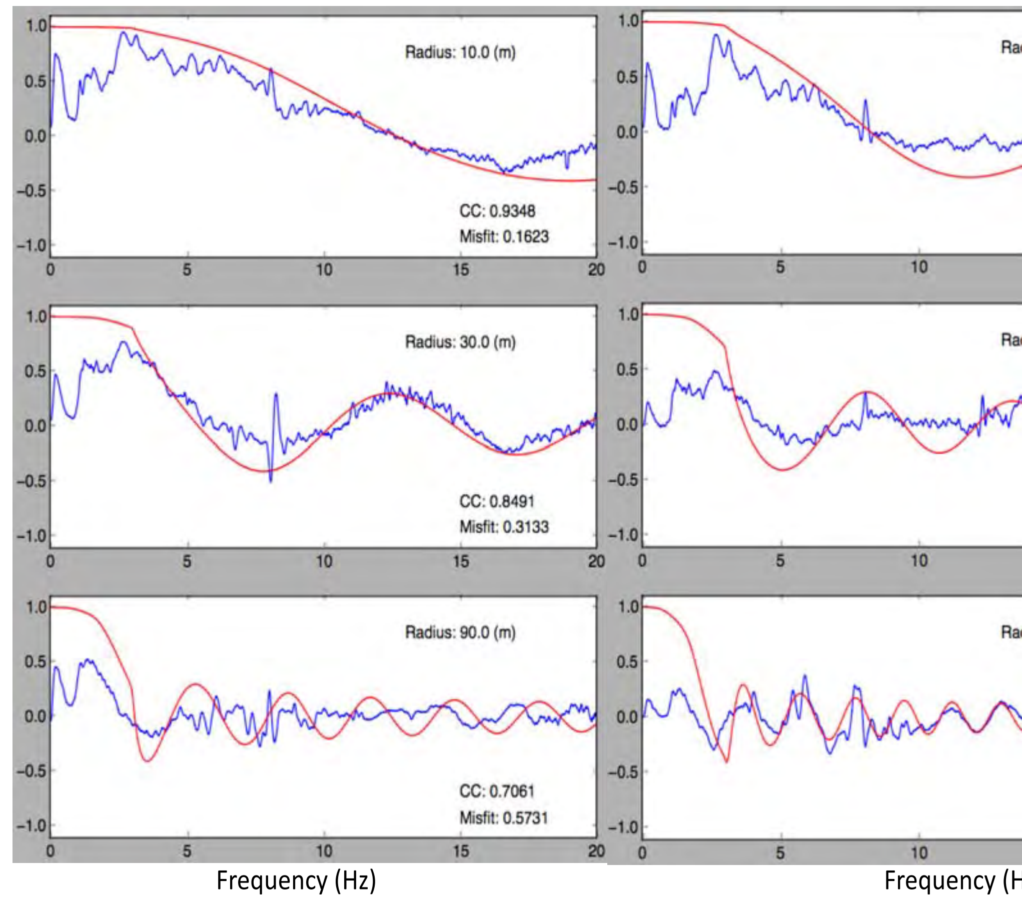
Model 2



Comparison of the SPAC between the Bayesian and forward iterative modeling

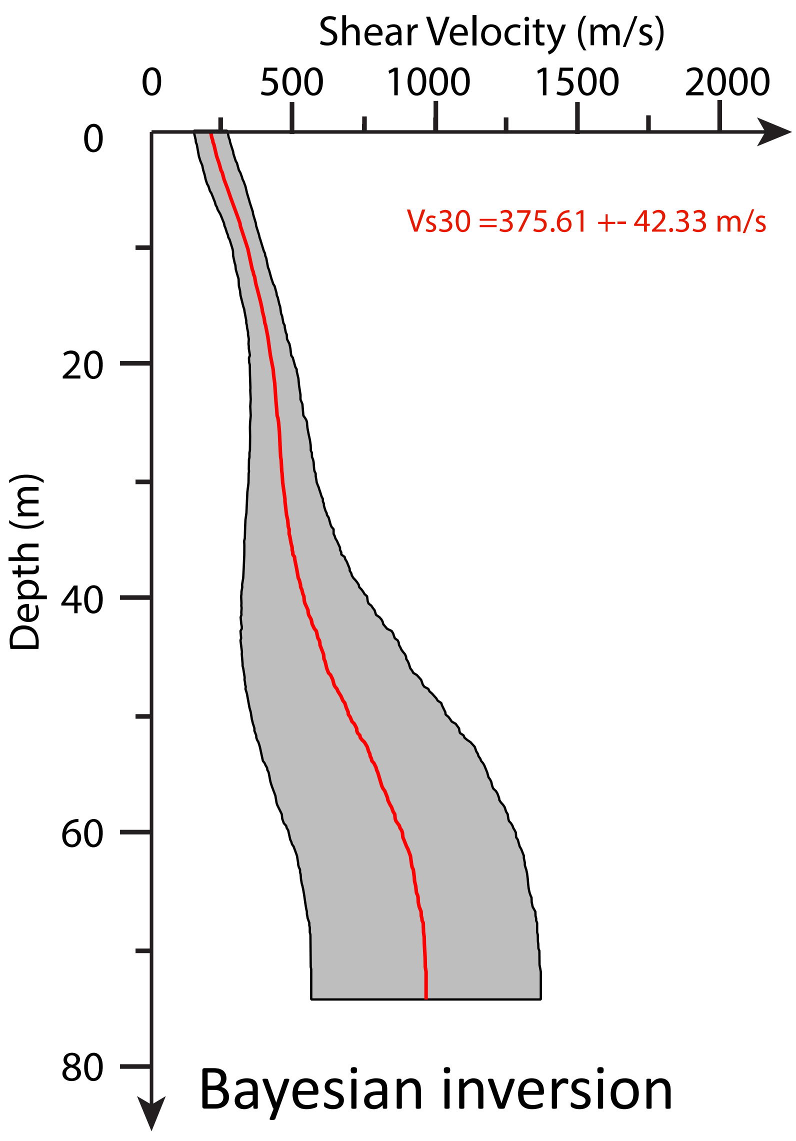


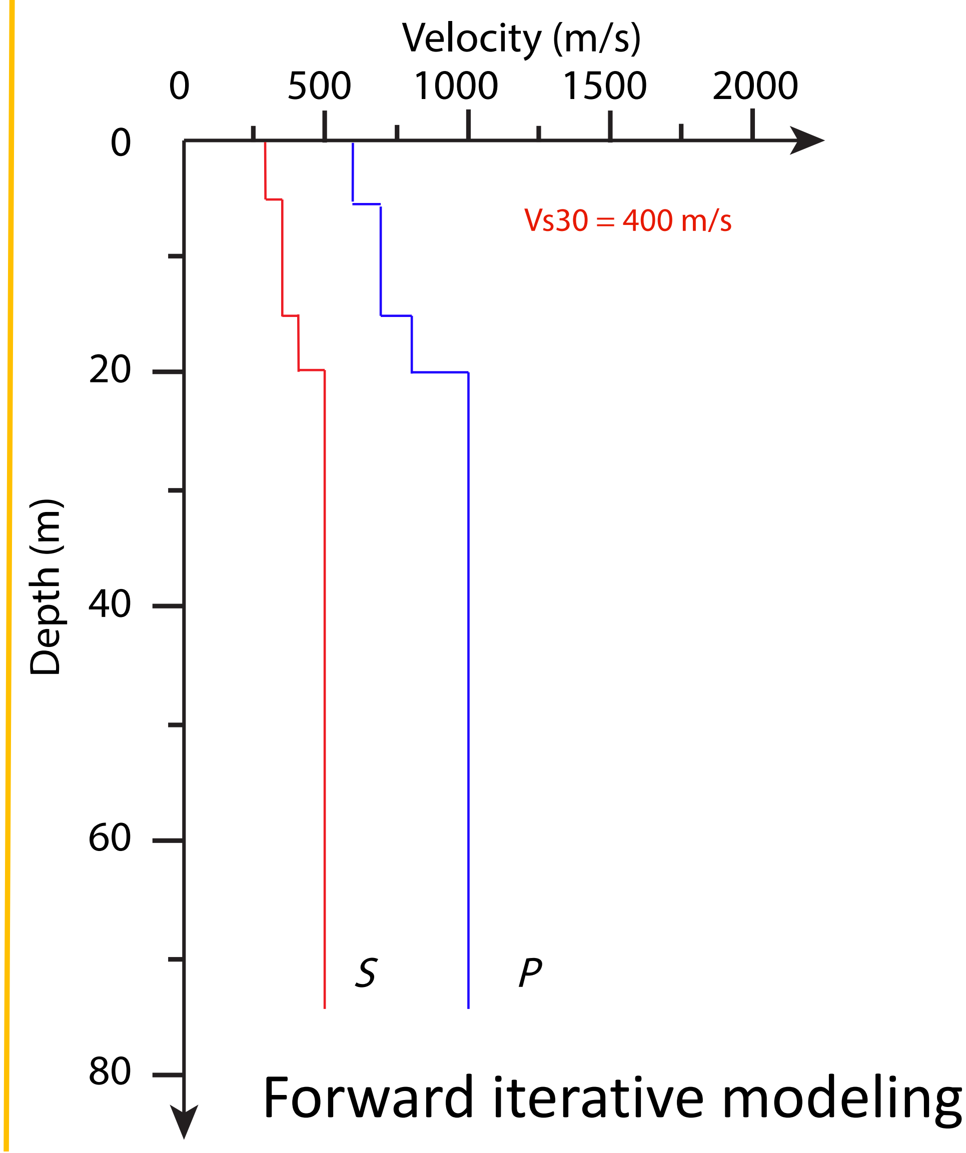
Bayesian inversion



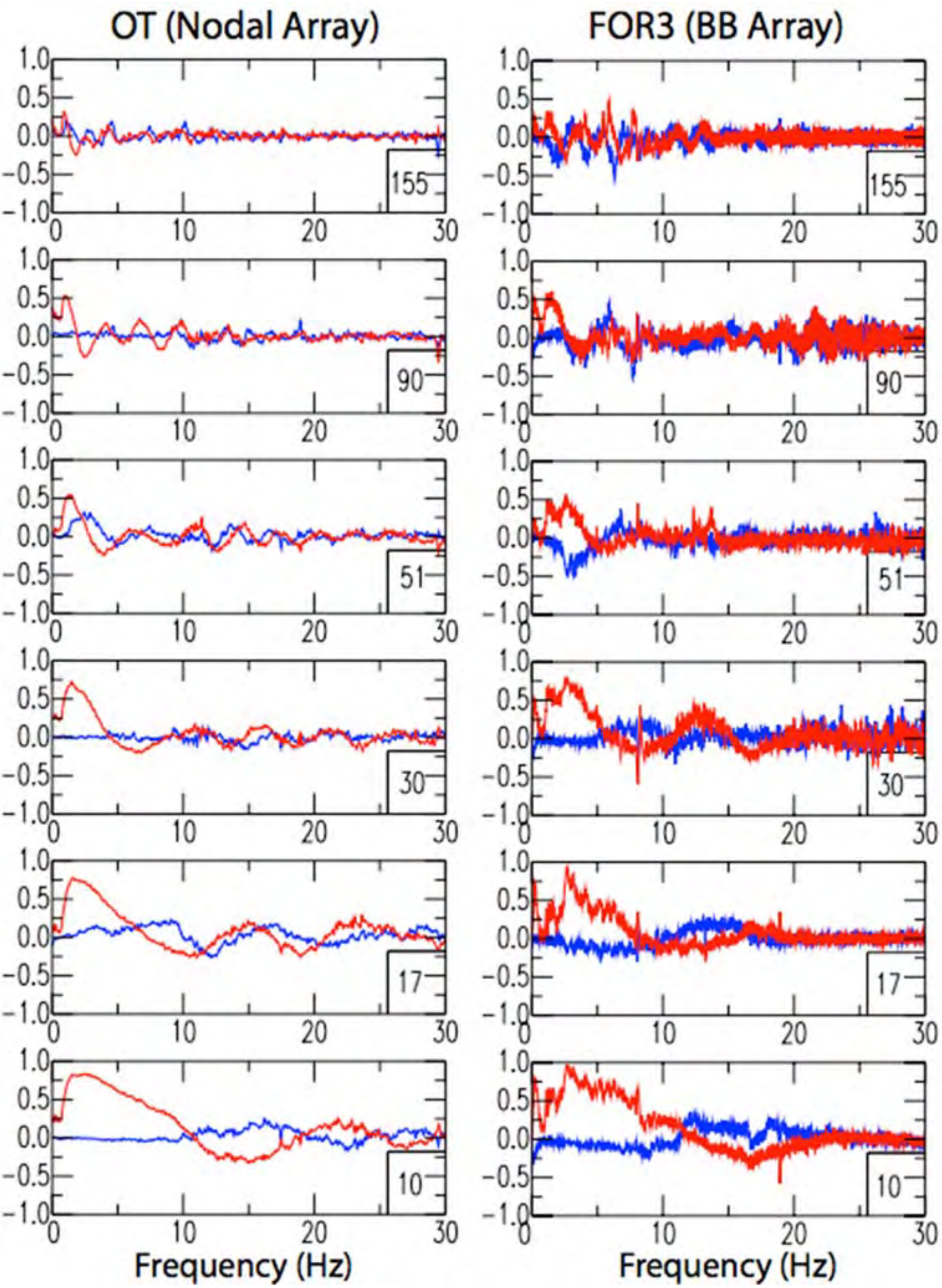
Forward iterative modeling

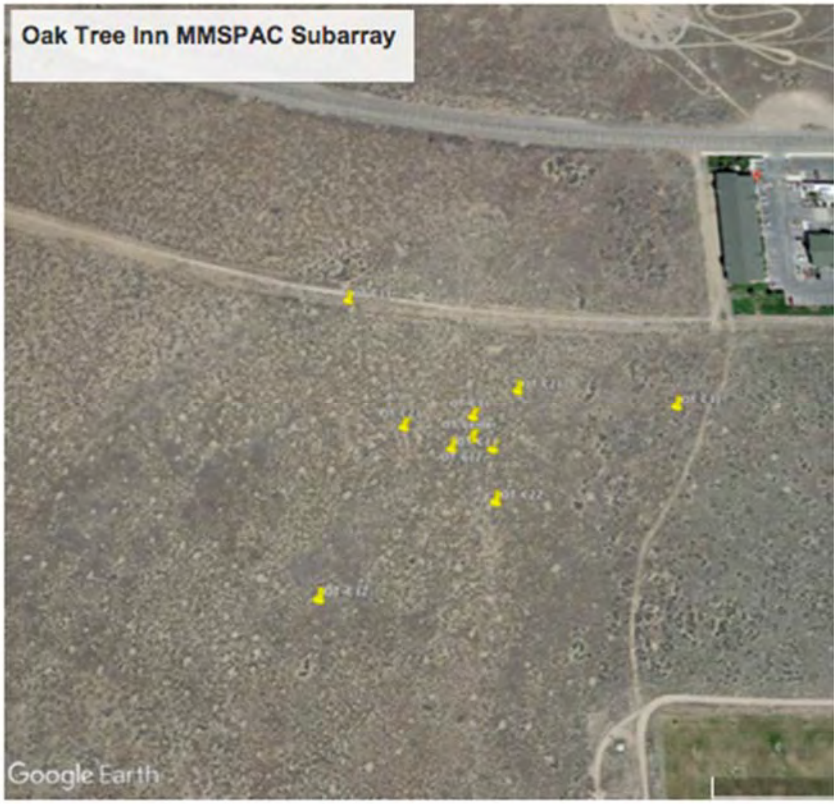
Comparison of the SPAC between the Bayesian and forward iterative modeling





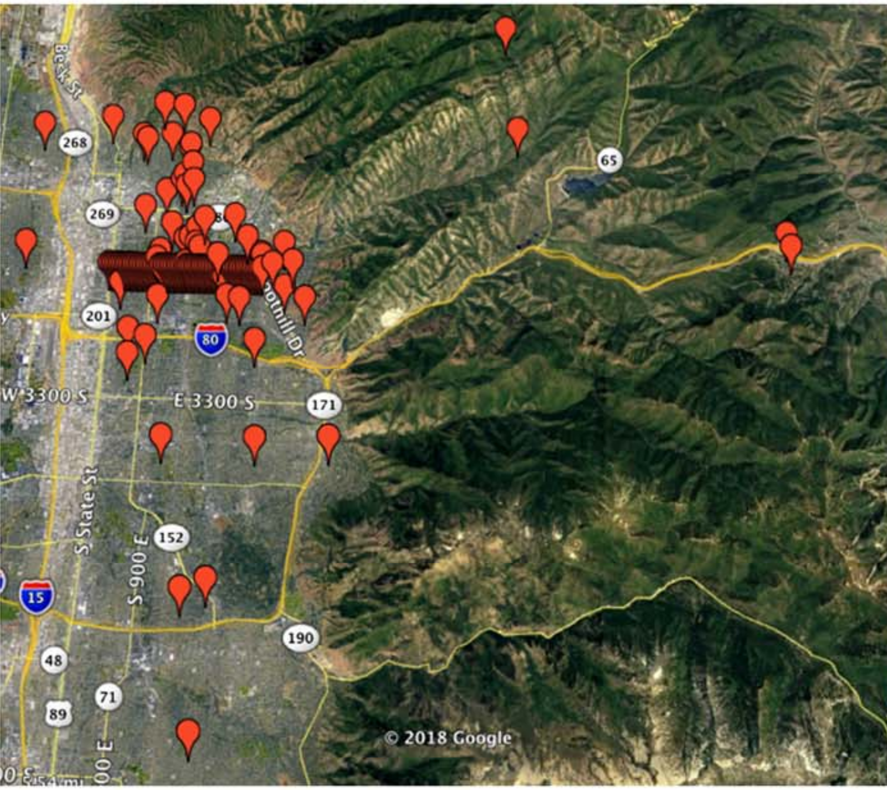
derived from Nodal and Broadband arrays



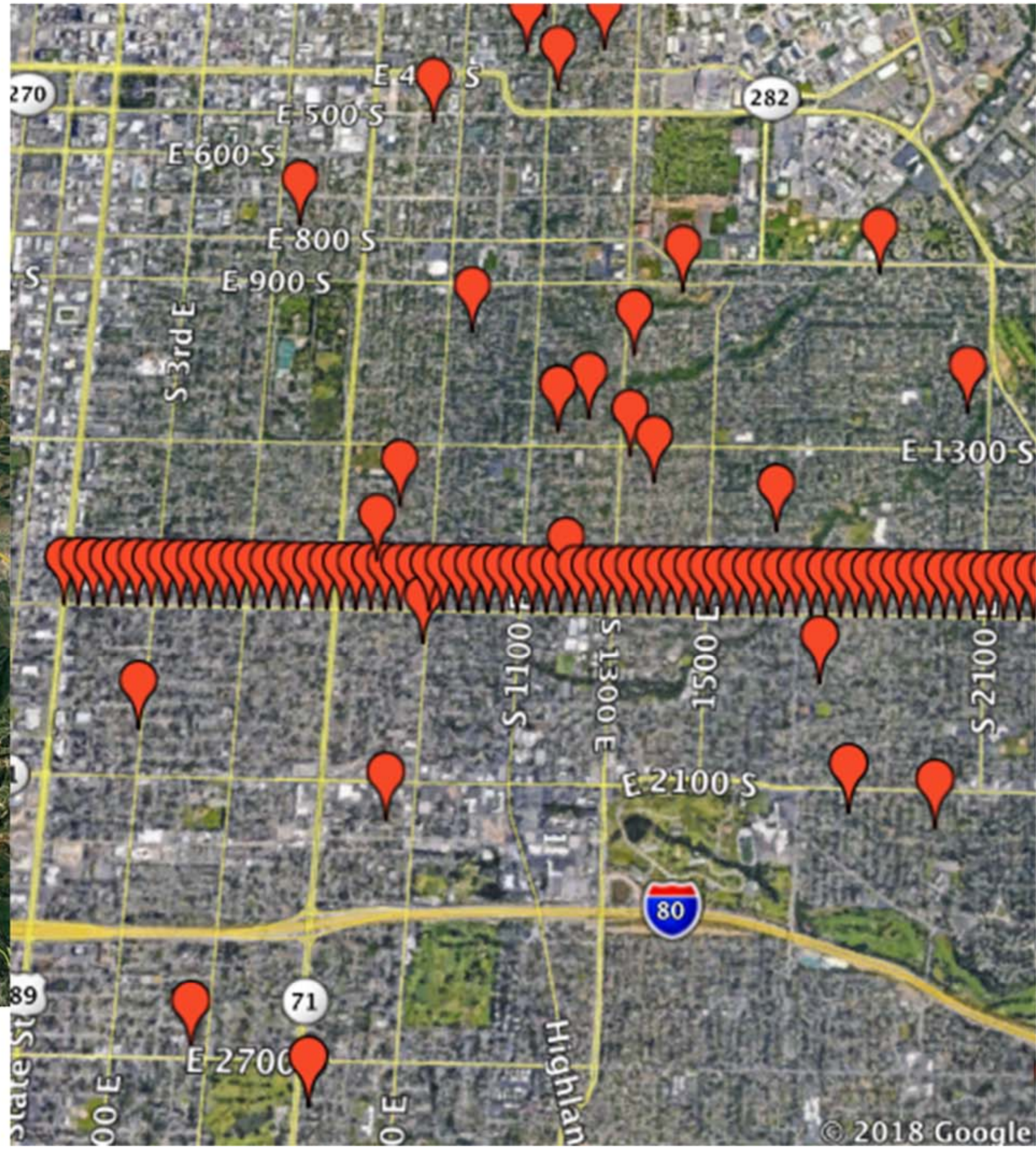


A node and a broadband station

n-going project



(Professor Fan-Chi Lin's Group)



Conclusions

Compared to the traditional SPAC method, the stable Bayesian method can provide an uncertainty for velocity model and Vs30

The Nodal array has more potential than the broadband array in the application to get the Vs30

Thank you
for your
attention

yes' Theorem

$$p(\mathbf{x}|\mathbf{d}) = \frac{p(\mathbf{d}|\mathbf{x})p(\mathbf{x})}{\int_{-\infty}^{\infty} p(\mathbf{d}|\mathbf{x})p(\mathbf{x})\,d\mathbf{x}}, \quad (3$$

where $p(\mathbf{d}|\mathbf{x})$ is the PDF of $\mathbf{d}$ given $\mathbf{x}$, and $\int_{-\infty}^{\infty} p(\mathbf{d}|\mathbf{x}) \times p(\mathbf{x})\,d\mathbf{x}$ normalizes the posterior PDF. In this section, we present an explicit expression of $p(\mathbf{d}|\mathbf{x})$ and $p(\mathbf{x})$. We also present a method for estimating the posterior PDF, $p(\mathbf{x}|\mathbf{d})$.

(Fukuda and Johnson, 2008, BS

Markov Chain Monte Carlo (MCMC) – Metropolis Hastings

rithm:

$\vec{\theta}_0$,

$k = 0, K-1.$

$u \sim U[0,1]$,

$\vec{\theta}^* \sim pdf(\vec{\theta}_k)$

[if] $u < \min\left(1, \frac{\pi(\vec{\theta}^*)\mathcal{L}(\vec{\theta}^*|\vec{x})}{\pi(\vec{\theta}_k)\mathcal{L}(\vec{\theta}_k|\vec{x})}\right)$,

$\vec{\theta}_{k+1} = \vec{\theta}^*$;

[e]lse

$\vec{\theta}_{k+1} = \vec{\theta}_k$.

posterior $\propto$ likelihood $\times$ prior

$p(\vec{m}|\vec{D}_{obs}) \propto p(D_{obs}|\vec{m})\, p(\vec{m})$,

misfit function:

$$\Phi(\vec{m}) = (\vec{G}(\vec{m}) - \vec{D}_{obs})^T C_e^{-1} [\vec{G}(\vec{m}) - \vec{D}_{obs}]$$

Likelihood:

$$p(\vec{D}_{obs}|\vec{m}) = \frac{1}{\sqrt{(2\pi)^N |C_e|}} e^{-\frac{\Phi(\vec{m})}{2}}$$

SEISMIC LAND STREAMER IMAGING BENEATH SALT LAKE CITY

UTAH GROUND SHAKING WORKING GROUP – 2/13/18

Lee Liberty – Boise State University

Gabe Gribler, James St. Clair, Thomas Harper, Thomas Otheim

BOISE STATE UNIVERSITY

SEISMIC IMAGING OBJECTIVES

Earthquake hazard and risk assessments beneath urban centers

- Identify and characterize the Warm Springs fault beneath downtown SLC
- Identify and characterize the northern portions of the East Bench fault
- Identify and characterize faults within the step-over region of the Salt Lake front
- Generate a Vs_{30} map for Salt Lake City
- Liquefaction susceptibility via Vp and Vs measurements

    (map low Vs zones and identify shallow water table areas)

- Depth to bedrock/key boundaries via gravity, Vp, Vs, and reflection imaging

- Funding sources

USGS NEHRP #G15AP00054 – 2015 field campaign

USGS NEHRP #G17AP00052 – 2017 field campaign – in progress

BENEFITS OF SEISMIC LAND STREAMER COMPARED TO TRADITIONAL SEISMIC IMAGING

- Rapid data collection – 4-5 km/day
- Minimal field crew – one person operation
- Directly operate on city streets
- Predictable source/receiver geometry makes processing more simple
- Real time GPS allows for simple geometry
- Physical properties of road and sub road make for a uniform near surface
- Police or flagger assistance to control traffic and provide near continuous profiling
- Large seismic source relative to imaging depths allows for traffic noise during data collection

SUMMARY OF 2015/2017 FIELD CAMPAIGNS

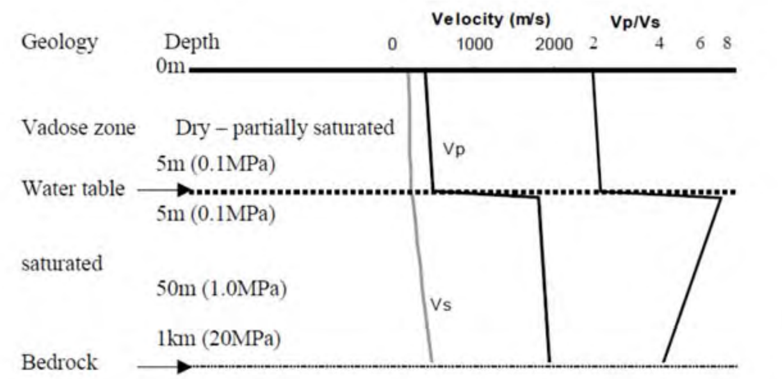
May, 2015 → 3 field days
5,576 48 channel shot gathers
2 m spaced shots (gaps at major roads)
15 km length along 9 west-east profiles
Police escort along most roads allowed near continuous profiling
Offsets: 5-65 m

May, 2017 → 5 field days
9839 shot gathers
20 km length along 13 profiles
Offsets: 10-70 m

Total:
35 km along 22 streets
2m spaced shots, 1.25 m spaced receivers
400 m/hour or a shot every 15 seconds
15,419 hammer hits

PHYSICAL PROPERTY ESTIMATES SALT LAKE CITY

Low Vs & Vp for Bonneville deposits
Higher Vs & Vp for alluvial fan deposits
High Vp for water saturated sediments
Good reflectivity in lake deposits, shallow groundwater
Poor reflectivity in alluvial fans, deeper water table

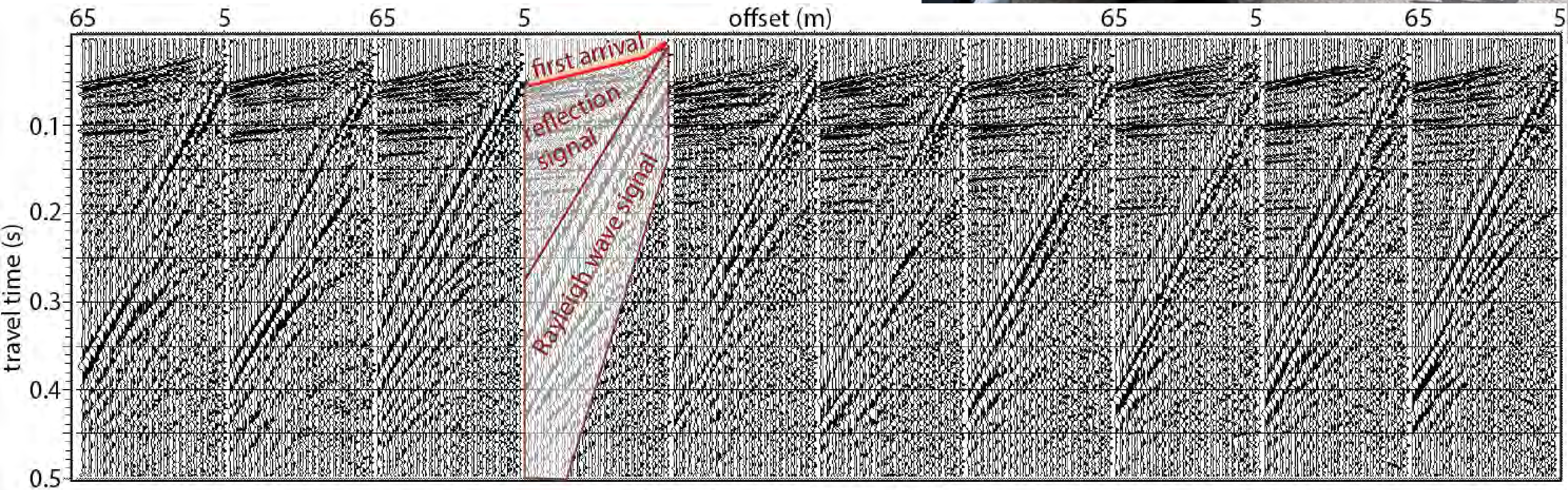


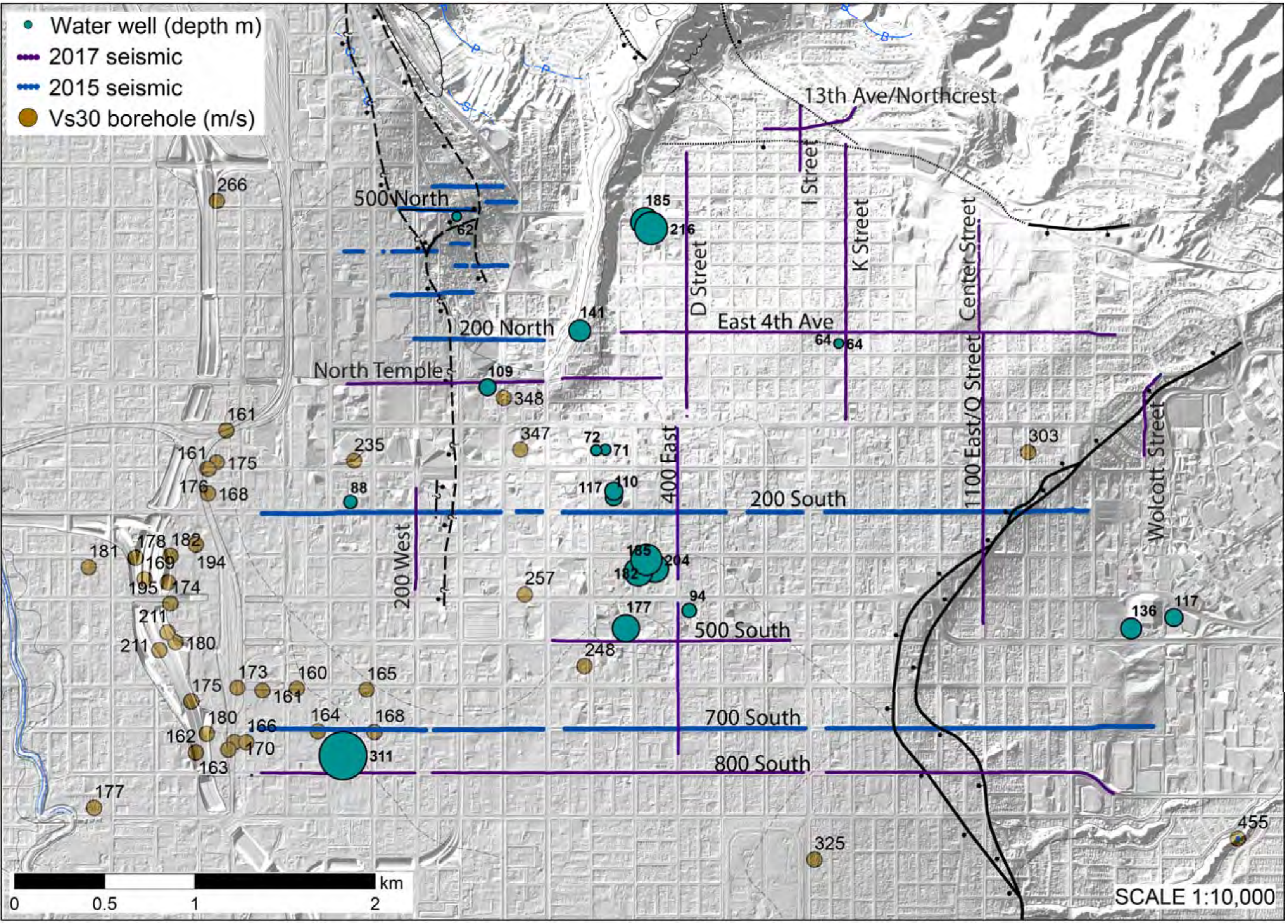
From Bartlett, S., 2004 - UDOT

					Cone Penetrometer				Gardner alpha	0.3	
600 South					Vs	G	E		Gardner beta	0.25	
Depth	Depth	Soil Type	Unit Weight	bulk density	Shear wave Velocity	Shear Modulus	Modulus	Vp - dry	Vp/Vs - dry	Vp - from Gardner	Vp/Vs - wet
(m)	(m)		(kN/m3)	g/cc	(m/s)	(kPa)	(kPa)	(m/s)		wet, fcn of density	
0	5	Alluvium	19.2	1.96	146	41700	113000	293.3535	2.01	1818.9	12.46
5	12	Upper Bonneville	18.2	1.86	170	53600	161000	353.7999	2.08	1468.6	8.64
12	16	Interbeds	18.8	1.92	235	106000	318000	489.3258	2.08	1672.0	7.11
16	22	Lower Bonneville	18.2	1.86	201	75000	225000	418.33	2.08	1468.6	7.31
22	25	Pleistocene	19.5	1.99	237	112000	335000	493.3645	2.08	1935.3	8.17

URBAN LAND STREAMER DESIGN

48 2-component shoes (vertical and in-line)
4.5 Hz geophones (interchangeable to 10, 40 Hz)
1.25 m spaced geophones (60 m aperture)
(now additional 30 m segment to extend to 90 m aperture)
2 m nominal shot spacing
Accelerated weight drop source (Arduino controlled)
One person performs all operations





DOWNTOWN SALT LAKE CITY LIDAR MAP WITH SEISMIC AND BOREHOLE LOCATIONS

36 Vs measurements

McDonald and Ashland (2008)

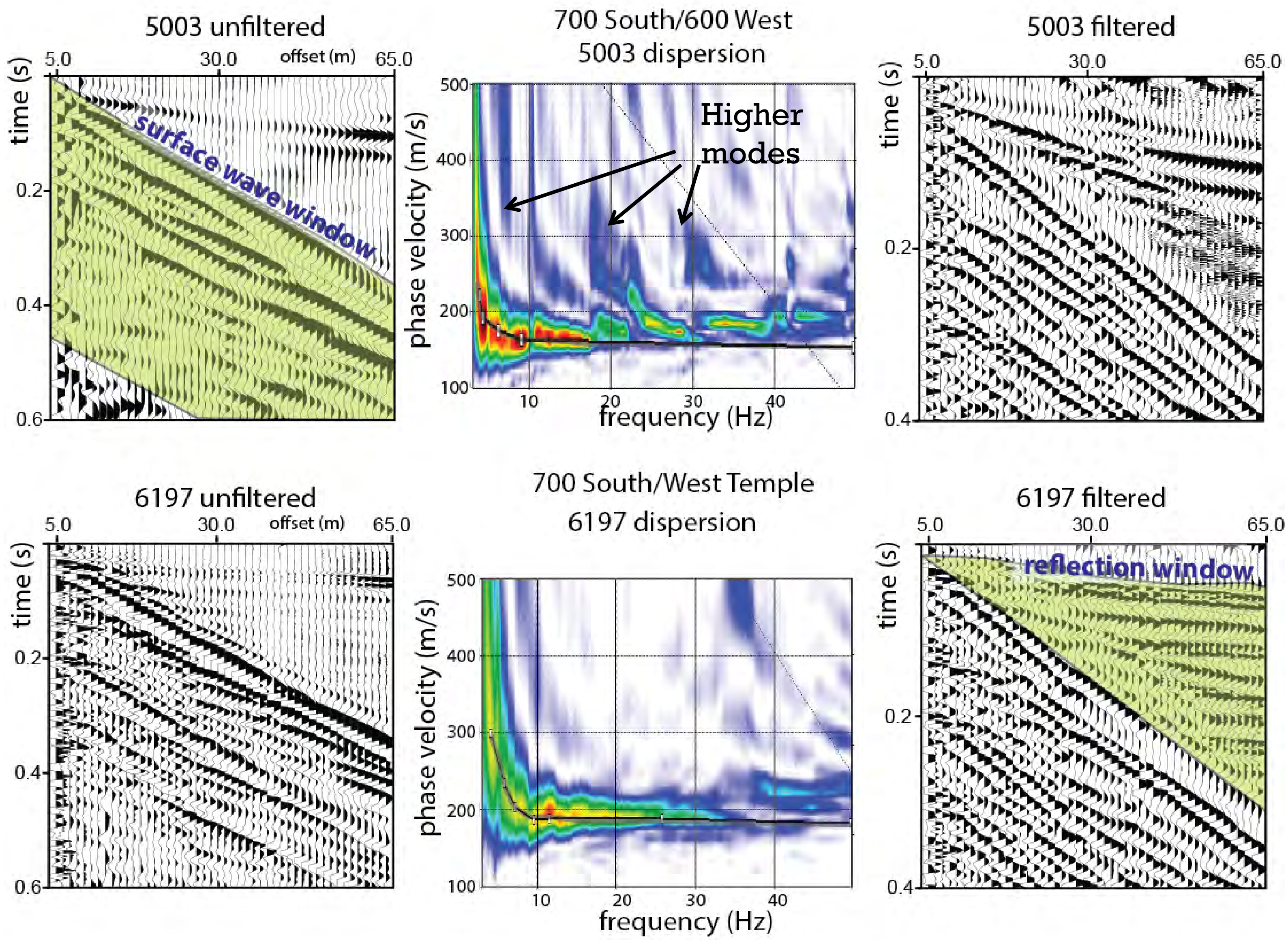
Mapped faults
McKean (2014)
Personious and Scott (2009)

VS (MASW) PROFILING

700 SOUTH SHOTS AND DISPERSION CURVES

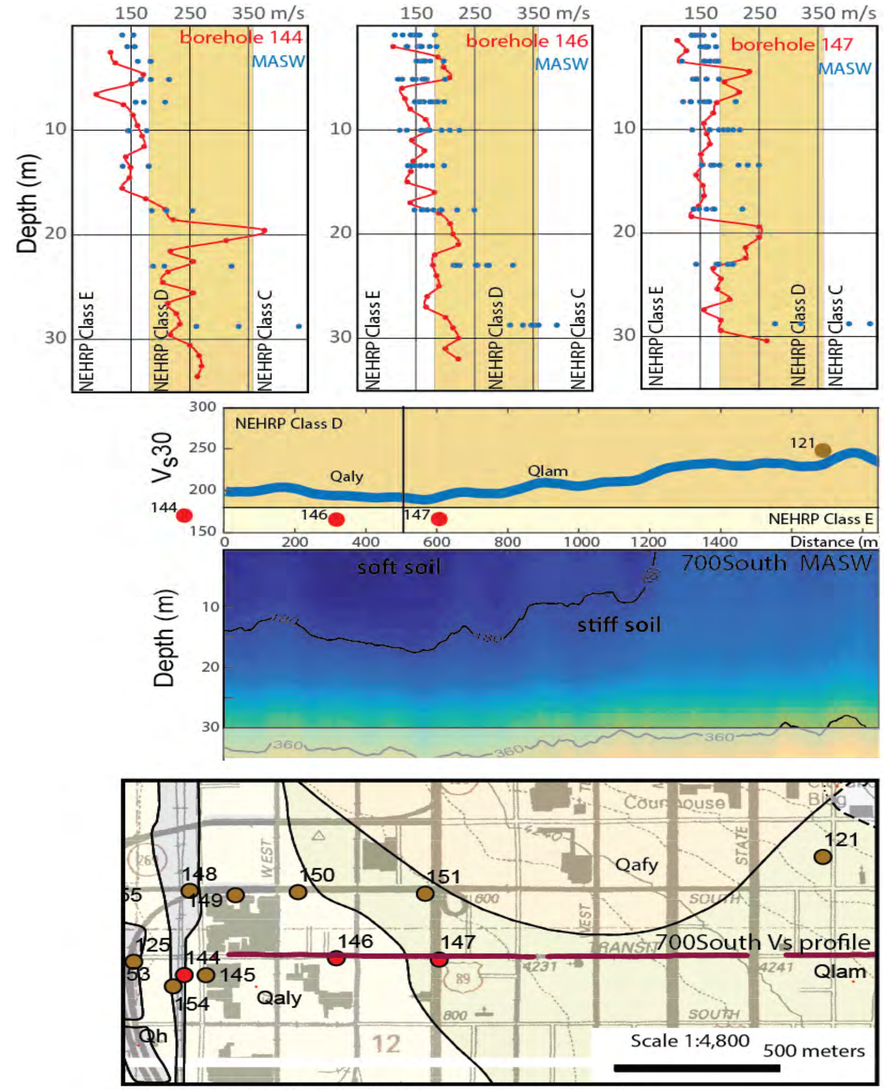
$$VS30M = \sum DI / \sum TI = 30 / \sum(DI/VSI)$$

SUMMATION OF THICKNESS (DI) DIVIDED BY VELOCITY (VSI) OF EACH LAYER



DO ROAD SURFACE/UTILITIES IMPACT SEISMIC MEASUREMENTS?

USUALLY NO – BUT CONCRETE ROADS AND TUNNELS ARE BAD



Qh - Fill and disturbed land over stream terrace deposits
Qaly - Holocene stream deposits
Qlam - Holocene to upper Pleistocene lacustrine and alluvial and marsh deposits
Qafy - Holocene to upper Pleistocene alluvial-fan deposits

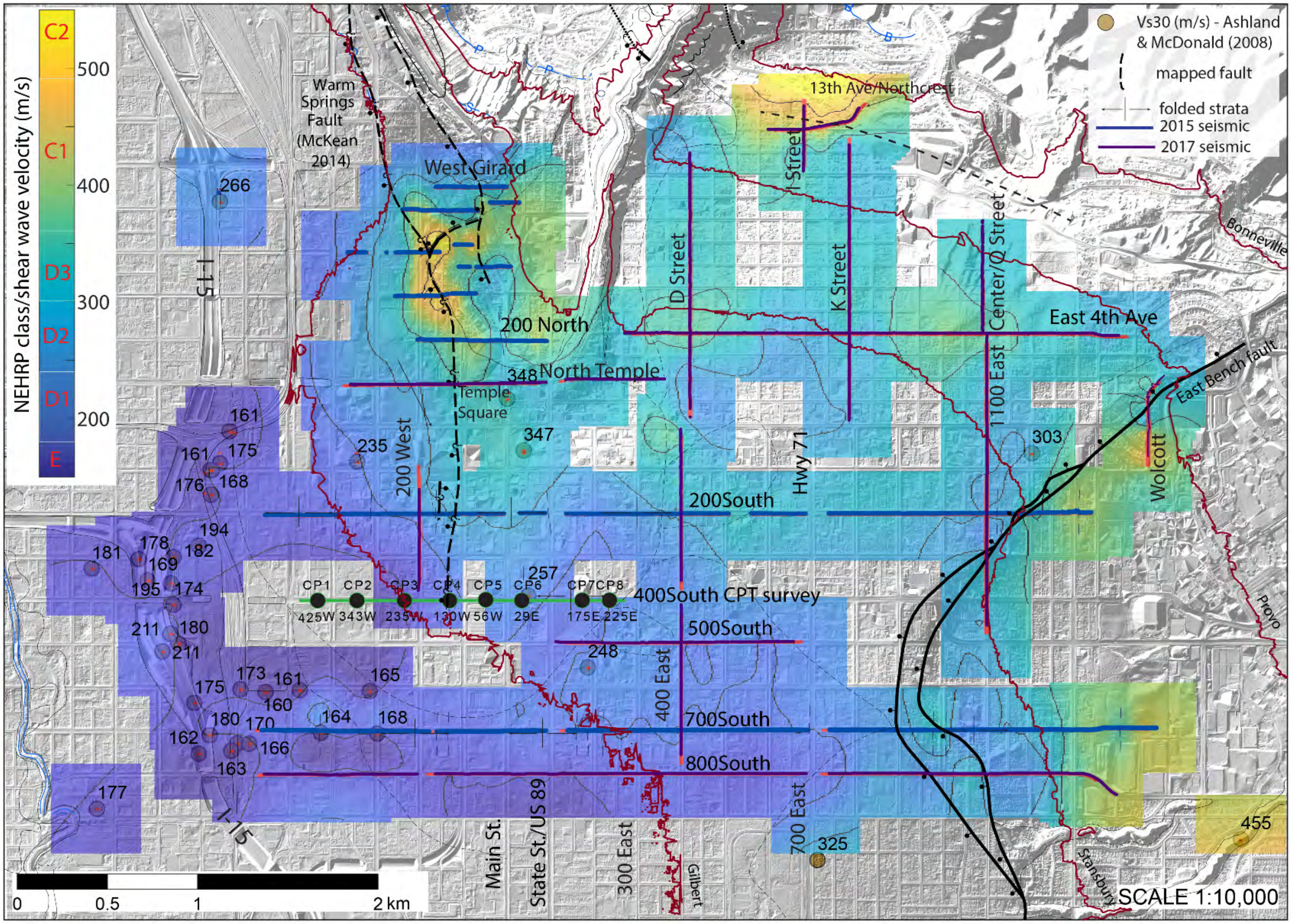
VS$_{30}$ MAP FOR DOWNTOWN SALT LAKE CITY

36 Vs measurements

McDonald and Ashland (2008)

15,000 additional Vs measurements

via seismic land streamer

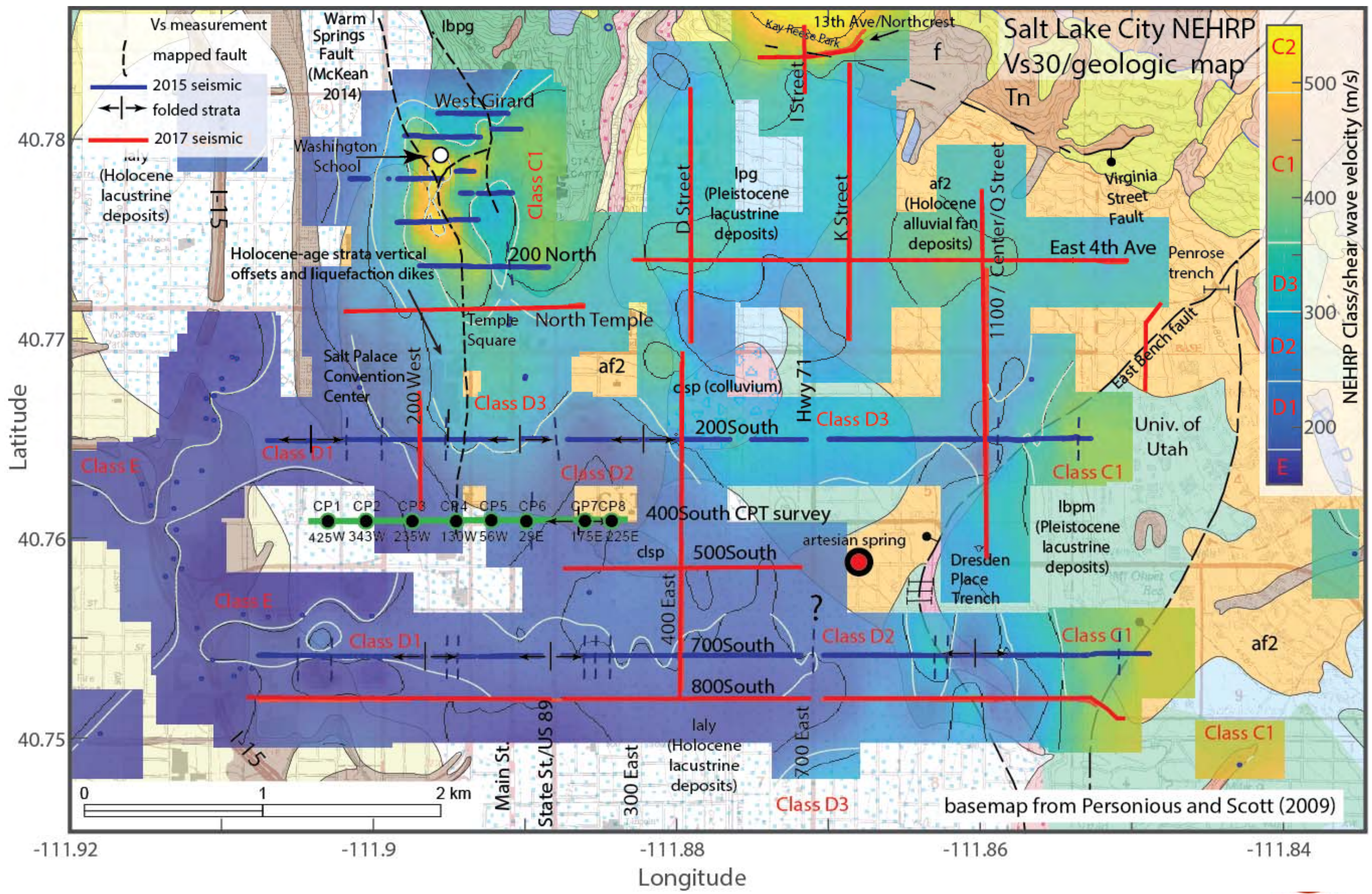


SALT LAKE CITY VS_{30} LAND STREAMER RESULTS WITH GEOLOGIC MAP

Low Vs for Bonneville deposits beneath western portions of downtown Salt Lake City

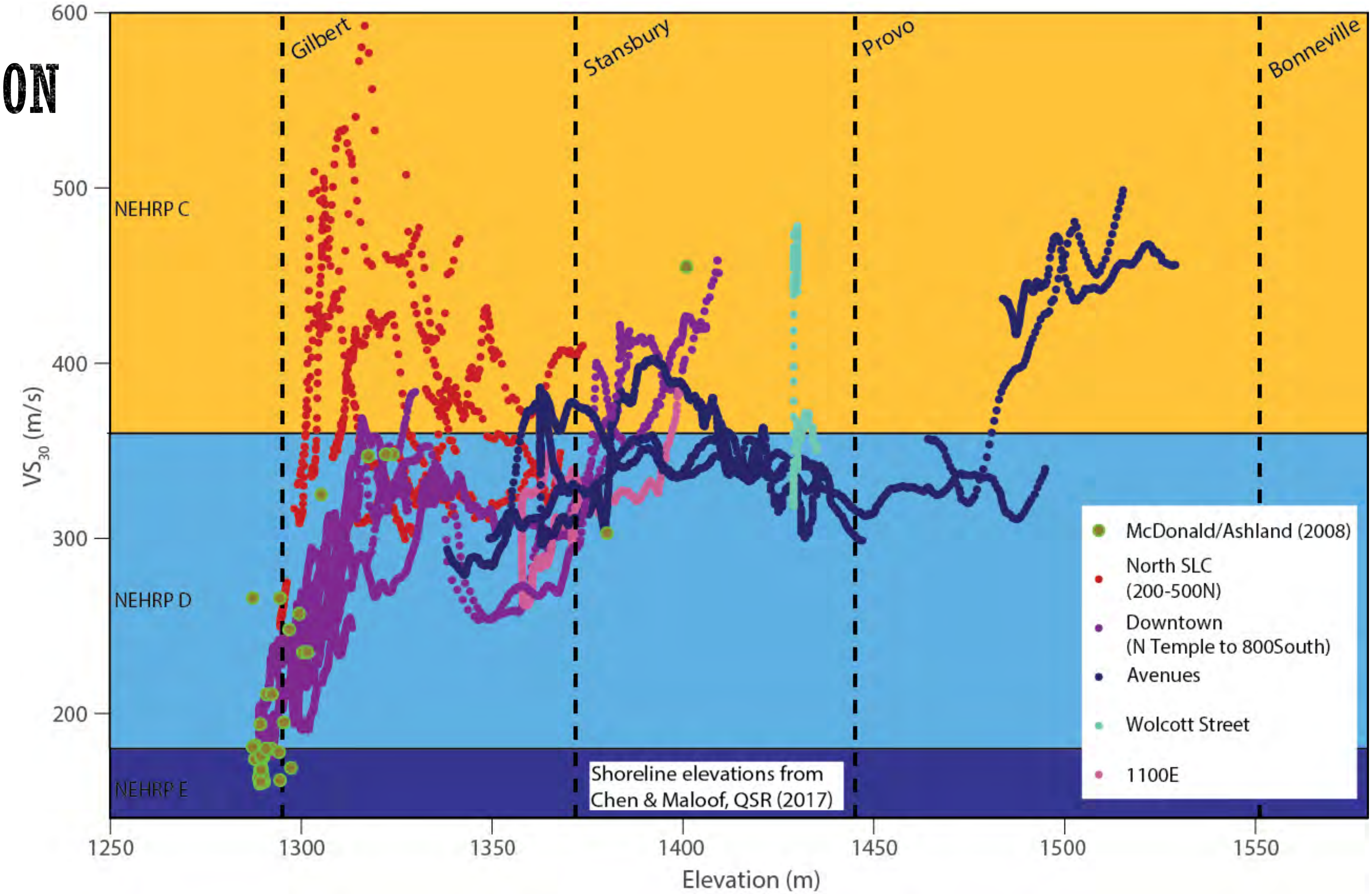
Increase in Vs30 from west to east

High Vs in the footwall or in fault zones



ELEVATION VS. VS_{30}

Linear Vs/elevation relationship at low elevations



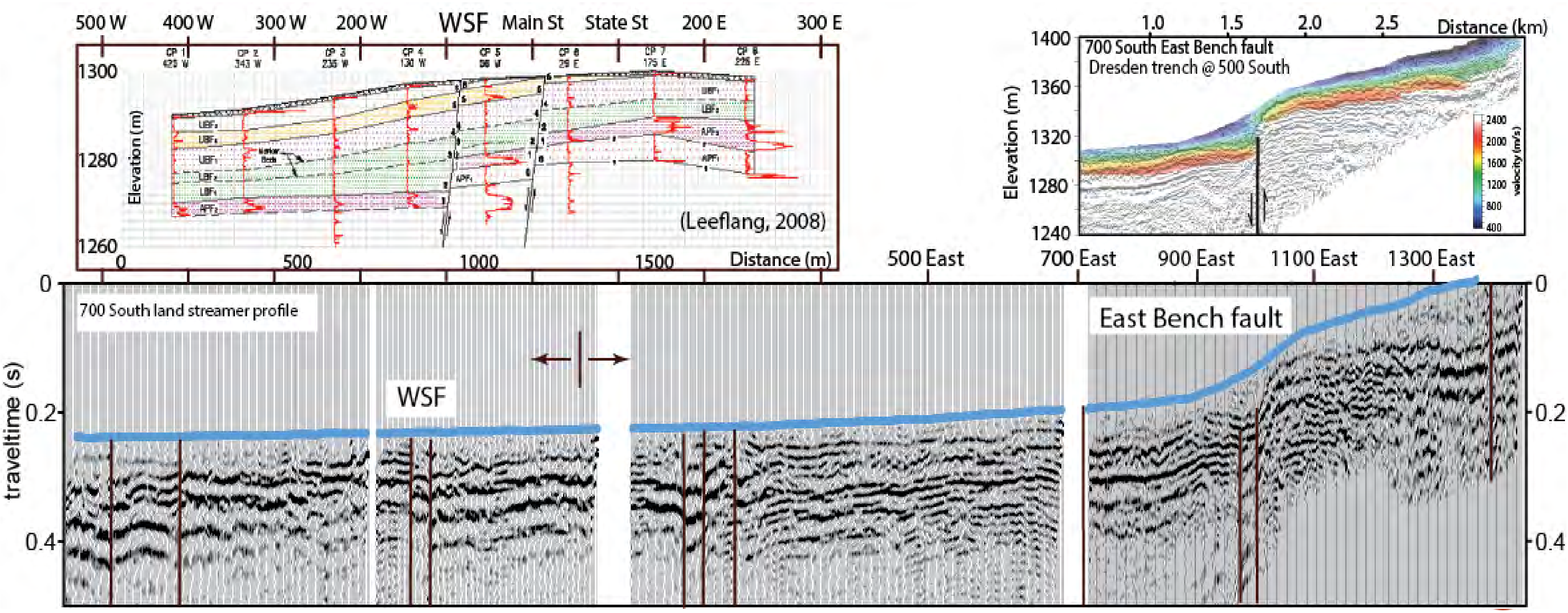
SUMMARY OF VS

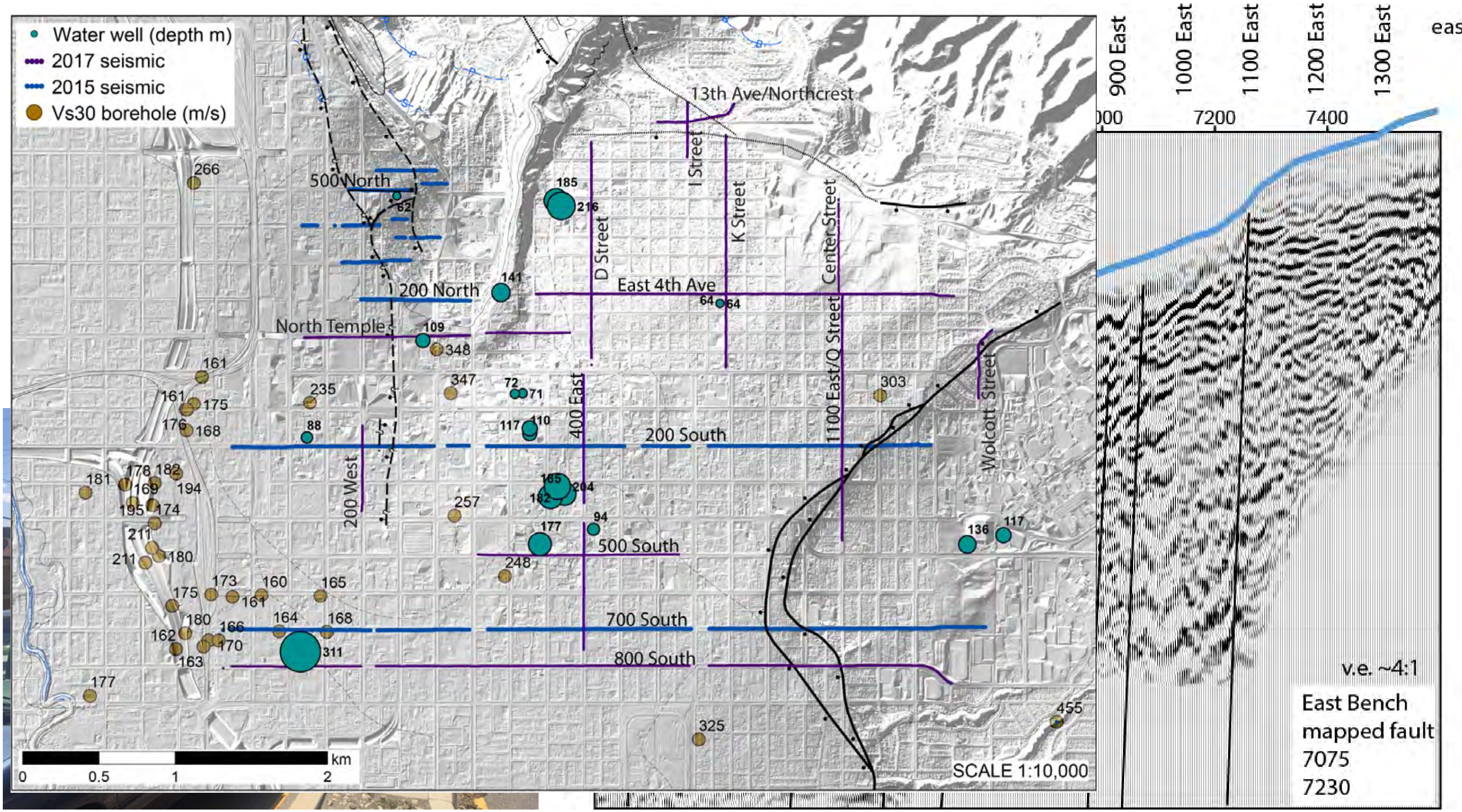
- Vs generally increases from west to east
- Vs generally follows a linear trend with elevation, with resets by Lake Bonneville shoreline highstands
- Vs increases at or near Warm Springs/East Bench faults

- To do:
- Produce map of probing depth sensitivities – how deep can our streamer image with surface waves?
- Produce "super gathers" to include lower frequency signals
- Examine shallow Vs (Vs10) relationship to mapped geology

700 SOUTH REFLECTION PROFILE (COMPARED TO 400S)

- **Dresden Place Trenches (1986):**
- ≥7 m deformation
- 3 m monoclinal warping—latest Pleistocene
- ≥4 m brittle deformation (fault offset)—Holocene



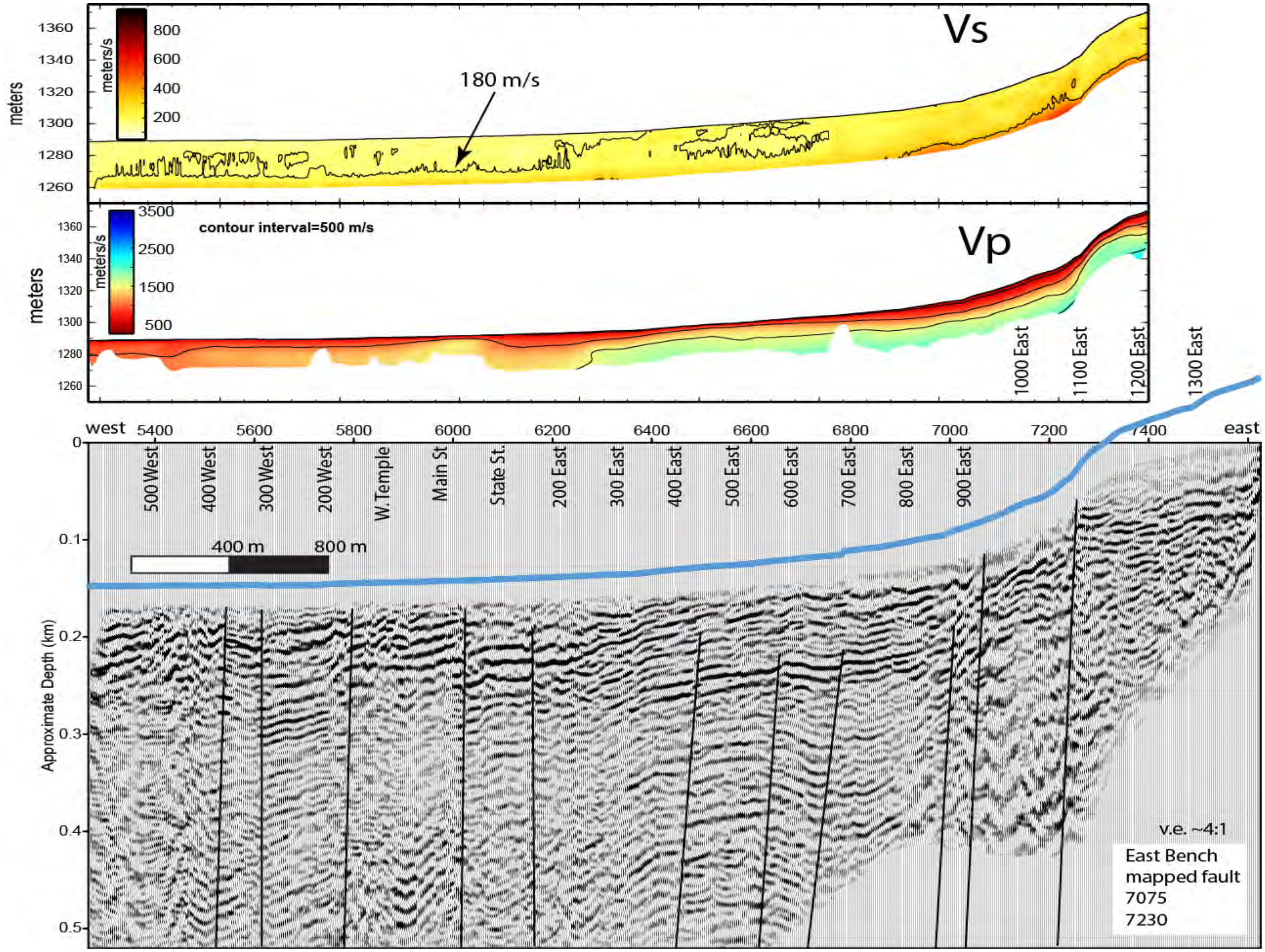


Water well (depth m)
2017 seismic
2015 seismic
Vs30 borehole (m/s)
13th Ave/Northcrest
500 North
200 North
North Temple
East 4th Ave
D Street
I Street
K Street
Center Street
1100 East/O Street
400 East
200 West
200 South
500 South
700 South
800 South
Wolcott Street
SCALE 1:10,000
0
0.5
1
2
km
900 East
1000 East
1100 East
1200 East
1300 East
east
7200
7400
v.e. ~4:1
East Bench
mapped fault
7075
7230

800 SOUTH

Vs and Vp velocities slow to the west

Seismic character is more chaotic to the west



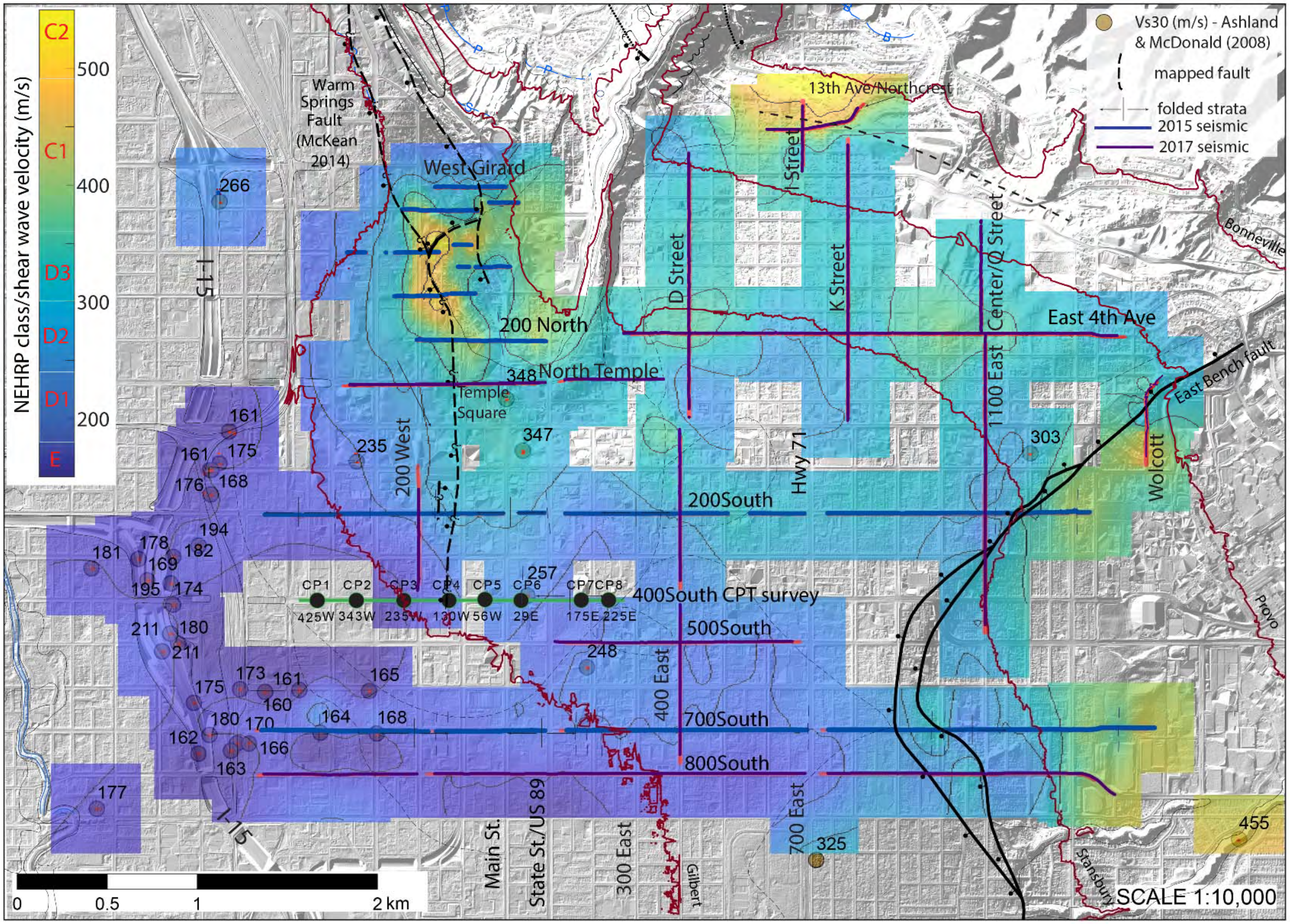
VS_{30} MAP FOR DOWNTOWN SLC

36 Vs measurements

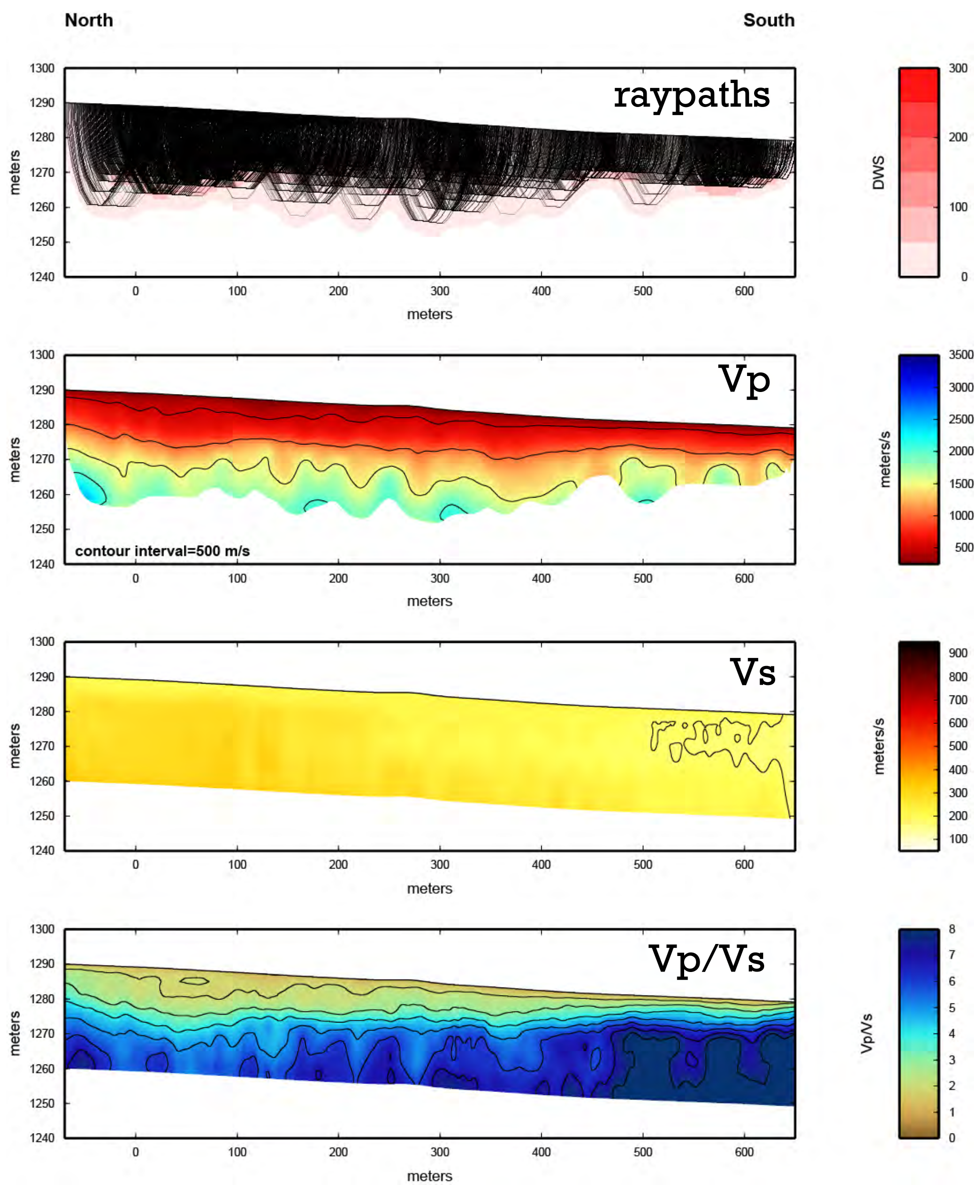
McDonald and Ashland (2008)

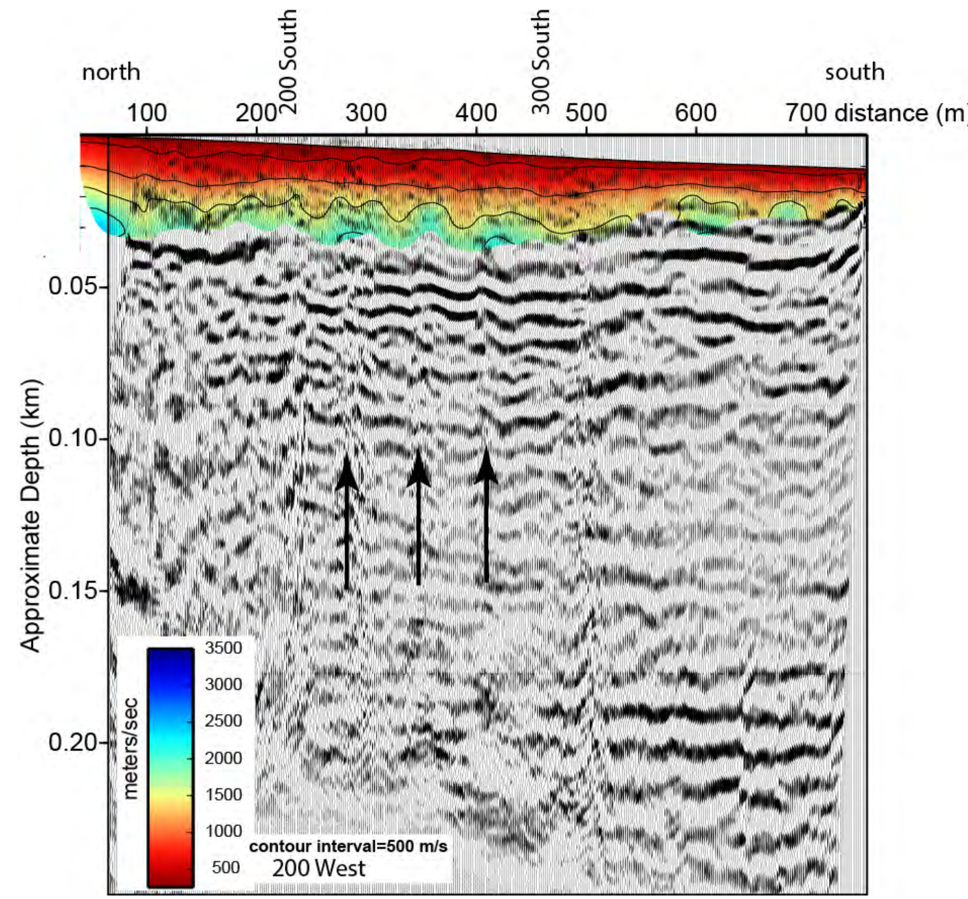
15,000 additional Vs measurements

via seismic land streamer

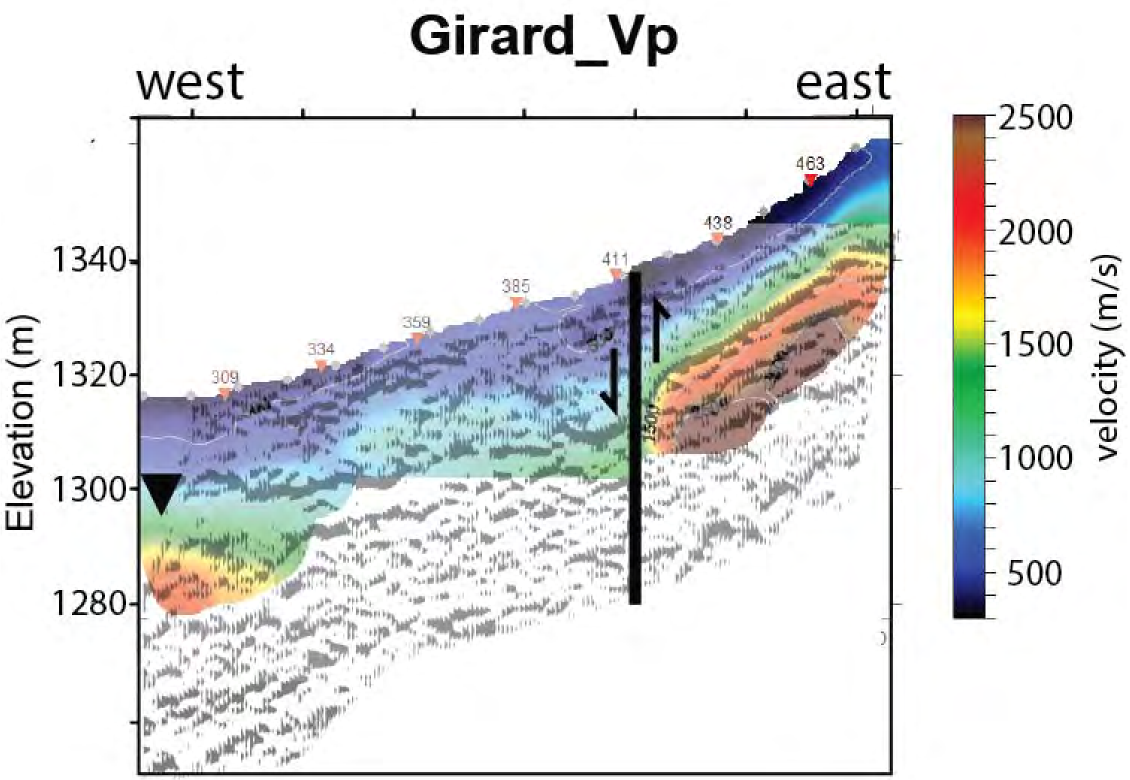


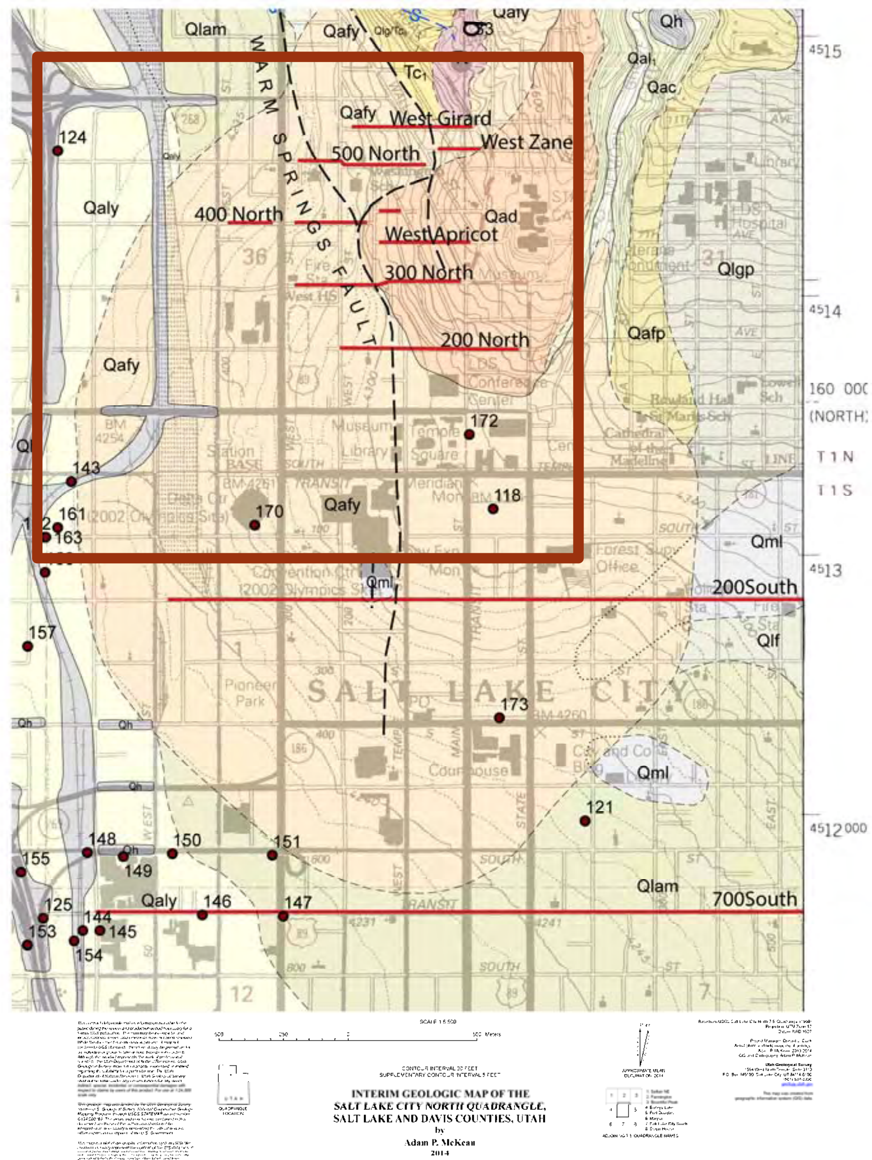
200 WEST SEISMIC REFLECTION/REFRACTION



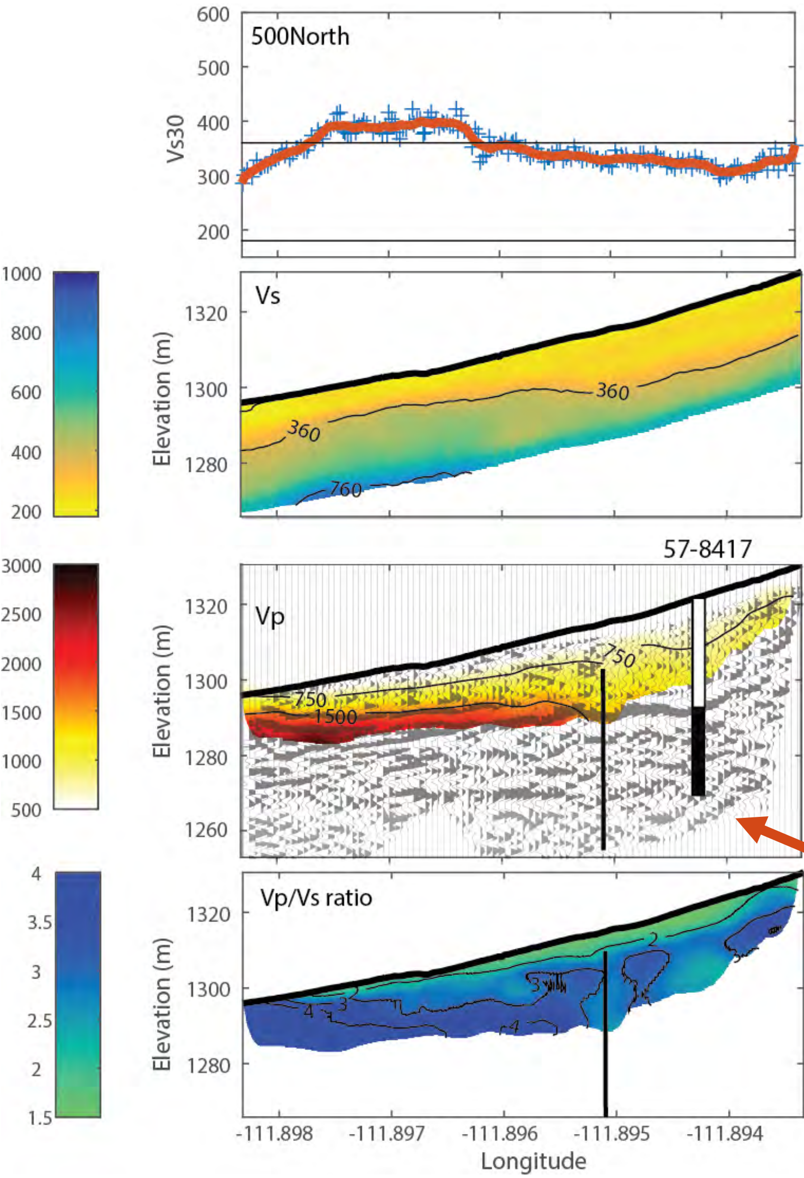


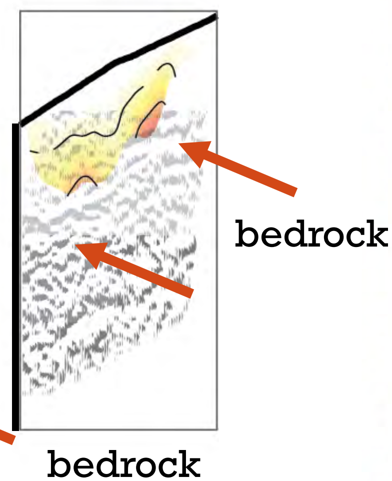
WEST GIRARD (20 M DEEP BEDROCK)

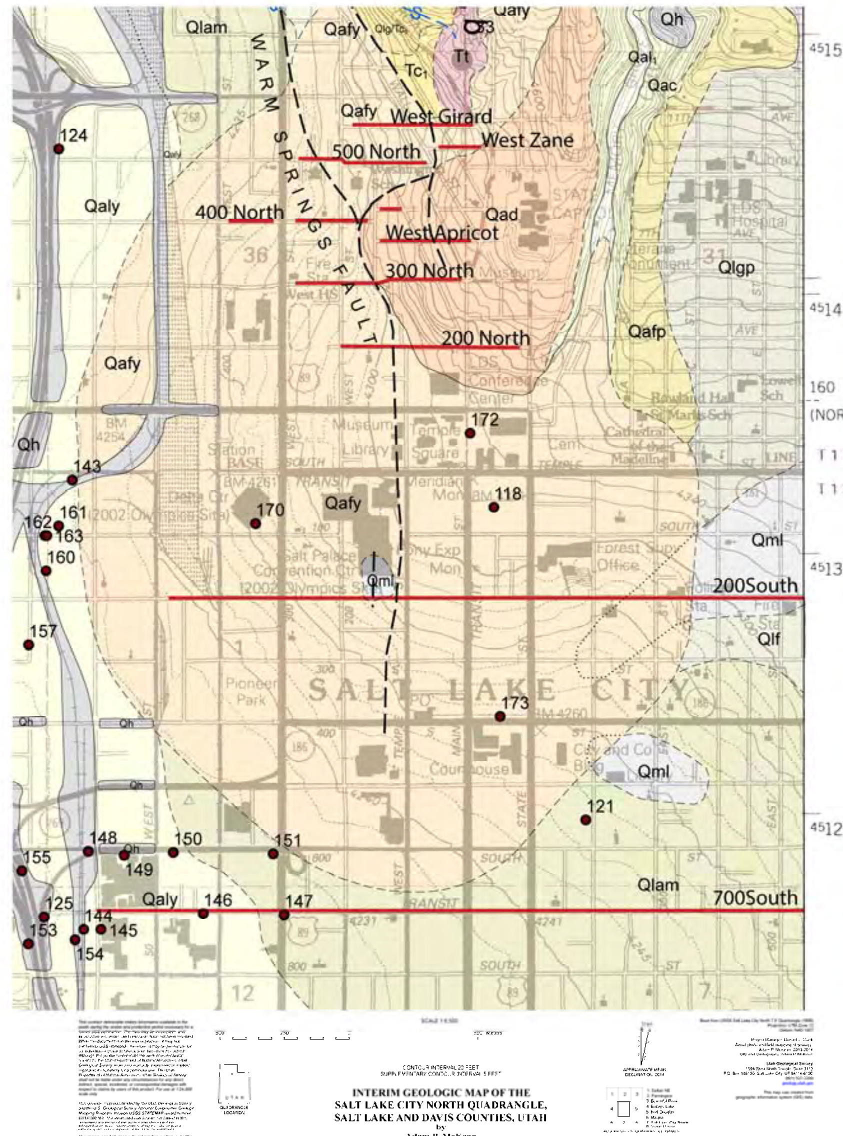


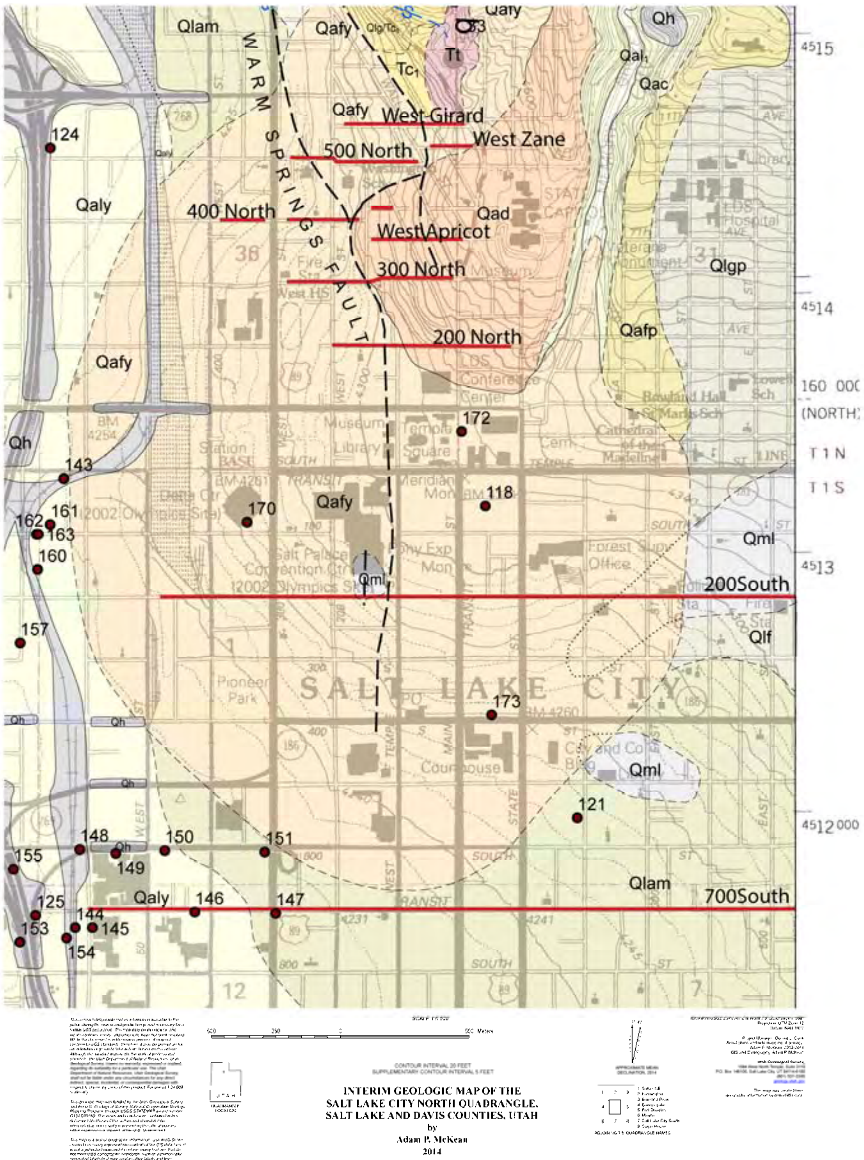


500 NORTH ZANE PROFILES

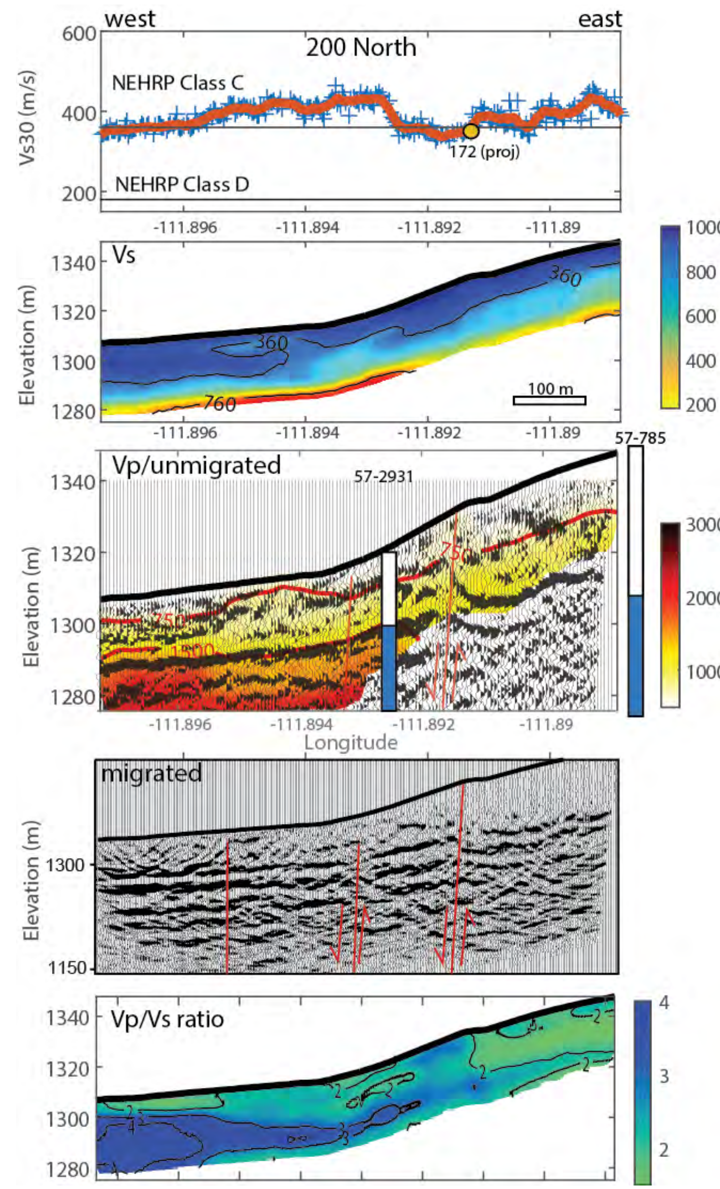




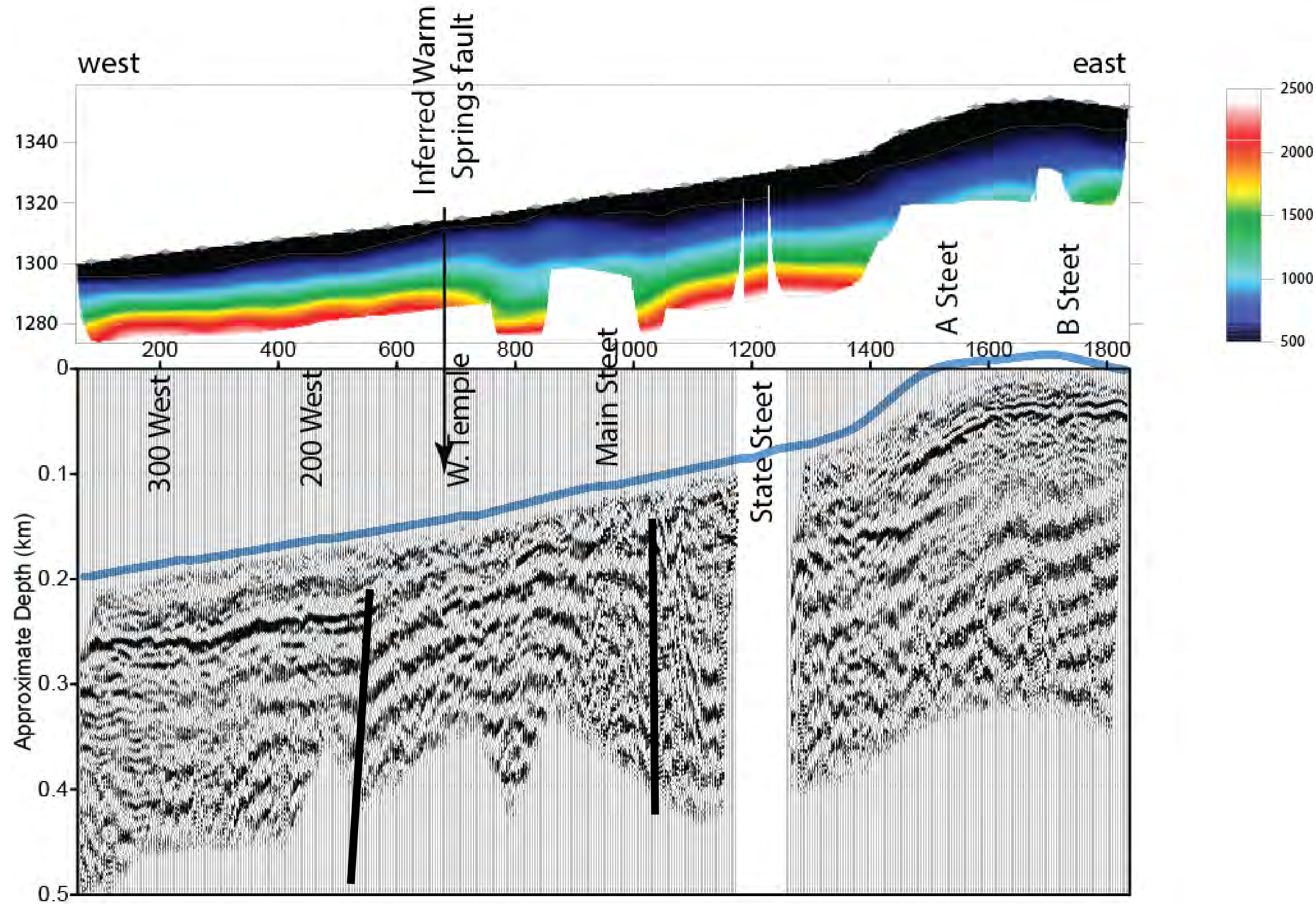




200 NORTH PROFILE

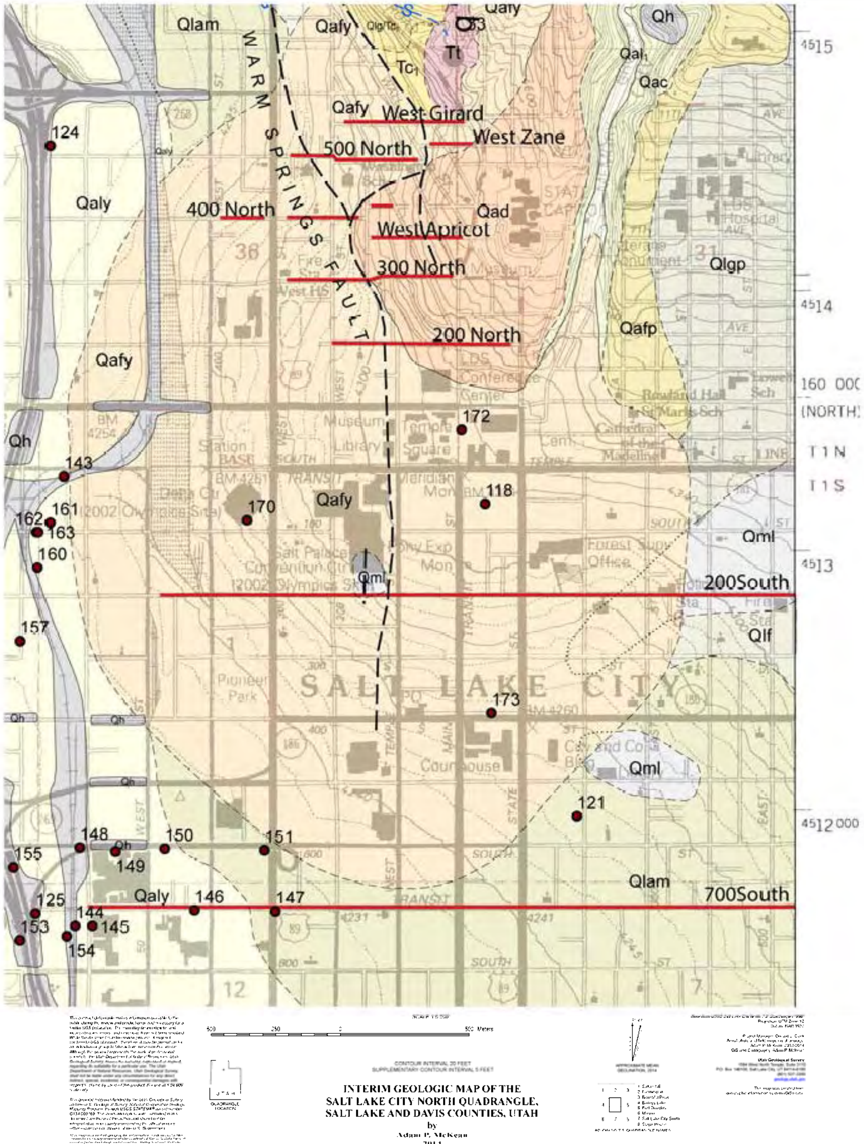


NORTH TEMPLE



Step in water table beneath West Temple

Fault beneath Main Street


WARM SPRINGS FAULT
West Girard
West Zane
500 North
400 North
West Apricot
300 North
200 North
200South
700South
SALT LAKE CITY
Qlam
Qafy
Qaly
Qh
Qad
Qlgp
Qafp
Qml
Qlf
Qac
Tt
124
143
161
162
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160
157
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173
121
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153
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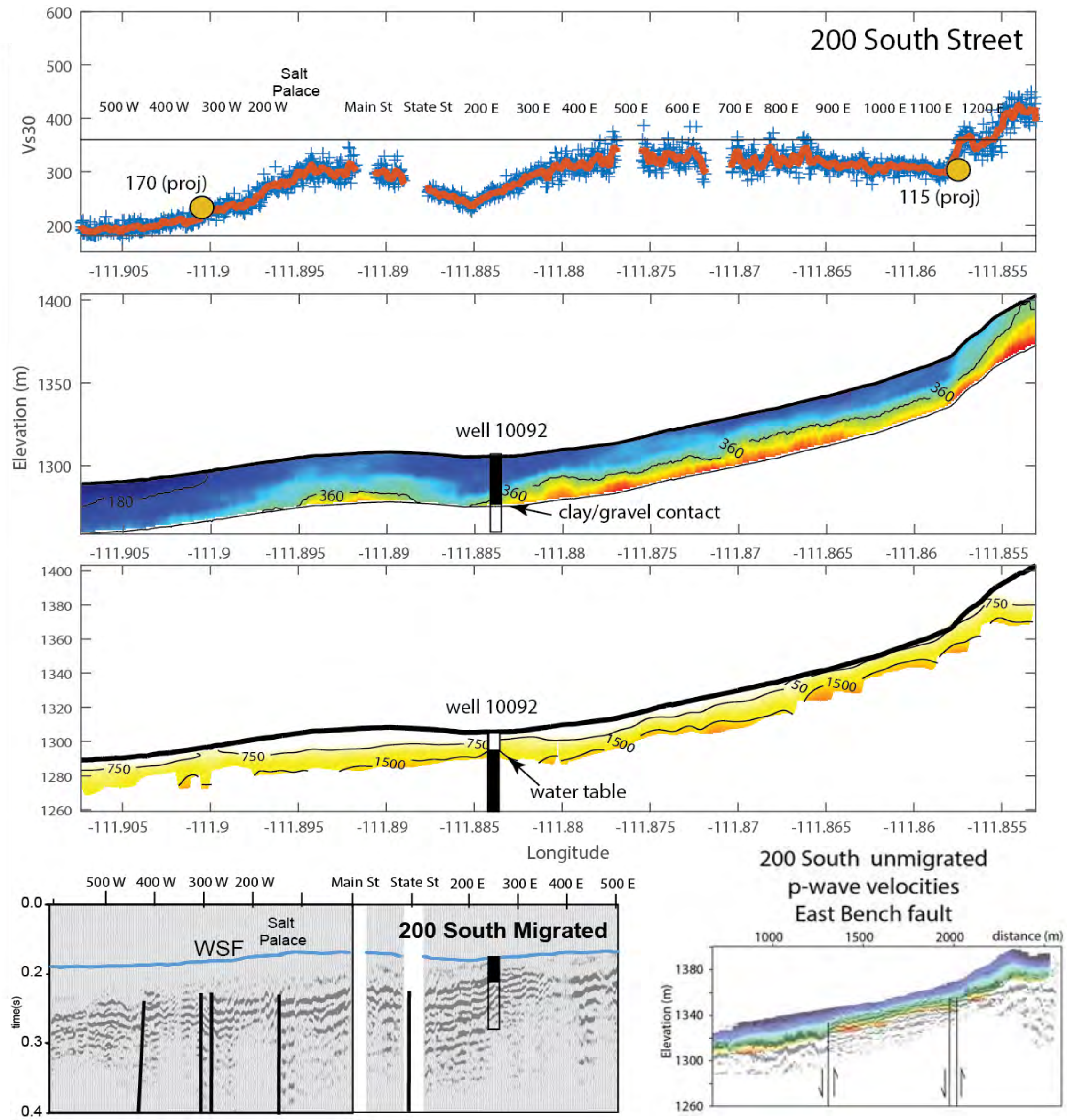
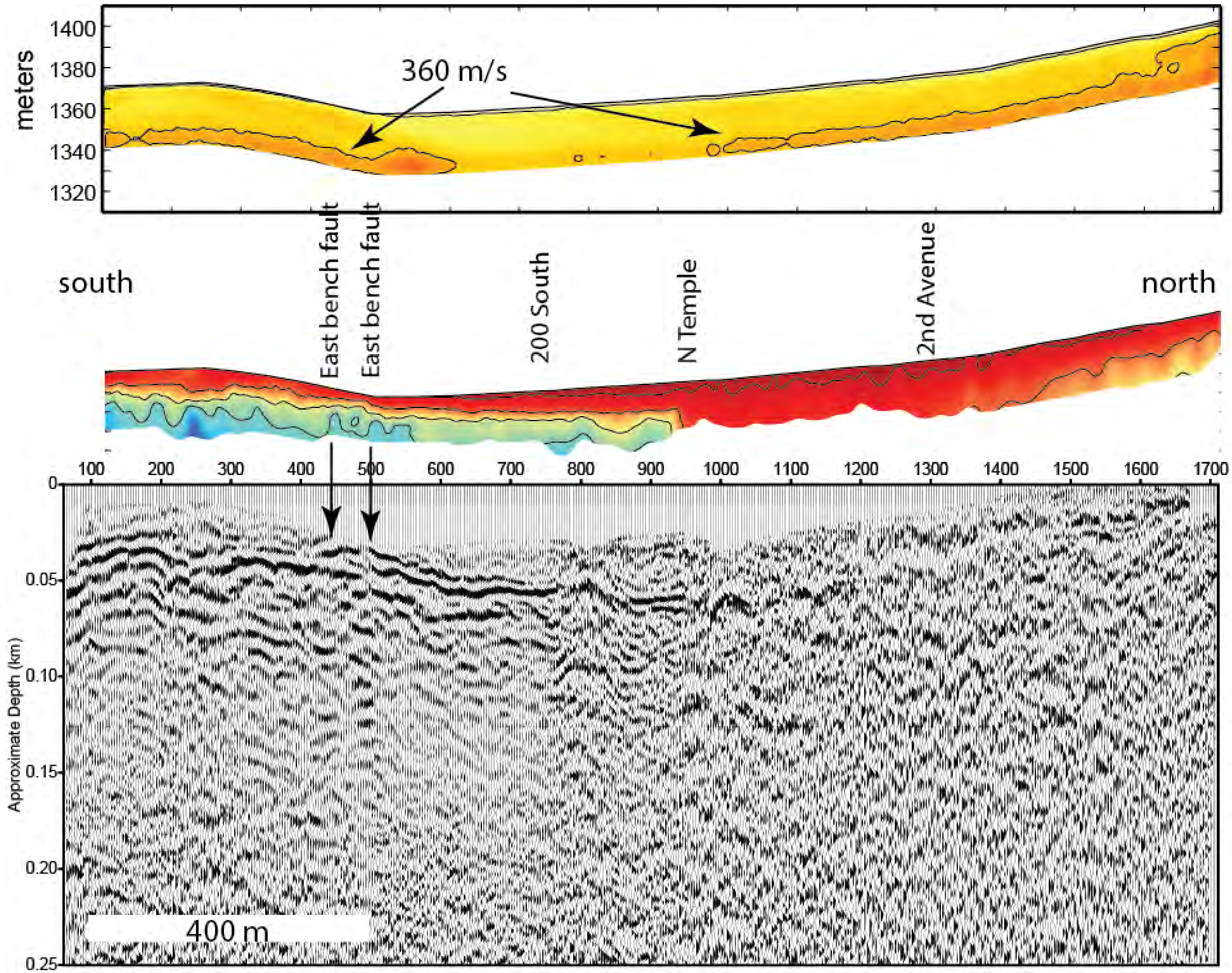
146
147
INTERIM GEOLOGIC MAP OF THE
SALT LAKE CITY NORTH QUADRANGLE,
SALT LAKE AND DAVIS COUNTIES, UTAH
by
Adam P. McKean
2014


200 South Street
Vs30
500 W
400 W
300 W
200 W
Salt Palace
Main St
State St
200 E
300 E
400 E
500 E
600 E
700 E
800 E
900 E
1000 E
1100 E
1200 E
170 (proj)
115 (proj)
Elevation (m)
well 10092
clay/gravel contact
water table
Longitude
200 South unmigrated p-wave velocities
East Bench fault
200 South Migrated
WSF
time(s)
distance (m)

1100 EAST

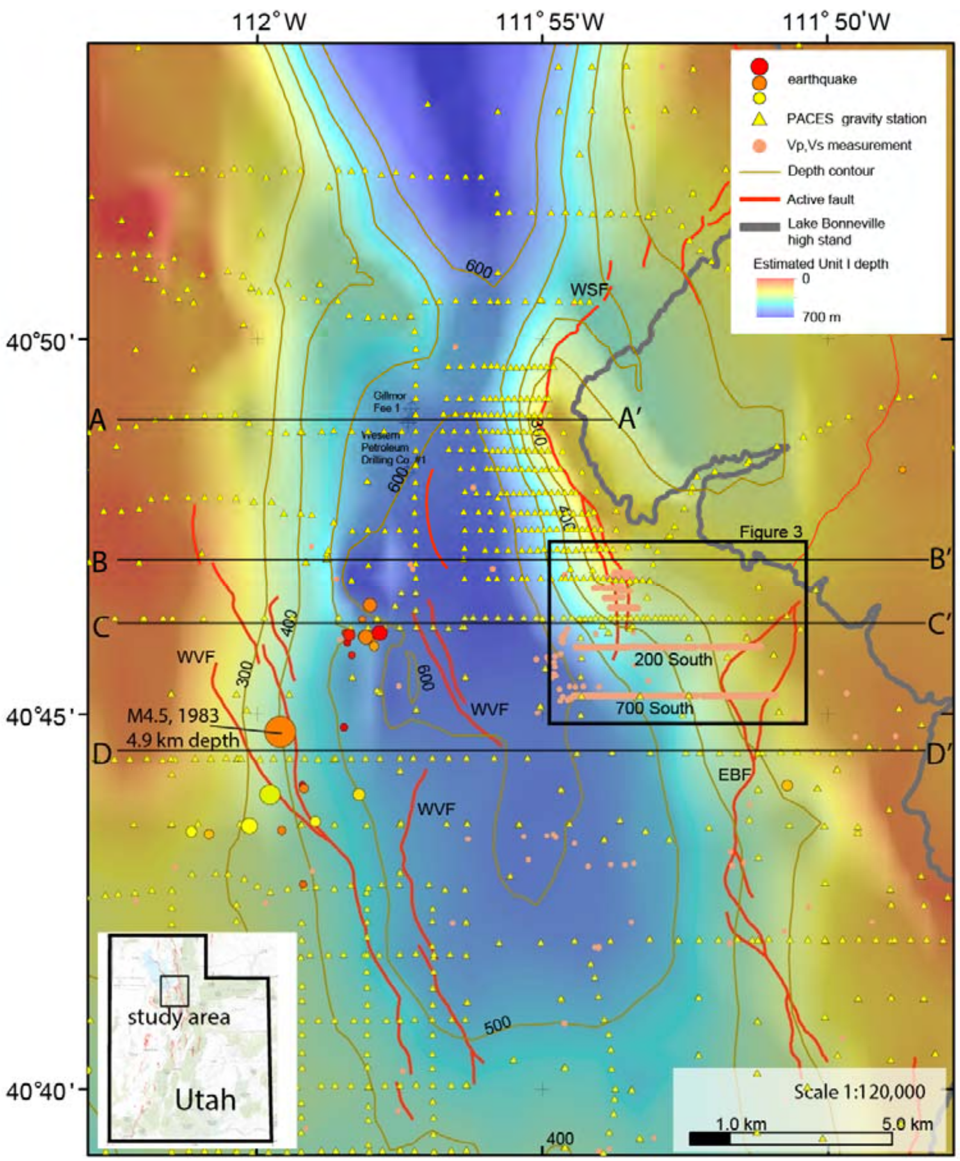
Vp

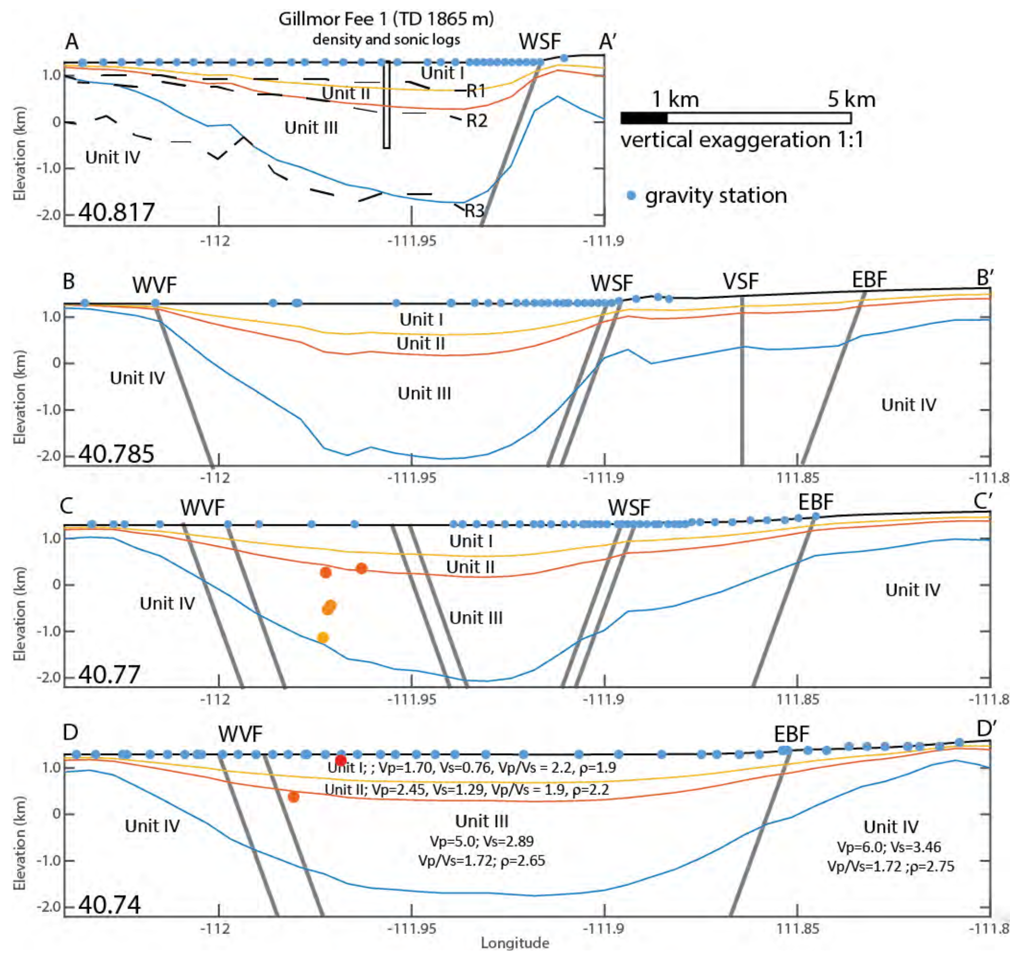


Seismic character changes beneath North Temple (fault?)

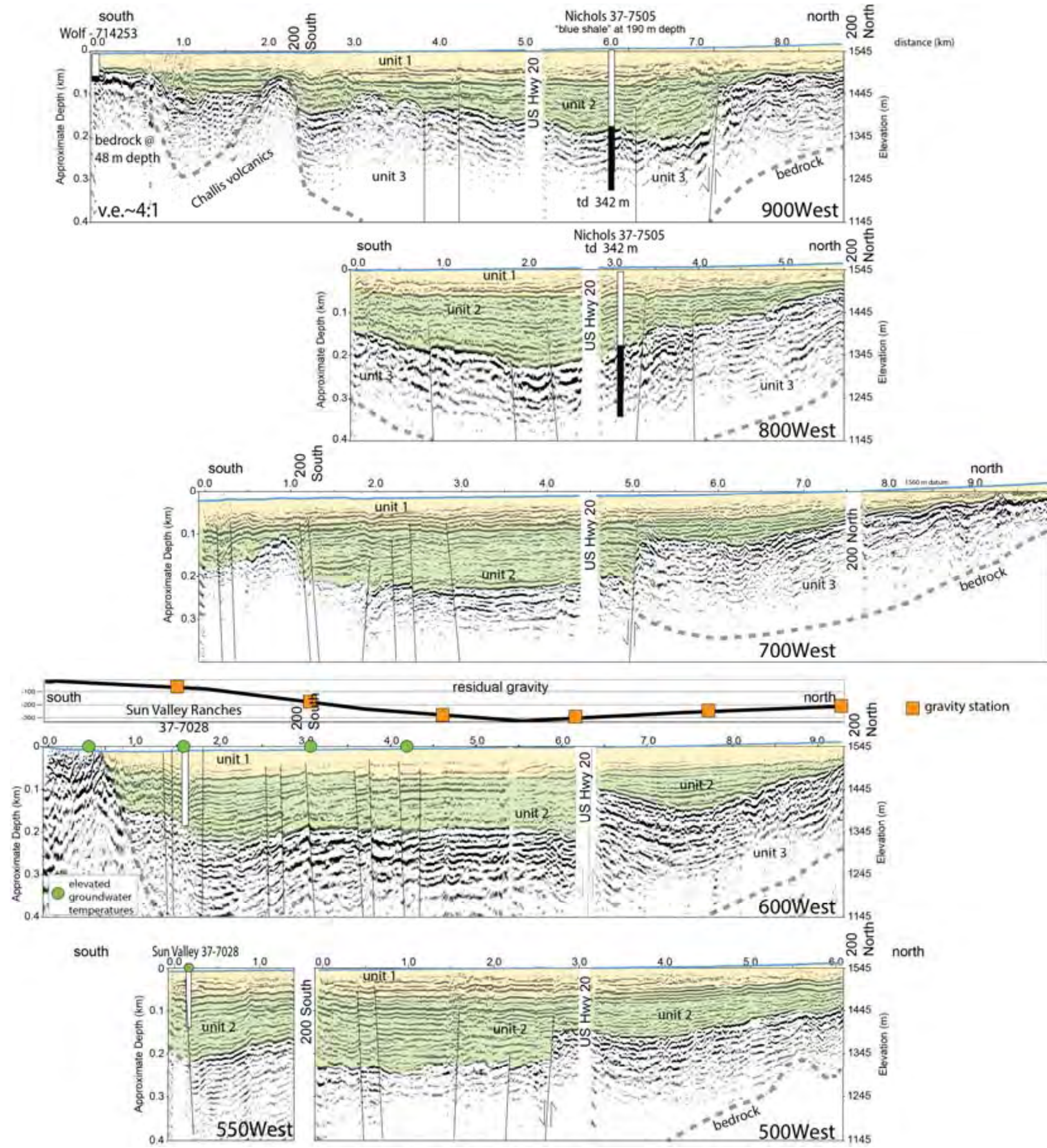
Shallow water table to the south
Deeper water table to the north

GRAVITY MODELS FOR WASATCH FRONT





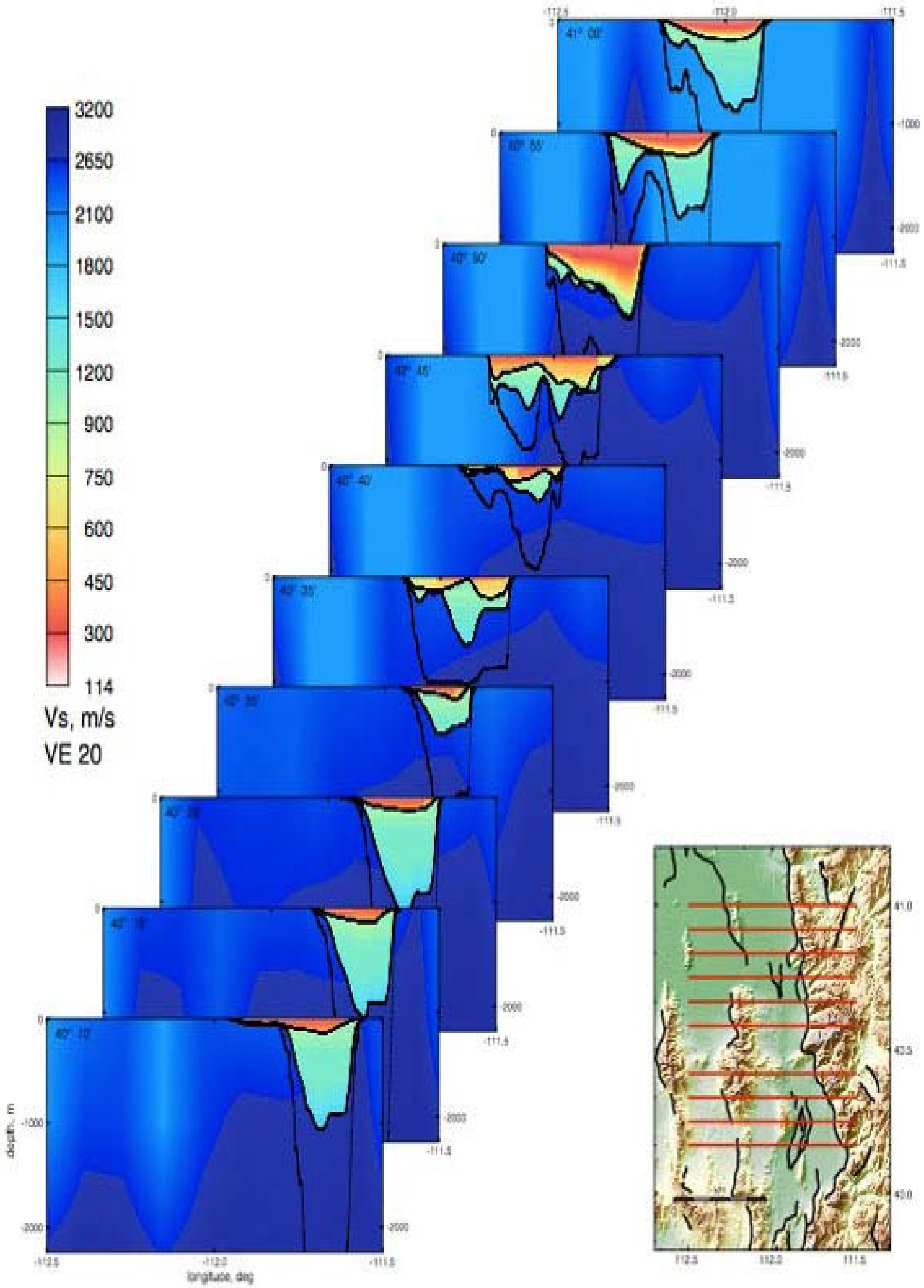
LAND STREAMER RESULTS FROM IDAHO – CAMAS PRAIRIE



UTAH GEOLOGICAL SURVEY

Wasatch Front Community Velocity Model

Greg McDonald, Utah Geological Survey
Harold Magistrale, FM Global
Kim Olsen, San Diego State University
James Pechmann, University of Utah



WFCVM development began in 2004-05

Harold Magistrale, Kim Olsen, Jim Pechmann

Based on SCEC models

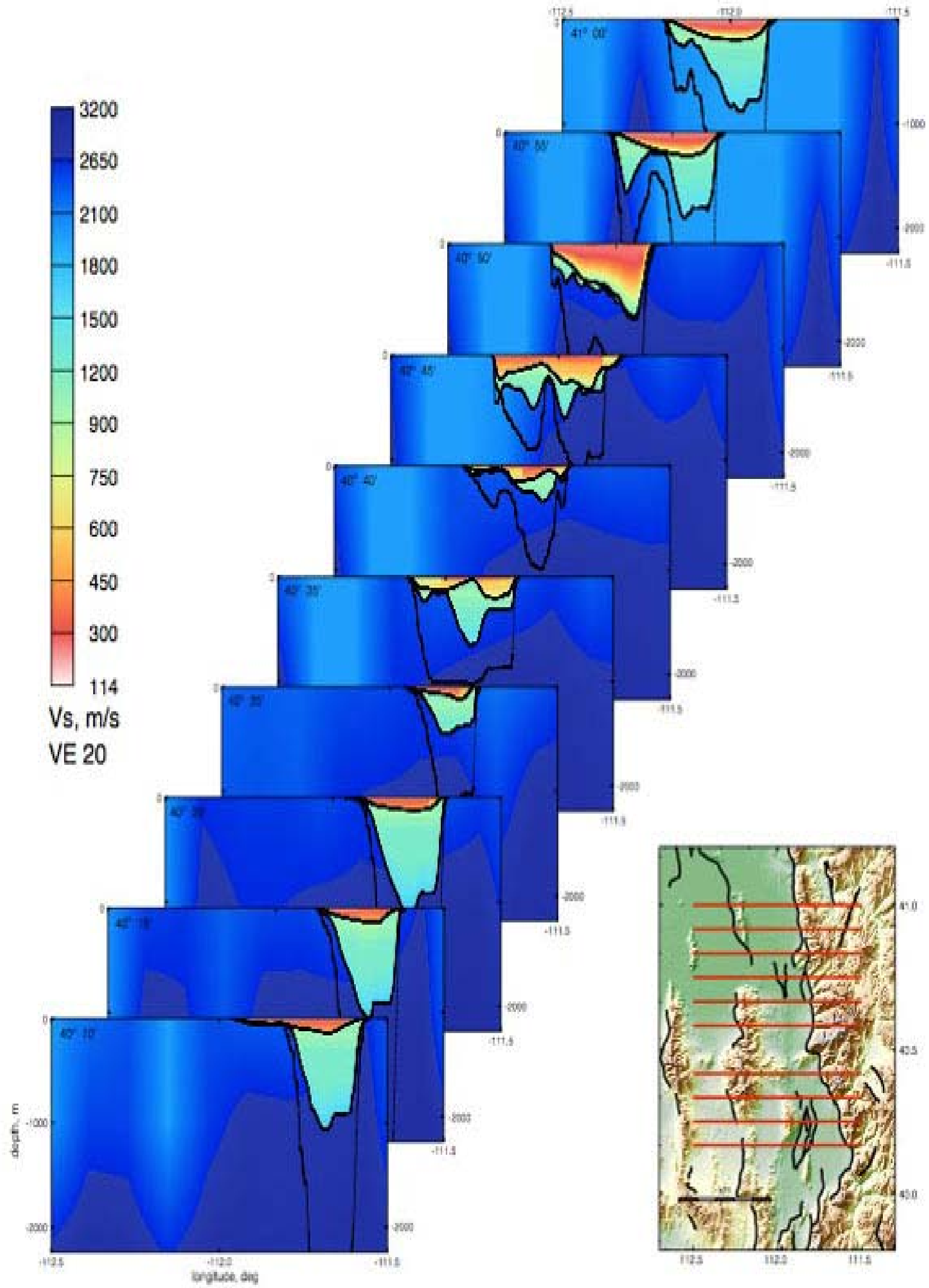
First draft submitted mid-2006

Most up-to-date version 3d (2010~14)

Validation by Olsen, Roten, and Pechmann

USGS

www.geology.utah.gov

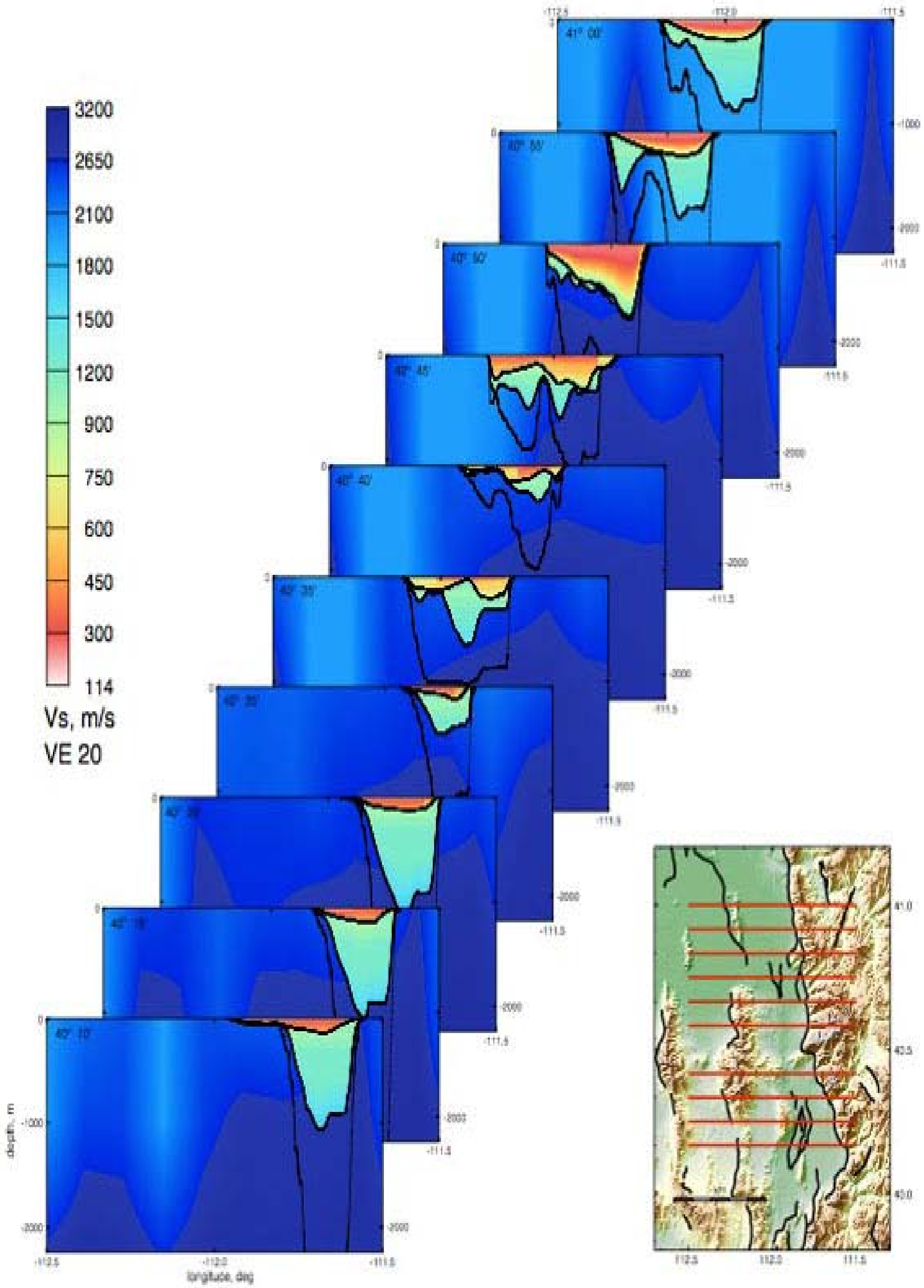


What is the WFCVM?

- A 3-D velocity structure model for basins along the Wasatch Front
- Used for ground-motion modeling

Main components

- Surfaces
  - geologic contacts
  - gravity inversion
  - seismic refraction
  - boreholes
- Seismic velocities
  - Boreholes
  - SASW
  - Empirical relations



Data sources

-Soil classes, Vs30
-Geophysical data
-Geotechnical boreholes
-Intrabasin interfaces
    -R1, R2, R3 in SLV
    -R1, basement (gravity, wells, seismic) in other basins
-Deep boreholes (seismic velocities)
-Crustal tomography
-Moho (upper mantle Vp)

Rule Based Seismic Velocity Model

-Compile geologic and geophysical information

examples: stratigraphy, surficial geology
oil well sonic logs
tomography results

-Define reference surfaces

examples: lithologic contacts (isoage surface)
isovelocity surface
tomography model nodes

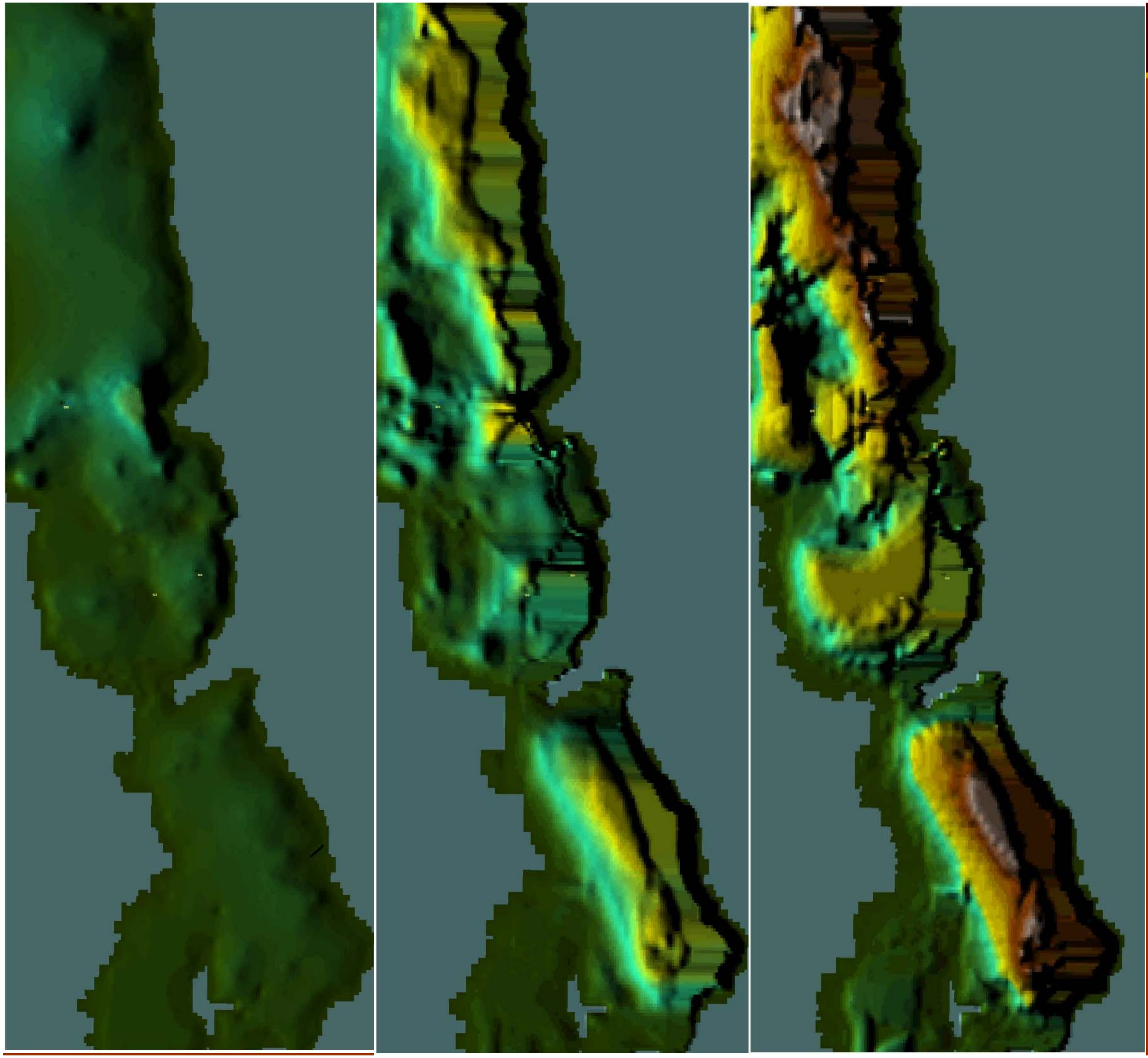
-Compare point of interest to objects and interpolate properties

examples: interpolation of age between surfaces
interpolation of velocity between tomography nodes

-Apply rule to get velocity (or other property) at point of interest

examples: Linear gradient between isovelocity surfaces
Faust's rule (velocity-age-depth relation)

$$Vp=k(da)1/6$$



Near surface soil conditons

--

Unconsolidated Quaternary sediments

--

R1

--

Semi-consolidated Tertiary sediments

--

R2

--

Tertiary bedrock

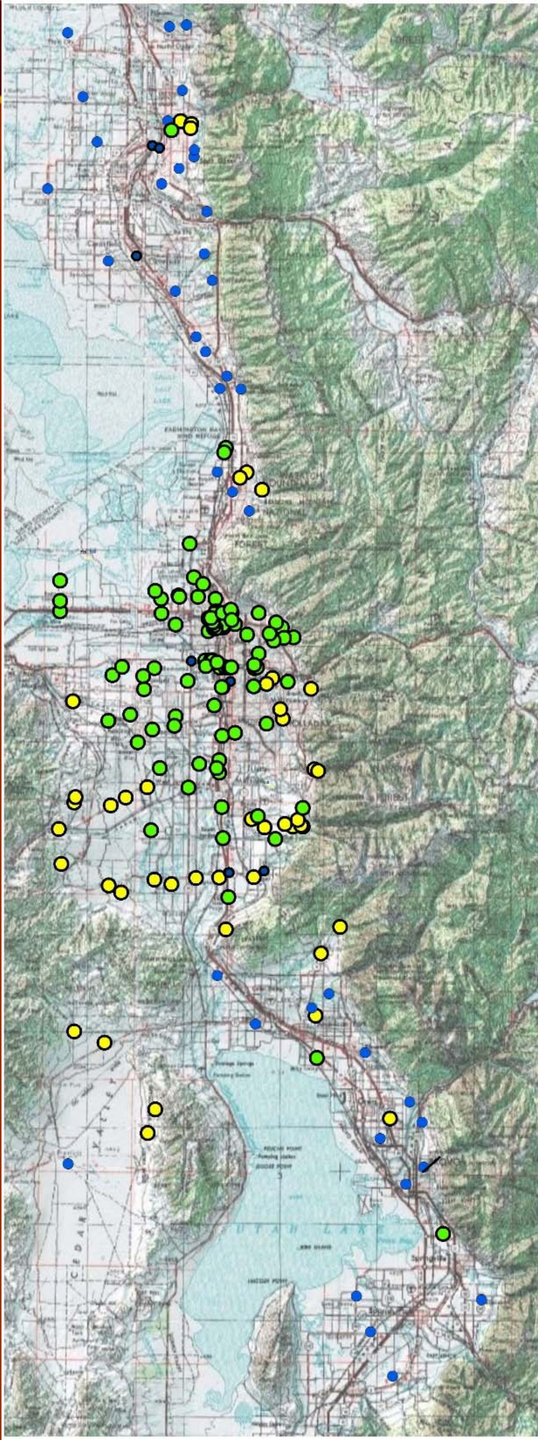
--

R3

--

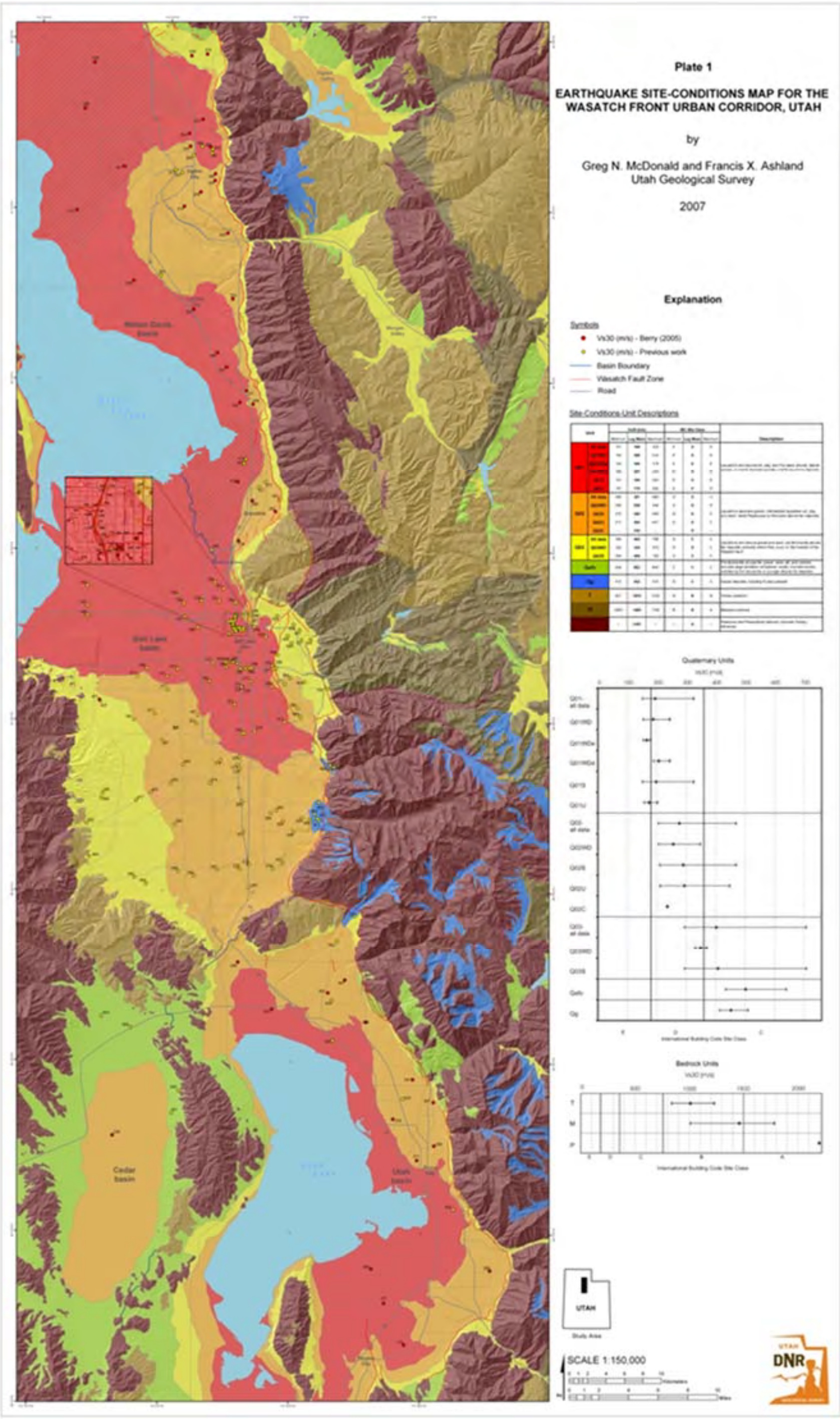
Basement rock

www.geology.utah.gov



Soil conditions

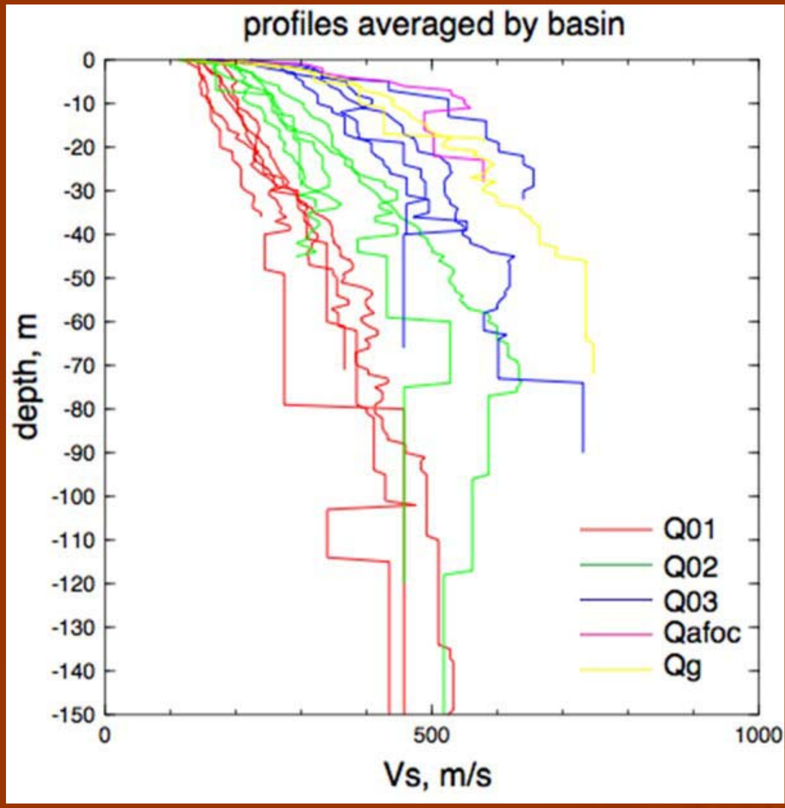
- Surficial geology
- Vs30
  - Compiled from literature and consultant's reports
  - Crosshole/Downhole
  - CPT
  - SASW
  - Vs collection campaigns
    SASW – USU Jim Bay and students
    USGS seismic
  - 204 sites total
    139 - Salt Lake basin
    24 - Weber basin
    16 - Davis basin
    20- Utah basin
    5 - Cedar Valley



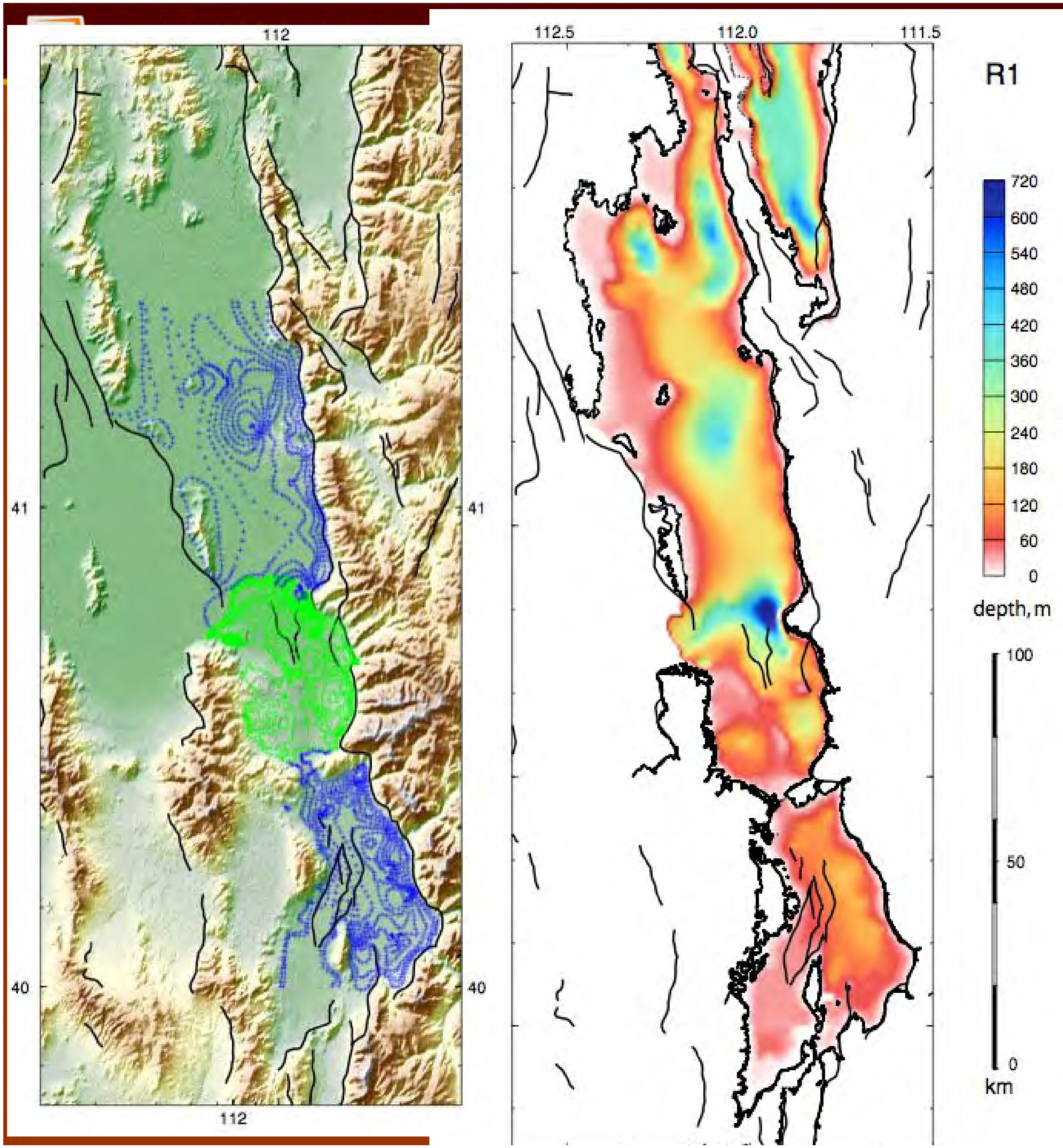
Mapped site-conditions units

Unit extents from surficial geology

Mean Vs30 to relate to IBC site classes

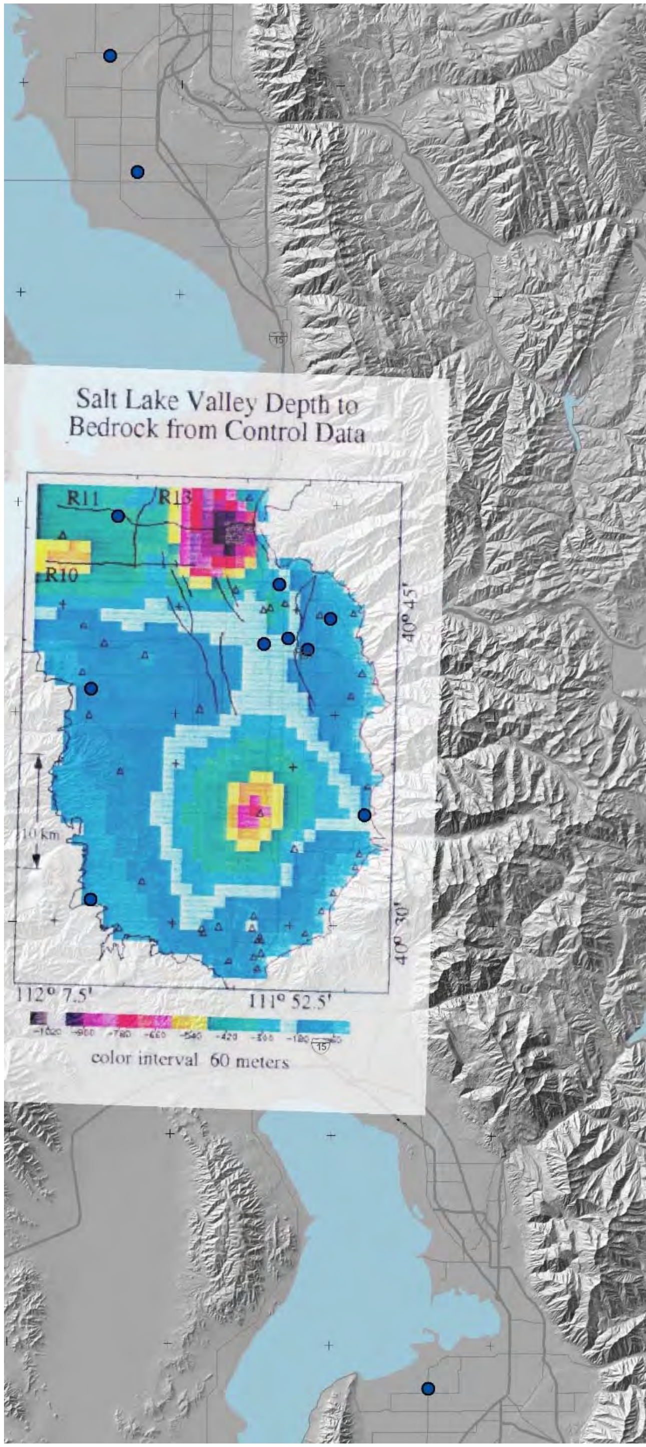


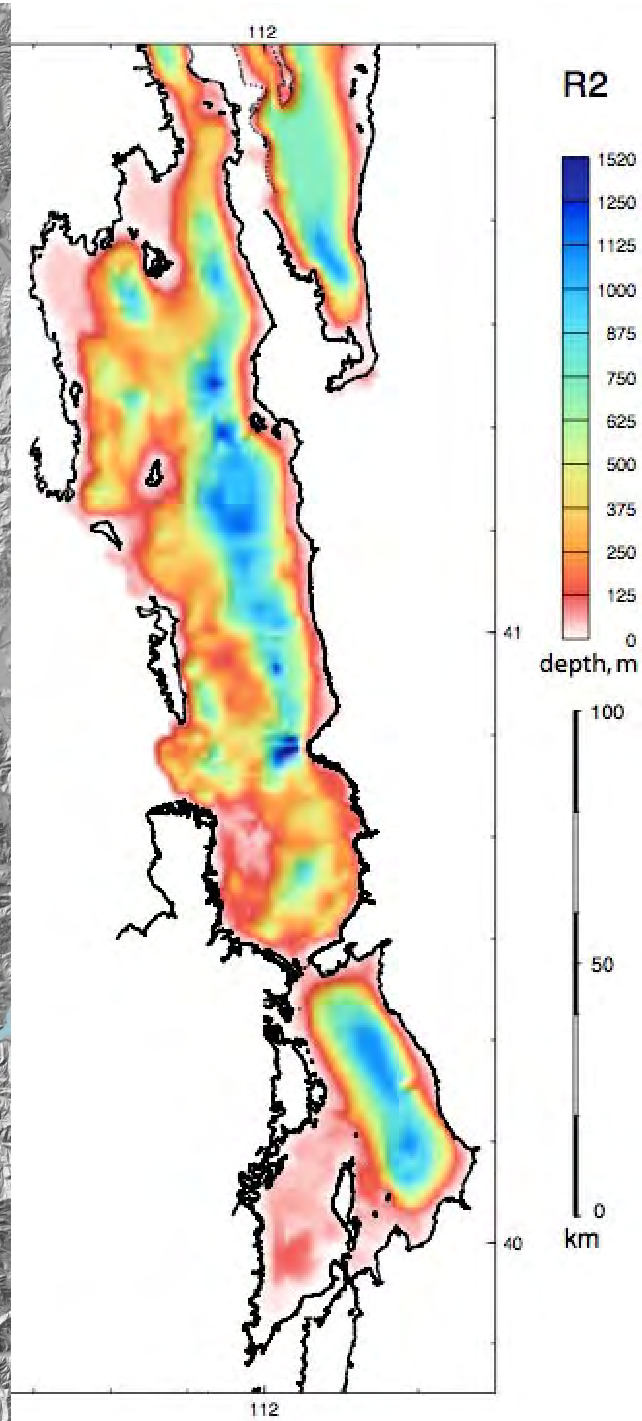
www.geology.utah.gov



R1 sources

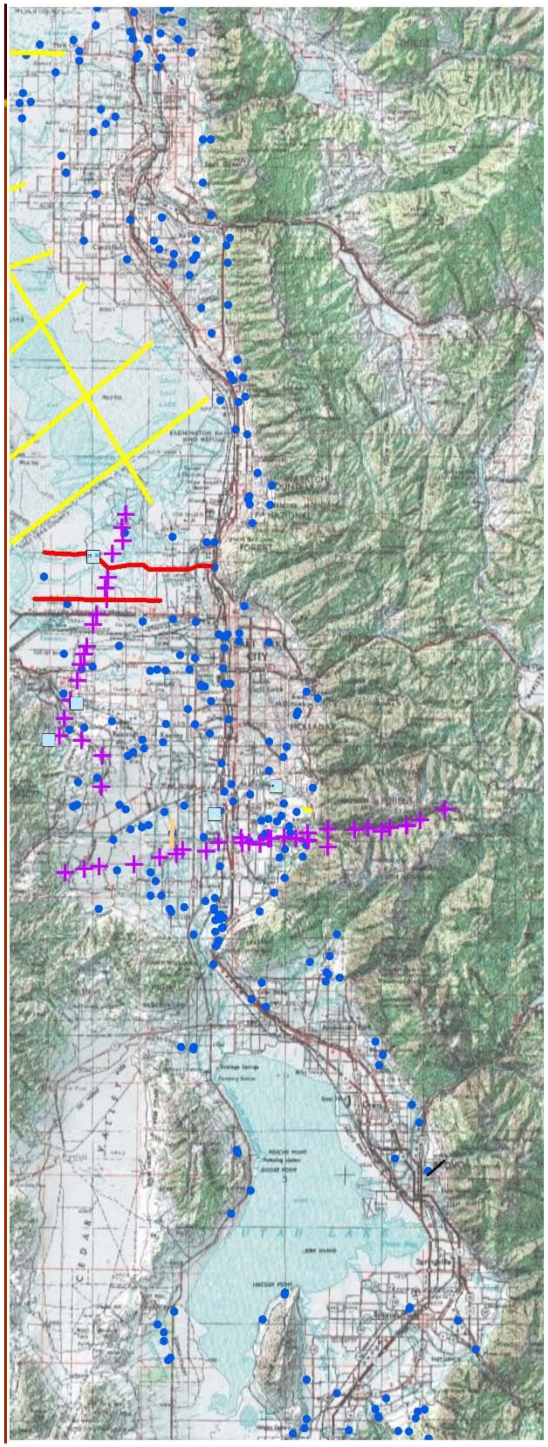
Deep boreholes/water rights wells
Seismic
Vs profiles
(Solomon et al 2004
Wong et al 2002)

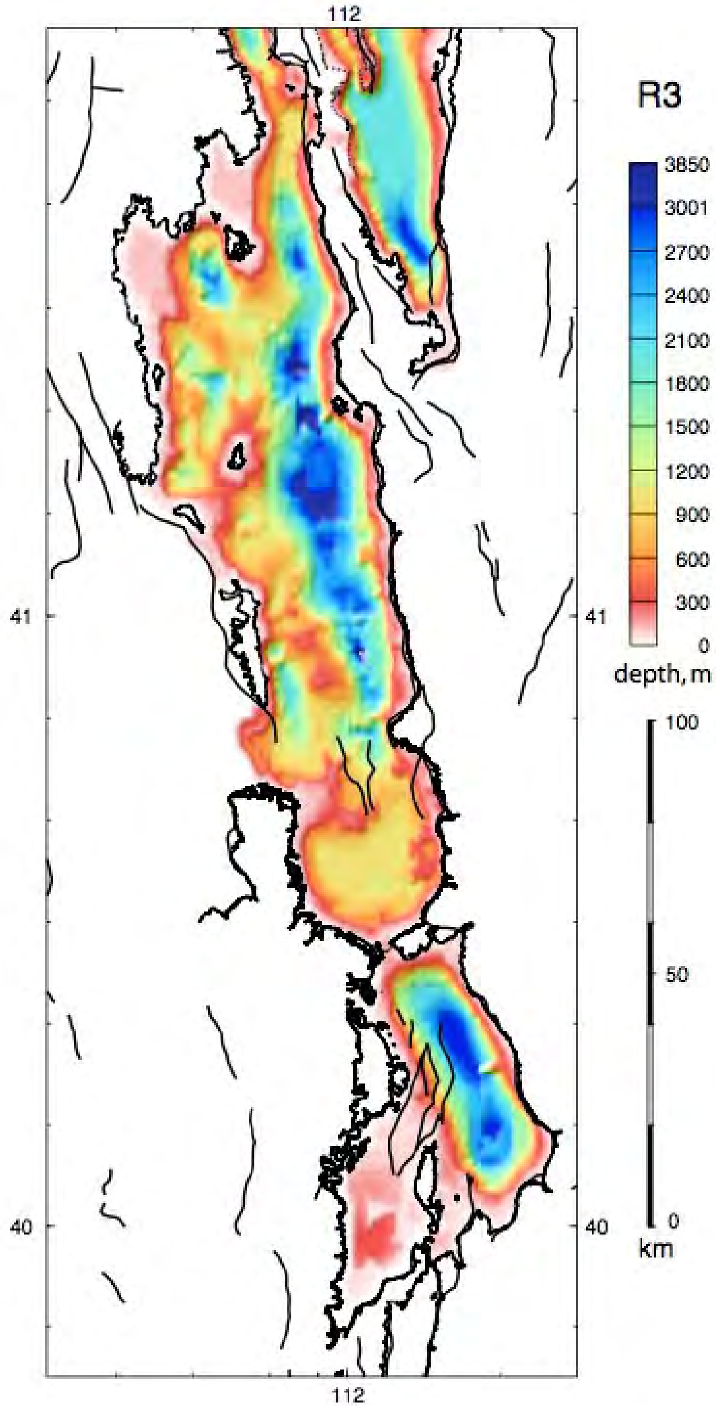




R2 sources

- Geophysics
  Gravity
  (Radkins,1990)
  Seismic
  Vs profiles
- Deep boreholes
  Lithologic contacts



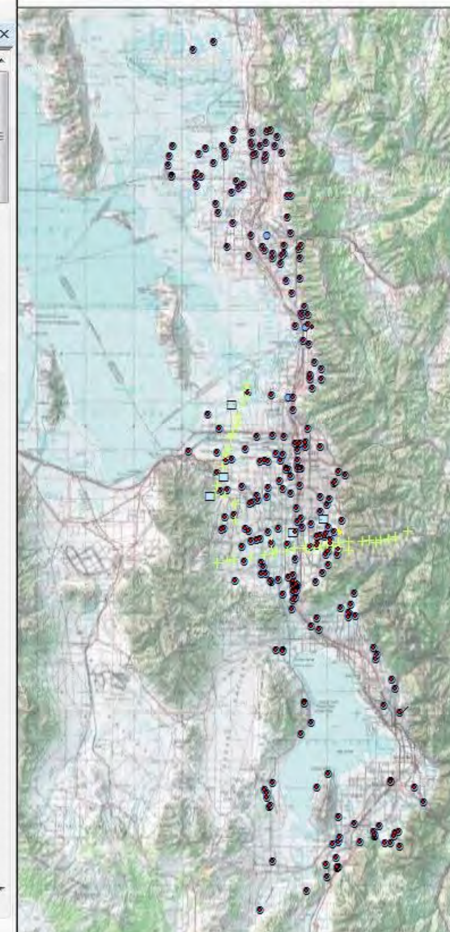


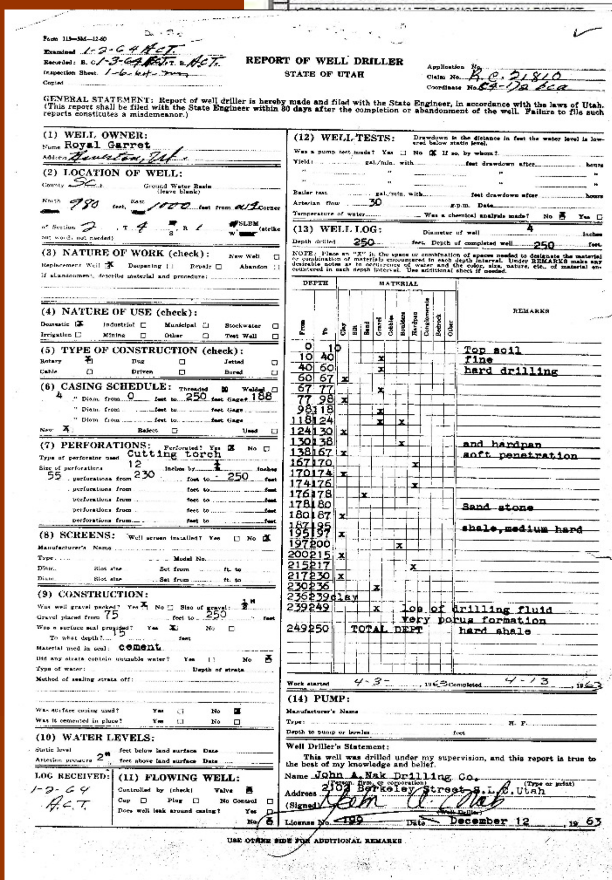
Basement (R3) sources

Deep boreholes
Gravity
Seismic
Mabey 1992
Bashore 1982
McNeil and Smith 1992
Mattick 1970

UTAH DNR — UTAH GEOLOGICAL SURVEY

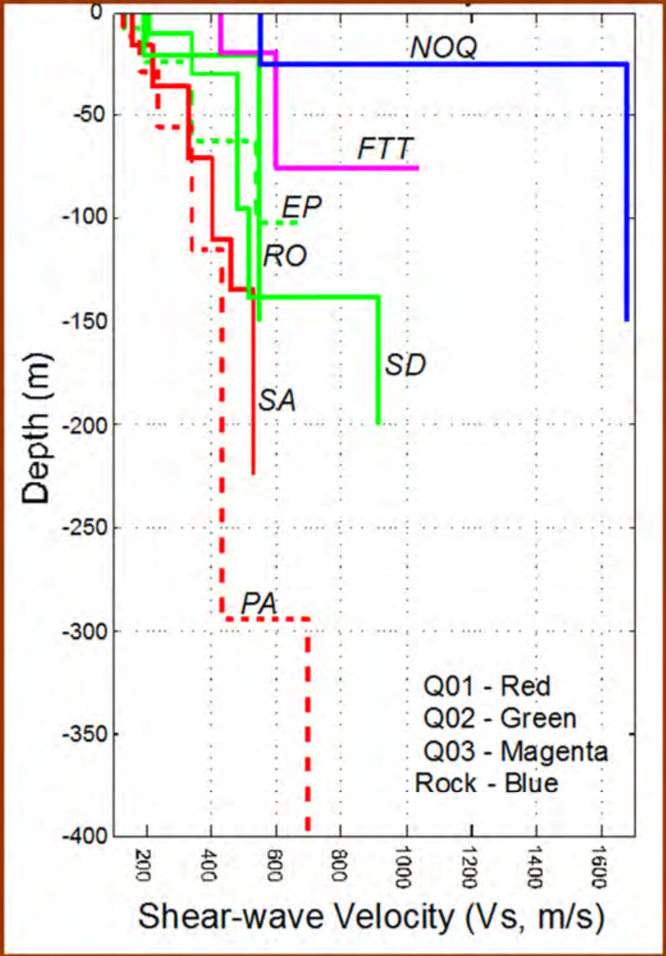
	OWNER	TD_FT	R1A_FT	R1B_FT	R2_FT	TUFATOP_FT	TUFABOT_FT	TD_M	R1A_M	R1AA_m	R1B_M	R2_M	R2
▸	SALT LAKE CITY COUNTY LAND FILL	340	225		316			104	69	69		96	96
	GRANGER-HUNTER IMPROVEMENT DISTRICT	1005	690		990	595	605	306	210	210		302	30
	JORDAN VALLEY WATER CONSERVANCY DISTRICT	875	847		847			267	258	258		258	25
	WHITE CITY WATER COMPANY INC.	950	725		725			290	221	221		221	22
	SANDY CITY CORPORATION	934	575		920			285	175	175		280	28
	MURRAY CITY CORPORATION	695	293		680			212	89	89		207	20
	JORDAN VALLEY WATER CONSERVANCY DISTRICT	960	850		850			293	259	259		259	25
	JORDAN VALLEY WATER CONSERVANCY DISTRICT	1010	985		985	985	995	308	300	300		300	30
	MONROC INC.	1090	684		1090			332	209	209		332	33
	LATTER DAY SAINTS HOSPITAL	710	100		680	100	204	216	30	30		207	20
	JORDAN VALLEY WATER CONSERVANCY DISTRICT	940	215		0			287	66	66		0	
	SALT LAKE CITY CORPORATION	604	585		0			184	178	178		0	
	CORNELIUS DEVELOPMENT CORPORATION	1473	1191		0			449	363	363		0	
	SALT LAKE CITY CORPORATION	470	0		0			143	0			0	
	SALT LAKE CITY CORPORATION	500	468		0	200	215	152	143	143		0	
	WILLIAMS, ROBERT L.	220	70		203			67	21	21		62	62
	COPPERTON IMPROVEMENT DISTRICT	990	310		985			302	95	95		300	30
	PROPERTY RESERVE INC.	1200	581	1030	0	581	633	366	177	177	314	0	
		1134	820		0	820	835	346	250	250		0	
		800	305		0			244	93	93		0	
		1088	174	531	0	174	200	332	53	53	162	0	
		793	440		0			242	134	134		0	
		1203	0		0			367	0			0	
		1007	687		0	80	143	307	209	209		0	
		1010	345	427	0	345	415	308	105	105	130	0	
		862	820		0	820	826	263	250	250		0	
		1000	0		0			305	0			0	
		1276	0		0			389	0			0	
		1508	525		0			460	160	160		0	
		1018	647	883	0			310	197	197	269	0	
		1385	470		0			422	143	143		0	
		1122	0		0			342	0			0	
		1275	500		0			389	152	152		0	
		116	63	113	0			35	19	19	34	0	
		683	552		680	552	600	208	168	168		207	20
		604	565		0	565	604	184	172	172		0	
		520	175	300	0			159	53	53	91	0	
		1000	807	948	0			305	246	246	289	0	
		943	0		0			288	0			0	
		482	195	472	0	195	205	147	59	59	144	0	
		1019	745		0	745	747	311	227	227		0	
		693	655		0	655	680	211	200	200		0	
		522	0		0			159	0			0	
		913	901		0	901	903	278	275	275		0	
		515	408		0			157	124	124		0	
		1005	674		0			306	205	205		0	

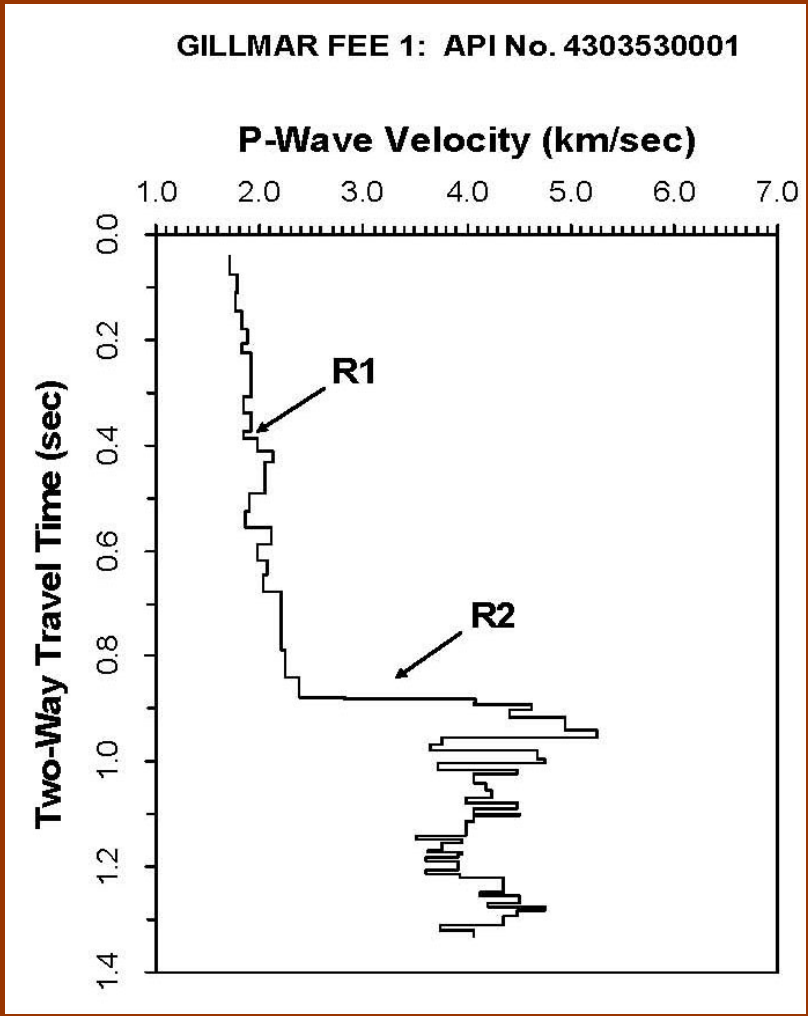




Well logs - lithologic interpretations

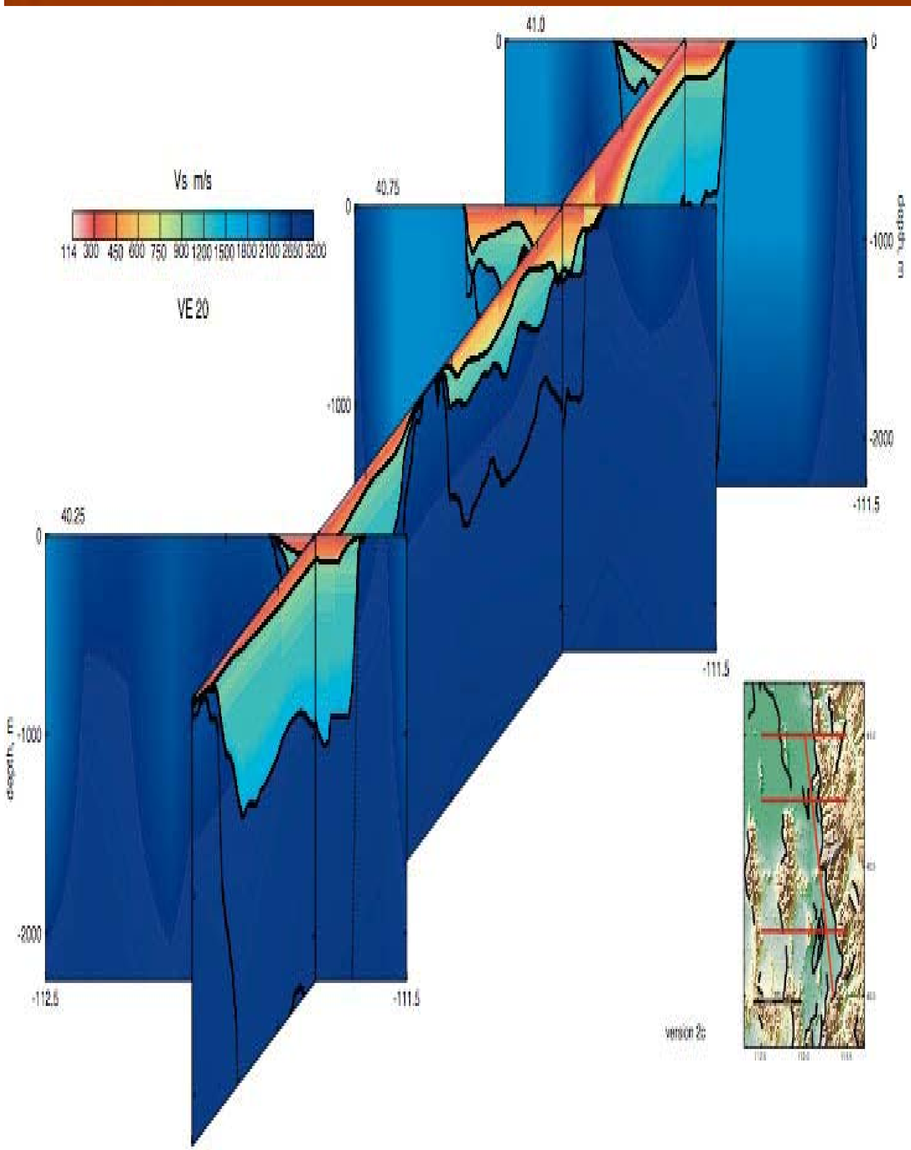
UTAH GEOLOGICAL SURVEY





S-wave minivibe soundings
W. Stephenson, R. Williams, J. Odum, D. Worley, R. Dart (USGS) J. McBride (BYU)

Sonic Logs
J. Pechmann, K. Jensen (UofU), H. Magistrale (FM Global)



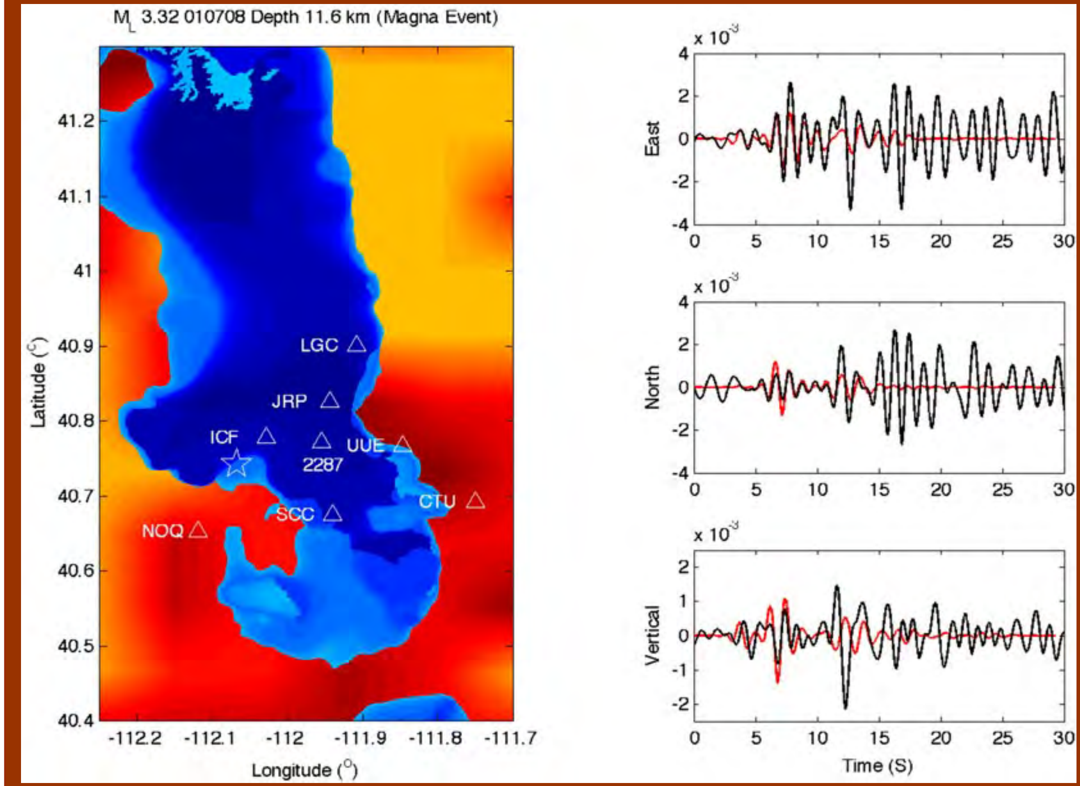
Above R1
- soil classes, Vs
- Vp from piecewise linear fits to geometric mean sonic log profiles
- If Vs geotech, Vp from modified mudline

R1-R2
- Vp from piecewise linear fits to geometric mean sonic log profiles
- If Vs geotech, get Vp from original sigma

R2-R3
- Sonic logs R2-R3 gradient
- R2 to R3 Vp from Faust’s rule (velocity-age-depth relation)

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

UTAH GEOLOGICAL SURVEY



WFCVM validation

Olsen, Roten, Pechmann 2006

Moschetti, Ramirez-Guzman

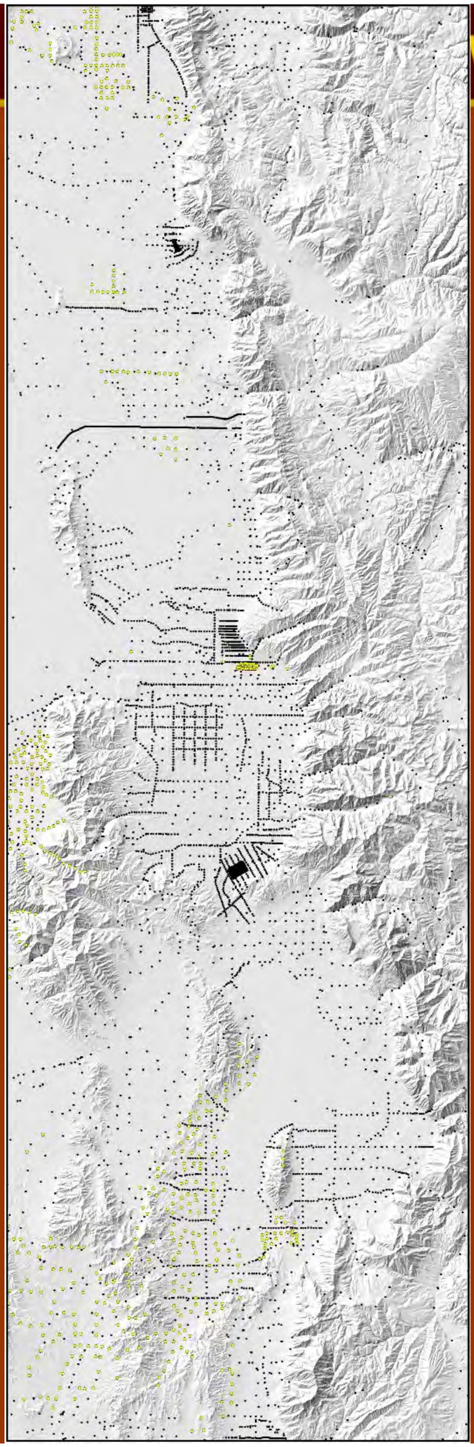
WFCVM has been used by several modeling groups:

Ground Motion Predictions from 0-10 Hz for M7 Earthquake on the Salt Lake City Segment, D. Roten, K, Olsen, H. Magistrale, J. Pechmann, V. Cruz-Atienza

3D Nonlinear Earthquake Ground Motion Simulation in the Salt Lake Basin, J. Bielak and R. Taborda

Ground Motions in the Salt Lake Basin from Dynamic Modeling of a M7 Earthquake on the Wasatch Fault, R. Archuleta, Q. Liu, R. Smith, and C. Puskas

Long period (T > 1-s) earthquake simulations
M. Moschetti, S. Hartzell, L. Ramirez-Guzman, A. Frankel, S. Angster, W. Stephenson



WFCVM potential updates/future work

- Collect data for Weber/Davis and Utah basins
- Expand model to include Wasatch-adjacent basins and back valleys
- Compile/update with Vs data collected since 2008
- Update basin geometries with more recent gravity data

Rupture Direction, Hanging Wall, Basin, and Distance Effects on Ground Motions from Large Normal-Faulting Earthquakes

Kim B. Olsen

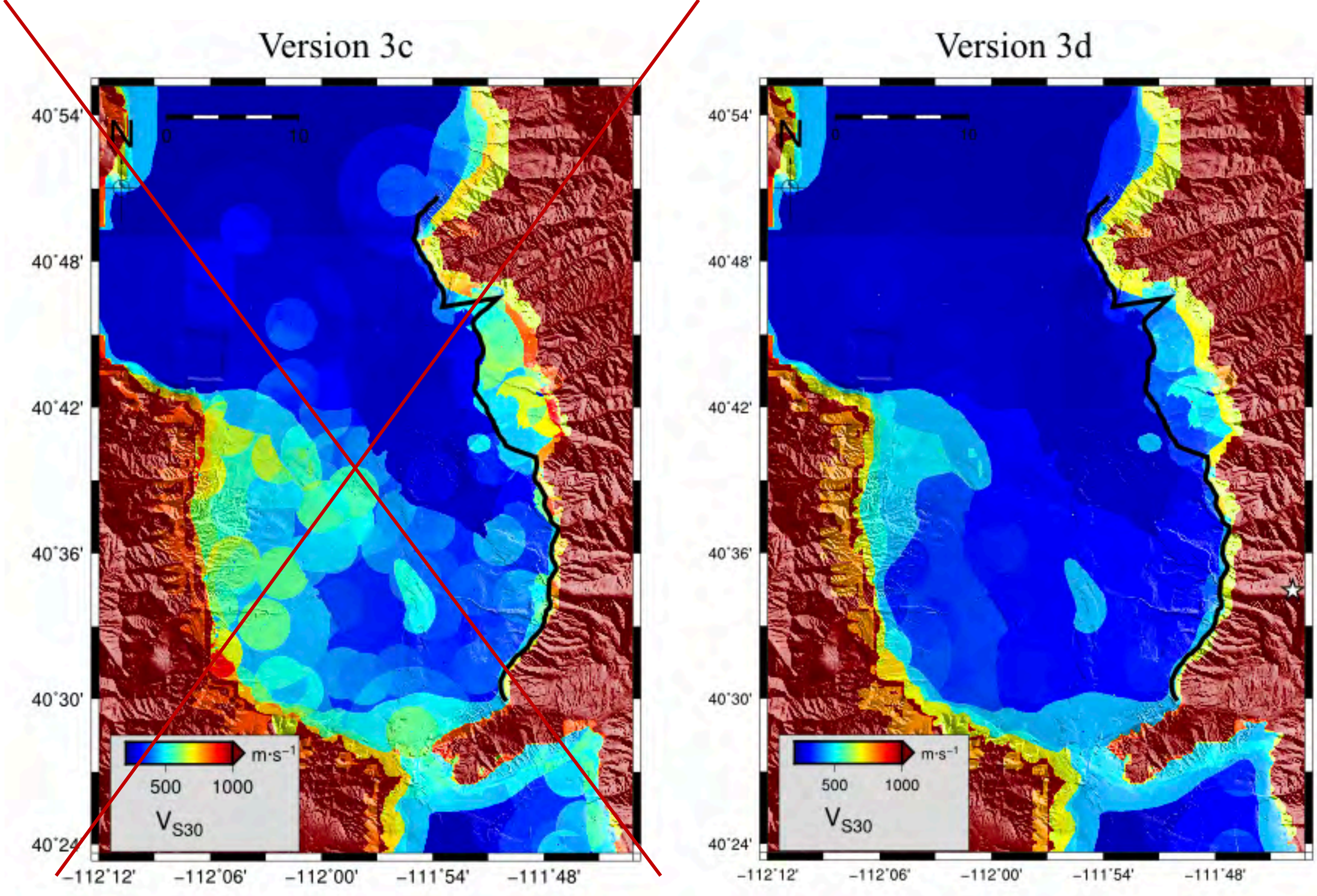
Nan Wang, Daniel Roten and James C. Pechmann

Based on NEHRP awards G14AP00044 & G14AP00045

UGS Meeting Feb 13, 2018

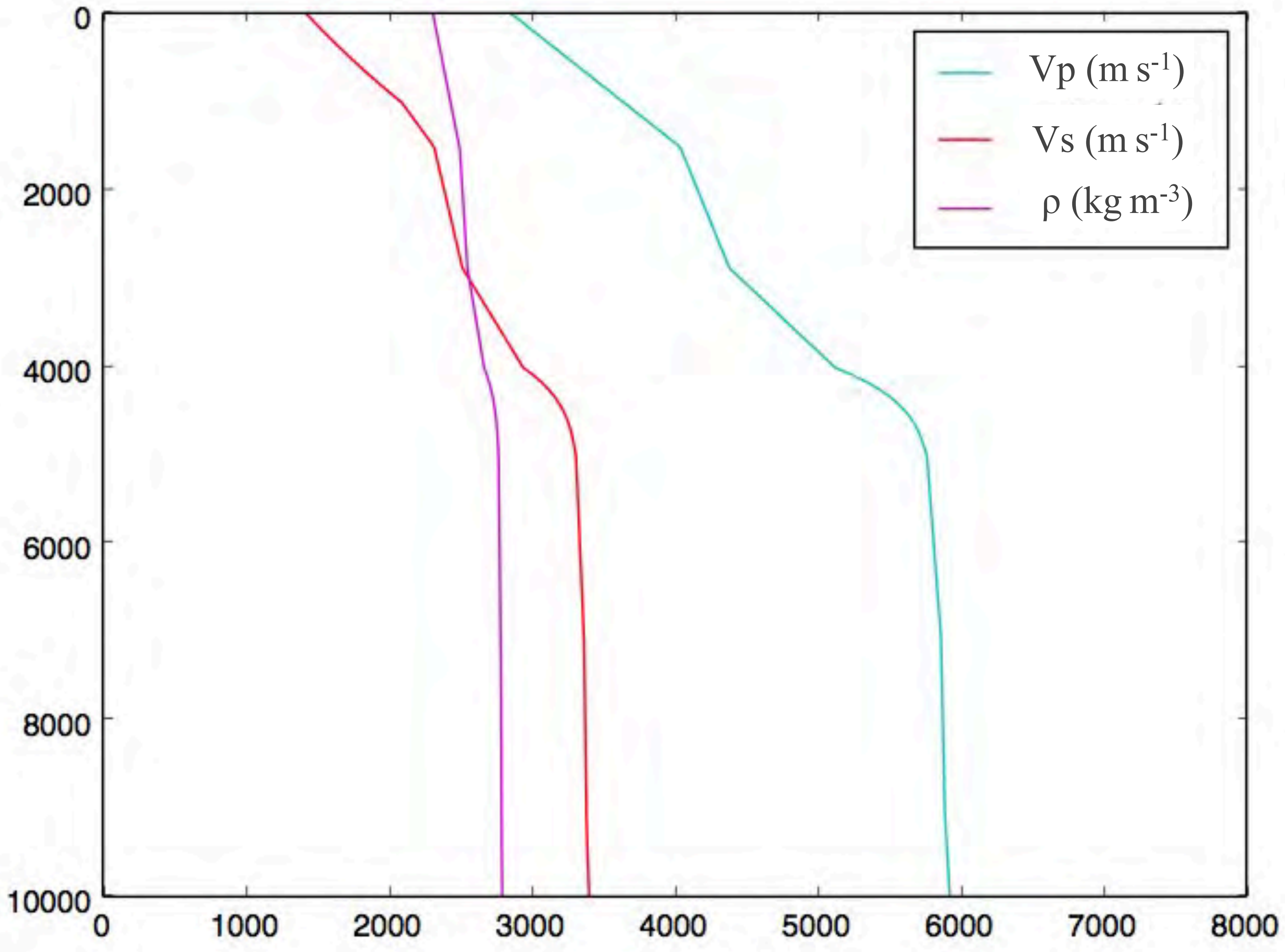
Outline

- Ground motion amplification from 3D simulations in the SLB
- Comparison of simulated amplification to NGA-West2 GMPEs
- What controls ground motion amplification in the SLB (source/path)?
- Can recent directivity model predict directional amplification effects?
- Causes of simulation versus GMPE bias at 0-1.5 km and 4-10 km
- Hanging-wall effects

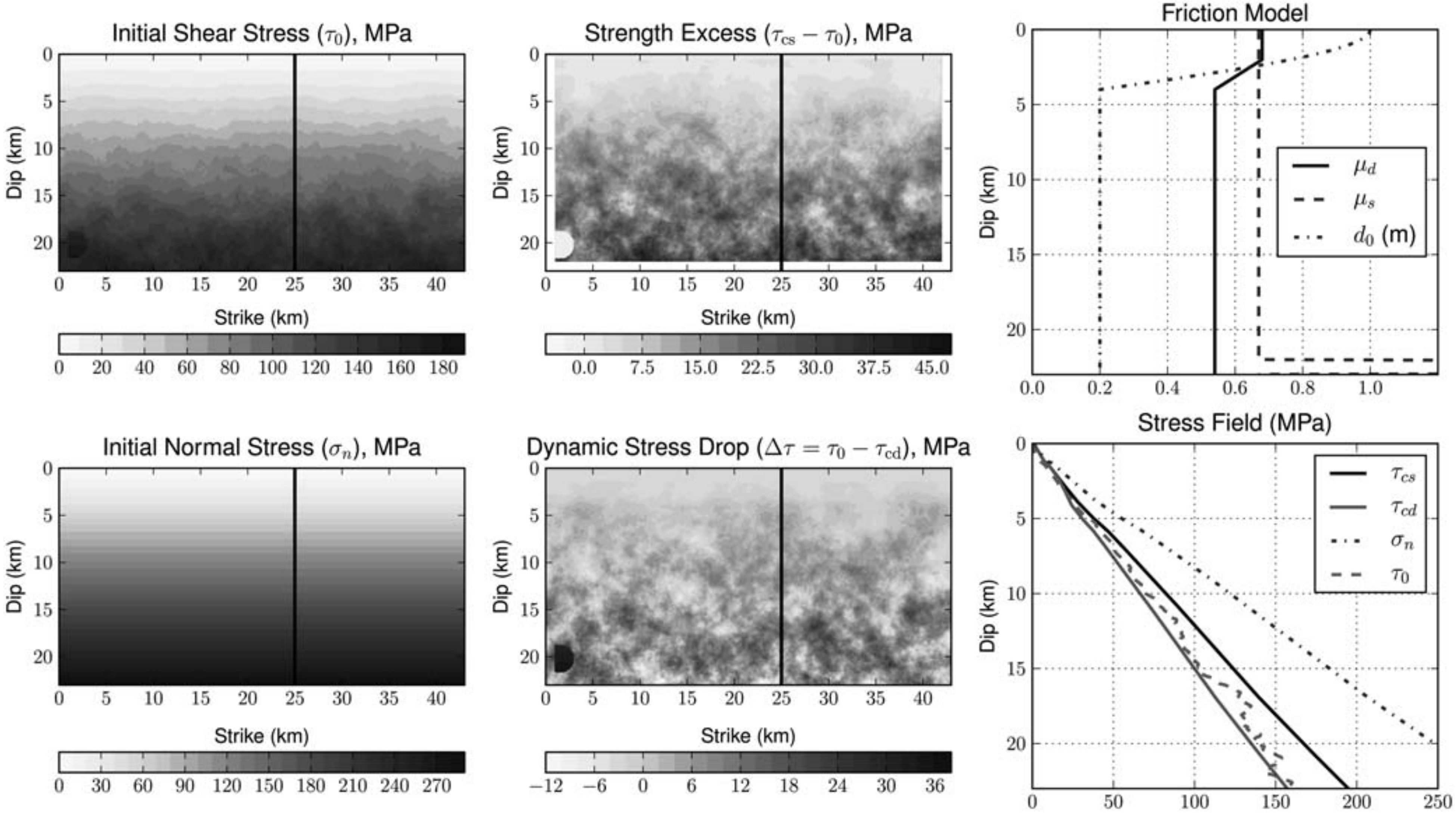


Roten et al. (2011) re-done in fixed CVM

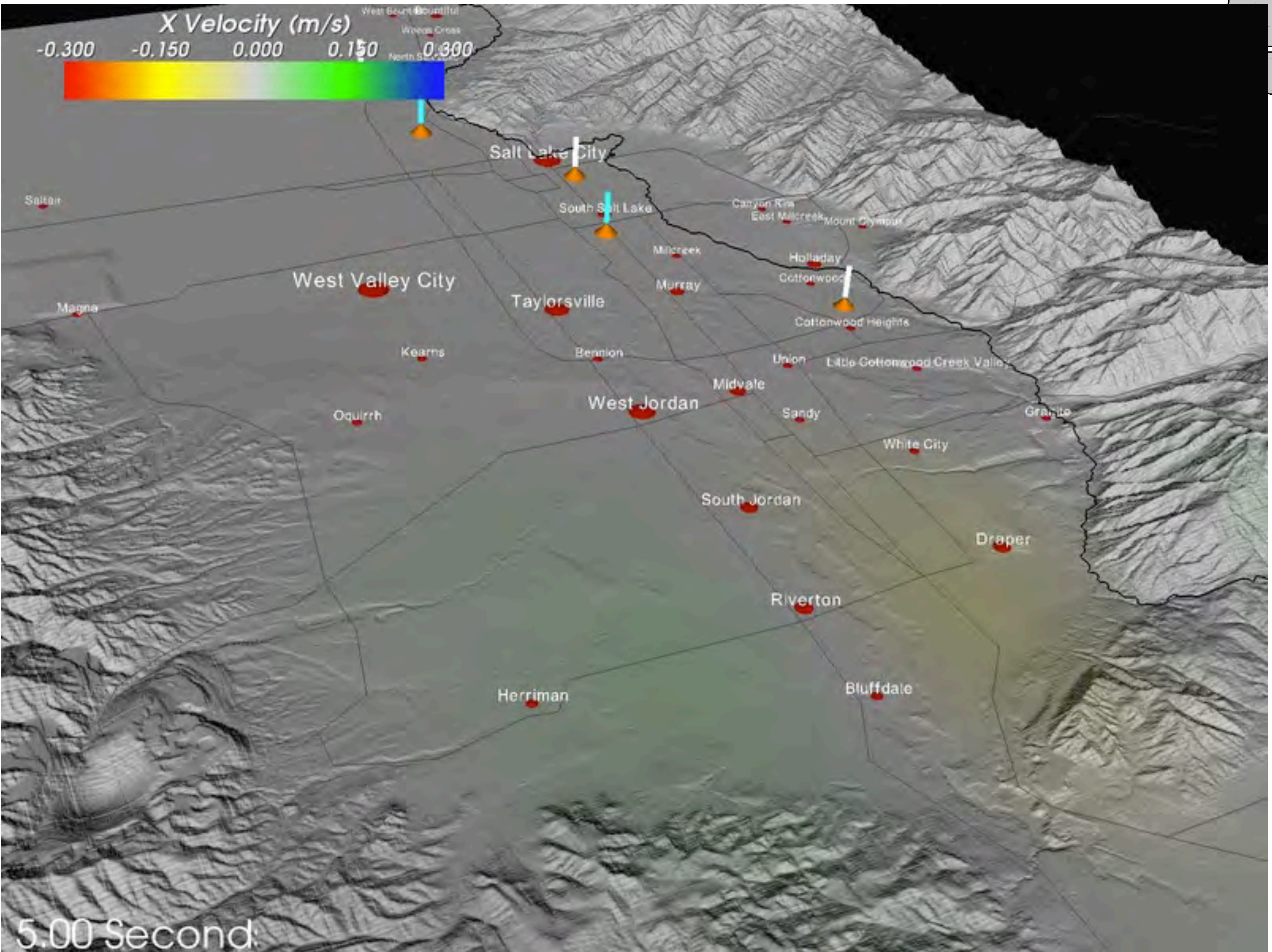
Additional set of 6-scenario simulations with 1-D rock velocity model

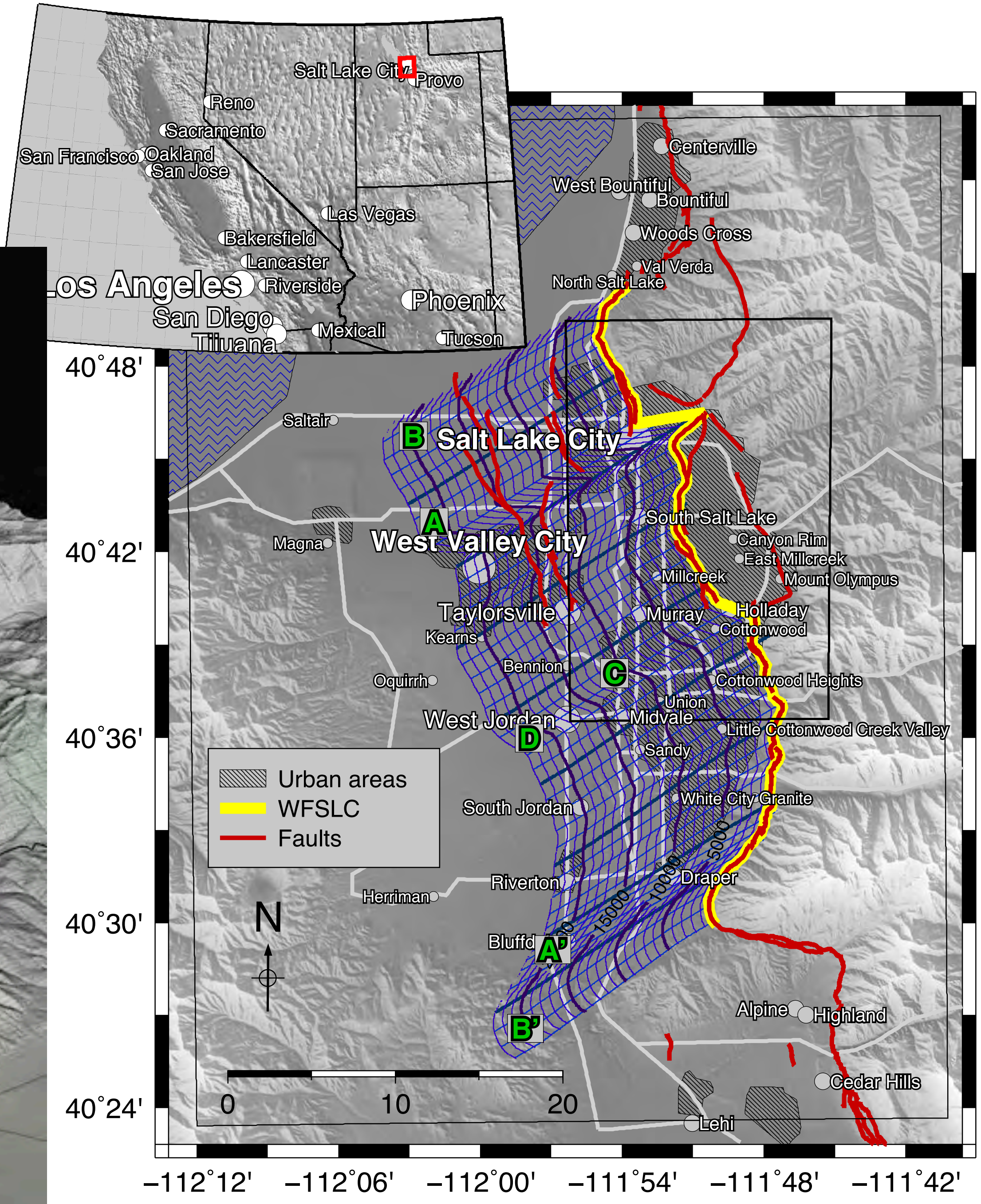


Source Descriptions from Dynamic Ruptures



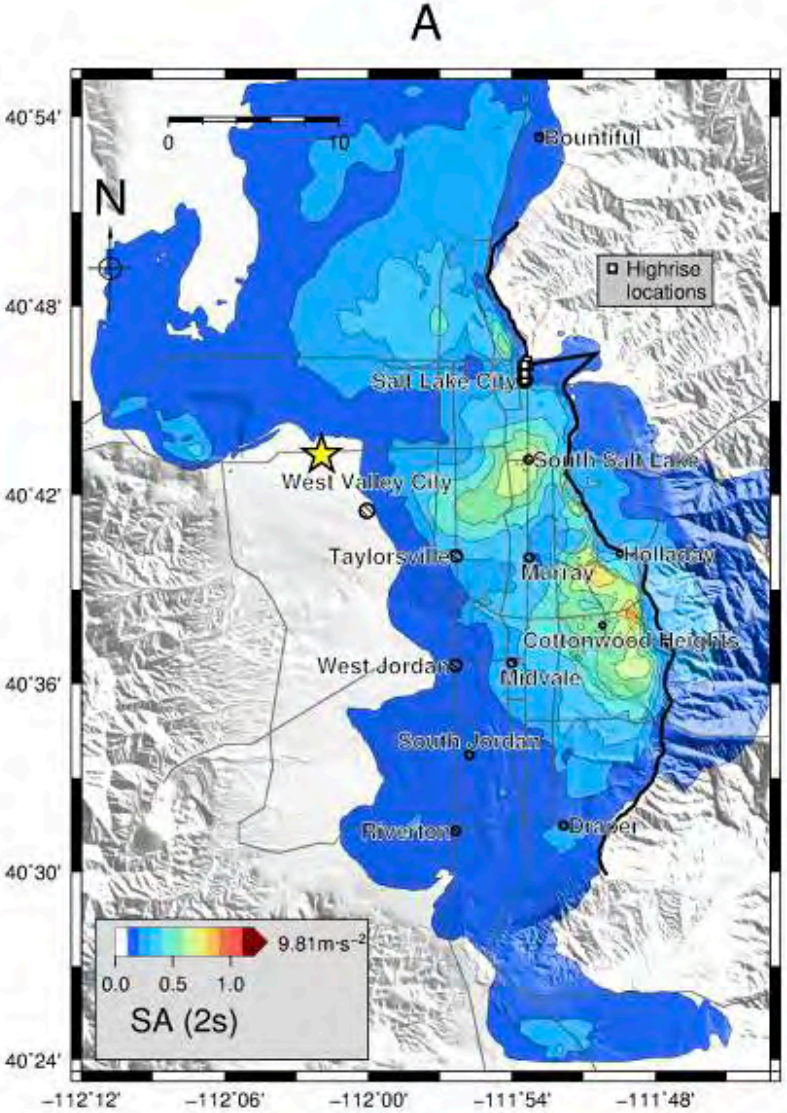
All simulations use Wasatch Fault model as in Roten et al. (2011).





Basin Amplification

3D


A
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10
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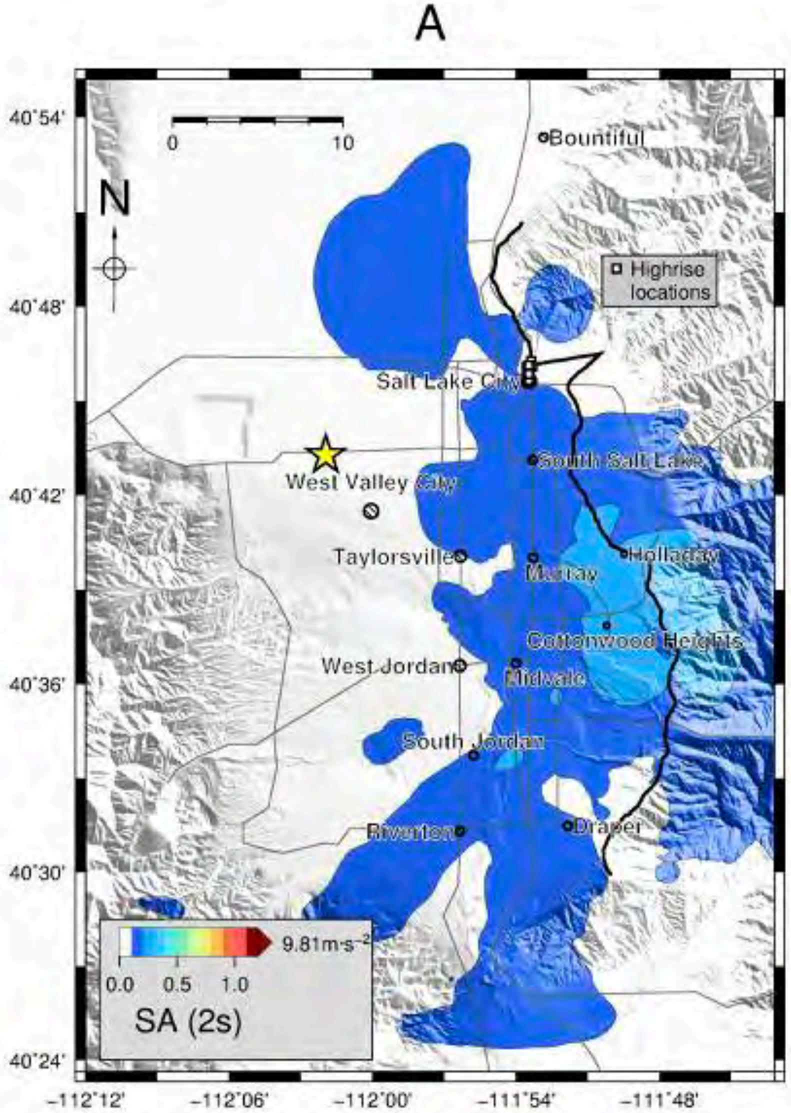
Bountiful
Highrise locations
Salt Lake City
South Salt Lake
West Valley City
Taylorsville
Murray
Holladay
Cottonwood Heights
West Jordan
Midvale
South Jordan
Riverton
Draper
9.81m·s⁻²
0.0 0.5 1.0
SA (2s)
40°54'
40°48'
40°42'
40°36'
40°30'
40°24'
-112°12'
-112°06'
-112°00'
-111°54'
-111°48'

1D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Highrise locations
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40°24'
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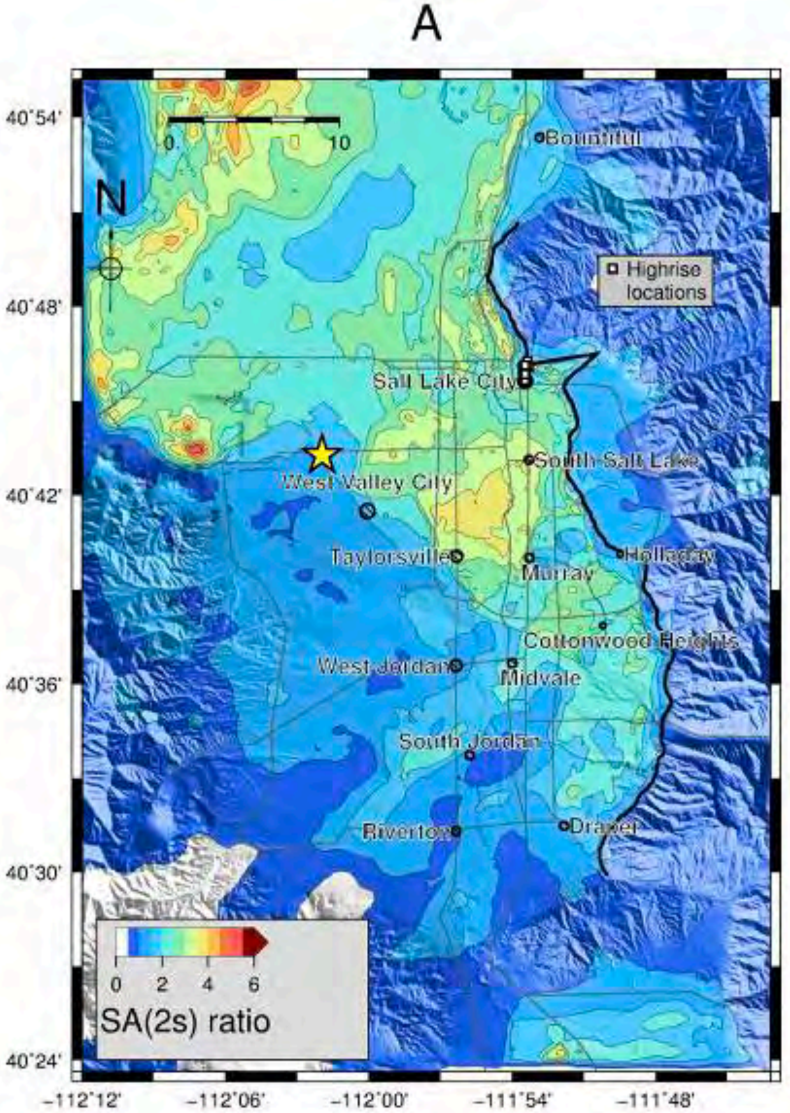
-112°00'
-111°54'
-111°48'

3D/1D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Bountiful
Highrise locations
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Draper
0 2 4 6
SA(2s) ratio
40°54'
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40°36'
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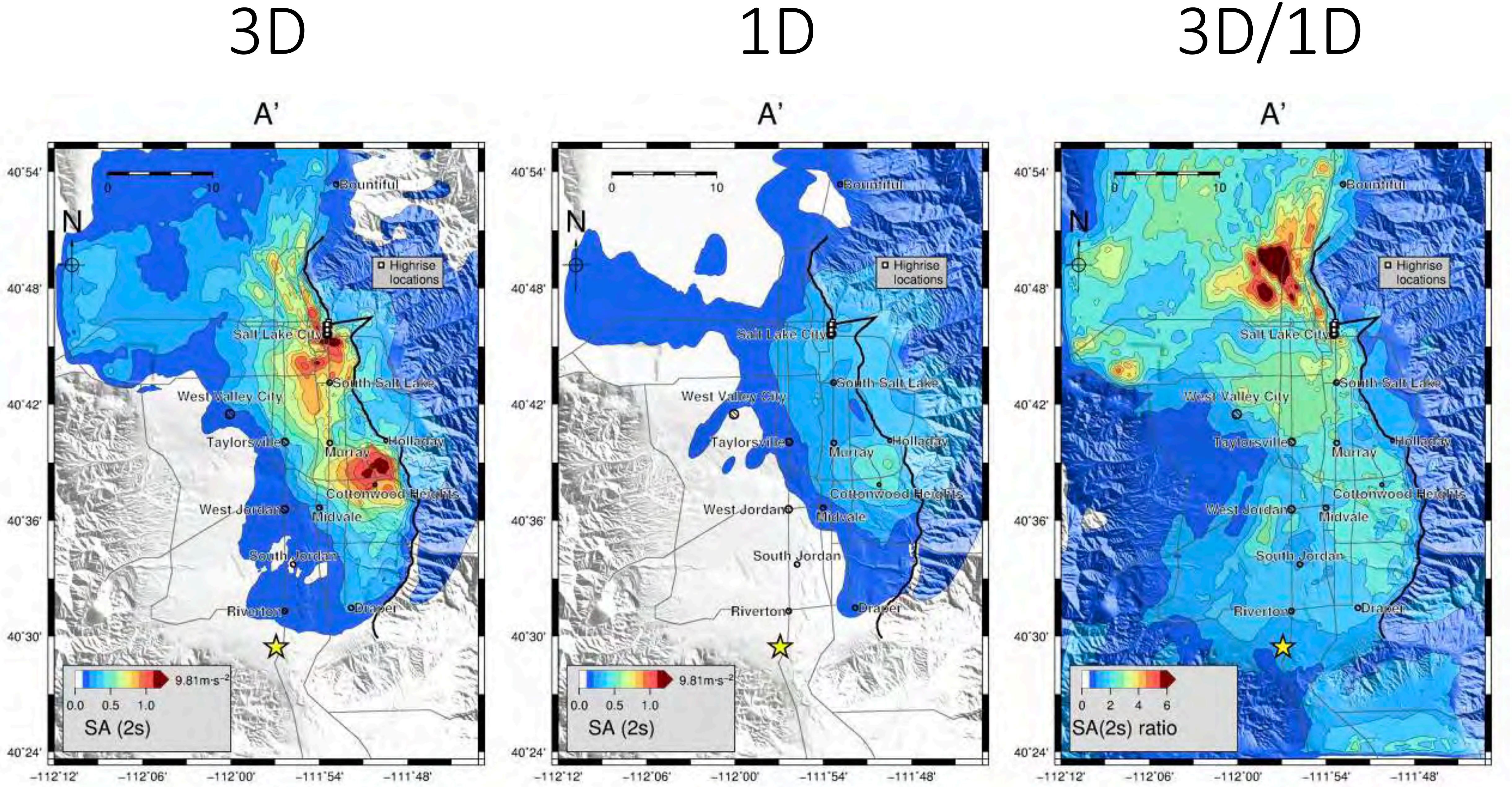
-112°00'
-111°54'
-111°48'


3D
1D
3D/1D
A'
A'
A'
Bountiful
Highrise locations
Salt Lake City
South Salt Lake
West Valley City
Taylorsville
Murray
Holladay
Cottonwood Heights
West Jordan
Midvale
South Jordan
Riverton
Draper
0
10
N
9.81m·s⁻²
0.0 0.5 1.0
SA (2s)
0 2 4 6
SA(2s) ratio
40°54'
40°48'
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40°36'
40°30'
40°24'
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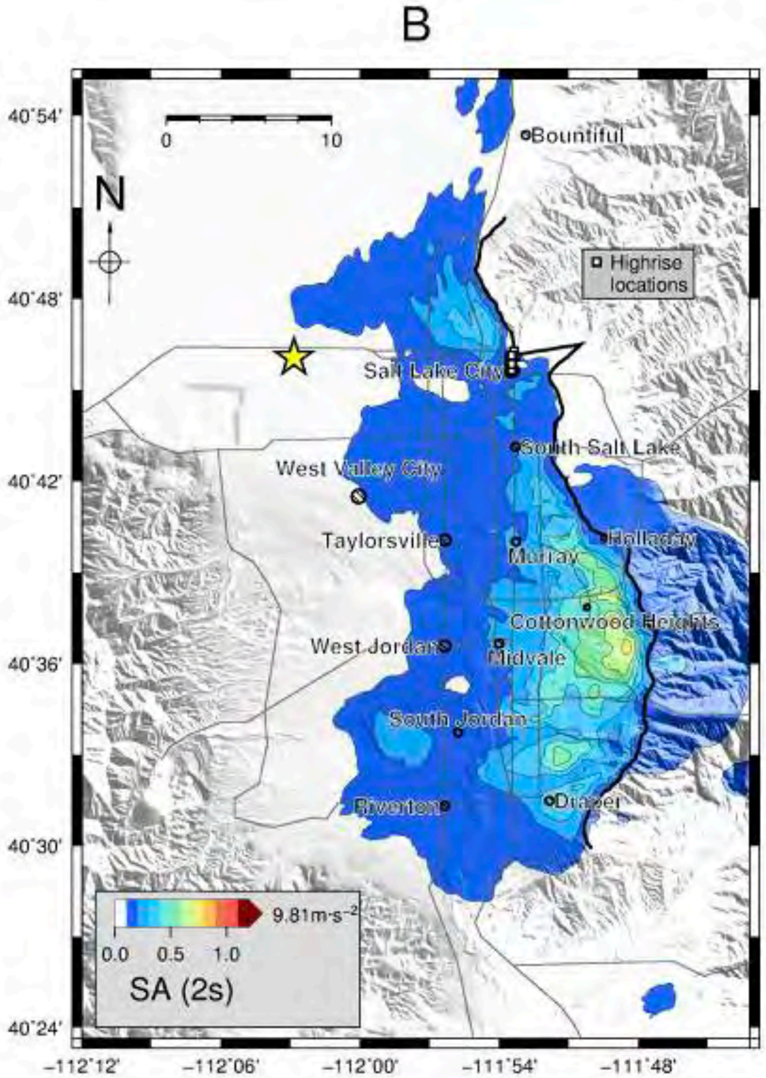
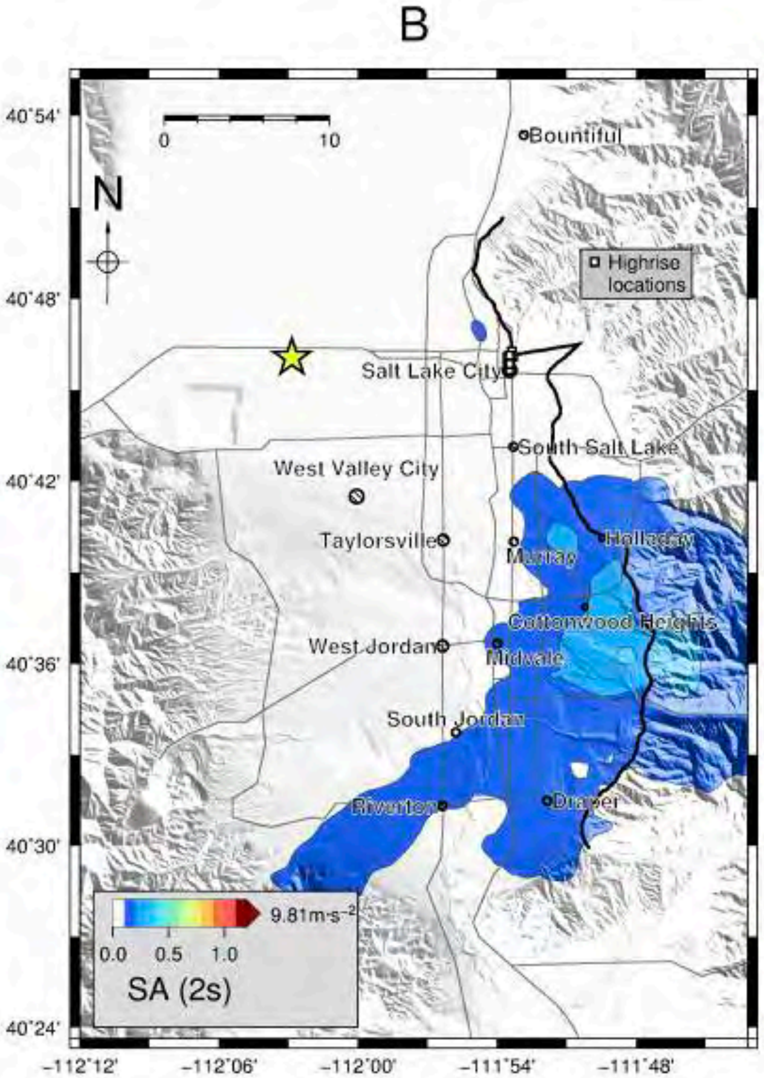
-112°06'
-112°00'
-111°54'
-111°48'

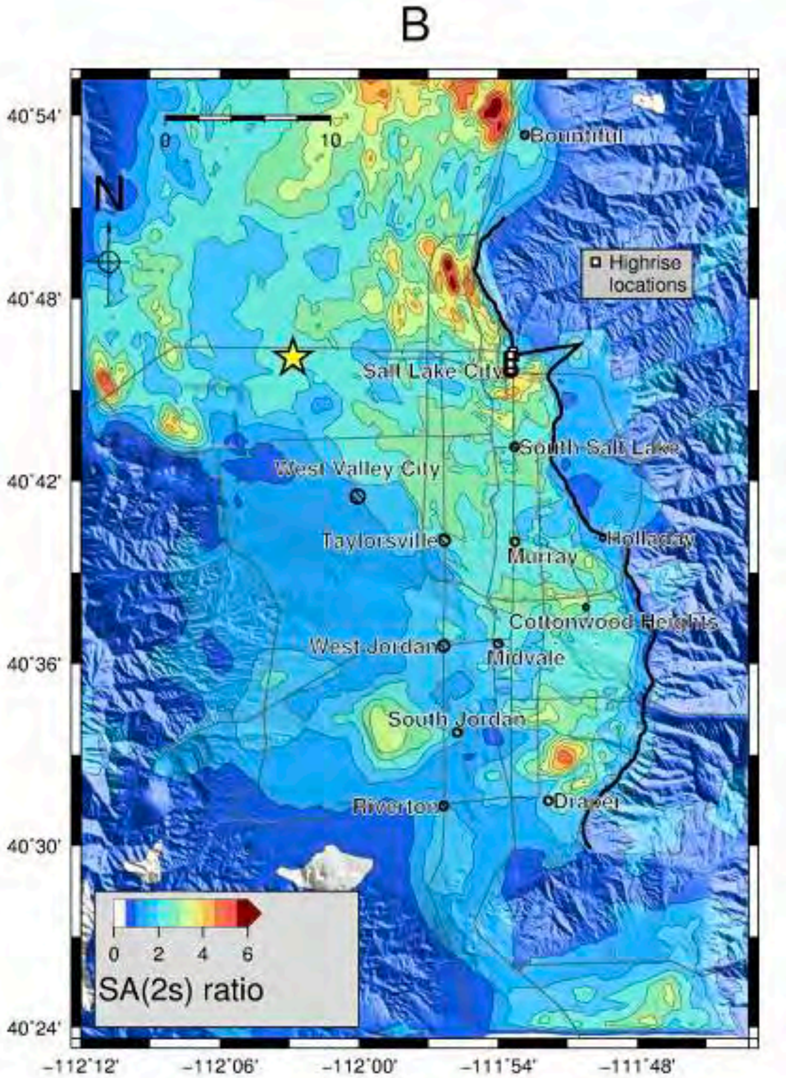
3D


B
Bountiful
Highrise locations
Salt Lake City
South Salt Lake
West Valley City
Taylorsville
Murray
Holladay
Cottonwood Heights
West Jordan
Midvale
South Jordan
Riverton
Draper
9.81m·s⁻²
0.0 0.5 1.0
SA (2s)

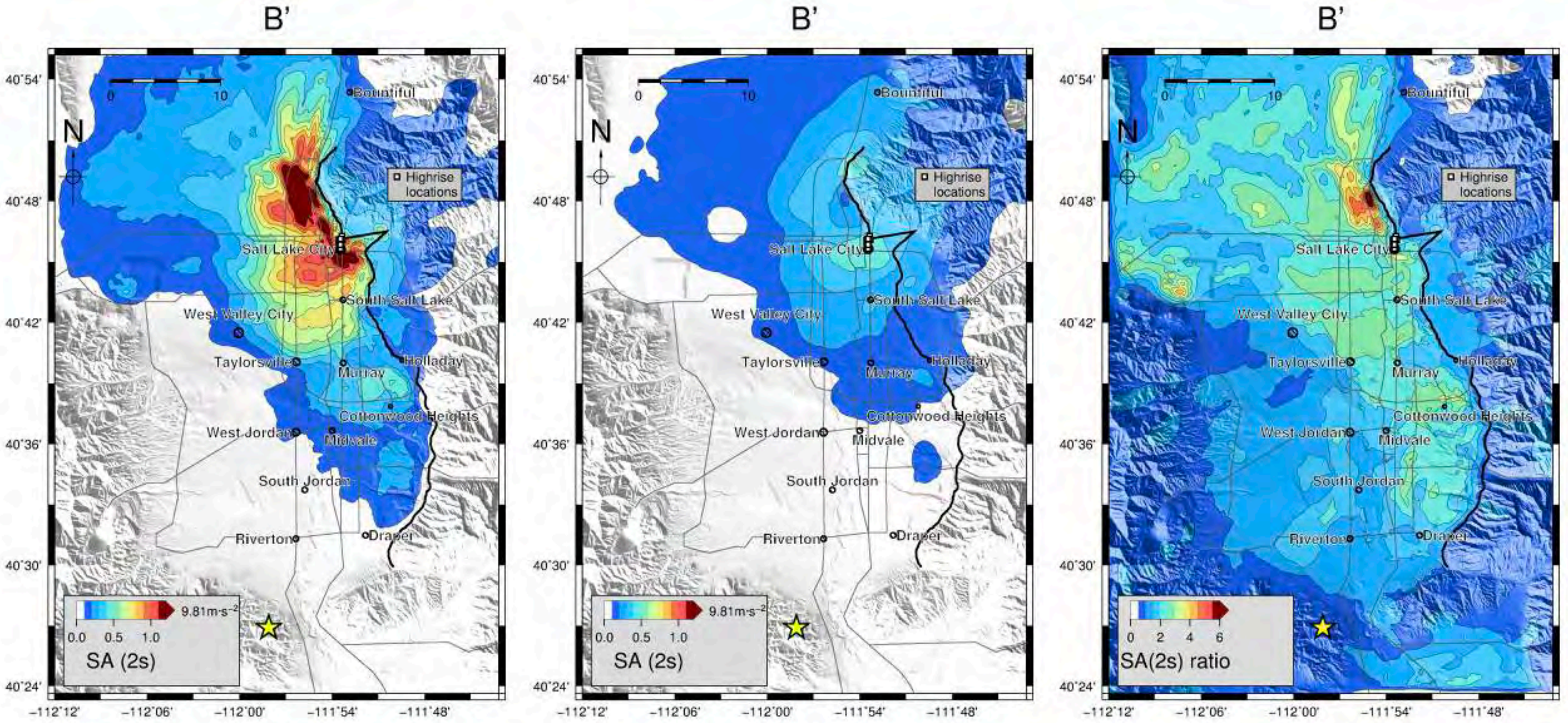
1D


B
Bountiful
Highrise locations
Salt Lake City
South Salt Lake
West Valley City
Taylorsville
Murray
Holladay
Cottonwood Heights
West Jordan
Midvale
South Jordan
Riverton
Draper
9.81m·s⁻²
0.0 0.5 1.0
SA (2s)

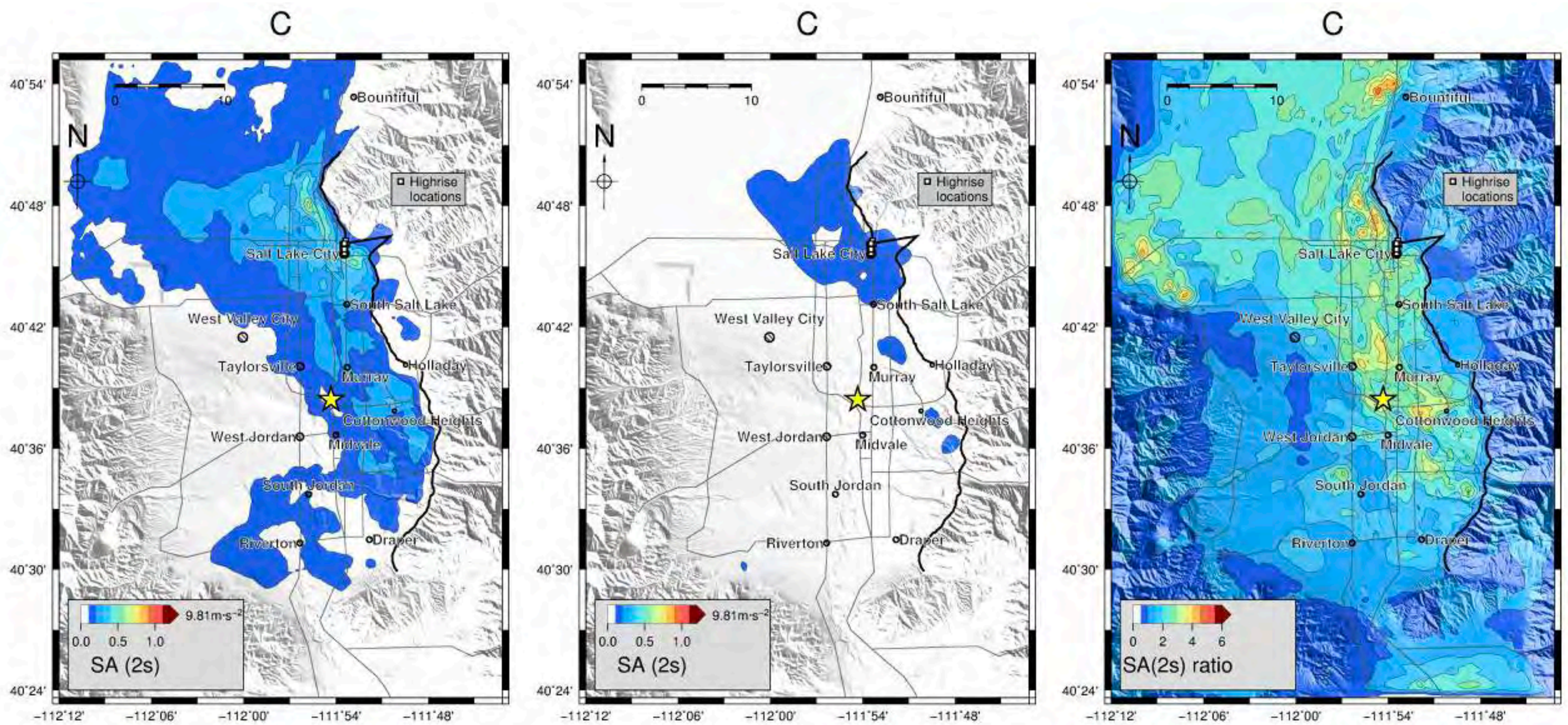
3D/1D


B
Bountiful
Highrise locations
Salt Lake City
South Salt Lake
West Valley City
Taylorsville
Murray
Holladay
Cottonwood Heights
West Jordan
Midvale
South Jordan
Riverton
Draper
0 2 4 6
SA(2s) ratio

3D 1D 3D/1D


B'
B'
B'
Bountiful
Highrise locations
Salt Lake City
South Salt Lake
West Valley City
Taylorsville
Murray
Holladay
Cottonwood Heights
West Jordan
Midvale
South Jordan
Riverton
Draper
N
0
10
9.81m·s^{-2}
0.0 0.5 1.0
SA (2s)
0 2 4 6
SA(2s) ratio
40°54'
40°48'
40°42'
40°36'
40°30'
40°24'
−112°12'
−112°06'
−112°00'
−111°54'
−111°48'

3D 1D 3D/1D


3D
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3D/1D
C
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40°54'
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40°24'
-112°12'
-112°06'
-112°00'
-111°54'
-111°48'
0
10
N
Highrise locations
Bountiful
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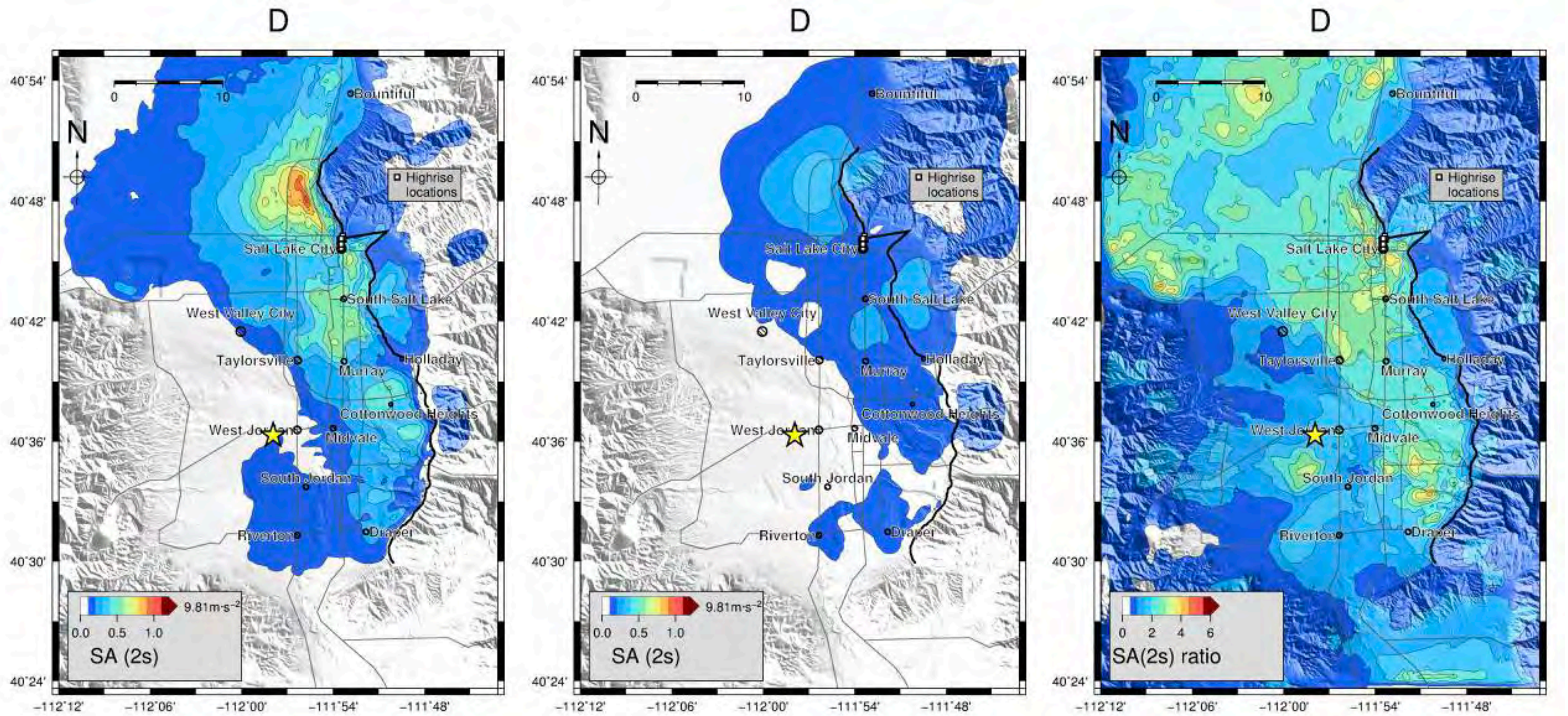
Midvale
South Jordan
Riverton
Draper
0.0 0.5 1.0
9.81m·s⁻²
SA (2s)
0 2 4 6
SA(2s) ratio

3D 1D 3D/1D


D
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Highrise locations
Bountiful
Salt Lake City
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West Valley City
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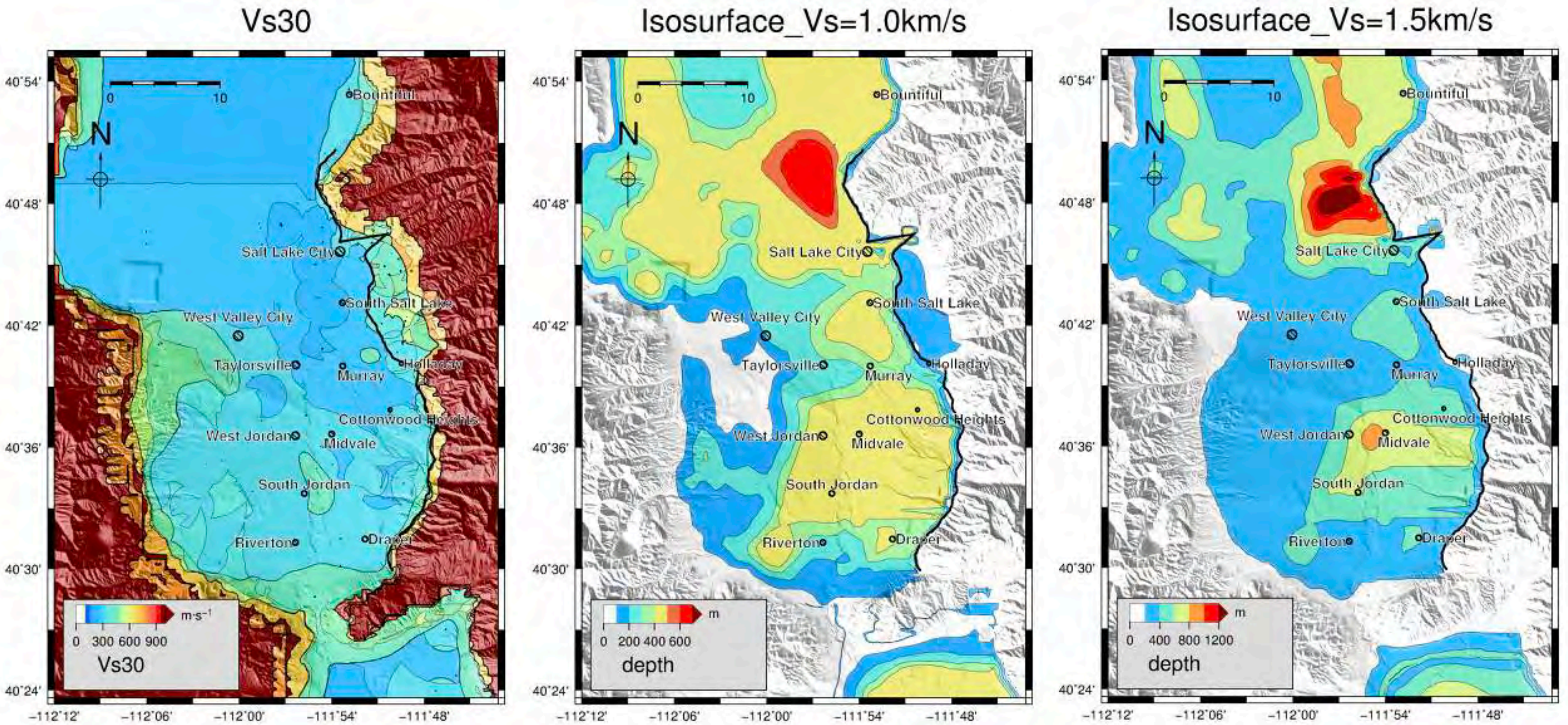
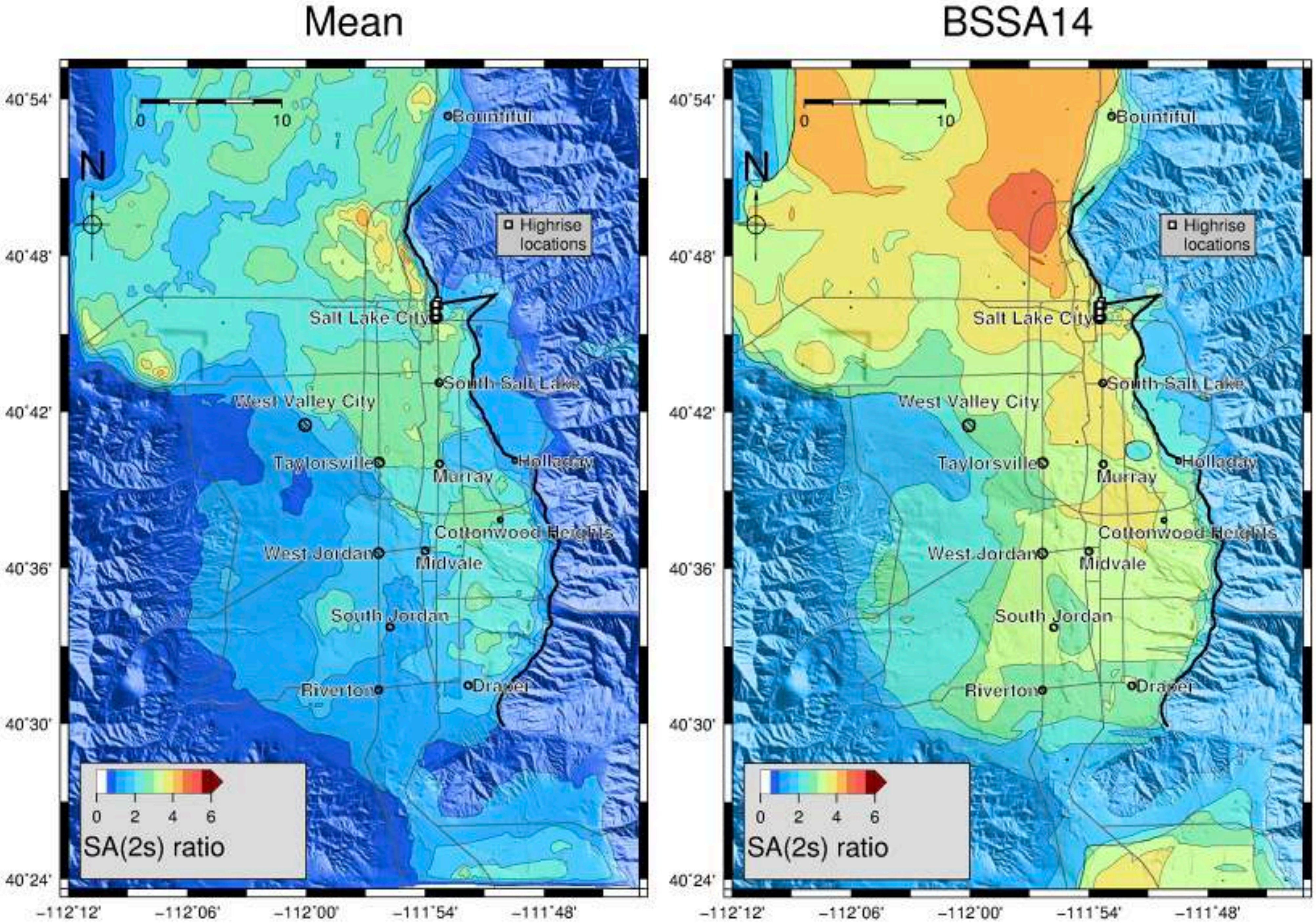
-111°48'

Basin Parameters



Comparison of mean 3D/1D amplification from simulations to BSSA14



Regression for Basin Amplification

$$W_{nj} = \begin{cases} 1, & if\ (D_n^{bin} - \Delta D/2) \ \le D_j \le (D_n^{bin} + \Delta D/2) \\ 0, & otherwise \end{cases}$$

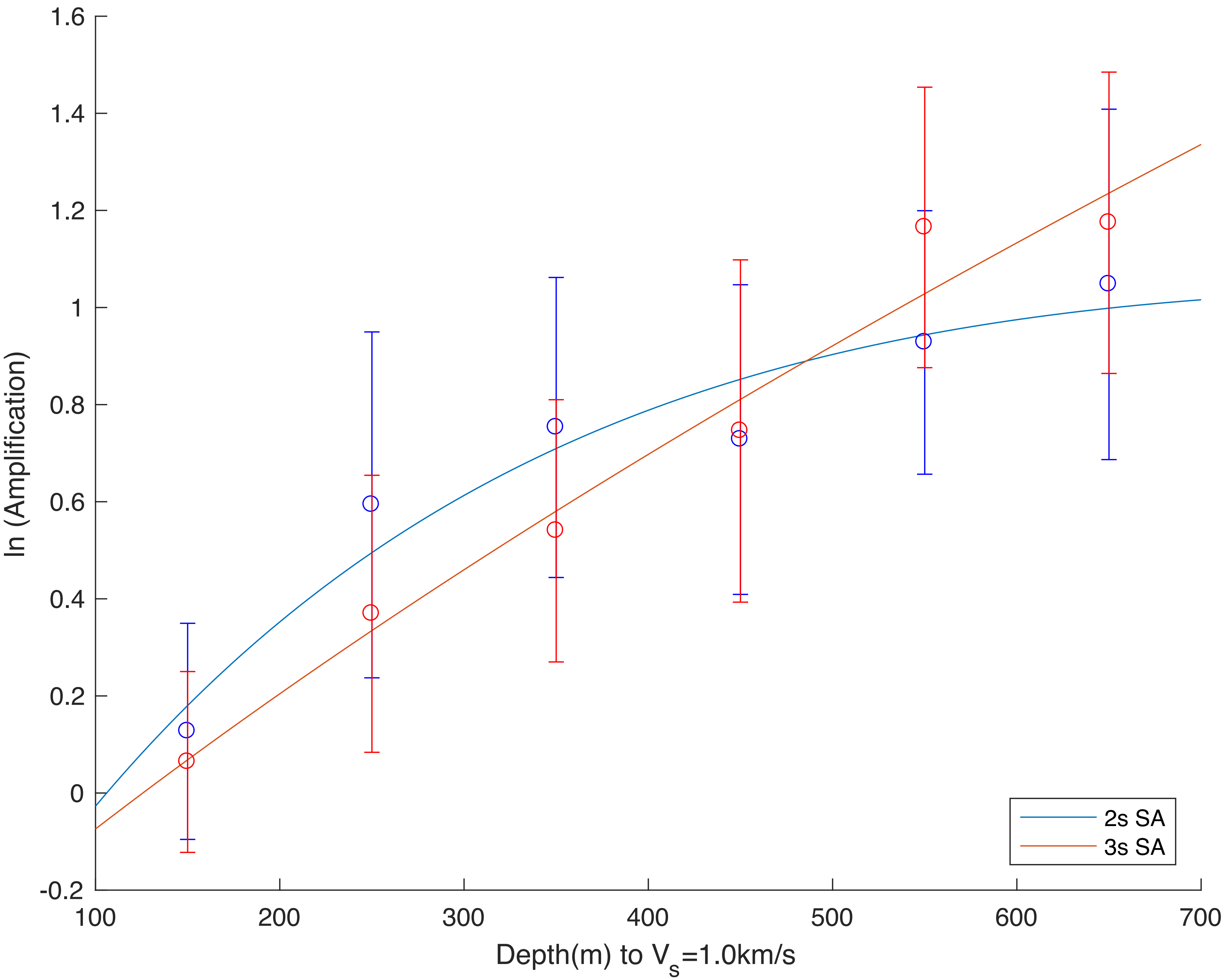
$$B(D_n, T_m) = \left(N_{sn} \sum_{j=1}^{N_{site}} W_{nj} \right)^{-1} \sum_{i=1}^{N_{sn}} \sum_{j=1}^{N_{site}} W_{nj} \ln \left[SA_{ij}^{3d}(T_m) / SA_{ij}^{1d}(T_m) \right]$$

$$A(D,T) = a_0(T) + a_1(T)[1 - \exp(-D/300)] + a_2(T)[1 - \exp(-D/4000)]$$

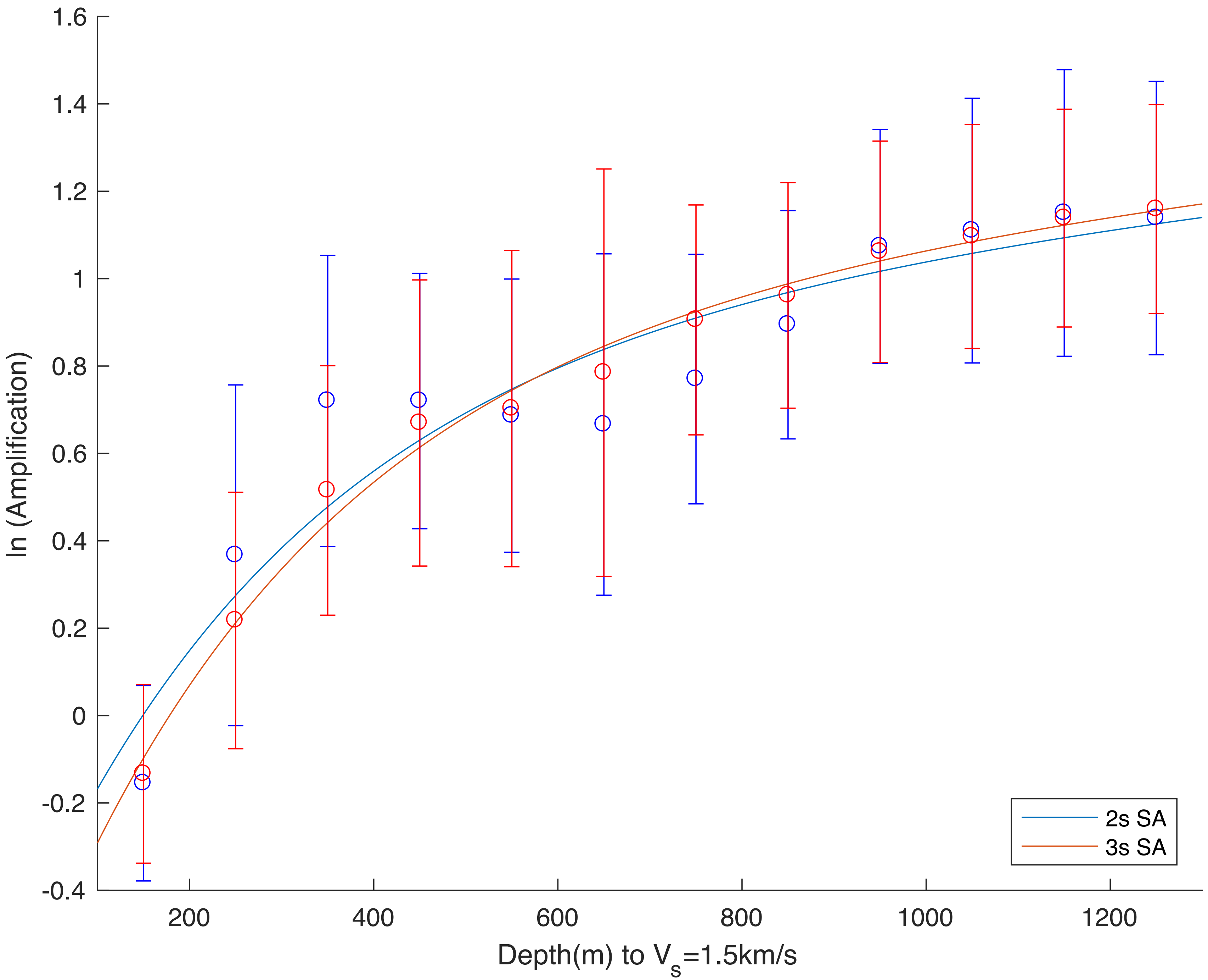
where

$$a_i(T) = b_i + c_i T, \qquad i = 0,1,2$$

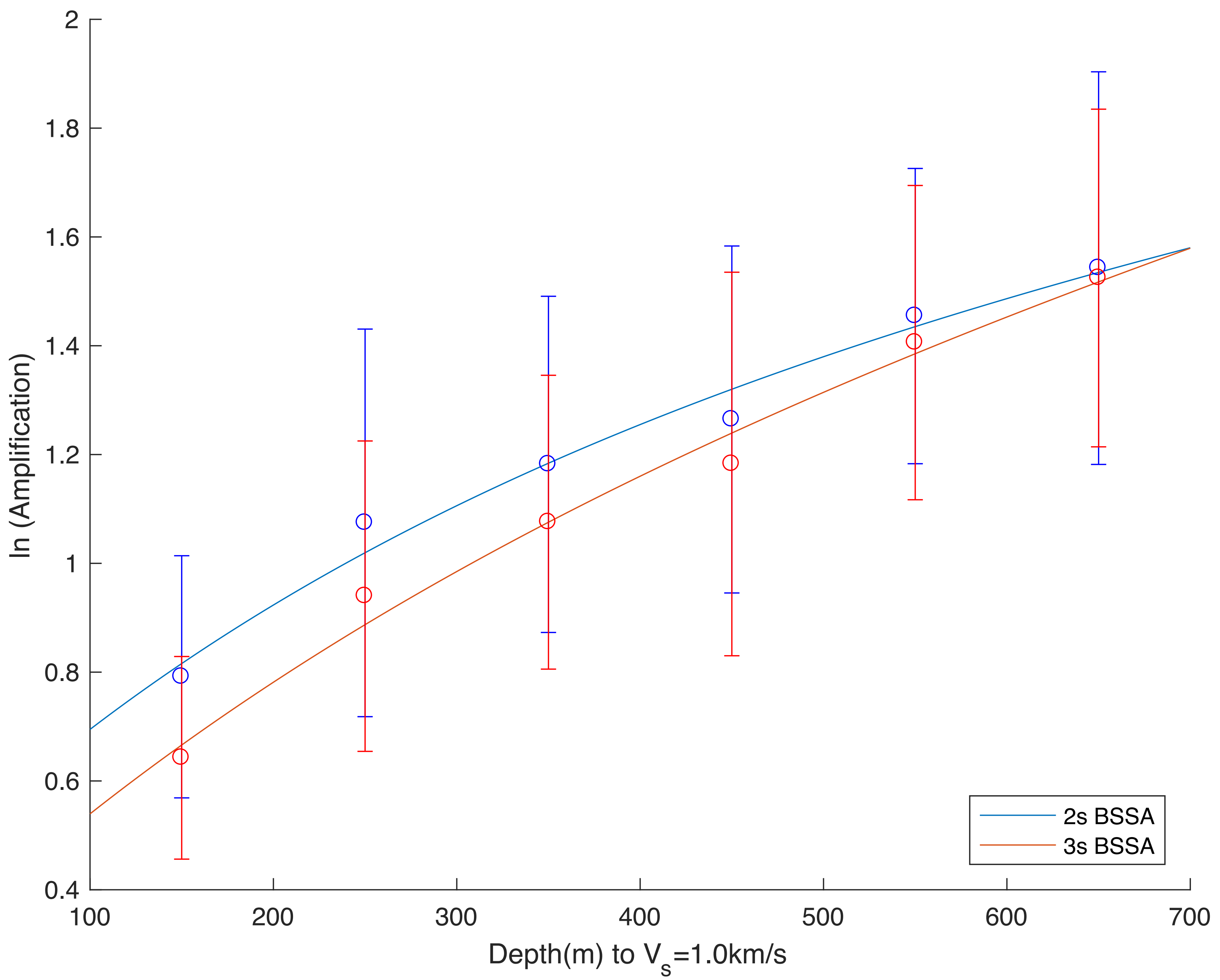
Natural log amplification factors as a function of depth



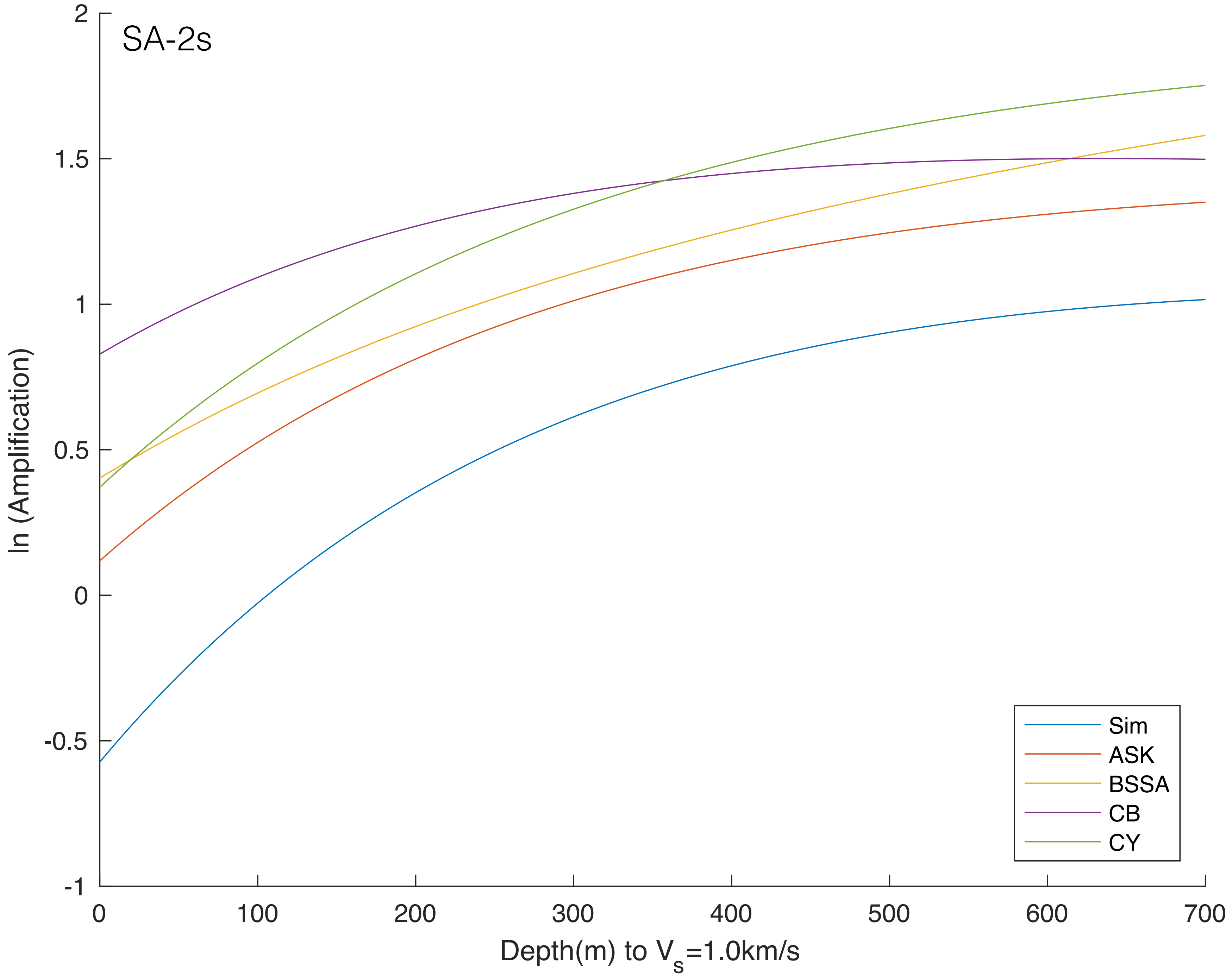
Natural log amplification factors as a function of depth



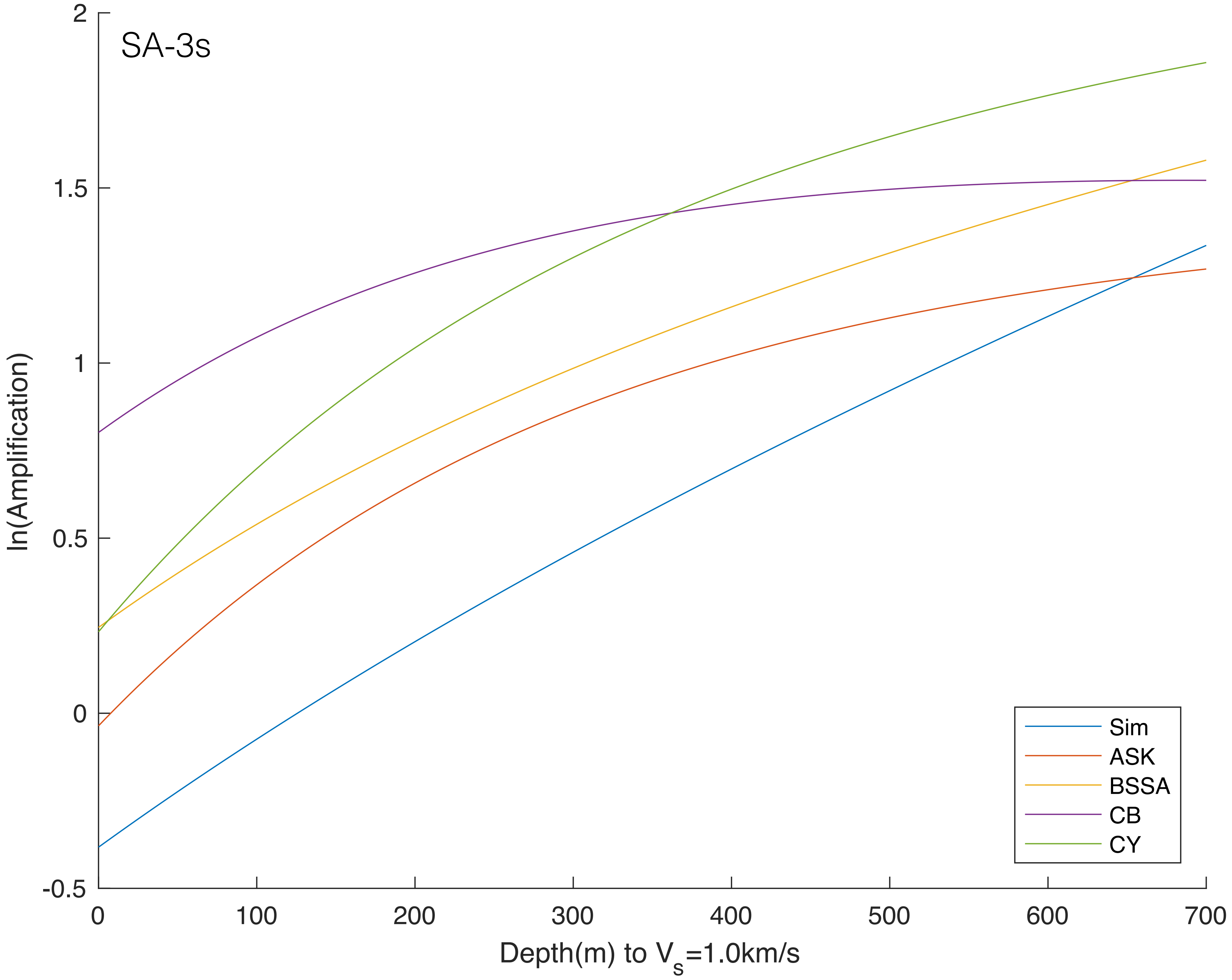
Natural log amplification factors as a function of depth.



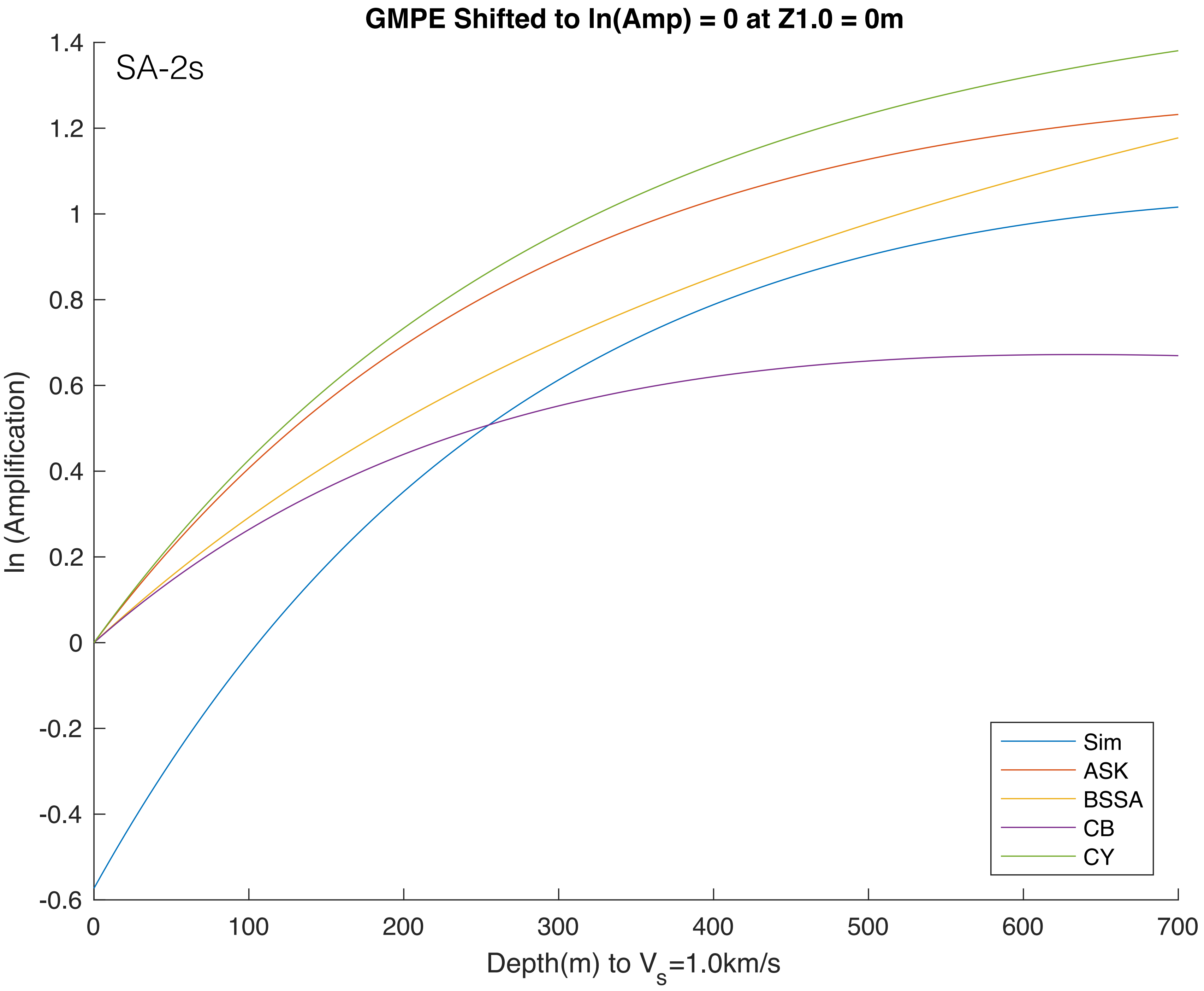
Comparison of the basin depth amplification factors regression results for 2s period from the GMPEs to the regression results for the simulations.



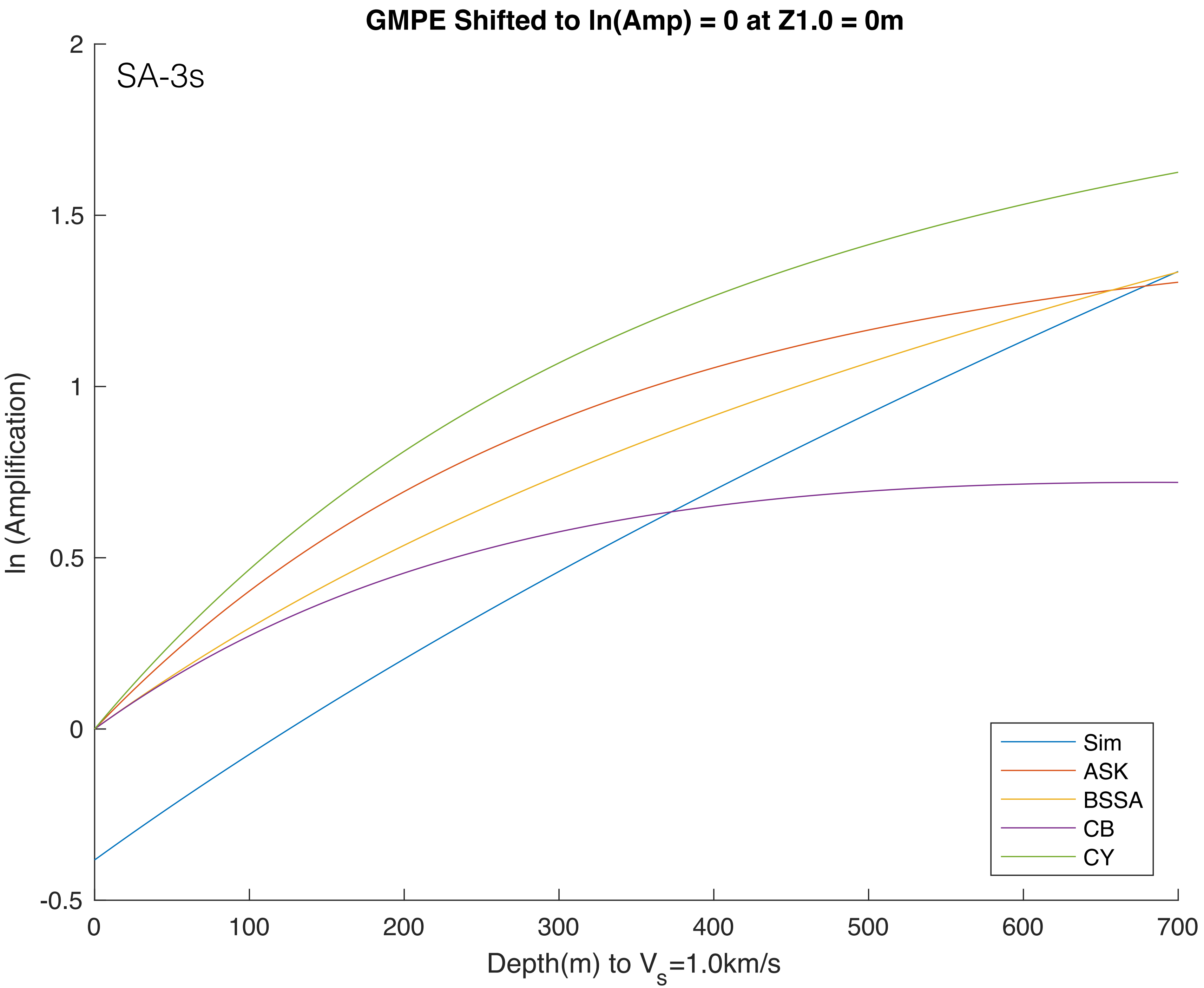
Comparison of the basin depth amplification factors regression results for 3s period from the GMPEs to the regression results for the simulations.



Comparison of the regression results for the basin depth amplification factors at a period of 2s from the GMPEs to the results of the simulations. The GMPEs' regression curves are shifted to ln(Amp)=0 at a depth to the Vs=1.0 km/s isosurface of 0 m.

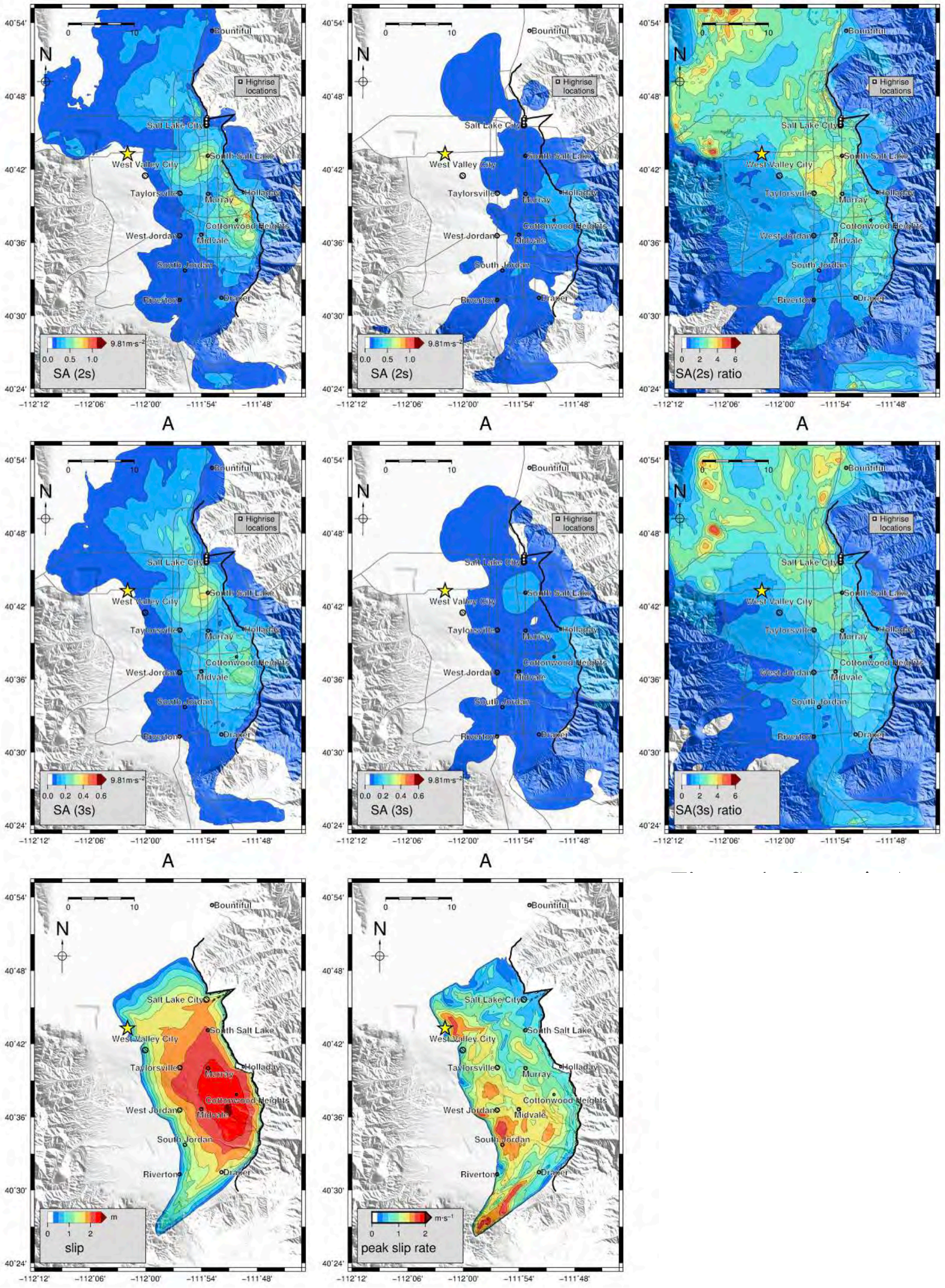


Comparison of the regression results for the basin depth amplification factors at a period of 2s from the GMPEs to the results of the simulations. The GMPEs' regression curves are shifted to ln(Amp)=0 at a depth to the Vs=1.0 km/s isosurface of 0m.

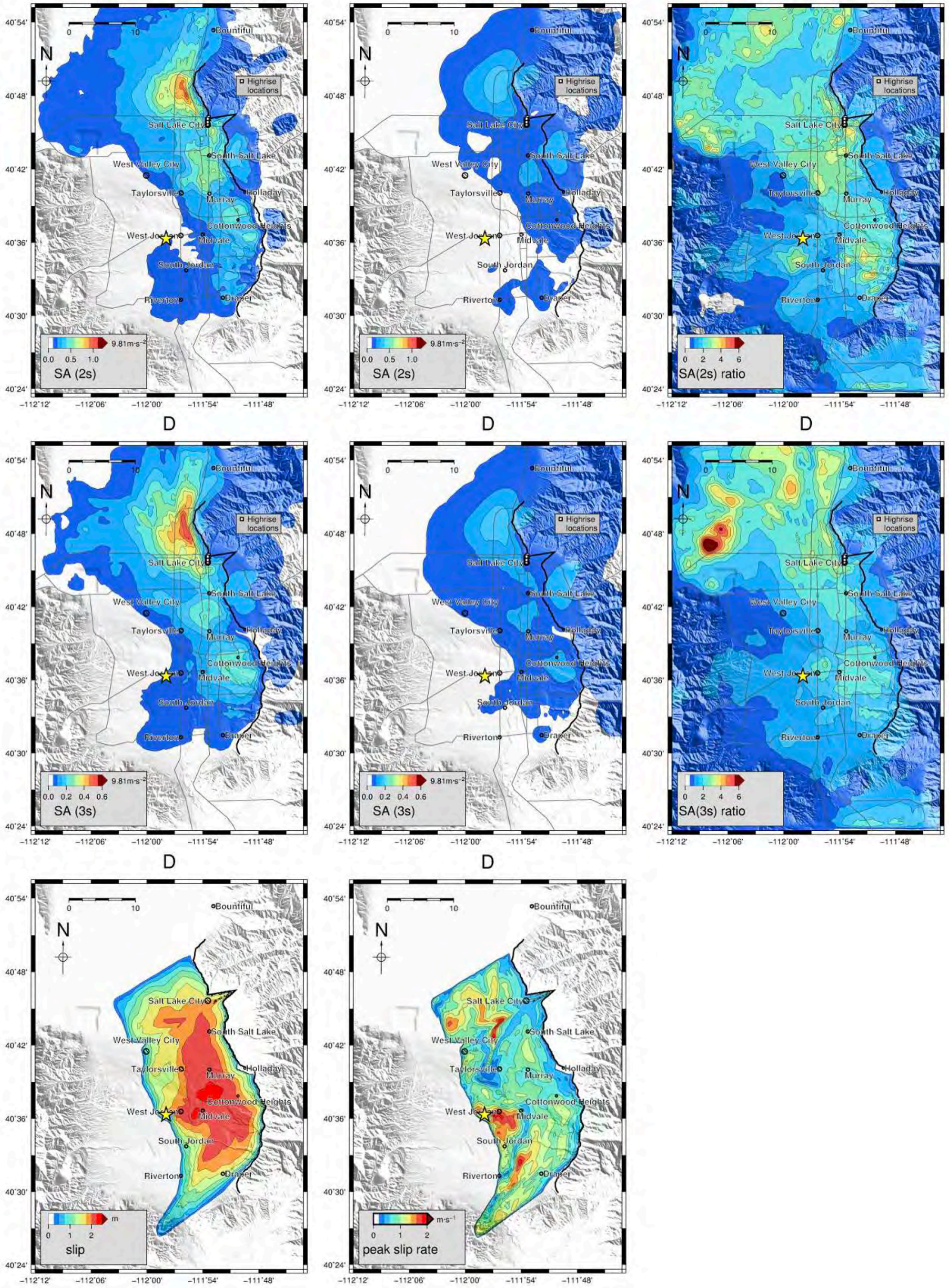


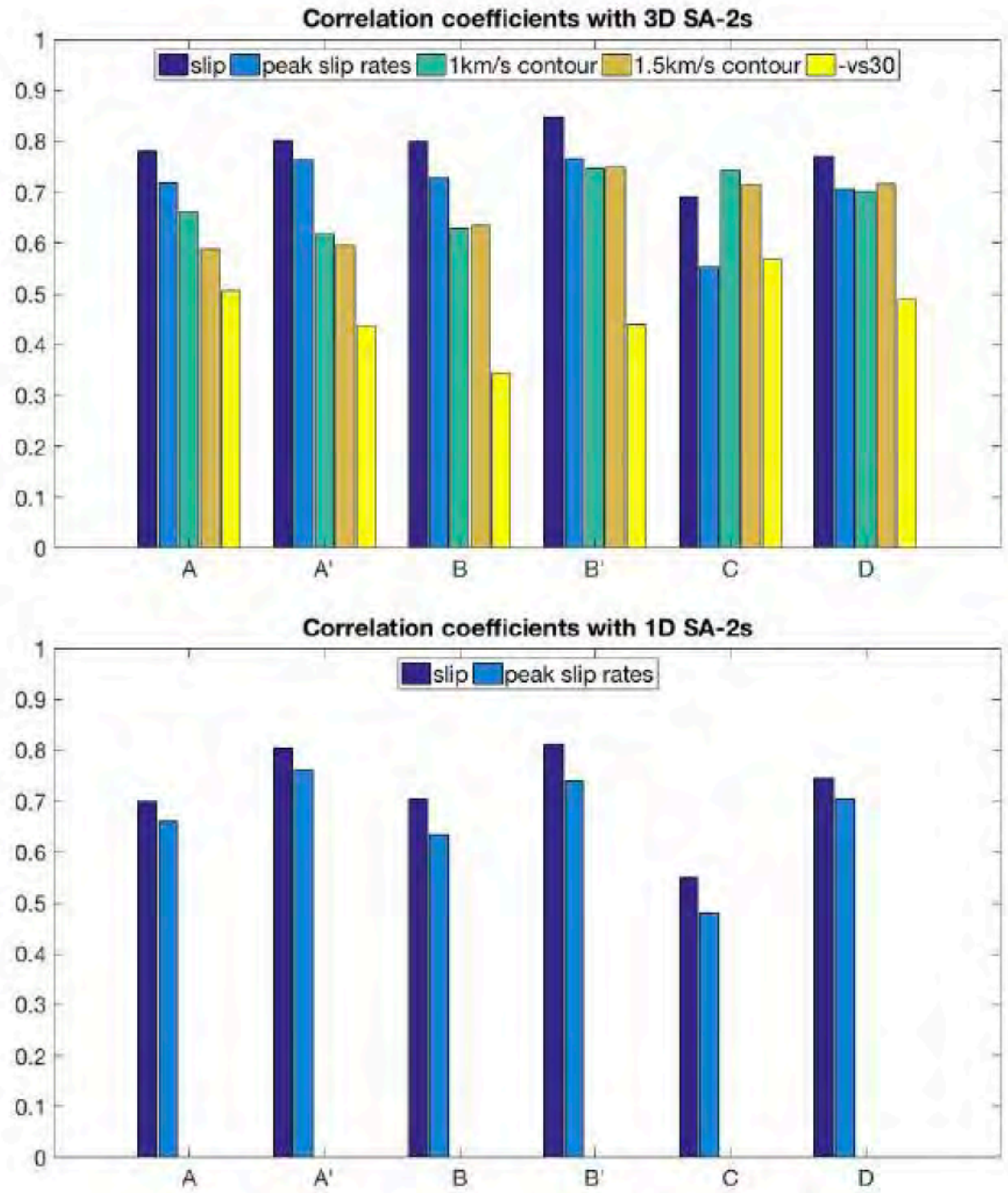
Correlation of SAs with source parameters

Correlation with slip and peak slip rate



Correlation with slip and peak slip rate

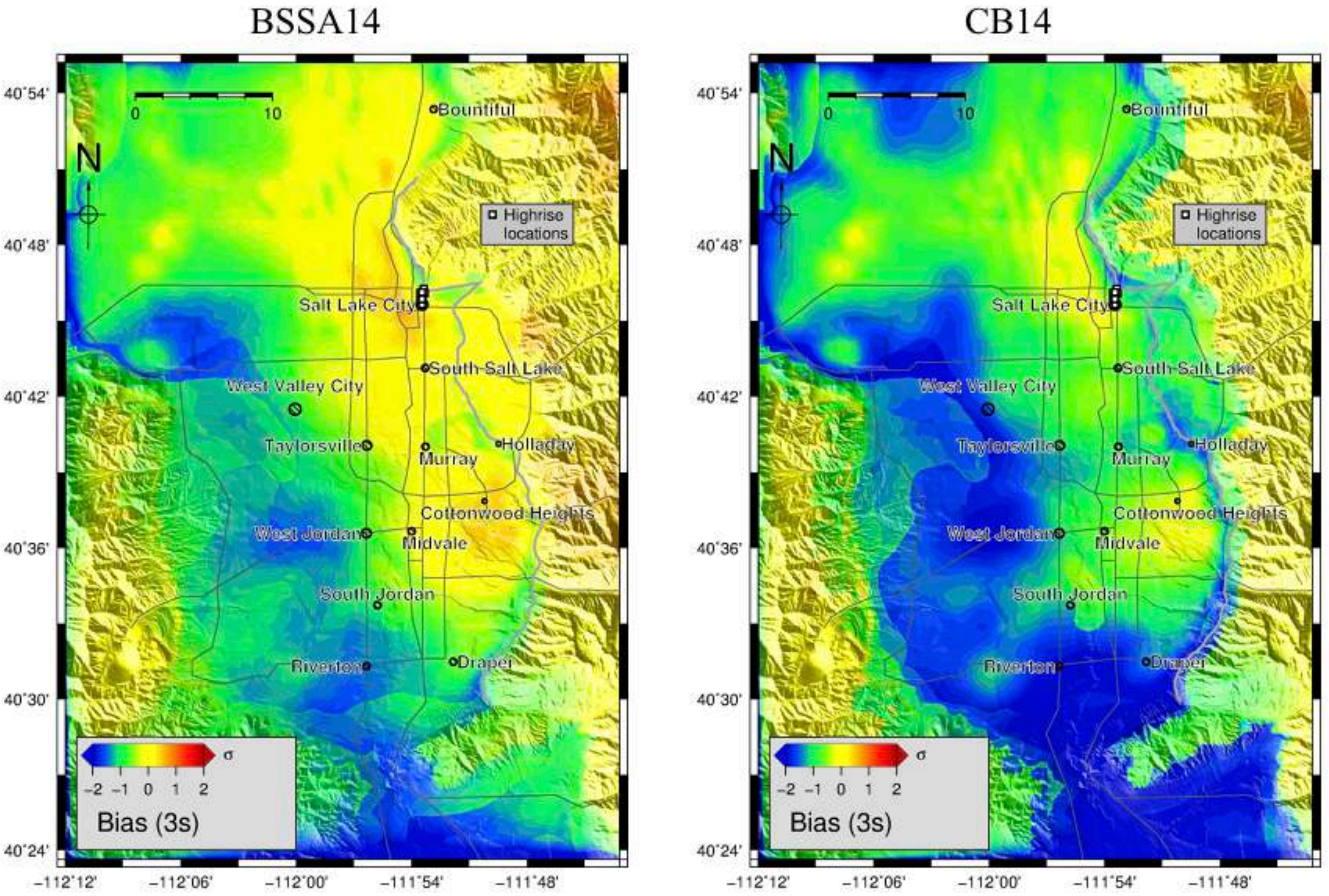




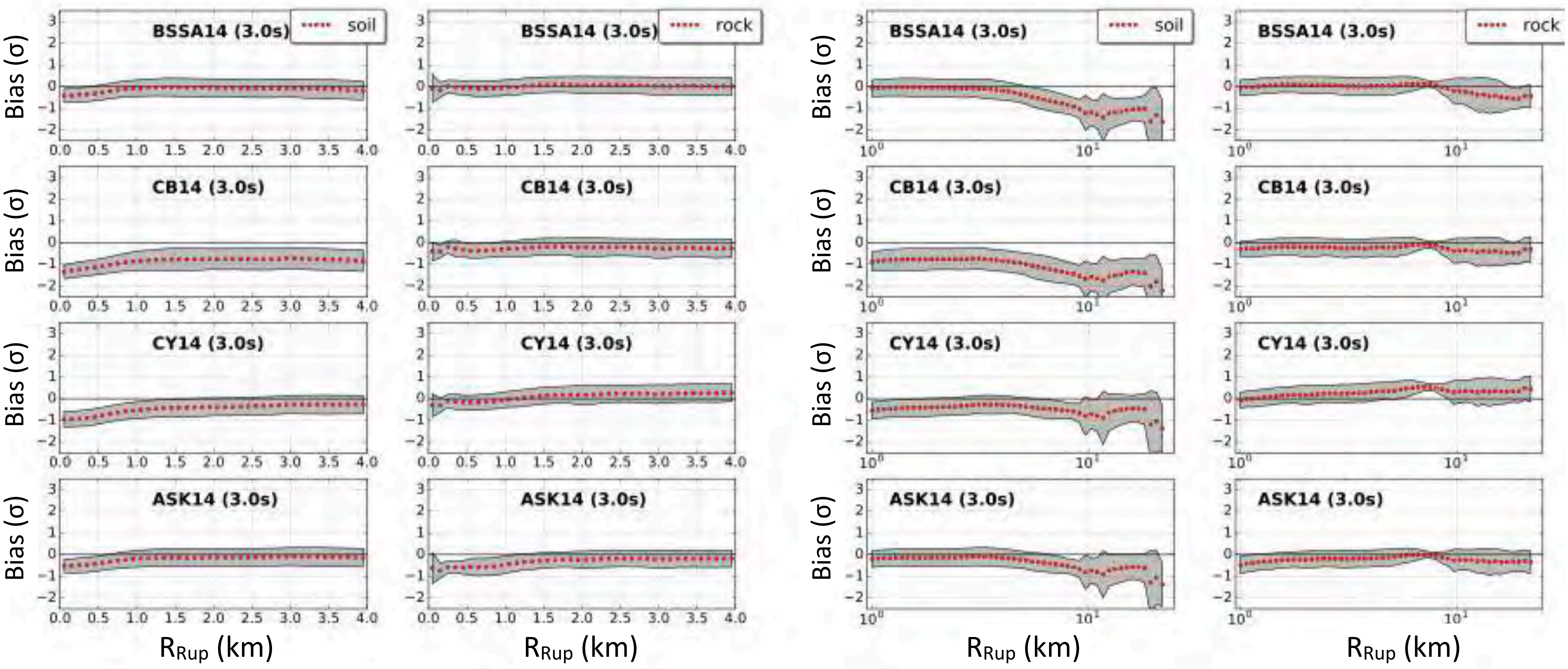
Correlation coefficients with 3D SA-2s
slip
peak slip rates
1km/s contour
1.5km/s contour
-vs30
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
A
A'
B
B'
C
D
Correlation coefficients with 1D SA-2s
slip
peak slip rates
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
A
A'
B
B'
C
D

Distance Dependence for Ground Motion

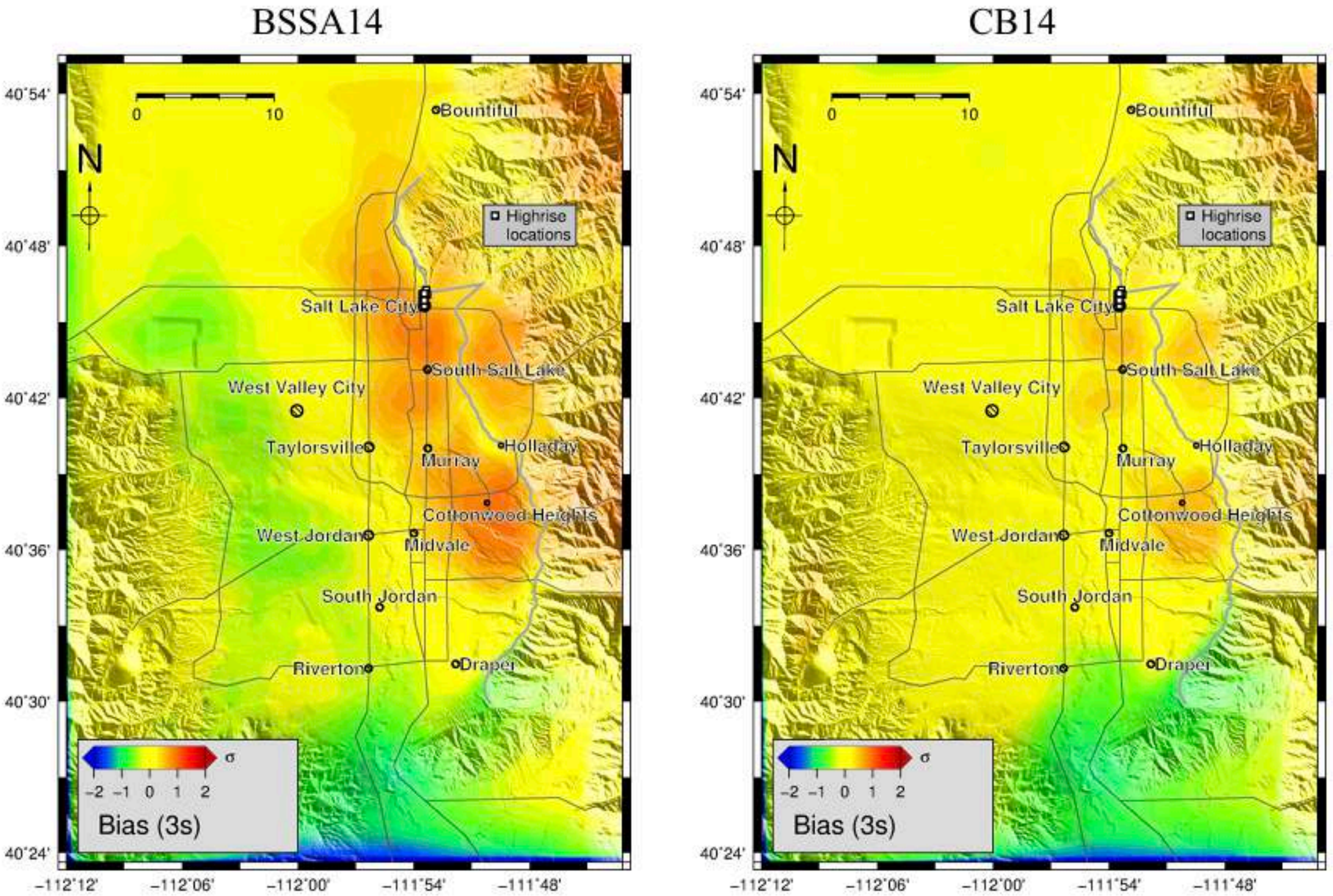
Bias between the ensemble of SA-3s(3D) and (left) BSSA14 and (right) CB14.



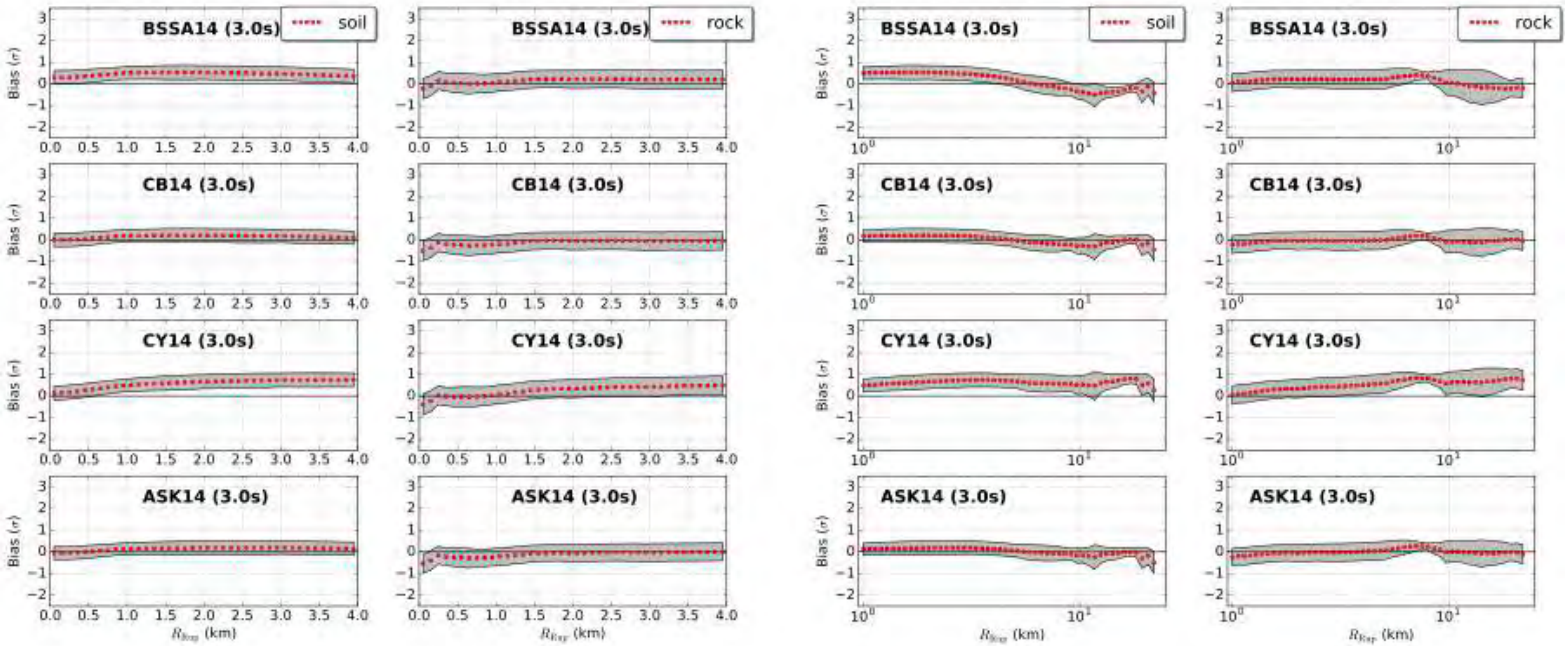
Bias between the 6-scenario ensemble of SA-3s(1D) and four leading NGAWest2 GMPEs for soil sites (Vs30 < 750m/s) and rock sites (Vs30 > 750 m/s).



Bias between the ensemble of SA-3s(1D) and (left) BSSA14 and (right) CB14.



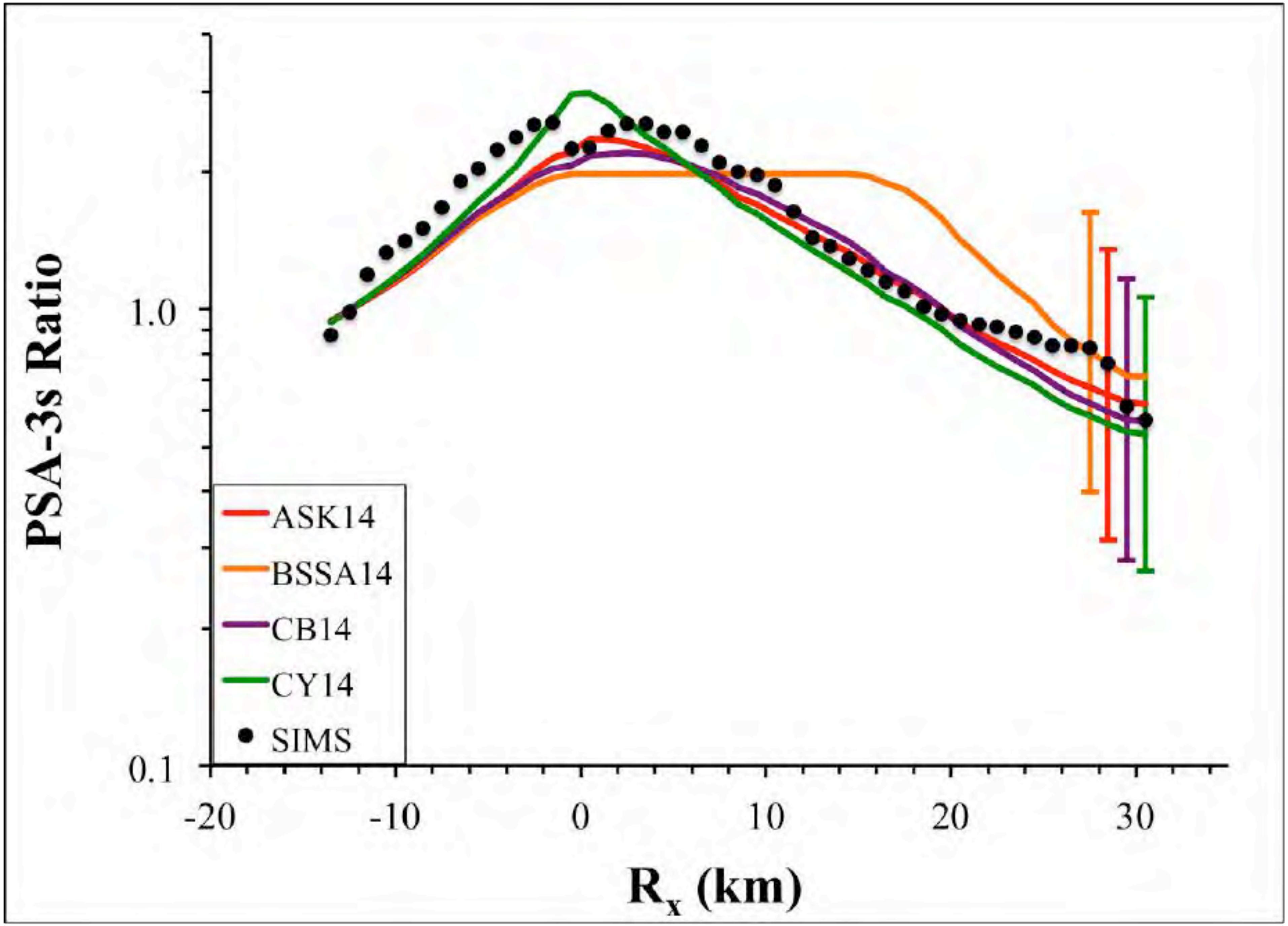
Bias between the 6-scenario ensemble of SA-3s(1D) and NGAWest2 GMPEs for soil sites (Vs30 < 750m/s) and rock sites (Vs30 > 750 m/s).



Hanging Wall Effects

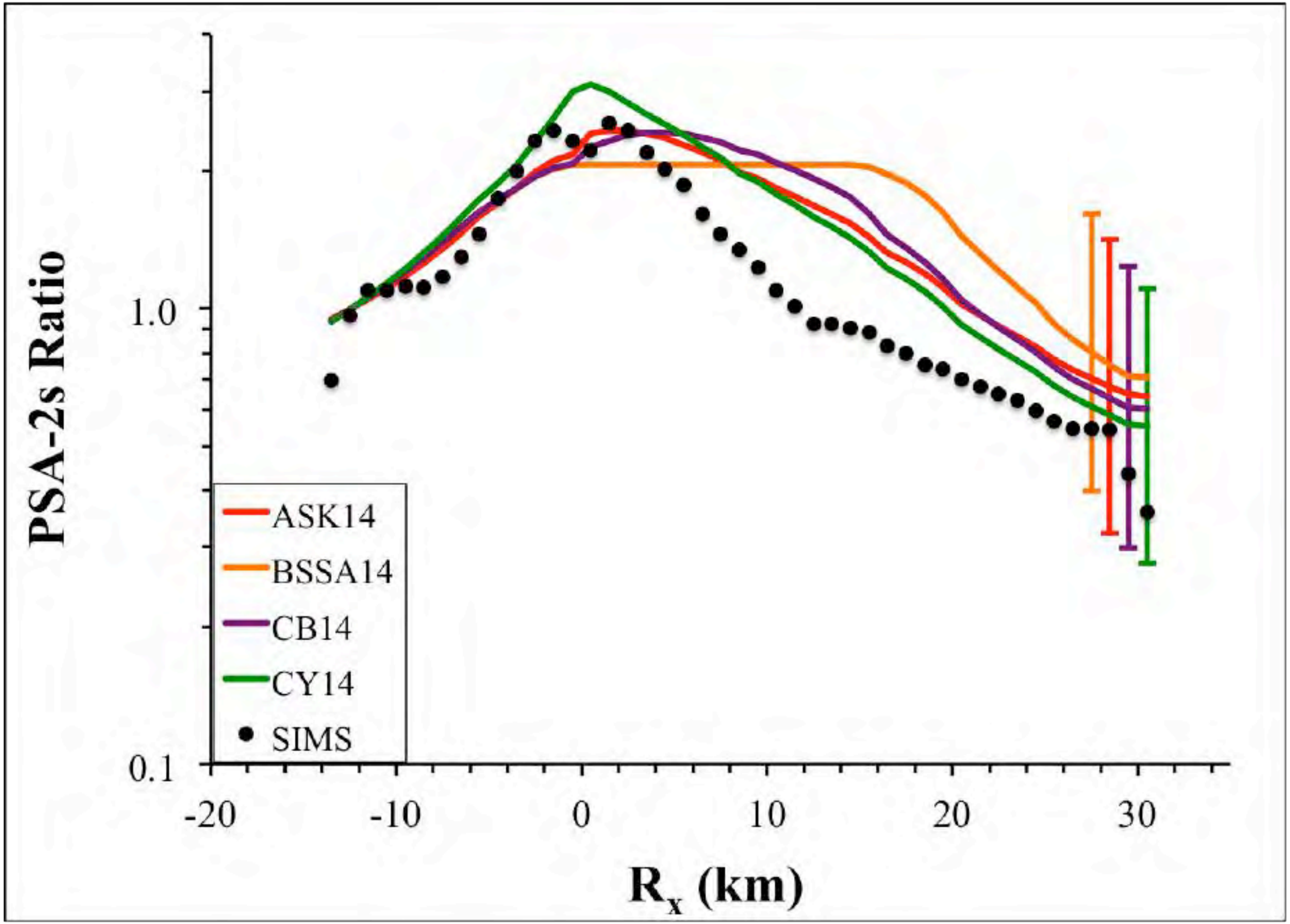
Hanging-wall Effects

SA-3s



Hanging-wall Effects

SA-2s

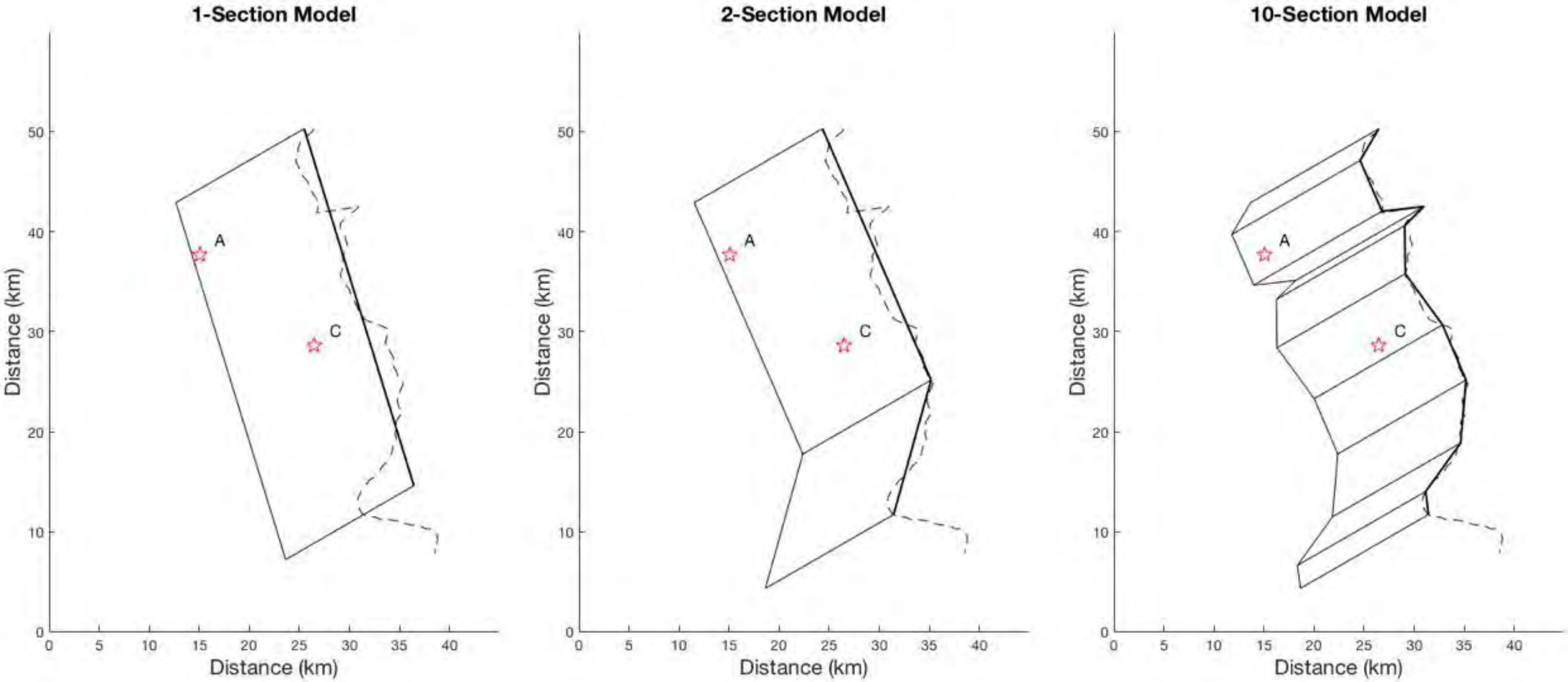


Directivity

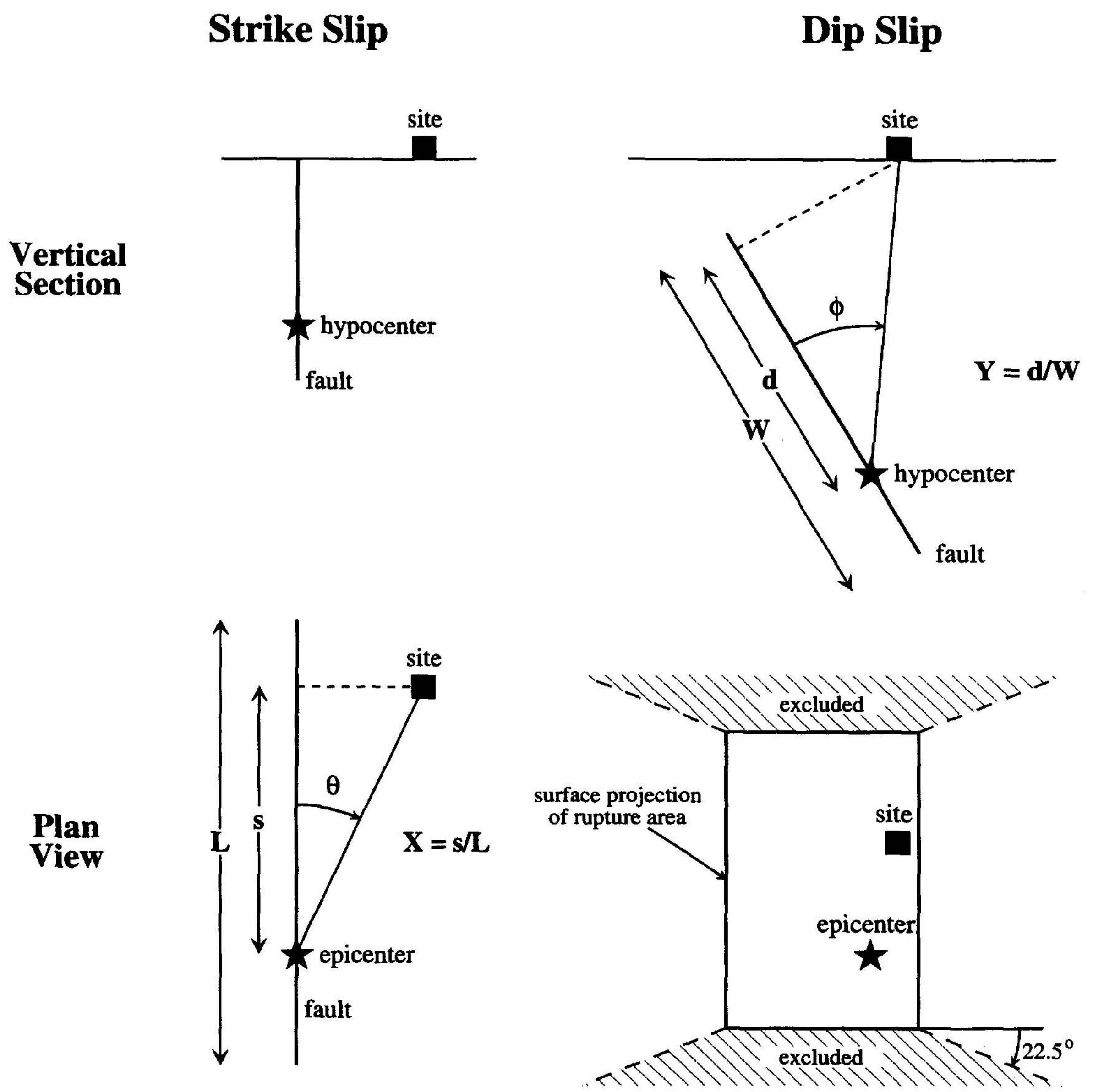
Bayless and Somerville (2013) Multi-Segment Directivity Approach

$$f_D = f_D(d, R_x, W, R_{rup}, M_w, A_z, T) = [C_0(T) + C_1(T)\ \ln(d)\ \cos(R_x/W)]\ T_{CD}(R_{rup}, W)\ T_{Mw}(M_w)\ T_{Az}(A_z),$$

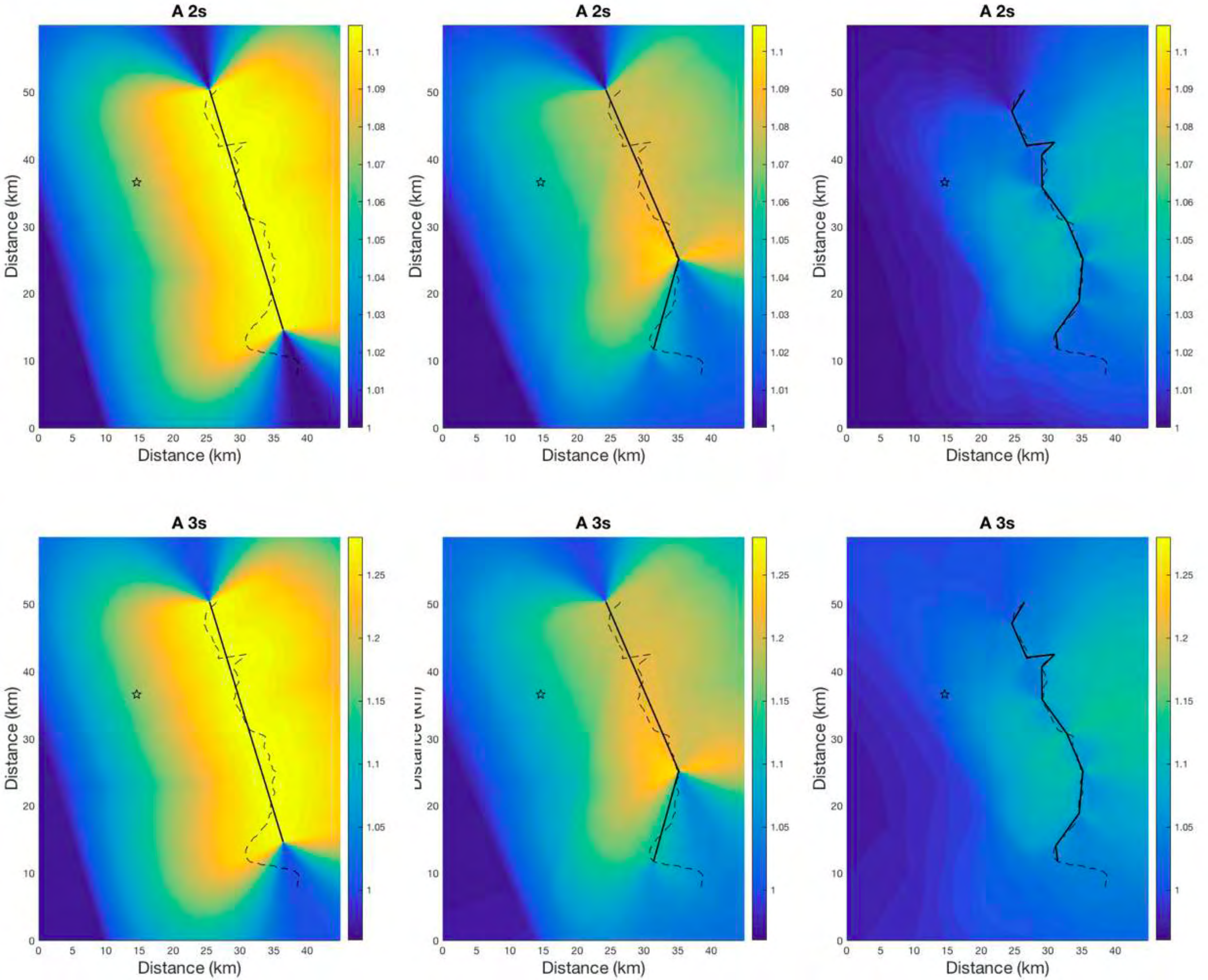
Surface projections of WFSLC approximation models used in the calculation of directivity factors with the Bayless et al. (2013) model.



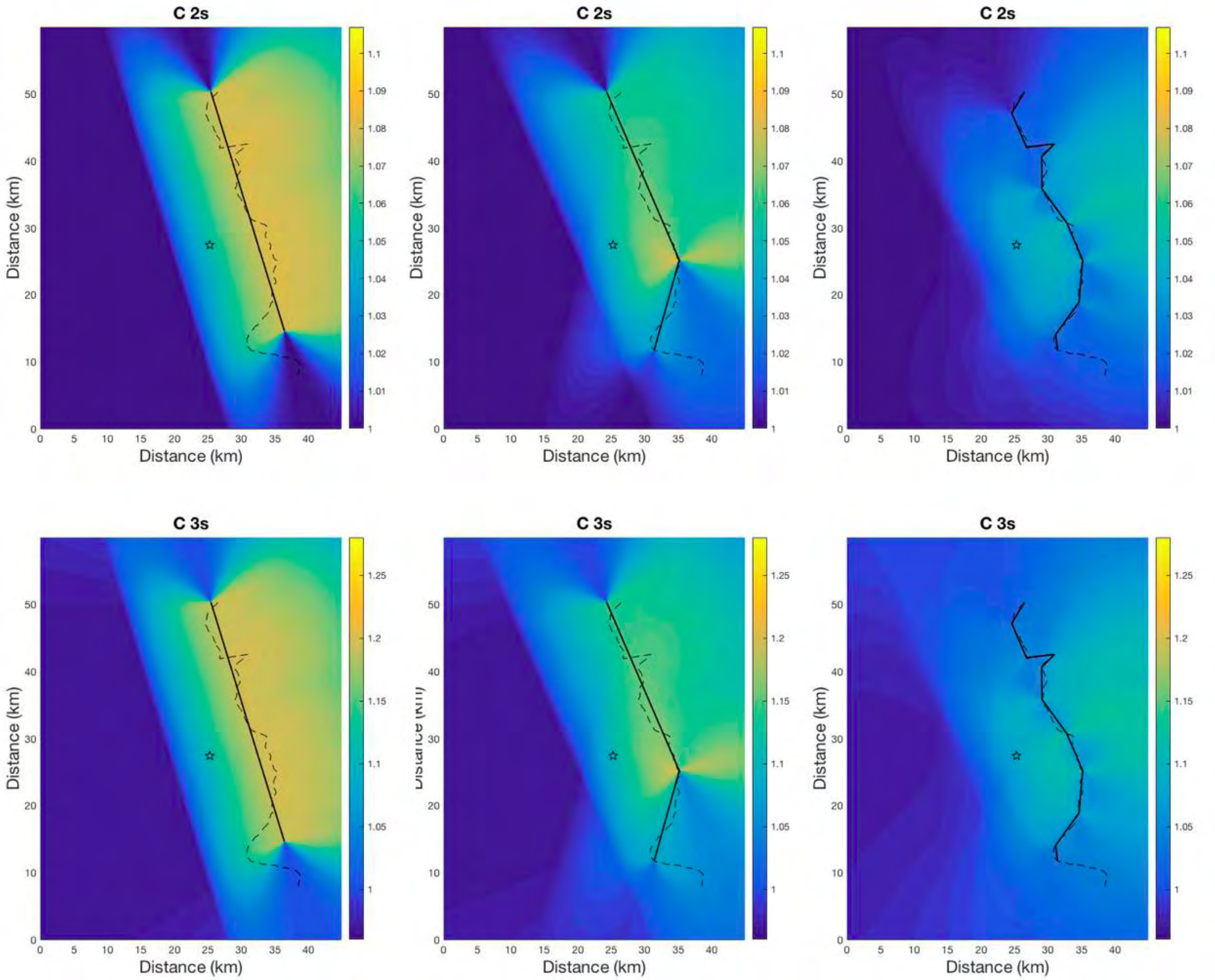
Multi-segment version of Somerville et al. (1997)



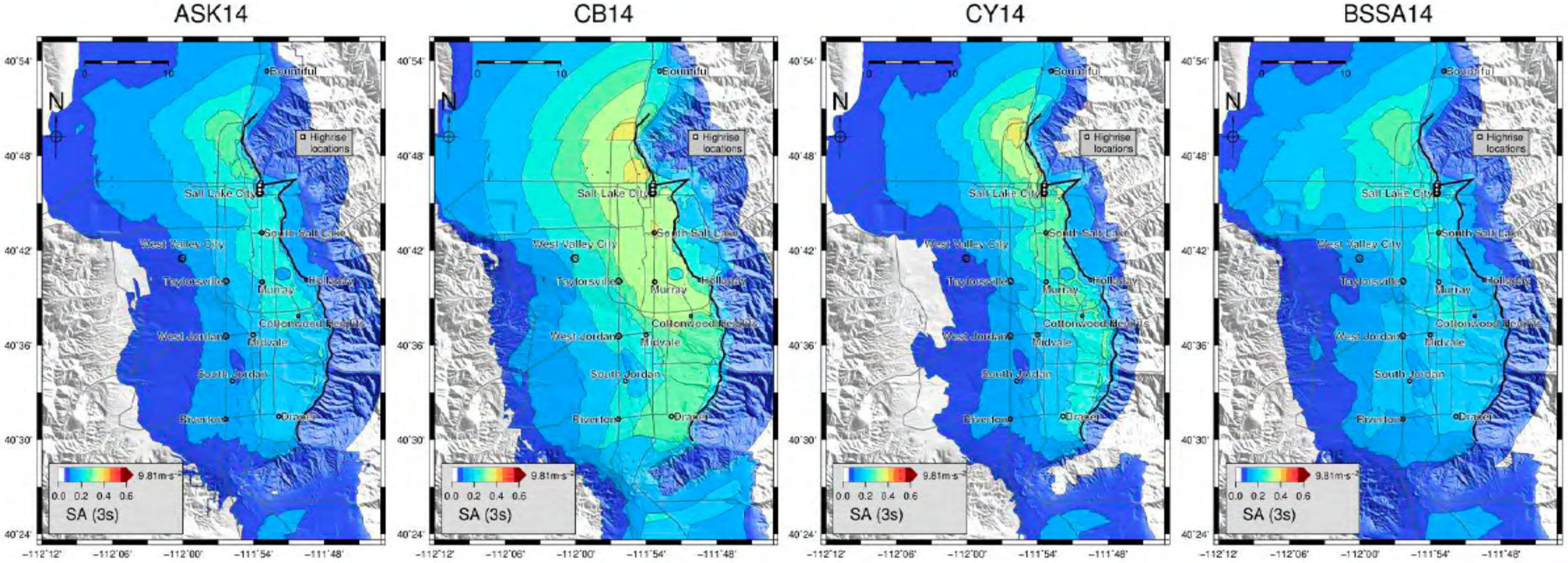
Maps of the directivity factors calculated from different WFSLC approximation models for scenario A



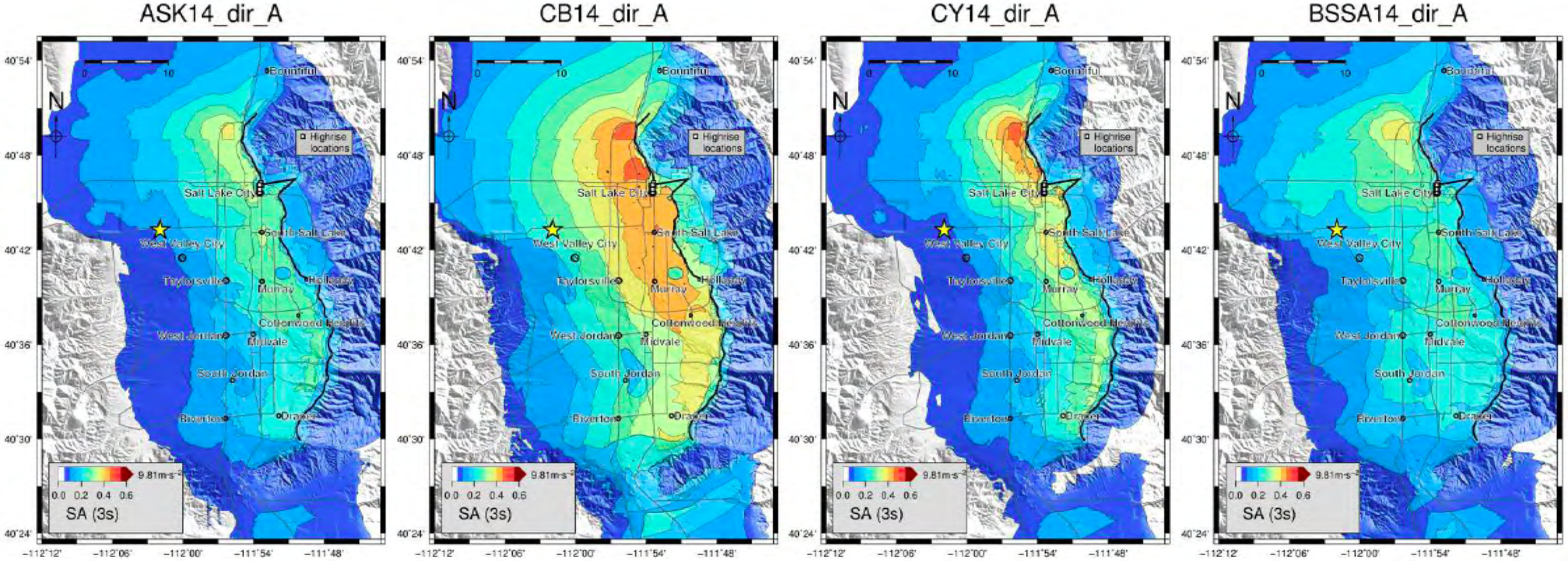
Maps of the directivity factors calculated from different WFSLC approximation models for scenario C



SA-3s for Scenario A.



SA-3s for Scenario A, modified with the directivity term from Bayless and Somerville (2013).



Conclusions

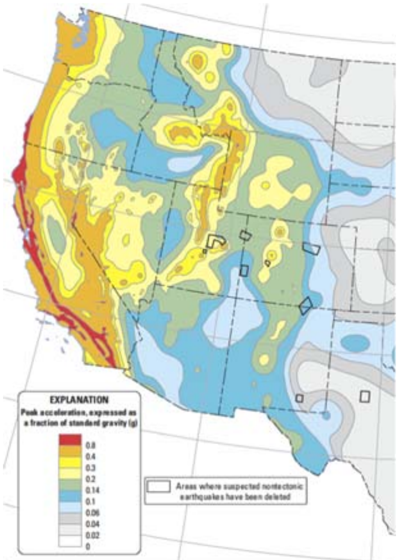
- SA-1D are generally smoother and smaller in amplitude than SA-3D due to higher Vs30 values and the lack of underlying 3D structure
- The SAs show a strong correlation [0.6 to 0.8] with Vs=1.0 km/s and Vs=1.5 km/s in the WFCVM
- Parametric models for the 1.0 km/s isosurface show amplification factors of up to ~2.7 and ~3.7 above the deepest part of the basin for SAs
- Correlations between the long-period scenario ground motions in the SLV and the underlying fault slip range from 0.55 to 0.87
- The correlations with peak slip rate are somewhat lower, ranging from 0.41 to 0.80
- The source correlations are larger for the simulations using the 3D basin model, as compared to those obtained from the 1D model, suggesting an interaction between the source characteristics and the basin structure

Conclusions (cont.)

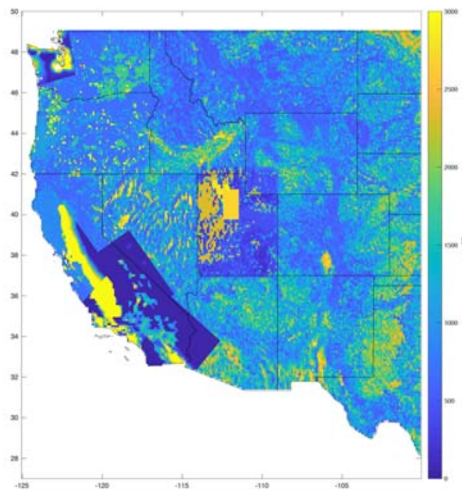
- Bayless and Somerville (2013) multi-segment directivity model increases the SA values by less than 30% for the scenarios
- The WF scenario ground motions on soil sites show a gradual increase in bias from Rrup=0 to 1-1.5 km -→ basin edge effect and/or entrapment of waves in the deeper parts of the basin, scenario specific conditions such as slip distributions not captured by the GMPEs + velocity strengthening in source model
- The WF scenario ground motions on soil sites show a gradual decrease in bias from Rrup~4 to ~10 km → basin as well as directivity effects, westward termination of the WF, slip in the M7 scenarios?
- GMPEs do a reasonably good job of predicting the increased ground motions over the hanging wall for SA-3s, but overpredict slightly for SA-2s

Incorporating basin effects into NSHM

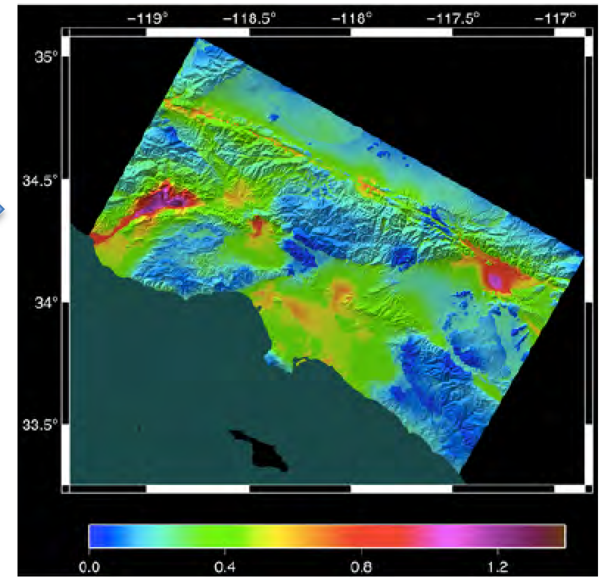
Default basin depths



WUS-wide basin depths



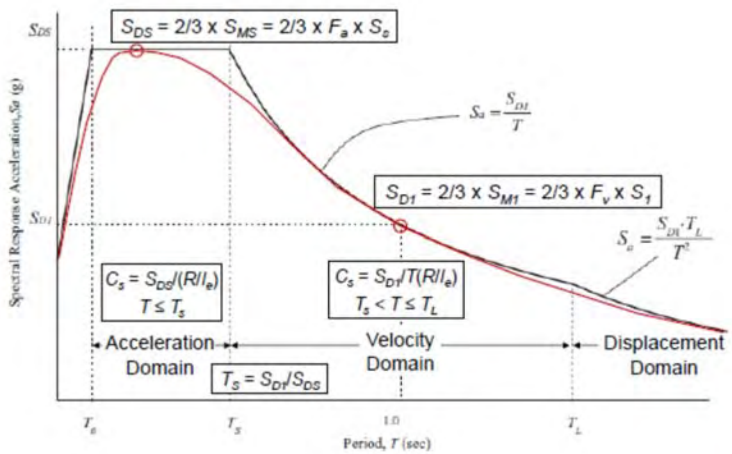
3-D ground motion simulations



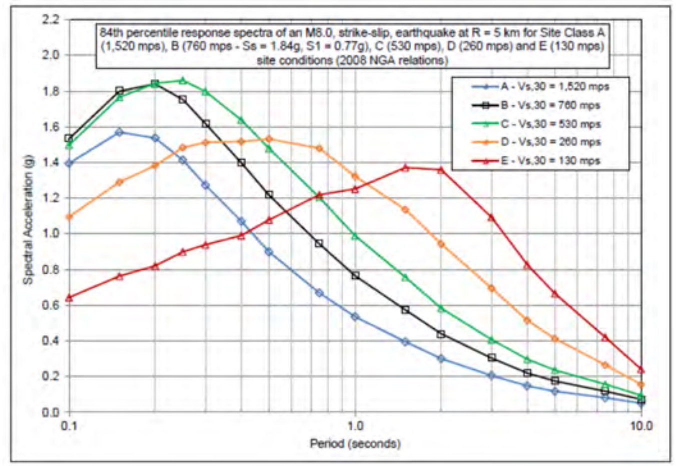
1) **Empirically based GMPEs, default basin depths**
2) **Empirically based GMPEs, basin depths from seismic velocity models**
3) **Empirically based GMPEs, basin amplifications from 3-D simulations**

Multi-Period Spectrum:

ASCE 7 Design Spectrum based on Ss and S1:



Kircher study showing that the spectral shape varies:



- **Solution:** USGS to develop maps for more periods and site-classes in addition to the Ss and S1 value maps at BC site-class.
- **At long periods:** due to the questionable accuracy of GMPEs, multi-period spectra can benefit from utilizing simulations

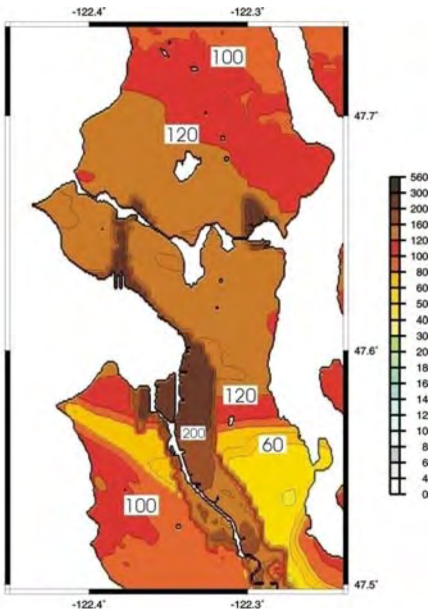
(slide courtesy Sanaz Rezaeian)

Outline

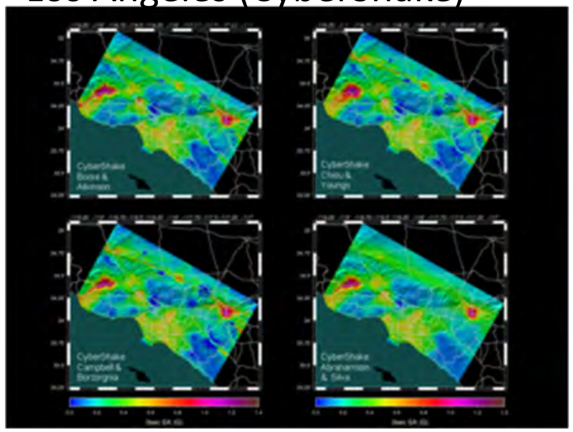
- ***Plan for incorporating basin effects from empirically based GMPEs – presentation by Mark Petersen (USGS)***
  - Sensitivity of hazard to basin depths (NSHM-2018)
  - Plan for developing WUS-wide Zx maps (NSHM-2018/2020)
- ***Context for simulation-based seismic hazard analyses across the U.S.***
- ***US Geological Survey efforts around "urban seismic hazard maps"***
- ***Plan for harmonizing Urban and National Seismic Hazard Models (USHM/NSHM)***
- ***Plan for incorporating ground motions from 3-D simulations into NSHM***
  - Update from Working Group on Urban Seismic Hazard Maps: white paper on harmonizing USHMs and NSHM
  - Incorporating 3-D ground motions into the NSHM

Working Group motivation: Urban seismic hazard maps

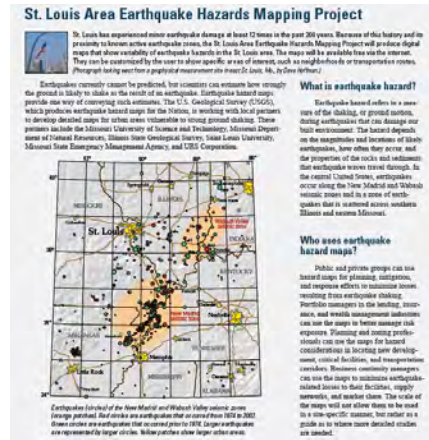
Seattle



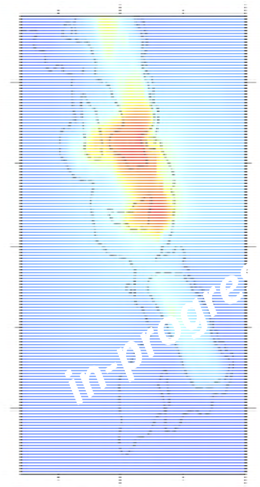
Los Angeles (CyberShake)



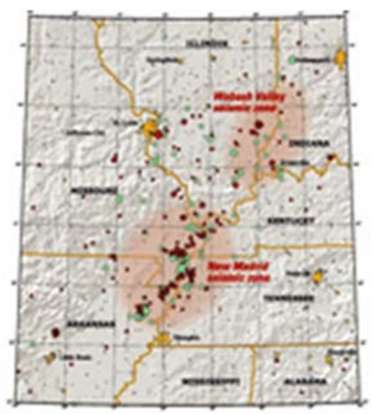
St. Louis



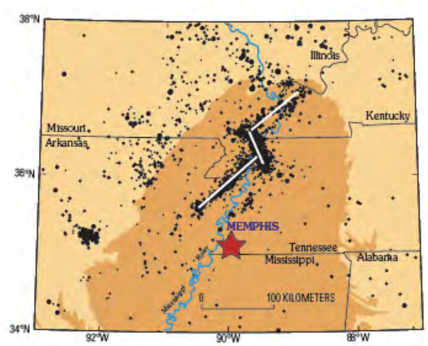
Salt Lake City



Evansville, IN



Memphis



Multiple classes of urban seismic hazard maps

- 3-D simulation-based ground-motions* (Seattle and southern California)
- Near-vertical propagation of S-waves to account for effects of shallow sub-surface
- Vs30-based GMPE calculations

Working Group Composition, Goals, History

- Internal U.S. Geological Survey Working Group
- Goals
  - Address technical and programmatic issues related to USHMs
  - Responding to available urban seismic hazard maps
  - *(Largely focusing on incorporating ground motions from 3-D simulations)*

Morgan Moschetti*
Nico Luco*
Brad Aagaard
Annemarie Baltay*
Mike Blanpied
Oliver Boyd*
Art Frankel*
Rob Graves*
Steve Hartzell
Sue Perry
Mark Petersen*
Sanaz Rezaeian
Bill Stephenson
Eric Thompson*
Rob Williams
Kyle Withers

OPINION

Integrate Urban-Scale Seismic Hazard Analyses with the U.S. National Seismic Hazard Model

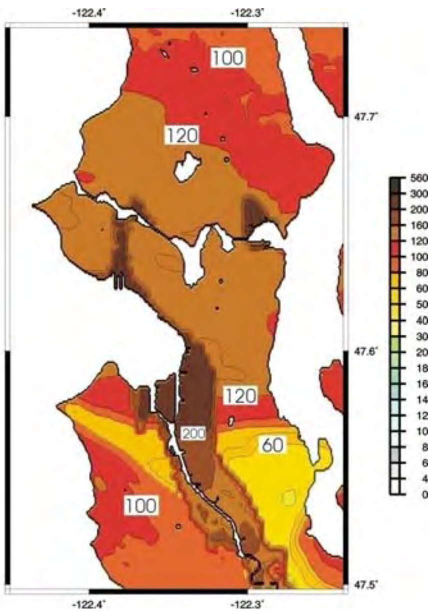
For more than 20 yrs, damage patterns and instrumental recordings have highlighted the influence of the local 3D geologic structure on earthquake ground motions (e.g., **M** 6.7 Northridge, California, Gao *et al.*, 1996; **M** 6.9 Kobe, Japan, Kawase, 1996; **M** 6.8 Nisqually, Washington, Frankel *et al.*, 2002). Although this and other local-scale features are critical to improving seismic hazard forecasts, historically they have not been explicitly incorporated into the U.S. National Seismic Hazard Model (NSHM, national model and maps), primarily because the necessary basin maps and methodologies were not available at the national scale. Instead, the U.S. Geological Survey (USGS), its partners, and external groups developed urban seismic hazard maps (urban models and maps) that consider detailed site effects in local areas (e.g., Wong *et al.*, 2002; Cramer *et al.*, 2006; Frankel *et al.*, 2007; Graves *et al.*, 2011). The disconnect between the urban and national hazard models, however, means that the national models, which underlie U.S. building codes and other applications, do not make use of all of the scientific results informing earthquake ground-shaking comparison of hazard in different parts of the country (Frankel *et al.*, 2000; Moschetti *et al.*, 2015; Rezaeian *et al.*, 2015). Since 1996, the hazard maps have directly formed the basis for the seismic provisions in U.S. building codes (Leyendecker *et al.*, 2000; Frankel *et al.*, 2002; Petersen *et al.*, 2008, 2015; Luco *et al.*, 2015). The connection between U.S. building codes and the NSHM represents one critical way in which knowledge about earthquake occurrences and effects can be used to reduce seismic risk. Because of this role, the NSHM updates must achieve widespread consensus from the scientific and engineering communities. This model-vetting process has historically been achieved through a series of public workshops, which have solicited feedback and new scientific models (Frankel *et al.*, 2000; Petersen *et al.*, 2015). As a consequence, the NSHM represents a state-of-practice for earthquake science.

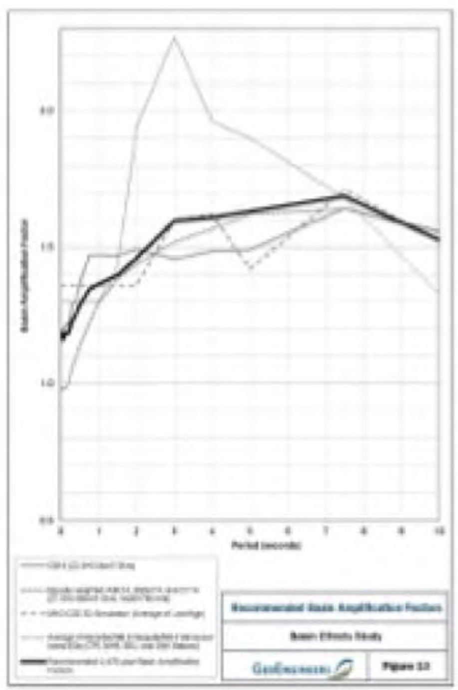
Urban-Scale Seismic Hazard Assessments

In parallel with these national-scale analyses, a growing number

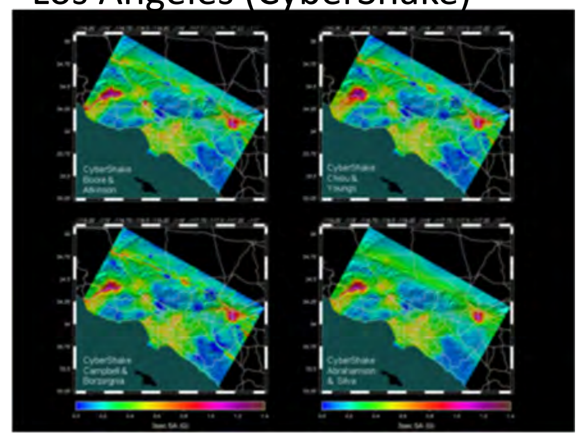
Local engineering use of ground motions from 3-D simulations

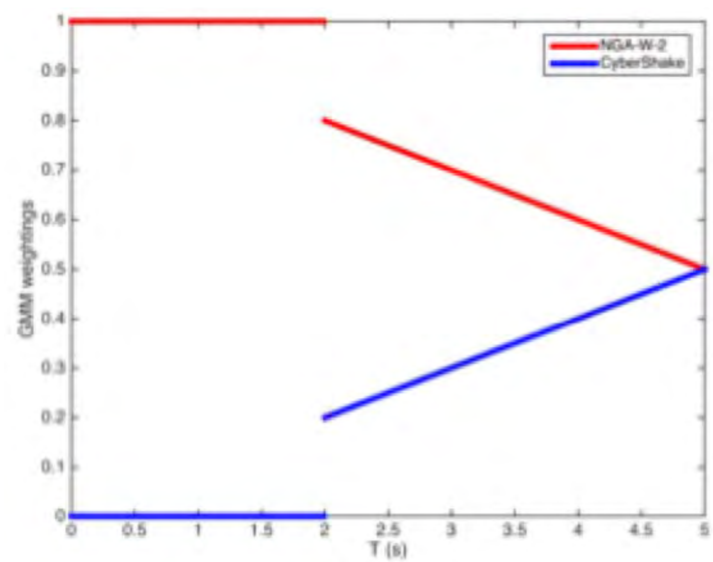
Seattle





Los Angeles (CyberShake)





Working Group Recommendations on integrating USHMs and NSHM

- NSHM should integrate well-vetted features of USHMs with national-scale seismic hazard assessments
- Moving forward we expect that USHMs will make increasingly important contributions to NSHM
- USHMs remain independent products
  - USHMs are a "platform for cutting-edge research into topics affecting earthquake ground shaking forecasts and have helped to define important scientific questions and motivate future research"
  - Integration of USHM features will be facilitated by early and on-going coordination with NSHMP

Background on and plan for incorporating ground motions from 3-D simulations into NSHM

- Based on feedback from WG-USHM, Earthquake Hazards Program, NSHMP Steering Committee
- Only incorporate well-vetted components from earthquake simulations
  - Focus on basin amplifications
  - Not (currently) considering effects from path, directivity, source complexity
- Validate the simulated ground motions (or components); are simulations providing improvements to empirically based predictions

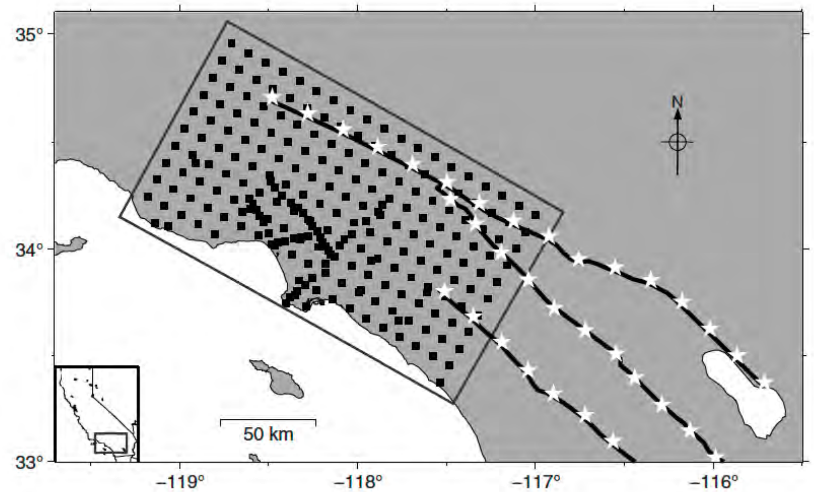
Averaging-based factorization (ABF)

(Wang and Jordan, 2014)

$$G(r,k,x,s) \equiv \ln Y(r,k,x,s).$$

$$A \underset{R}{\leftarrow} B \underset{K}{\leftarrow} C \underset{X}{\leftarrow} D \underset{S}{\leftarrow} E.$$

$$G(r,k,x,s) = A + B(r) + C(r,k) + D(r,k,x) + E(r,k,x,s).$$



Successive averaging over sets of simulated ground motions permits parameterization of simulated ground motions into terms similar to GMPEs:

E: Total excitation level; source complexity

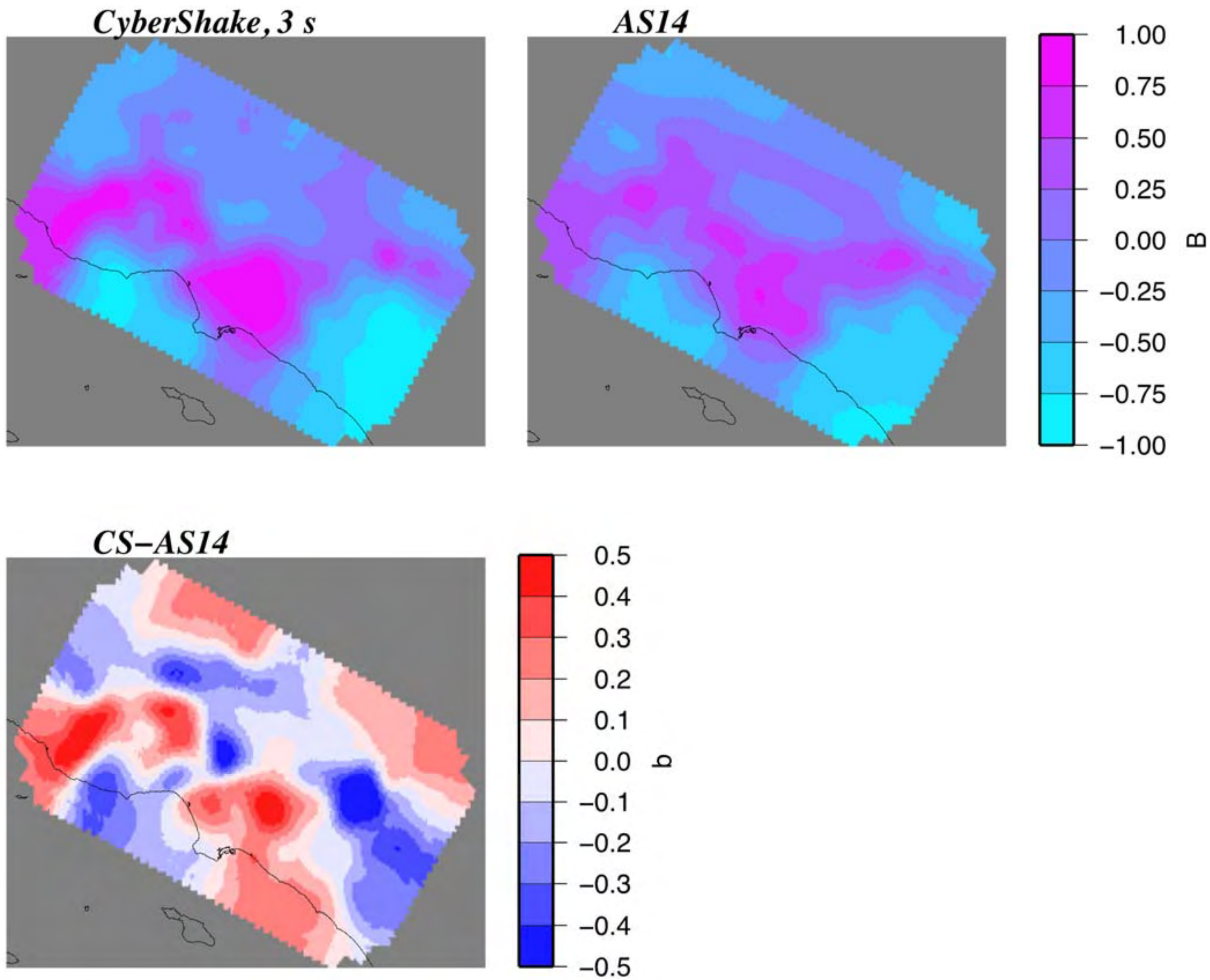
D: expectation over slip functions S; directivity effect

C: Expectation over hypocenters X; path effect

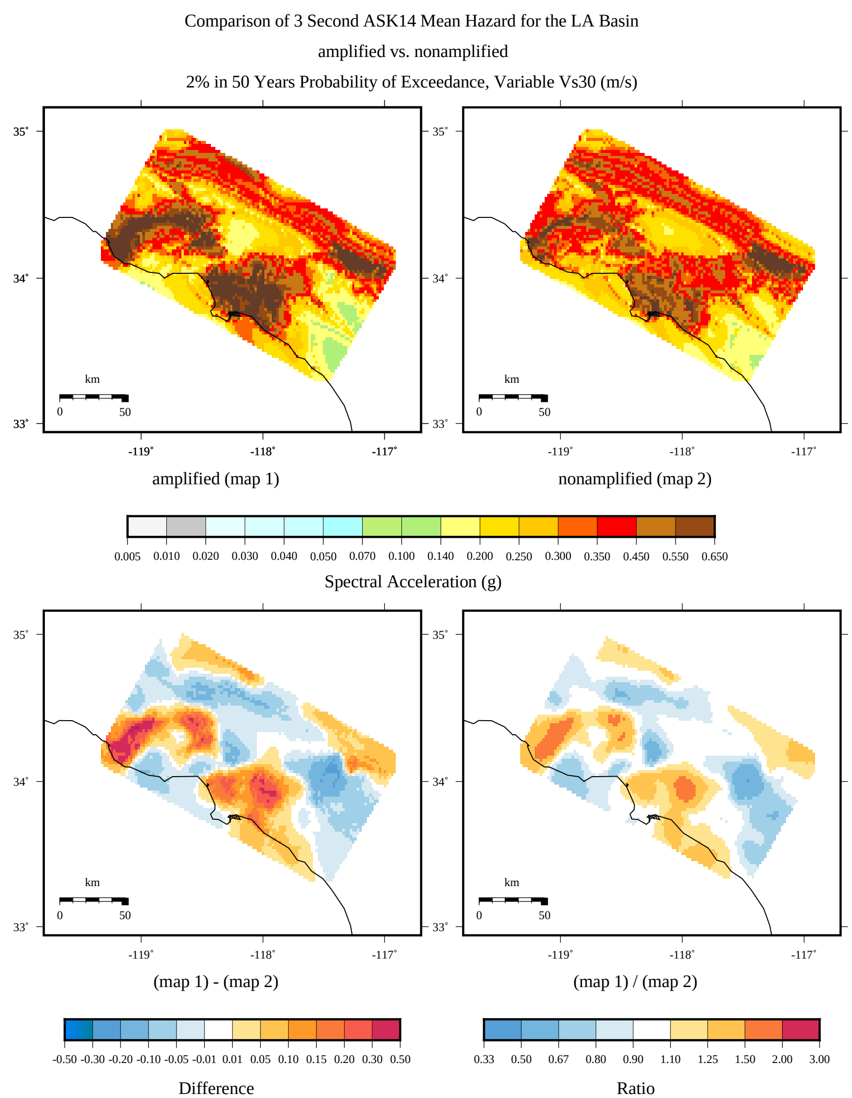
B: Expectation over seismic sources K; site effect

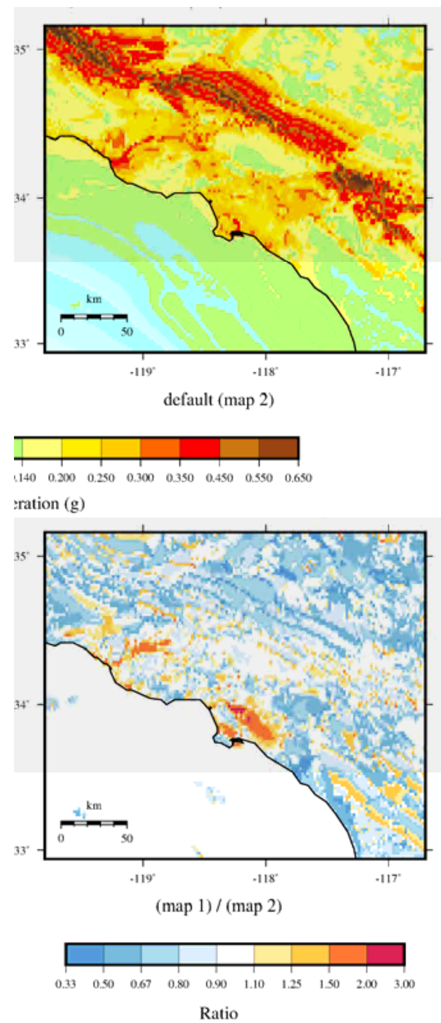
A: Expectation over all sites R; regional excitation level

Basin amplifications, CyberShake, ABF

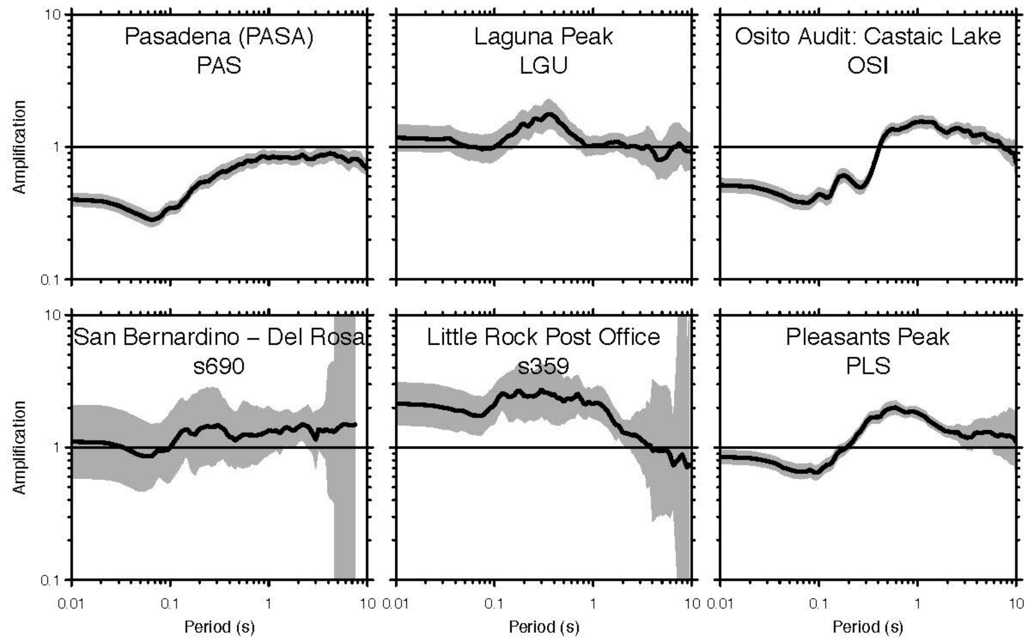


Hazard sensitivity tests, 3-s: Basin effects from 3-D simulations





Validation of 3-D-simulation-derived site amplification factors: LA (future SLC?)

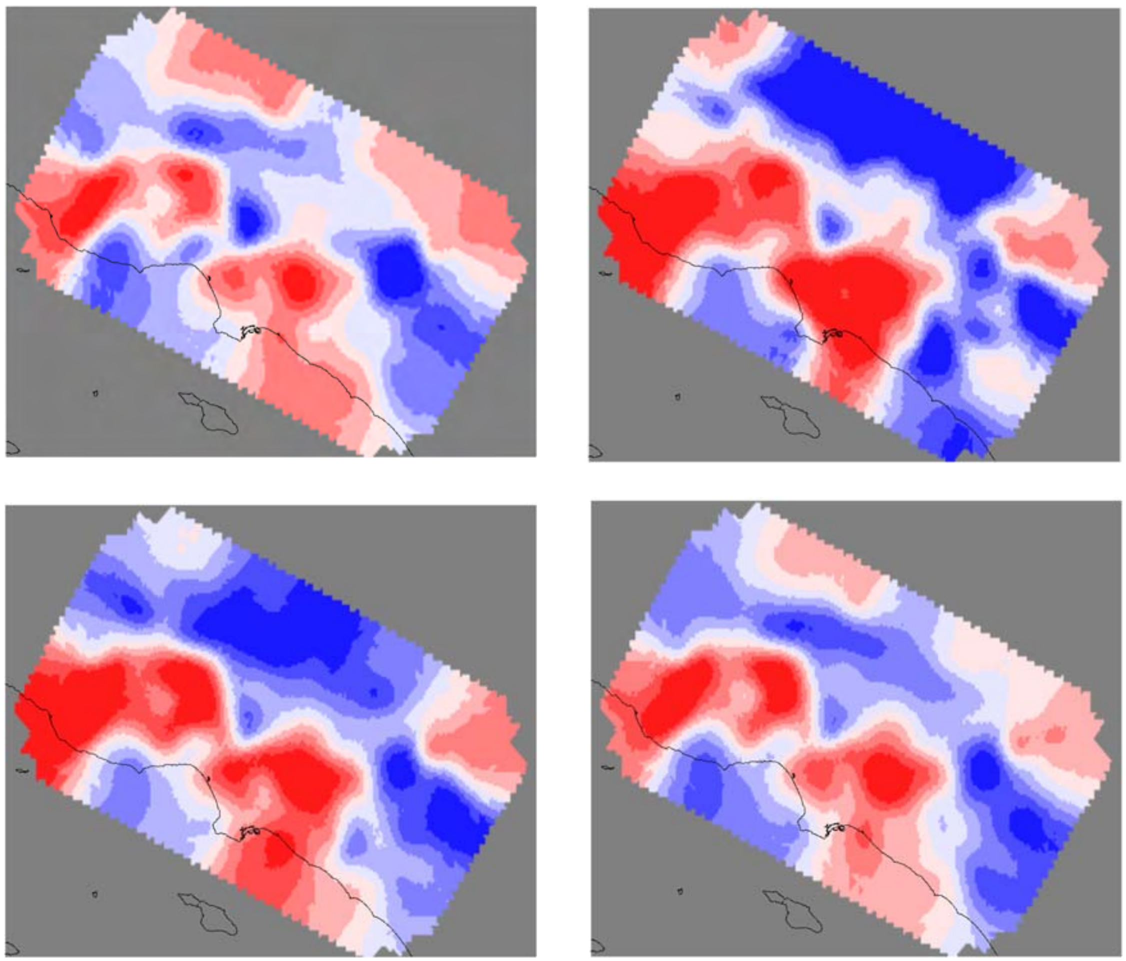


Moschetti et al. (2017, WCEE)

- Empirical amplification factors, Thompson and Wald (2016)
- Comparison of small-M ground motions with GMPE-predictions
- Use simulation-derived site response terms to assess whether empirical amplification factors improve

Basin amplifications, CyberShake, ABF

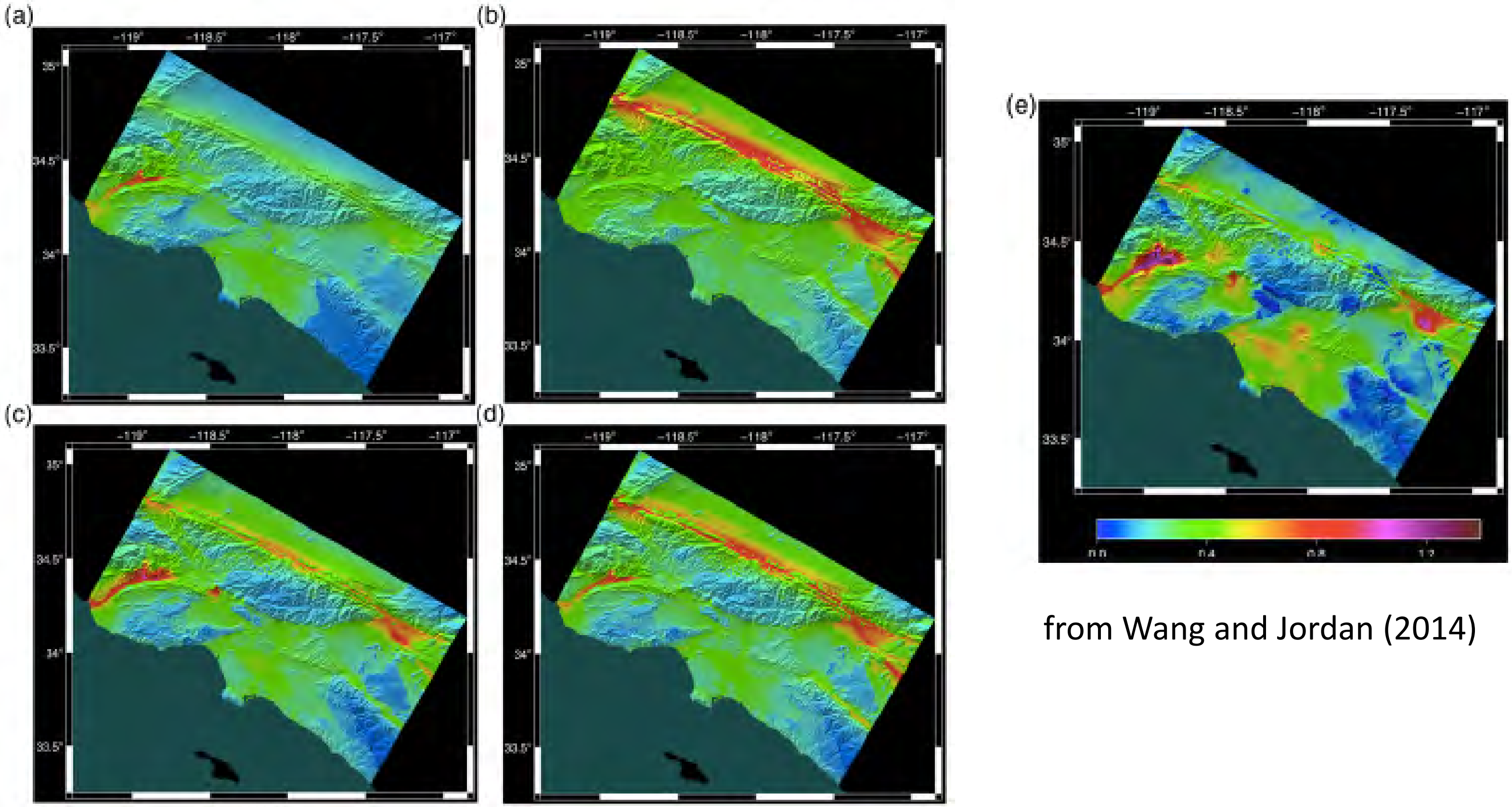
3-s SA



Plan for implementing ground motions from 3-D simulations into NSHM

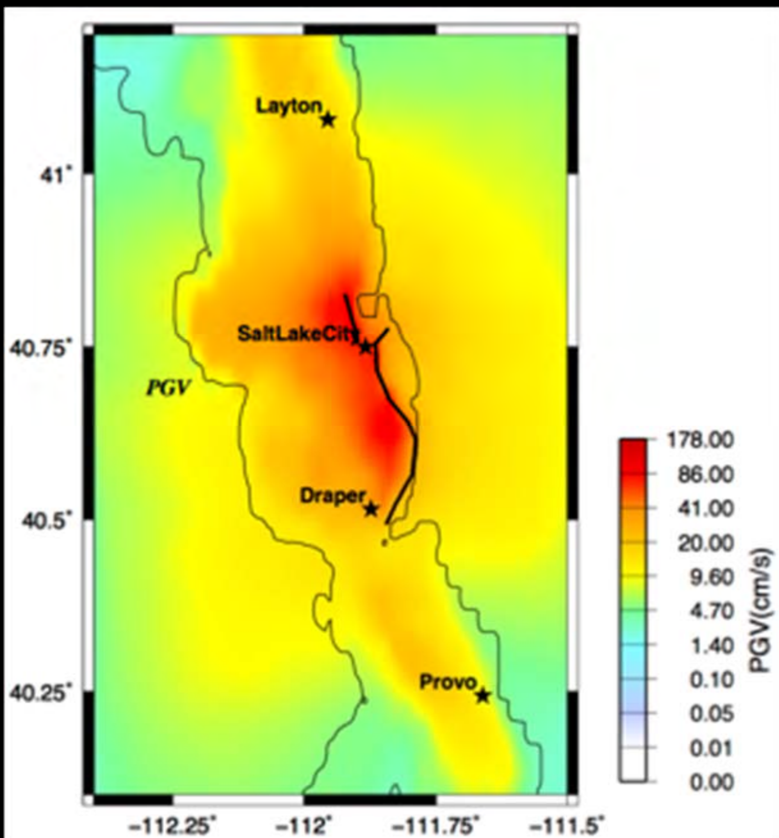
- Empirically based GMPEs, with basin amplifications from 3-D simulations
  - Implementation of basin amplification terms from CyberShake in nshm-haz code and sensitivity testing (Los Angeles)
  - Validation of 3-D-simulation-derived amplification factors—comparison with small-M earthquake data
  - Sensitivity testing for other regions and incorporation, 2020 NSHM
    - NSHM GMMs would presumably use weightings between simulated and empirically based GMPEs (period-dependent, similar to SCEC-UGMS recommendations?)
    - On-going simulation efforts in Seattle and Salt Lake City

Seismic hazard maps from 3-D simulations



from Wang and Jordan (2014)

3-D ground motion simulations of the Salt Lake City segment of the Wasatch fault zone: Scenarios and applications to seismic hazard



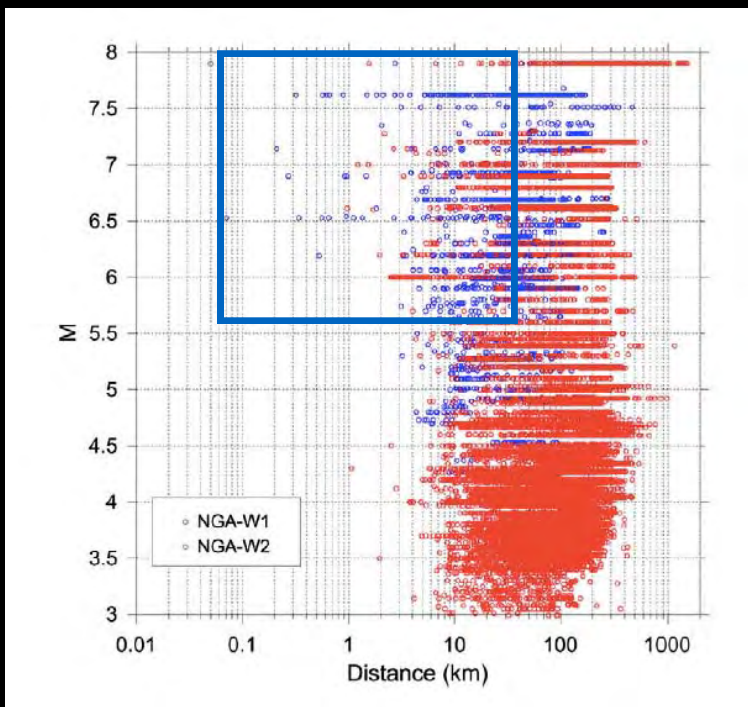
Morgan Moschetti

(Stephen Hartzell, Leonardo Ramirez-Guzman, Steve Angster, Arthur Frankel, Peter Powers, Eric Thompson)

Utah Geological Survey: Utah Ground Shaking Working Group
February 13, 2018
Salt Lake City, UT

USGS science for a changing world

Motivation for use of earthquake simulations



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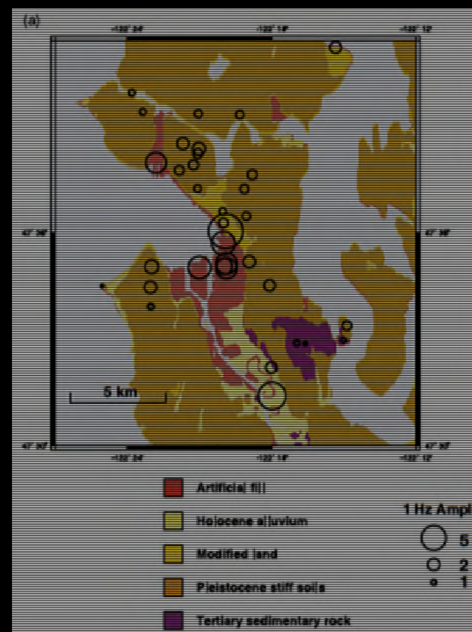

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Outline

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  - jurxqg#p rwlrq#sdwwhuqv
  - jurxqg#p rwlrq#yduldelolw|#iurp #vlp xodwlrqv
- Hiihfw#rq#jurxqg#p rwlrq#ri#ydu|lqj#hduwktxdnh#uxswxuh#sdudp hwhuv
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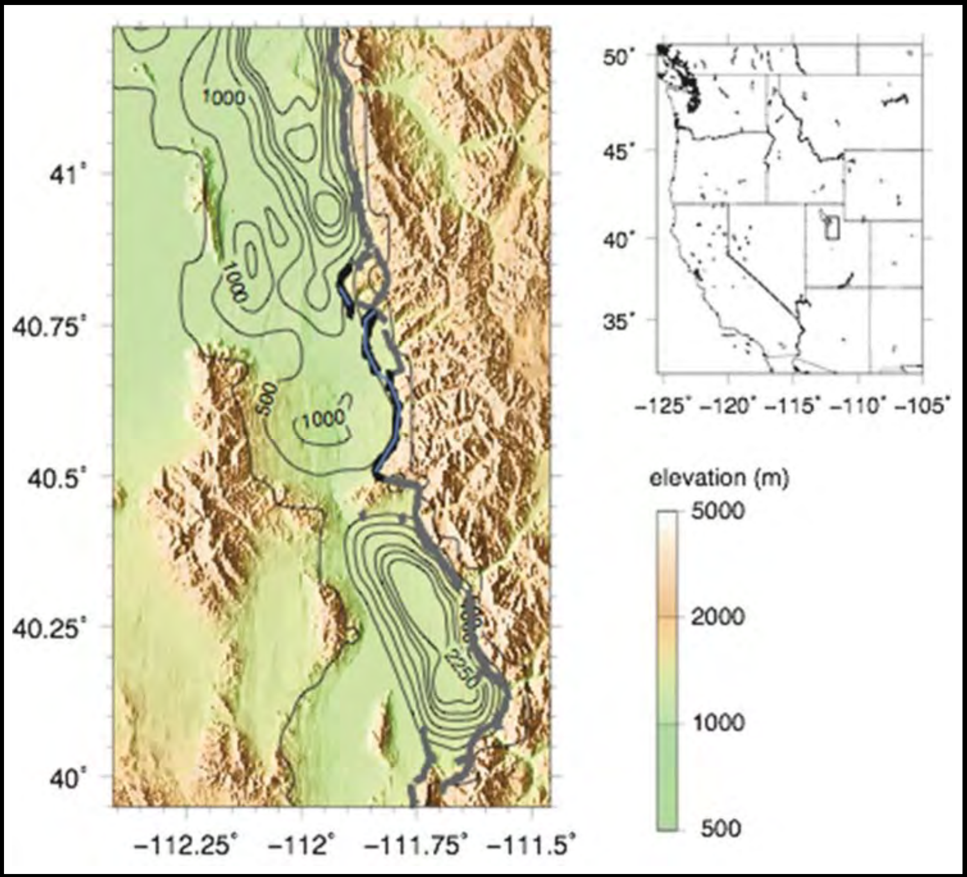
Salt Lake City segment, Wasatch Fault Zone



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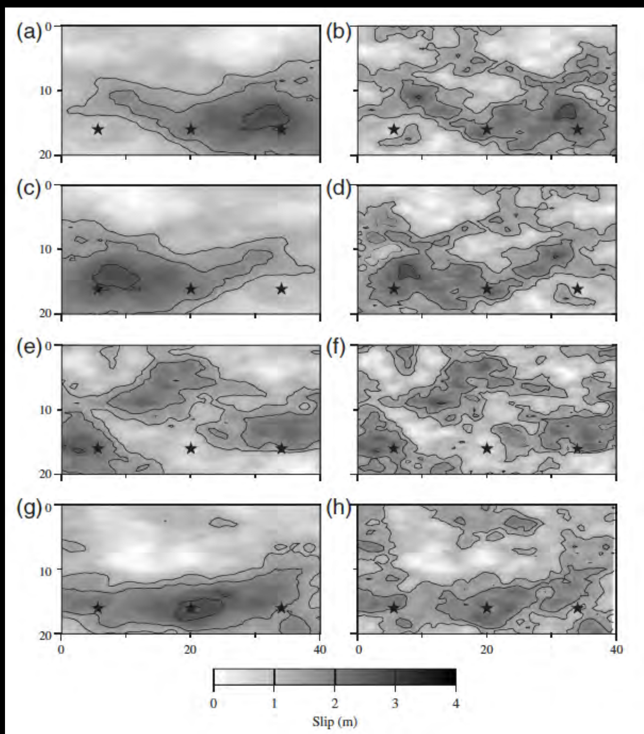
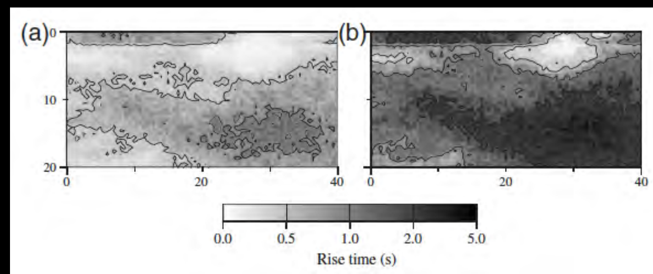
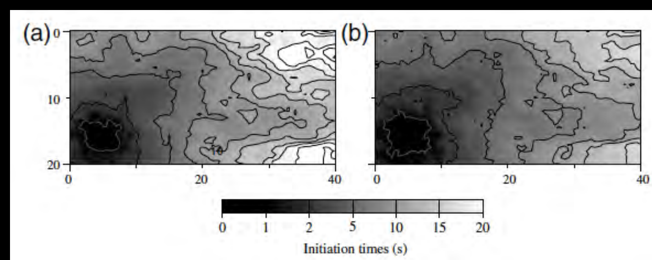
Earthquake rupture models







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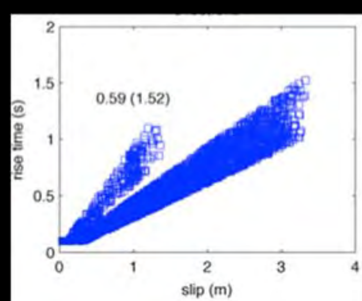
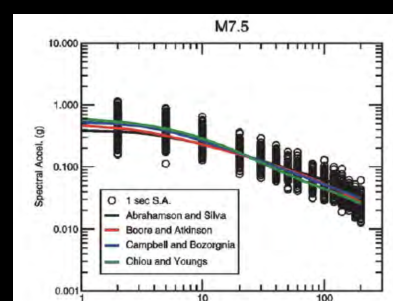
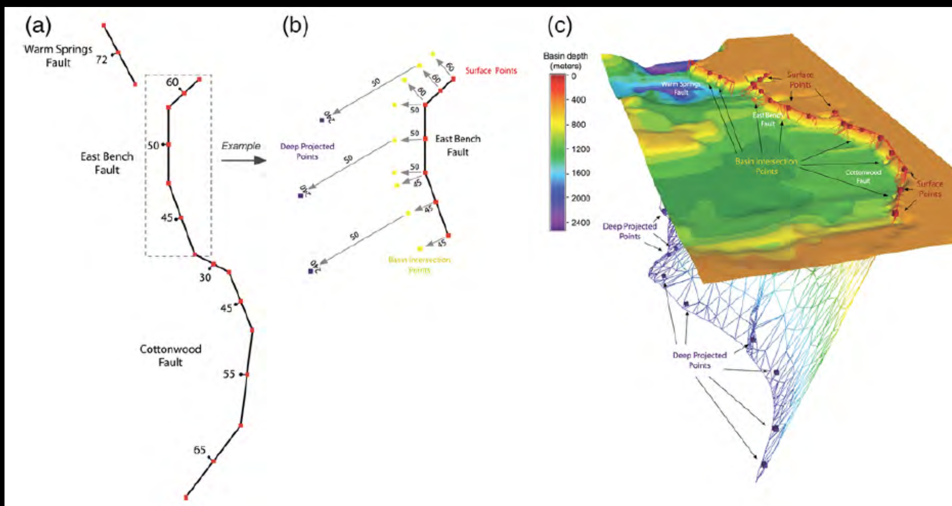
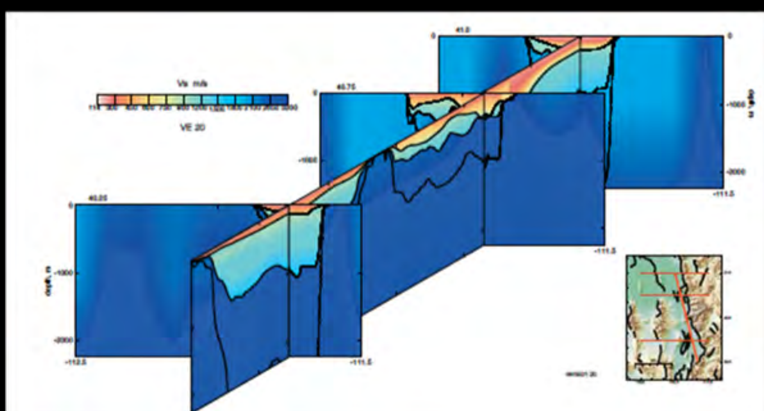




Fault representation and Seismic velocity model





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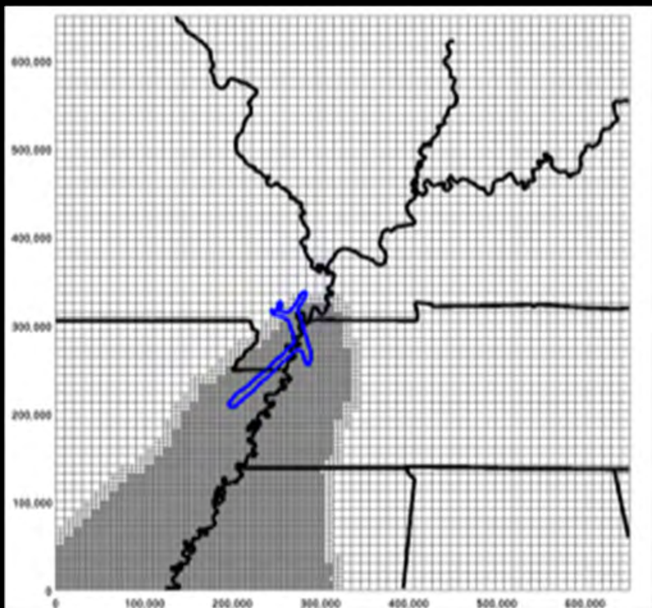
Wave propagation and simulations



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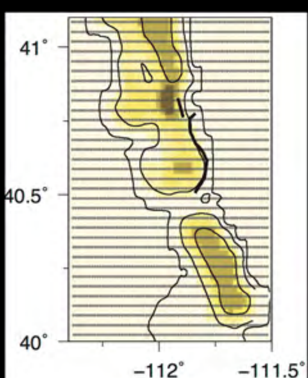

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- ipd{@4#K}
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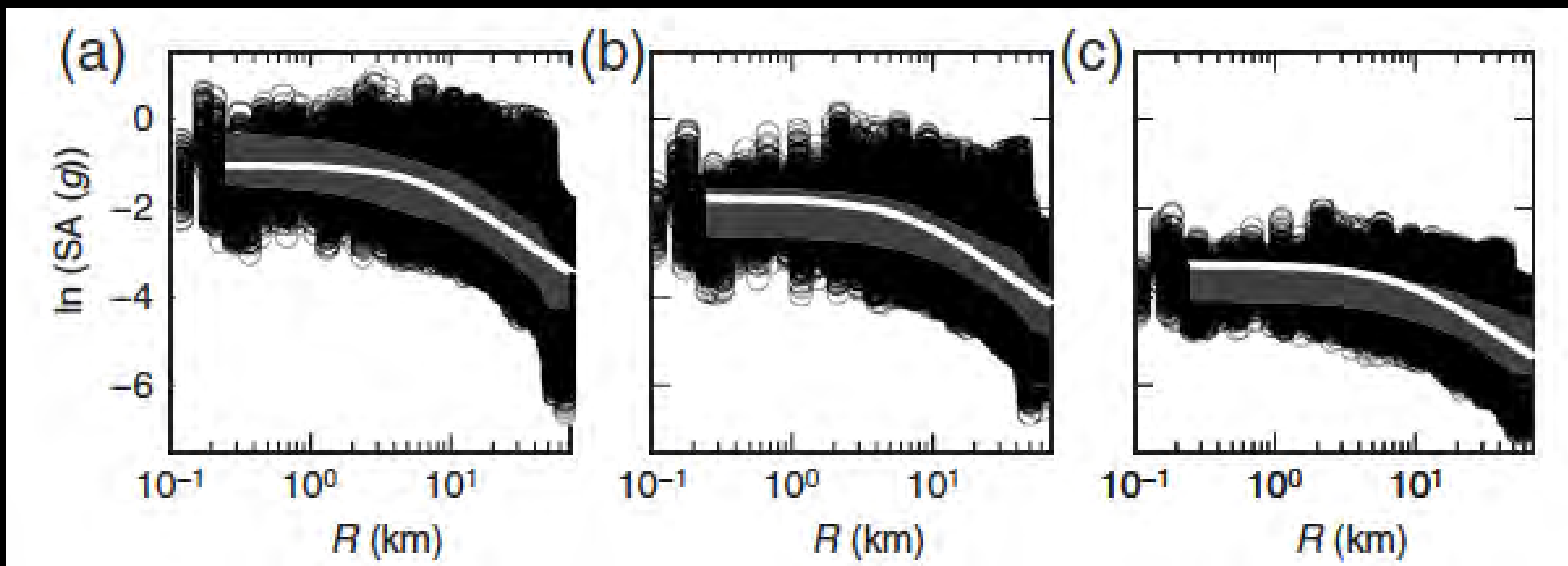
Simulated ground motions

418#v 6#v :18#v

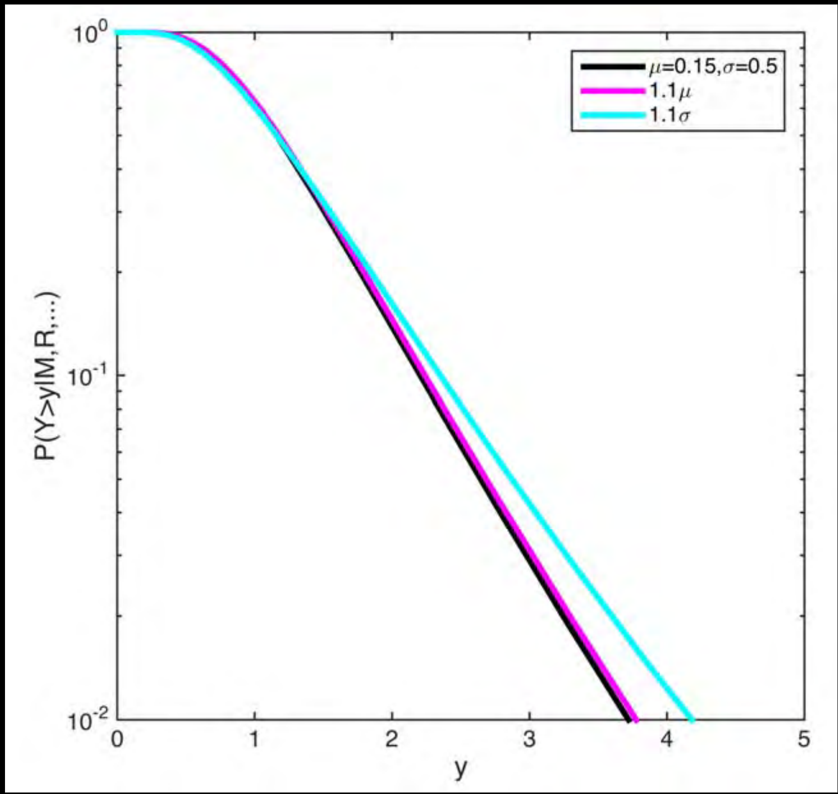


Ground motion simulations in PSHA

$$P(PGA > x \mid m, r) = 1 - \Phi\left(\frac{\ln x - \overline{\ln PGA}}{\sigma_{\ln PGA}}\right)$$

$$\lambda(IM > x) = \sum_{i=1}^{n_{sources}} \lambda(M_i > m_{\min}) \int_{m_{\min}}^{m_{\max}} \int_{0}^{r_{\max}} P(IM > x \mid m, r) f_{M_i}(m) f_{R_i}(r)\, dr\, dm$$

Baker (2008), An Introduction to PSHA



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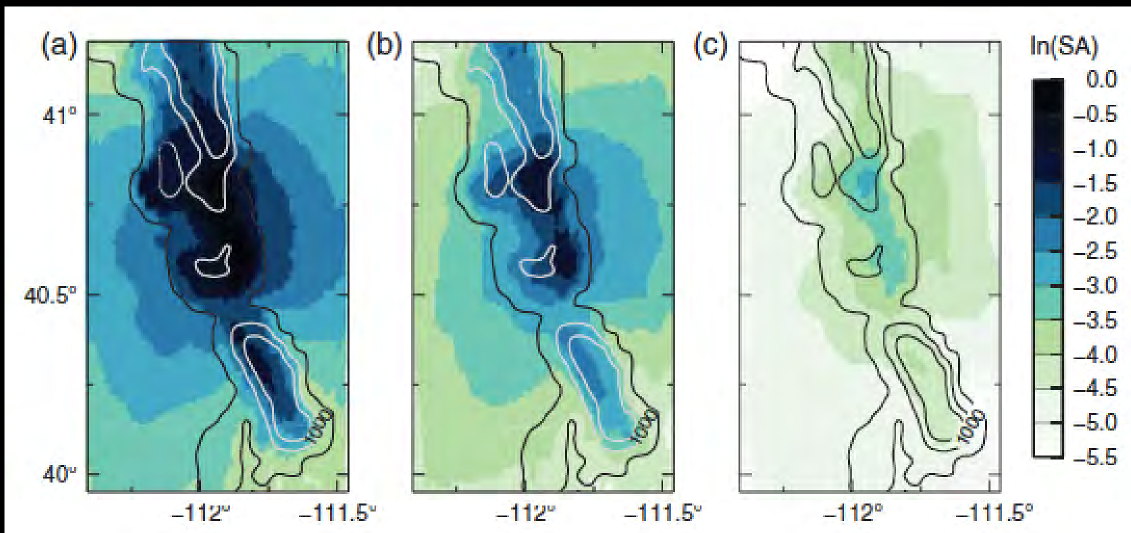

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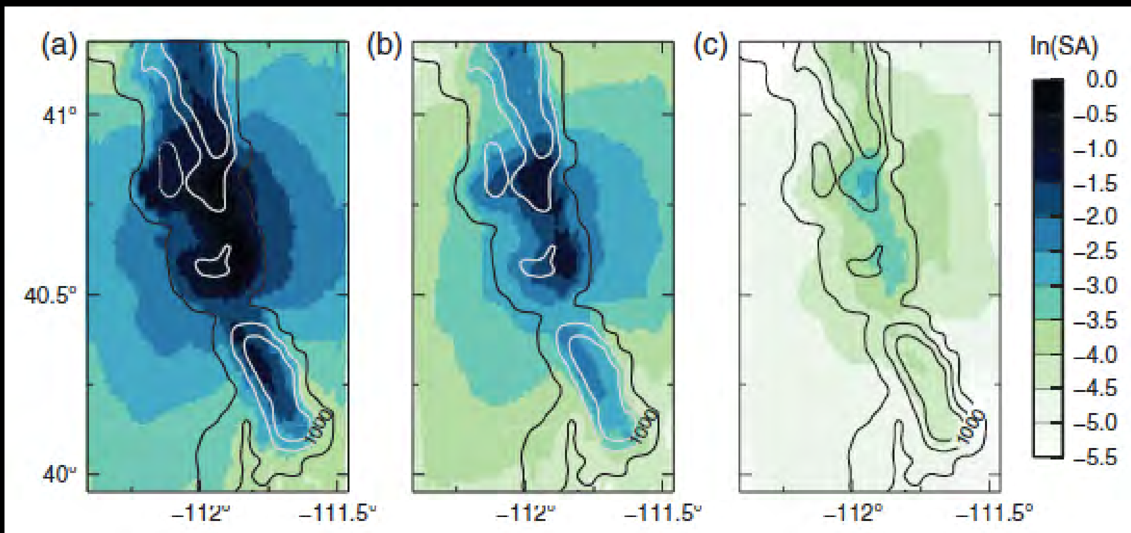

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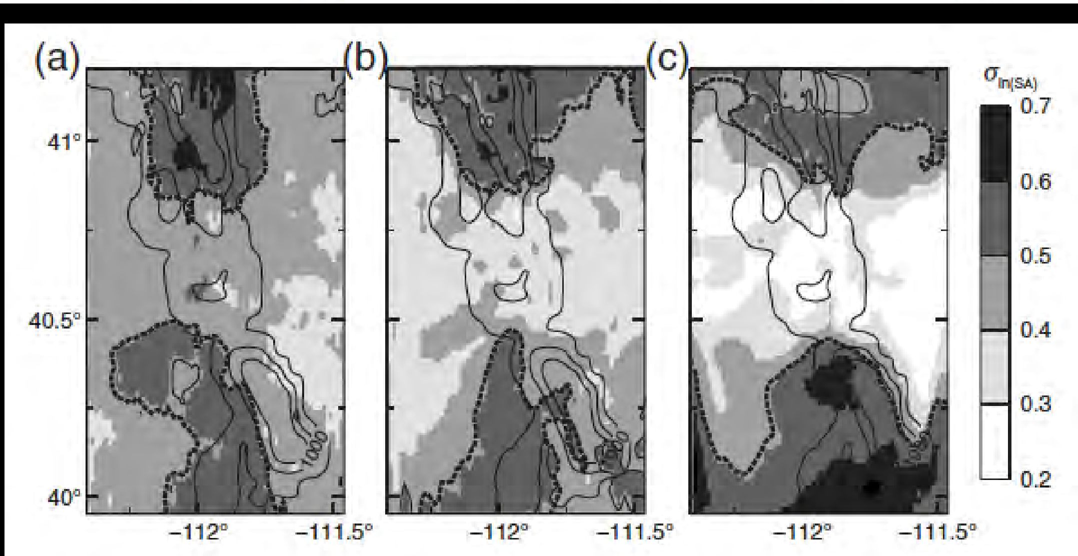

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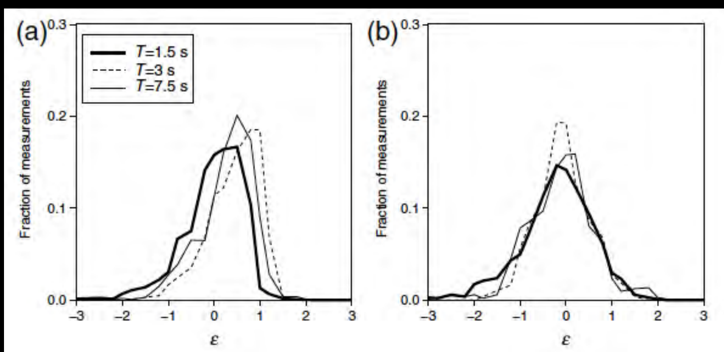
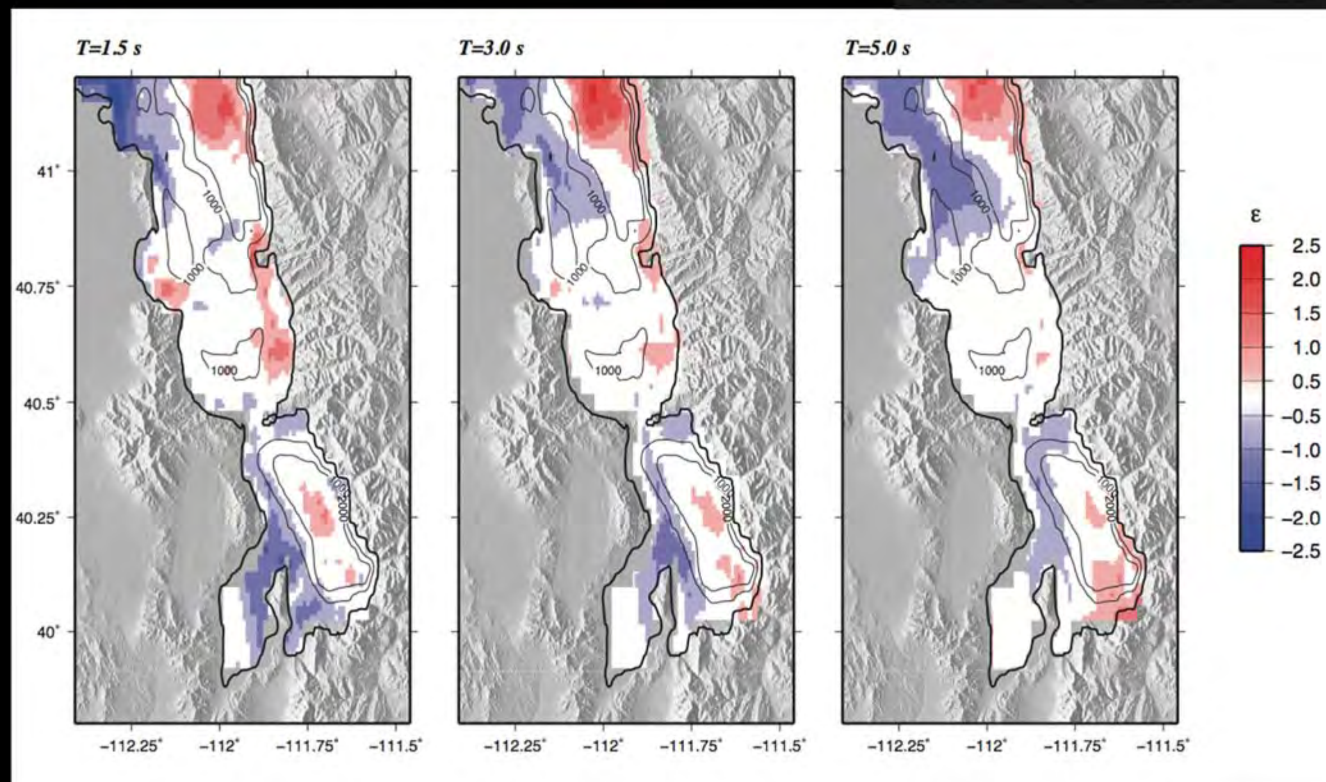
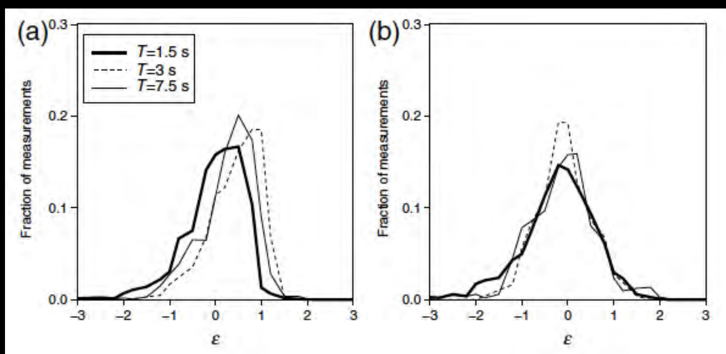
Ground motion residuals (total)

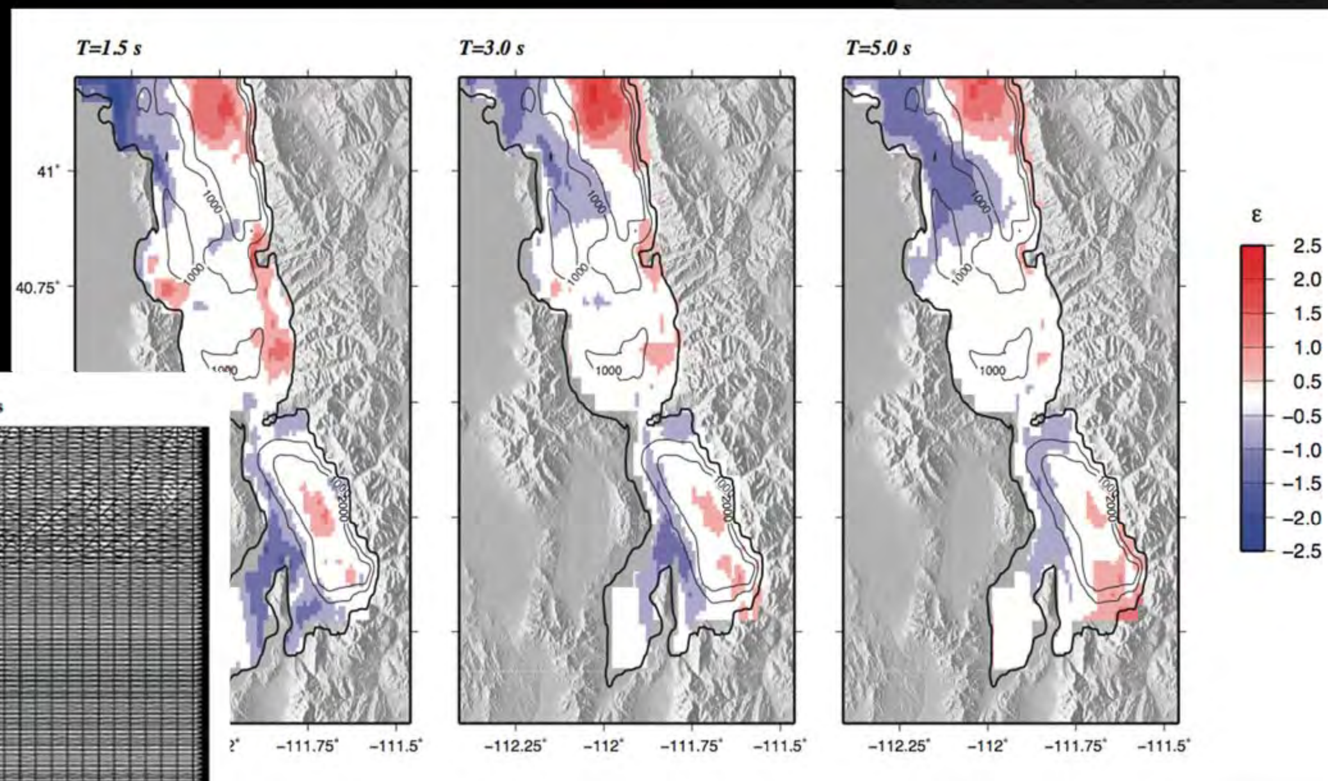


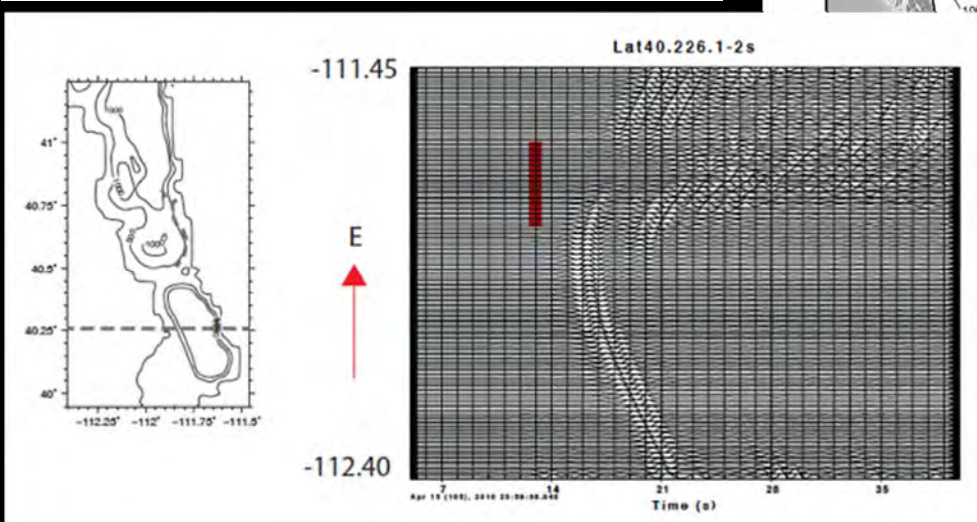
$$\varepsilon = \frac{lnSA - \mu_{GMPE}}{\sigma_{GMPE}}$$



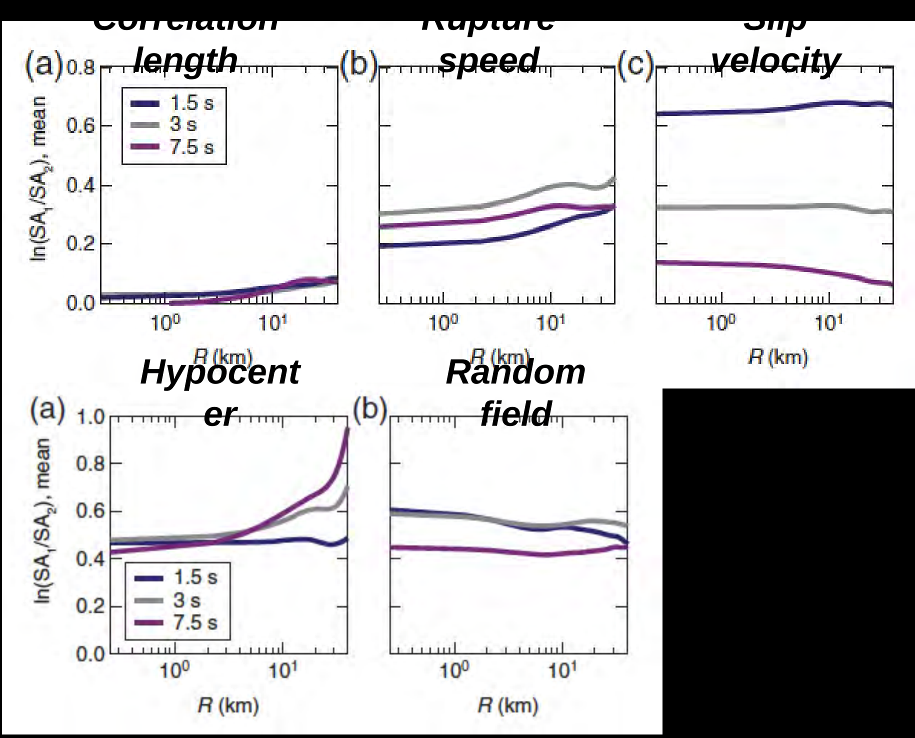
Ground motion residuals (total)

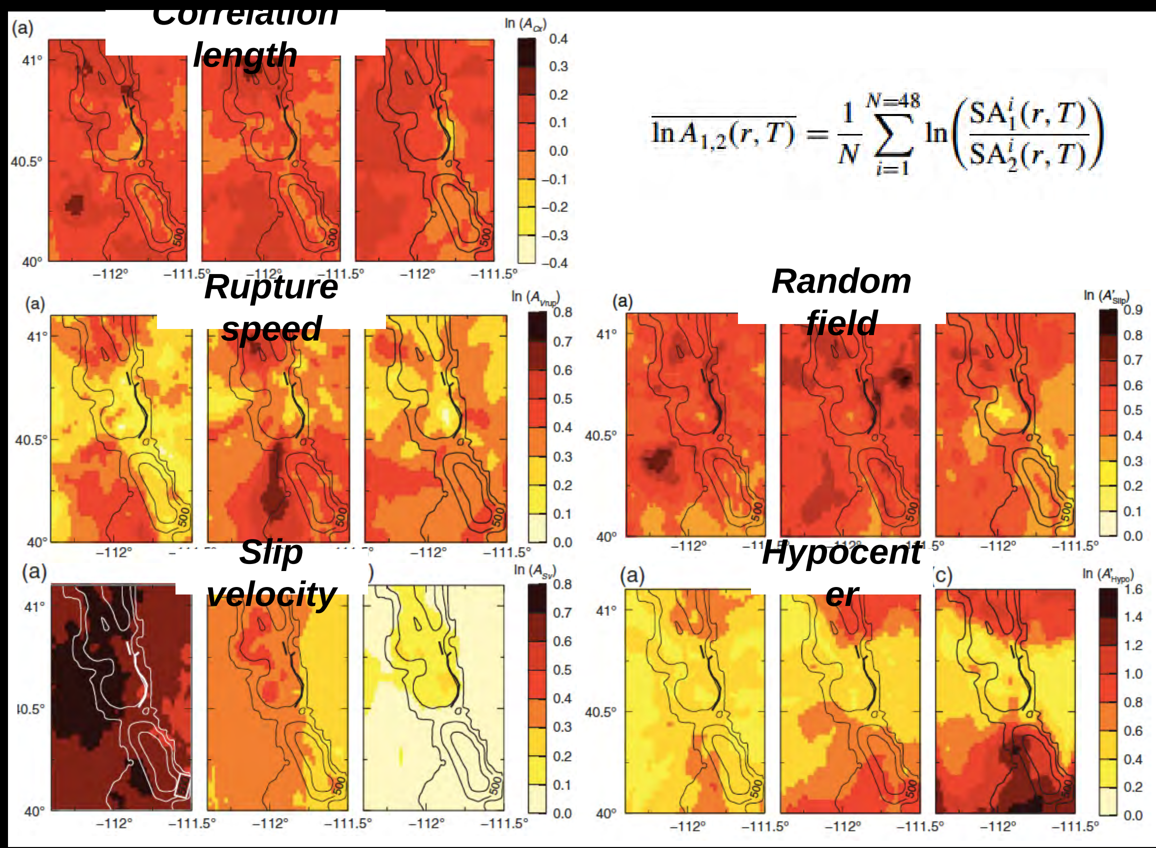




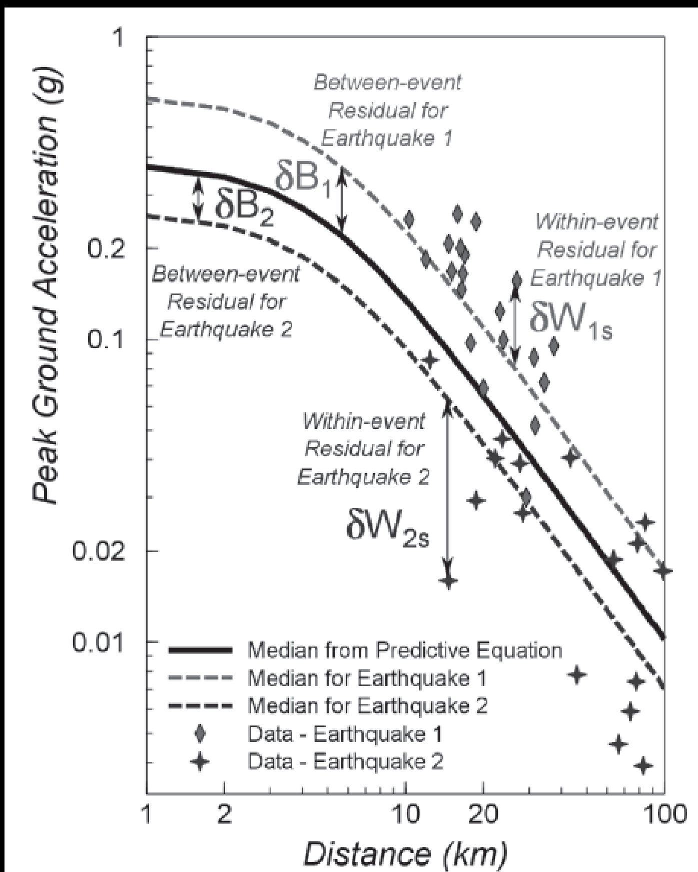


Ground motion amplifications from variations in rupture parameters





Comparison of simulated ground motions with empirically based GMPEs



Pure Appl. Geophys.

DOI 10.1007/s00024-017-1615-x

Pure and Applied Geophysics

CrossMark

Within-Event and Between-Events Ground Motion Variability from Earthquake Rupture Scenarios

Jorge G. F. Crempien[1,2] and Ralph J. Archuleta[3,4]

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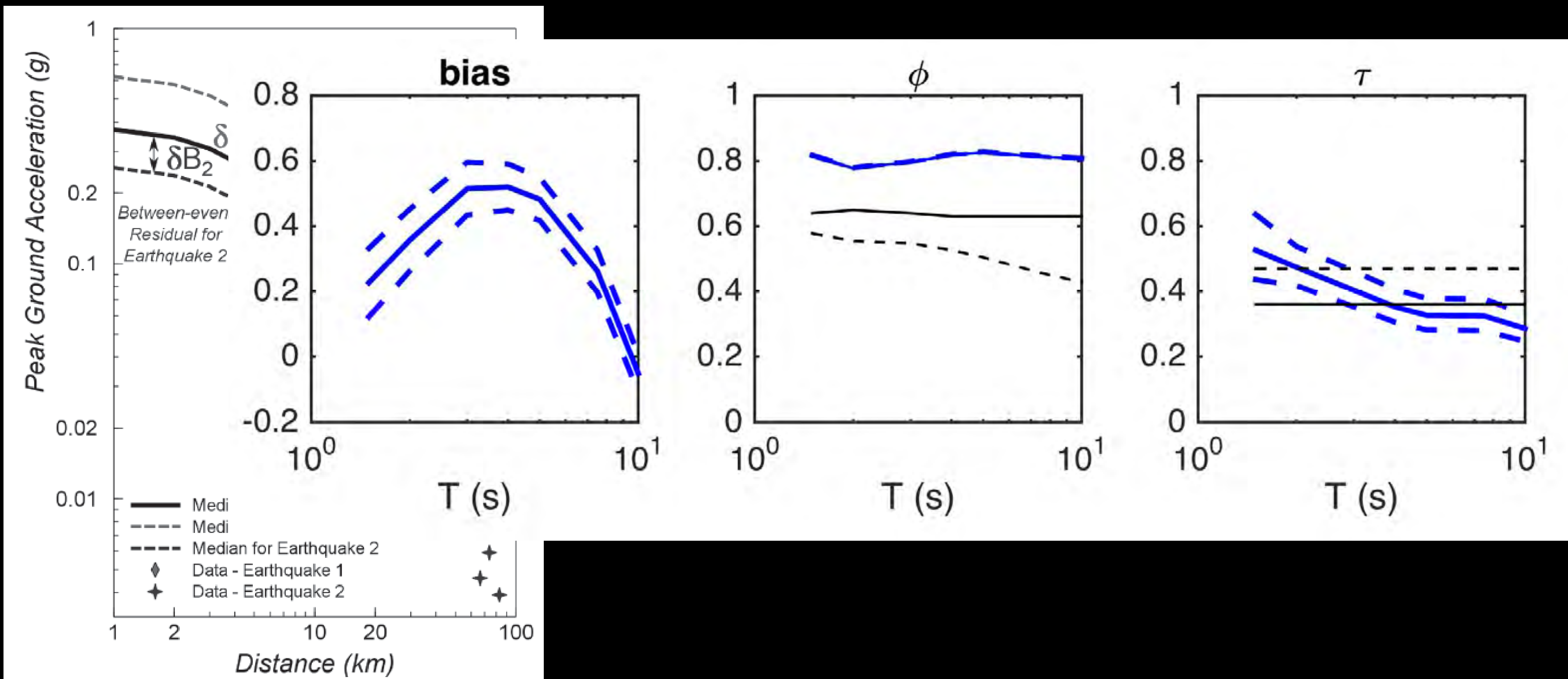
Comparison of simulated ground motions with empirically based GMPEs



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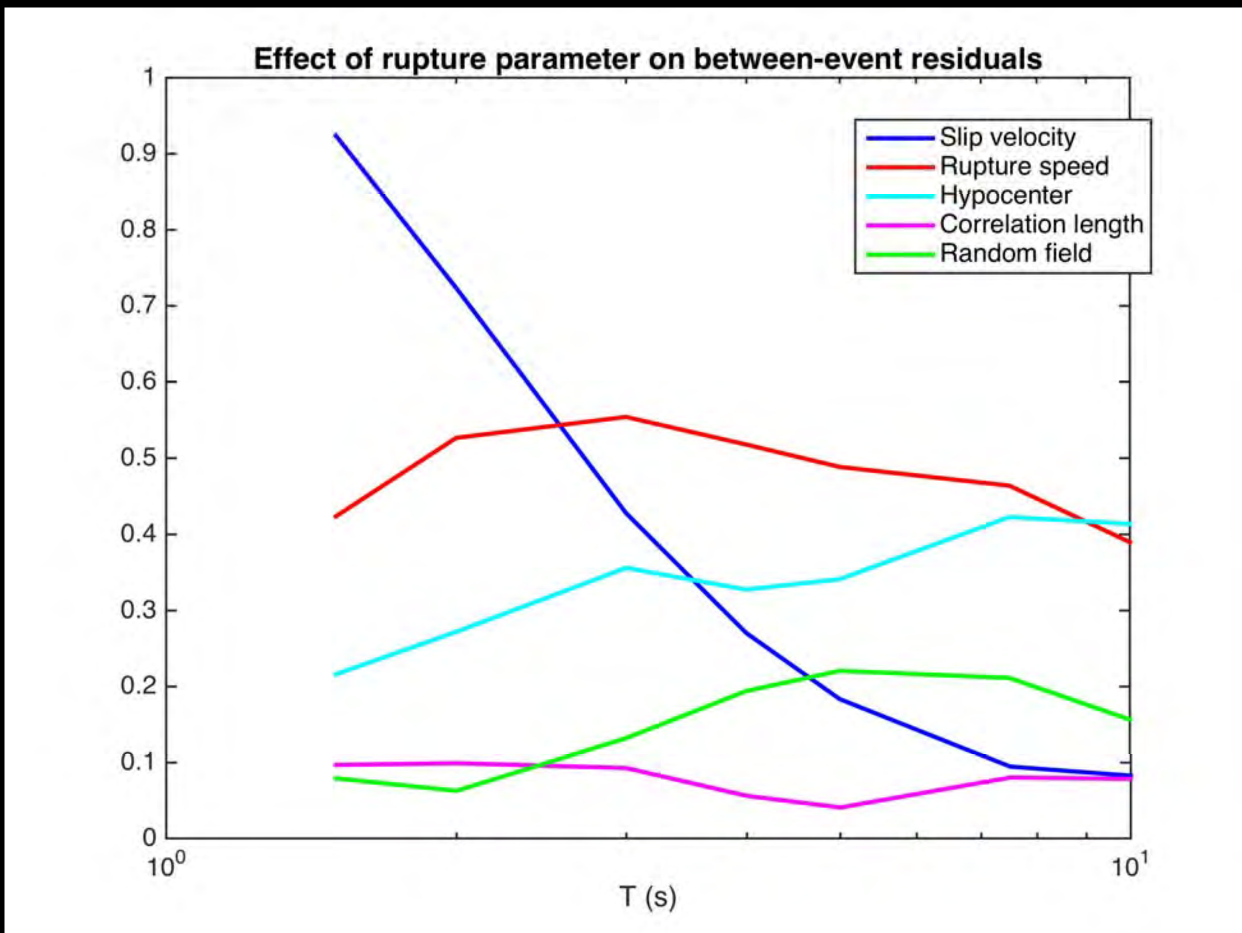
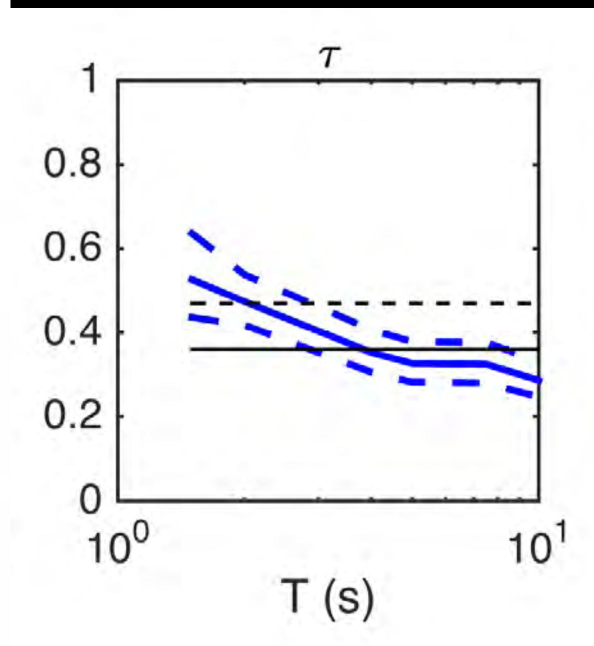
Comparison of simulated ground motions with empirically based GMPEs





Conclusions and future directions

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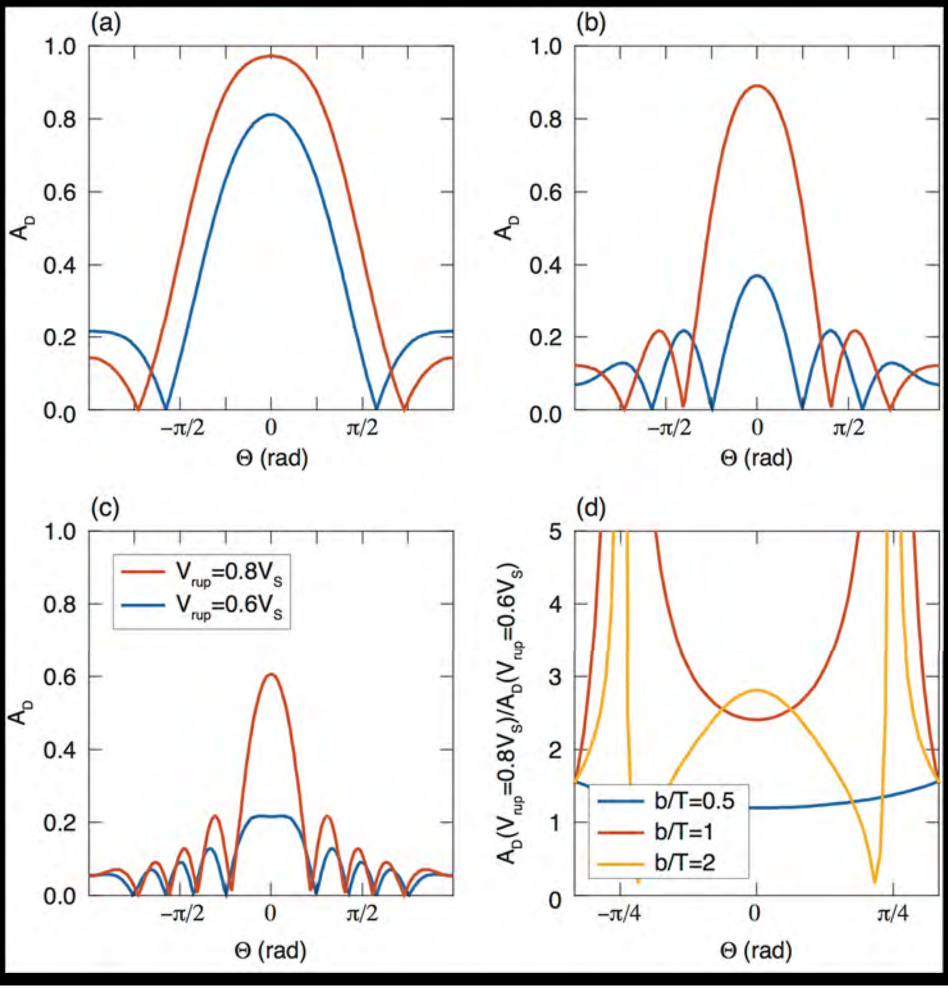
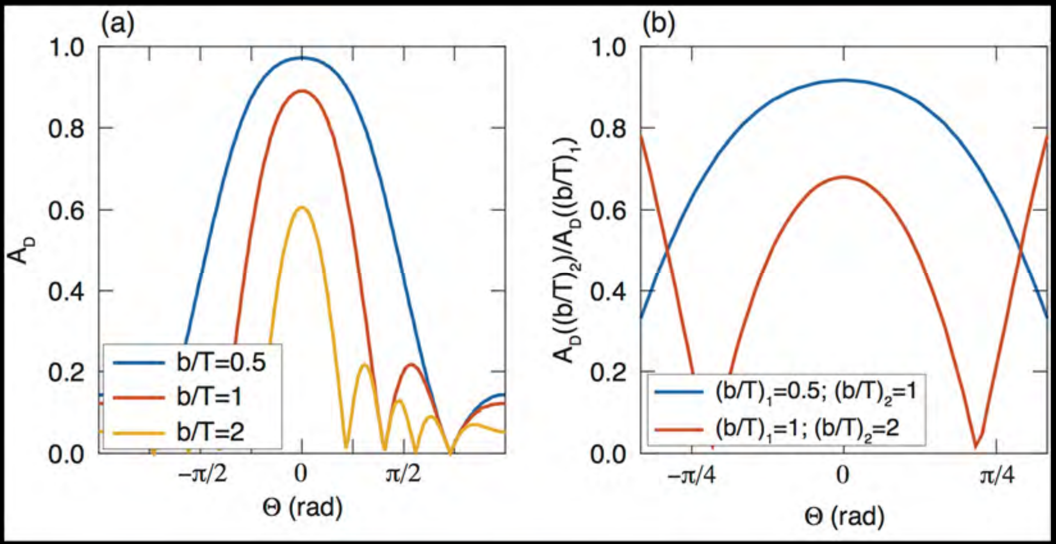
Rupture directivity, Ben-Menahem (1961, 1962)





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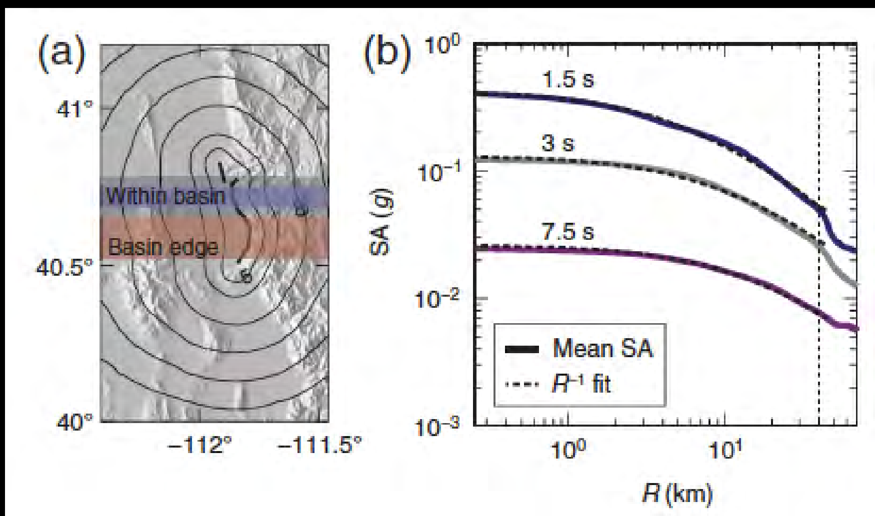

$$\mathrm{SA_{Sim}}(T,R) = \frac{\mathrm{SA}_0(T)}{1+\left(\frac{R}{R_c(T)}\right)}$$

T (s)	SA_0 (g)	R_c (km)	R^2, All Data
1.5	0.43	5.7	0.47
3	0.13	11.0	0.41
7.5	0.03	16.4	0.39

- Vlpsoh#dqdo|wlfdo#irup#iru#phdq#jurxqg#prwlrqv
- Ghshqghqw#rq#uhihuhqfh#+forvh0lq,#jurxqg#prwlrq#ohyho#dqg#fruqhu#glvwdqfh
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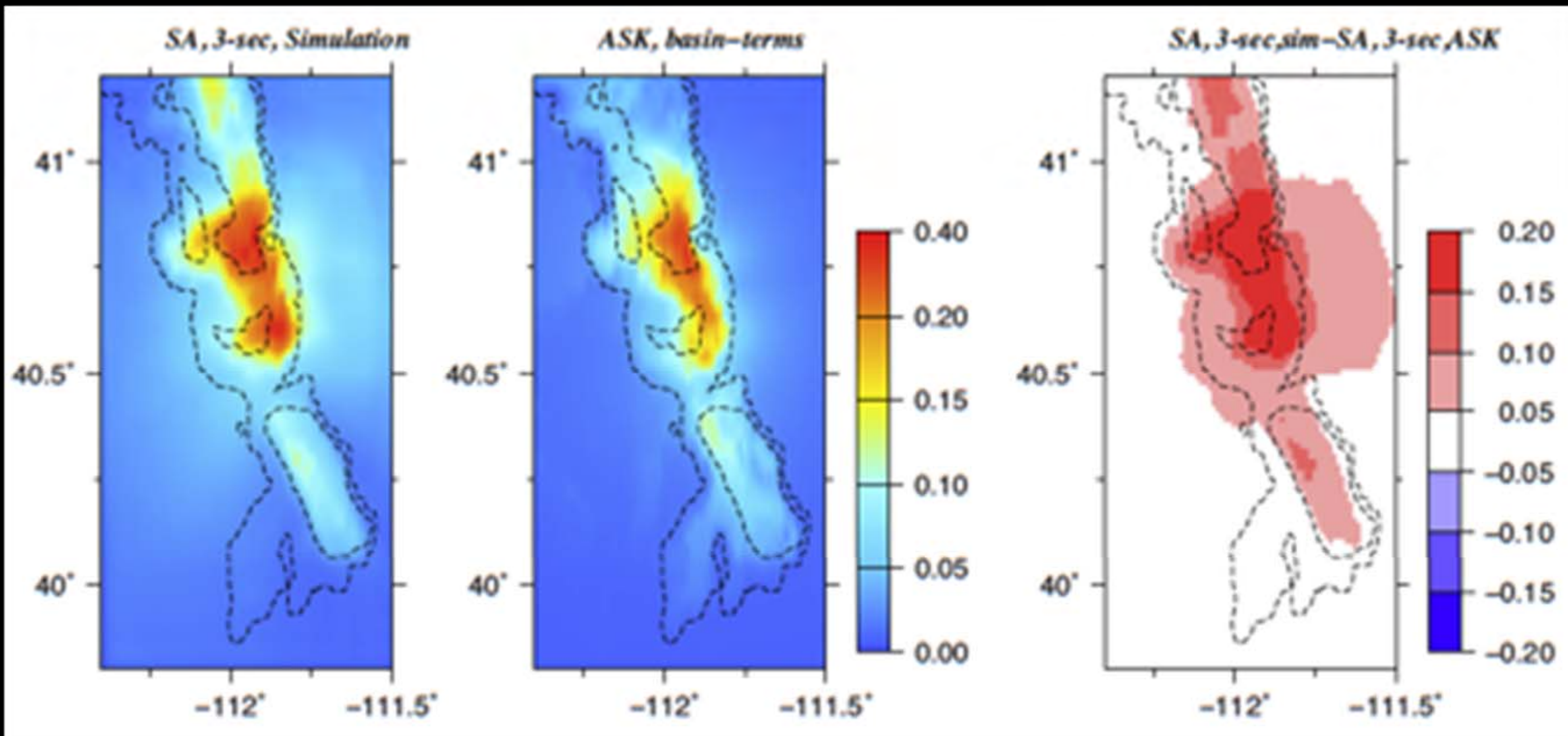
[redacted]

Probabilistic ground motions, 2% PE 50 years



3D Dynamic Rupture Simulations along the Wasatch Fault

Kyle Withers[1]

Utah Ground Shaking Working Group

Morgan Moschetti[1] and *Kenneth Duru*[2]

[1]Geologic Hazard Science Center, USGS, Golden, CO

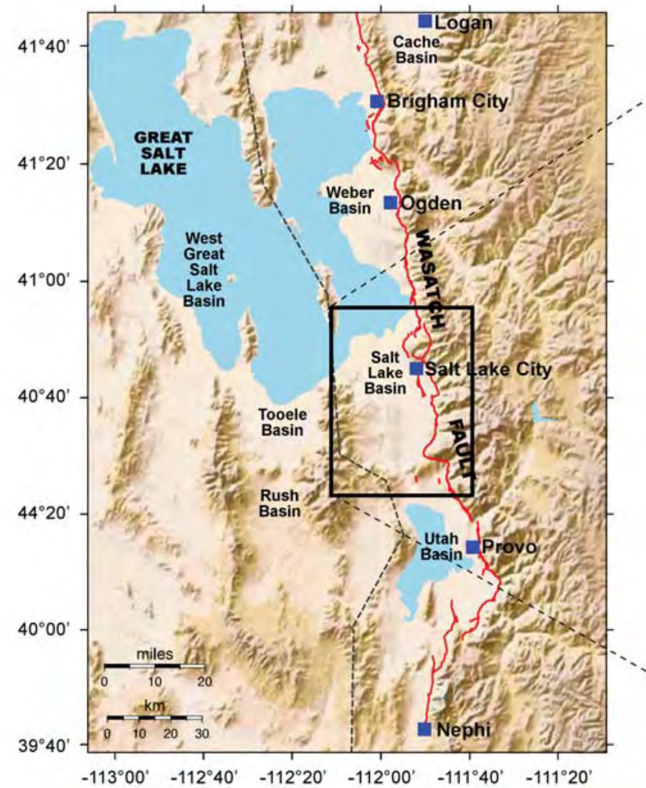
[2]Department of Earth and Environmental Sciences, LMU Munich

Outline

- Objectives and Motivation: extend ground motion to frequencies of interest to engineers along normal faults, specifically the Salt Lake City segment of the Wasatch Fault
- Limitations of kinematic techniques
- Approach: fully physics-based spontaneous earthquake ruptures
- Simulations: initial conditions and example ruptures
- Results: rupture and ground motion analysis
- Conclusions and future work

Objectives

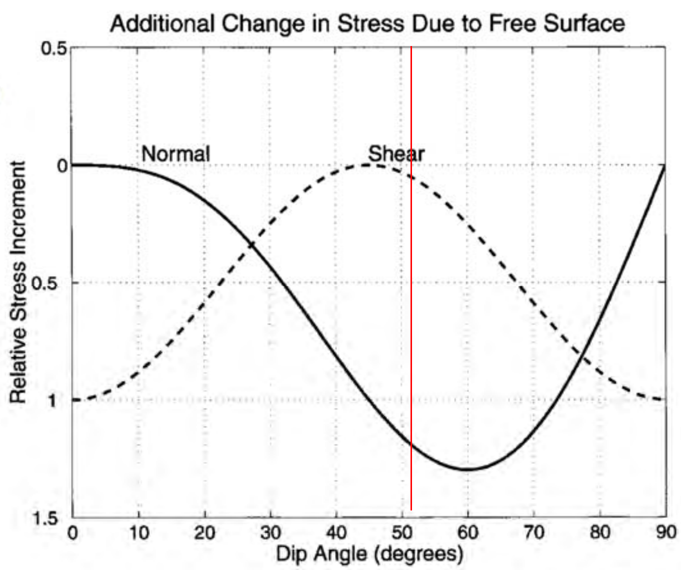
- Better constrain seismic hazard in bandwidth important for engineers (0.1 -10 Hz), particularly in data lacking regions along dip-slip faults
- Determine influence of fault geometry and topography on both rupture and ground-motion amplification
- Develop database of ruptures for Salt Lake City segment of Wasatch Fault, Utah

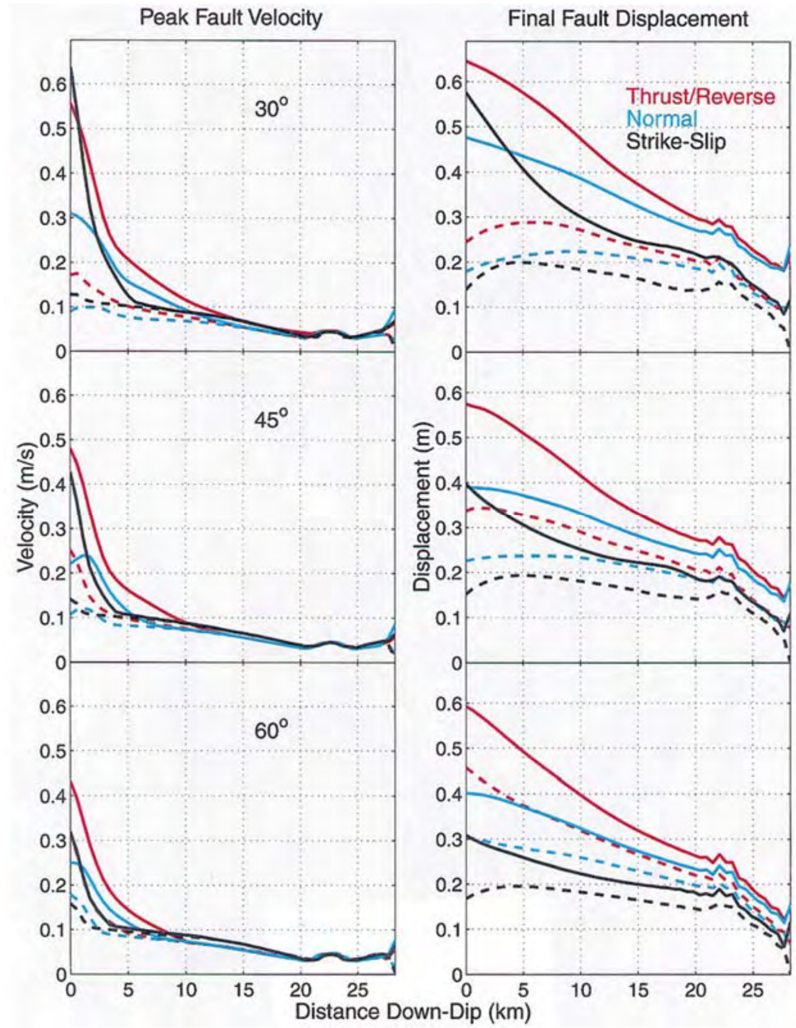


Limitations of Kinematic Simulations

- Asymmetric geometry of dip-slip faults can have large effects on the dynamics of earthquake rupture, leading to larger motion on the FW than the HW.

$$\Delta\tau = -\tau\cos^2 2\theta$$
$$\Delta\sigma_n = -4\tau\sin^3\theta\cos\theta$$

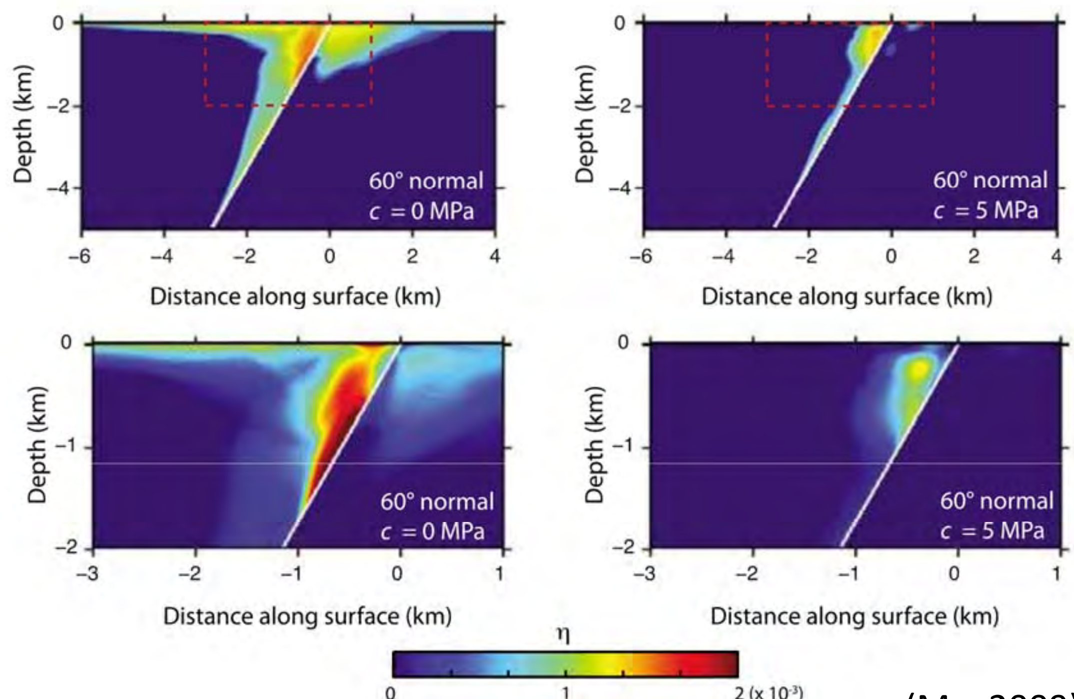




Oglesby et. al., 2000

Asymmetry in rupture-induced inelastic strain across dipping faults

- Inelastic strain is larger and broader in the HW compared to the FW, leading to reduced asymmetry in ground motion across the HW and FW (compared to elastic solutions)



(Ma, 2009)

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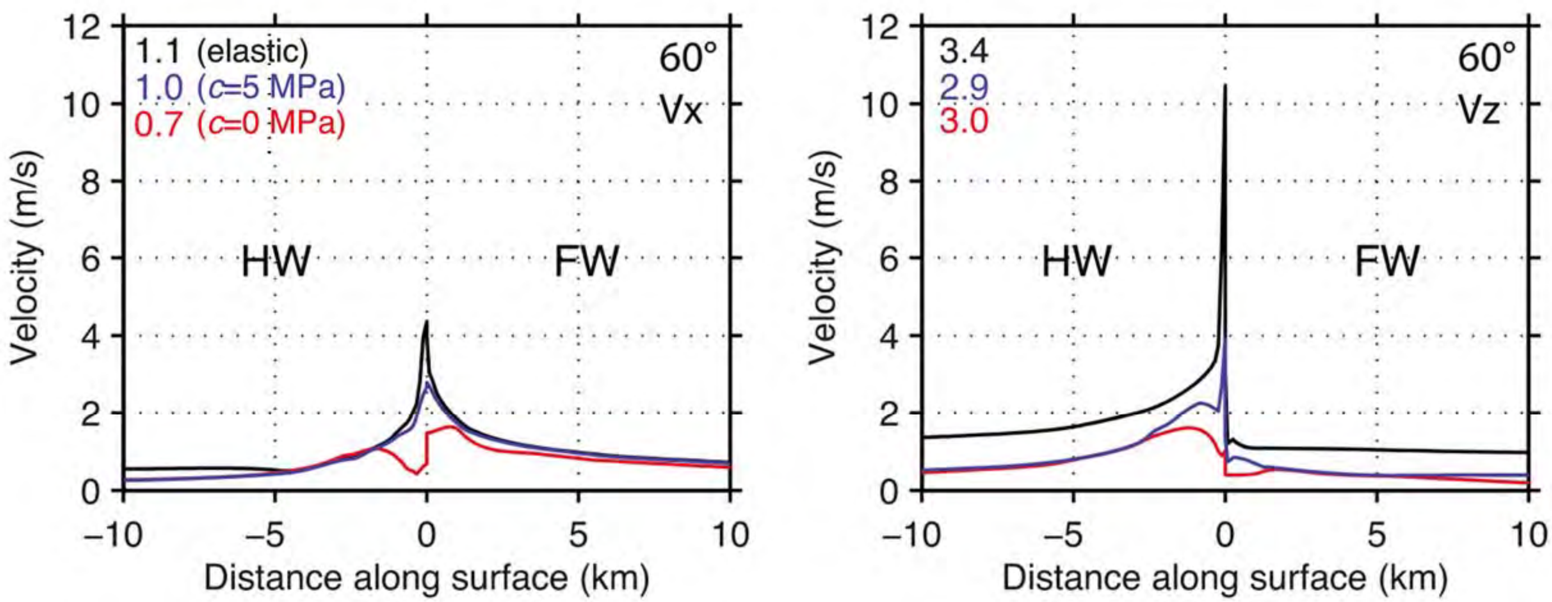
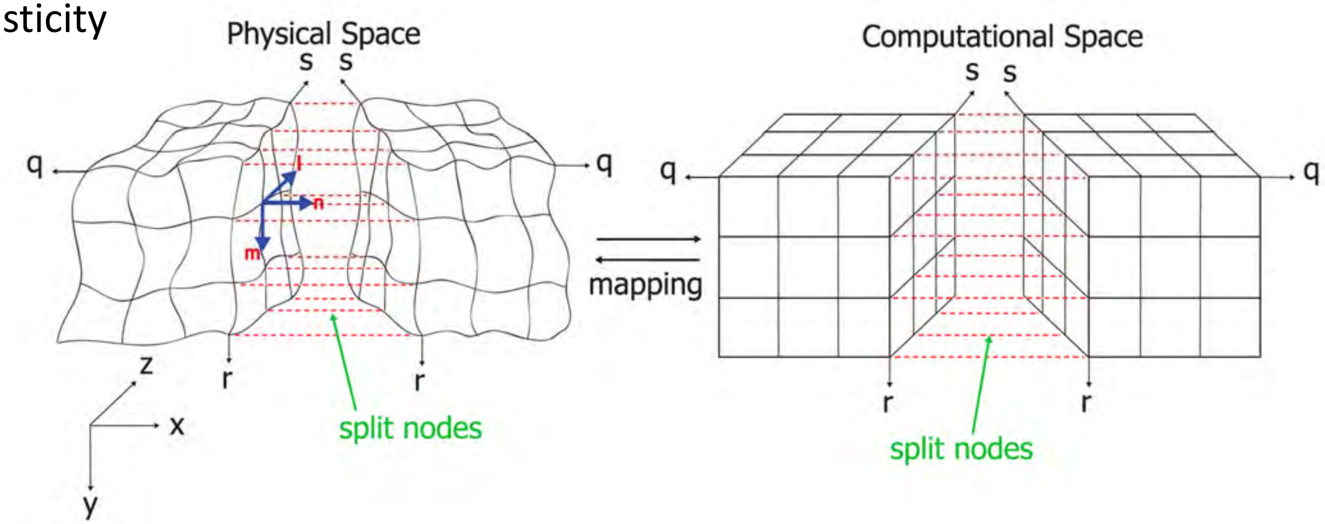


(Ma, 2009)

Waveqlab3D (Finite Difference Quake and Wave Laboratory)

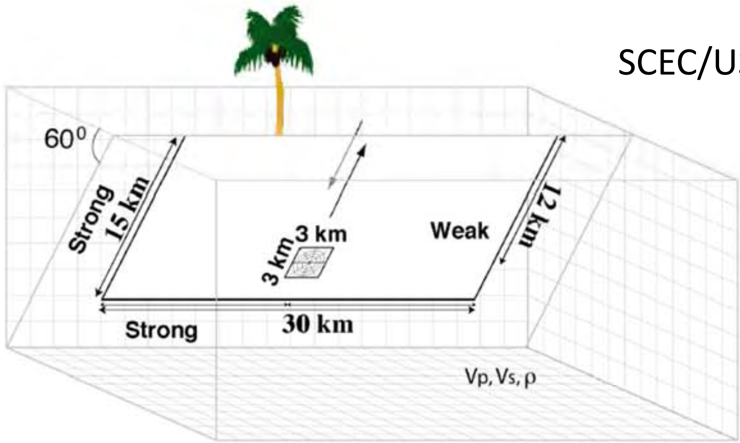
- Finite difference summation-by-parts dynamic rupture (and wave-propagation) code can handle
  - complex fault geometry (both short and long-wavelength variations)
  - nonlinearity, i.e. off-fault plasticity
  - 3D media heterogeneity
  - anelastic attenuation, Q(f)
  - free-surface topography

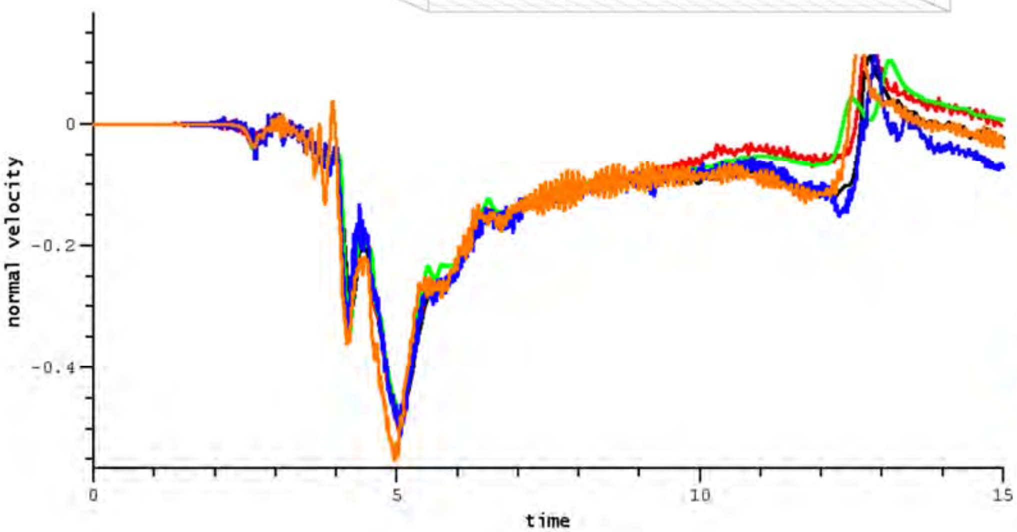


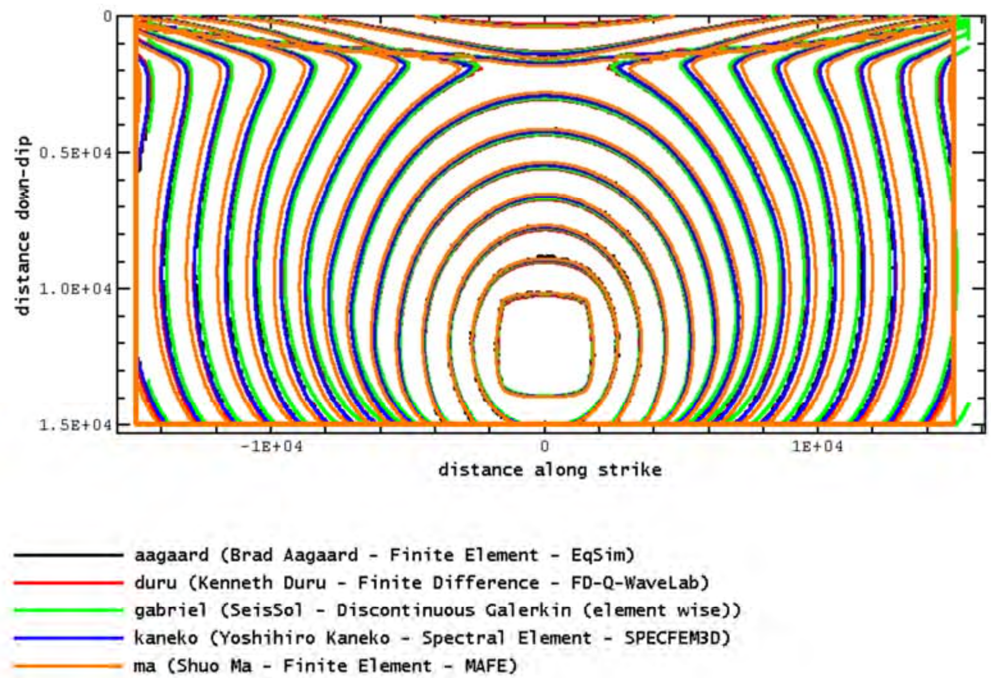
Duru and Dunham, 2016

Dynamic Rupture Validation along a Dipping Fault

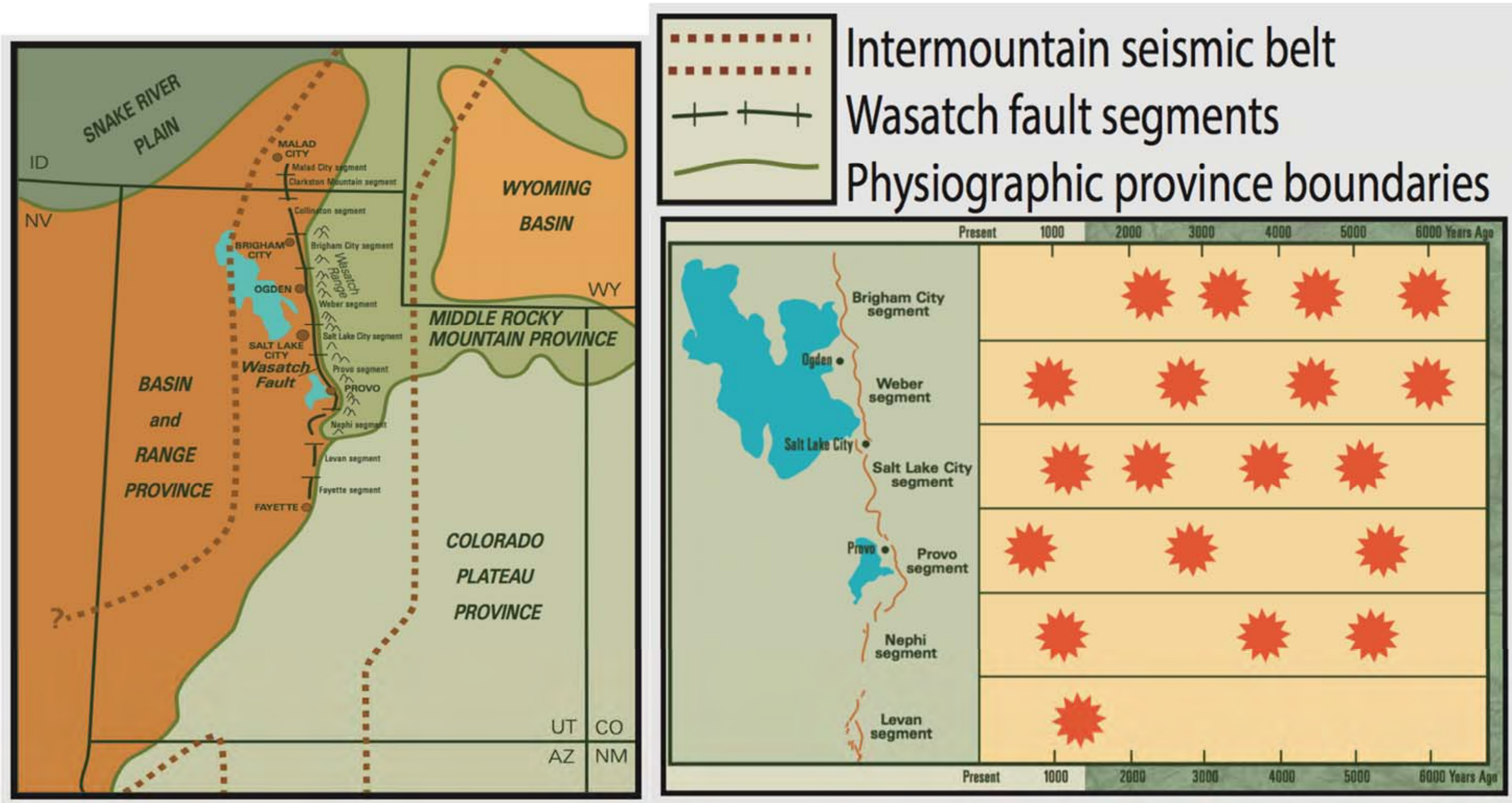
SCEC/USGS Spontaneous Rupture Code Verification Project: TPV10-13





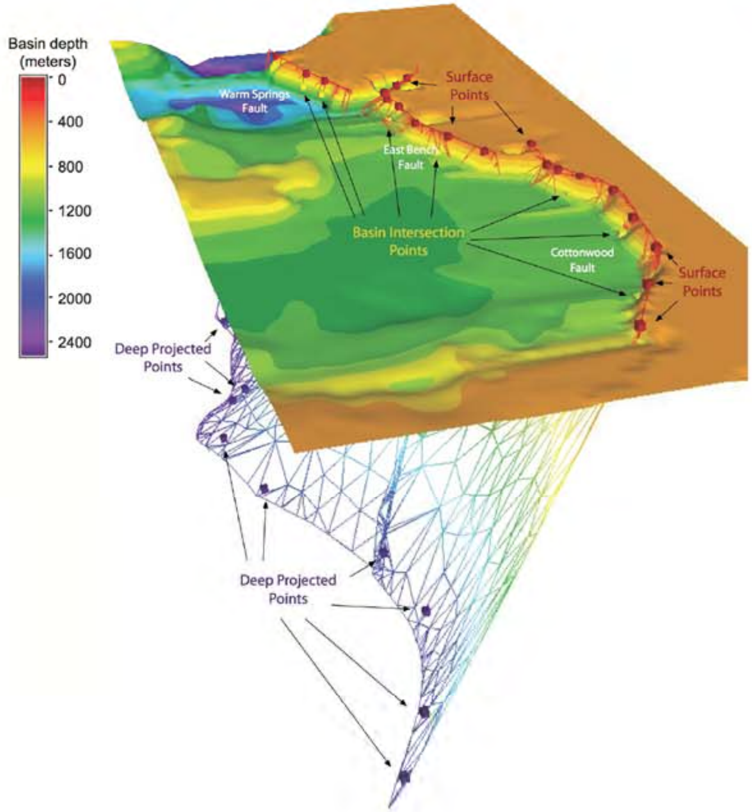


Study Area: Wasatch Fault Zone

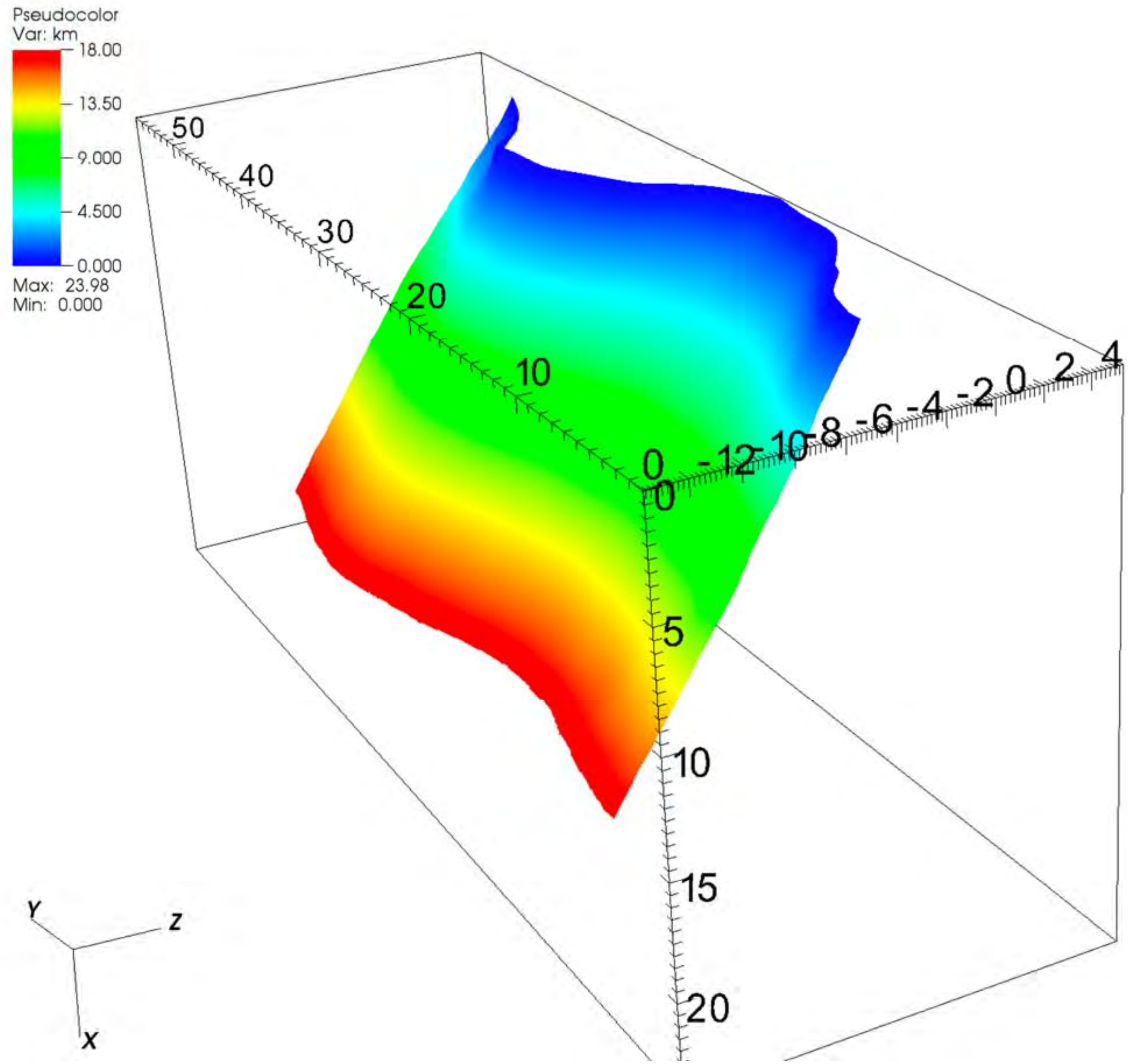


Extracted from “Utah Geological Survey Public Information Series 40: The Wasatch Fault.”

Fault Geometry

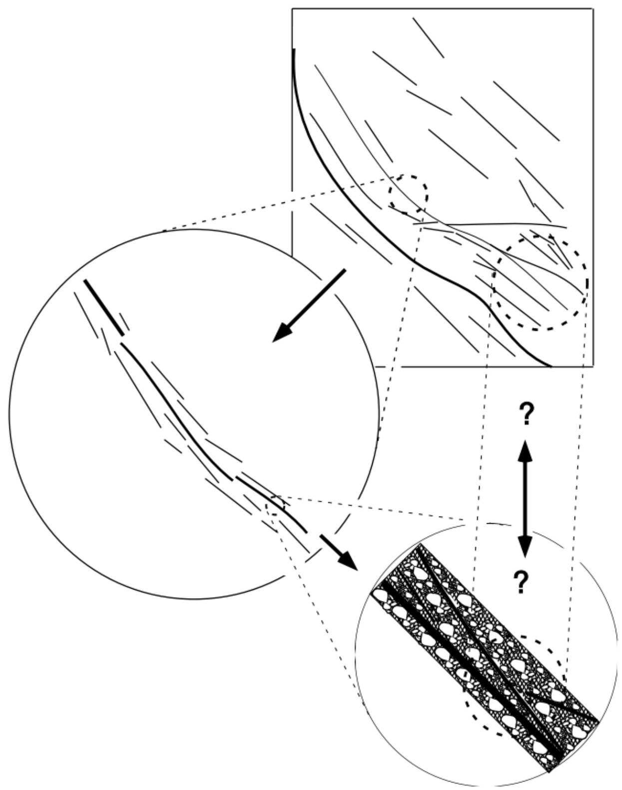


(Moschetti, 2017)

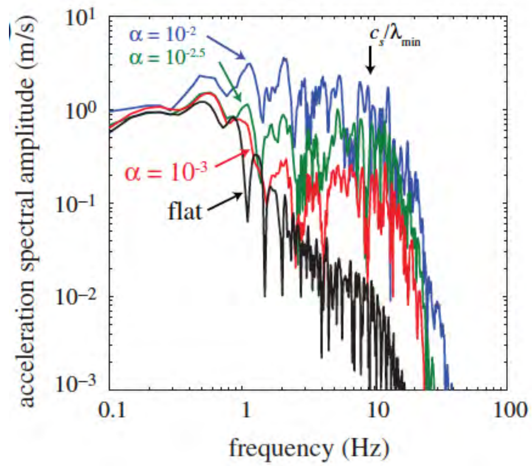


Rough Faults

- Roughness is observed at all scales



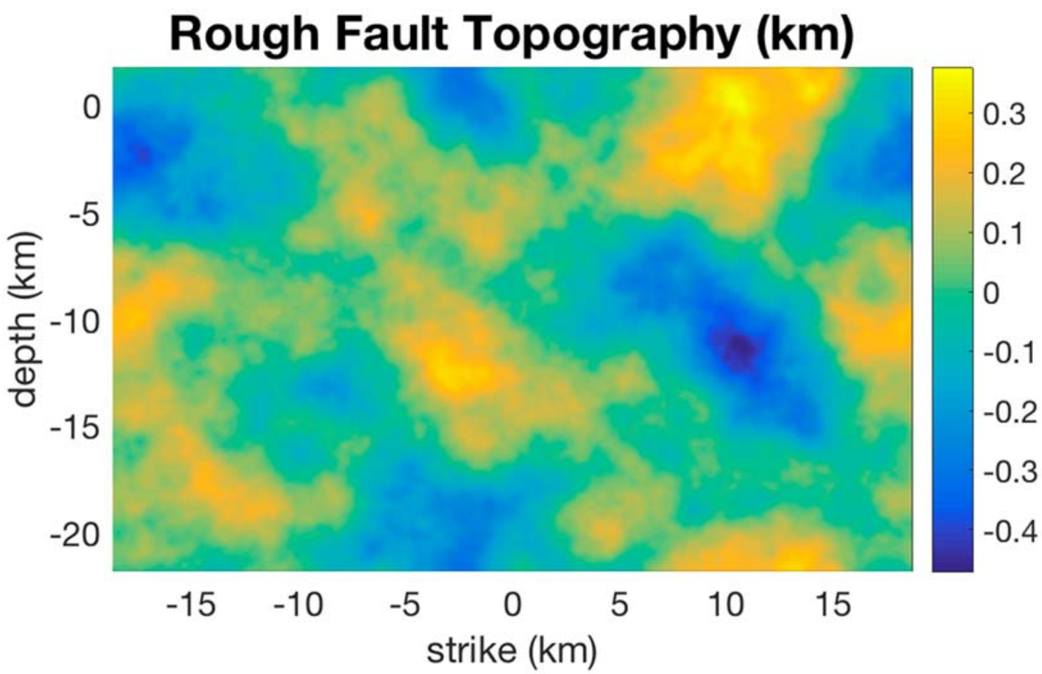
(Ben-Zion, 2003)



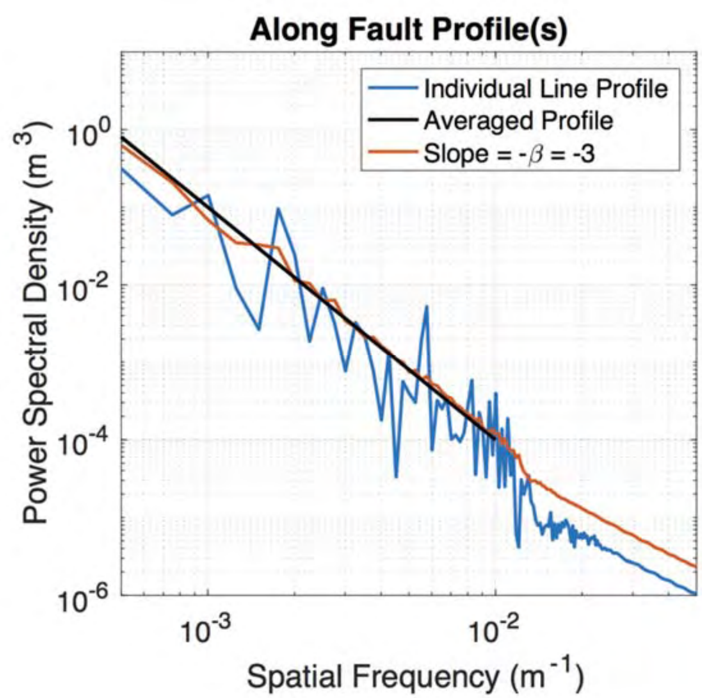
(Dunham, 2011)

Rough Fault Complexity

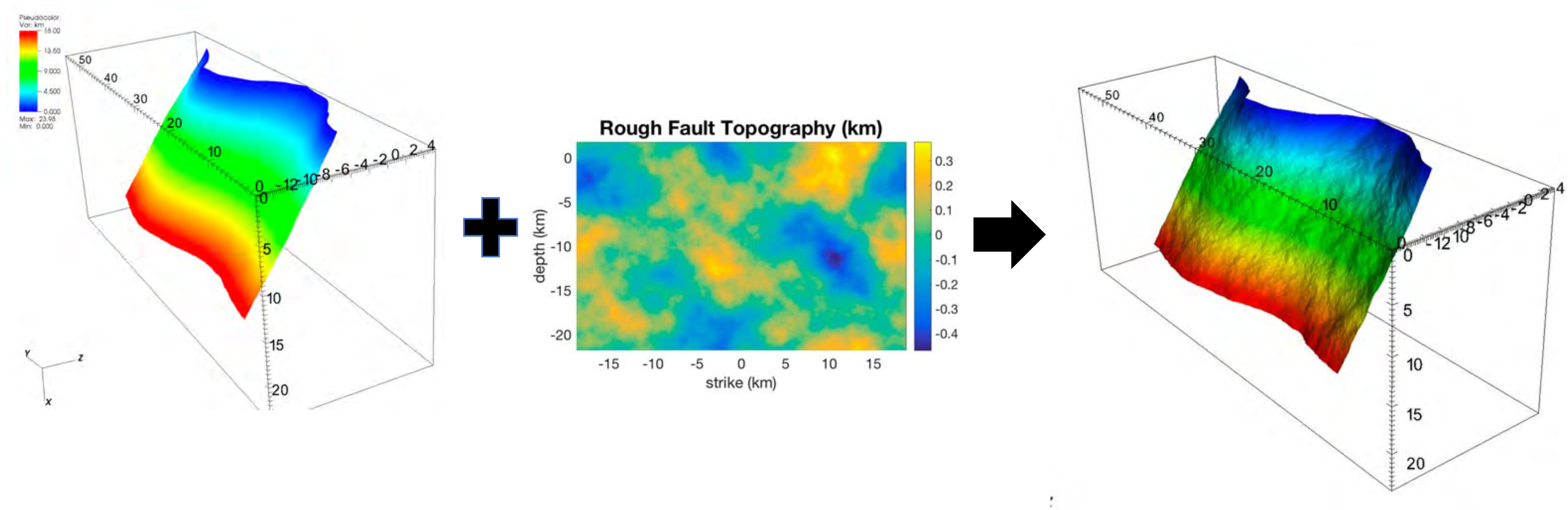
α = 0.05



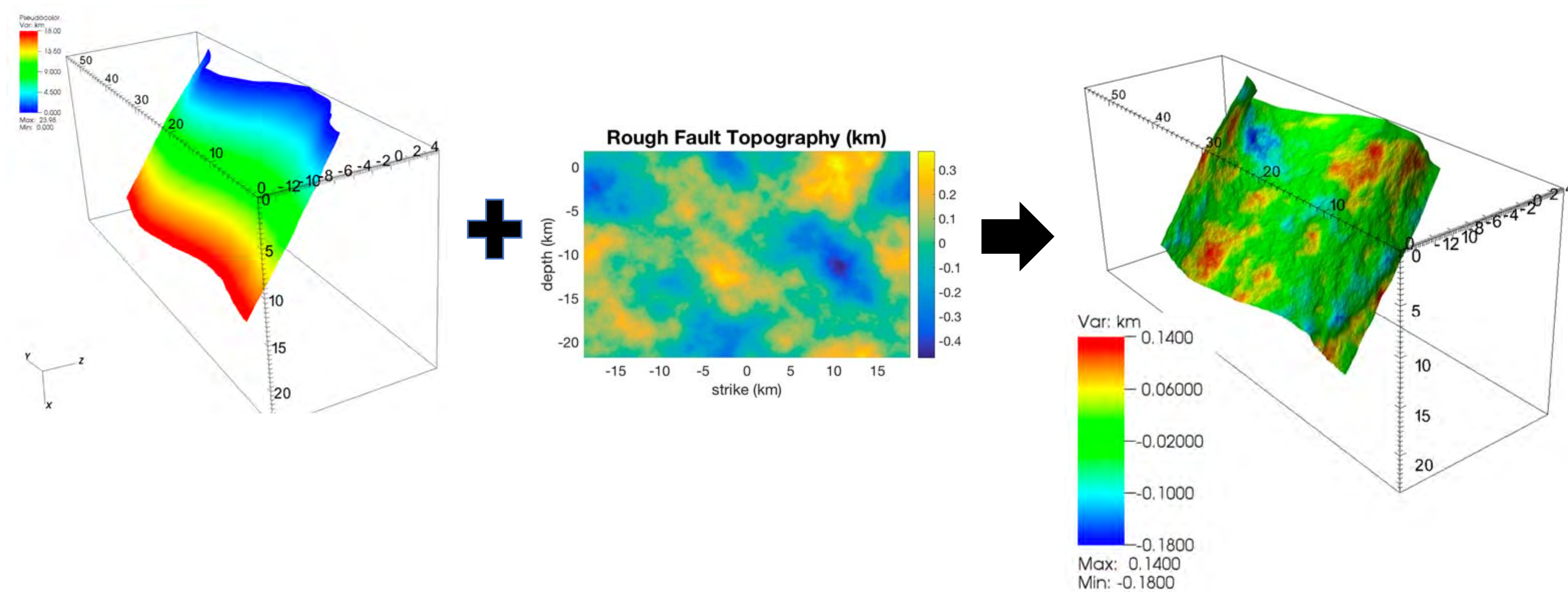
Hurst Exponent = (β-1)/2 = 1



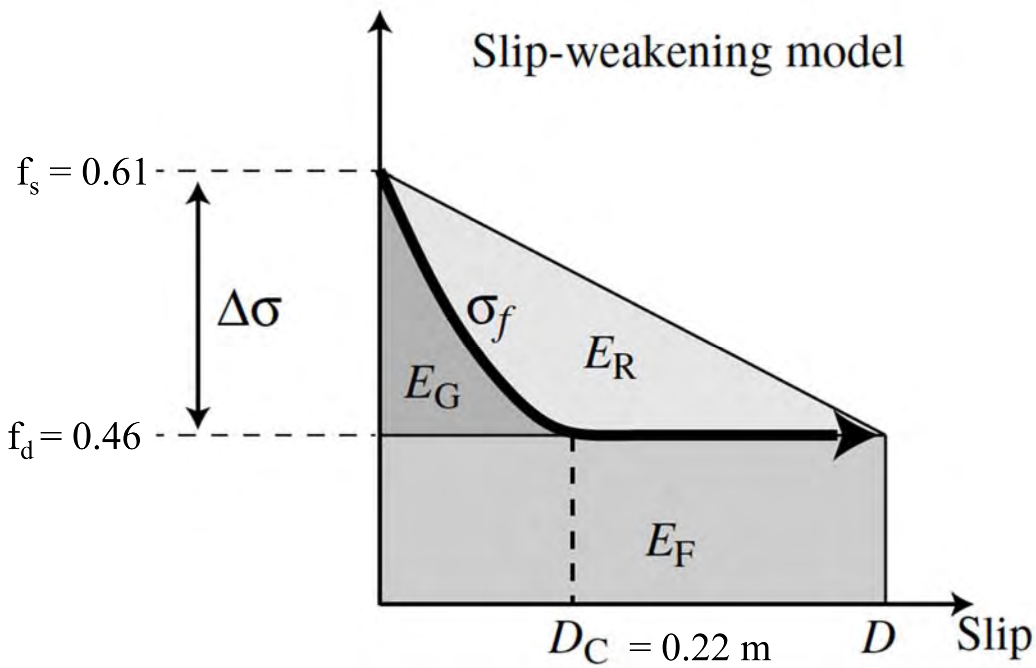
Superimposing Fault Roughness

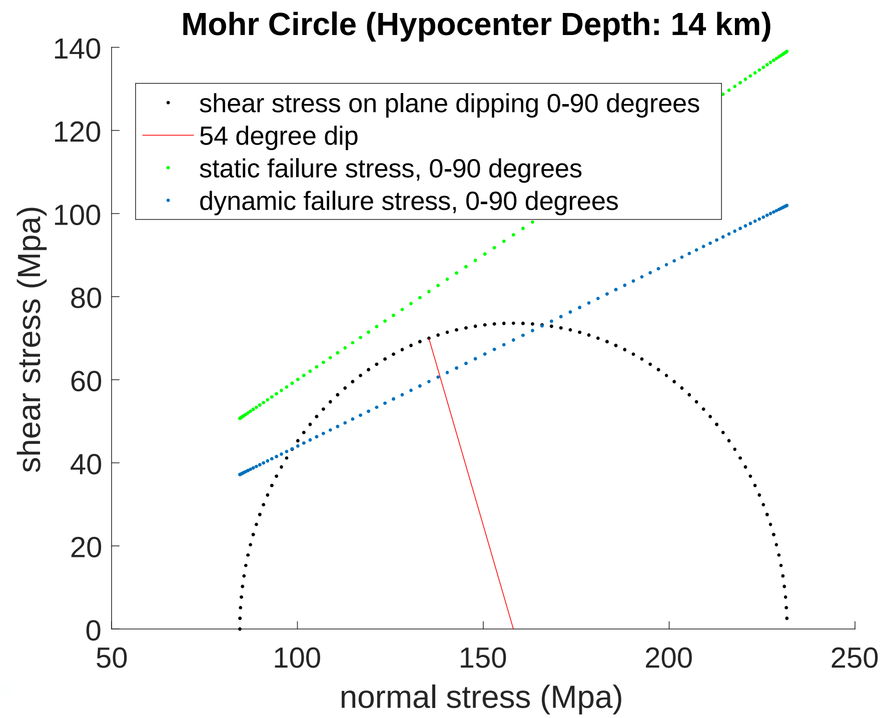


Superimposing Fault Roughness (Difference)

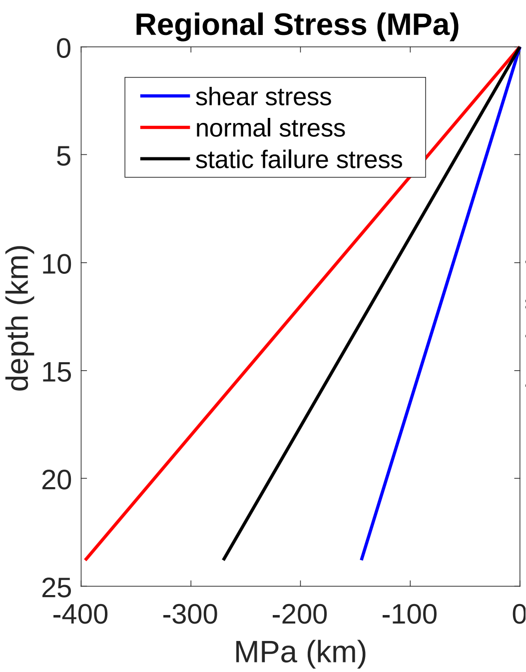


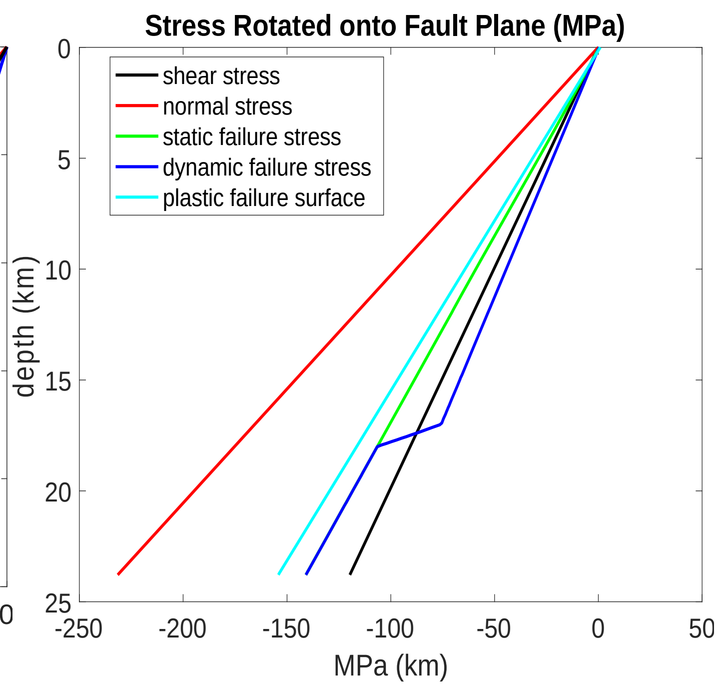
Friction Parameters





Initial Stress Conditions



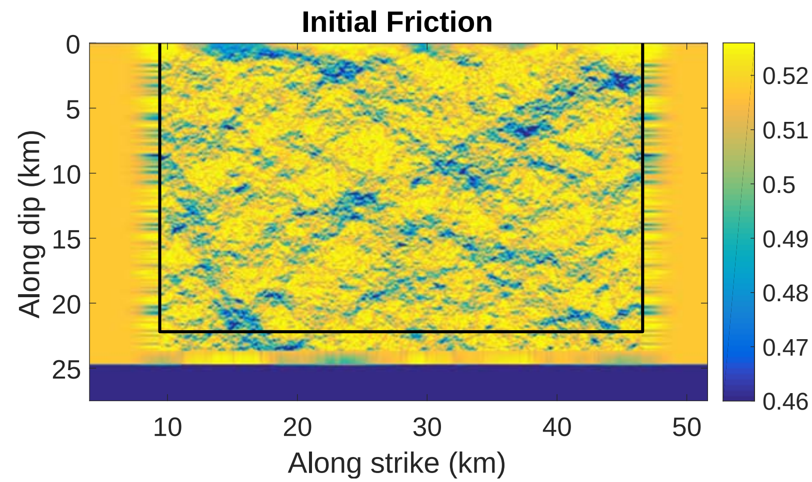


Plastic Parameters:

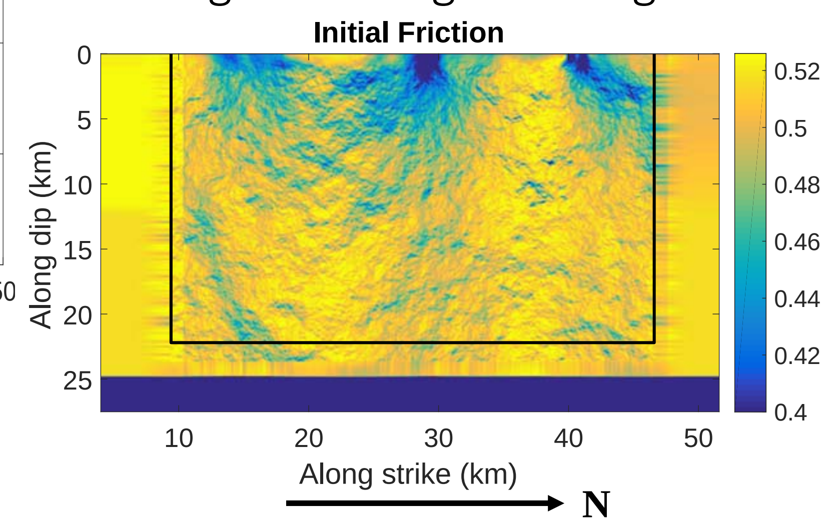
cohesion = 1.18 MPa

$\phi = 0.7$

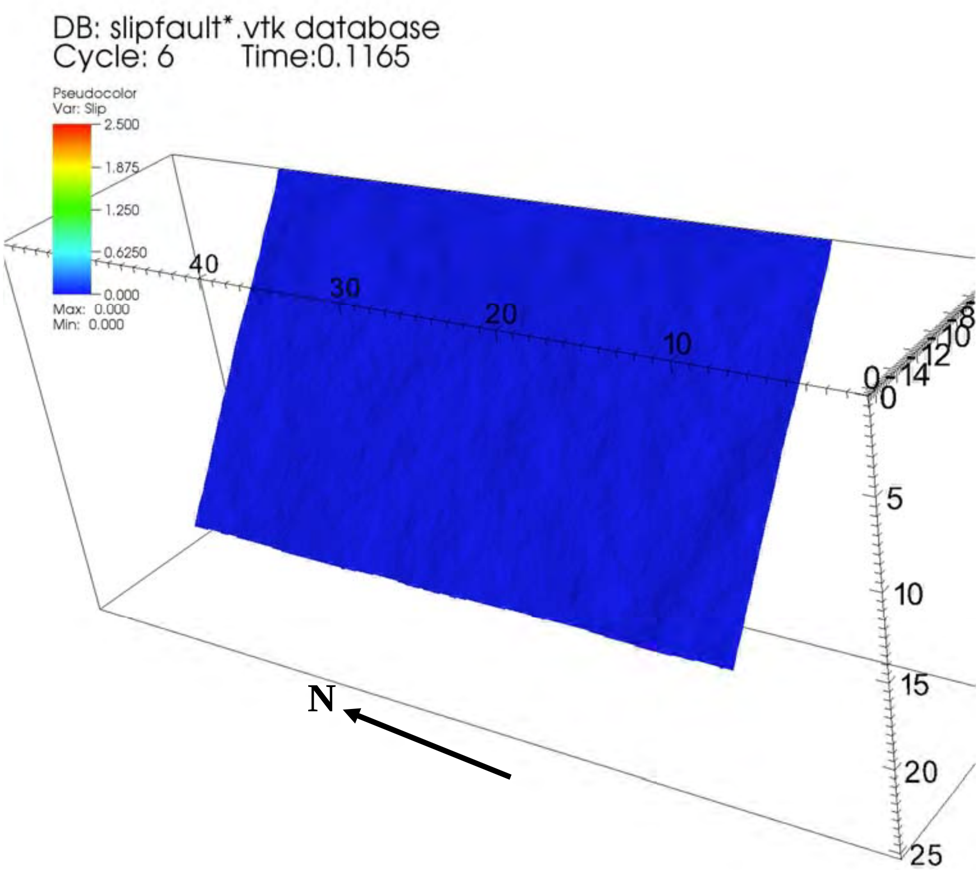
Background Planar + Roughness

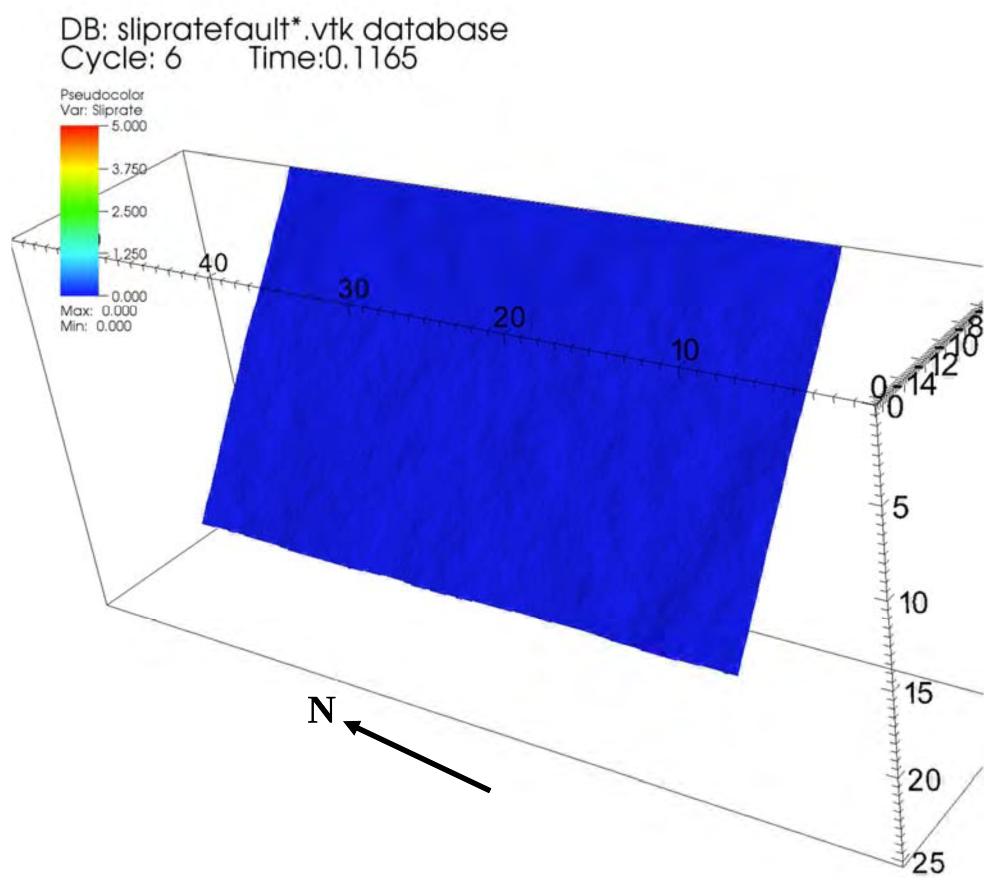


Long-Wavelength + Roughness

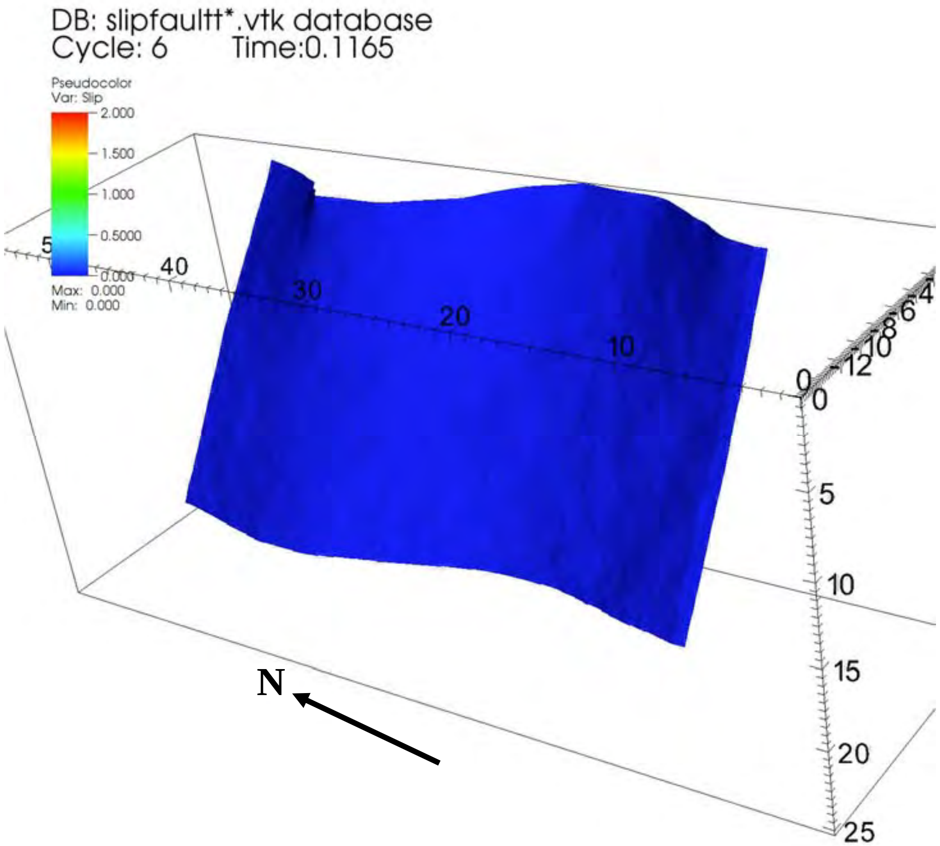


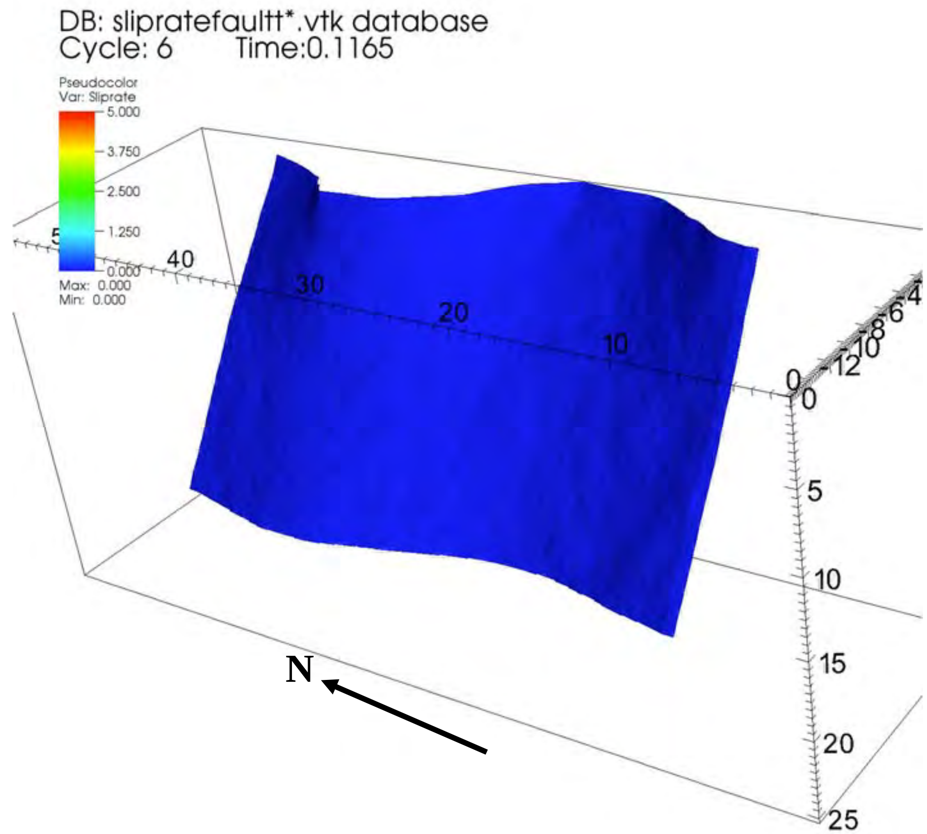
Animations of Slip and Slip-rate



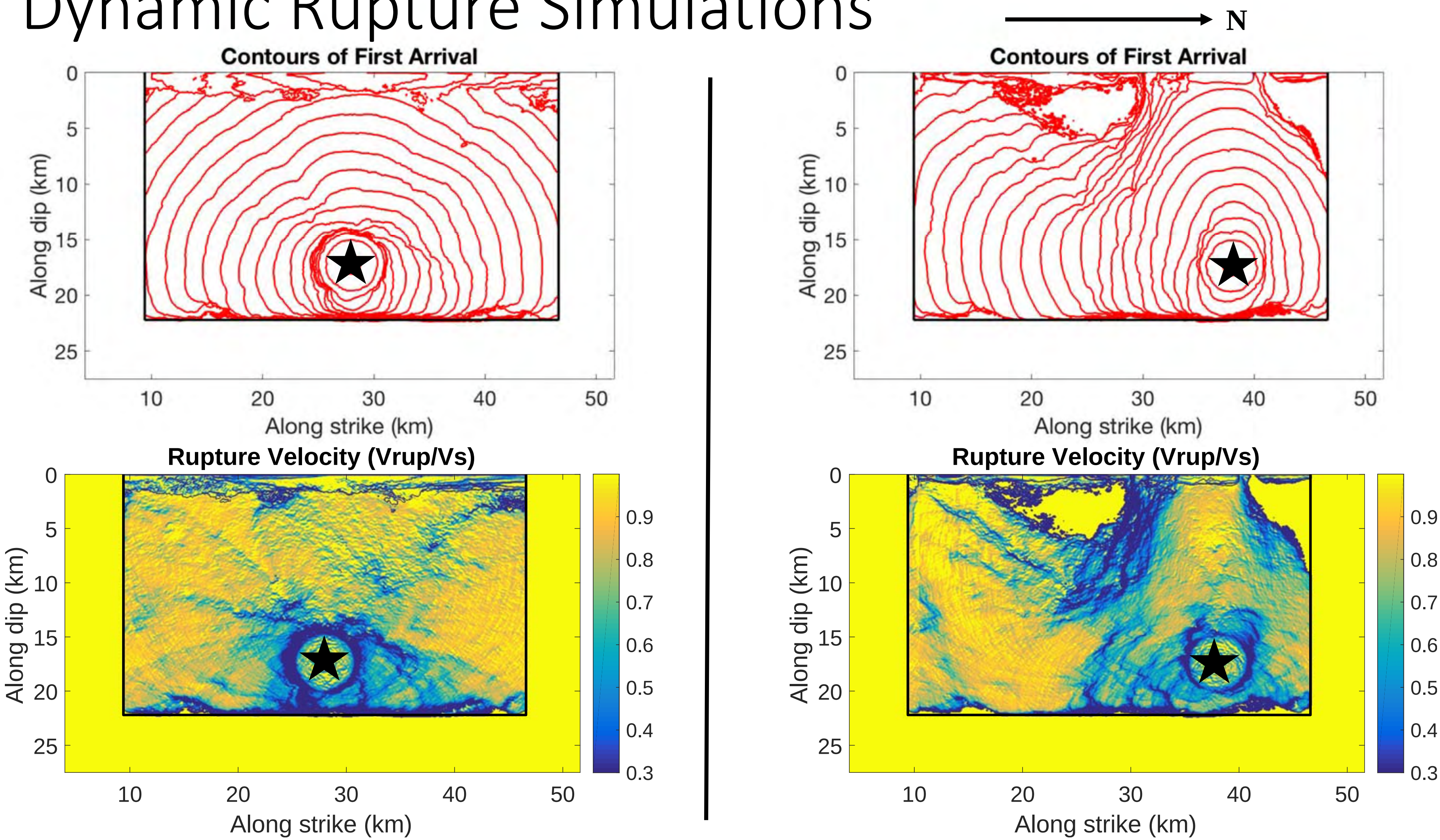


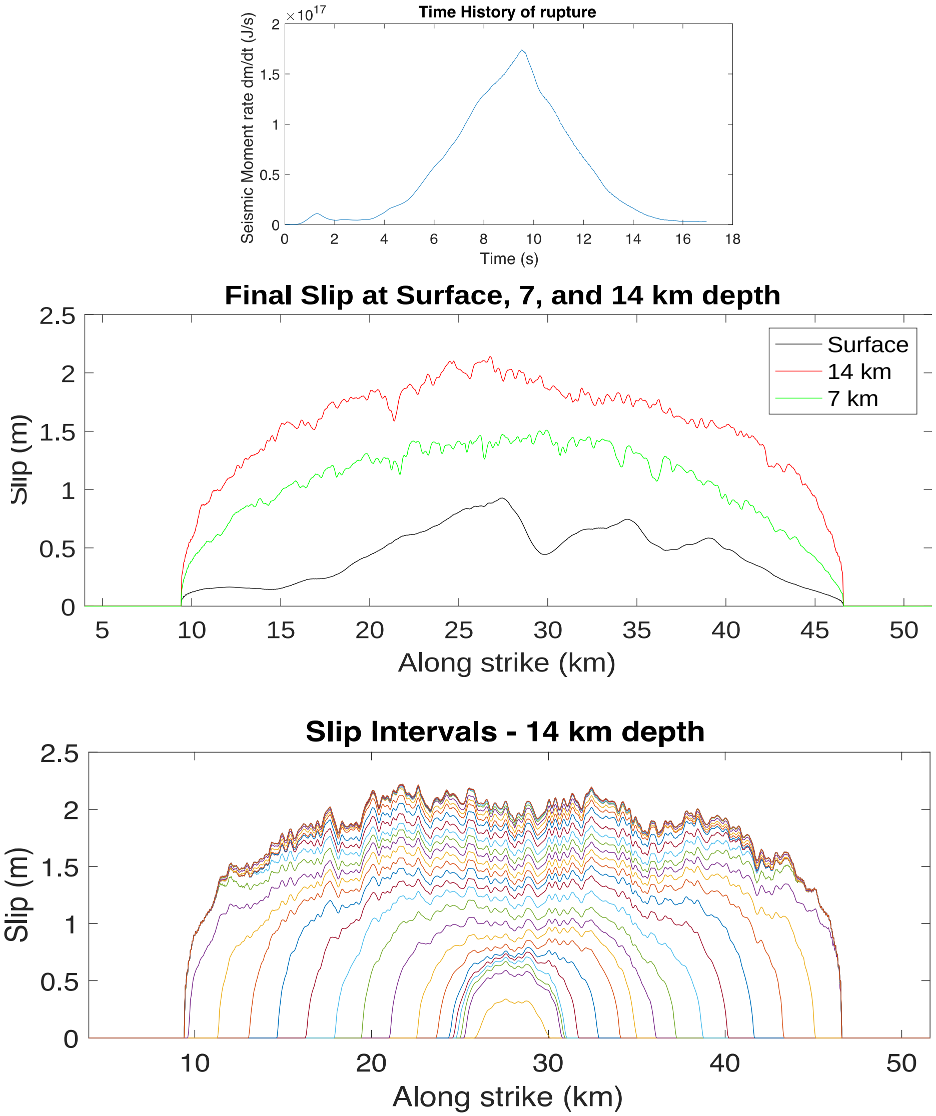
Animations of Slip and Slip-rate



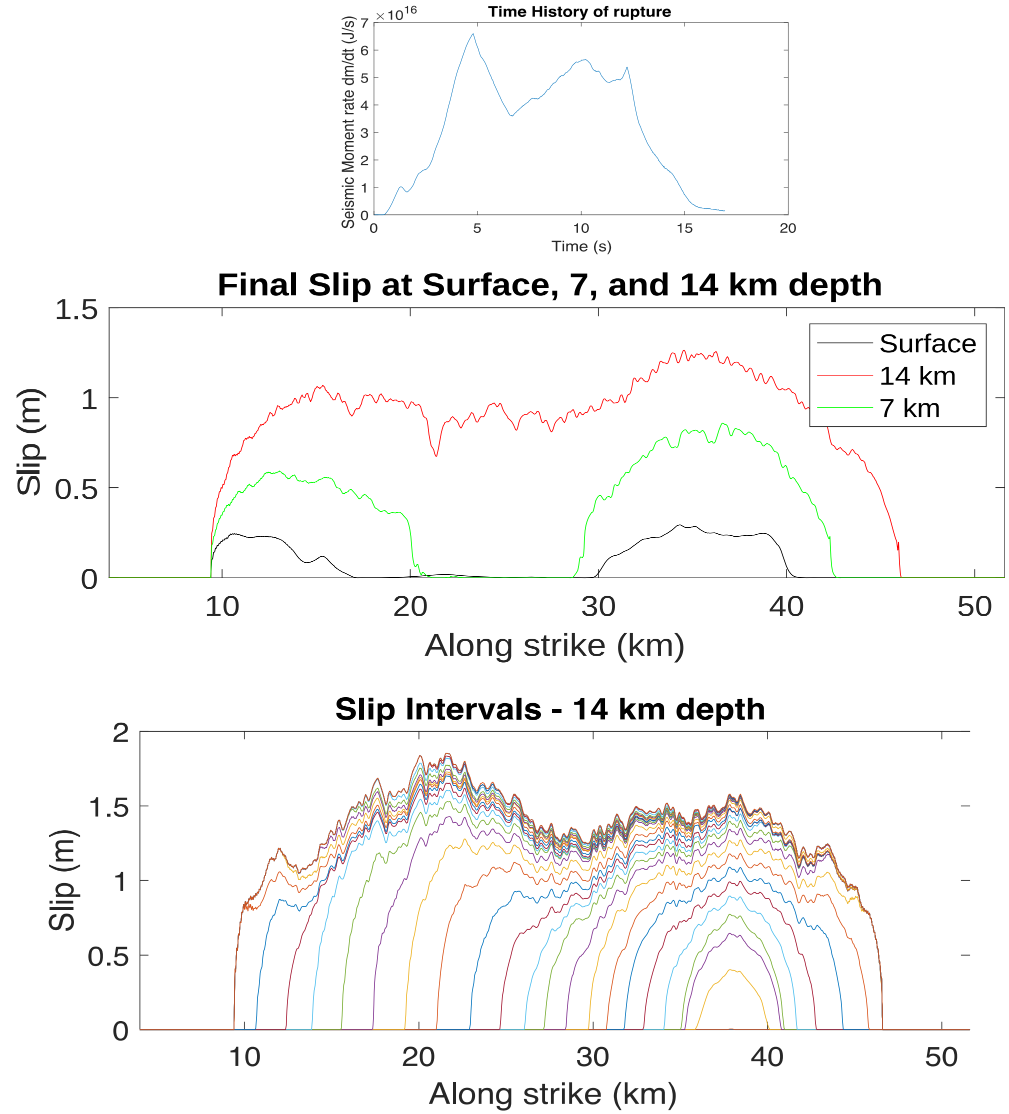


Dynamic Rupture Simulations



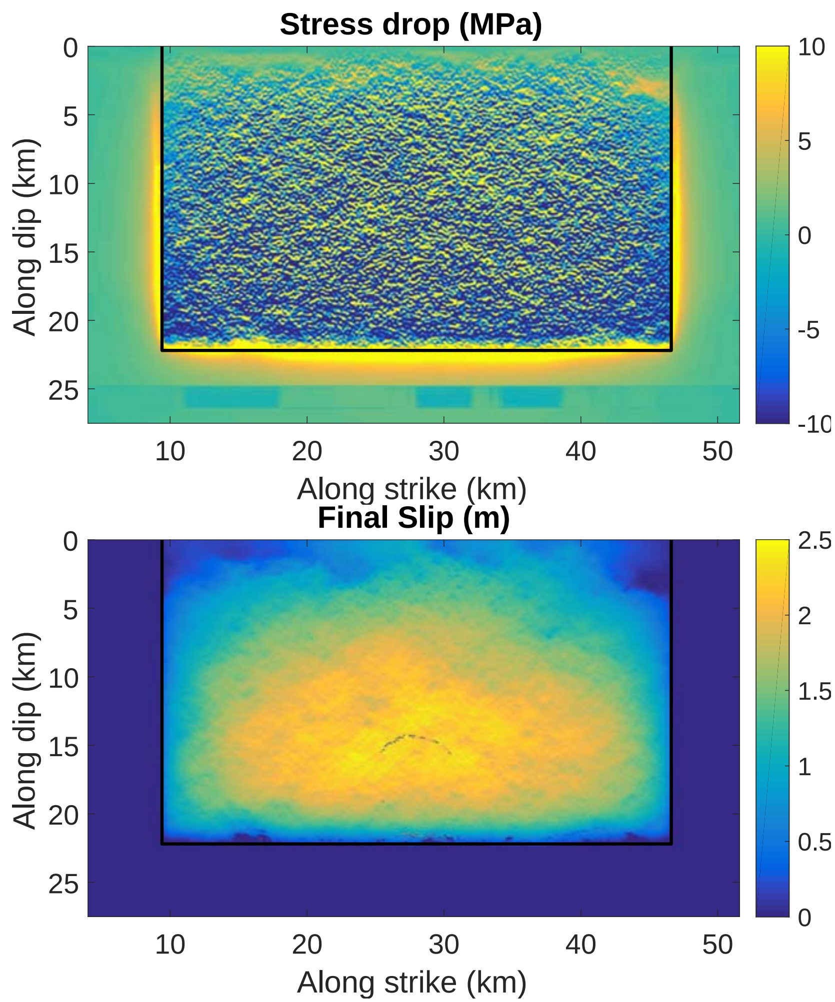


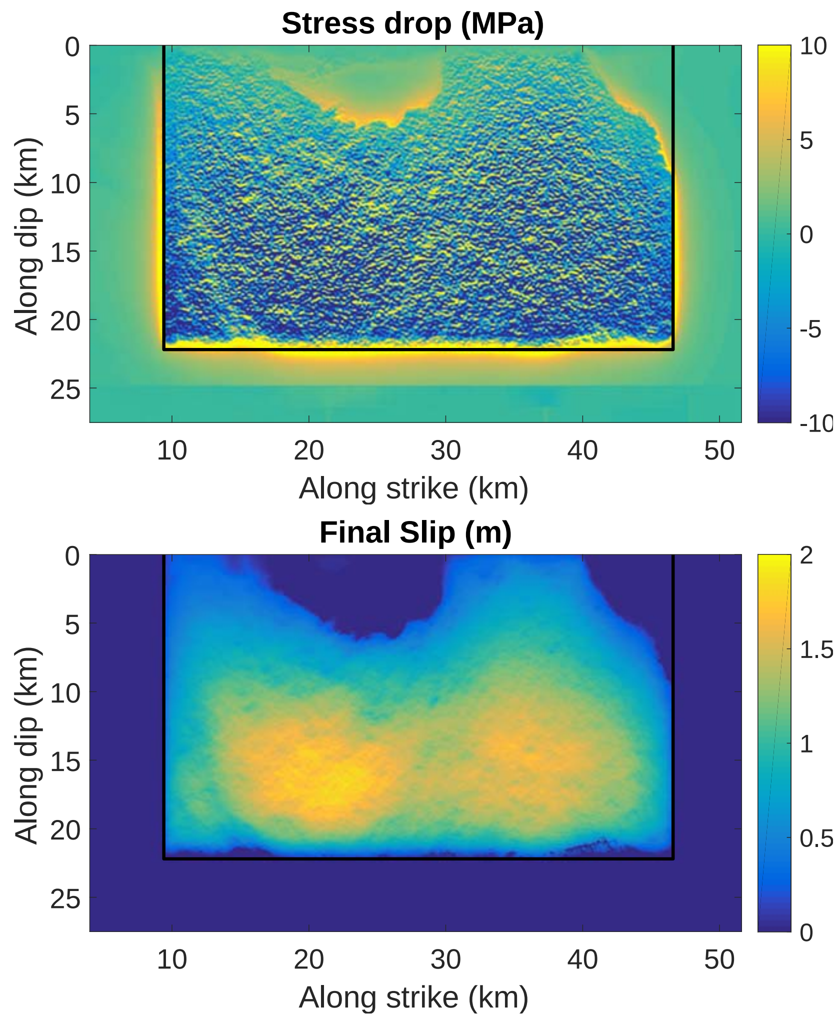
Time History of rupture
Seismic Moment rate dm/dt (J/s)
×10^17
Time (s)
Final Slip at Surface, 7, and 14 km depth
Surface
14 km
7 km
Slip (m)
Along strike (km)
Slip Intervals - 14 km depth
Slip (m)
Along strike (km)



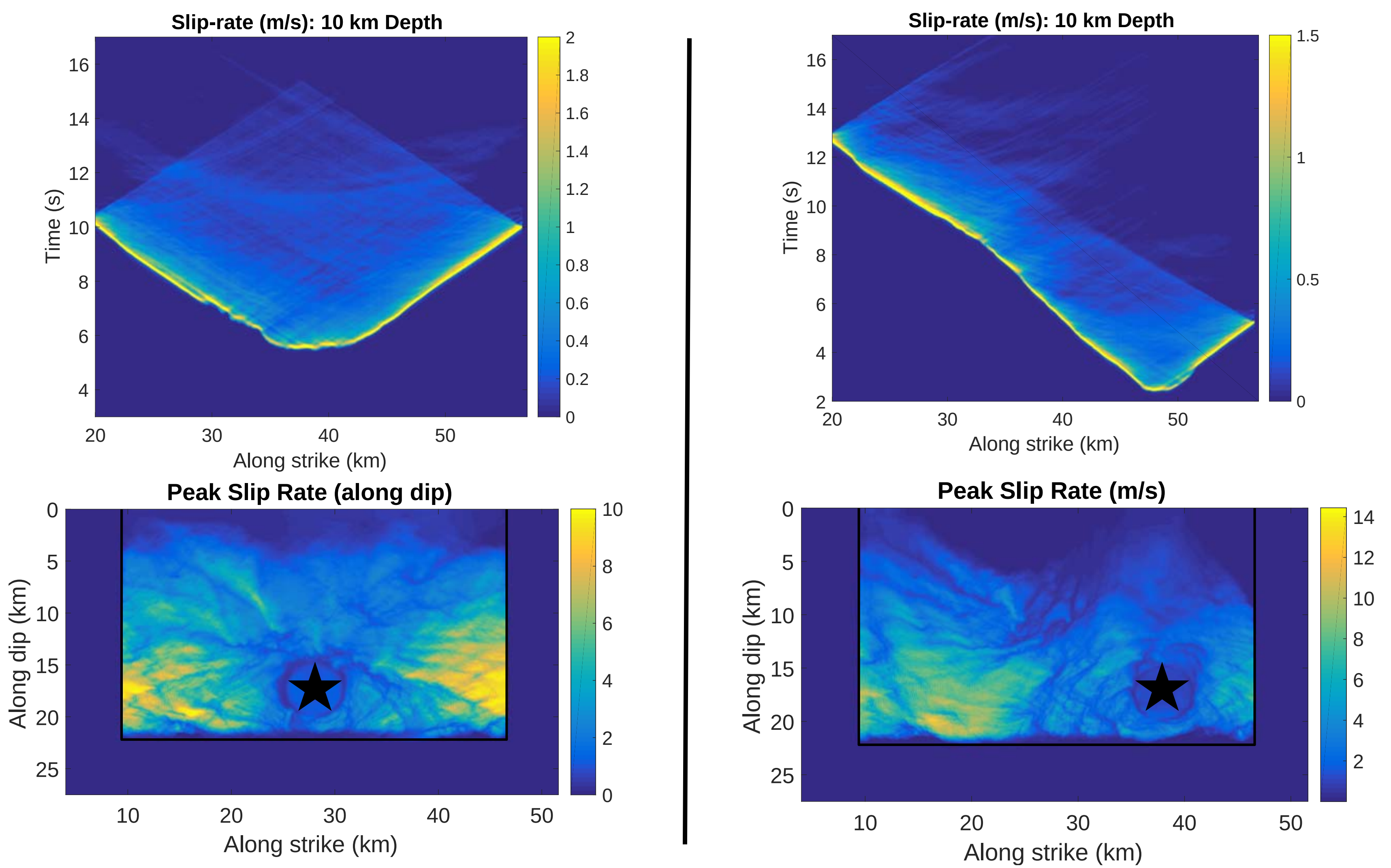
Time History of rupture
Seismic Moment rate dm/dt (J/s)
×10^16
Time (s)
Final Slip at Surface, 7, and 14 km depth
Surface
14 km
7 km
Slip (m)
Along strike (km)
Slip Intervals - 14 km depth
Slip (m)
Along strike (km)

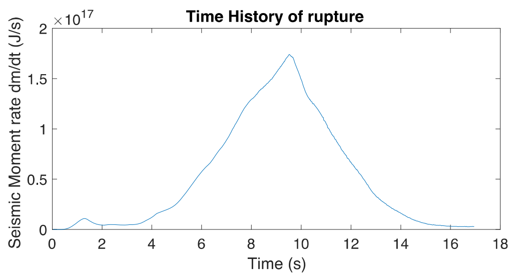
Dynamic Rupture Simulations



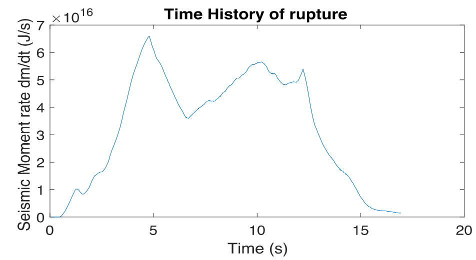


Dynamic Rupture Simulations

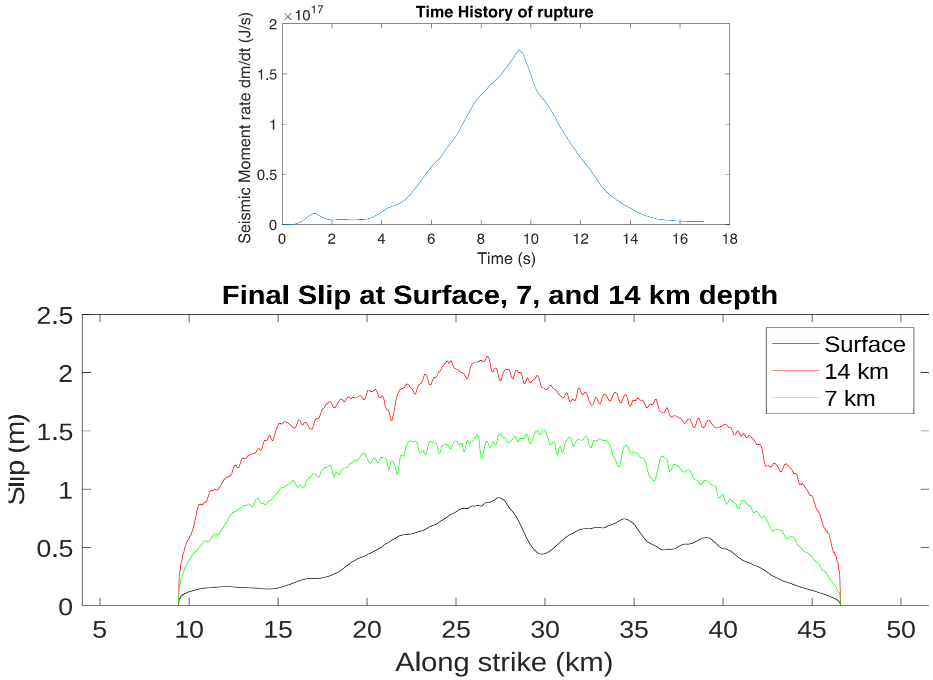


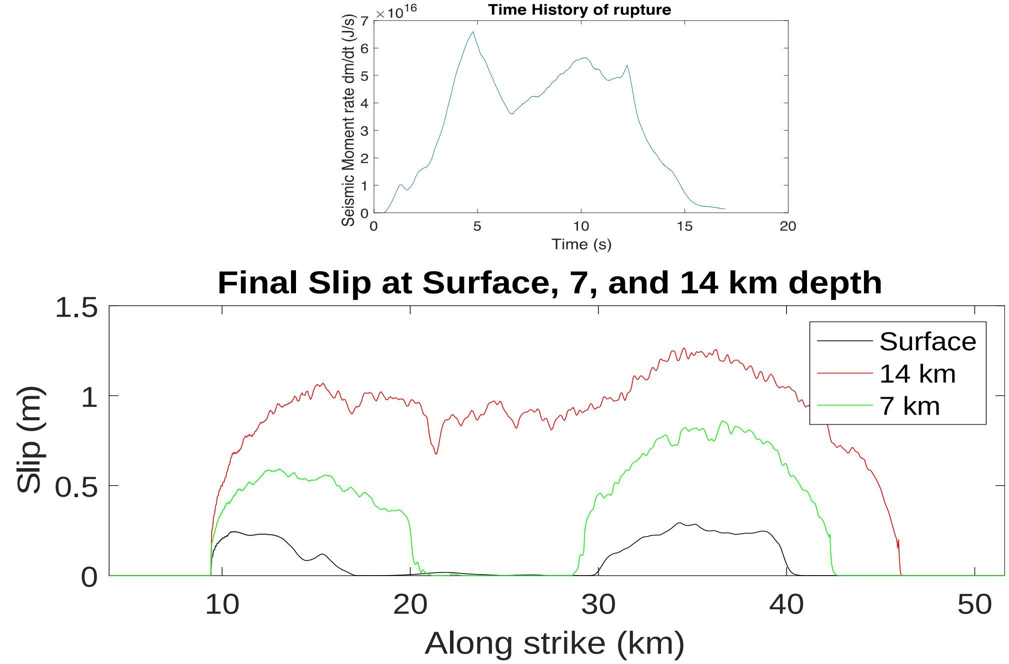


Time History of rupture
×10^17
Seismic Moment rate dm/dt (J/s)
Time (s)
0
0.5
1
1.5
2
0
2
4
6
8
10
12
14
16
18



Time History of rupture
×10^16
Seismic Moment rate dm/dt (J/s)
Time (s)
0
1
2
3
4
5
6
7
0
5
10
15
20


Time History of rupture
Seismic Moment rate dm/dt (J/s)
×10^17
Time (s)
Final Slip at Surface, 7, and 14 km depth
Slip (m)
Along strike (km)
Surface
14 km
7 km


Time History of rupture
Seismic Moment rate dm/dt (J/s)
×10^16
Time (s)
Final Slip at Surface, 7, and 14 km depth
Slip (m)
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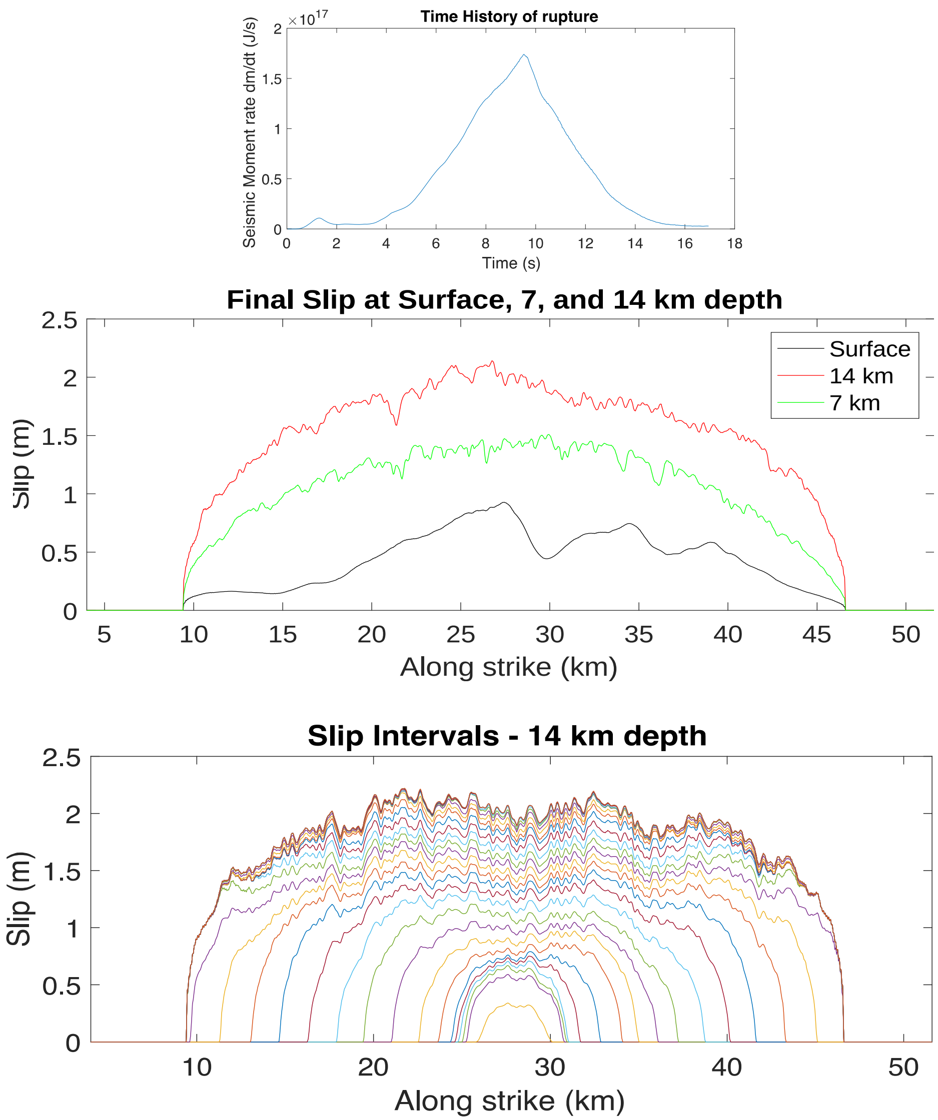
14 km
7 km


Time History of rupture
Seismic Moment rate dm/dt (J/s)
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Time (s)
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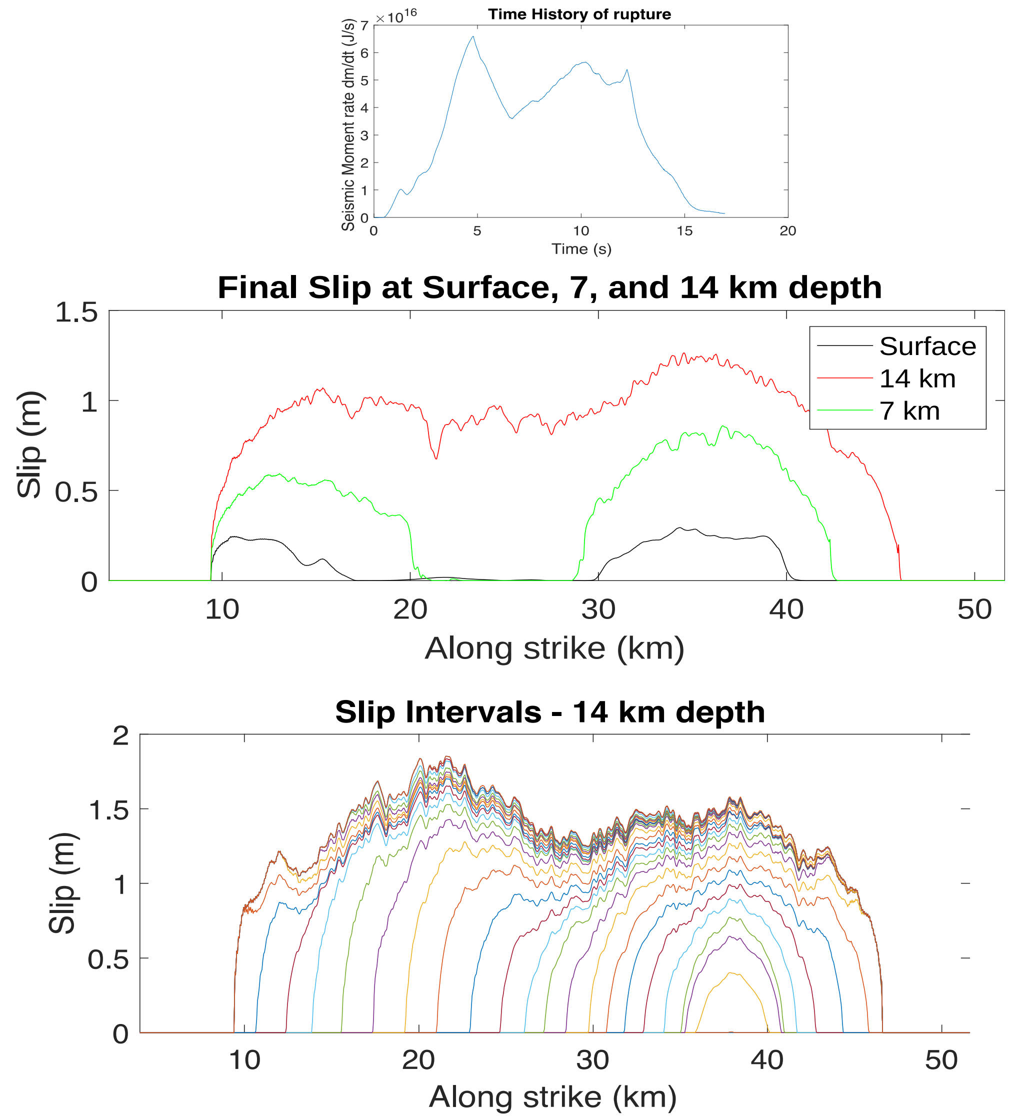
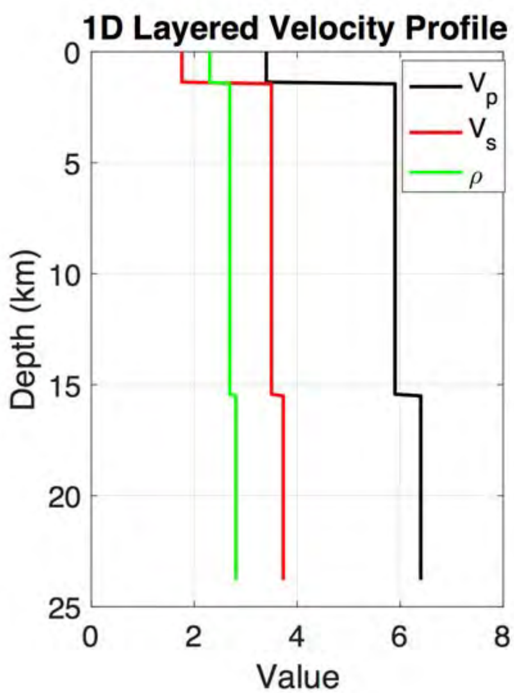
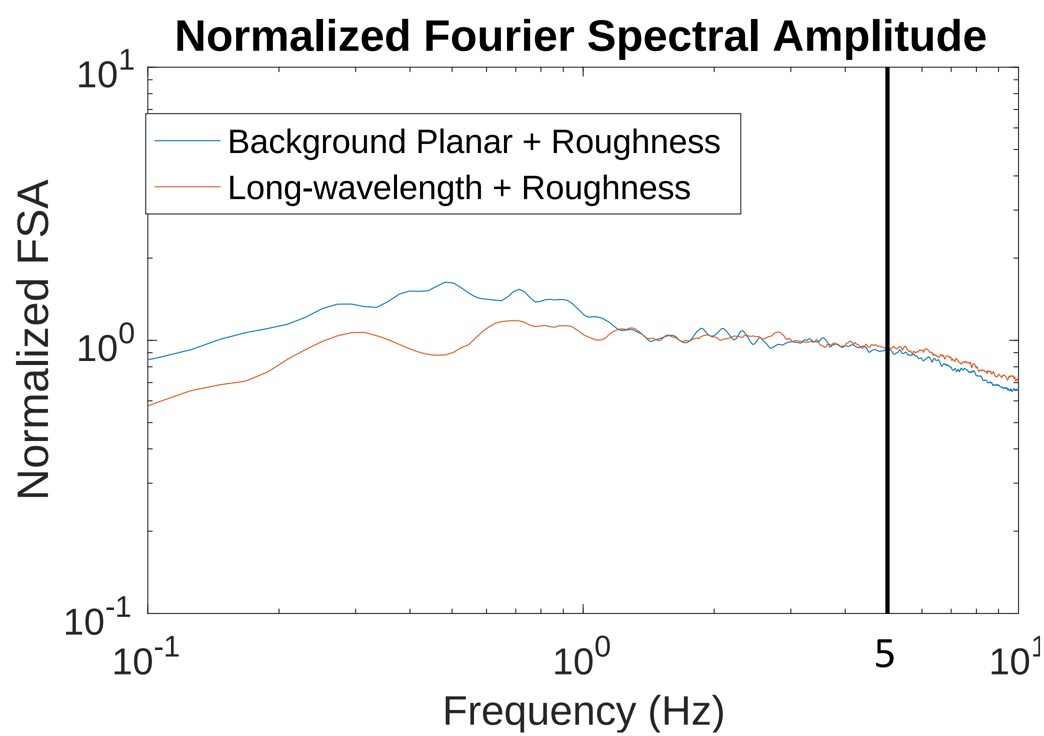
Along strike (km)

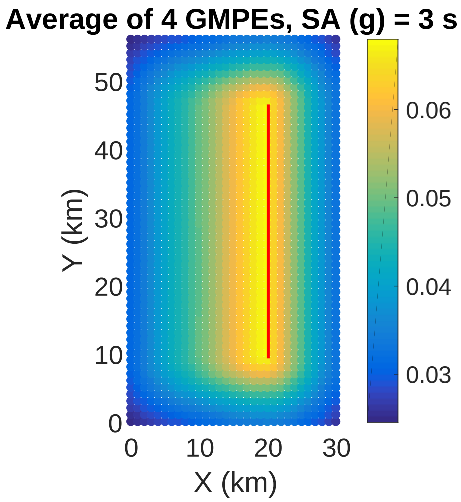

Time History of rupture
Seismic Moment rate dm/dt (J/s)
×10^16
Time (s)
Final Slip at Surface, 7, and 14 km depth
Slip (m)
Along strike (km)
Surface
14 km
7 km
Slip Intervals - 14 km depth
Slip (m)
Along strike (km)

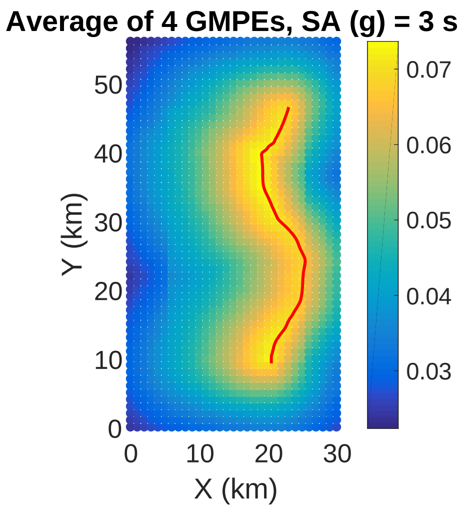
Ground Motion



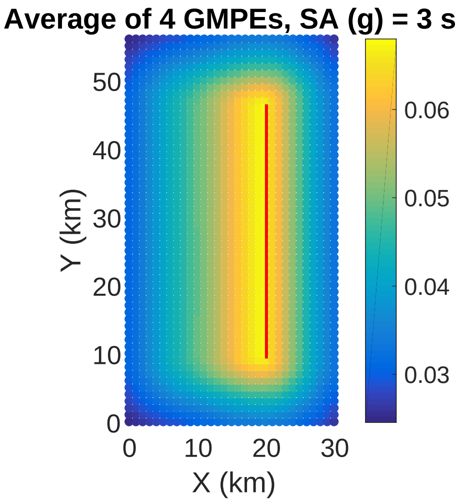


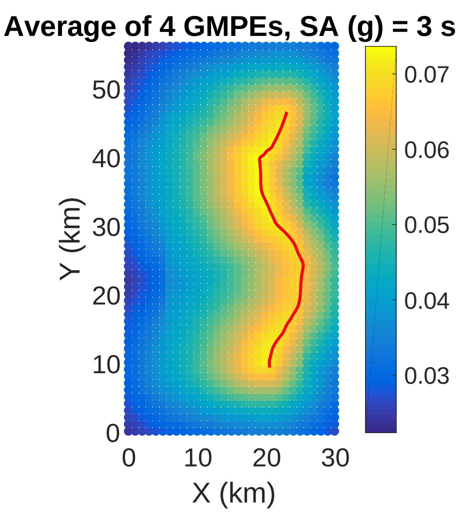
Ground Motion

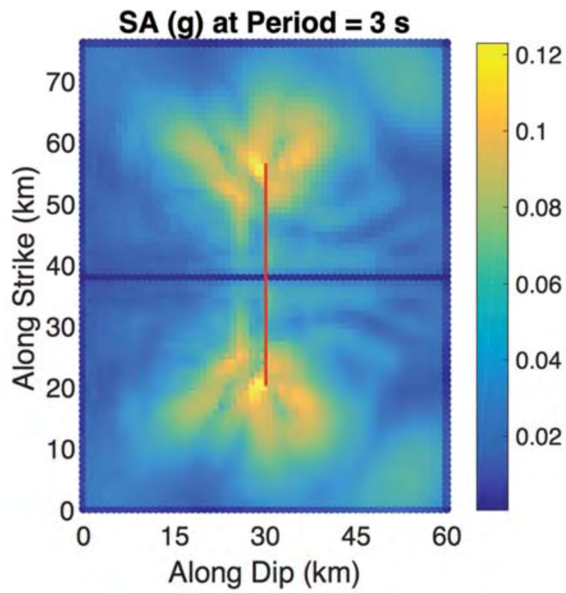


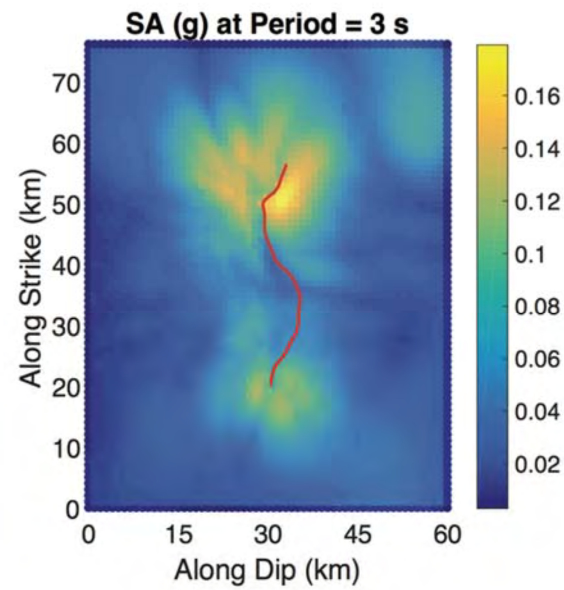


Ground Motion

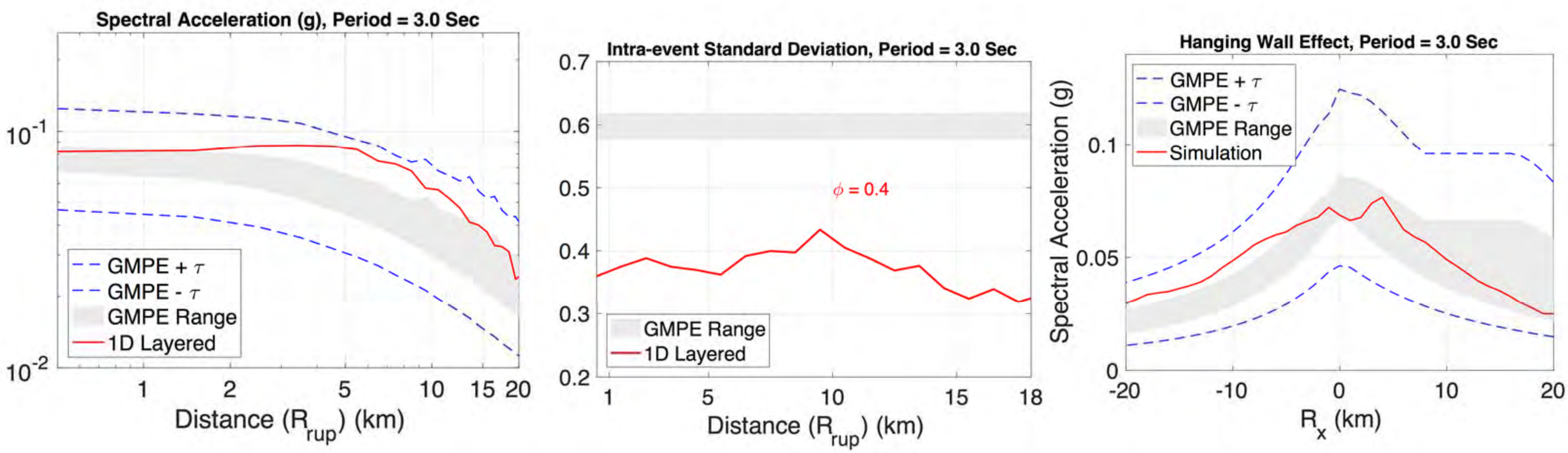








Ground Motion: Long-Wavelength + Roughness



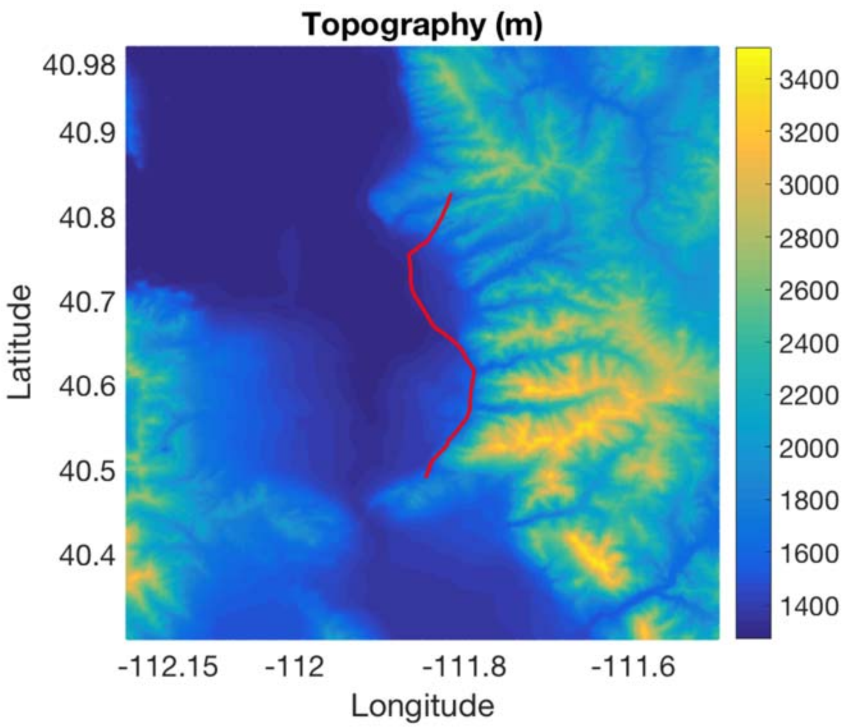
Conclusions

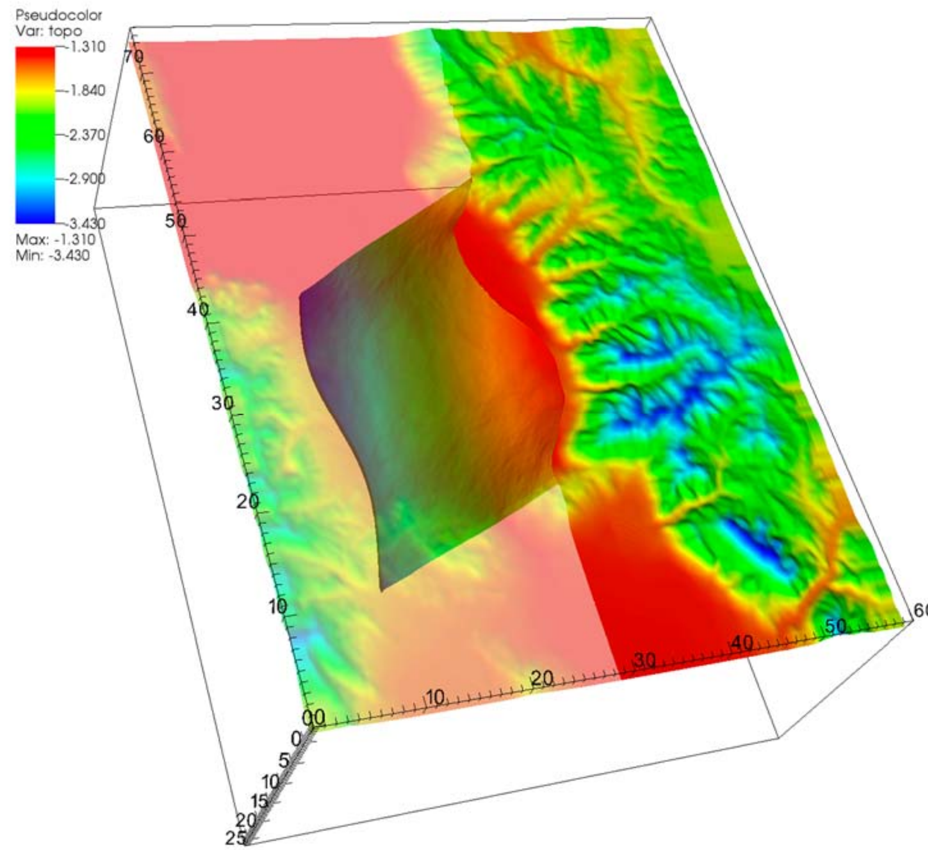
- Ran spontaneous rupture simulations along dipping faults, with characteristics matching that of Salt Lake City segment of Wasatch Fault
- Both short and long-wavelength geometrical complexity along the fault generates complex rupture features
- Rough-fault geometry generates comparable spectral energy to that of observations
- Initial comparison of synthetics with leading GMPEs show good fits

Future Work

- Additional dynamic rupture simulations with varying hypocenter locations, rough fault topographies, stress conditions, etc…
- Correlation of ground motions (spatially/frequency)?
- Path vs. site effects (affecting uncertainty)
- Stress transfer to other parts of Wasatch fault
- Multi-segment rupture

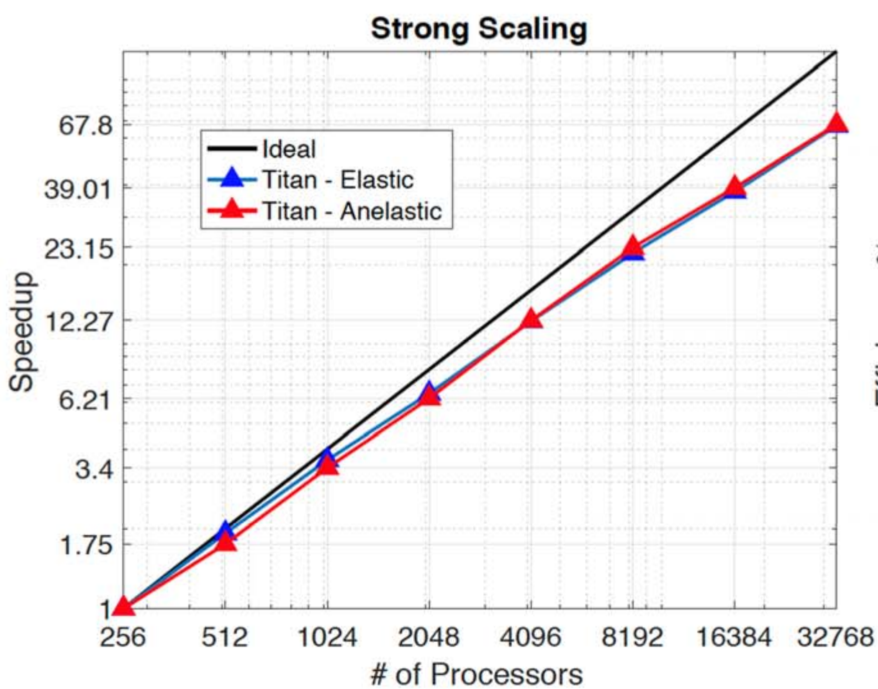
Free-surface Topography

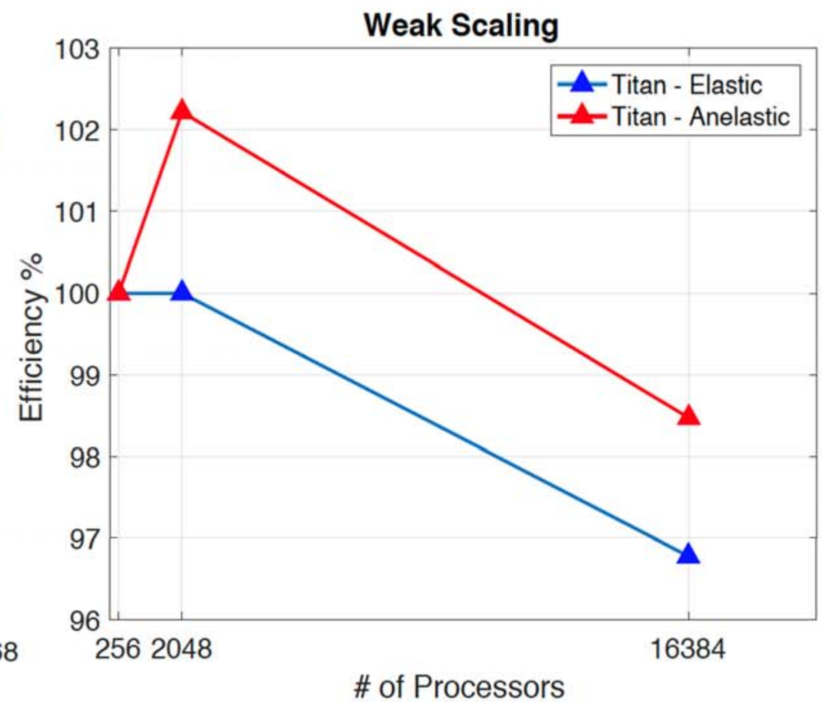




Additional Slides

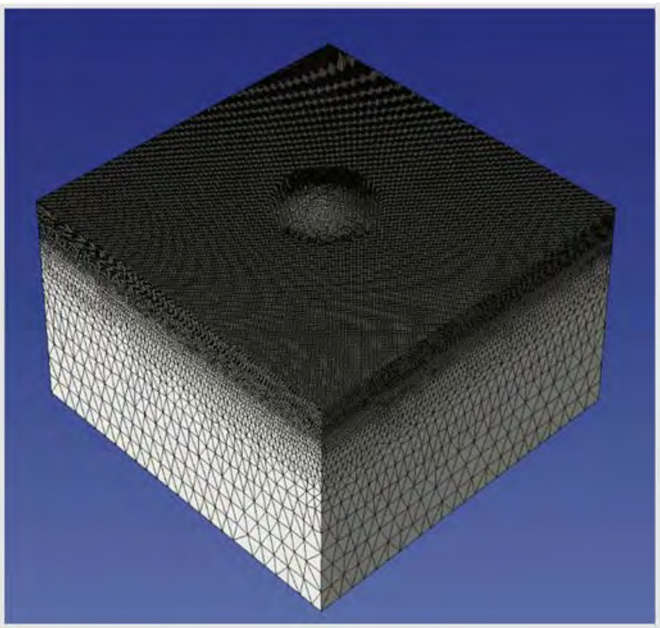
Strong and Weak Scaling

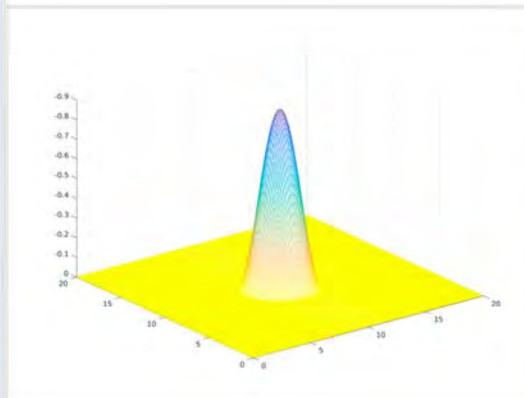


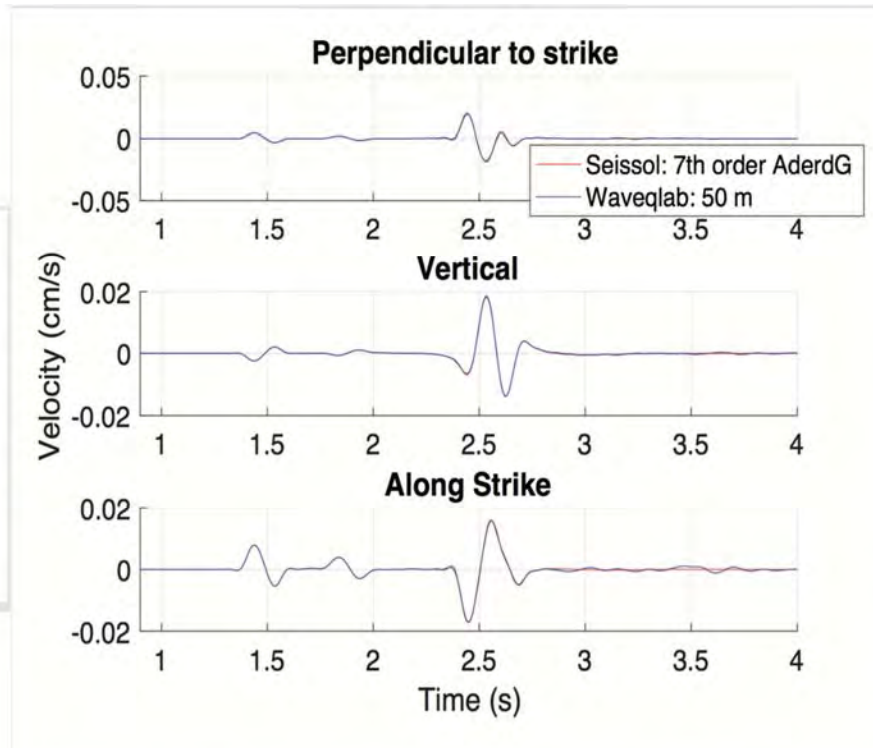


Free-surface Topography Validation

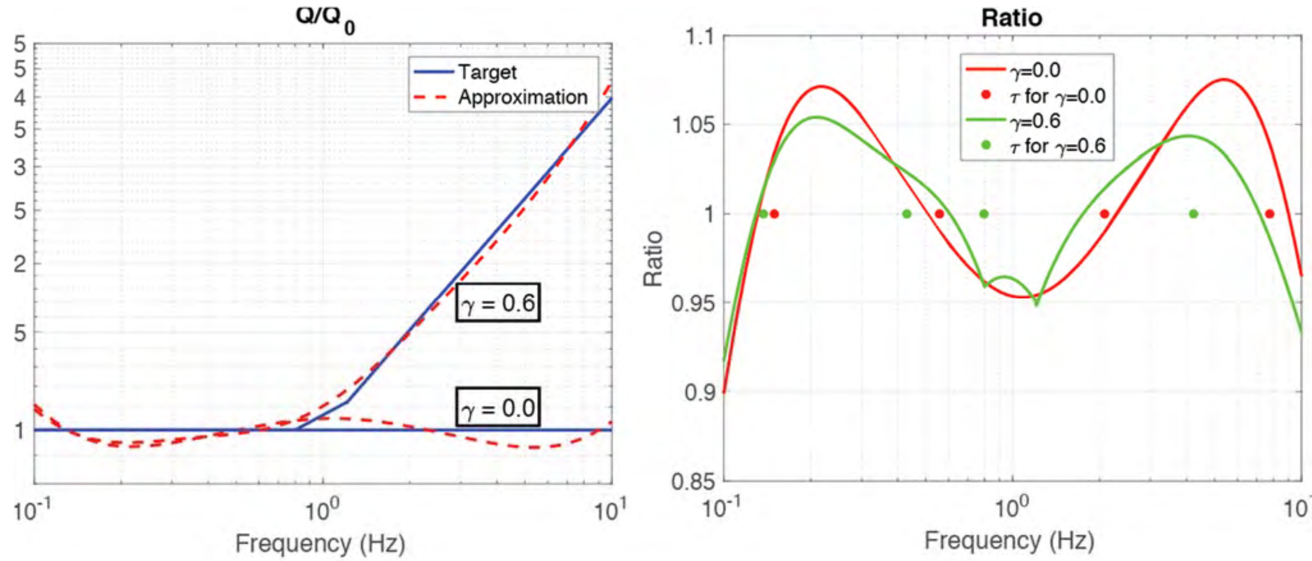
- Simple Gaussian Hill Model, comparison with Seissol

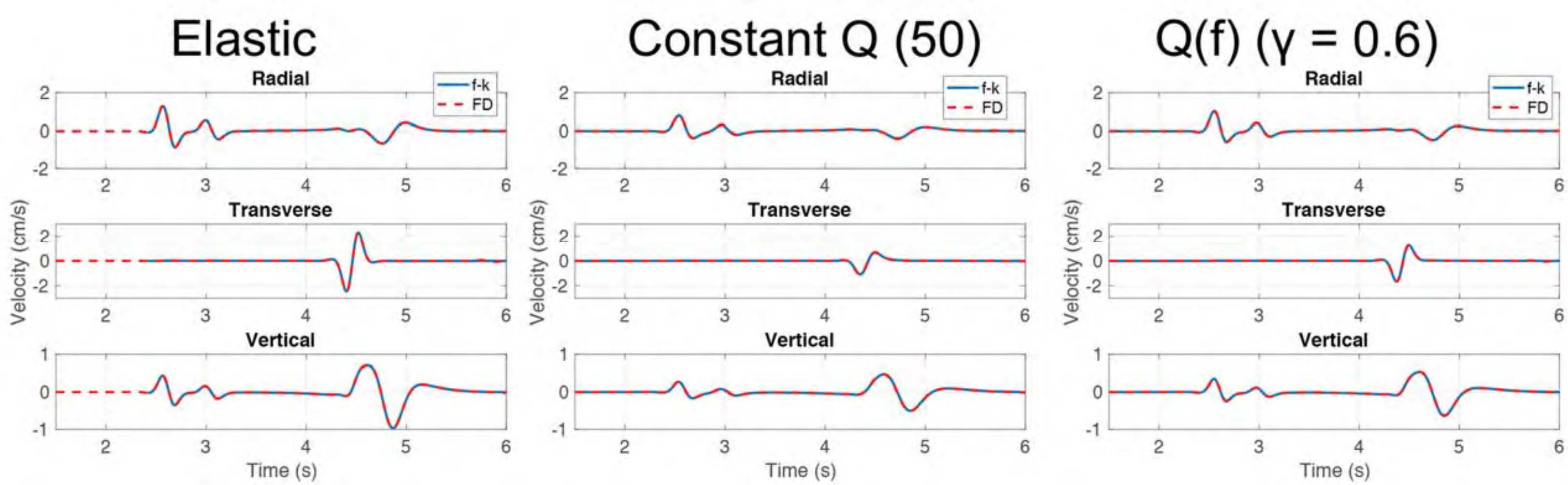






Q(f) Validation





Implementation of WUS Sedimentary Basin Effects into the 2018 NSHM

Case Study: Wasatch Front

Mark Petersen
USGS, Golden, CO

2018 Utah Earthquake Working Groups Meeting

Tuesday, February 13th, 2018

USGS science for a changing world

Background

- In the 2014 NSHM, we accounted for average sedimentary basin effects in the WUS by using default basin depths calculated from NGA-West2 GMMs
- These default Z_x terms have been shown to underestimate the hazard at long periods ($T \geq 1$ s) in areas of the WUS with deep basins, maybe not for shallow basins
- As part of the development of the 2018 NSHM we show the sensitivity of hazard to basin depths derived from three different methods.

2014 NSHM: Default Zx Terms

Default Basin Depths (km) Calculated from NGA-West2 GMMs

Site Class	V_{s30} (m/s)	ASK14($Z_{1.0}$)	BSSA14($Z_{1.0}$)	CB14($Z_{2.5}$)	CY14($Z_{1.0}$)
A	2000	0.000	0.000	0.201	0.000
A/B	1500	0.000	0.001	0.279	0.001
B	1080	0.005	0.005	0.406	0.005
B/C	760	0.048	0.041	0.607	0.041
C	530	0.213	0.194	0.917	0.194
C/D	365	0.401	0.397	1.40	0.400
D	260	0.475	0.486	2.07	0.485
D/E	185	0.497	0.513	3.06	0.513
E	150	0.502	0.519	3.88	0.519

Methods

- Method #1: LOCAL For 4 regions in the WUS (LA Basin, Bay Area, Wasatch Front, and Seattle) from published local seismic velocity models.
- Method #2: VS30 For the entire WUS, from the USGS V_{s30} database (Yong *et al.*, 2016)
- Method #3: COMPOSITE For the entire WUS, a composite basin depth model based on published regional and national velocity models. The composite model is a weighted average where the weights are dependent on the ability of the GMMs and basin model to reduce the variance of observed intra-event ground motion residuals in the NGA-West2 GMMs for the WUS (Boyd *et al.*, 2018).

Method 1: Z_x Terms from Local Seismic Velocity Models

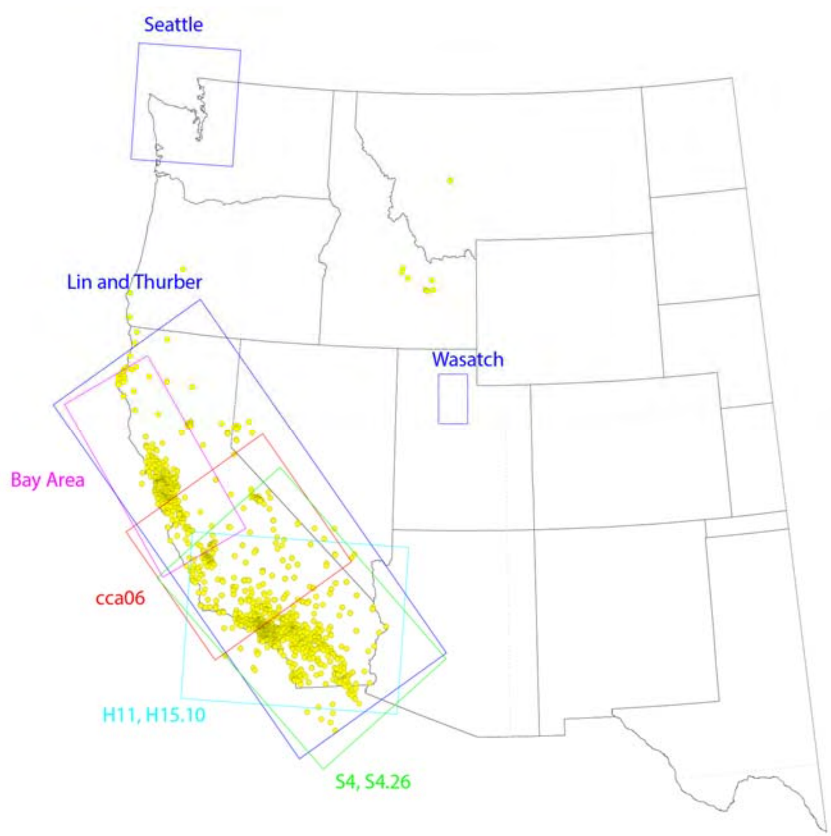


Figure 2 (from Boyd *et al.*, 2018). NGA-W2 station locations (circles) and outlines of the regional velocity models. The national models cover the entire region.

1. Uniform V_{s30} hazard maps are run for each region using Z_x terms from local seismic velocity models for 0.02 degree grids.

Velocity Models
BayArea10 (Aagaard *et al.*, 2010)
S4.26m01 (Lee *et al.*, 2014)
Seattle07 (Stephenson, 2007)
Wasatch08(Magistrale *et al.*, 2008)

Site Class	V_{s30} (m/s)
A	2000
A/B	1500
B	1080
B/C	760
C	530
C/D	365
D	260
D/E	185
E	150

Method 2: Z_x Terms Calculated from USGS V_{s30} Database

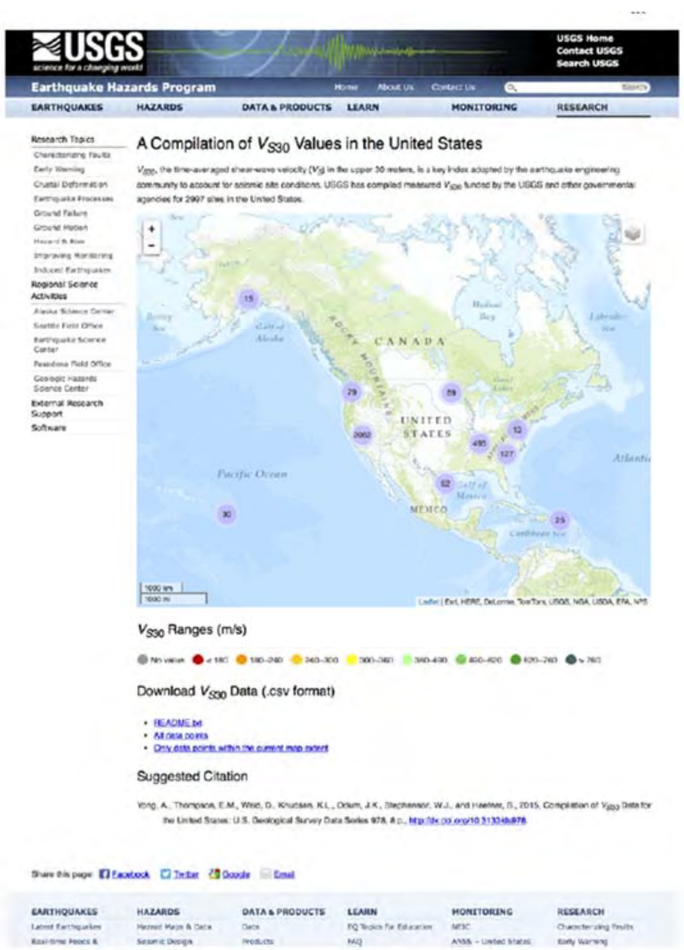


Figure 1. Screenshot of the U.S. Geological Survey Web site for data about V_{S30} (time-averaged shear-wave velocity to a depth of 30 meters; http://earthquake.usgs.gov/research/vs30/).

Figure 1 (from *Yong et al.*, 2016)

1. Using V_{s30} value from the USGS V_{s30} Database, calculate $Z_{1.0}$ (using CY14 GMM) and $Z_{2.5}$ (using CB14 GMM) for a 0.1 degree grid over the entire WUS.

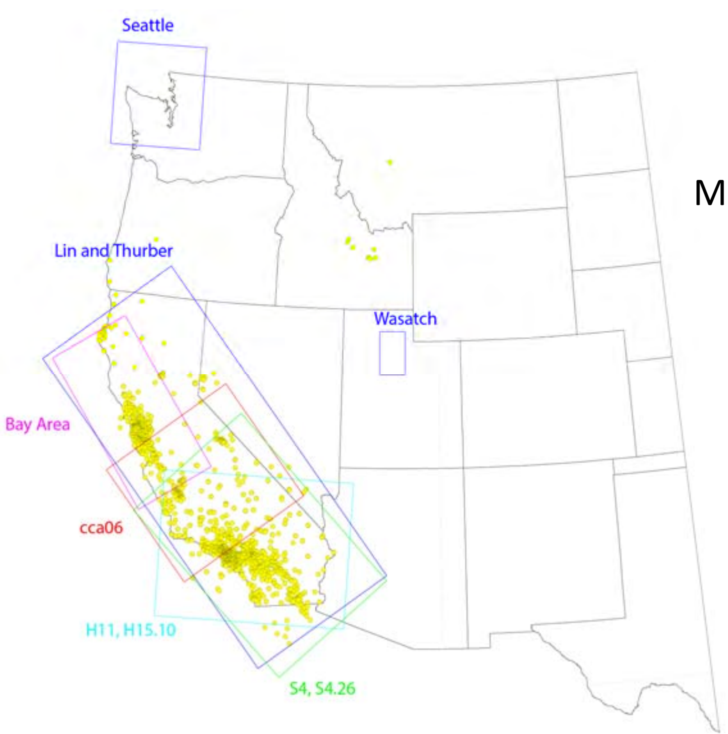
2. Uniform V_{s30} hazard maps are run using calculated $Z_{1.0}$ and $Z_{2.5}$ values.

Site Class	V_{s30} (m/s)
A	2000
A/B	1500
B	1080
B/C	760
C	530
C/D	365
D	260
D/E	185
E	150

Method 1-3

METHOD 1: LOCAL

Velocity Models
BayArea10 (Aagaard *et al.*, 2010)
S4.26m01 (Lee *et al.*, 2014)
Seattle07 (Stephenson, 2007)
Wasatch08(Magistrale *et al.*, 2008)



METHOD 2: VS30

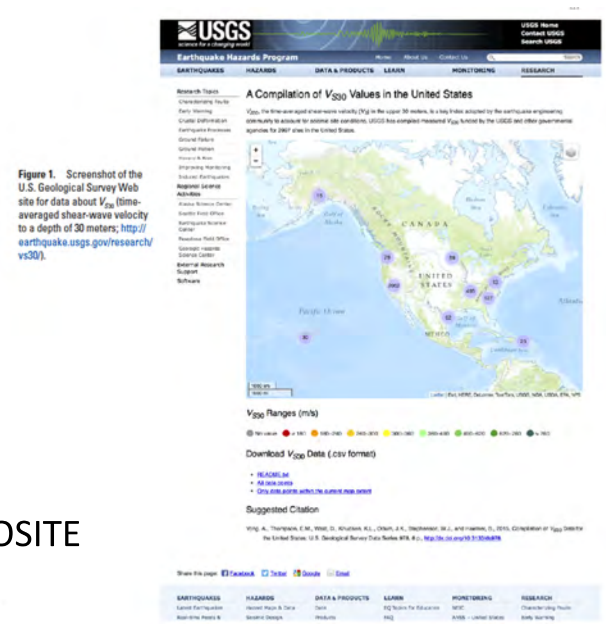


Figure 1 (from *Yong et al.*, 2016)

METHOD 3: COMPOSITE

Velocity Models
SR16 (national)
SL15 (national)
BayArea10
H15.10
S4
S4.26
S4.26m01
cca06
LinCA10
Seattle07
Wasatch08

Amplification Factors

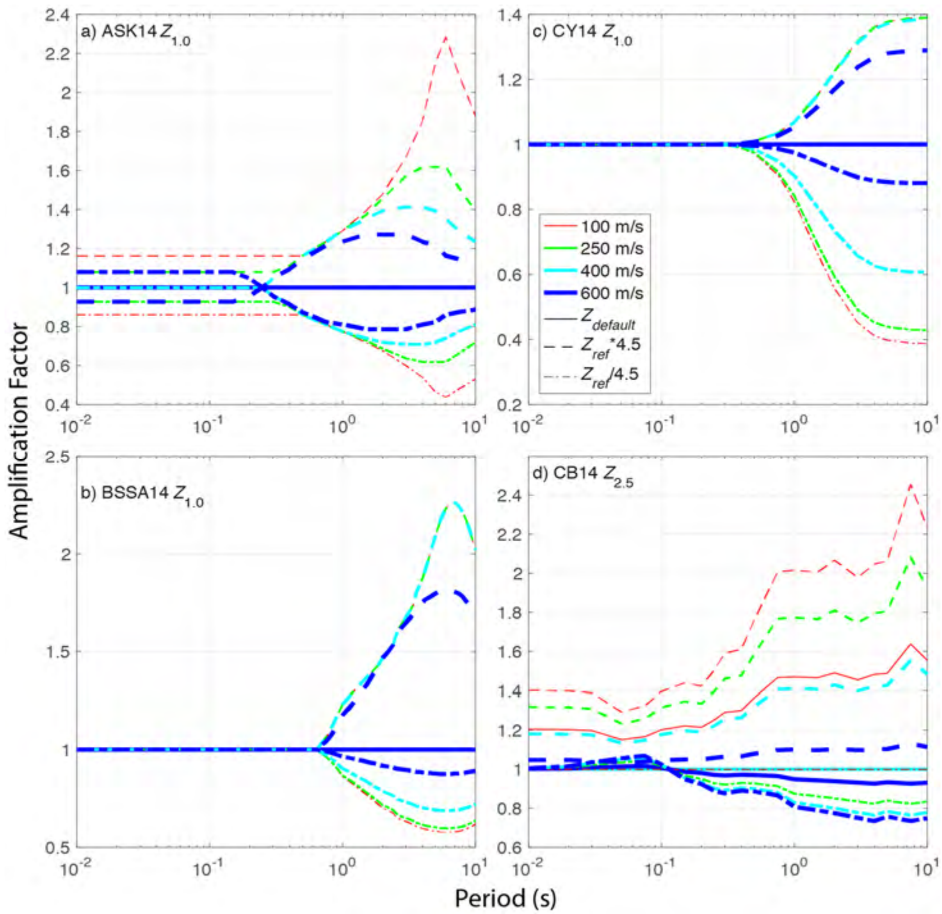
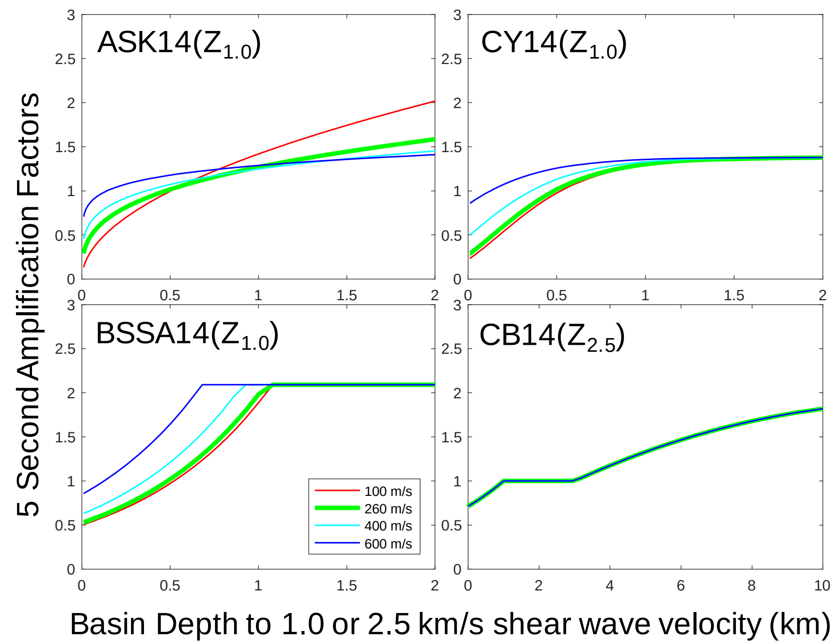
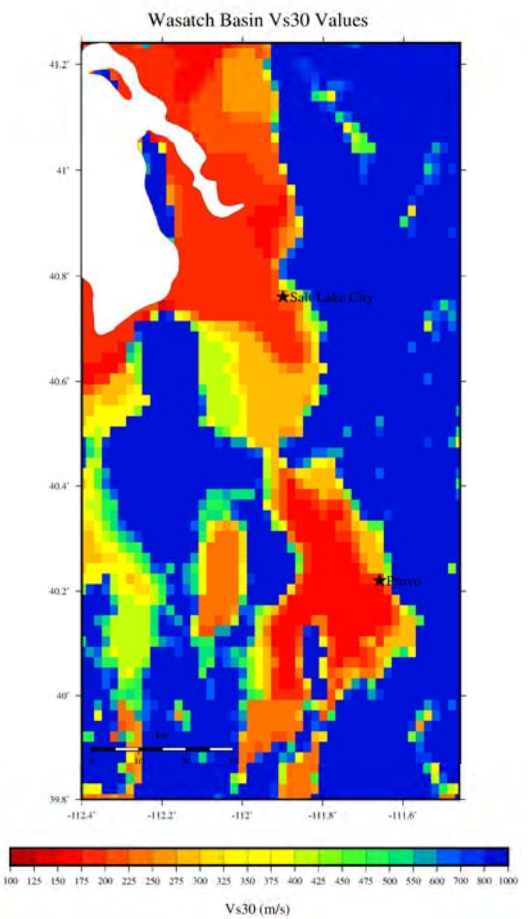


Figure 1 (from Boyd *et al.*, 2018). Amplification factors for the NGA-West2 GMMs used in the 2014 NSHM. The thickest lines are for a V_{S30} of 600 m/s and the thinnest for 100 m/s. Solid lines are for a Z_X value equal to the default value. Dashed lines are for a Z_X value equal to 4.5 times the reference value and dashed-dot lines are for 1/4.5 of the reference value.



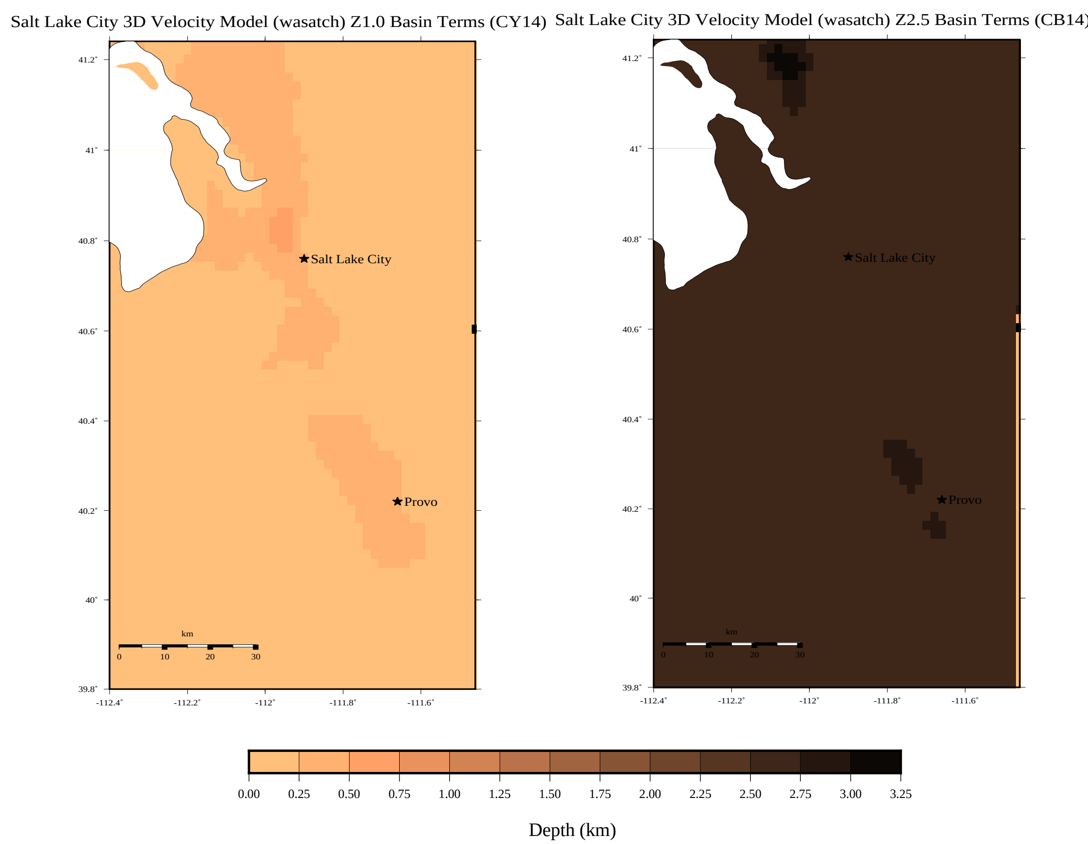
Wasatch Front

Local Seismic Velocity Model*



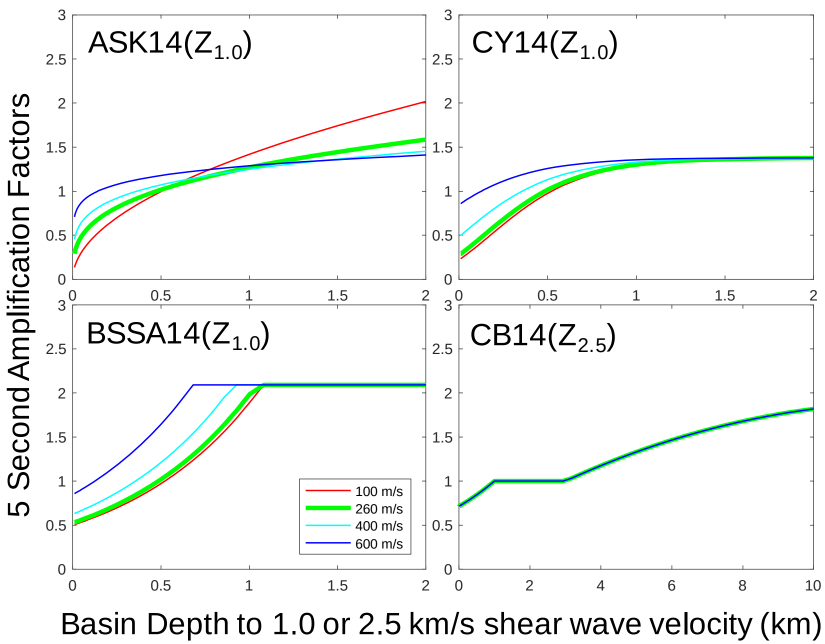
Basin Depths (Z_x)

$Z_{1.0}$ $Z_{2.5}$



*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

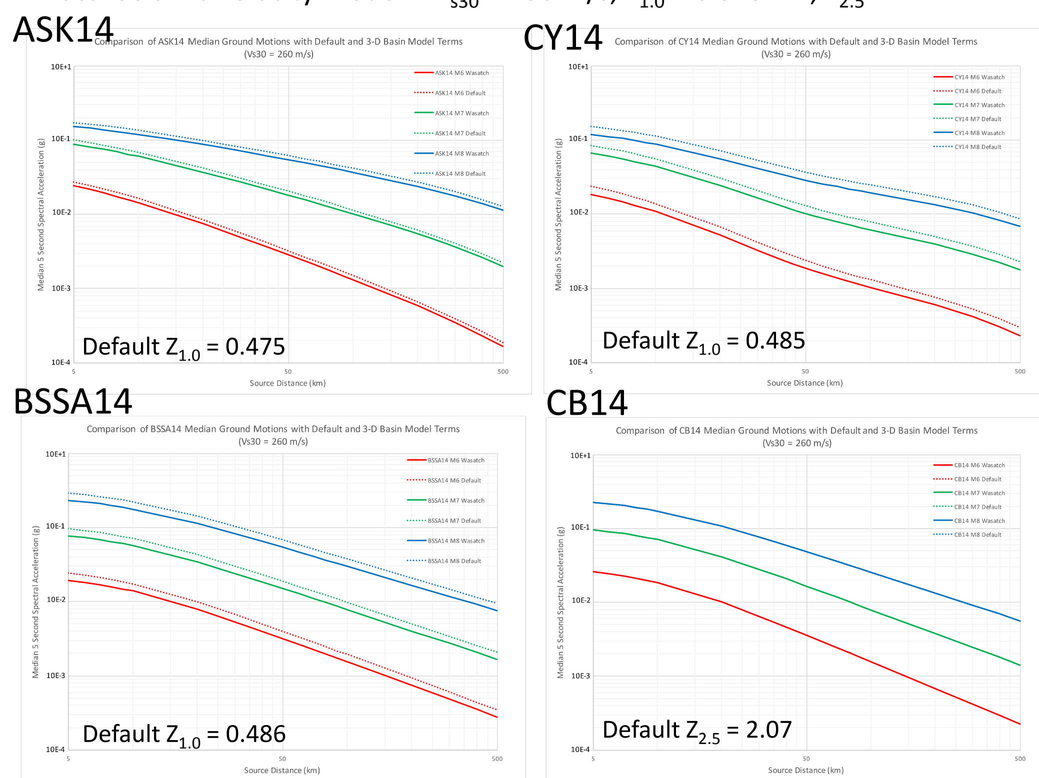
5 Second Amplification Factors from NGA-West2 GMMs



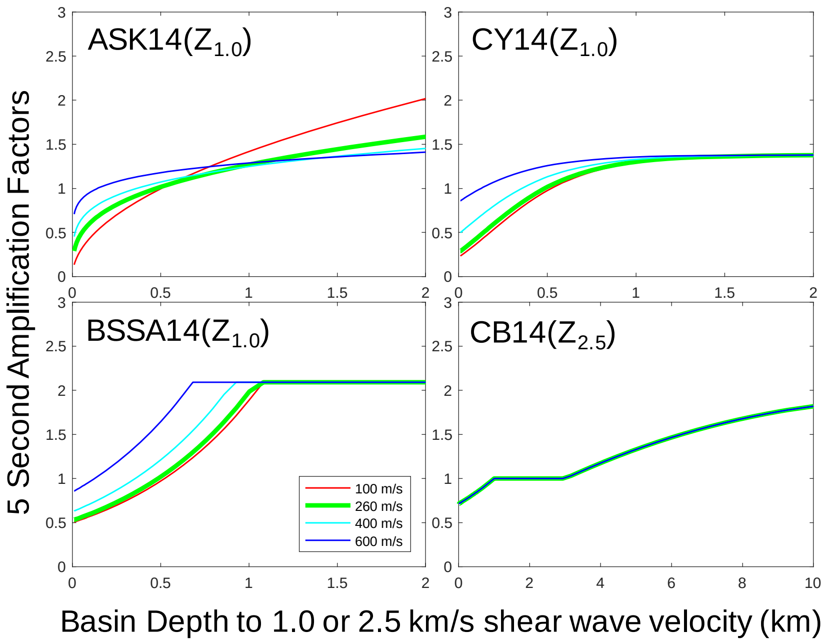
Note: $Z_{1.0}$ is 0.315 km at SLC, therefore, ground motions are deamplified for GMMs that use $Z_{1.0}$. $Z_{2.5}$ is 2.71 km, therefore, CB14 ground motions do not change.

5 Second Median Ground Motions for NGA-West2 GMMs at Salt Lake City, UT (40.76, -111.9), V_{s30} = 260 m/s, 2% in 50 Years PE

Local Seismic Velocity Model*: V_{s30} = 230 m/s, $Z_{1.0}$ = 0.315 km, $Z_{2.5}$ = 2.71 km



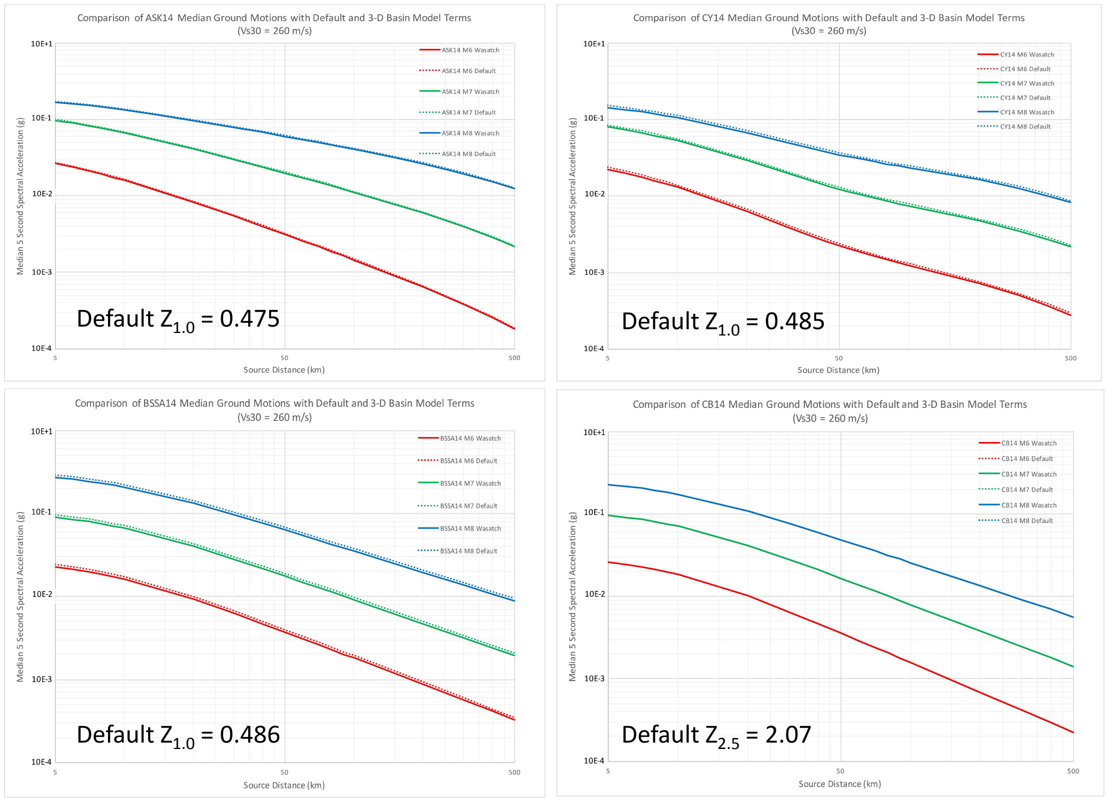
5 Second Amplification Factors from NGA-West2 GMMs



Note: $Z_{1.0}$ is 0.434 km at Provo, therefore, ground motions are deamplified for GMMs that use $Z_{1.0}$. $Z_{2.5}$ is 2.71 km, therefore, CB14 ground motions do not change.

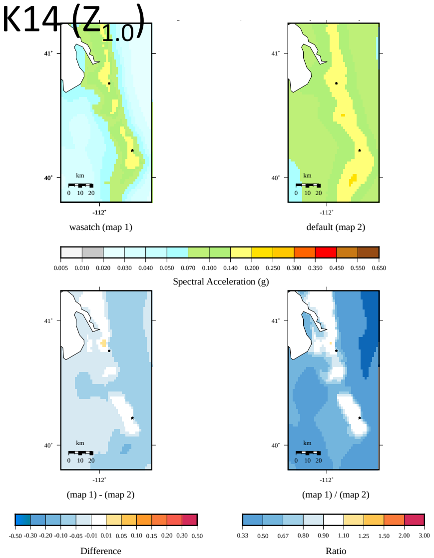
5 Second Median Ground Motions for NGA-West2 GMMs at Provo, UT (40.22, -111.66), V_{s30} = 260 m/s, 2% in 50 Years PE

Local Seismic Velocity Model*: V_{s30} = 186 m/s, $Z_{1.0}$ = 0.434 km, $Z_{2.5}$ = 2.71 km

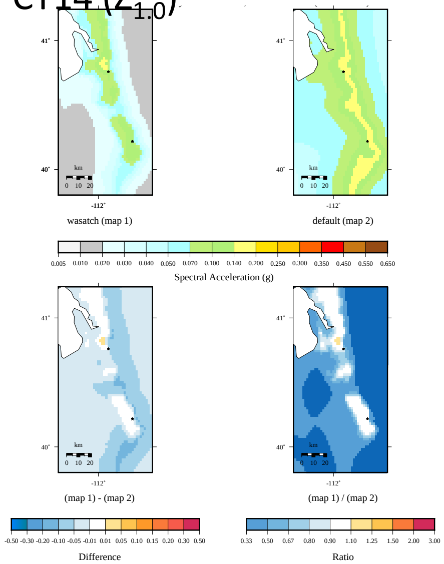


5 Second Hazard from NGA-West2 GMMs, 2%
V_{s30} = 260 m/s, 2% in 50 Years PE

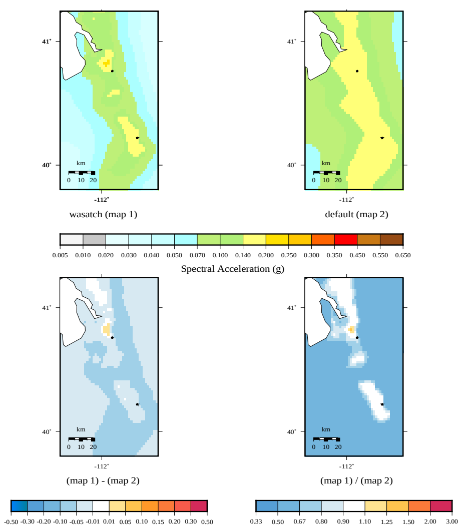
ASK14 ($Z_{1.0}$)



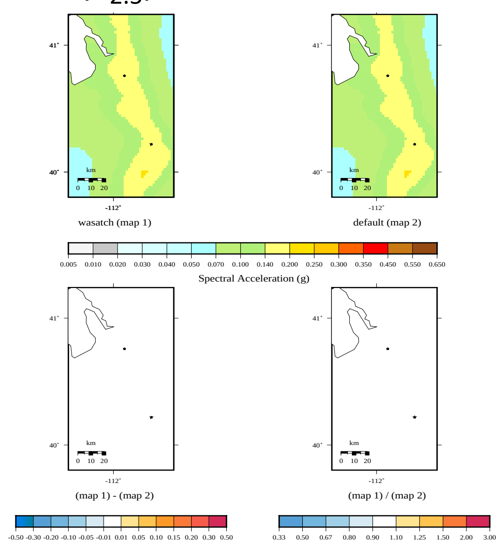
CY14 ($Z_{1.0}$)



BSSA14 ($Z_{1.0}$)

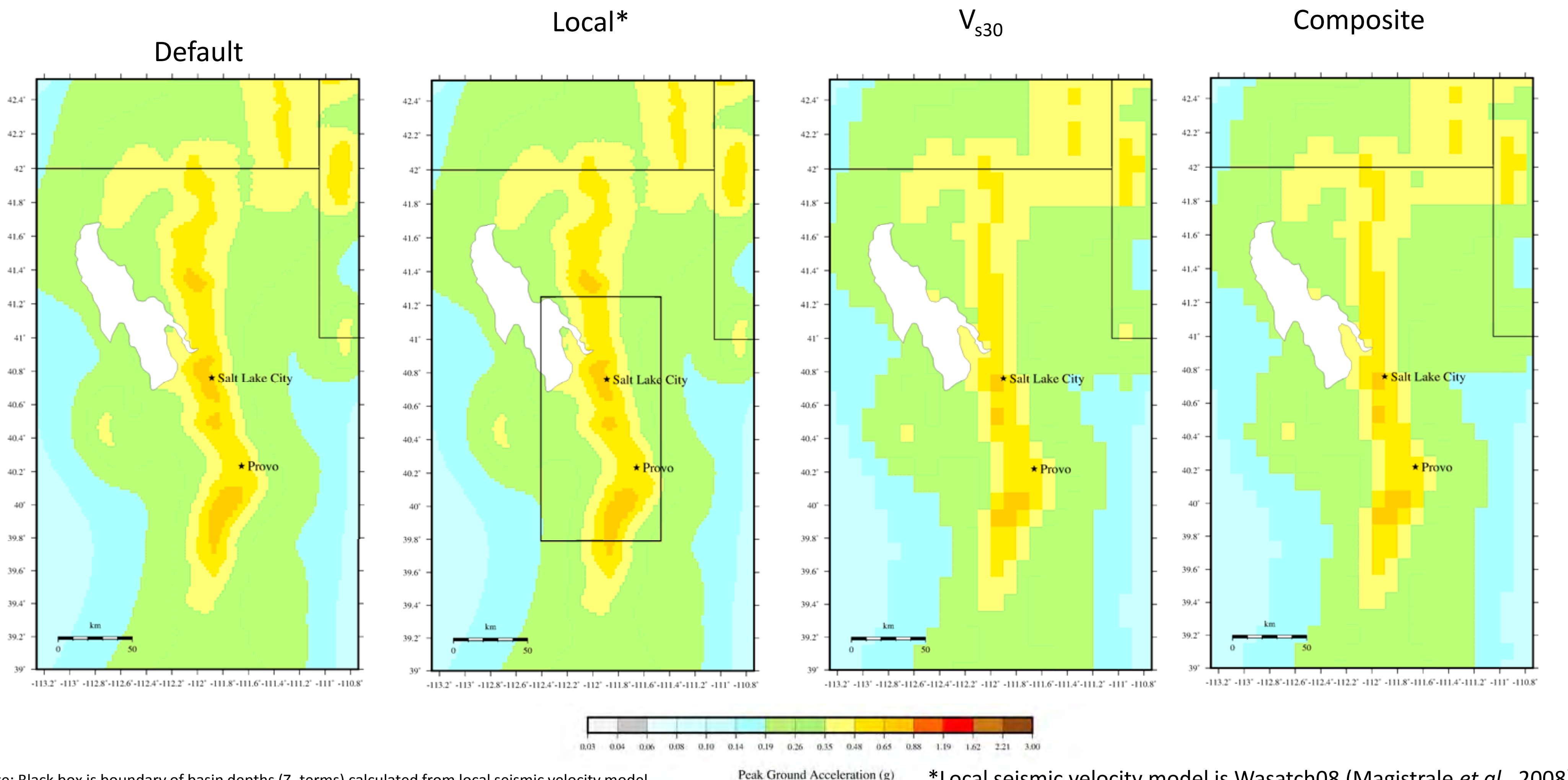


CB14 ($Z_{2.5}$)



Comparison of PGA Total Mean Hazard

V_{s30} = 760 m/s, 2% in 50 Years PE



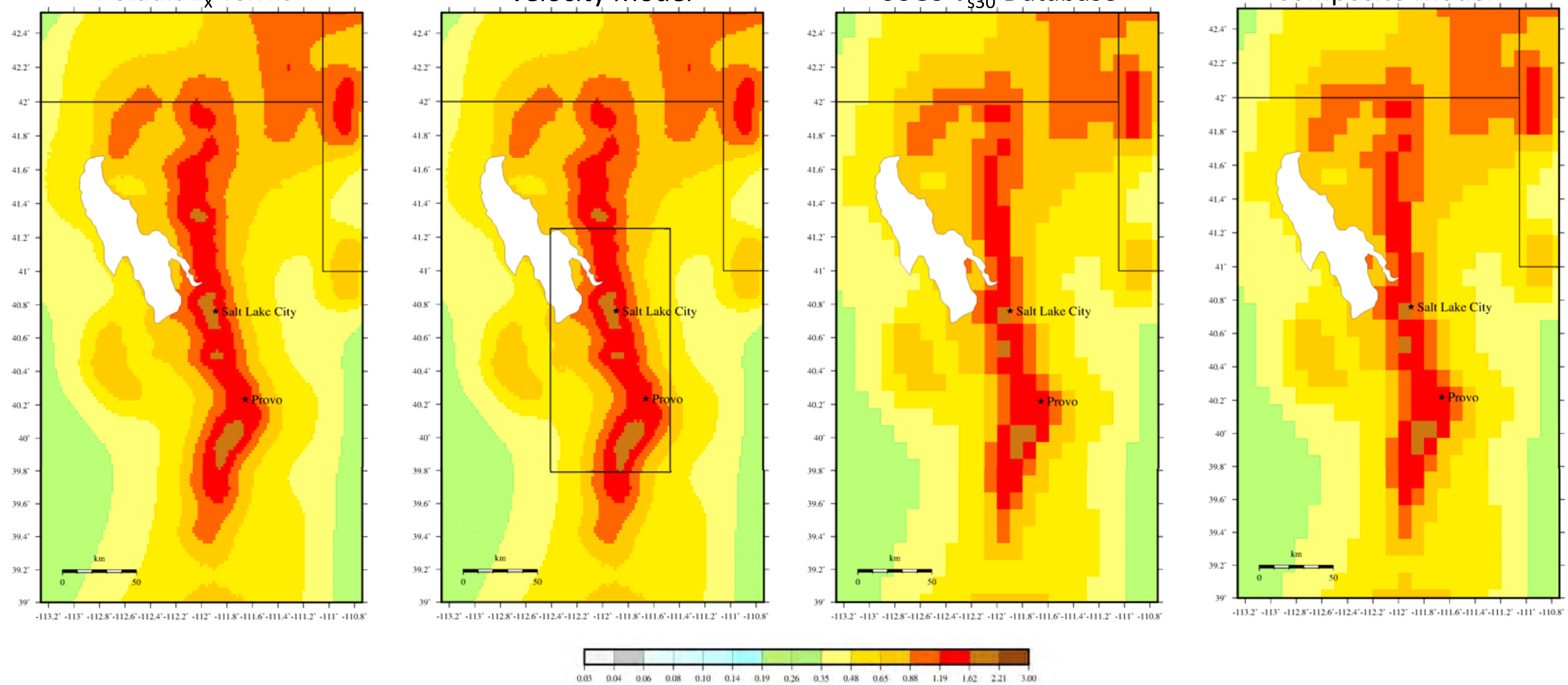
Note: Black box is boundary of basin depths (Z_x terms) calculated from local seismic velocity model.

*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

Comparison of 0.2 Second Total Mean Hazard

V_{s30} = 760 m/s, 2% in 50 Years PE

Default Z_x Terms | Z_x Terms from Local Seismic Velocity Model* | Z_x Terms Calculated from USGS V_{s30} Database | Z_x Terms from Composite Model



0.2 Second Spectral Acceleration (g)

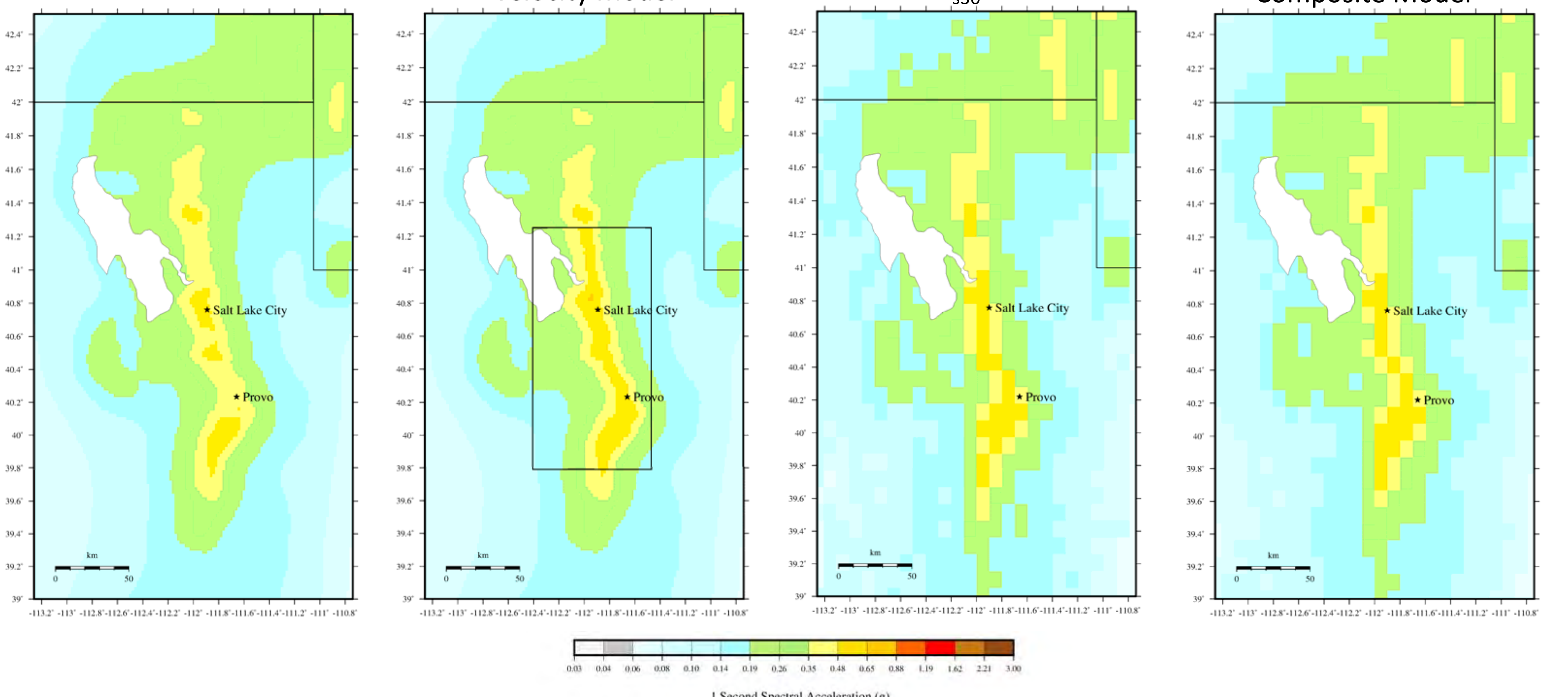
Note: Black box is boundary of basin depths (Z_x terms) calculated from local seismic velocity model.

*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

Comparison of 1 Second Total Mean Hazard

V_{s30} = 760 m/s, 2% in 50 Years PE

Default Z_x Terms | Z_x Terms from Local Seismic Velocity Model* | Z_x Terms Calculated from USGS V_{s30} Database | Z_x Terms from Composite Model

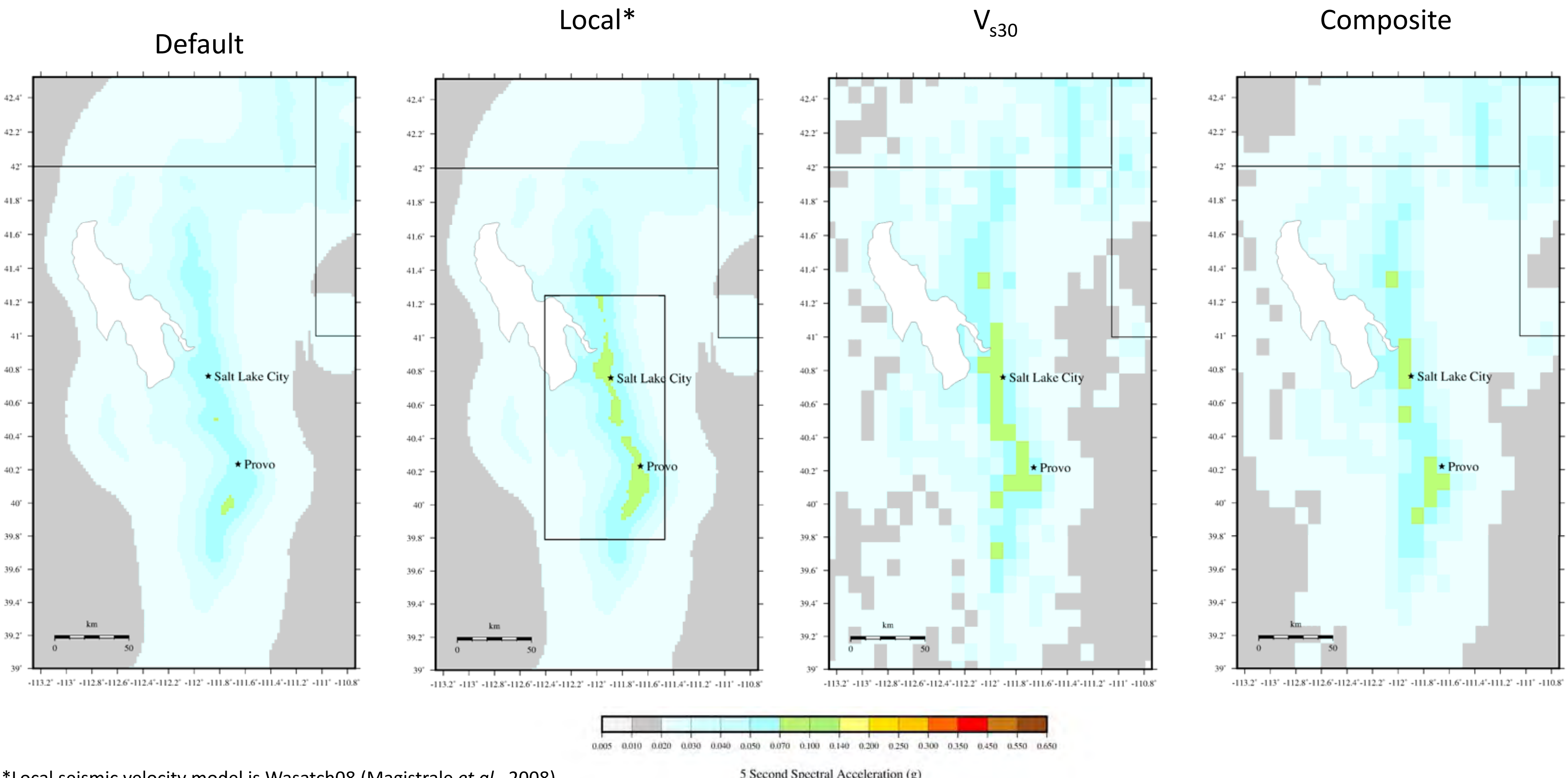


Note: Black box is boundary of basin depths (Z_x terms) calculated from local seismic velocity model.

*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

Comparison of 5 Second Total Mean Hazard

V_{s30} = 760 m/s, 2% in 50 Years PE

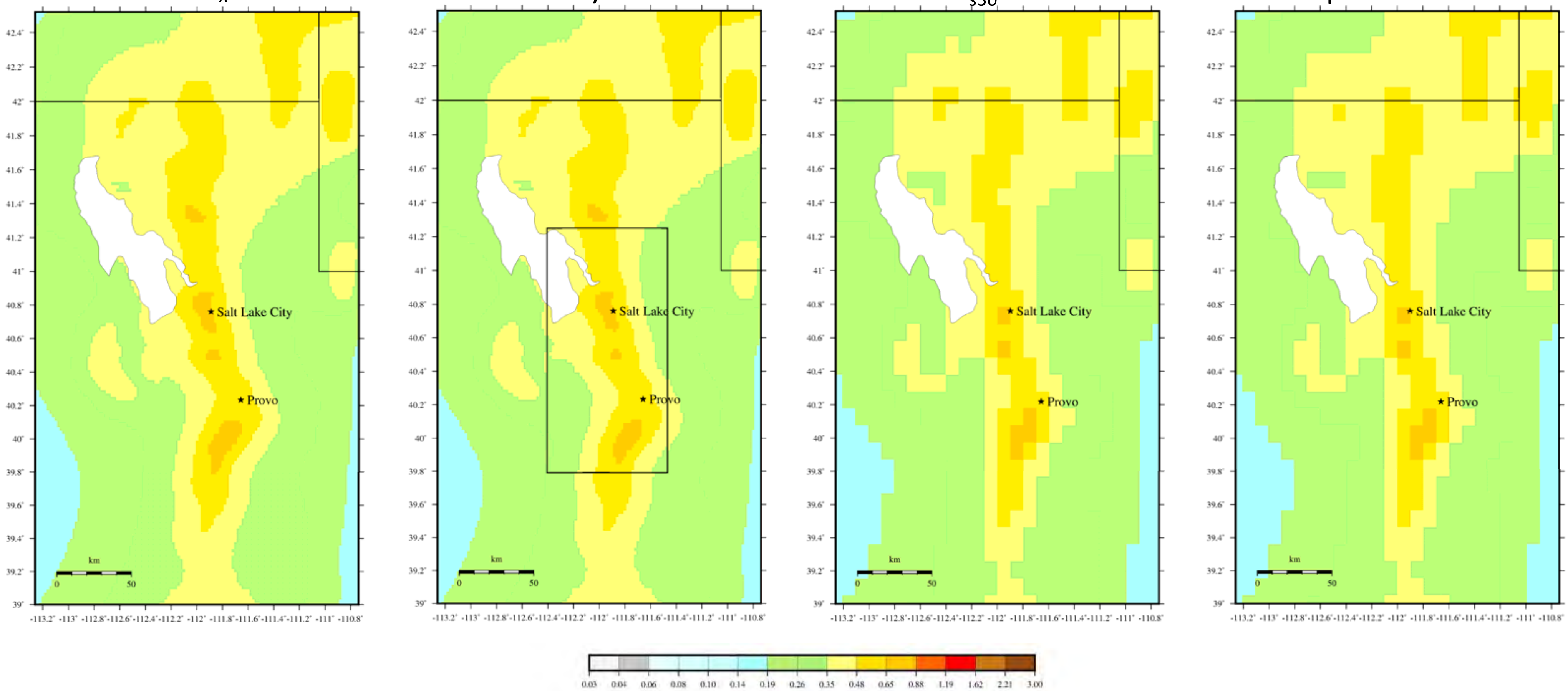


*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

Comparison of PGA Total Mean Hazard

V_{s30} = 260 m/s, 2% in 50 Years PE

Default Z_x Terms | Z_x Terms from Local Seismic Velocity Model* | Z_x Terms Calculated from USGS V_{s30} Database | Z_x Terms from Composite Model



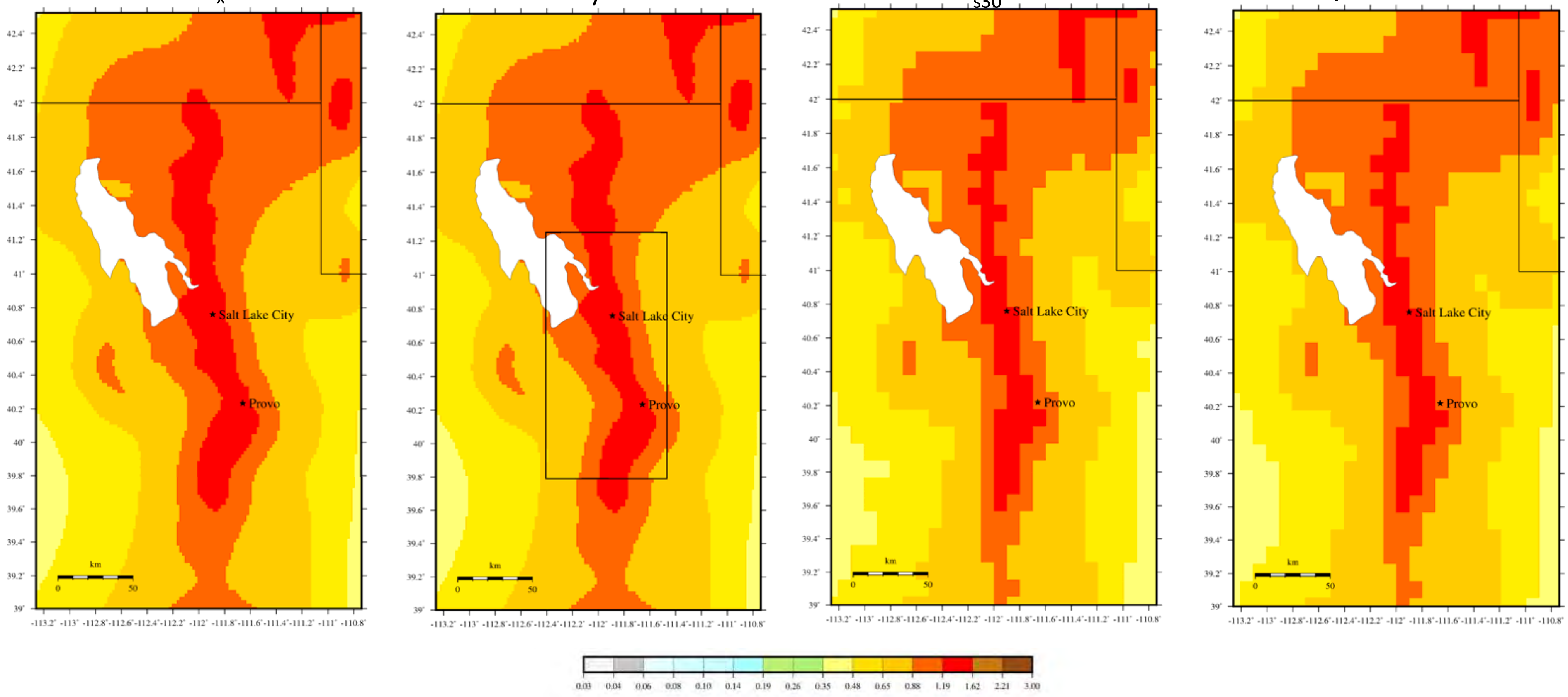
Note: Black box is boundary of basin depths (Z_x terms) calculated from local seismic velocity model.

*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

Comparison of 0.2 Second Total Mean Hazard

V_{s30} = 260 m/s, 2% in 50 Years PE

Default Z_x Terms | Z_x Terms from Local Seismic Velocity Model* | Z_x Terms Calculated from USGS V_{s30} Database | Z_x Terms from Composite Model



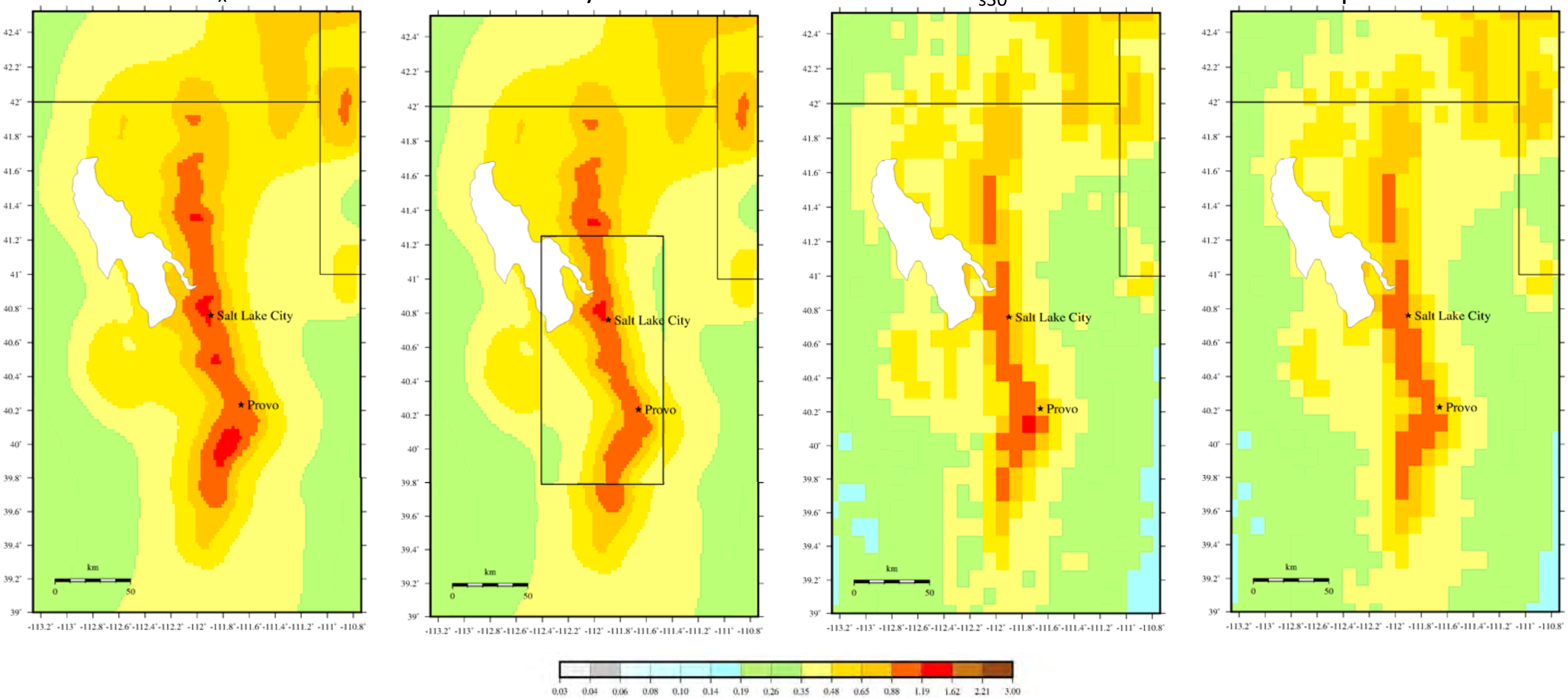
Note: Black box is boundary of basin depths (Z_x terms) calculated from local seismic velocity model.

*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

Comparison of 1 Second Total Mean Hazard

V_{s30} = 260 m/s, 2% in 50 Years PE

Default Z_x Terms | Z_x Terms from Local Seismic Velocity Model* | Z_x Terms Calculated from USGS V_{s30} Database | Z_x Terms from Composite Model



1 Second Spectral Acceleration (g)

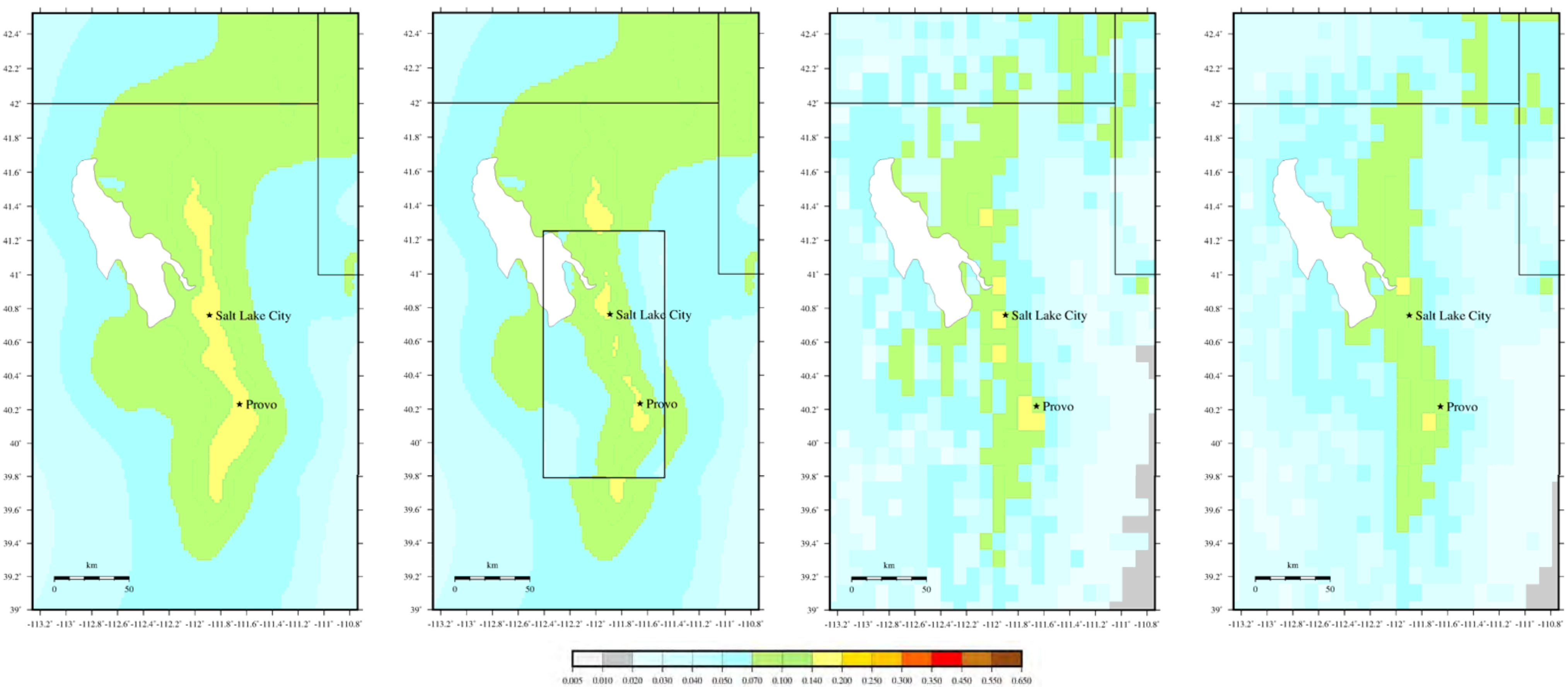
Note: Black box is boundary of basin depths (Z_x terms) calculated from local seismic velocity model.

*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

Comparison of 5 Second Total Mean Hazard

V_{s30} = 260 m/s, 2% in 50 Years PE

Default | Local* | V_{s30} | Composite

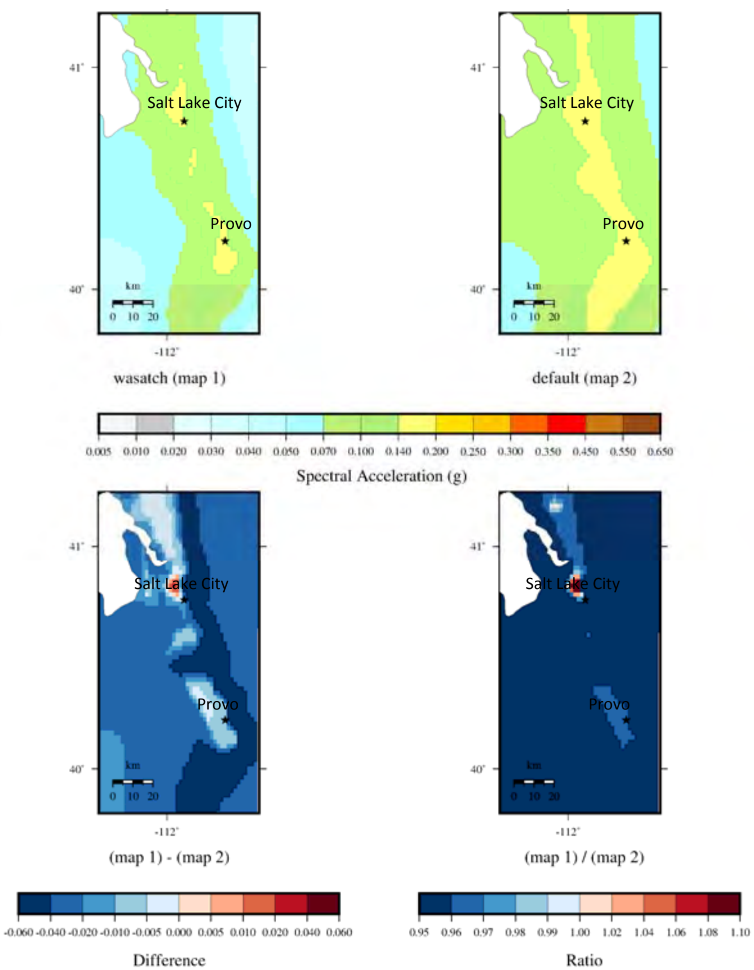


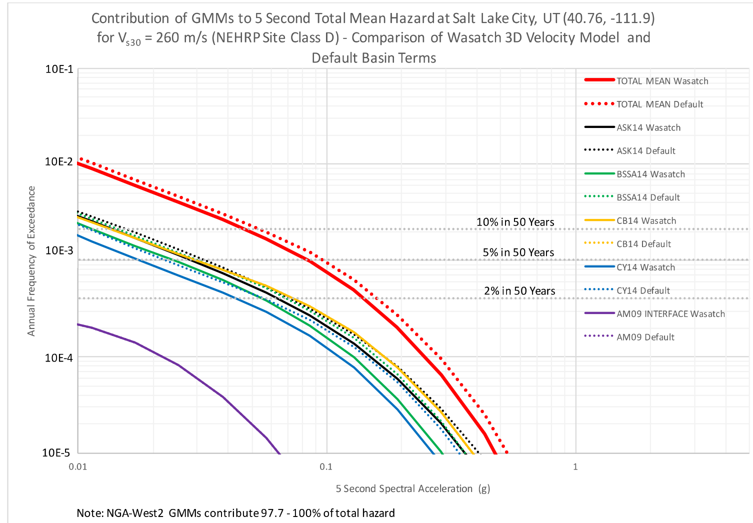
*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

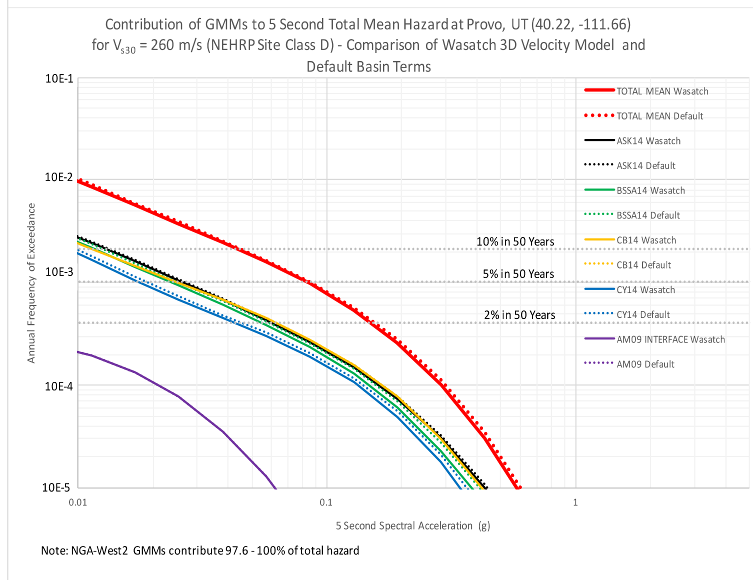
5 Second Spectral Acceleration (g)

5 Second Total Mean Hazard, V_{s30} = 260 m/s, 2% in 50 Years PE

Local* vs. Default





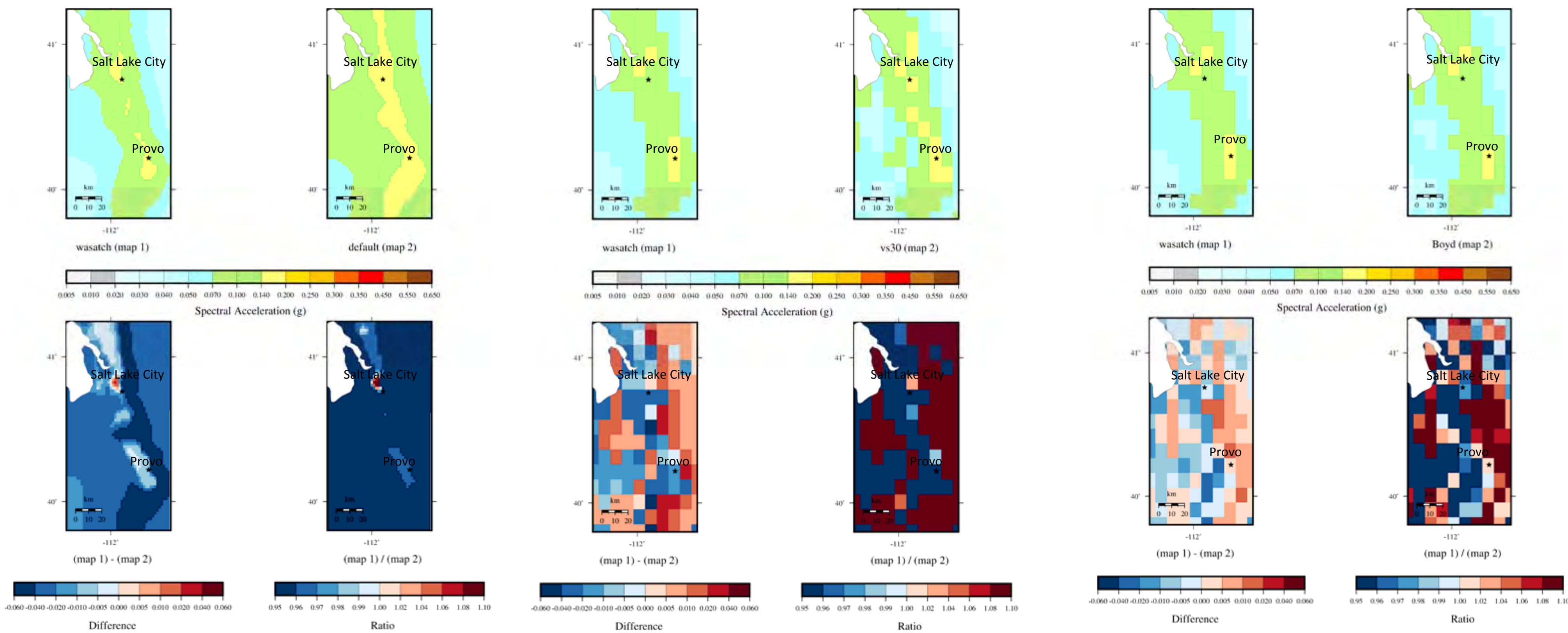


*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

5 Second Total Mean Hazard

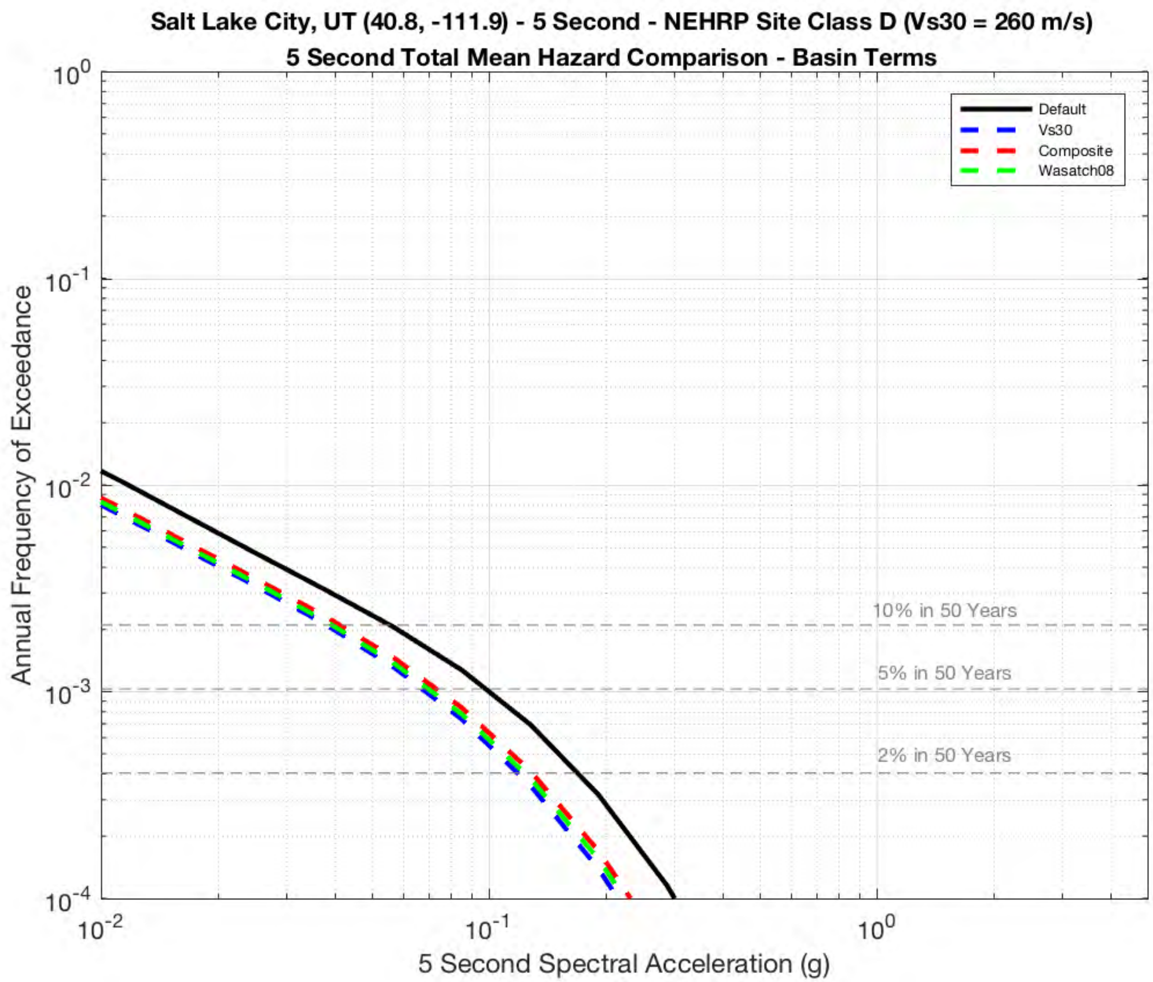
V_{s30} = 260 m/s, 2% in 50 Years PE

Local* vs. Default | Local* vs. V_{s30} | Local* vs. Composite

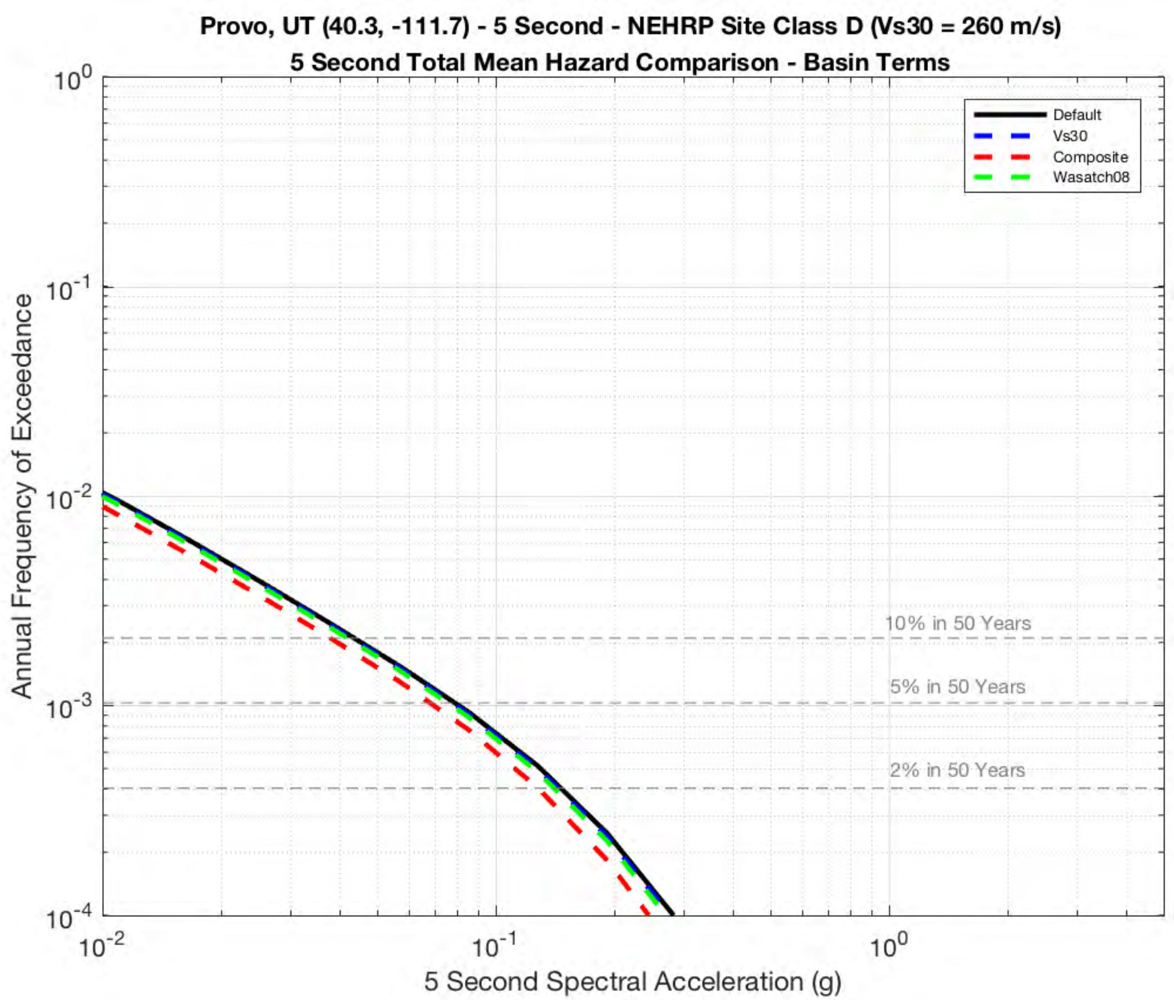


*Local seismic velocity model is Wasatch08 (Magistrale *et al.*, 2008)

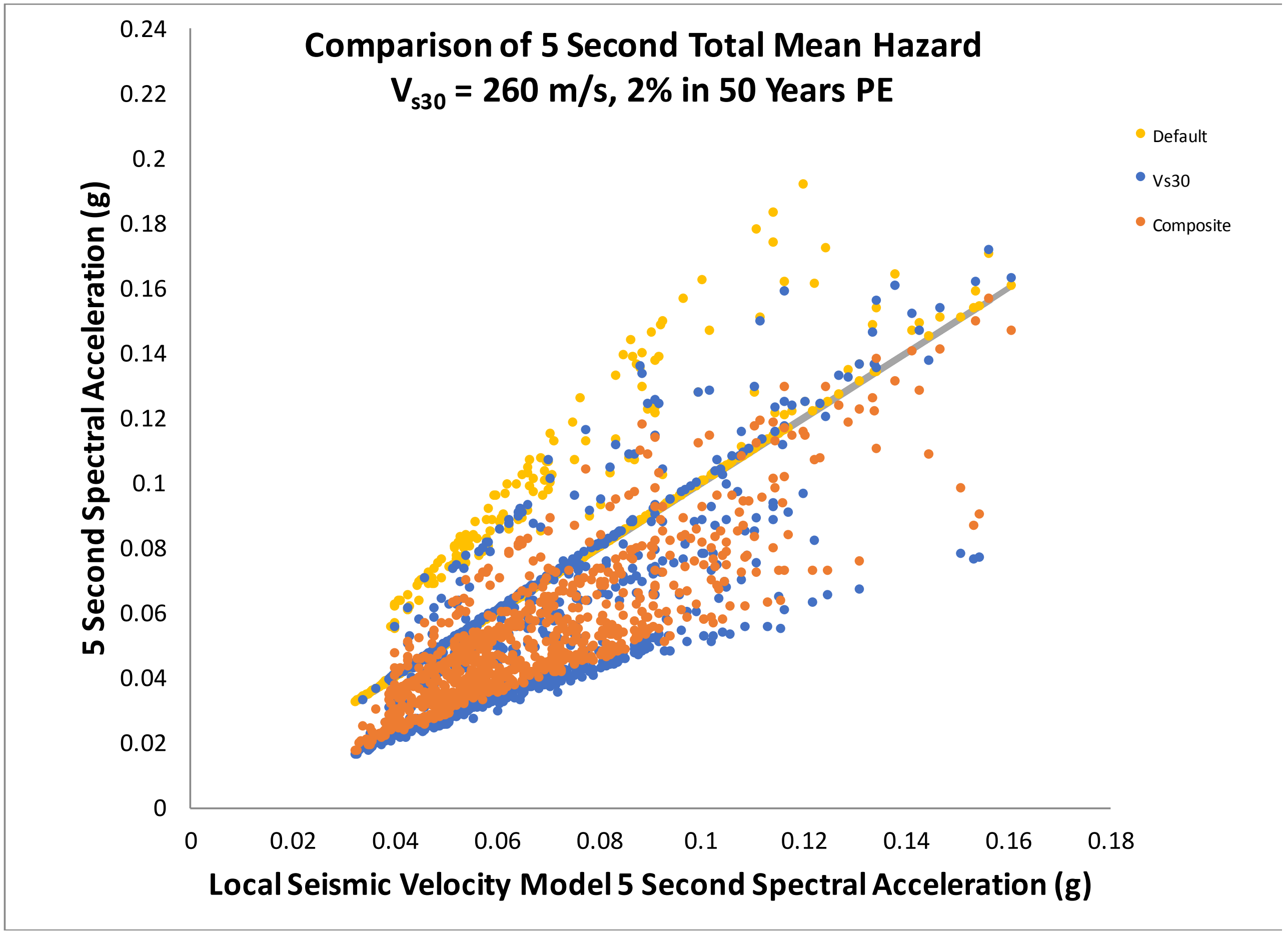
Hazard Curve Comparisons: Salt Lake City, UT



Hazard Curve Comparisons: Provo, UT

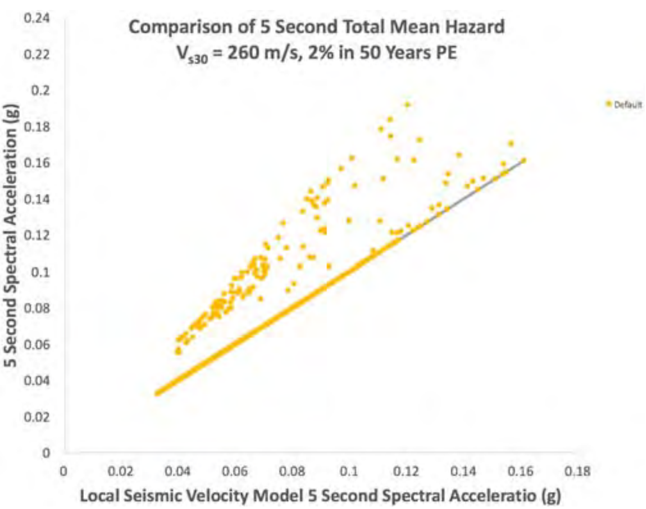


Summary Correlation Plot



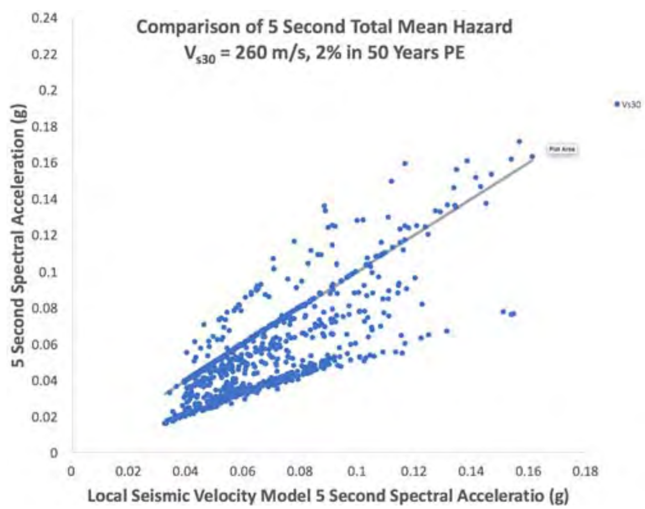
Individual Correlation Plots

Default



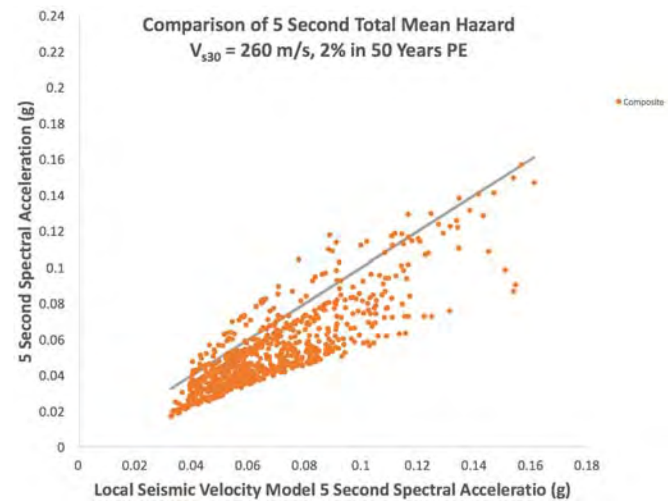
Correlation Coefficient = 0.90

V_{s30}



Correlation Coefficient = 0.76

Composite



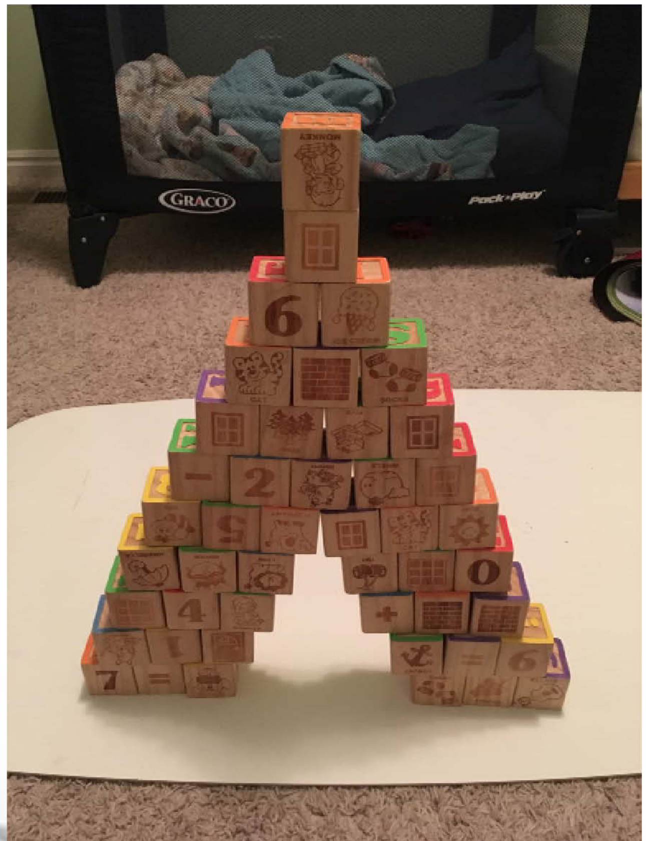
Correlation Coefficient = 0.85

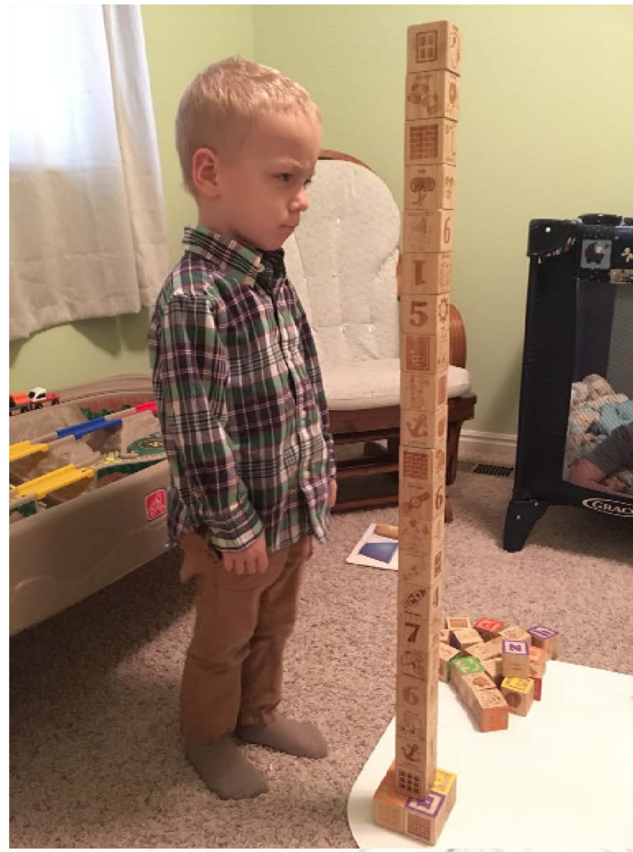
A User’s Perspective

How structural engineers use ground motions for building design.

By Eric Hoffman, PE

Proof of my qualifications-





ASCE 7-10 Seismic Design Process

Step 1 - Use the USGS website application to get risk- modified ground motion parameters, S_S and S_1 (MCE_R).

Step 2 - Modify MCE_R parameters for soil effects (Site Class A-F).

Step 3 - Multiply site-modified MCE_R ground motions parameters by 2/3 to get design spectral acceleration parameters (S_{DS} and S_{D1}).

Step 4 - Divide S_{DS} and S_{D1} by the ductility factor R to calculate the seismic response coefficient, C_S.

Step 5 - Multiply the building's weight by C_S to get the design Base Shear.

Step 6 - Distribute the base shear vertically to each level using the Equivalent Lateral Force procedure (ELF).

Step 7 – Analyze how the forces distribute through the diaphragms, shear walls, braces and frames.

Step 8 – For allowable stress design (ASD) reduce the force by a factor of 0.7.

Step 9 – Verify that the ASD design forces do not exceed the allowable capacities for each element.

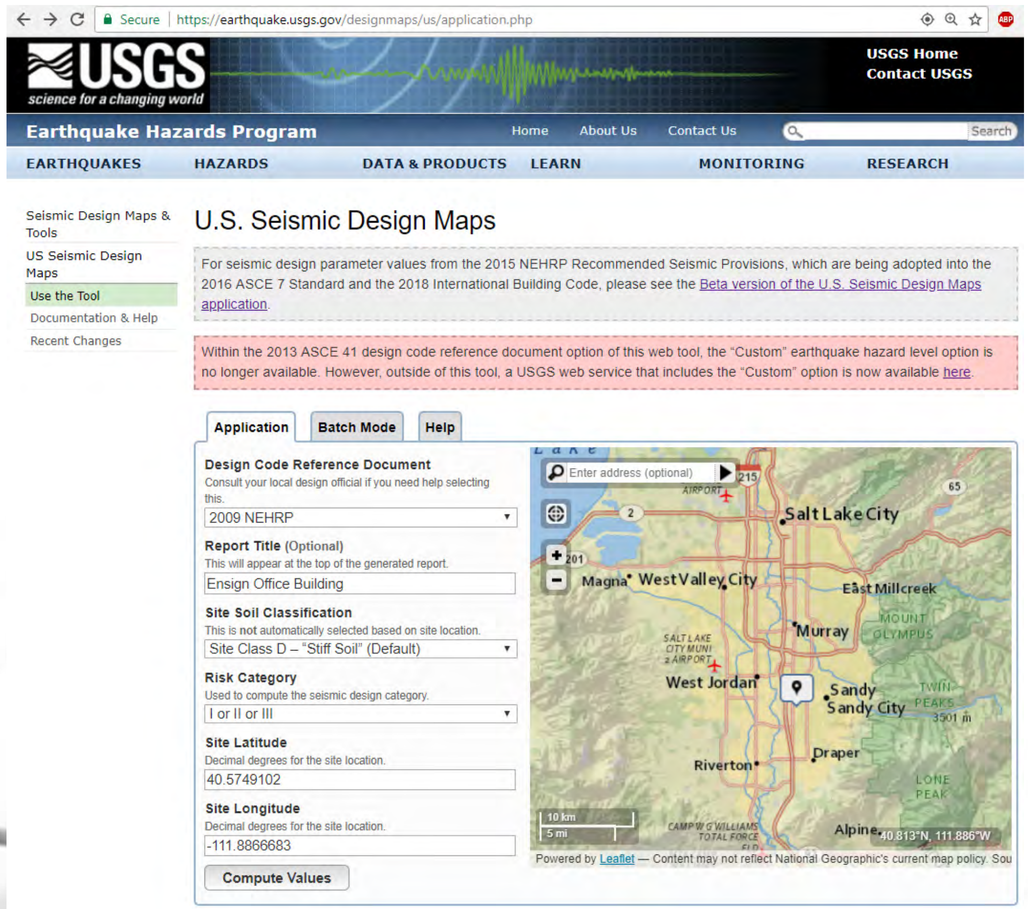
Step 10 – Check building deflections/drifts.

Design Example – Ensign Engineering's Office Building

- 45 West 10000 South, Sandy, UT
- 5 Story Steel Moment Frame Office Building
- Assume Site Class D
- Height = 68 ft
- Approx. Period = 0.82s

Step 1 - 3 –

Use the USGS website application to find risk-reduced ground motion parameters, S_S and S_1 (MCE_R).

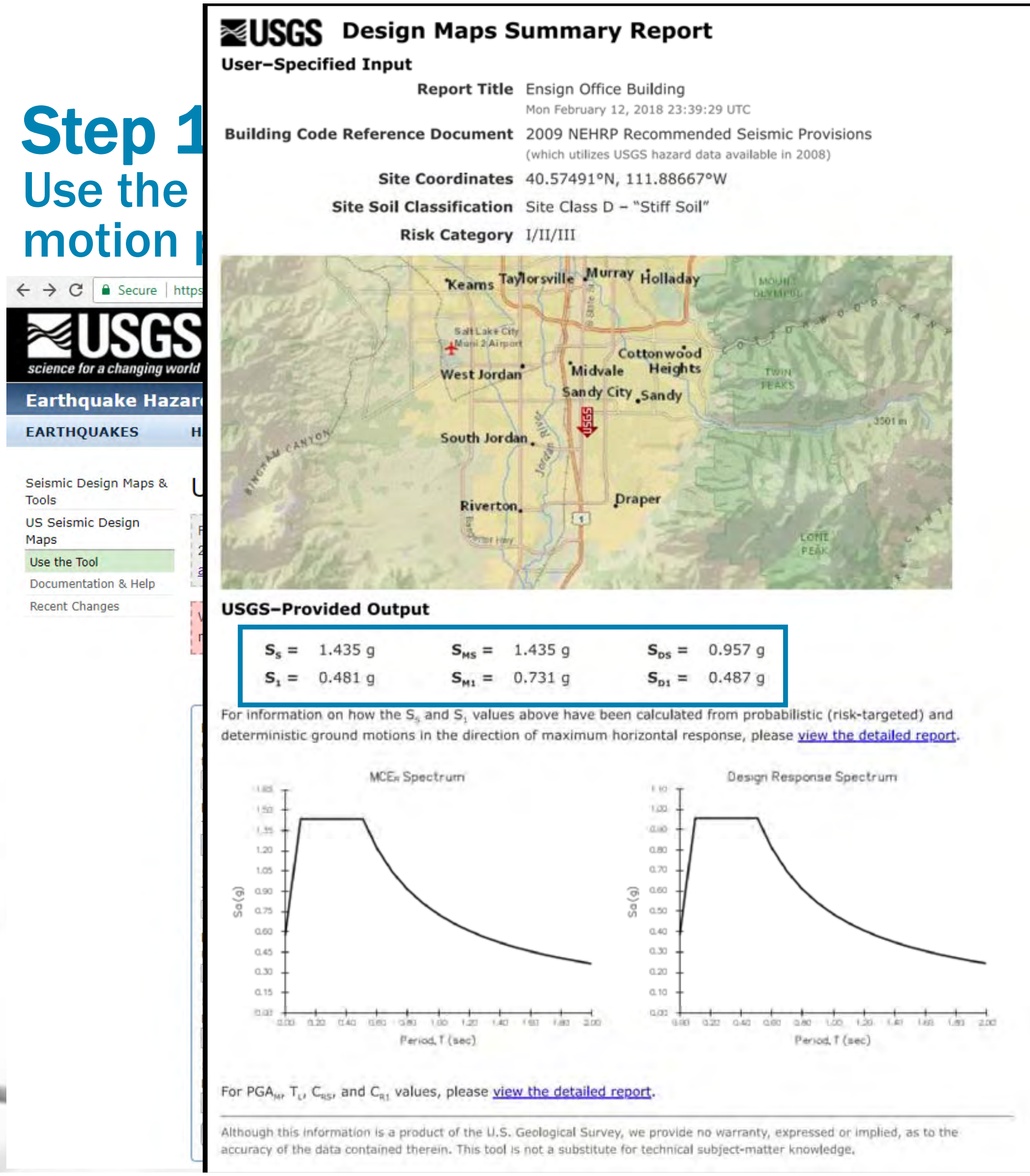


https://earthquake.usgs.gov/designmaps/us/application.php

- I selected 2009 NEHRP, so I can see a few more parameters.
- Enter Site Class, Risk Category and Location.

Step 1

Use the … reduced ground motion p…



Design Maps Summary Report

User–Specified Input

Report Title Ensign Office Building
Mon February 12, 2018 23:39:29 UTC

Building Code Reference Document 2009 NEHRP Recommended Seismic Provisions
(which utilizes USGS hazard data available in 2008)

Site Coordinates 40.57491°N, 111.88667°W

Site Soil Classification Site Class D – "Stiff Soil"

Risk Category I/II/III

USGS–Provided Output

S_S =	1.435 g	S_{MS} =	1.435 g	S_{DS} =	0.957 g
S_1 =	0.481 g	S_{M1} =	0.731 g	S_{D1} =	0.487 g

For information on how the S_S and S_1 values above have been calculated from probabilistic (risk-targeted) and deterministic ground motions in the direction of maximum horizontal response, please view the detailed report.

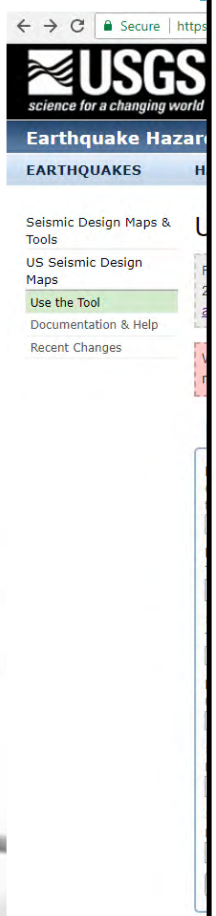
For PGA_M, T_L, C_{RS}, and C_{R1} values, please view the detailed report.

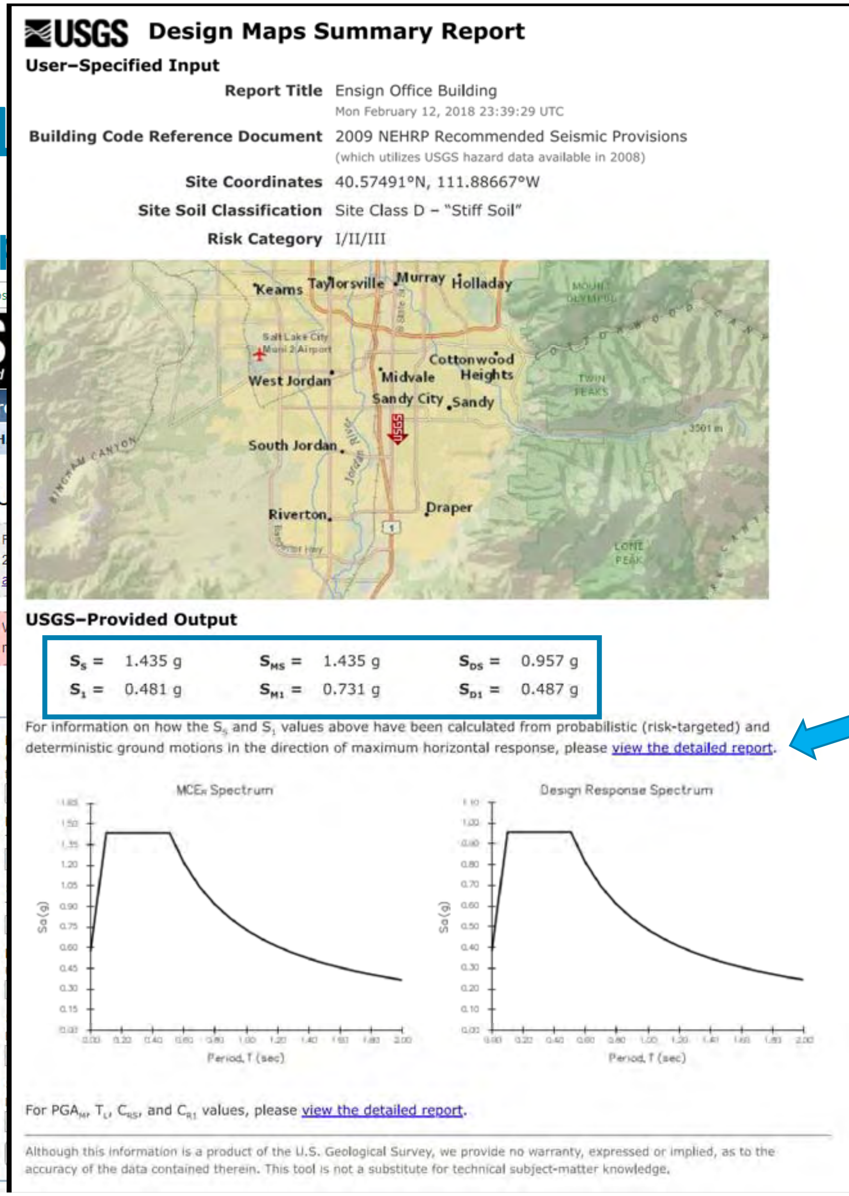
https://earthquake.usgs.gov/designmaps/us/application.php

- I selected 2009 NEHRP, so I can see a few more parameters.
- Enter Site Class, Risk Category and Location.

Step 1

Use the … reduced ground motion p…





USGS Design Maps Summary Report

User–Specified Input

Report Title	Ensign Office Building Mon February 12, 2018 23:39:29 UTC
Building Code Reference Document	2009 NEHRP Recommended Seismic Provisions (which utilizes USGS hazard data available in 2008)
Site Coordinates	40.57491°N, 111.88667°W
Site Soil Classification	Site Class D – "Stiff Soil"
Risk Category	I/II/III

USGS–Provided Output

S_S = 1.435 g	S_{MS} = 1.435 g	S_{DS} = 0.957 g
S_1 = 0.481 g	S_{M1} = 0.731 g	S_{D1} = 0.487 g

For information on how the S_S and S_1 values above have been calculated from probabilistic (risk-targeted) and deterministic ground motions in the direction of maximum horizontal response, please view the detailed report.

For PGA_M, T_L, C_{RS}, and C_{R1} values, please view the detailed report.

Although this information is a product of the U.S. Geological Survey, we provide no warranty, expressed or implied, as to the accuracy of the data contained therein. This tool is not a substitute for technical subject-matter knowledge.

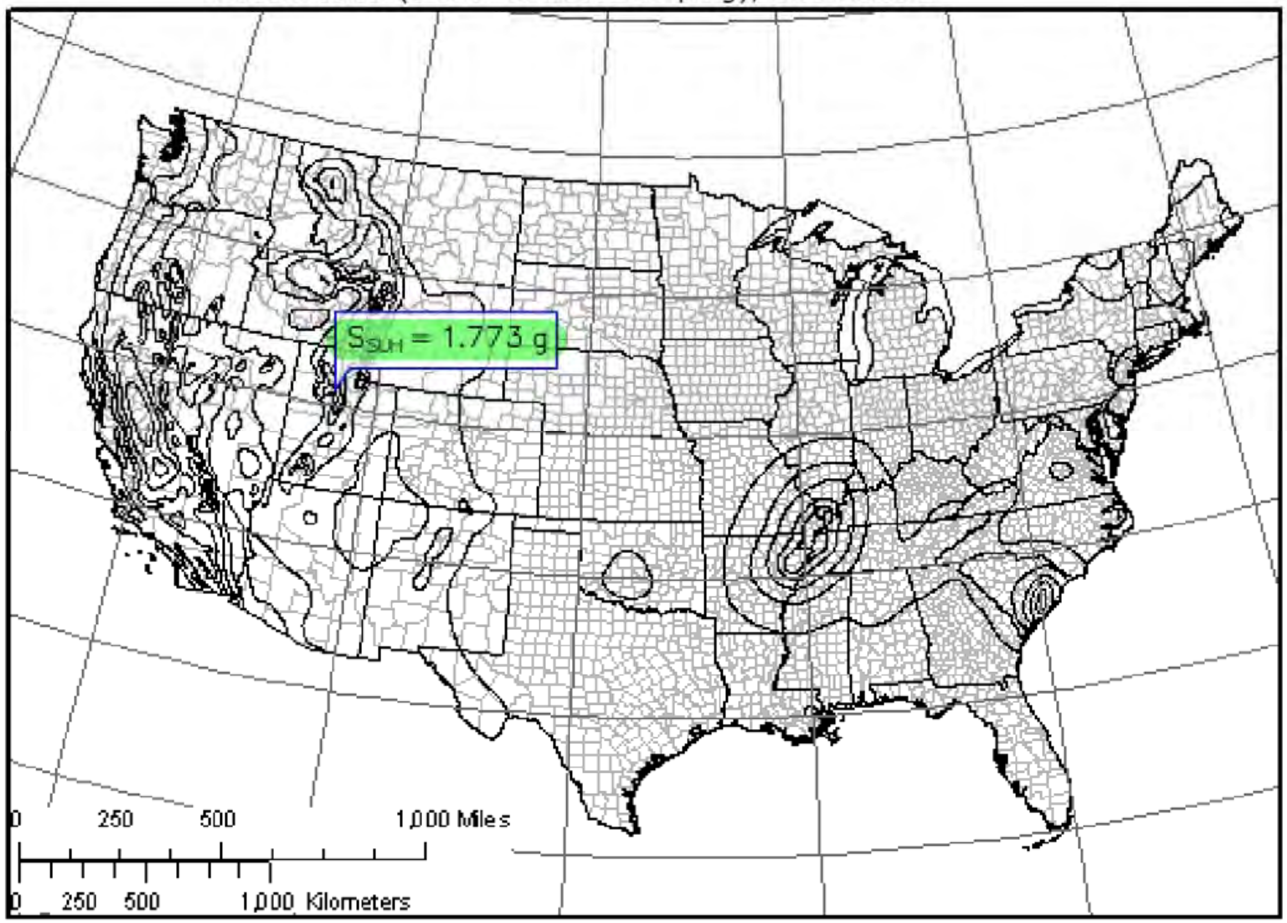
https://earthquake.usgs.gov/designmaps/us/application.php

- I selected 2009 NEHRP, so I can see a few more parameters.
- Enter Site Class, Risk Category and Location.

First, let's look at the USGS calculation of S_S

S_{SUH} = 1.773g
PSHA 2% in 50yr "Uniform Hazard" 0.2s response acceleration.

Figure 22–1: Uniform–Hazard (2% in 50–Year) Ground Motions of 0.2-Second Spectral Response Acceleration (5% of Critical Damping), Site Class B

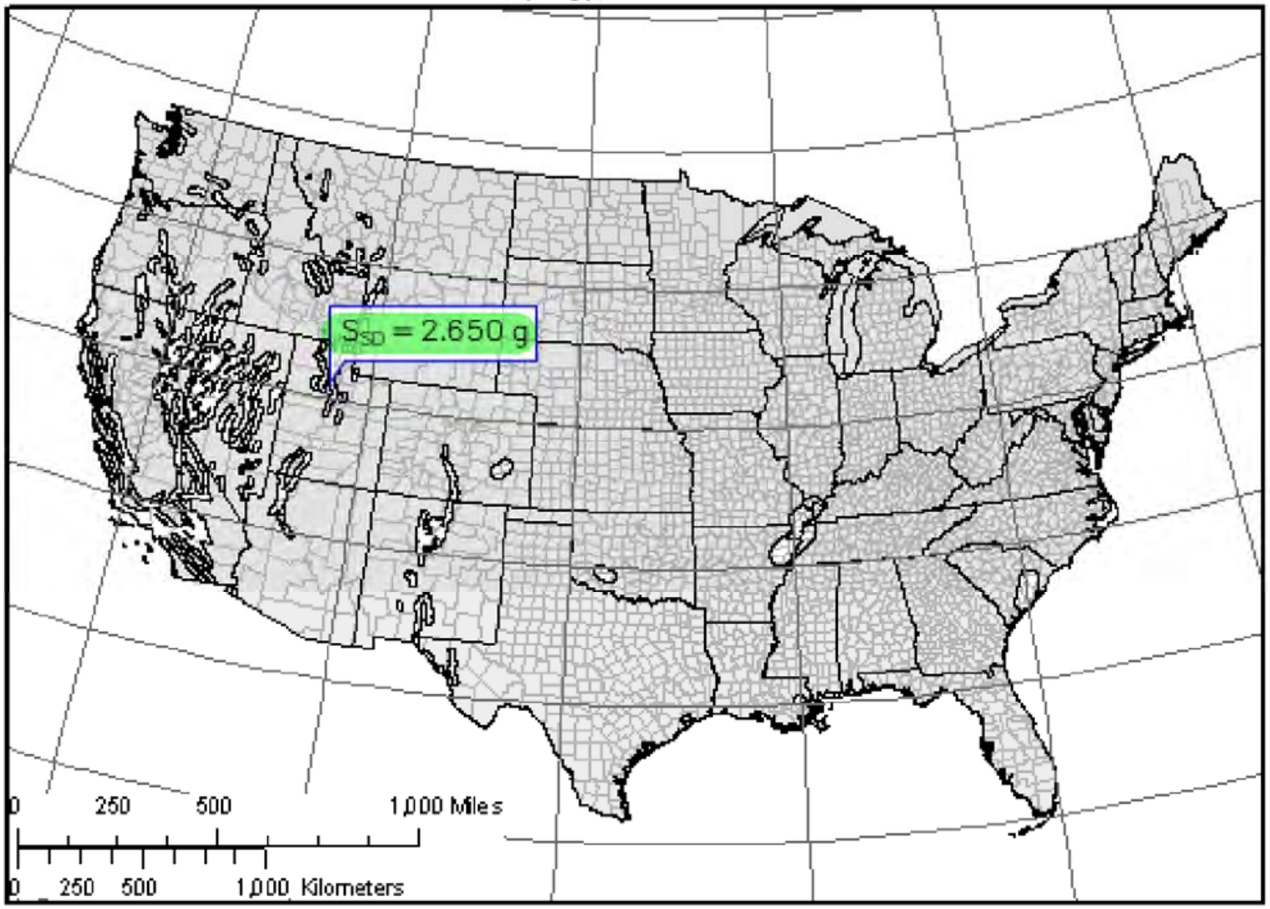


First, let's look at the USGS calculation of S_S

S_{SUH} = 1.773g
PSHA 2% in 50yr "Uniform Hazard" 0.2s response acceleration.

S_{SD} = 2.650g
This is the DSHA 0.2s response acceleration. (84th Percentile)

Figure 22–5: Deterministic Ground Motions of 0.2-Second Spectral Response Acceleration (5% of Critical Damping), Site Class B



First, let's look at the USGS calculation of S_S

S_{SUH} = 1.773g
PSHA 2% in 50yr "Uniform Hazard" 0.2s response acceleration.

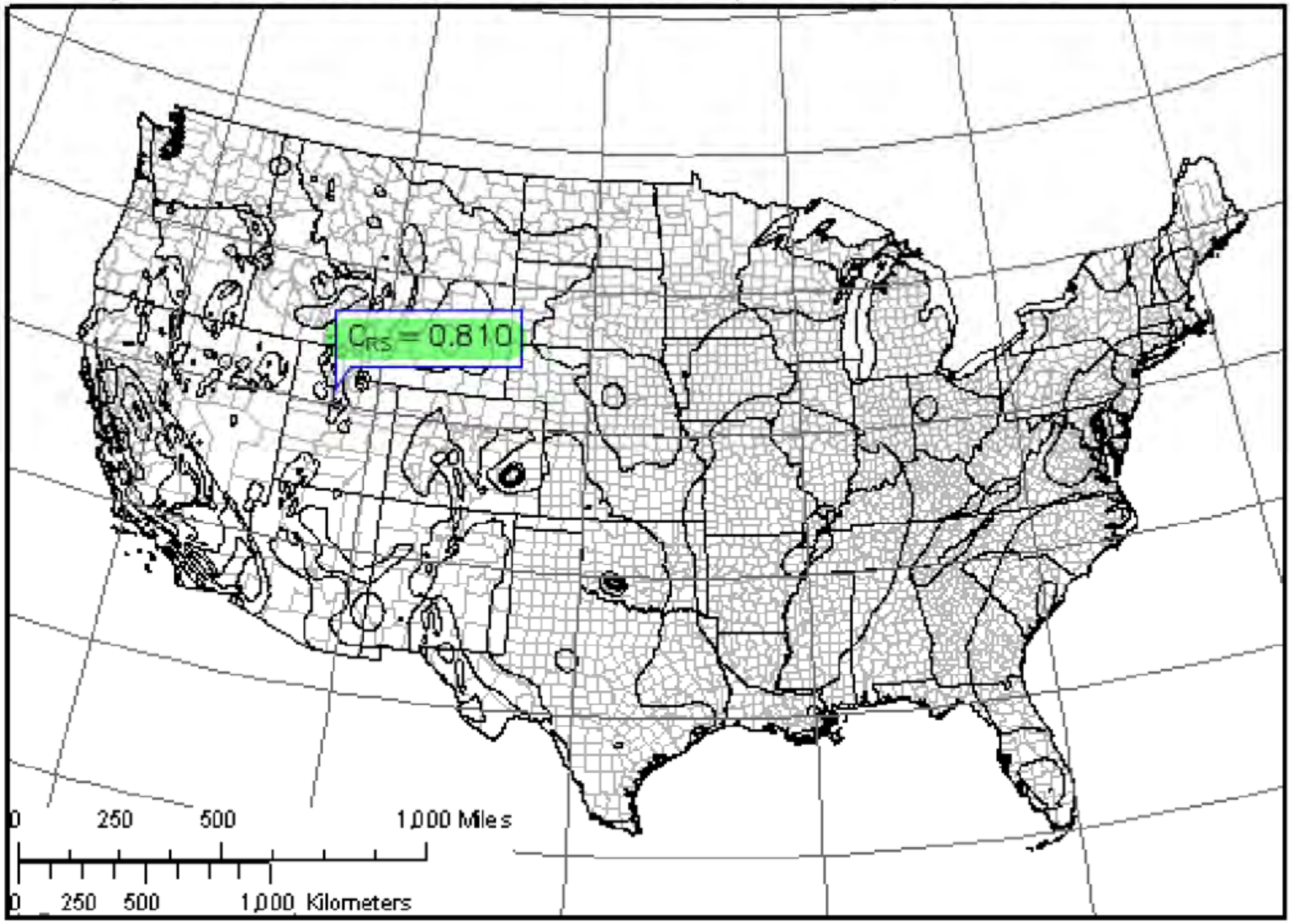
S_{SD} = 2.650g
This is the DSHA 0.2s response acceleration. (84^{th} Percentile)

C_{RS} = 0.81
This is the Risk Coefficient. This factor is intended to normalize the risk to a fragility curve from California.

$S_S = \min(C_{RS} * S_{SUH}, S_{SD}) =$ **1.436g**
$S_1 = \min(0.81*0.6, 0.88) =$ **0.481g**

MCE_R

Figure 22-3: Risk Coefficient at 0.2-Second Spectral Response Period



Now let's look at Site Coefficients and Design Accelerations

S_S = 1.436g
F_a = 1.0
$S_{MS} = F_a * S_S$ = 1.436g
S_{DS} = 2/3 * S_{MS} = **0.957g**

S_1 = 0.481g
F_v = 1.519
$S_{M1} = F_v * S_1$ = 0.731g
S_{D1} = 2/3 * S_{M1} = **0.487g**

Table 11.4-1: Site Coefficient F_a

Site Class	Spectral Response Acceleration Parameter at Short Period				
	$S_S \le 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	See Section 11.4.7 of ASCE 7				

Note: Use straight-line interpolation for intermediate values of S_S

For Site Class = D and S_s = 1.435 g, F_a = 1.000

Table 11.4-2: Site Coefficient F_v

Site Class	Spectral Response Acceleration Parameter at 1-Second Period				
	$S_1 \le 0.10$	$S_1 = 0.20$	$S_1 = 0.30$	$S_1 = 0.40$	$S_1 \ge 0.50$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	See Section 11.4.7 of ASCE 7				

Note: Use straight-line interpolation for intermediate values of S_1

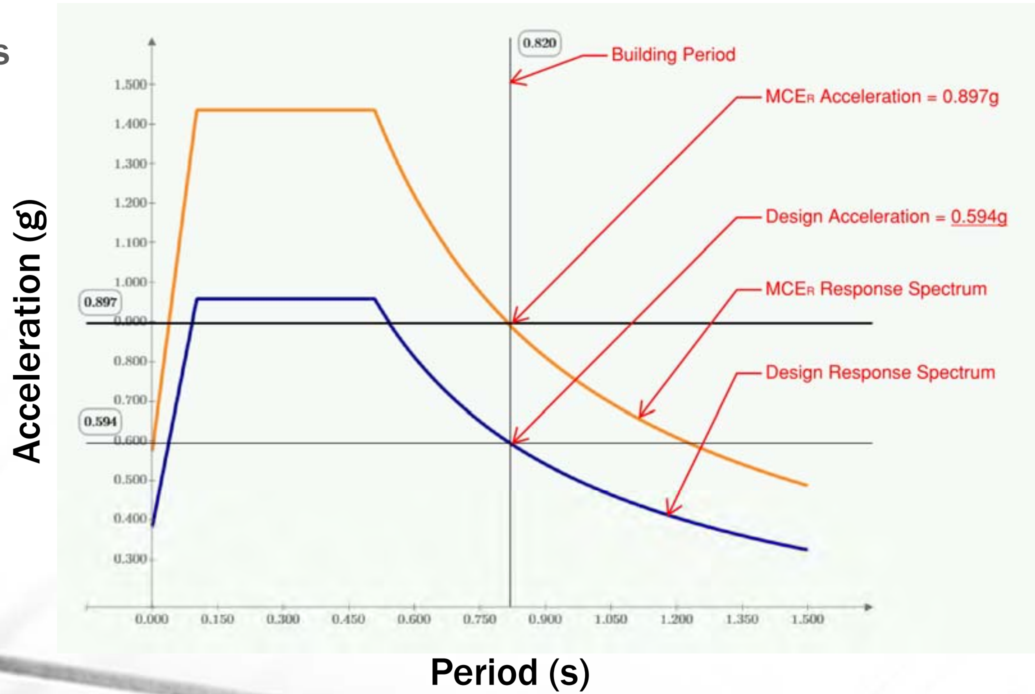
For Site Class = D and S_1 = 0.481 g, F_v = 1.519

From these values we can plot a Design Response Spectrum

S_S = 1.436g
S_{DS} = 2/3 * S_{MS} = 0.957g

S_1 = 0.481g
S_{D1} = 2/3 * S_{M1} = 0.487g

T = 0.82s



Code Basis for Design-

At MCE_R the code targets a <u>10% probability of collapse</u>. This is considered “Collapse Prevention”.

The code assumes that for traditional building design, there is a 1.5 safety factor against collapse, so we design for 2/3 MCE_R instead of MCE_R.

Step 4 –
Divide the design accelerations by the ductility factor R to calculate the seismic response coefficient, C_S.

- It is much easier to analyze a structure assuming it stays in the elastic range.
- So, we divide the Design Accelerations by a Response Modification Coefficient (R factor) which is a measure of how ductile a building system is. Typical R factors range from 1.5 to 8, with 8 being the most ductile. We can then analyze it assuming it remains elastic.
- Our example building is assumed to be a Special Steel Moment frame, R = 8.

Step 4 –
Divide the design accelerations by the ductility factor R to calculate the seismic response coefficient, C_S.

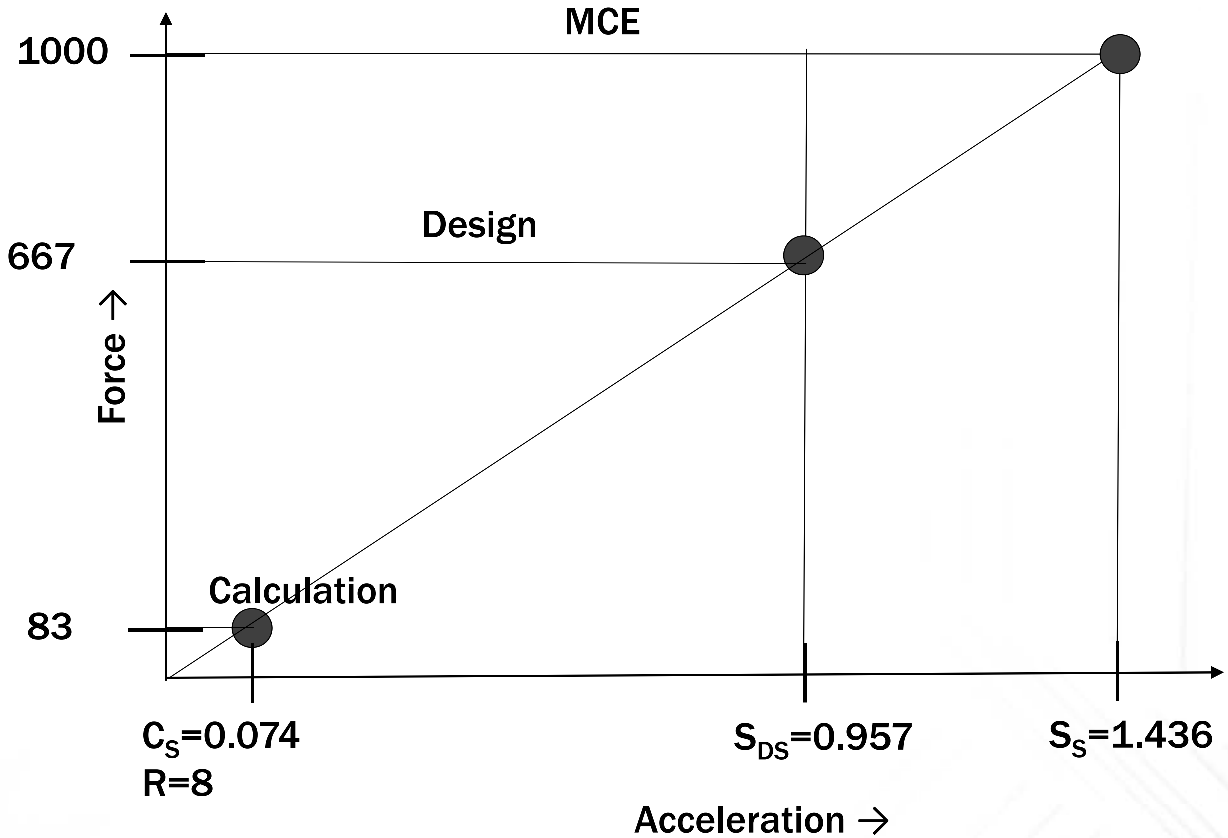
$C_S = \min[S_{DS}/R, S_{D1}/(T*R)]$

$S_{DS}/R = 0.957g / 8 = 0.120g$

$S_{D1}/(T * R) = 0.487g / (0.82 * 8) = 0.074g$

$C_S = 0.074g$

This is actual acceleration used in design. Theoretically, any response acceleration above this level would start to damage the building.


MCE
1000
Design
667
Force →
Calculation
83
C_S=0.074
R=8
S_DS=0.957
S_S=1.436
Acceleration →

Step 5 –

Multiply the building's weight by C_S to get the design Base Shear.

$F = m * a$

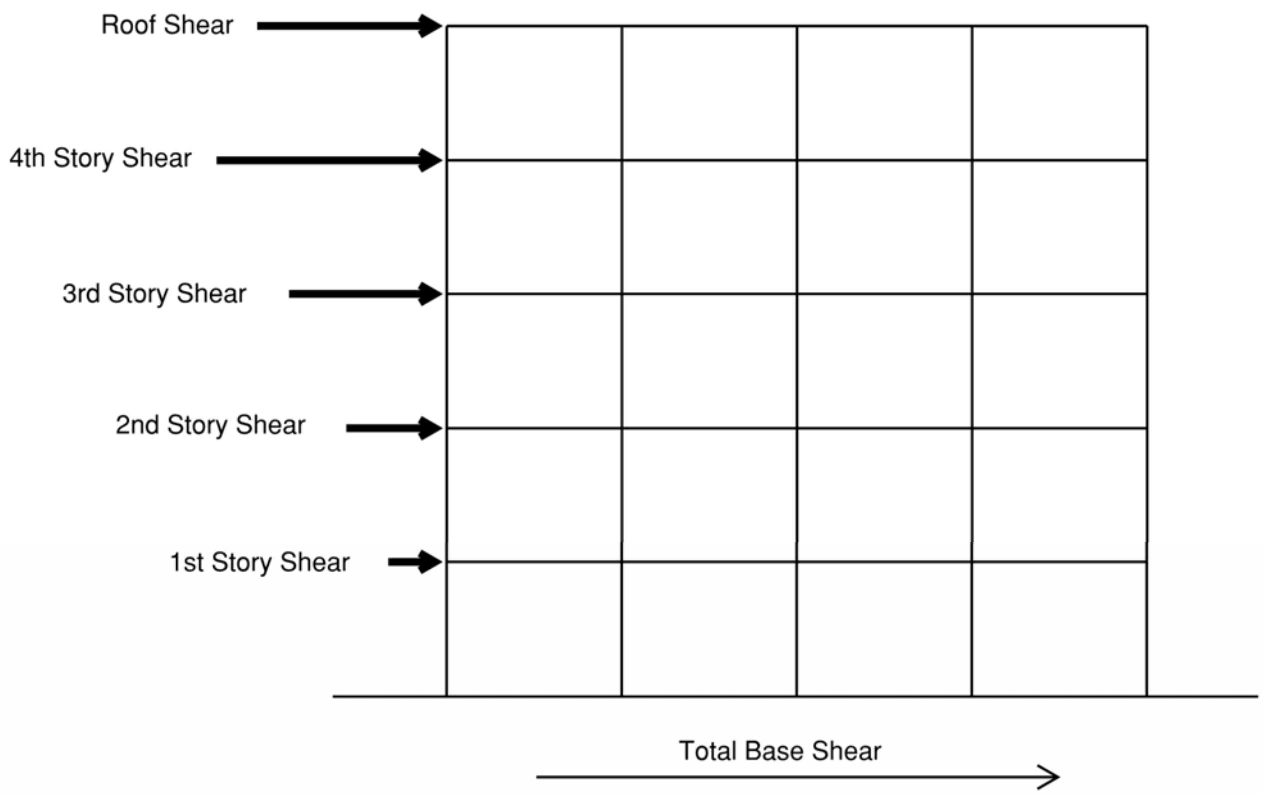
Base Shear (Lateral Force) = Building Mass * Design Acceleration

$V = Weight * C_S = Weight * 0.074g = Total Base Shear$

Step 6 –

Distribute the base shear vertically to each level using the Equivalent Lateral Force procedure (ELF).

$$C_{vx} := \frac{w_x \cdot h_x^{\,k}}{\sum_{i=1}^{n} w_i \cdot h_i^{\,k}}$$



Step 7 – 11
Design the building for the calculated forces

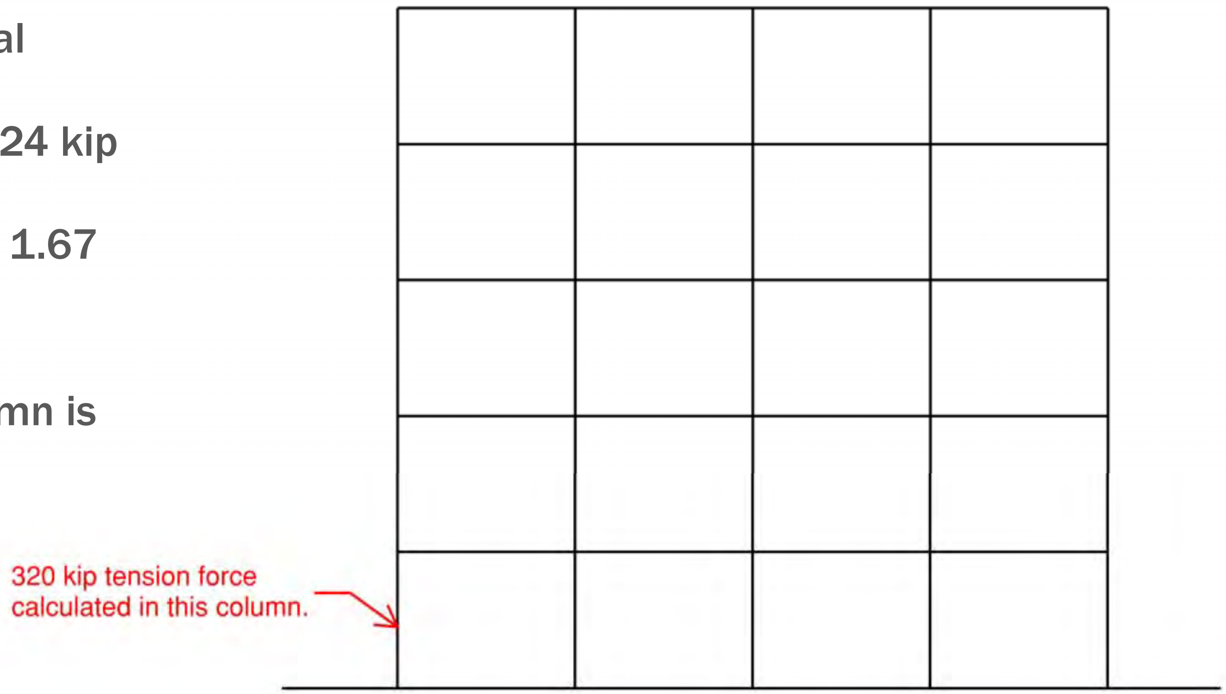
Force in Column = 320 kip axial

ASD Force = 0.7 * 320 kip = 224 kip

Column capacity is including a 1.67 safety factor is 235 kip

235 kip > 224 kip, so the column is okay.

Check drift



ASCE 7-10 Seismic Design Process

Step 1 - Use the USGS website application to get risk- modified ground motion parameters, S_S and S_1 (MCE_R).

Step 2 - Modify MCE_R parameters for soil effects (Site Class A-F).

Step 3 - Multiply site-modified MCE_R ground motions parameters by 2/3 to get design spectral acceleration parameters (S_{DS} and S_{D1}).

Step 4 - Divide S_{DS} and S_{D1} by the ductility factor R to calculate the seismic response coefficient, C_S.

Step 5 - Multiply the building's weight by C_S to get the design Base Shear.

Step 6 - Distribute the base shear vertically to each level using the Equivalent Lateral Force procedure (ELF).

Step 7 – Analyze how the forces distribute through the diaphragms, shear walls, braces and frames.

Step 8 – For allowable stress design (ASD) reduce the force by a factor of 0.7.

Step 9 – Verify that the ASD design forces do not exceed the allowable capacities for each element.

Step 10 – Check building deflections/drifts.

In summary-

We looked at a taller building, but most buildings are short period. So-

1. Get mapped PSHA and DSHA 0.2s Response Accelerations. (1.773g and 2.650g)
2. Reduce PSHA by Risk Coefficient (0.81 x 1.773 = 1.436g)
3. Take minimum between DSHA and reduced PSHA = 1.436g (MCE_R)
4. Modify for site response and multiply by 2/3 (1.436 * 1.0 * 2 / 3 = 0.957g)
5. Divide by Ductility Factor, R (0.957g / 8 = 0.120g)

Hence –

- A response acceleration of 0.120g theoretically could initiate damage in a short building.
- The building's ductility allows it to continue to take damage up to 0.957g. There should be minimal loss of life up to this acceleration.
- Residual building capacity allows additional load beyond 0.957g, but at 1.436g a code building will have a 10% likelihood of collapse.
- The ability of the building to withstand 1.773g or 2.650g accelerations is unknown. > 10% likelihood of collapse.

<u>If instead of designing for the code minimums, a client wants me to design for a 7.0M Wasatch Fault Rupture, what design accelerations should I use?</u>

Questions?

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801.735.5197

2018 UGSWG

COMPARE 2018 IBC TO WASATCH FAULT RUPTURE

Public Expectations

Most lay people expect that the code protects them from a Wasatch fault rupture. Many structural engineers also have the same perception.

How close are the code MCE_R values compared to the 84th percentile deterministic values from a Wasatch fault rupture?

This Study

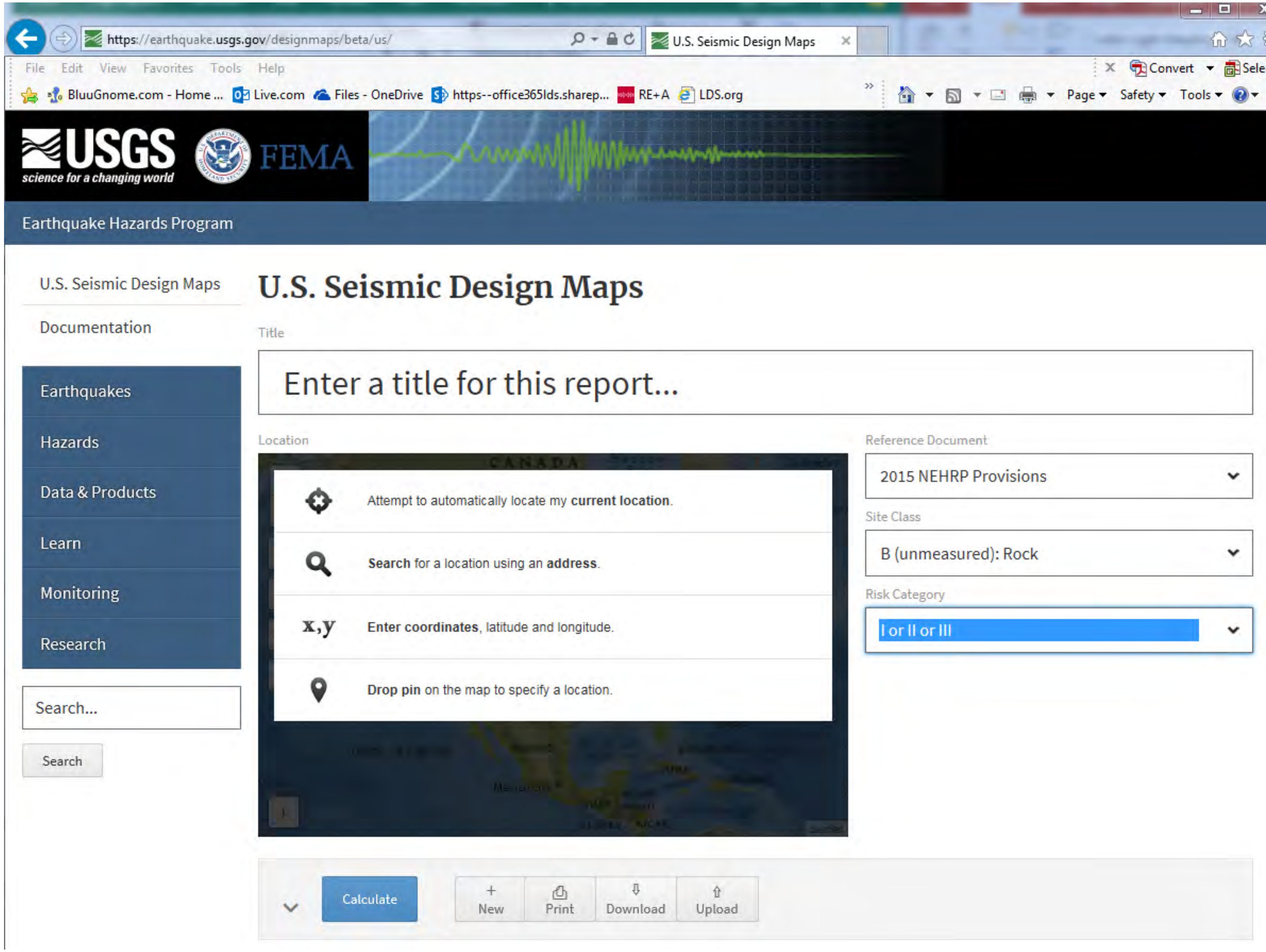
- Comparisons are based on dense soil/soft rock with a shear wave velocity of 760 m/s (2,500 f/t)
  - Boundary between Site Class B and Site Class C
- Does not compare other site classifications or site coefficients
- Uses ASCE 7-16
  - Derived from NGA West 2 GMPE's and 2014 USGS Seismic Hazard Maps
- Only looks at 2 periods – 0.2 S and 1.0 S
- First: Compare values from USGS Website: Probabilistic vs. 84th Percentile Deterministic
- Second: Look at NGA West 2 sensitivities using the PEER Spreadsheet

Apples to Apples: Comparing NGA West 2 to Code

- NGA West 2 calculates RotD50
- Code requires RotD100
- Adjustments to get from RotD50 to RotD100
  - 0.2 S = 1.1
  - 1.0 S = 1.3

USGS Website

Use Site Class B (Unmeasured) Rock to get 760 m/s values.



Information provided by USGS Webtool

Engineers no longer use the 2% in 50 year "Uniform Hazard" ground motion for building design.

They use a "Risk-targeted" ground motions which is the "Uniform Hazard" ground motion, multiplied by a risk factor C_{RS}, which converts the "Uniform Hazard" to a ground motion level that equates to a 1% risk of collapse in 50 years.

NGA2 calculates RotD50. Codes uses RotD100. To get code deterministic, multiply median by 1.1 or 1.3 to convert to RotD100. Then multiple by 1.8 to convert to approximate 84th percentile.

Site Coefficients and Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameters

Risk-targeted Ground Motion (0.2 s)

$C_{RS}S_{SUH} = 0.864 \times 1.578 = 1.363$ g

Deterministic Ground Motion (0.2 s)

Median * 1.1 (RotD100) * 1.8

$S_{SD} = 2.778$ g

$S_S \equiv$ "Lesser of $C_{RS}S_{SUH}$ and S_{SD}" $= 1.363$ g

Risk-targeted Ground Motion (1.0 s)

$C_{R1}S_{1UH} = 0.878 \times 0.552 = 0.485$ g

Deterministic Ground Motion (1.0 s)

Median * 1.3 (RotD100) * 1.8

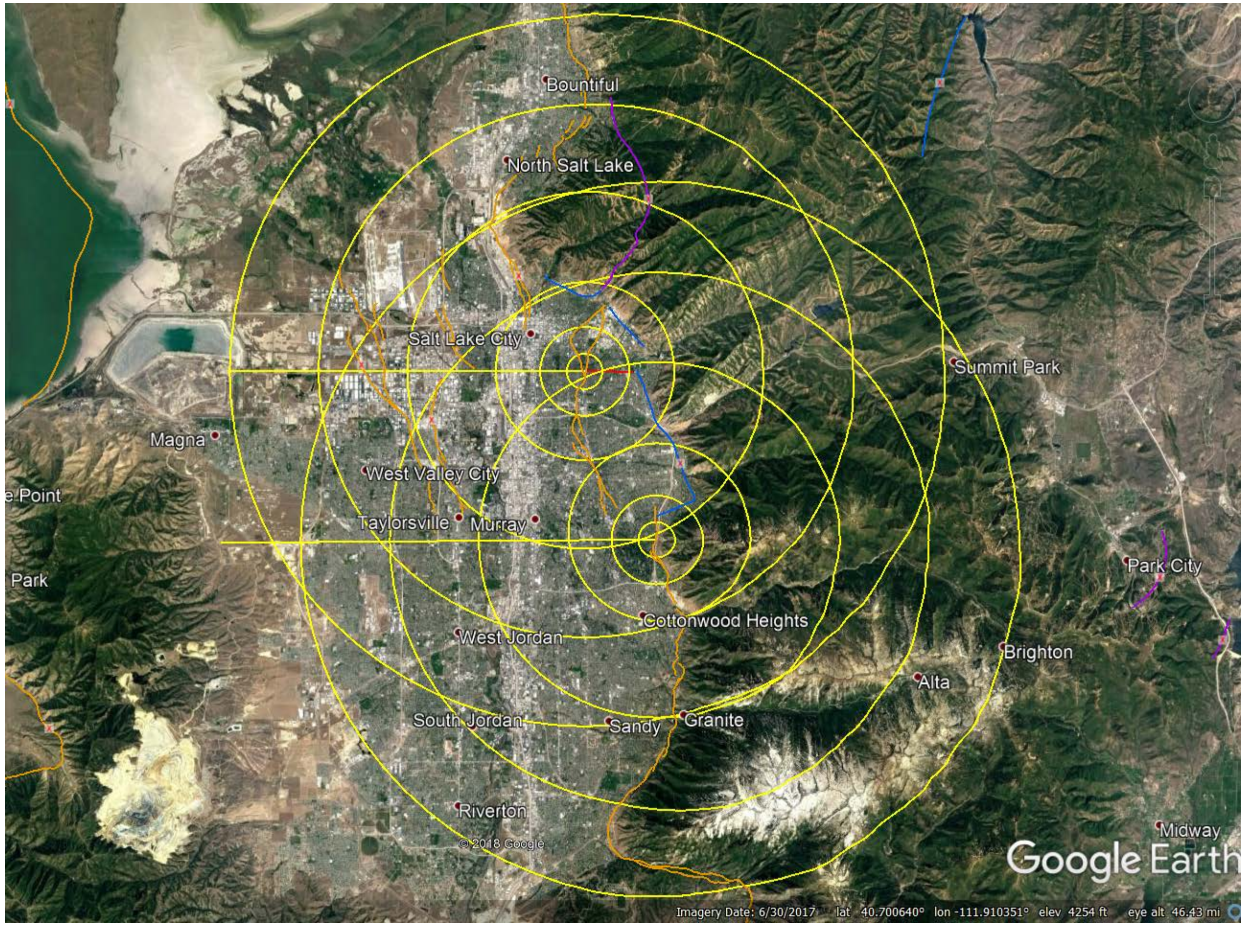
$S_{1D} = 1.155$ g

$S_1 \equiv$ "Lesser of $C_{R1}S_{1UH}$ and S_{1D}" $= 0.485$ g

Calculate Values on Two Lines Across Salt Lake Valley

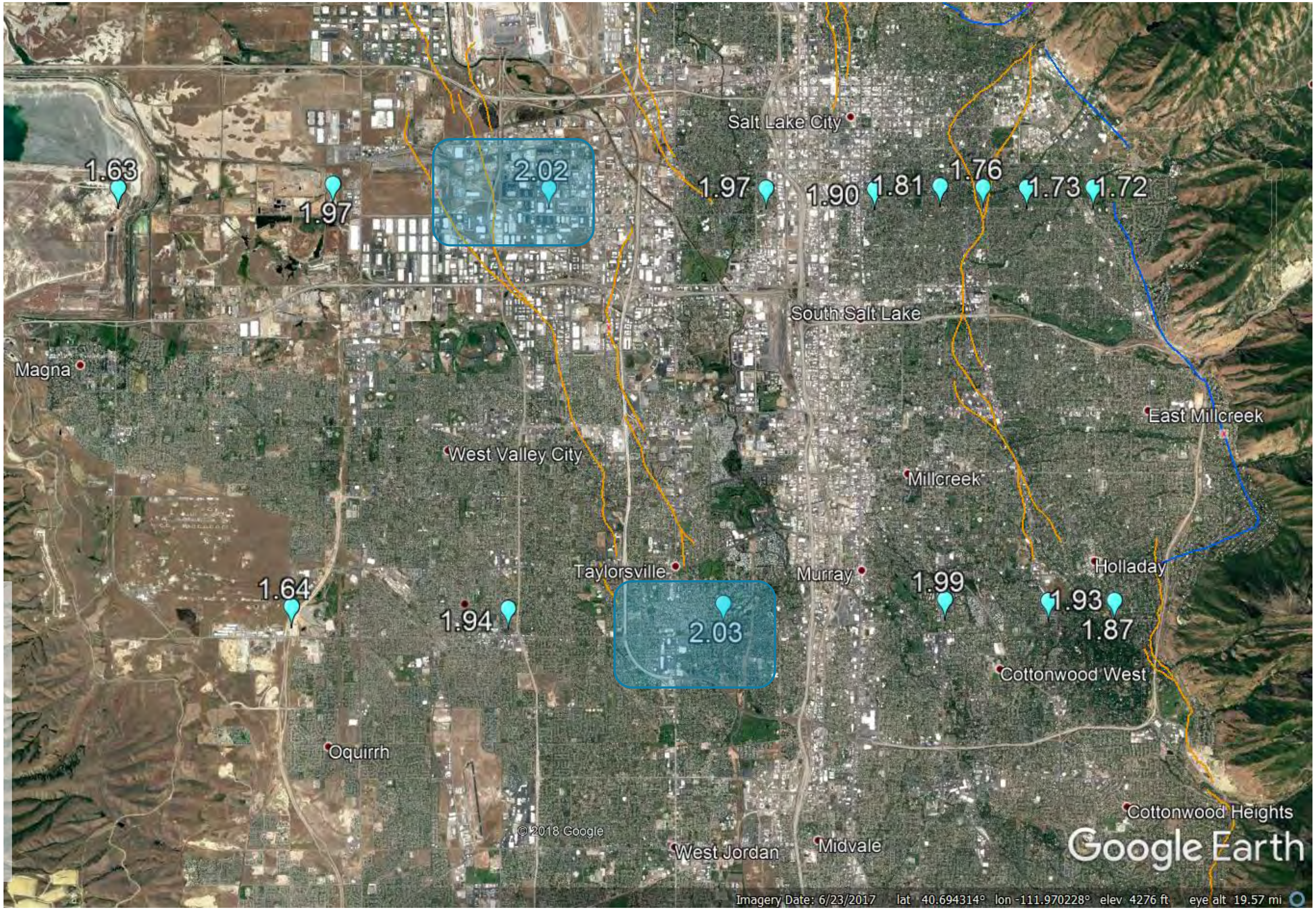
5300 South & 1300 South

- 1 km from fault
- 2.5 km from fault
- 5 km from fault
- 10 km from fault
- 15 km from fault
- 20 km from fault



Input into Excel Spreadsheet

UGSWG 2018										
	0.2 S Response					1.0 S Response				
	84th Percentile Deterministic	Uniform Hazard	Risk Coef.	MCE_R	2/3 MCE_R	84th Percentile Deterministic	Uniform Hazard	Risk Coef.	MCE_R	2/3 MCE_R
Site Description	S_{SD}	S_{SUH}	C_{RS}	S_S	S_{DS}	S_{1D}	S_{1UH}	C_{R1}	S_1	S_{D1}
5300 S 1 km W	2.547	1.579	0.862	1.360	0.907	1.121	0.575	0.870	0.500	0.333
Deterministic/Value		1.61		1.87	2.81		1.95		2.24	3.37
5300 S 2.5 km W	2.742	1.650	0.860	1.419	0.946	1.163	0.594	0.867	0.515	0.344
Deterministic/Value		1.66		1.93	2.90		1.96		2.26	3.38
5300 S 5 km W	2.932	1.712	0.859	1.471	0.981	1.186	0.607	0.865	0.526	0.350
Deterministic/Value		1.71		1.99	2.99		1.95		2.25	3.39
5300 S 10 km W	2.942	1.687	0.858	1.447	0.965	1.101	0.583	0.868	0.506	0.338
Deterministic/Value		1.74		2.03	3.05		1.89		2.18	3.26
5300 S 15 km W	2.415	1.437	0.869	1.248	0.832	0.871	0.500	0.875	0.437	0.292
Deterministic/Value		1.68		1.94	2.90		1.74		1.99	2.98
5300 S 20 km W	1.681	1.166	0.879	1.026	0.684	0.609	0.412	0.879	0.363	0.242
Deterministic/Value		1.44		1.64	2.46		1.48		1.68	2.52



0.2 Second

84th % Deterministic/MCE_R

In some cases 84th % is twice the MCE_R. (3 times the design (2/3 MCE_R).

Selected Wasatch Front Cities

UGSWG 2018												
			0.2 S Response					1.0 S Response				
			84th Percentile Deterministic	Uniform Hazard	Risk Coef.	MCE_R	2/3 MCE_R	84th Percentile Deterministic	Uniform Hazard	Risk Coef.	MCE_R	2/3 MCE_R
Site Description	**Site Lat.**	**Site Long.**	S_{SD}	S_{SUH}	C_{RS}	S_S	S_{DS}	S_{1D}	S_{1UH}	C_{R1}	S_1	S_{D1}
Tooele	40.531	-112.299	2.794	0.770	0.928	0.714	0.476	1.182	0.278	0.929	0.258	0.172
Deterministic/Value				3.63		3.91	5.87		4.25		4.58	6.87
Bountiful	40.882	-111.878	2.701	1.631	0.861	1.404	0.936	1.187	0.602	0.870	0.524	0.349
Deterministic/Value				1.66		1.92	2.89		1.97		2.27	3.40
Ogden	41.222	-111.97	2.983	1.580	0.863	1.363	0.909	1.254	0.565	0.880	0.497	0.331
Deterministic/Value				1.89		2.19	3.28		2.22		2.52	3.79
Brigham City	41.513	-112.016	2.778	1.578	0.864	1.363	0.909	1.155	0.552	0.878	0.485	0.323
Deterministic/Value				1.76		2.04	3.06		2.09		2.38	3.58
Provo	40.234	-111.669	3.056	1.628	0.857	1.396	0.931	1.294	0.589	0.875	0.515	0.343
Deterministic/Value				1.88		2.19	3.28		2.20		2.51	3.77

Results

- 84^{th} percentile deterministic Wasatch fault ground motion values are significantly higher (1.6 to 2.5 time higher) than code MCE_R ground motion values.
- This is true even 20 km west of the fault.
- The code allows a 10% probability of collapse at MCE_R. What is the risk if the building experiences a ground motion twice as large?

NGA West 2 Sensitivities

Peer Excel Spreadsheet

PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

PEER

WEIGHTED AVERAGE of 2014 NGA WEST-2 GMPEs

Last updated: 06 05 14

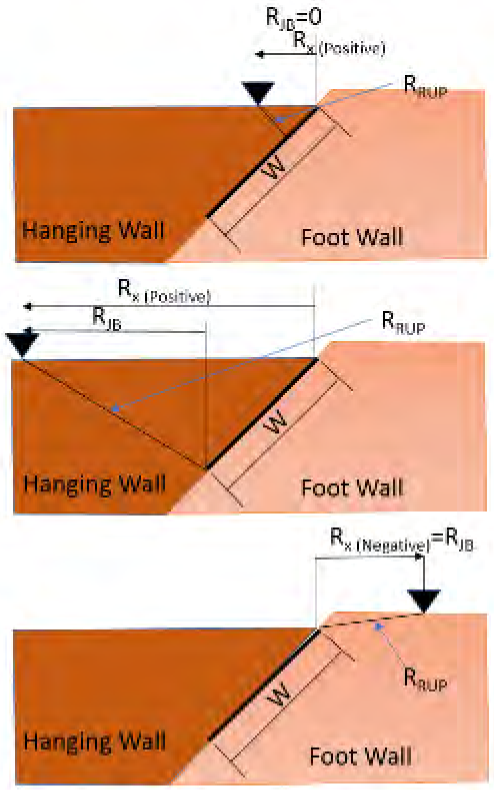
by Emel Seyhan, PhD, PEER & UCLA -- email: emel.seyhan@gmail.com, peer_center@berkeley.edu

Range of Values Used

Coefficient		Min.	Max.	Best Guess (Default Used PEER Spreadsheet)
Magnitude	M_W	6.5	7.5	7.2
Shear Wave Velocity	V_{S30} (m/s)			760 m/s
Dip (Deg)		35	65	50
Coseismic Rupture	Z_{TOR} (km)	0	0	0 (at surface)
Hypocentral Depth	Z_{HYP} (km)	12	18	15 (Bottom of seismogenic crust)
Depth to V_S=1 km/S	$Z_{1.0}$ (km)	0.15	0.55	0.35
Depth to V_S=2.5 km/S	$Z_{2.5}$ (km)	1	3	
Fault Rupture Width	W (km)			Calculated (dip & seismogenic depth)
VS30 Flag				Measured
Region				California
FAS				No

Slice Through Salt Lake Valley at 5300 S.

Used Mathcad to Calculate Distances Based on Dip Angle



$R_{RUP}=R_x*\sin(dip)$

$R_{JB}=R_x - W*\cos(dip) >=0$

R_{RUP}(for $R_x <= W/\cos(dip) = R_x*\sin(dip)$

R_{RUP} (for $R_x > W/\cos(dip) = [R_x^2 + W^2 - 2*R_x*W*\cos(dip)]^{1/2}$

$R_{RUP}=(R_x^2 + height^2)^{1/2}$

$= R_x$ if level ground

The following slides are based on …

- 0.2 Second Response
- Weighted average using factor of 0.22 for ASK14, BSSA14 & CB14, and 0.12 for I14.

Variability in NGA 2 Models (Lowest to Highest)

	ASK14	BSSA14	CB14	CY14	I14	Max	Min	Difference	% Diff.
1.0 km	1.28	0.88	1.53	1.22	1.31	1.53	0.88	0.65	74%
2.5 km	1.33	0.88	1.68	1.22	1.15	1.68	0.88	0.80	92%
5.0 km	1.31	0.88	1.83	1.20	0.95	1.83	0.88	0.96	109%
10 km	1.12	0.88	1.76	1.04	0.68	1.76	0.68	1.08	158%
15 km	0.80	0.80	1.19	0.76	0.53	1.19	0.53	0.67	127%
20 km	0.54	0.55	0.76	0.53	0.42	0.76	0.42	0.34	81%

Dip Only – Compared to 50 deg. (Seismogenic Depth = 15 km)

		1 km	2.5 km	5 km	10 km	15 km	20 km
35 deg.		4%	6%	10%	21%	51%	98%
65 deg.		-4%	-6%	-11%	-30%	-36%	-30%

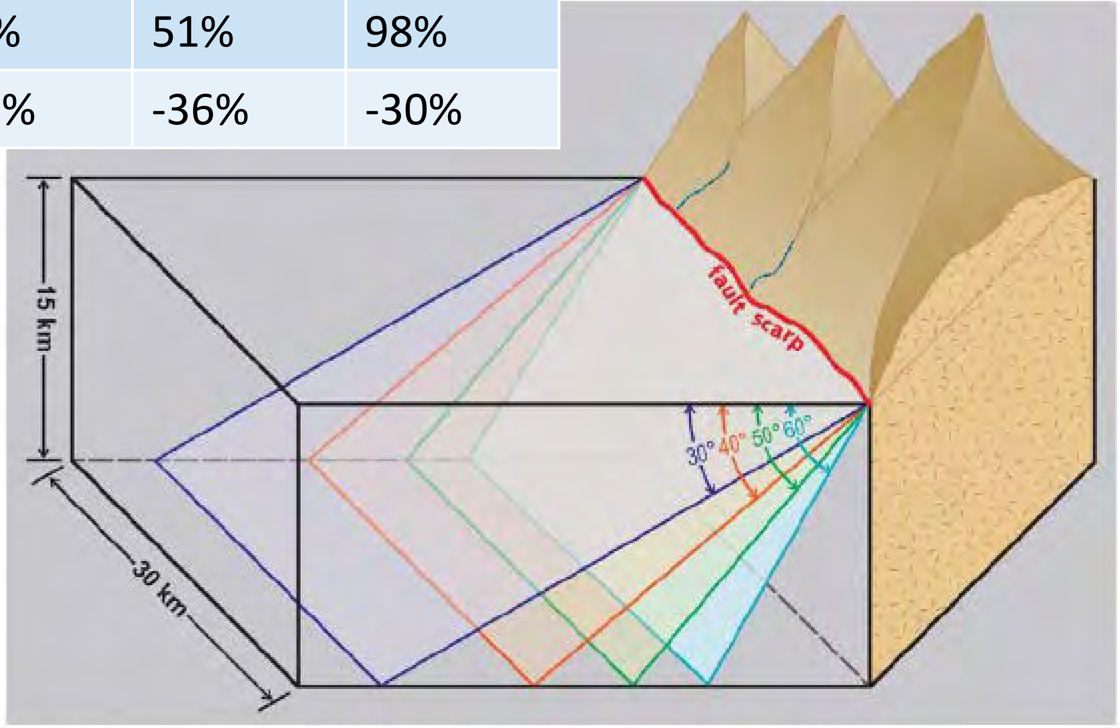


Figure 3.2-1. Schematic diagram showing the non-linear increase in fault area with decreasing dip angles.

Seismogenic Depth Only (Compared to 15km) (Dip = 50 deg.)

		1 km	2.5 km	5 km	10 km	15 km	20 km
12 km		-3%	-2%	-1%	-3%	-16%	-14%
18 km		3%	3%	2%	2%	17%	17%

Dip and Seismogenic Depth (Worst Case)

		1 km	2.5 km	5 km	10 km	15 km	20 km
Above Base		8%	9%	12%	22%	52%	103%
Below Base		-7%	-8%	-14%	-37%	-42%	-35%

Magnitude (Base 7.2) Vary (6.5, 7.0, 7.1, 7.3, 7.5, 8.0)

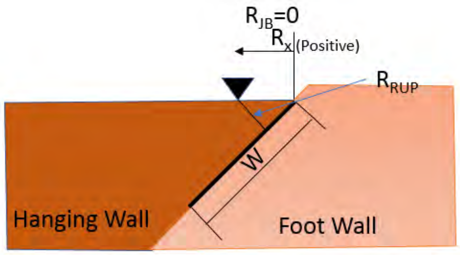
	1 km	2.5 km	5 km	10 km	15 km	20 km
6.5	-10%	-11%	-14%	-18%	-20%	-23%
7.0	-2%	-2%	-3%	-5%	-5%	-6%
7.1	-1%	-1%	-2%	-2%	-3%	-3%
7.3	1%	1%	2%	2%	3%	3%
7.5	3%	3%	5%	7%	8%	10%
8.0	7%	9%	13%	20%	23%	28%

Vary Z1 (Compare to 0.35 km)

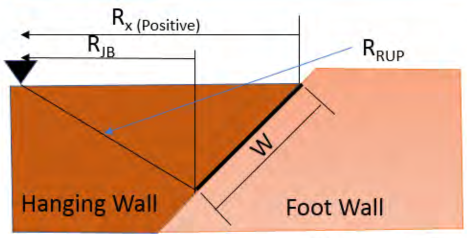
		1 km	2.5 km	5 km	10 km	15 km	20 km
0.55 km		0%	0%	0%	0%	0%	0%
0.15 km		-2%	-2%	-2%	-2%	-2%	-2%

Conclusions

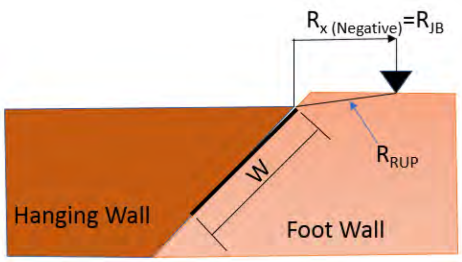
- There is huge variability in the ground motion prediction models (74% to 158% comparing lowest to highest)
- The single largest factor affecting ground motion is angle of dip.
- There is significantly more variability in ground motion 10 km and greater from the fault than there is in 5 km and less.
- Magnitudes from 6.5 to 7.5 have relatively small impact on ground motion, especially considering the variability in dip and the GMPE's



R_{RUP}=R_x*sin(dip)



R_{JB}=R_x - W*cos(dip) >=0
R_{RUP}(for R_x <= W/cos(dip) = R_x*sin(dip)
R_{RUP} (for R_x > W/cos(dip) = $[R_x^2 + W^2 - 2*R_x*W*\cos(dip)]^{1/2}$



$R_{RUP}=(R_x^2 + height^2)^{1/2}$
= R_x if level ground

Hanging Wall over Fault

$W := 40\ km$

Intermountain Medical Center
Lat: 40.6613 Long:-111.8912

$R_{X1} := 7 \cdot km$

$Dip := 55\ deg$

$R_{JB} := 0$

$R_{RUP} := R_{X1} \cdot \sin(Dip) = 5.734\ km$

$W \cdot \cos(Dip) = 22.943\ km$

Hanging Wall West of Fault

Tooele
Lat: 40.5306 Long:-112.2985

$R_{X2} := 40\ km$

$R_{JB} := \max(R_{X2} - W \cdot \cos(Dip), 0) = 17.057\ km$

$$R_{RUP} := \begin{cases} R_{X2} \cdot \sin(Dip) & \text{if } R_{X2} \le \dfrac{W}{\cos(Dip)} \\ \sqrt{R_{X2}^2 + W^2 - 2 \cdot R_{X2} \cdot W \cdot \cos(Dip)} & \text{else} \end{cases} = 32.766\ km$$

Footwall East of Fault

$R_{X3} := -1.6\ km$

Brent's House
Lat:40.7386 Long:-111.8357

$R_B := 1.6\ km$

$R_{RUP} := 1.6\ km$

Use values provided by Dr. James Pechmann from the University of Utah. **The value of W** is based on the seismogenic depth with could vary between 12 km to 18 km. Calculate the various values of W based on seismognic depth. When this happens, the values of R X, R JB, and R RUP vary.

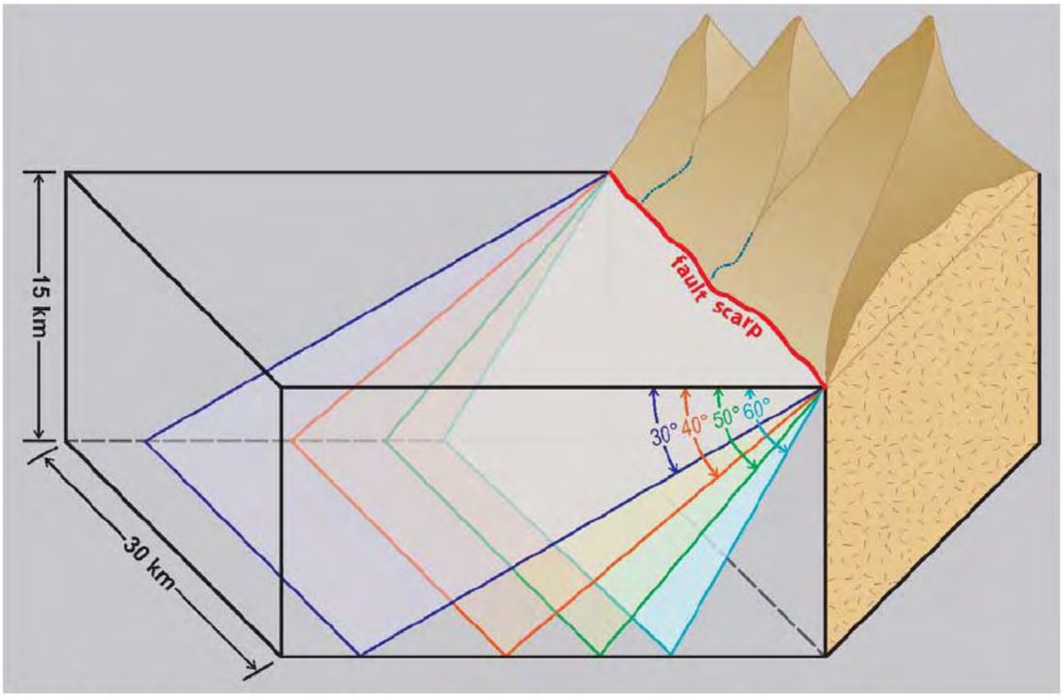


Figure 3.2-1. Schematic diagram showing the non-linear increase in fault area with decreasing dip angles.

$$Dip := \begin{bmatrix} 35 \\ 40 \\ 45 \\ 50 \\ 55 \\ 60 \\ 65 \end{bmatrix}$$

$$Seismogenic15 := 15 \cdot km$$

Calculate horiz. distance to bottom of fault (x)

$$W_{15} := \frac{Seismogenic15}{\sin(Dip)} = \begin{bmatrix} 26.152 \\ 23.336 \\ 21.213 \\ 19.581 \\ 18.312 \\ 17.321 \\ 16.551 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg \quad x15 := \frac{Seismogenic15}{\tan(Dip)} = \begin{bmatrix} 21.422 \\ 17.876 \\ 15.000 \\ 12.586 \\ 10.503 \\ 8.660 \\ 6.995 \end{bmatrix} km$$

$$Seismogenic12 := 12 \cdot km$$

$$W_{12} := \frac{Seismogenic12}{\sin(Dip)} = \begin{bmatrix} 20.921 \\ 18.669 \\ 16.971 \\ 15.665 \\ 14.649 \\ 13.856 \\ 13.241 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg \quad x12 := \frac{Seismogenic12}{\tan(Dip)} = \begin{bmatrix} 17.138 \\ 14.301 \\ 12.000 \\ 10.069 \\ 8.402 \\ 6.928 \\ 5.596 \end{bmatrix} km$$

$$Seismogenic18 := 18 \cdot km$$

$$W_{18} := \frac{Seismogenic18}{\sin(Dip)} = \begin{bmatrix} 31.382 \\ 28.003 \\ 25.456 \\ 23.497 \\ 21.974 \\ 20.785 \\ 19.861 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg \quad x18 := \frac{Seismogenic18}{\tan(Dip)} = \begin{bmatrix} 25.707 \\ 21.452 \\ 18.000 \\ 15.104 \\ 12.604 \\ 10.392 \\ 8.394 \end{bmatrix} km$$

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Hanging Wall West of Fault

$R_{X1} = 7.000\ km$ $\qquad j := 1..7$

Intermountain Medical Center (IMC)

Lat: 40.6613 Long:-111.8912

$R_X := R_{X1} = 7.000\ km$

$x := x15$

$$R_{JB15_j} := \max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.005 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$x := x12$

$$R_{JB12_j} := \max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.072 \\ 1.404 \end{bmatrix} km$$

$x := x18$

$$R_{JB18_j} := \max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$$

$W := W_{15}$

$$R_{RUP15_j} := \begin{cases} R_X \cdot \sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{\cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot \cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 4.015 \\ 4.500 \\ 4.950 \\ 5.362 \\ 5.734 \\ 6.062 \\ 6.344 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{12}$

$$R_{RUP12_j} := \begin{cases} R_X \cdot \sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{\cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot \cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 4.015 \\ 4.500 \\ 4.950 \\ 5.362 \\ 5.734 \\ 6.062 \\ 6.344 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{18}$

$$R_{RUP18_j} := \begin{cases} R_X \cdot \sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{\cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot \cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 4.015 \\ 4.500 \\ 4.950 \\ 5.362 \\ 5.734 \\ 6.062 \\ 6.344 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

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$$W_{15}=\begin{bmatrix}26.152\\23.336\\21.213\\19.581\\18.312\\17.321\\16.551\end{bmatrix} km \quad W_{12}=\begin{bmatrix}20.921\\18.669\\16.971\\15.665\\14.649\\13.856\\13.241\end{bmatrix} km \quad W_{18}=\begin{bmatrix}31.382\\28.003\\25.456\\23.497\\21.974\\20.785\\19.861\end{bmatrix} km \quad Dip=\begin{bmatrix}35.000\\40.000\\45.000\\50.000\\55.000\\60.000\\65.000\end{bmatrix} deg$$

$$R_{X1}=7.000\ km$$

$$R_{JB15}=\begin{bmatrix}0.000\\0.000\\0.000\\0.000\\0.000\\0.000\\0.005\end{bmatrix} km \quad R_{JB12}=\begin{bmatrix}0.000\\0.000\\0.000\\0.000\\0.000\\0.072\\1.404\end{bmatrix} km \quad R_{JB18}=\begin{bmatrix}0.000\\0.000\\0.000\\0.000\\0.000\\0.000\\0.000\end{bmatrix} km \quad Dip=\begin{bmatrix}35.000\\40.000\\45.000\\50.000\\55.000\\60.000\\65.000\end{bmatrix} deg$$

$$R_{RUP15}=\begin{bmatrix}4.015\\4.500\\4.950\\5.362\\5.734\\6.062\\6.344\end{bmatrix} km \quad R_{RUP12}=\begin{bmatrix}4.015\\4.500\\4.950\\5.362\\5.734\\6.062\\6.344\end{bmatrix} km \quad R_{RUP18}=\begin{bmatrix}4.015\\4.500\\4.950\\5.362\\5.734\\6.062\\6.344\end{bmatrix} km \quad Dip=\begin{bmatrix}35.000\\40.000\\45.000\\50.000\\55.000\\60.000\\65.000\end{bmatrix} deg$$

W varies by both Dip angle and seismogenic depth. The minimum value of W (13.24 km) is at a shallow seismogenic depth (12 km) and a steep dip angle (65 degrees). The maximum value of W (31.38) is at a deep seismogenic depth (18 km) and a shallow angle (35 degrees).

RX is the same for all seismogenic depths.

R JB is 0, except where seismogenic depth is shallow (12 km) and dip is steep (60 or 65 degrees). It gets as large as 1.40 km.

R RUP is the same for all seismogenic depths. It varies only by angle. The minimum value is 4.01 km, the maximum value is 6.34 km.

Run a sensitivity analysis for the IMC site. Use the 7 pairs of Dip and W. Set R X, R JB, and R RUP for the various values for the pairs of Dip and W.

The seismogenic depth does not affect the values of R except at the 12 km depth.
Run the 65 degree dip angle twice. Once with R JB at 0.0 km and once with R JB at 1.40 km to see how the values change.

Hanging Wall West of Fault

$R_{X2} = 40.000\ km$

$j := 1..7$

Tooele
Lat: 40.5306 Long:-112.2985

$R_X := R_{X2} = 40.000\ km$

$x := x15$

$$R_{JB15_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 18.578 \\ 22.124 \\ 25.000 \\ 27.414 \\ 29.497 \\ 31.340 \\ 33.005 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$x := x12$

$$R_{JB12_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 22.862 \\ 25.699 \\ 28.000 \\ 29.931 \\ 31.598 \\ 33.072 \\ 34.404 \end{bmatrix} km$$

$x := x18$

$$R_{JB18_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 14.293 \\ 18.548 \\ 22.000 \\ 24.896 \\ 27.396 \\ 29.608 \\ 31.606 \end{bmatrix} km$$

$W := W_{15}$

$$R_{RUP15_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 23.877 \\ 26.729 \\ 29.155 \\ 31.249 \\ 33.092 \\ 34.744 \\ 36.254 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{12}$

$$R_{RUP12_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 25.820 \\ 28.363 \\ 30.463 \\ 32.247 \\ 33.799 \\ 35.182 \\ 36.437 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{18}$

$$R_{RUP18_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 22.985 \\ 25.847 \\ 28.425 \\ 30.722 \\ 32.780 \\ 34.641 \\ 36.252 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$W_{15} = \begin{bmatrix} 26.152 \\ 23.336 \\ 21.213 \\ 19.581 \\ 18.312 \\ 17.321 \\ 16.551 \end{bmatrix} km \quad W_{12} = \begin{bmatrix} 20.921 \\ 18.669 \\ 16.971 \\ 15.665 \\ 14.649 \\ 13.856 \\ 13.241 \end{bmatrix} km \quad W_{18} = \begin{bmatrix} 31.382 \\ 28.003 \\ 25.456 \\ 23.497 \\ 21.974 \\ 20.785 \\ 19.861 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$R_{X2} = 40.000\ km$

$$R_{JB15} = \begin{bmatrix} 18.578 \\ 22.124 \\ 25.000 \\ 27.414 \\ 29.497 \\ 31.340 \\ 33.005 \end{bmatrix} km \quad R_{JB12} = \begin{bmatrix} 22.862 \\ 25.699 \\ 28.000 \\ 29.931 \\ 31.598 \\ 33.072 \\ 34.404 \end{bmatrix} km \quad R_{JB18} = \begin{bmatrix} 14.293 \\ 18.548 \\ 22.000 \\ 24.896 \\ 27.396 \\ 29.608 \\ 31.606 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$R_{RUP15} = \begin{bmatrix} 23.877 \\ 26.729 \\ 29.155 \\ 31.249 \\ 33.092 \\ 34.744 \\ 36.254 \end{bmatrix} km \quad R_{RUP12} = \begin{bmatrix} 25.820 \\ 28.363 \\ 30.463 \\ 32.247 \\ 33.799 \\ 35.182 \\ 36.437 \end{bmatrix} km \quad R_{RUP18} = \begin{bmatrix} 22.985 \\ 25.847 \\ 28.425 \\ 30.722 \\ 32.780 \\ 34.641 \\ 36.252 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

R X is the same for all seismogenic depths.

R JB varies by both seismogenic depth and dip. The smallest value of R JB (14.29 km) is at deep seismogenic depth and shallow angle (i.e. bottom of fault extends way west). The largest value of R JB (34.40 km) is as a shallow seismogenic depth and steep angle (i.e. the bottom of fault is furthest to the east).

R RUP varies by both seismogenic depth and dip. It is similar to R JB. The smallest value of R RUP (22.96 km) is at deep seismogenic depth and shallow angle (i.e. bottom of fault extends way west). The largest value of R RUP (36.44 km) is as a shallow seismogenic depth and steep angle (i.e. the bottom of fault is furthest to the east).

Run a sensitivity analysis for the IMC site. Use the 7 pairs of Dip and W using. Set R X, R JB, and R RUP for the various values for the pairs of Dip and W.

The seismogenic depth does not affect the values of R except at the 12 km depth.
Run the 65 degree dip angle twice. Once with R JB at 0.0 km and once with R JB at 1.40 km to see how the values change.

Footwall East of Fault

Brent's House
Lat:40.7386 Long:-111.8357

$R_{X3} = -1.600\ km$

$R_B := 1.6\ km$

$R_{RUP} := 1.6\ km$

The three values of R do not vary with seismogenic depth or with angle of dip.

Hanging Wall West of Fault

$R_{X4} := 1\ km$

$j := 1..7$

1 KM West of Scarp

Lat: 40.656 Long:-111.819

$R_X := R_{X4} = 1.000\ km$

$x := x15$

$R_{JB15_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$x := x12$

$R_{JB12_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$

$x := x18$

$R_{JB18_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$

$W := W_{15}$

$R_{RUP15_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 0.574 \\ 0.643 \\ 0.707 \\ 0.766 \\ 0.819 \\ 0.866 \\ 0.906 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$W := W_{12}$

$R_{RUP12_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 0.574 \\ 0.643 \\ 0.707 \\ 0.766 \\ 0.819 \\ 0.866 \\ 0.906 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$W := W_{18}$

$R_{RUP18_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 0.574 \\ 0.643 \\ 0.707 \\ 0.766 \\ 0.819 \\ 0.866 \\ 0.906 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$$W_{15} = \begin{bmatrix} 26.152 \\ 23.336 \\ 21.213 \\ 19.581 \\ 18.312 \\ 17.321 \\ 16.551 \end{bmatrix} km \quad W_{12} = \begin{bmatrix} 20.921 \\ 18.669 \\ 16.971 \\ 15.665 \\ 14.649 \\ 13.856 \\ 13.241 \end{bmatrix} km \quad W_{18} = \begin{bmatrix} 31.382 \\ 28.003 \\ 25.456 \\ 23.497 \\ 21.974 \\ 20.785 \\ 19.861 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$R_X = 1.000\ km$

$$R_{JB15} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad R_{JB12} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad R_{JB18} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$R_{RUP15} = \begin{bmatrix} 0.574 \\ 0.643 \\ 0.707 \\ 0.766 \\ 0.819 \\ 0.866 \\ 0.906 \end{bmatrix} km \quad R_{RUP12} = \begin{bmatrix} 0.574 \\ 0.643 \\ 0.707 \\ 0.766 \\ 0.819 \\ 0.866 \\ 0.906 \end{bmatrix} km \quad R_{RUP18} = \begin{bmatrix} 0.574 \\ 0.643 \\ 0.707 \\ 0.766 \\ 0.819 \\ 0.866 \\ 0.906 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

Hanging Wall West of Fault

$R_{X5} := 2.5\ km$ $j := 1..7$

2.5 KM West of Scarp

Lat: 40.656 Long:-111.837

$R_X := R_{X5} = 2.500\ km$

$x := x15$

$R_{JB15_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$ $Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$x := x12$

$R_{JB12_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$

$x := x18$

$R_{JB18_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$

$W := W_{15}$

$R_{RUP15_j} := \text{if } R_X \le \frac{W_j}{cos(Dip_j)} : R_X \cdot sin(Dip_j); \text{ else } \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km$ $Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$W := W_{12}$

$R_{RUP12_j} := \text{if } R_X \le \frac{W_j}{cos(Dip_j)} : R_X \cdot sin(Dip_j); \text{ else } \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km$ $Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$W := W_{18}$

$R_{RUP18_j} := \text{if } R_X \le \frac{W_j}{cos(Dip_j)} : R_X \cdot sin(Dip_j); \text{ else } \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km$ $Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$$W_{15} = \begin{bmatrix} 26.152 \\ 23.336 \\ 21.213 \\ 19.581 \\ 18.312 \\ 17.321 \\ 16.551 \end{bmatrix} km \quad W_{12} = \begin{bmatrix} 20.921 \\ 18.669 \\ 16.971 \\ 15.665 \\ 14.649 \\ 13.856 \\ 13.241 \end{bmatrix} km \quad W_{18} = \begin{bmatrix} 31.382 \\ 28.003 \\ 25.456 \\ 23.497 \\ 21.974 \\ 20.785 \\ 19.861 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$R_X = 2.500\ km$$

$$R_{JB15} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad R_{JB12} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad R_{JB18} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$R_{RUP15} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km \quad R_{RUP12} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km \quad R_{RUP18} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

Hanging Wall West of Fault

$R_{X5} := 2.5\ km$

$j := 1..7$

2.5 KM West of Scarp

Lat: 40.656 Long:-111.837

$R_X := R_{X5} = 2.500\ km$

$x := x15$

$$R_{JB15_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$x := x12$

$$R_{JB12_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$$

$x := x18$

$$R_{JB18_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$$

$W := W_{15}$

$$R_{RUP15_j} := \begin{cases} R_X \cdot sin(Dip_j) & \text{if } R_X \le \dfrac{W_j}{cos(Dip_j)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} & \text{else} \end{cases} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{12}$

$$R_{RUP12_j} := \begin{cases} R_X \cdot sin(Dip_j) & \text{if } R_X \le \dfrac{W_j}{cos(Dip_j)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} & \text{else} \end{cases} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{18}$

$$R_{RUP18_j} := \begin{cases} R_X \cdot sin(Dip_j) & \text{if } R_X \le \dfrac{W_j}{cos(Dip_j)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} & \text{else} \end{cases} = \begin{bmatrix} 1.434 \\ 1.607 \\ 1.768 \\ 1.915 \\ 2.048 \\ 2.165 \\ 2.266 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$W_{15}=\begin{bmatrix}26.152\\23.336\\21.213\\19.581\\18.312\\17.321\\16.551\end{bmatrix} km \quad W_{12}=\begin{bmatrix}20.921\\18.669\\16.971\\15.665\\14.649\\13.856\\13.241\end{bmatrix} km \quad W_{18}=\begin{bmatrix}31.382\\28.003\\25.456\\23.497\\21.974\\20.785\\19.861\end{bmatrix} km \quad Dip=\begin{bmatrix}35.000\\40.000\\45.000\\50.000\\55.000\\60.000\\65.000\end{bmatrix} deg$$

$R_X = 2.500\ km$

$$R_{JB15}=\begin{bmatrix}0.000\\0.000\\0.000\\0.000\\0.000\\0.000\\0.000\end{bmatrix} km \quad R_{JB12}=\begin{bmatrix}0.000\\0.000\\0.000\\0.000\\0.000\\0.000\\0.000\end{bmatrix} km \quad R_{JB18}=\begin{bmatrix}0.000\\0.000\\0.000\\0.000\\0.000\\0.000\\0.000\end{bmatrix} km \quad Dip=\begin{bmatrix}35.000\\40.000\\45.000\\50.000\\55.000\\60.000\\65.000\end{bmatrix} deg$$

$$R_{RUP15}=\begin{bmatrix}1.434\\1.607\\1.768\\1.915\\2.048\\2.165\\2.266\end{bmatrix} km \quad R_{RUP12}=\begin{bmatrix}1.434\\1.607\\1.768\\1.915\\2.048\\2.165\\2.266\end{bmatrix} km \quad R_{RUP18}=\begin{bmatrix}1.434\\1.607\\1.768\\1.915\\2.048\\2.165\\2.266\end{bmatrix} km \quad Dip=\begin{bmatrix}35.000\\40.000\\45.000\\50.000\\55.000\\60.000\\65.000\end{bmatrix} deg$$

Hanging Wall West of Fault

$R_{X6} := 5\ km$

$j := 1..7$

5 KM West of Scarp

Lat: 40.656 Long:-111.8656

$R_X := R_{X6} = 5.000\ km$

$x := x15$

$$R_{JB15_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$x := x12$

$$R_{JB12_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$$

$x := x18$

$$R_{JB18_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km$$

$W := W_{15}$

$$R_{RUP15_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 2.868 \\ 3.214 \\ 3.536 \\ 3.830 \\ 4.096 \\ 4.330 \\ 4.532 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{12}$

$$R_{RUP12_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 2.868 \\ 3.214 \\ 3.536 \\ 3.830 \\ 4.096 \\ 4.330 \\ 4.532 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{18}$

$$R_{RUP18_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 2.868 \\ 3.214 \\ 3.536 \\ 3.830 \\ 4.096 \\ 4.330 \\ 4.532 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$W_{15} = \begin{bmatrix} 26.152 \\ 23.336 \\ 21.213 \\ 19.581 \\ 18.312 \\ 17.321 \\ 16.551 \end{bmatrix} km \quad W_{12} = \begin{bmatrix} 20.921 \\ 18.669 \\ 16.971 \\ 15.665 \\ 14.649 \\ 13.856 \\ 13.241 \end{bmatrix} km \quad W_{18} = \begin{bmatrix} 31.382 \\ 28.003 \\ 25.456 \\ 23.497 \\ 21.974 \\ 20.785 \\ 19.861 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$R_X = 5.000\ km$

$$R_{JB15} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad R_{JB12} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad R_{JB18} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$R_{RUP15} = \begin{bmatrix} 2.868 \\ 3.214 \\ 3.536 \\ 3.830 \\ 4.096 \\ 4.330 \\ 4.532 \end{bmatrix} km \quad R_{RUP12} = \begin{bmatrix} 2.868 \\ 3.214 \\ 3.536 \\ 3.830 \\ 4.096 \\ 4.330 \\ 4.532 \end{bmatrix} km \quad R_{RUP18} = \begin{bmatrix} 2.868 \\ 3.214 \\ 3.536 \\ 3.830 \\ 4.096 \\ 4.330 \\ 4.532 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

Hanging Wall West of Fault

$R_{X7} := 10\ km$ $j := 1..7$

10 KM West of Scarp

Lat: 40.656   Long:-111.9256

$R_X := R_{X7} = 10.000\ km$

$x := x15$

$R_{JB15_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 1.340 \\ 3.005 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$x := x12$

$R_{JB12_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 1.598 \\ 3.072 \\ 4.404 \end{bmatrix} km$

$x := x18$

$R_{JB18_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 1.606 \end{bmatrix} km$

$W := W_{15}$

$R_{RUP15_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 5.736 \\ 6.428 \\ 7.071 \\ 7.660 \\ 8.192 \\ 8.660 \\ 9.063 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$W := W_{12}$

$R_{RUP12_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 5.736 \\ 6.428 \\ 7.071 \\ 7.660 \\ 8.192 \\ 8.660 \\ 9.063 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$W := W_{18}$

$R_{RUP18_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 5.736 \\ 6.428 \\ 7.071 \\ 7.660 \\ 8.192 \\ 8.660 \\ 9.063 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$$W_{15} = \begin{bmatrix} 26.152 \\ 23.336 \\ 21.213 \\ 19.581 \\ 18.312 \\ 17.321 \\ 16.551 \end{bmatrix} km \quad W_{12} = \begin{bmatrix} 20.921 \\ 18.669 \\ 16.971 \\ 15.665 \\ 14.649 \\ 13.856 \\ 13.241 \end{bmatrix} km \quad W_{18} = \begin{bmatrix} 31.382 \\ 28.003 \\ 25.456 \\ 23.497 \\ 21.974 \\ 20.785 \\ 19.861 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$R_X = 10.000\ km$

$$R_{JB15} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 1.340 \\ 3.005 \end{bmatrix} km \quad R_{JB12} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 1.598 \\ 3.072 \\ 4.404 \end{bmatrix} km \quad R_{JB18} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 1.606 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$R_{RUP15} = \begin{bmatrix} 5.736 \\ 6.428 \\ 7.071 \\ 7.660 \\ 8.192 \\ 8.660 \\ 9.063 \end{bmatrix} km \quad R_{RUP12} = \begin{bmatrix} 5.736 \\ 6.428 \\ 7.071 \\ 7.660 \\ 8.192 \\ 8.660 \\ 9.063 \end{bmatrix} km \quad R_{RUP18} = \begin{bmatrix} 5.736 \\ 6.428 \\ 7.071 \\ 7.660 \\ 8.192 \\ 8.660 \\ 9.063 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

Hanging Wall West of Fault

$R_{X8} := 15\ km$

$j := 1..7$

15 KM West of Scarp

Lat: 40.656 Long:-111.9848

$R_X := R_{X8} = 15.000\ km$

$x := x15$

$R_{JB15_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 2.414 \\ 4.497 \\ 6.340 \\ 8.005 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$x := x12$

$R_{JB12_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.699 \\ 3.000 \\ 4.931 \\ 6.598 \\ 8.072 \\ 9.404 \end{bmatrix} km$

$x := x18$

$R_{JB18_j} := max(R_X - x_j, 0) = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 2.396 \\ 4.608 \\ 6.606 \end{bmatrix} km$

$W := W_{15}$

$$R_{RUP15_j} := \begin{cases} R_X \cdot sin(Dip_j) & \text{if } R_X \le \dfrac{W_j}{cos(Dip_j)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} & \text{else} \end{cases} = \begin{bmatrix} 8.604 \\ 9.642 \\ 10.607 \\ 11.491 \\ 12.287 \\ 12.990 \\ 13.595 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{12}$

$$R_{RUP12_j} := \begin{cases} R_X \cdot sin(Dip_j) & \text{if } R_X \le \dfrac{W_j}{cos(Dip_j)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} & \text{else} \end{cases} = \begin{bmatrix} 8.604 \\ 9.642 \\ 10.607 \\ 11.491 \\ 12.287 \\ 12.990 \\ 13.595 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$W := W_{18}$

$$R_{RUP18_j} := \begin{cases} R_X \cdot sin(Dip_j) & \text{if } R_X \le \dfrac{W_j}{cos(Dip_j)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos(Dip_j)} & \text{else} \end{cases} = \begin{bmatrix} 8.604 \\ 9.642 \\ 10.607 \\ 11.491 \\ 12.287 \\ 12.990 \\ 13.595 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$W_{15} = \begin{bmatrix} 26.152 \\ 23.336 \\ 21.213 \\ 19.581 \\ 18.312 \\ 17.321 \\ 16.551 \end{bmatrix} km \quad W_{12} = \begin{bmatrix} 20.921 \\ 18.669 \\ 16.971 \\ 15.665 \\ 14.649 \\ 13.856 \\ 13.241 \end{bmatrix} km \quad W_{18} = \begin{bmatrix} 31.382 \\ 28.003 \\ 25.456 \\ 23.497 \\ 21.974 \\ 20.785 \\ 19.861 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$R_X = 15.000\ km$

$$R_{JB15} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 2.414 \\ 4.497 \\ 6.340 \\ 8.005 \end{bmatrix} km \quad R_{JB12} = \begin{bmatrix} 0.000 \\ 0.699 \\ 3.000 \\ 4.931 \\ 6.598 \\ 8.072 \\ 9.404 \end{bmatrix} km \quad R_{JB18} = \begin{bmatrix} 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 2.396 \\ 4.608 \\ 6.606 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$R_{RUP15} = \begin{bmatrix} 8.604 \\ 9.642 \\ 10.607 \\ 11.491 \\ 12.287 \\ 12.990 \\ 13.595 \end{bmatrix} km \quad R_{RUP12} = \begin{bmatrix} 8.604 \\ 9.642 \\ 10.607 \\ 11.491 \\ 12.287 \\ 12.990 \\ 13.595 \end{bmatrix} km \quad R_{RUP18} = \begin{bmatrix} 8.604 \\ 9.642 \\ 10.607 \\ 11.491 \\ 12.287 \\ 12.990 \\ 13.595 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

Hanging Wall West of Fault

$R_{X8} := 20\ km$

$j := 1..7$

20 KM West of Scarp

Lat: 40.656 Long:-112.0440

$R_X := R_{X8} = 20.000\ km$

$x := x15$

$R_{JB15_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 2.124 \\ 5.000 \\ 7.414 \\ 9.497 \\ 11.340 \\ 13.005 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$x := x12$

$R_{JB12_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 2.862 \\ 5.699 \\ 8.000 \\ 9.931 \\ 11.598 \\ 13.072 \\ 14.404 \end{bmatrix} km$

$x := x18$

$R_{JB18_j} := max\left(R_X - x_j, 0\right) = \begin{bmatrix} 0.000 \\ 0.000 \\ 2.000 \\ 4.896 \\ 7.396 \\ 9.608 \\ 11.606 \end{bmatrix} km$

$W := W_{15}$

$R_{RUP15_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 11.472 \\ 12.856 \\ 14.142 \\ 15.321 \\ 16.383 \\ 17.321 \\ 18.126 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$W := W_{12}$

$R_{RUP12_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 11.472 \\ 12.856 \\ 14.142 \\ 15.321 \\ 16.383 \\ 17.321 \\ 18.126 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$W := W_{18}$

$R_{RUP18_j} := \begin{cases} R_X \cdot sin\left(Dip_j\right) & \text{if } R_X \le \dfrac{W_j}{cos\left(Dip_j\right)} \\ \sqrt{R_X^2 + W_j^2 - 2 \cdot R_X \cdot W_j \cdot cos\left(Dip_j\right)} & \text{else} \end{cases} = \begin{bmatrix} 11.472 \\ 12.856 \\ 14.142 \\ 15.321 \\ 16.383 \\ 17.321 \\ 18.126 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$

$$W_{15} = \begin{bmatrix} 26.152 \\ 23.336 \\ 21.213 \\ 19.581 \\ 18.312 \\ 17.321 \\ 16.551 \end{bmatrix} km \quad W_{12} = \begin{bmatrix} 20.921 \\ 18.669 \\ 16.971 \\ 15.665 \\ 14.649 \\ 13.856 \\ 13.241 \end{bmatrix} km \quad W_{18} = \begin{bmatrix} 31.382 \\ 28.003 \\ 25.456 \\ 23.497 \\ 21.974 \\ 20.785 \\ 19.861 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$R_X = 20.000\ km$

$$R_{JB15} = \begin{bmatrix} 0.000 \\ 2.124 \\ 5.000 \\ 7.414 \\ 9.497 \\ 11.340 \\ 13.005 \end{bmatrix} km \quad R_{JB12} = \begin{bmatrix} 2.862 \\ 5.699 \\ 8.000 \\ 9.931 \\ 11.598 \\ 13.072 \\ 14.404 \end{bmatrix} km \quad R_{JB18} = \begin{bmatrix} 0.000 \\ 0.000 \\ 2.000 \\ 4.896 \\ 7.396 \\ 9.608 \\ 11.606 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

$$R_{RUP15} = \begin{bmatrix} 11.472 \\ 12.856 \\ 14.142 \\ 15.321 \\ 16.383 \\ 17.321 \\ 18.126 \end{bmatrix} km \quad R_{RUP12} = \begin{bmatrix} 11.472 \\ 12.856 \\ 14.142 \\ 15.321 \\ 16.383 \\ 17.321 \\ 18.126 \end{bmatrix} km \quad R_{RUP18} = \begin{bmatrix} 11.472 \\ 12.856 \\ 14.142 \\ 15.321 \\ 16.383 \\ 17.321 \\ 18.126 \end{bmatrix} km \quad Dip = \begin{bmatrix} 35.000 \\ 40.000 \\ 45.000 \\ 50.000 \\ 55.000 \\ 60.000 \\ 65.000 \end{bmatrix} deg$$

Site-Specific Performance-Based Seismic Design Ground Motions: Case Study

Ivan Wong and Patricia Thomas

Meeting of the Utah Ground Shaking Working Group

Salt Lake City, UT
13 February 2018

Lettis Consultants International, Inc.
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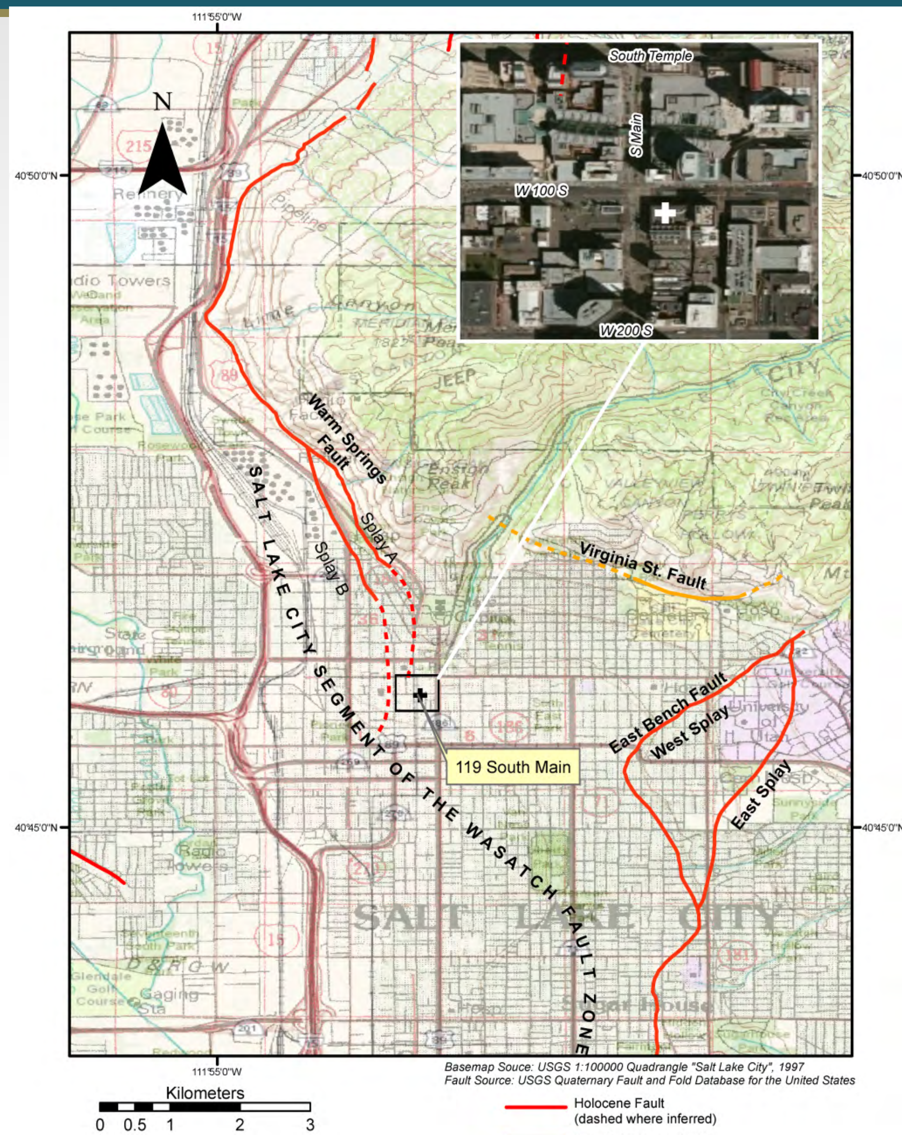
Introduction

- Site-specific probabilistic and deterministic seismic hazard analyses were performed for the 111 Main building in downtown Salt Lake City
- Design criteria were developed in accordance with ASCE 7-10, the IBC, and the Tall Building Initiative Guidelines for Performance-Based Seismic Design of Tall Buildings
- Horizontal and vertical MCEr spectra were computed (geometric mean – no maximum component).
- Seven sets of three-component time histories were developed.

Site Vicinity Map



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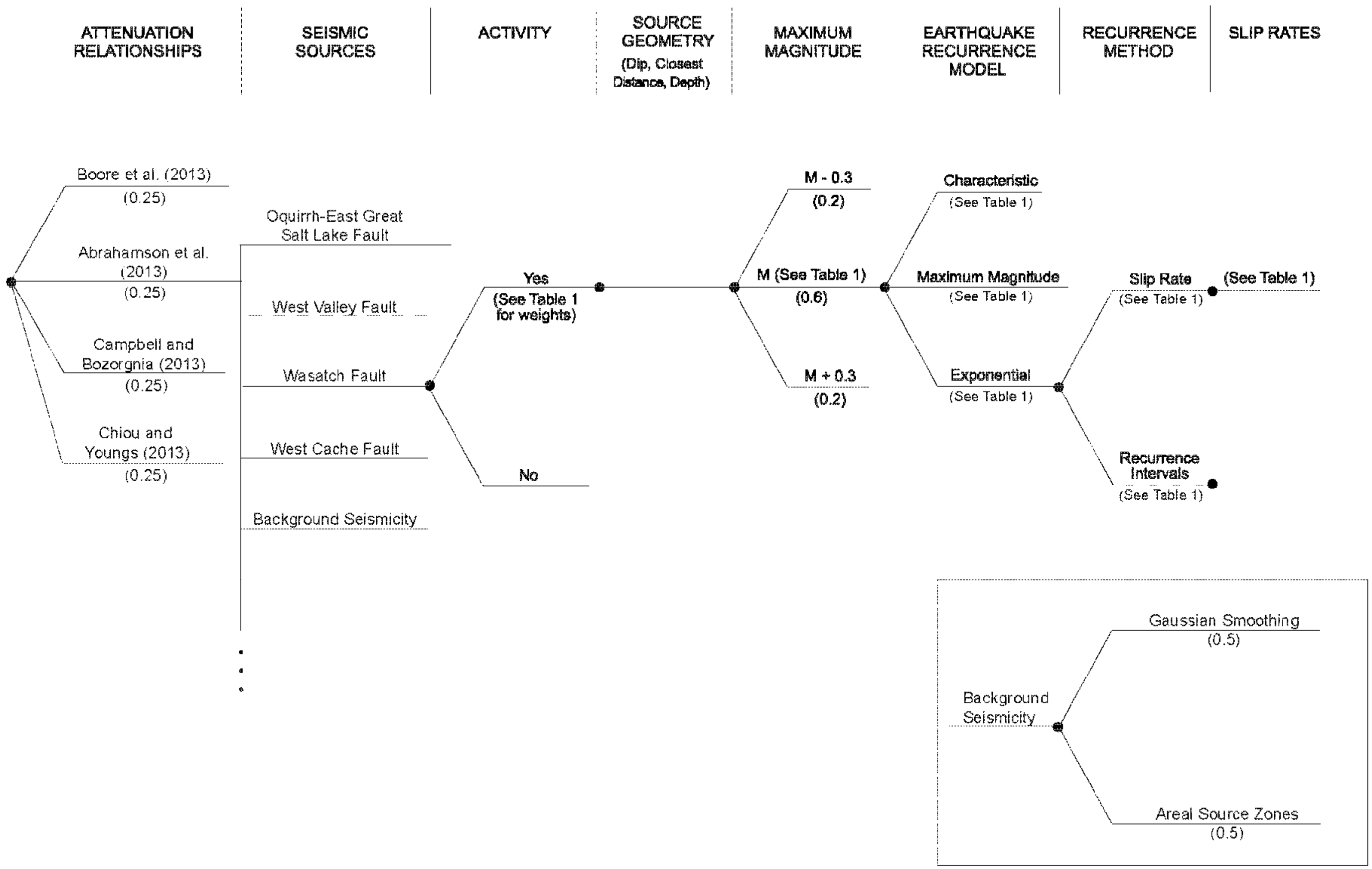
Issues

- Rupture scenarios for the Salt Lake City segment in downtown Salt Lake City including the West Valley fault zone
- Effects of the near-surface geology
- Effects of the Salt Lake Basin
- Effects of forward rupture directivity on normal faults
- Surface faulting hazard in downtown Salt Lake City
- Accounting for the elapsed time since the last large earthquake on the Salt Lake City segment (Patricia's talk)

Seismic Hazard Model Logic Tree



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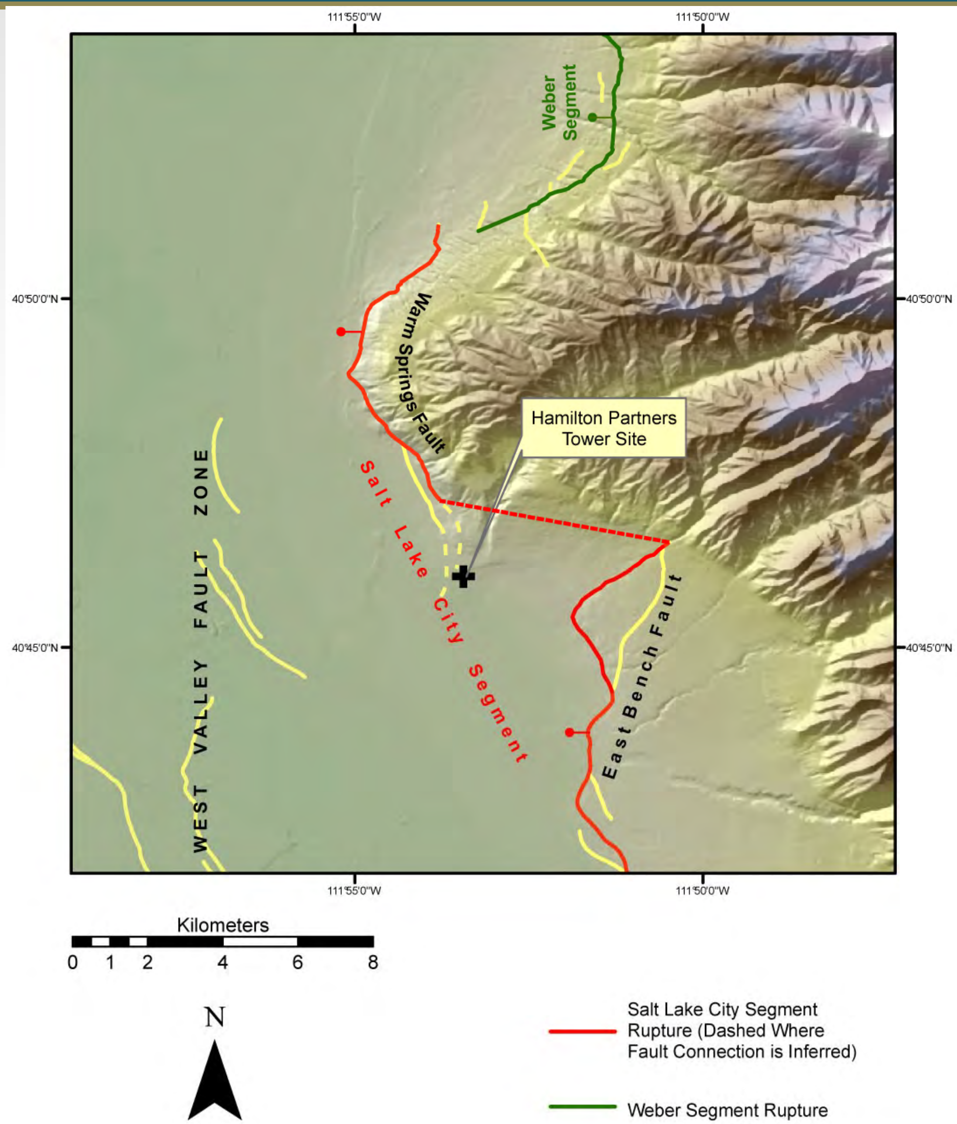
Rupture Scenario A for the East Bench – Warm Springs Faults Stepover Zone



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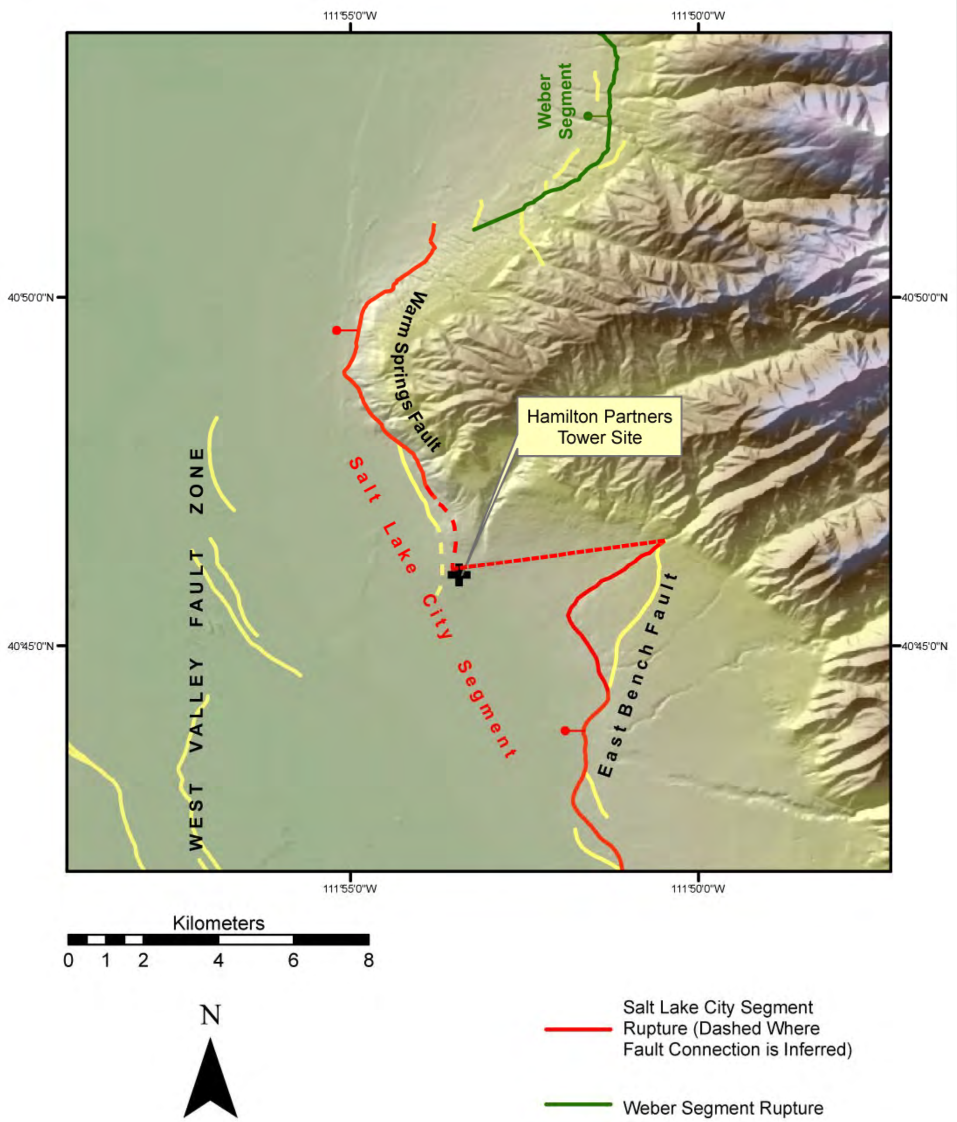
Rupture Scenario B for the East Bench – Warm Springs Faults Stepover Zone



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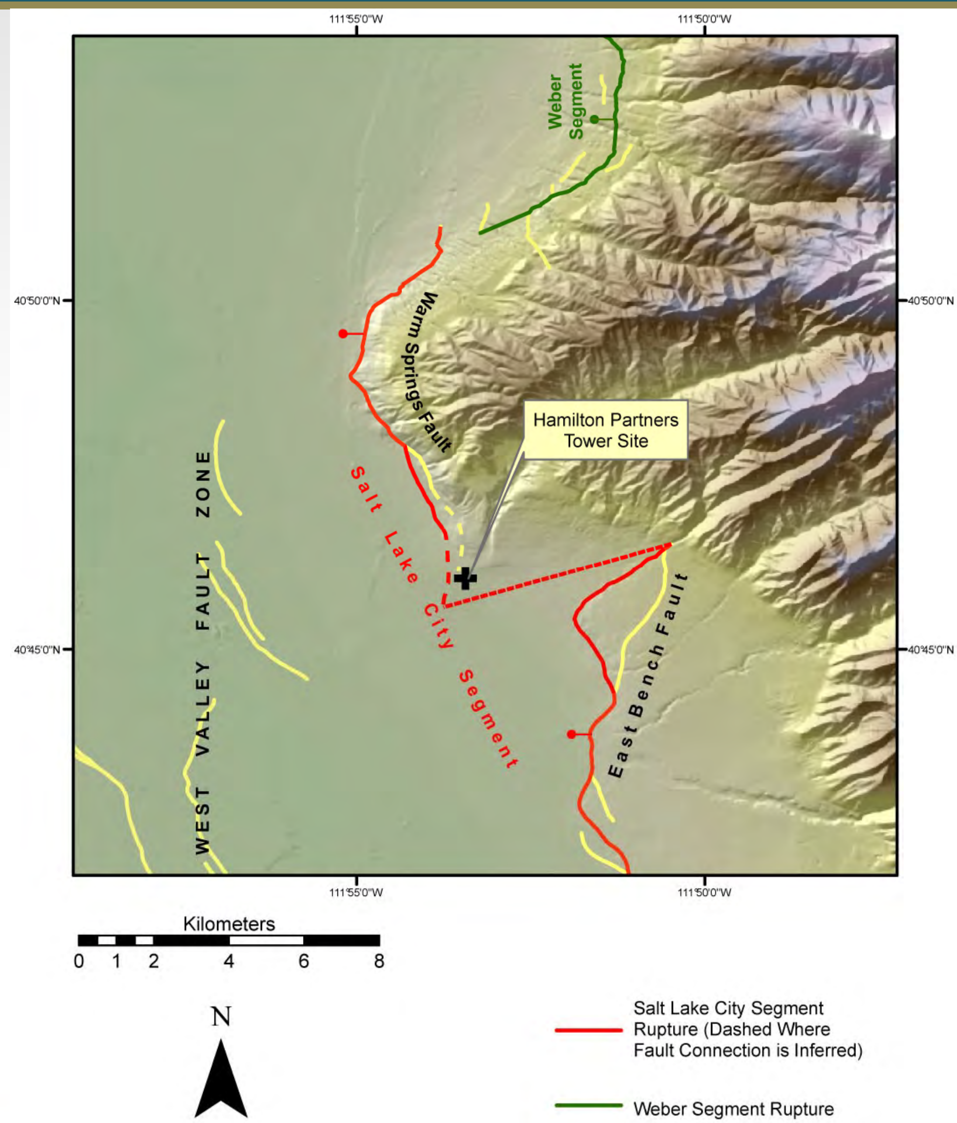
Rupture Scenario C for the East Bench – Warm Springs Faults Stepover Zone



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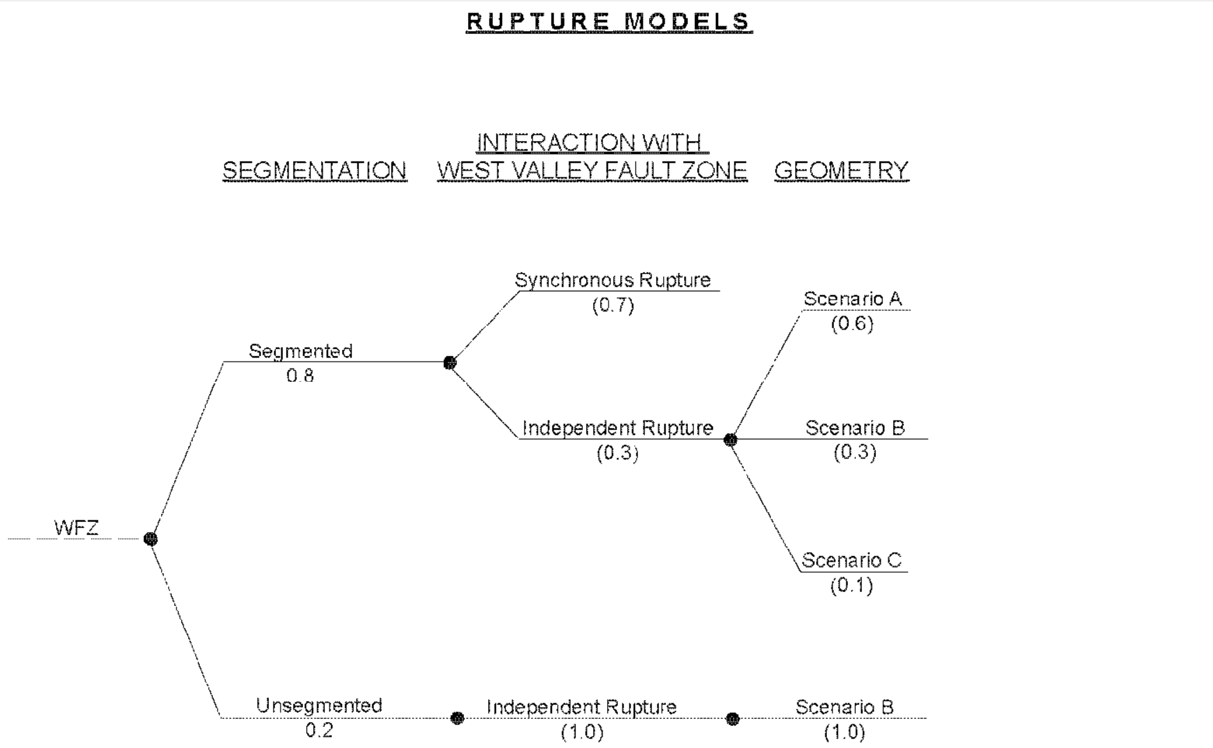
Logic Tree for Wasatch Fault Zone Rupture Models



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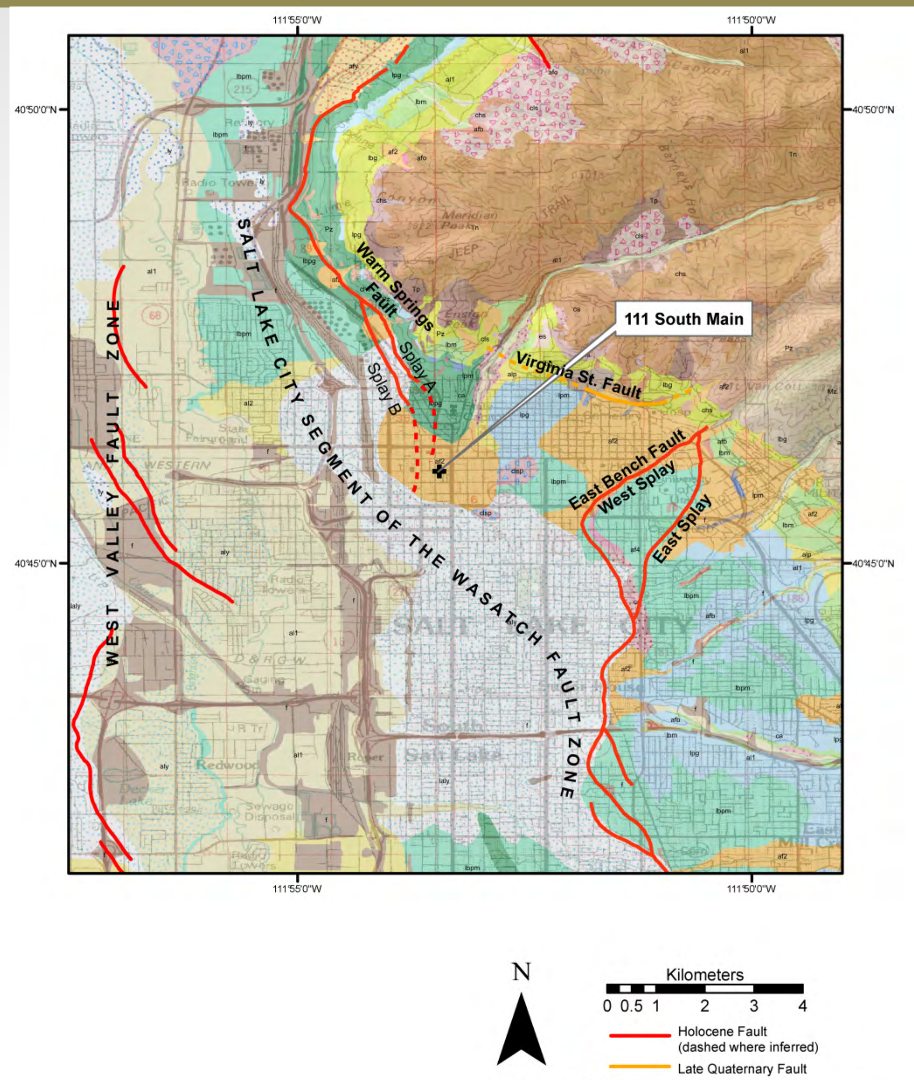
Surficial Geology in Salt Lake City



Basemap Souce: USGS, "Geologic Map of SLC Segment etc., Utah", Map M - 243 (Personius & Scott, 2009)
Fault Source: USGS Quaternary Fault and Fold Database for the United States

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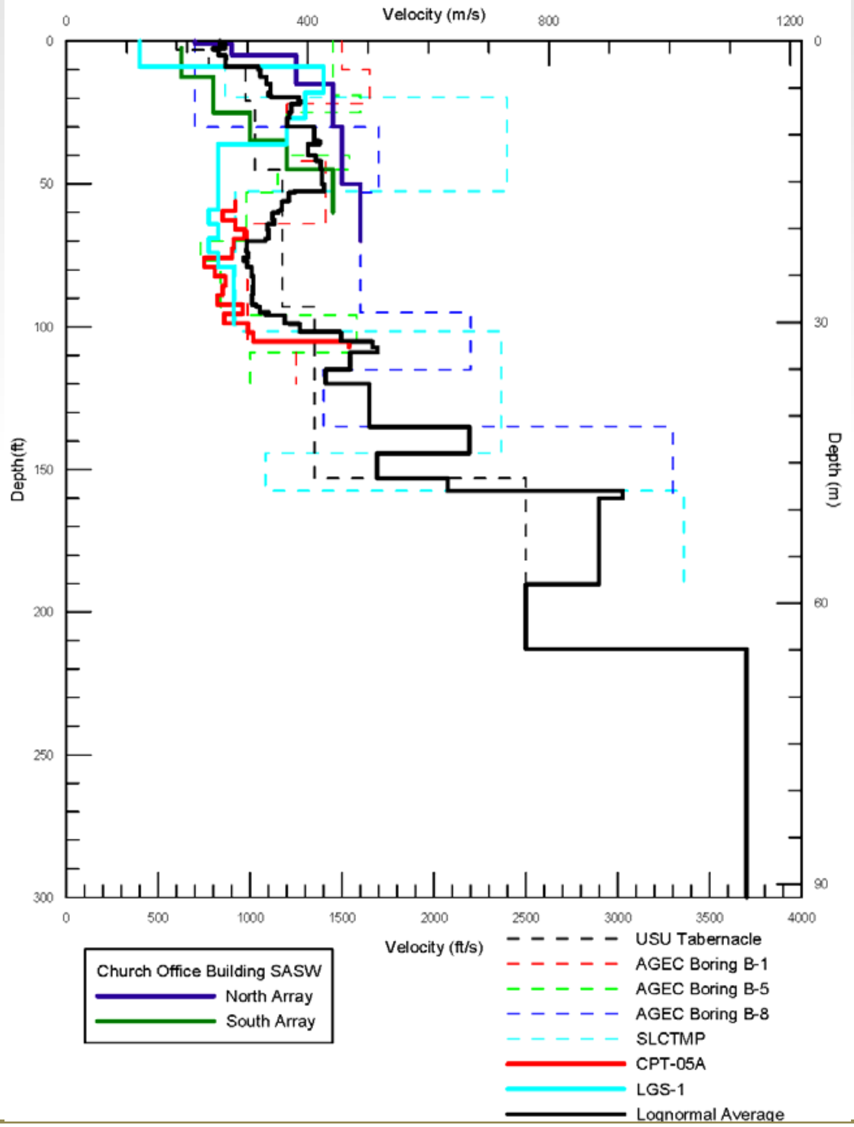
Vs Profiles for Downtown Salt Lake City



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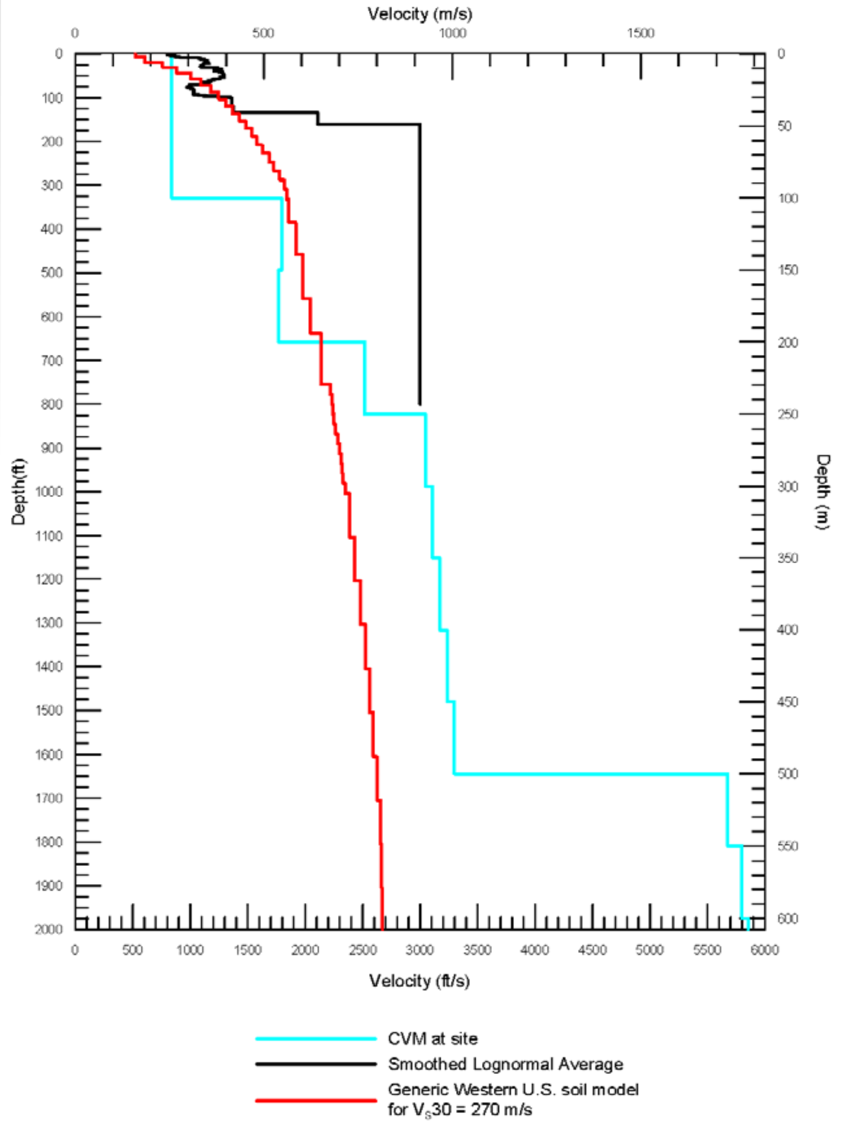
Basecase Vs Profile and Generic Soil Model Used in Site Response Analysis



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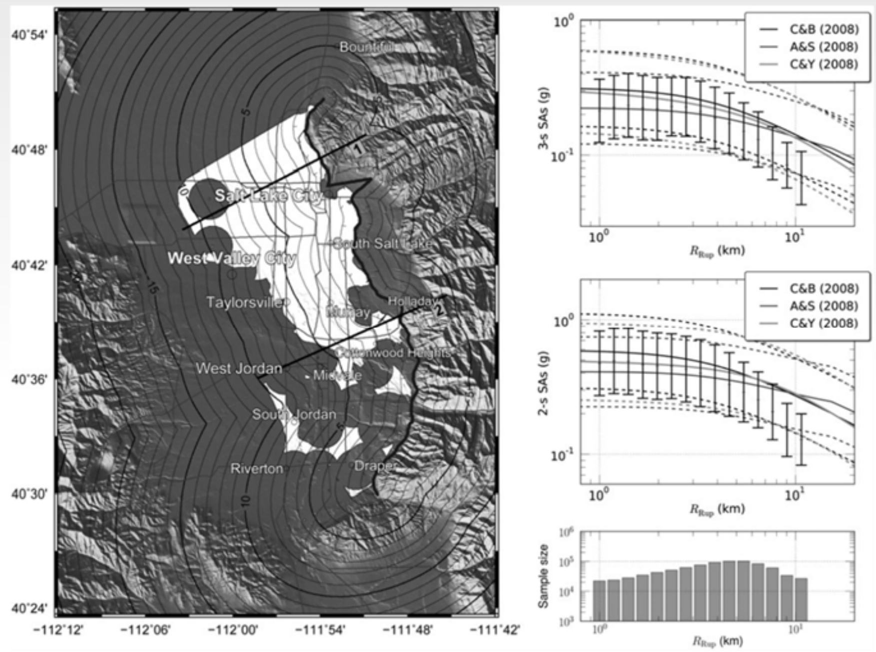
Basin Effects

- Basin modeling by Roten et al. (2011) indicate that the NGA-West1 models capture on average the amplification effects of the Salt Lake Basin on long-period ground motions.
- X



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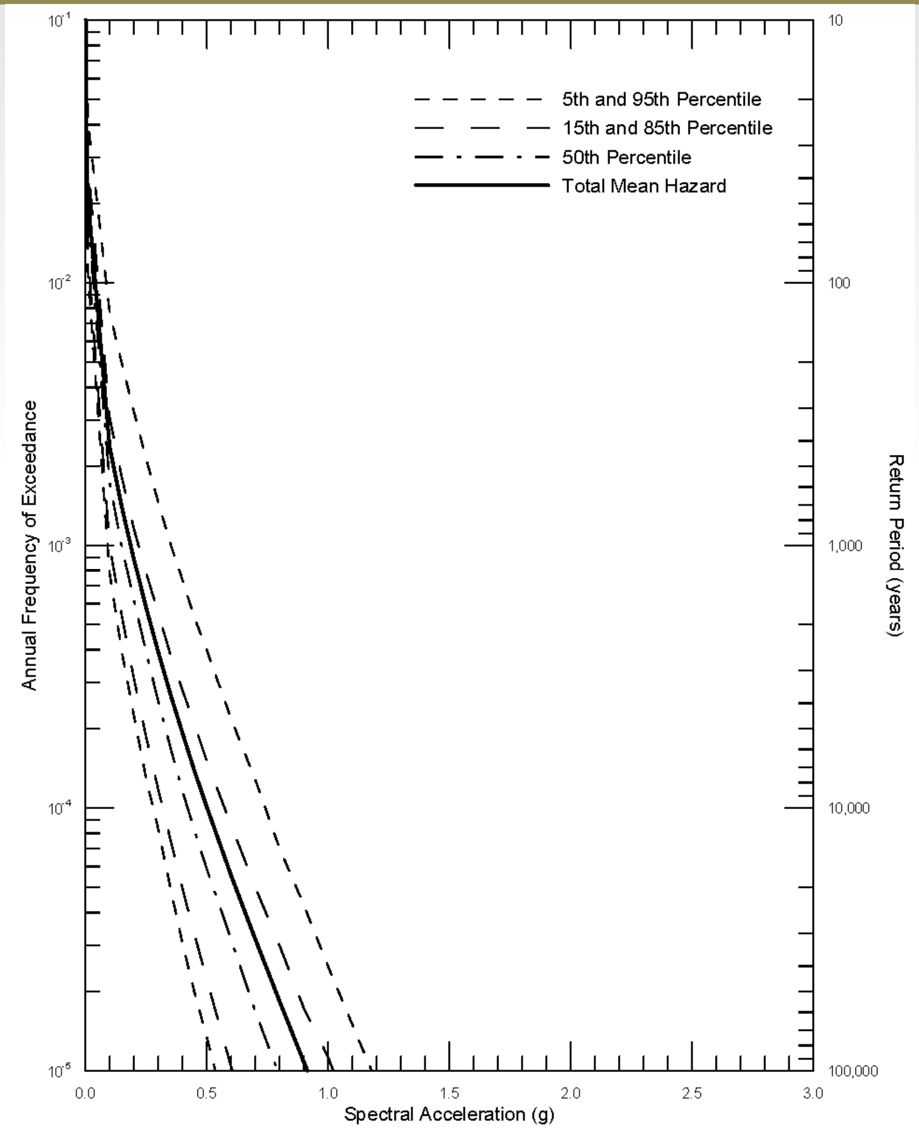
Seismic Hazard Curves for 4.0 Sec Horizontal Spectral Acceleration



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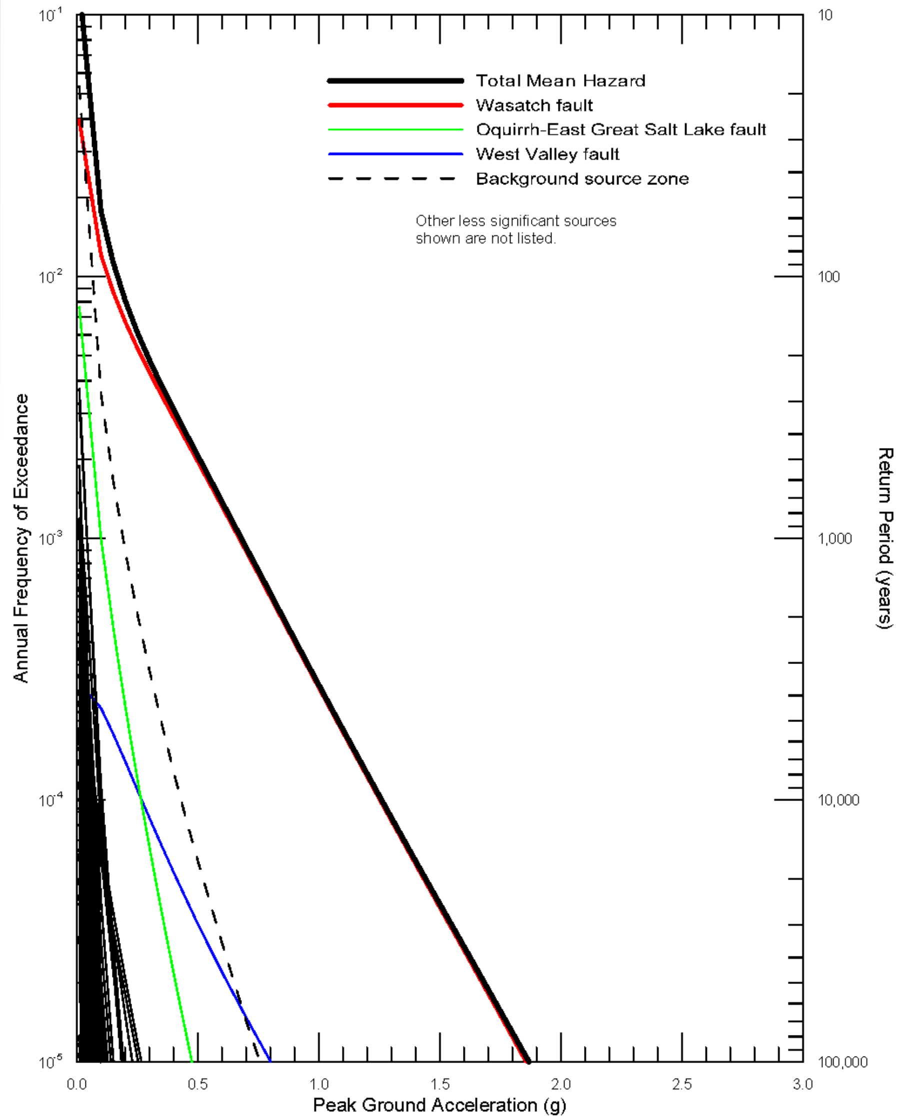
Seismic Source Contributions to Mean Peak Horizontal Acceleration Hazard



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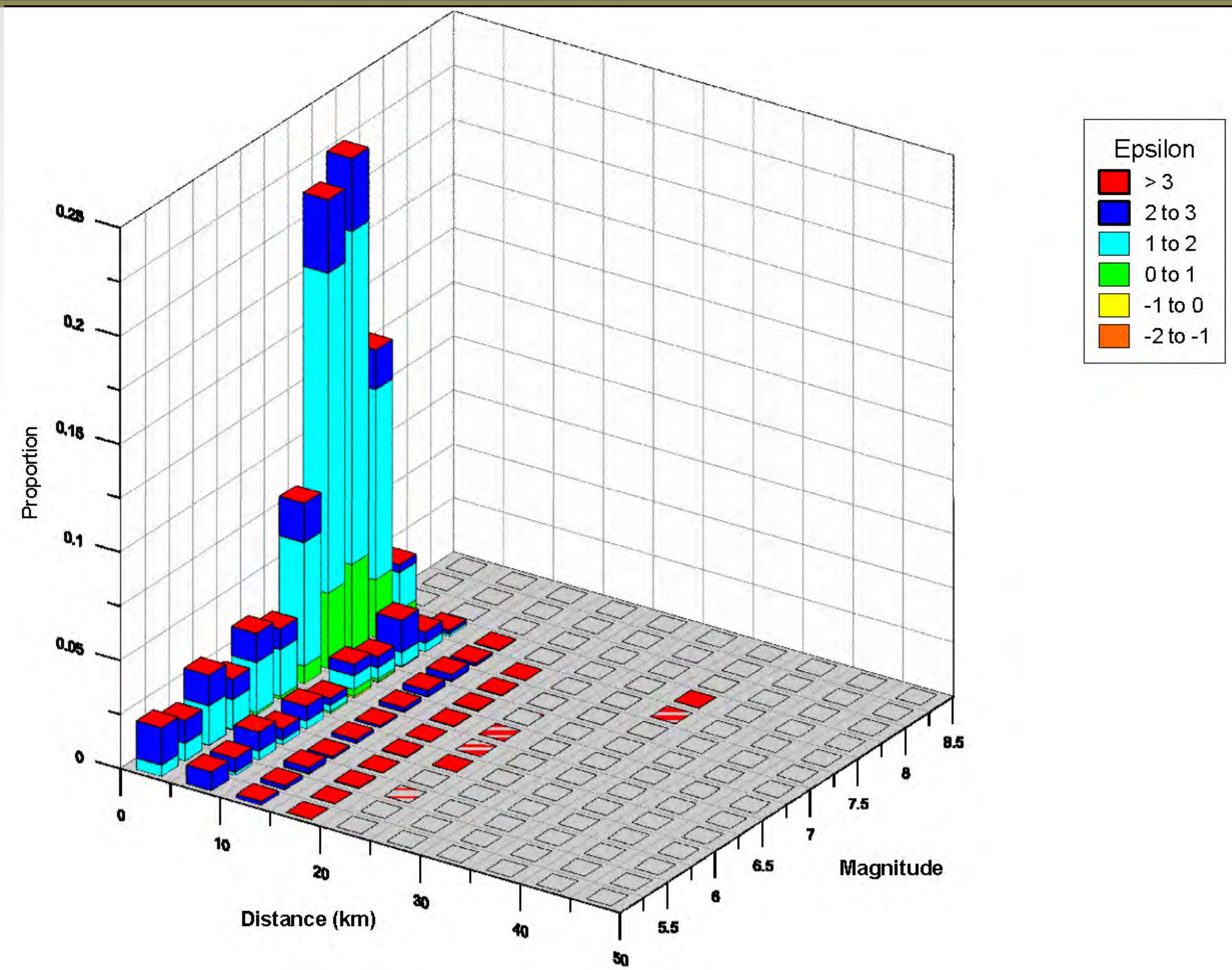
Magnitude and Distance Contributions to the Mean Peak Horizontal Acceleration Hazard at 2,475-Year Return Period



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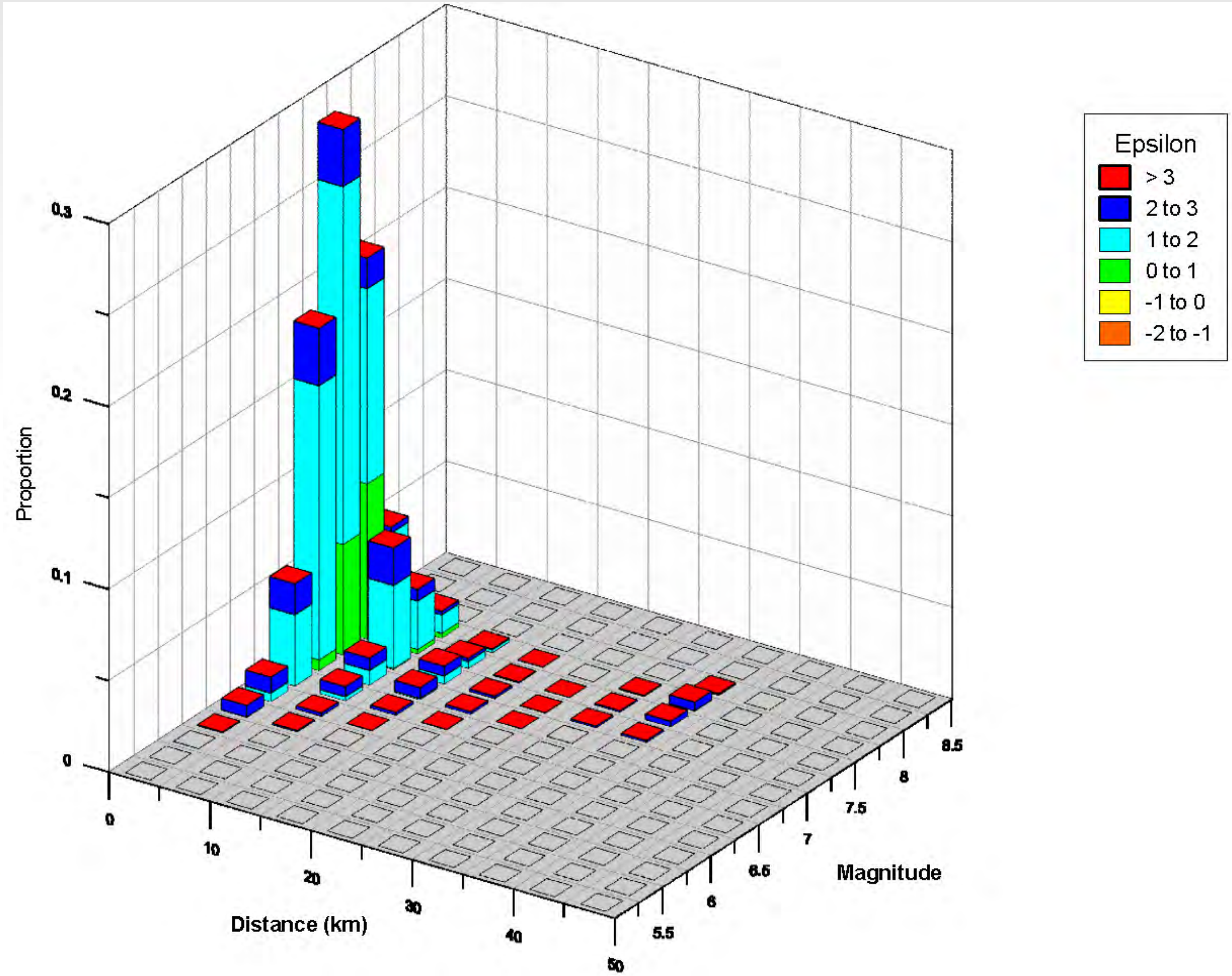
Magnitude and Distance Contributions to the Mean 4.0 Sec Horizontal Spectral Acceleration Hazard at 2,475-Year Return Period



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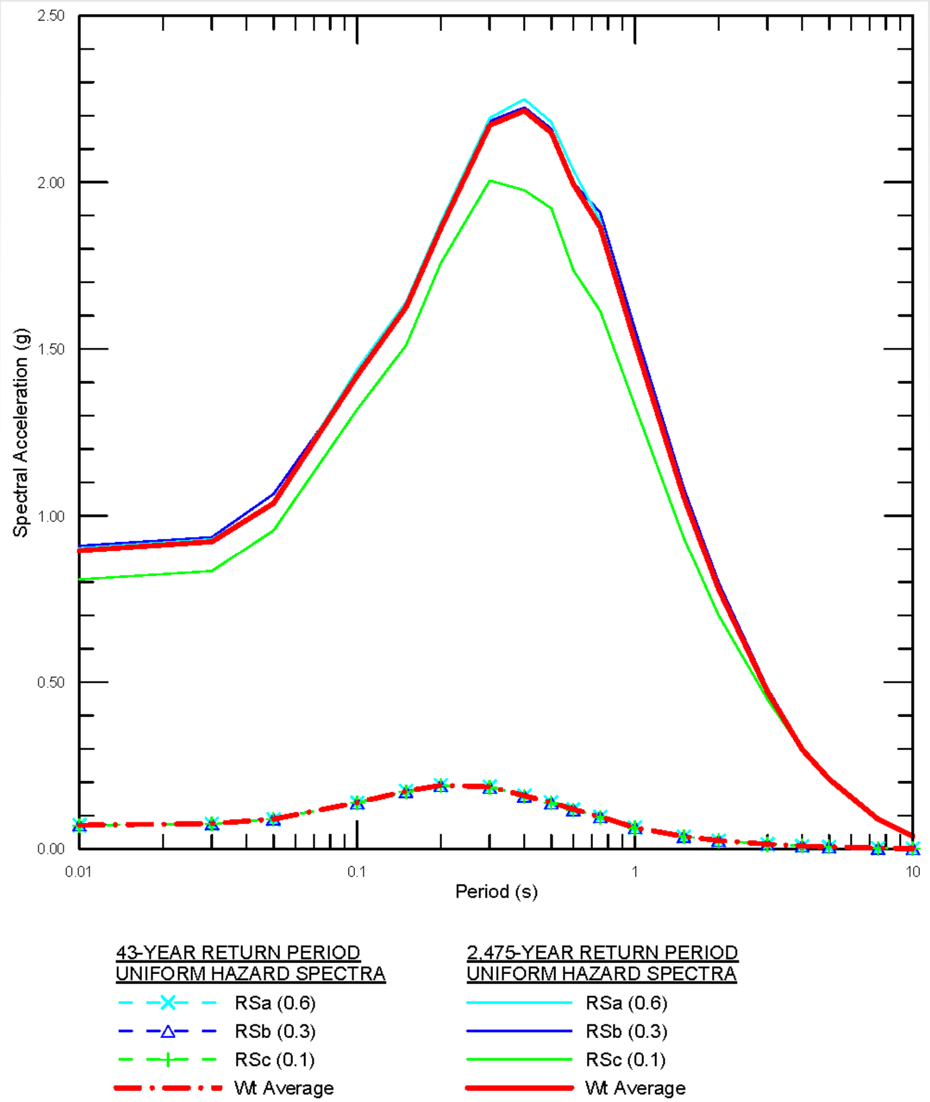
Sensitivity to East Bench-Warm Springs Faults Stepover – 5%-Damped Uniform Hazard Spectra at 43- and 2,475-Year Return Periods



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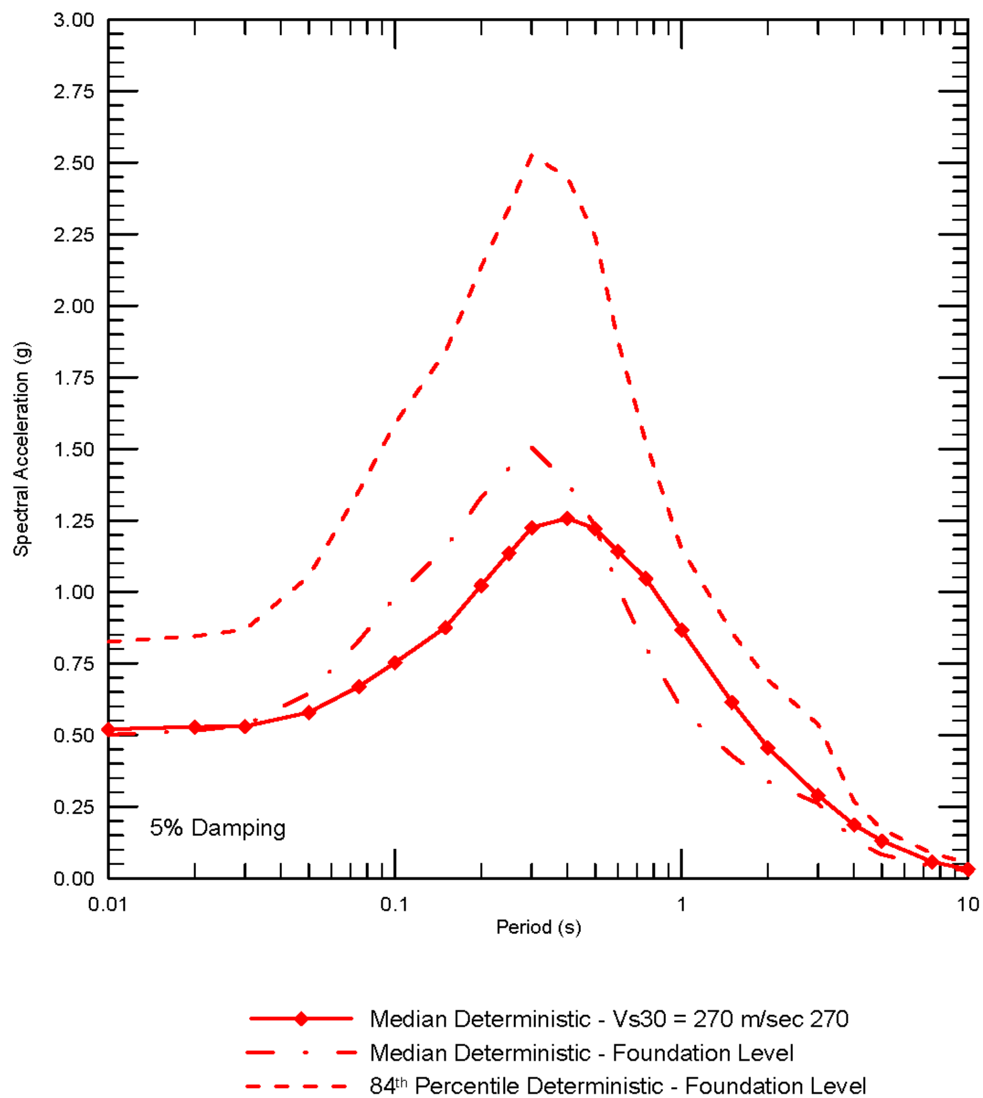
5%-Damped Deterministic Spectra Before and After Site Response Analysis



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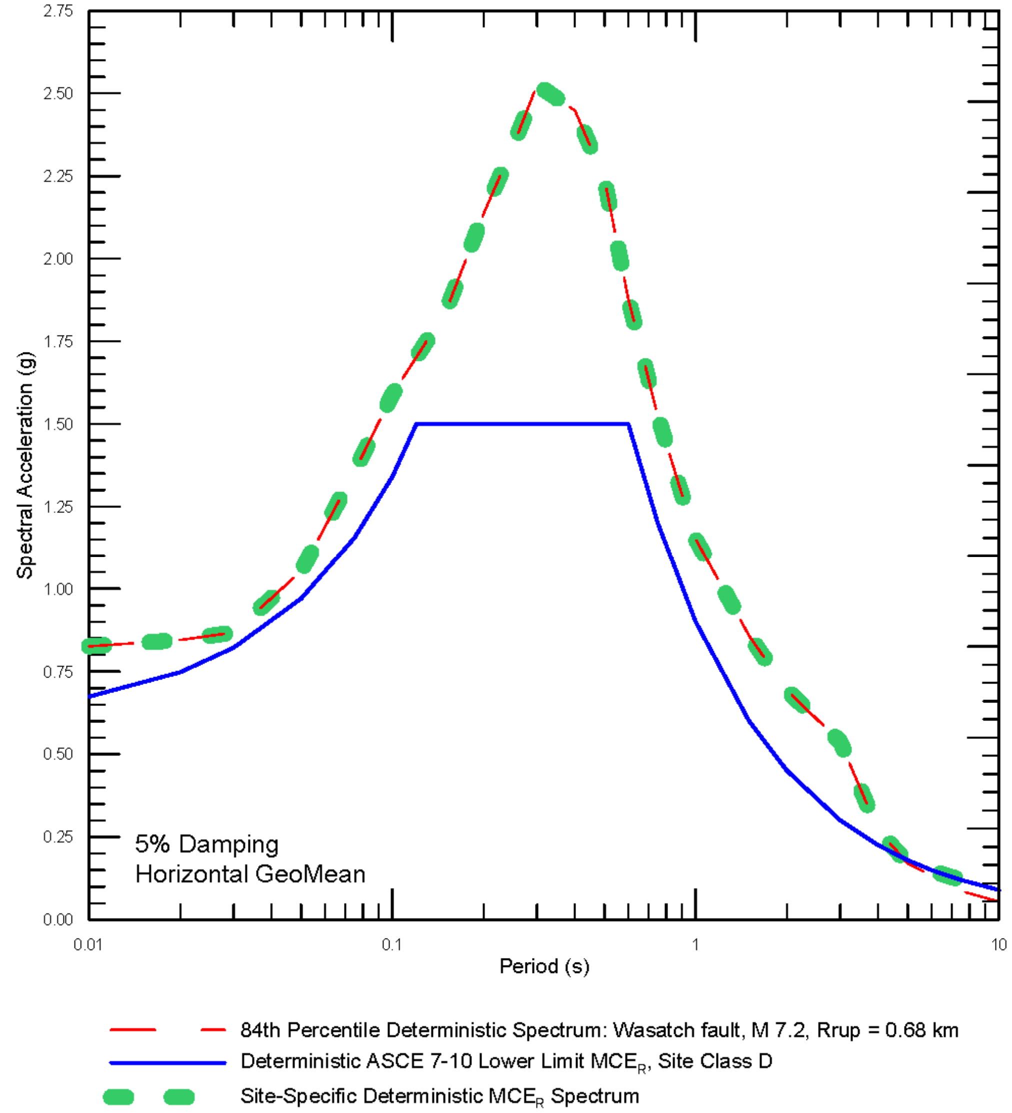
Deterministic MCE_R Spectrum Compared With ASCE 7-05 Lower Limit Deterministic MCE Spectrum



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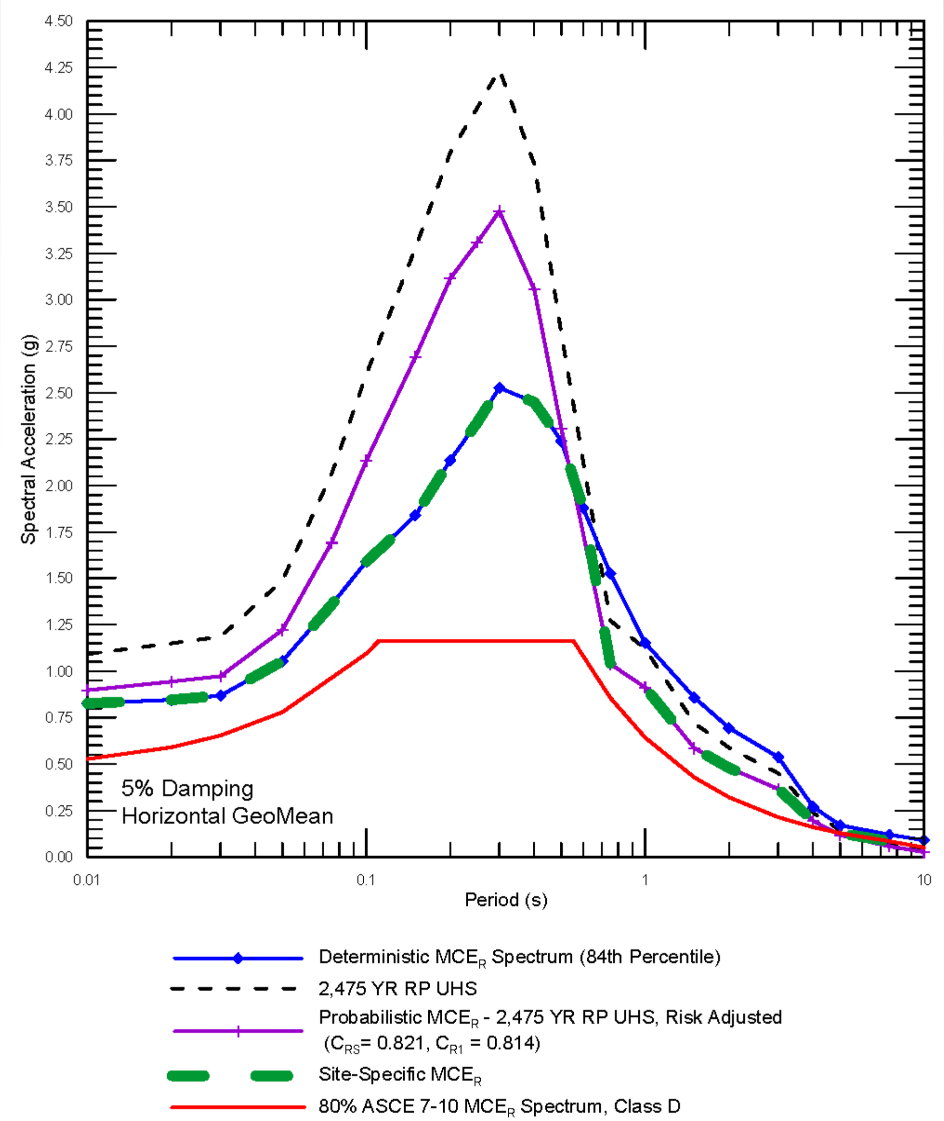
Site-Specific Horizontal MCE$_R$ Spectrum



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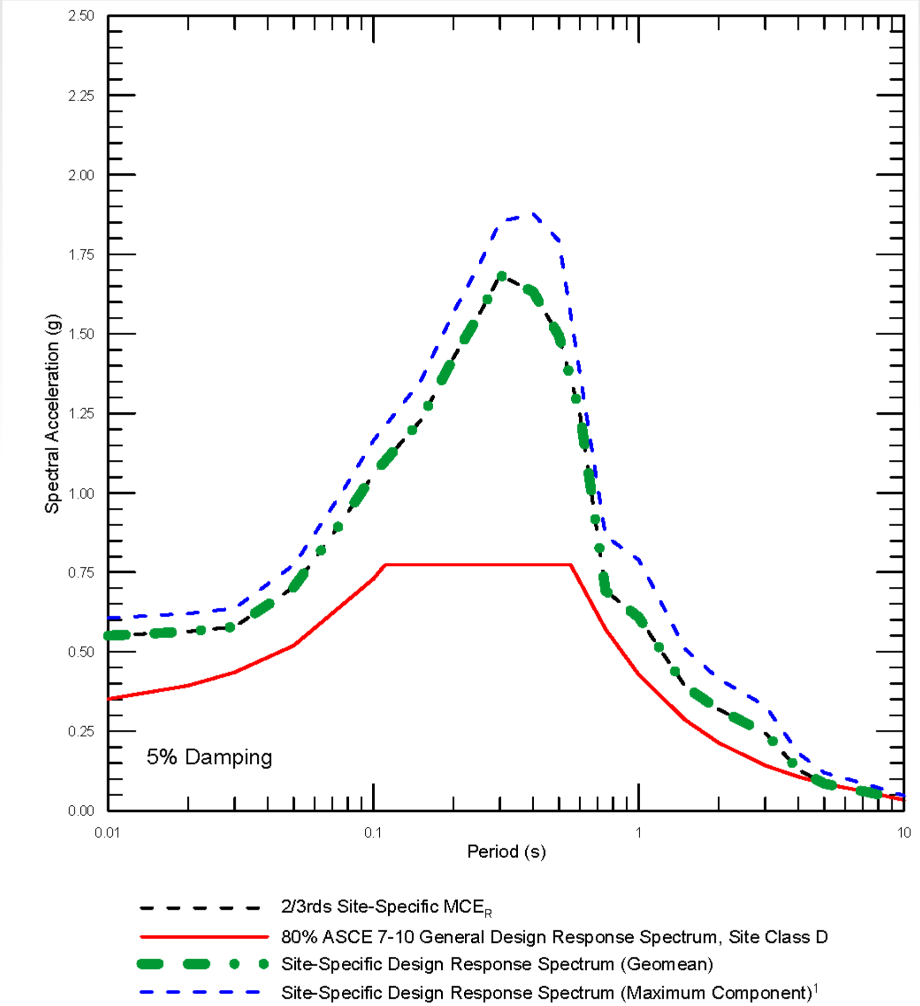
Site-Specific Horizontal Design Response Spectrum



[1] For this project, the Design Response Spectrum is not being used for final design. Geometric mean horizontal Design Response Spectrum is provided for preliminary analyses. If the Design Response Spectrum is to be used for final design, the maximum direction horizontal Design Response Spectrum should be used.

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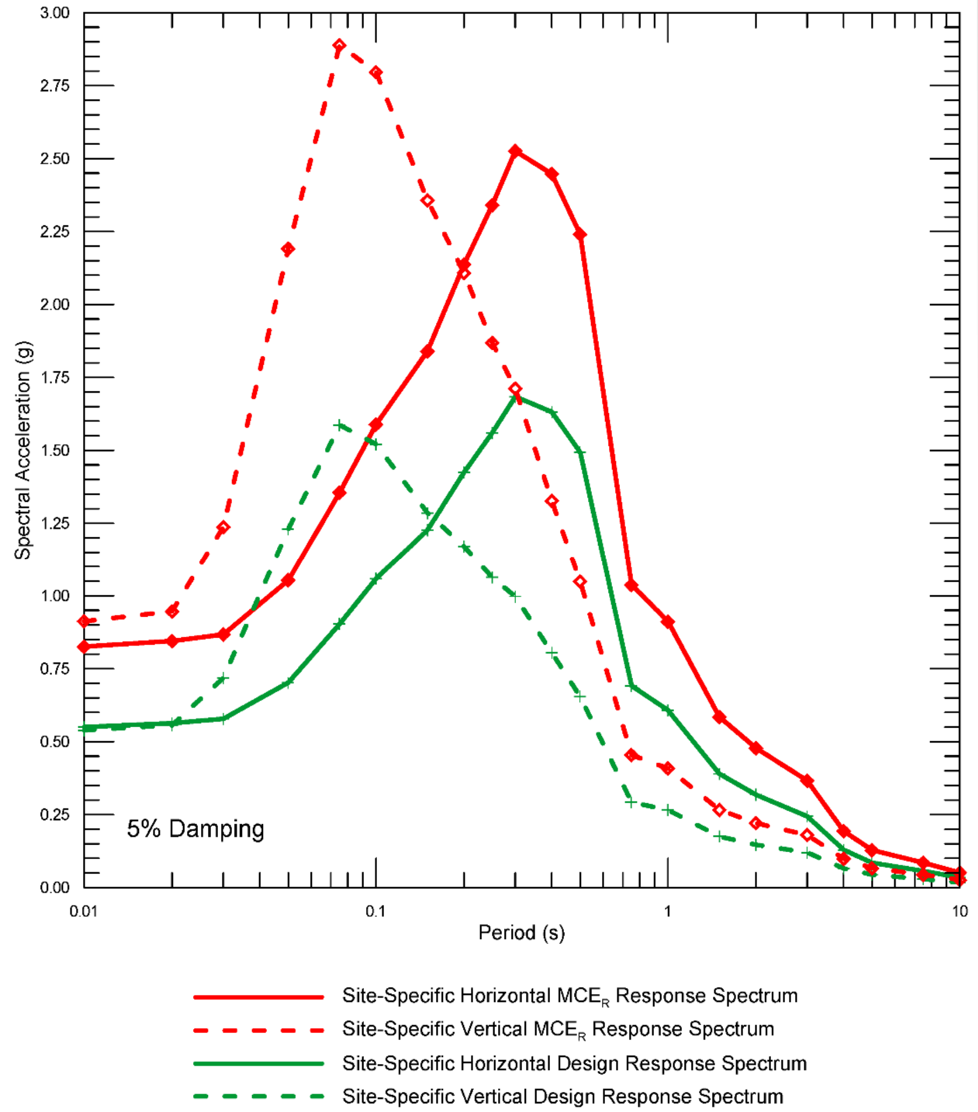
Site-Specific Horizontal and Vertical MCER and Design Response Spectra



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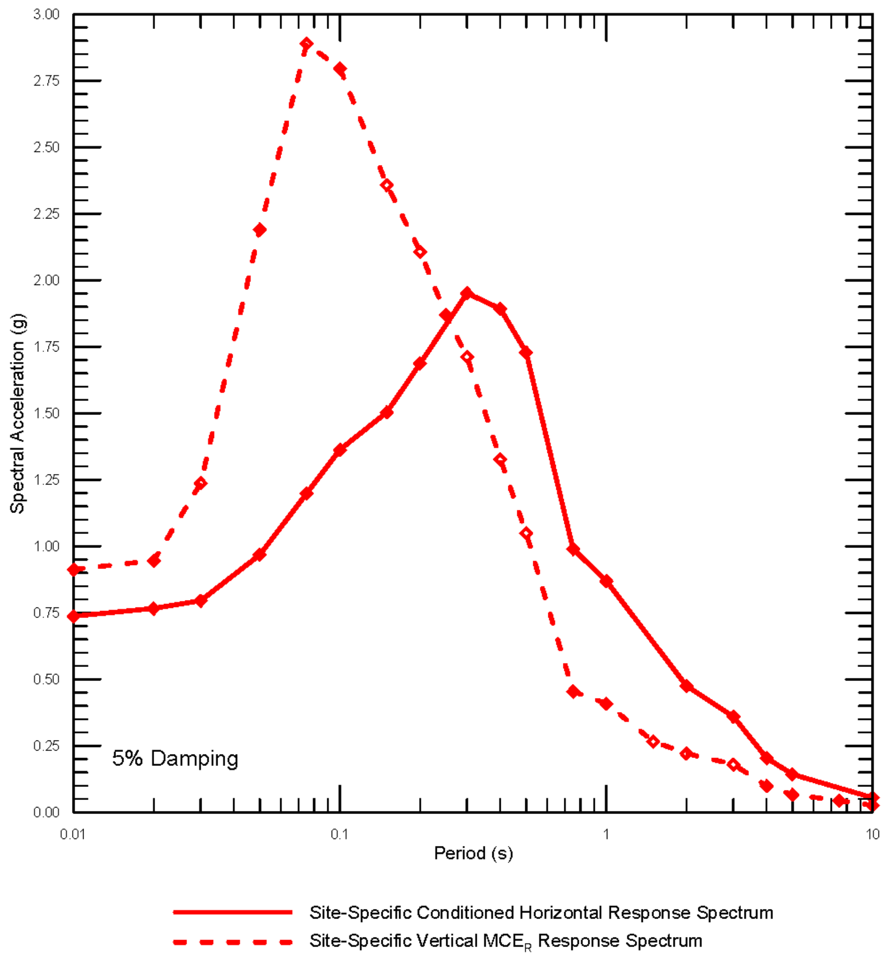
Site-Specific Conditional Horizontal and Vertical MCE_R Response Spectra



Note: Conditioned Horizontal Response Spectrum computed including correlation of V/H ratio and horizontal ground motion from Gulerce and Abrahamson (2011)

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Summary

- There are still several issues that require additional data to improve site-specific seismic design in Salt Lake City and the Wasatch Front
- As previously described, those issues include the rupture behavior of the Salt Lake City segment, forward rupture directivity, and basin effects.
-

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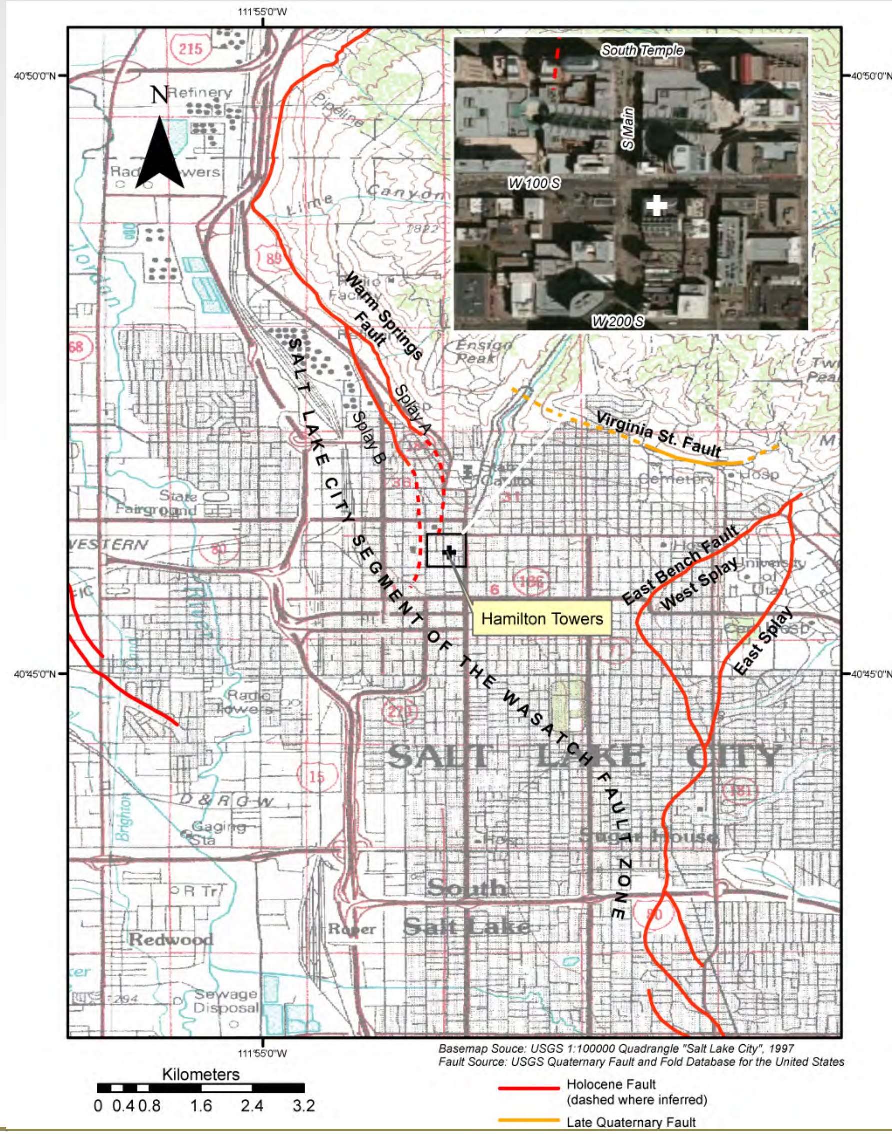
Active Faults Near the Site



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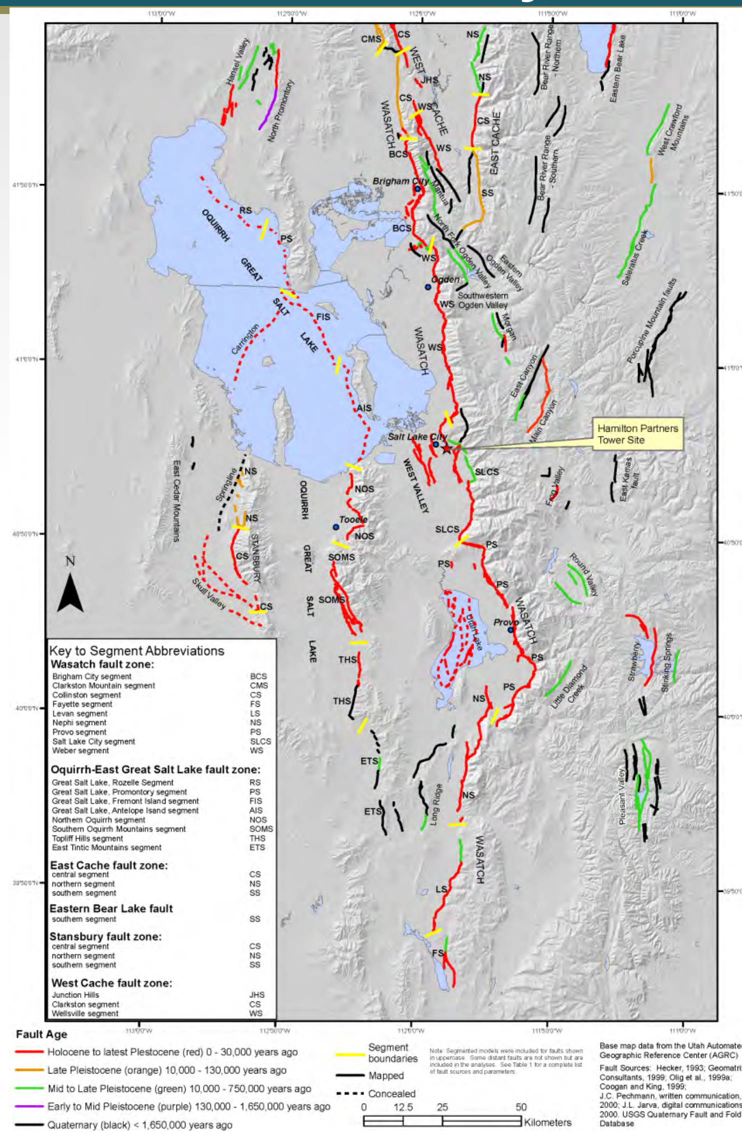
Selected Quaternary Fault Sources Included in the Hazard Analysis



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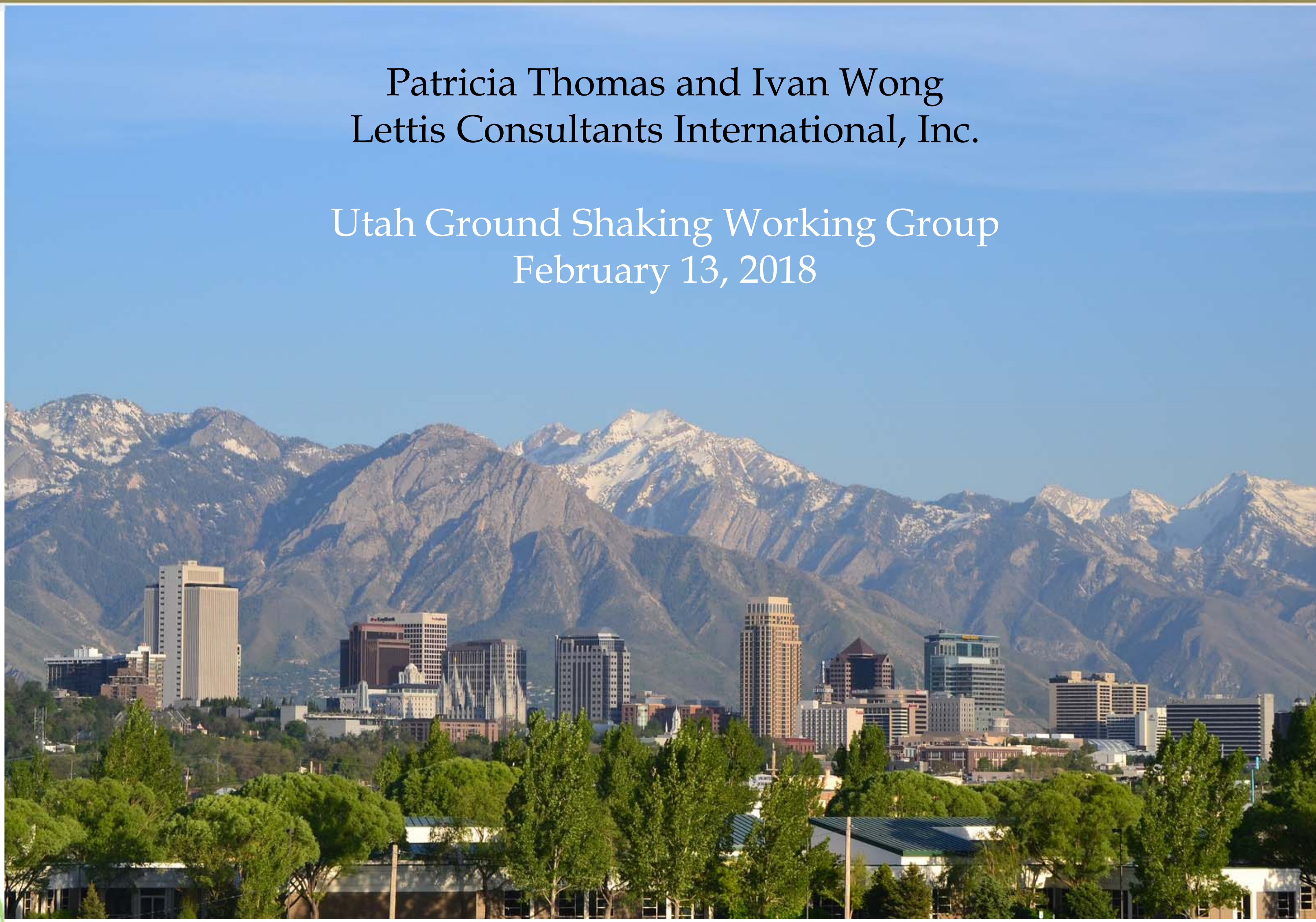
The Impact on Seismic Hazard from Modeling the Time-Dependent Behavior of the Wasatch Fault

Patricia Thomas and Ivan Wong
Lettis Consultants International, Inc.

Utah Ground Shaking Working Group
February 13, 2018



WGUEP Members

Ivan Wong, URS (now LCI) (Chair)
Bill Lund, UGS (Co-Chair)
Walter Arabasz, UUSS
Tony Crone, USGS
Chris DuRoss, UGS (now USGS)
Mike Hylland, UGS
Nico Luco, USGS
Susan Olig, URS (now consultant)
Jim Pechmann, UUSS
Steve Personius, USGS
Mark Petersen, USGS
David Schwartz, USGS
Bob Smith, UU
Patricia Thomas, URS (now LCI)

Assistance from Steve Bowman, UGS and Rich Briggs, USGS

UUSS university of utah seismograph stations

USGS

UTAH DNR GEOLOGICAL SURVEY

THE UNIVERSITY OF UTAH Department of Geology & Geophysics

URS

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Implementation of the WGUEP Model for Time-Dependent Hazard Calculations

- WGUEP developed a seismic source model that includes the Wasatch and the Oquirrh-Great Salt Lake fault zones and 45 other faults/fault segments along with background seismicity in the Wasatch Front Region (39°N to 42.5°N, 110.75°W to 113.25°W).
- Time-independent rupture probabilities were calculated for individual faults, background earthquakes and the region for M ≥ 5, 6.0 and 6.75 for a suite of time periods up to 100 years.
- Time-dependent probabilities were calculated for Wasatch and the Great Salt Lake fault zones where the data is available on the expected mean frequency of earthquakes and the elapsed time since the most recent large earthquake.
- Even for these faults, significant weight was given to the time-independent model.

Quaternary Faults

- 47 faults included in the WGUEP model
- 6 segments with multiple rupture models
- 4 pairs of antithetic faults which can rupture simultaneously

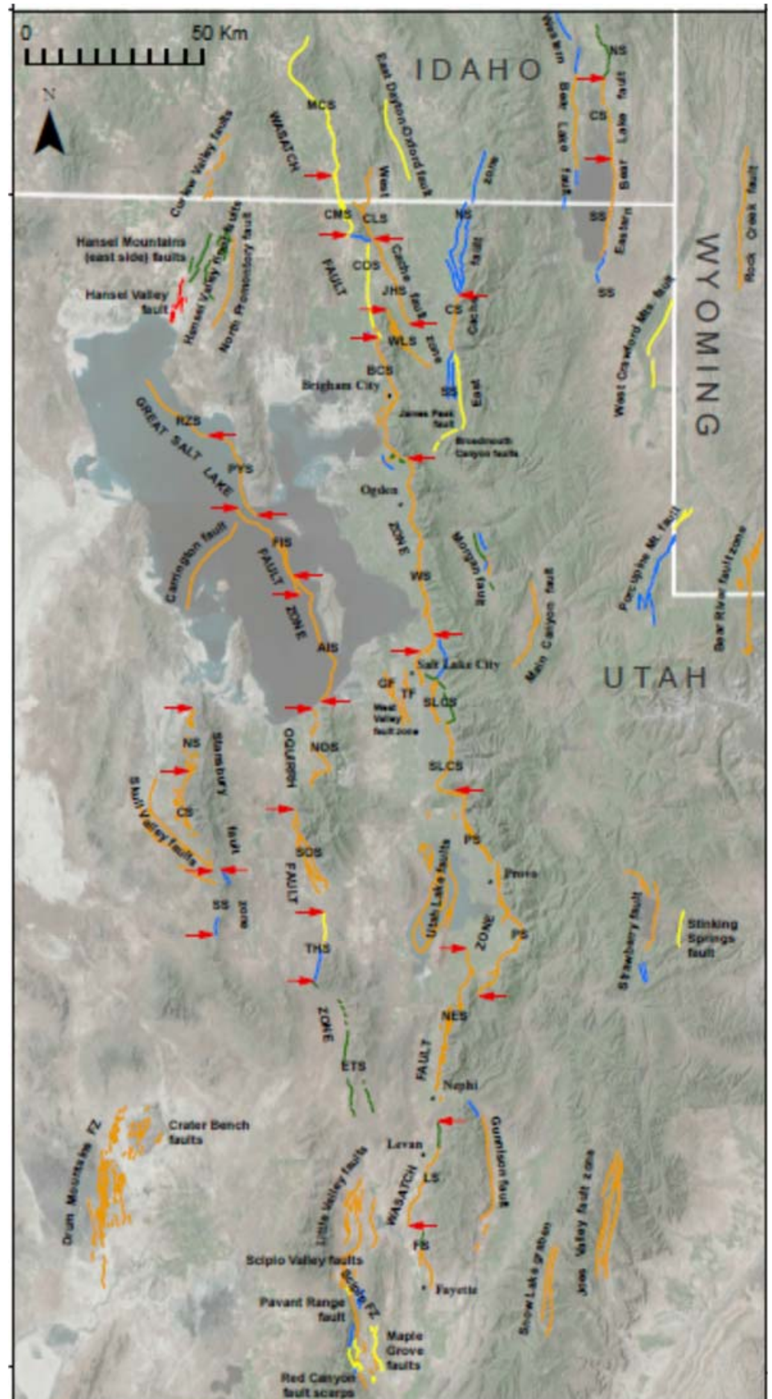
EXPLANATION

Segment boundary

Most Recent Fault Rupture (yrs)

- <1,600,000
- <750,000
- <130,000
- <15,000
- <150

AIS = Antelope Island segment
BCS = Brigham City segment
CLS = Clarkston segment
CMS = Clarkston Mt. segment
COS = Collinston segment
CS = Central segment
ETS = East Tintic segment
FIS = Fremont Island segment
FS = Fayette segment
FZ = Fault zone
GF = Granger fault
JHS = Junction Hills segment
LS = Levan segment
MCS = Malad City segment
NES = Nephi segment
NOS = Northern Oquirrh segment
NS = Northern segment
PS = Provo segment
PYS = Promontory segment
RZS = Rozelle segment
SLCS = Salt Lake City segment
SOS = Southern Oquirrh segment
SS = Southern segment
TF = Taylorsville fault
THS = Topliff Hill segment
WLS = Wellsville segment
WS = Weber segment



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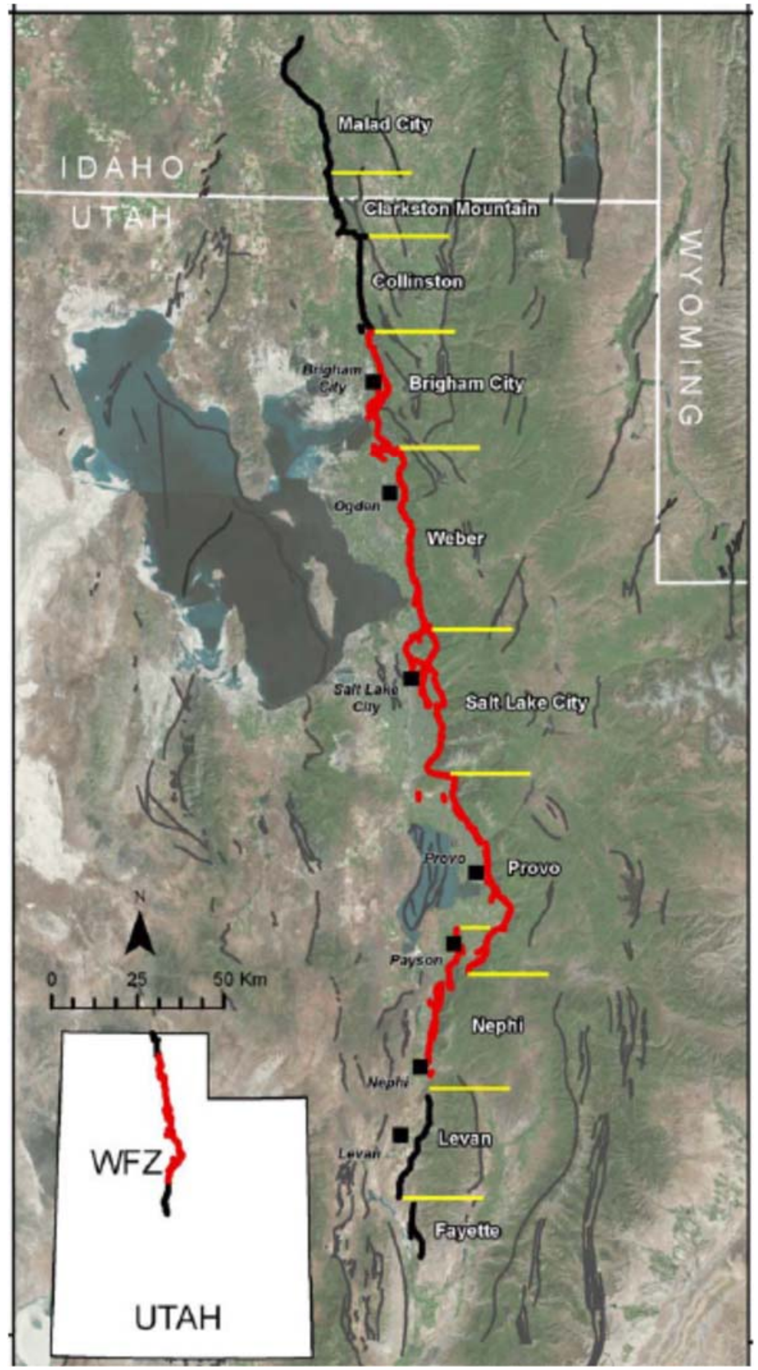
10 Segments of WFZ

- 5 Central Segments
  - Brigham City
  - Weber
  - Salt Lake City
  - Provo
  - Nehpi
- Higher slip rates
- Paleoseismic data from numerous trenching studies



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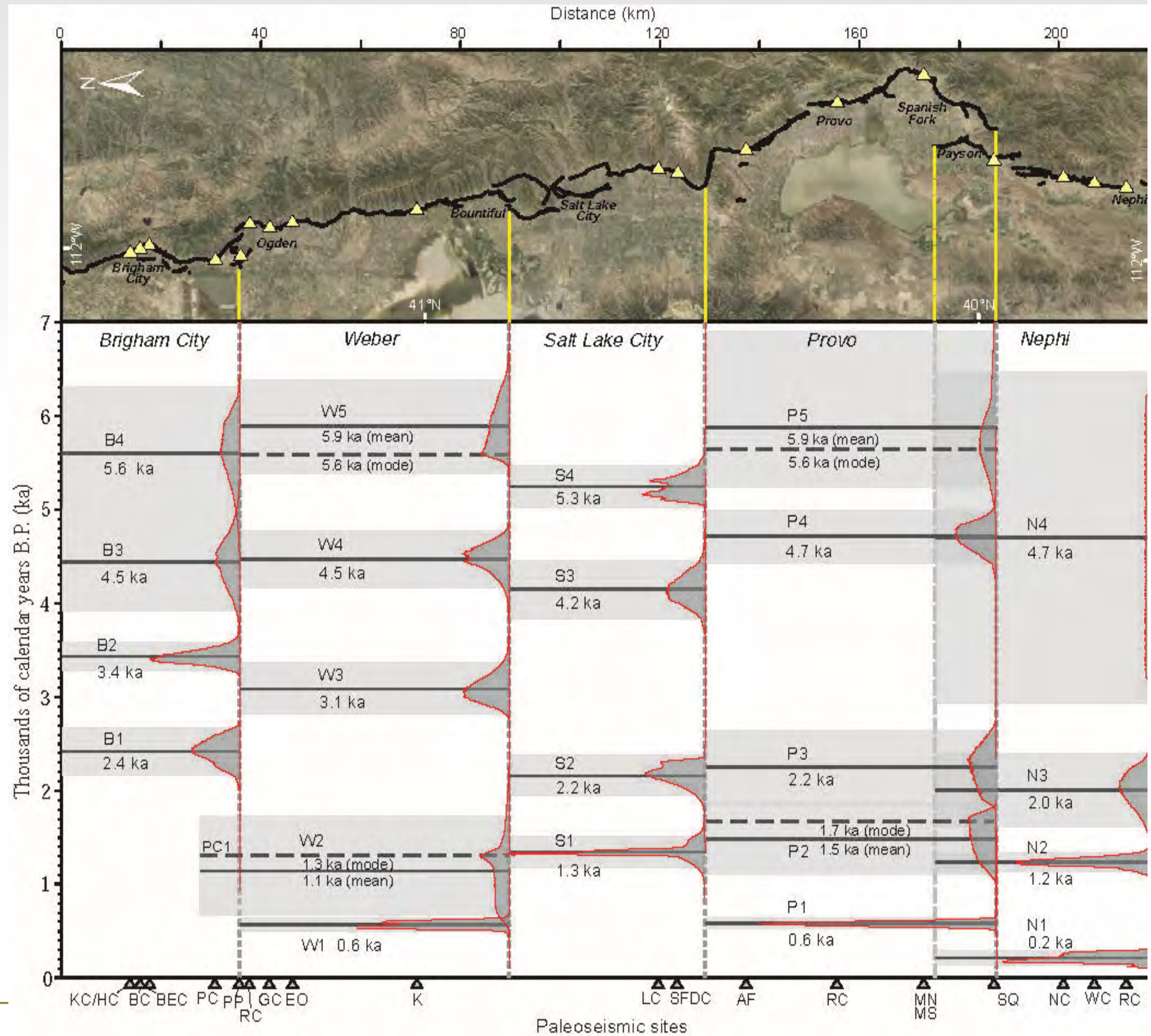
Paleoseismic Data for Central WFZ

- 22 paleoseismic research sites along the central WFZ
- 4 – 5 events identified for each of the segments
- Rupture models developed based on earthquake chronologies and displacement estimates per segment



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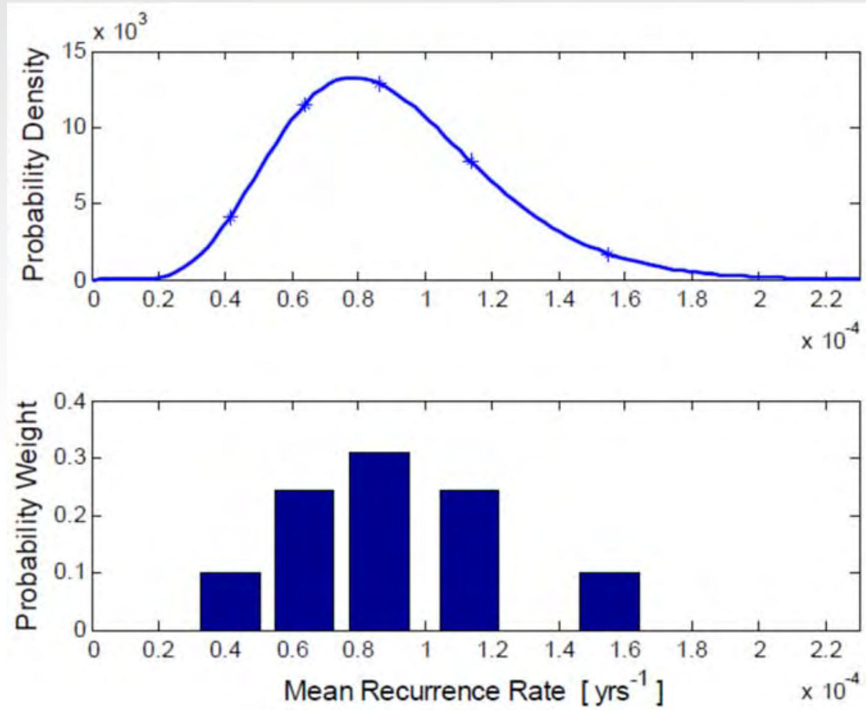
Central Wasatch Fault Zone Rupture Models

Rupture Model	Rupture Sources	Rupture Model Wt.	Earthquakes
SSR	B, W, S, P, N	0.7	22 SSR
Int. C	B, W, S, P, N, B+W	0.075	18 SSR, 2 MSR
Int. A	B, W, S, P, N, B+W, S+P	0.05	16 SSR, 3 MSR
Int. B	B, W, S, P, N, B+W, P+N	0.05	16, SSR, 3 MSR
MSR	B, W, S, P, N, B+W, W+S, S+P, P+N, S+P+N	0.025	7 SSR, 7 MSR
Unsegmented	floating	0.1	

Recurrence Intervals

- Implemented the earthquake RI approach from CEUS-SSC report.
- The gamma distribution discretized into a five-point approximation.
- The method includes sample size uncertainty.
- Uncertainty in event timing found to be insignificant relative to sample size uncertainty.



Segment	Wt. Mean Poisson RI
BCS	1500
WS	1427
SLCS	1331
PS	1235
NS	1080

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Time Dependent Probability Model

- A time-dependent renewal process model embodies the expectation that after one earthquake on a fault, another earthquake is unlikely until sufficient time has elapsed for stress to gradually re-accumulate.

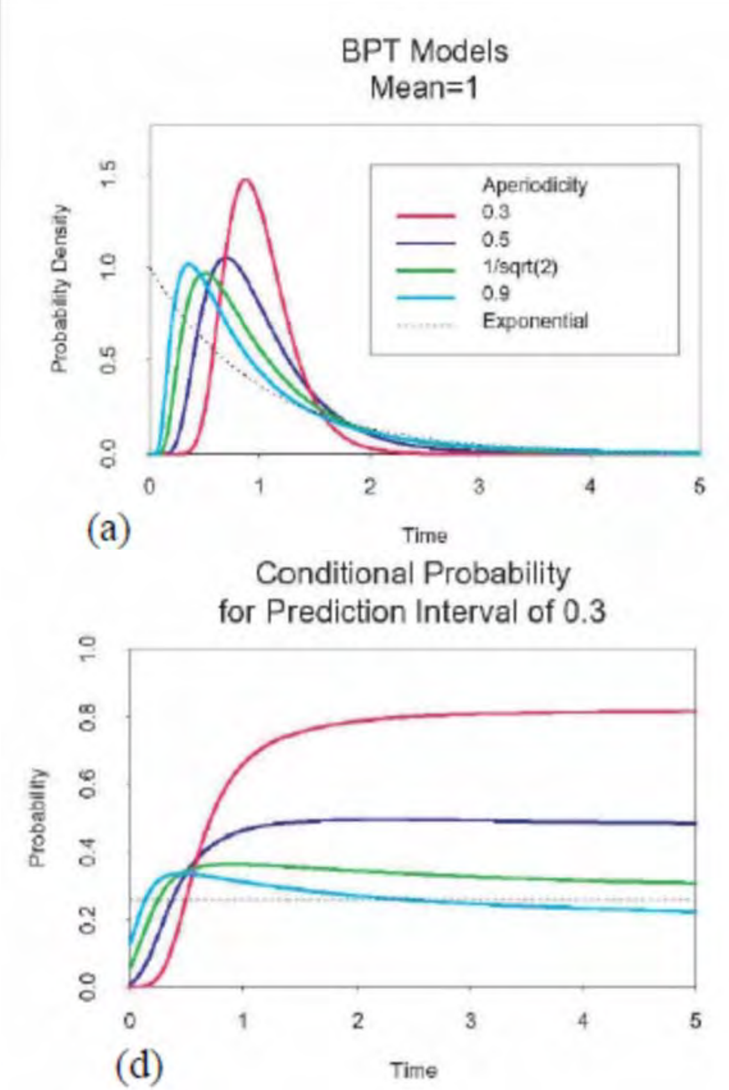
- The BPT model (Mathews et al., 2002) is one such model where stress increases from a ground state to a stress threshold.

- The BPT probability density function is given by:

$$f_{BPT}(t) = \sqrt{\frac{\mu}{2\pi a^2 t^3}} \exp\{-\frac{(t-\mu)^2}{2\mu t a^2}\}$$

- The BPT model requires the mean recurrence interval, μ, and the aperiodicity or COV, α, as input parameters.

- The BPT process reaches a finite quasi-stationary state in which the failure rate is independent of elapsed time. After that point, conditional probabilities do not continue to increase.



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Coefficient of Variation on Recurrence

- The standard deviation of inter-event RI divided by their mean is a measure of the periodicity of earthquakes on a fault.
- Smaller values of COV indicate more periodic recurrence and larger values indicate more random timing
- Based on the analysis of global dataset of repeating earthquakes (Ellsworth et al., 1999), WGCEP (2003, 2008) used a COV of 0.5 +/-0.2.
- While the data set for WFZ is small, the suitability of the global COV to the WFZ was tested by computing a composite COV for the central WFZ using grouped inter-event recurrence data.
- The composite COV is 0.5 +/-0.1 (2σ) with a minimum and maximum of about 0.3 to 0.7, supported the use of the range used by WGCEP based on the global data set.

Time-Dependent Rupture Probabilities, single-segment rupture model, M ≥ 6.75

Segment	Wt. Mean Poisson RI (years)	Mean Elasped Time Since Last Event (years)
BCS	1500	2491
WS	1427	626
SLCS	1331	1408
PS	1235	643
NS	1080	271

Fault Segment	50 Years	
	Poisson	BPT
Brigham City	3.2%	7.5%
Weber	3.5%	2.0%
Salt Lake City	3.6%	6.1%
Provo	4.0%	2.8%
Nephi	4.4%	0.5%

Sensitivity of Time-Dependent Rupture Probabilities to COV, single-segment rupture model, M ≥ 6.75

Fault Segment	Poisson Probability	BPT, $\alpha = 0.3$			BPT, $\alpha = 0.5$			BPT, $\alpha = 0.7$		
		Probability	Lapse Time / Mean RI	Ratio of BPT to Poisson Probability	Probability	Lapse Time / Mean RI	Ratio of BPT to Poisson Probabiltiy	Probability	Lapse Time / Mean RI	Ratio of BPT to Poisson Probability
Brigham City	3.2%	14.9%	1.7	4.6	6.3%	1.5	2.0	3.7%	1.3	1.2
Weber	3.4%	1.1%	0.5	0.3	2.0%	0.4	0.6	2.6%	0.38	0.8
Salt Lake City	3.6%	10.3%	1.0	2.9	5.5%	0.9	1.5	3.7%	0.74	1.0
Provo	4.0%	1.7%	0.5	0.4	3.1%	0.5	0.8	3.2%	0.39	0.8
Nephi	4.4%	<0.1%	0.3	0.007	0.48%	0.3	0.1	1.0%	0.21	0.2

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Equivalent-Poisson Rupture Rates

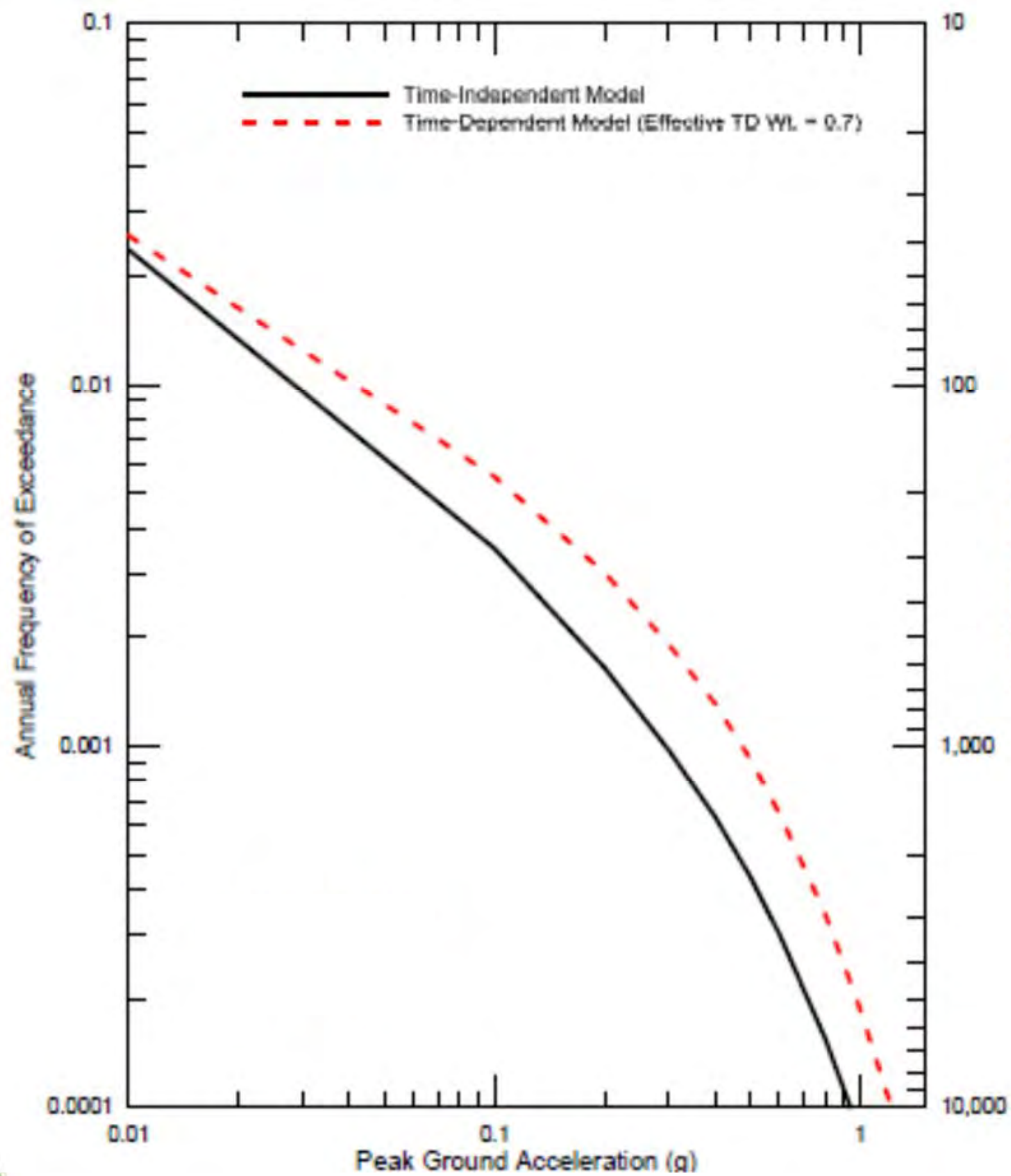
- Equivalent-Poisson rupture rates can be back calculated from the BPT rupture probabilities for a specified time interval and used in a PSHA to compute time-dependent hazard.

Segment	Wt. Mean Time-Independent Poisson RI (years)	Wt. Mean Time-Dependent Equivalent Poisson RI (years)
BCS	1500	535
WS	1427	2408
SLCS	1331	707
PS	1235	1510
NS	1080	6065

- Equivalent-Poisson RI for BCS and SLCS significantly lower than time-independent Poisson rates

Brigham City, Utah

- 2,475-yr Return Period PGA
  - TI: 0.52 g
  - TD: 0.74 g
- V_S30 = 760 m/sec
- NGA-West2 GMM



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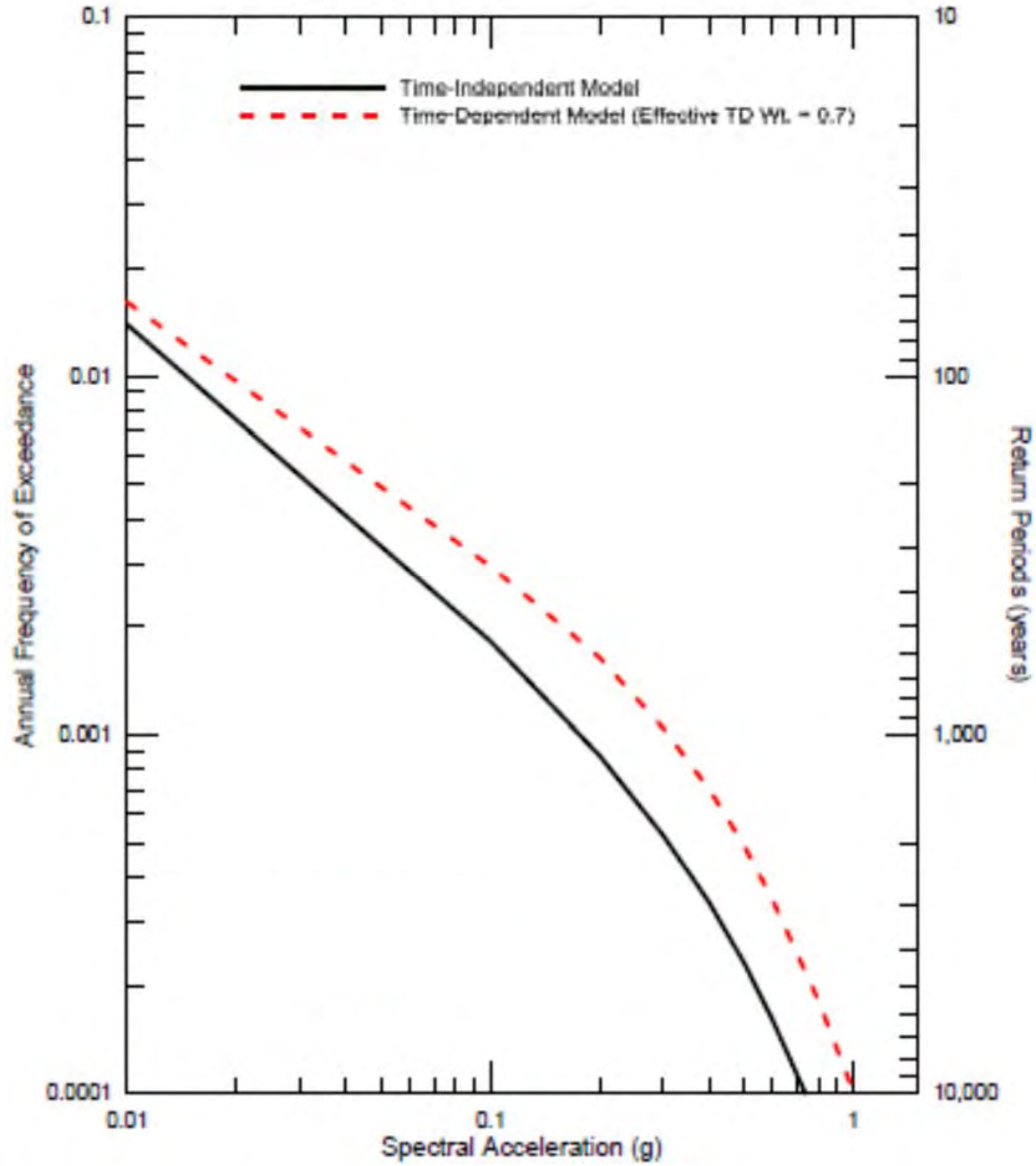
Brigham City, Utah

- 2,475-yr Return Period 1.0 sec SA
  - TI: 0.36 g
  - TD: 0.55 g
- V_S30 = 760 m/sec
- NGA-West2 GMM



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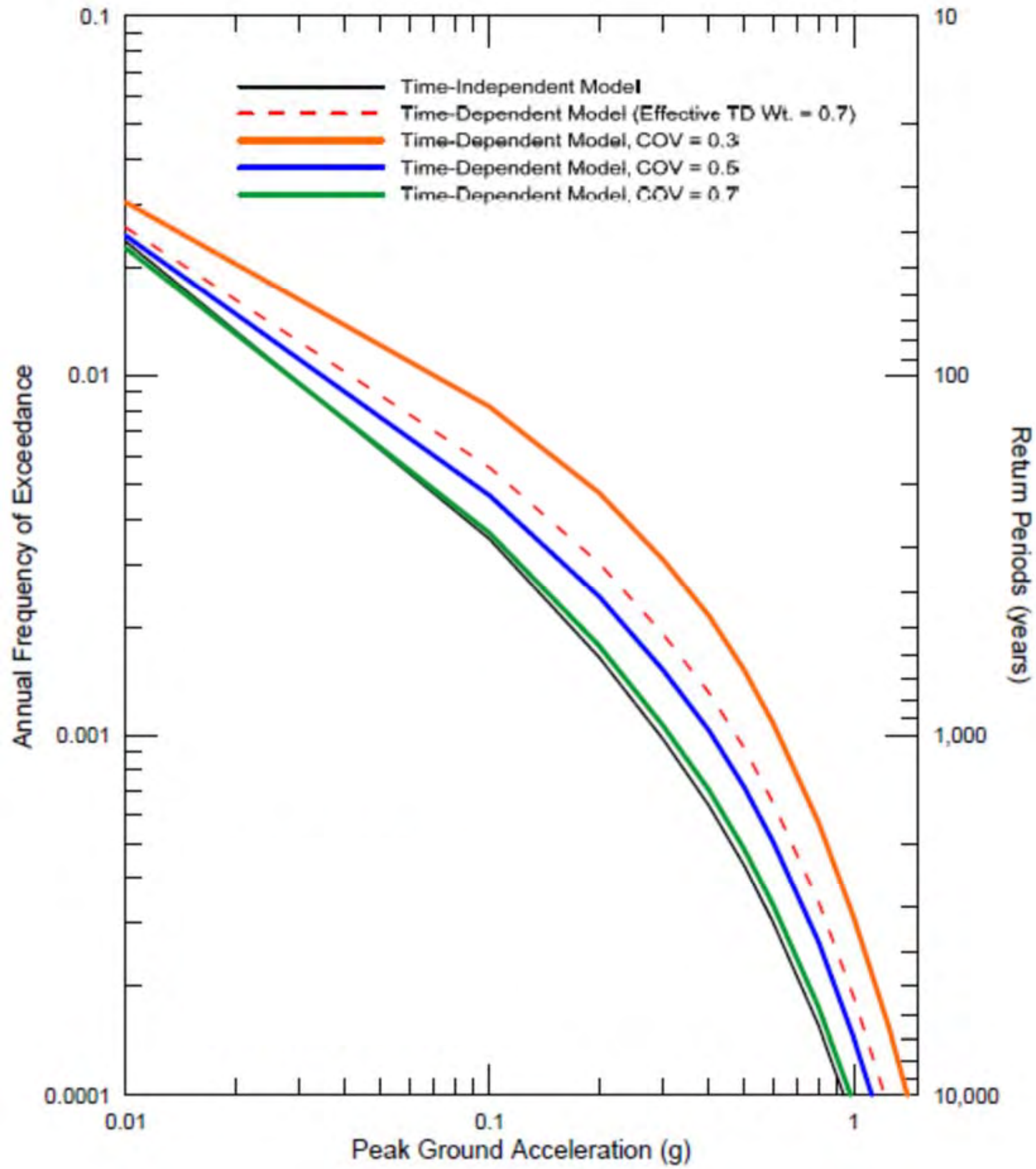
Brigham City, Utah

- 2,475-yr Return Period 1.0 sec SA

  TI: 0.52 g

TD, COV=0.3: 0.91 g
TD, COV=0.5: 0.66 g
TD, COV=0.7: 0.55 g



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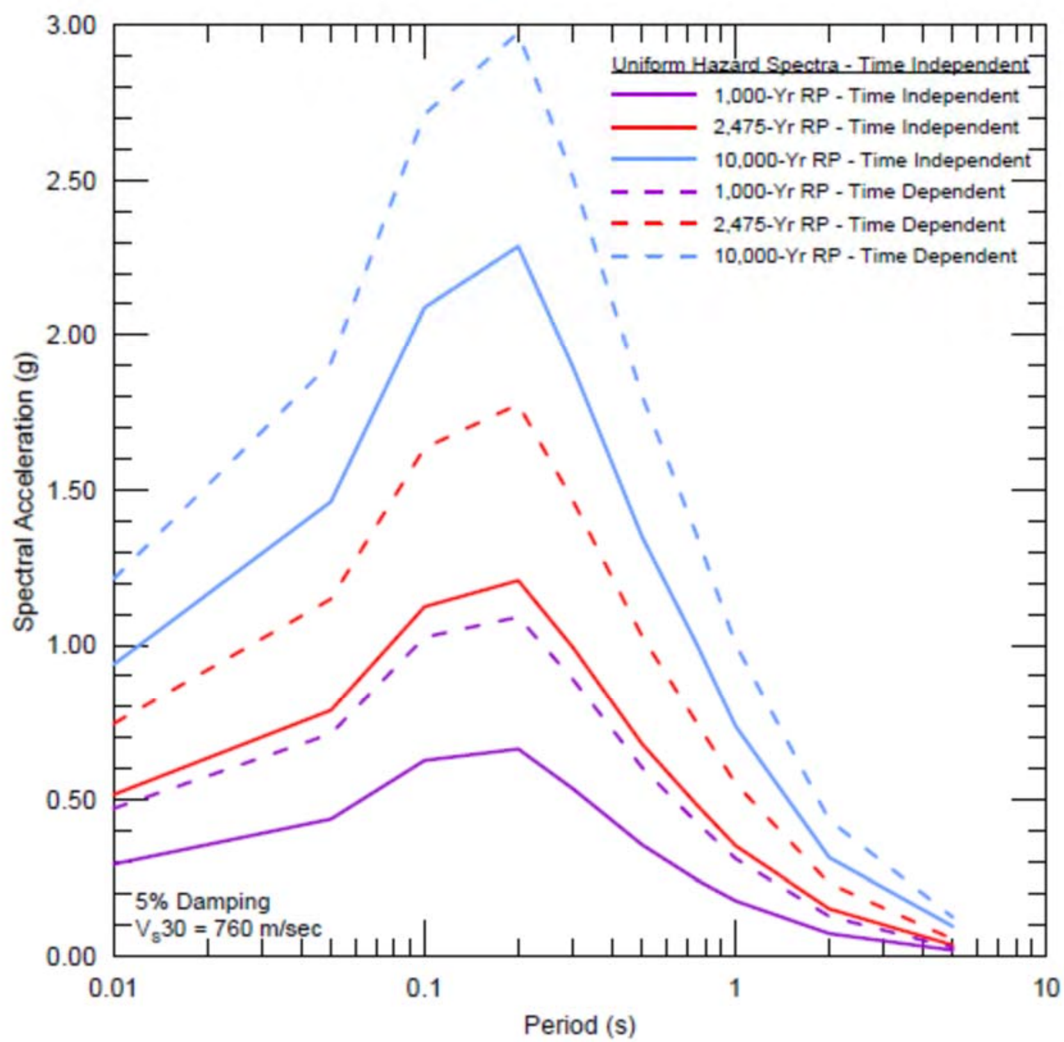
Brigham City, Utah

- 2,475-yr Return Period UHS

Time-Dependent UHS is 45-55% larger than Time-Independent



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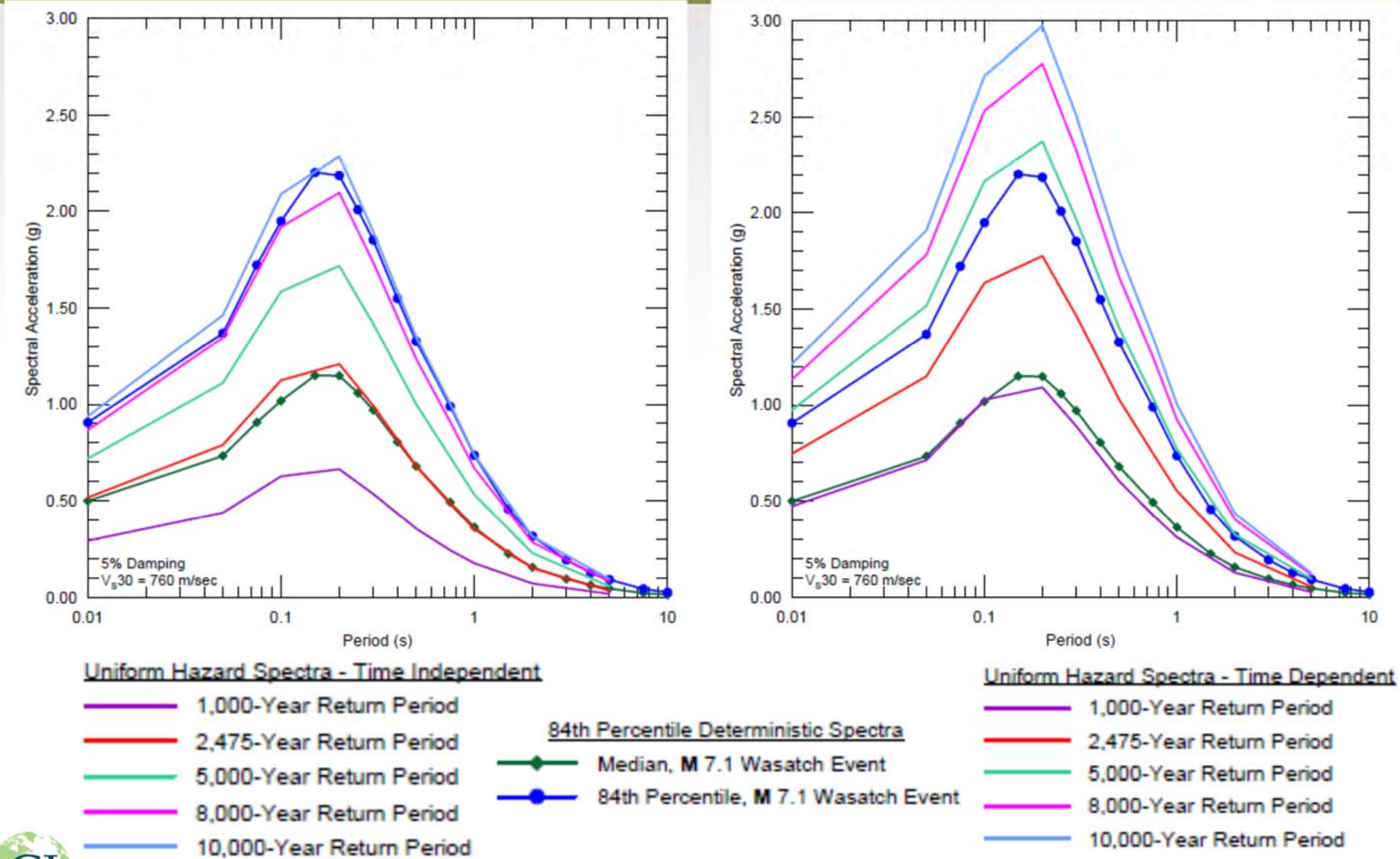
Comparison of Deterministic Spectrum with UHS – Brigham City Site



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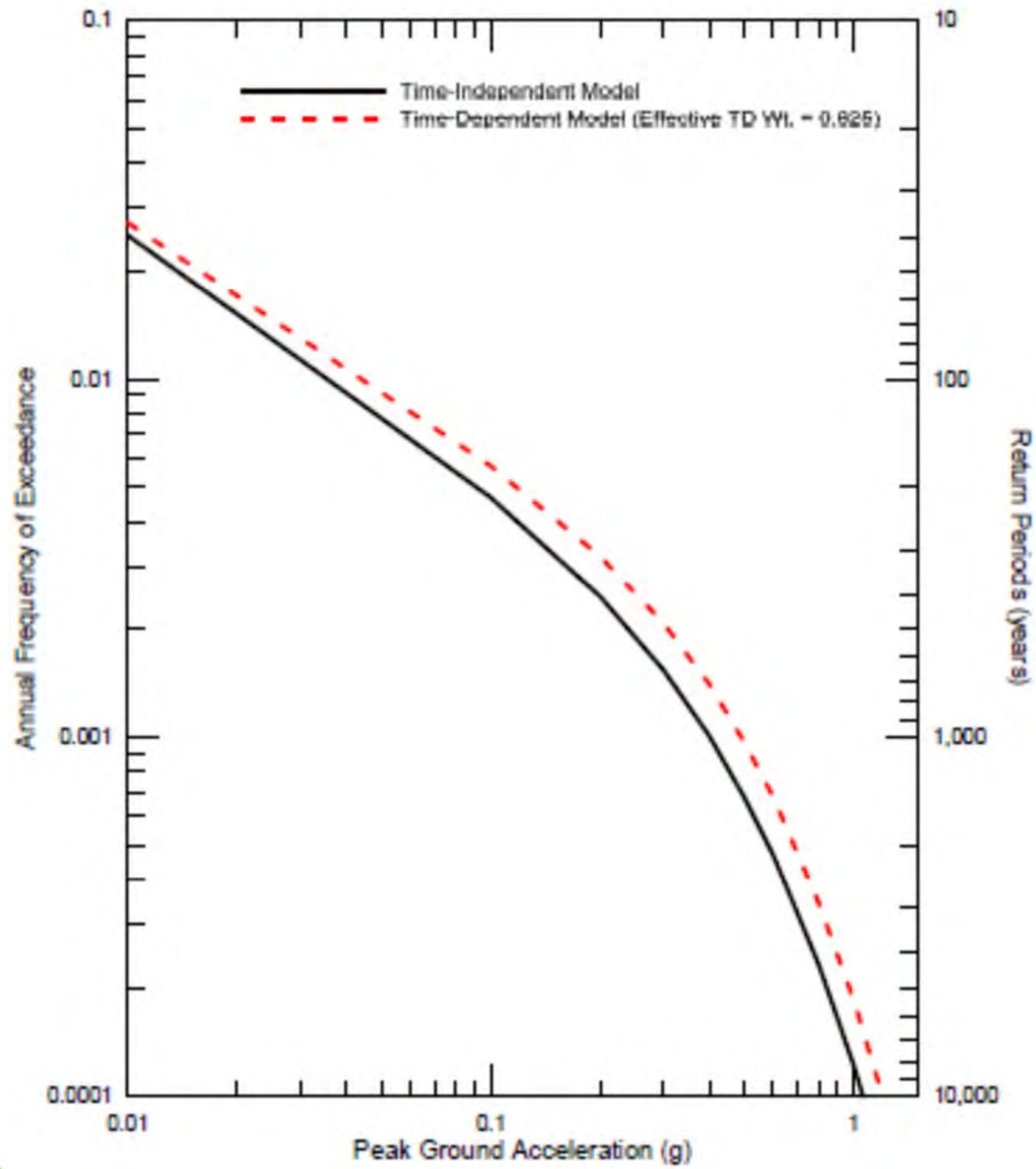
Salt Lake City, Utah

- 2,475-yr Return Period PGA
  - TI: 0.64 g
  - TD: 0.75 g
- V_S30 = 760 m/sec
- NGA-West2 GMM



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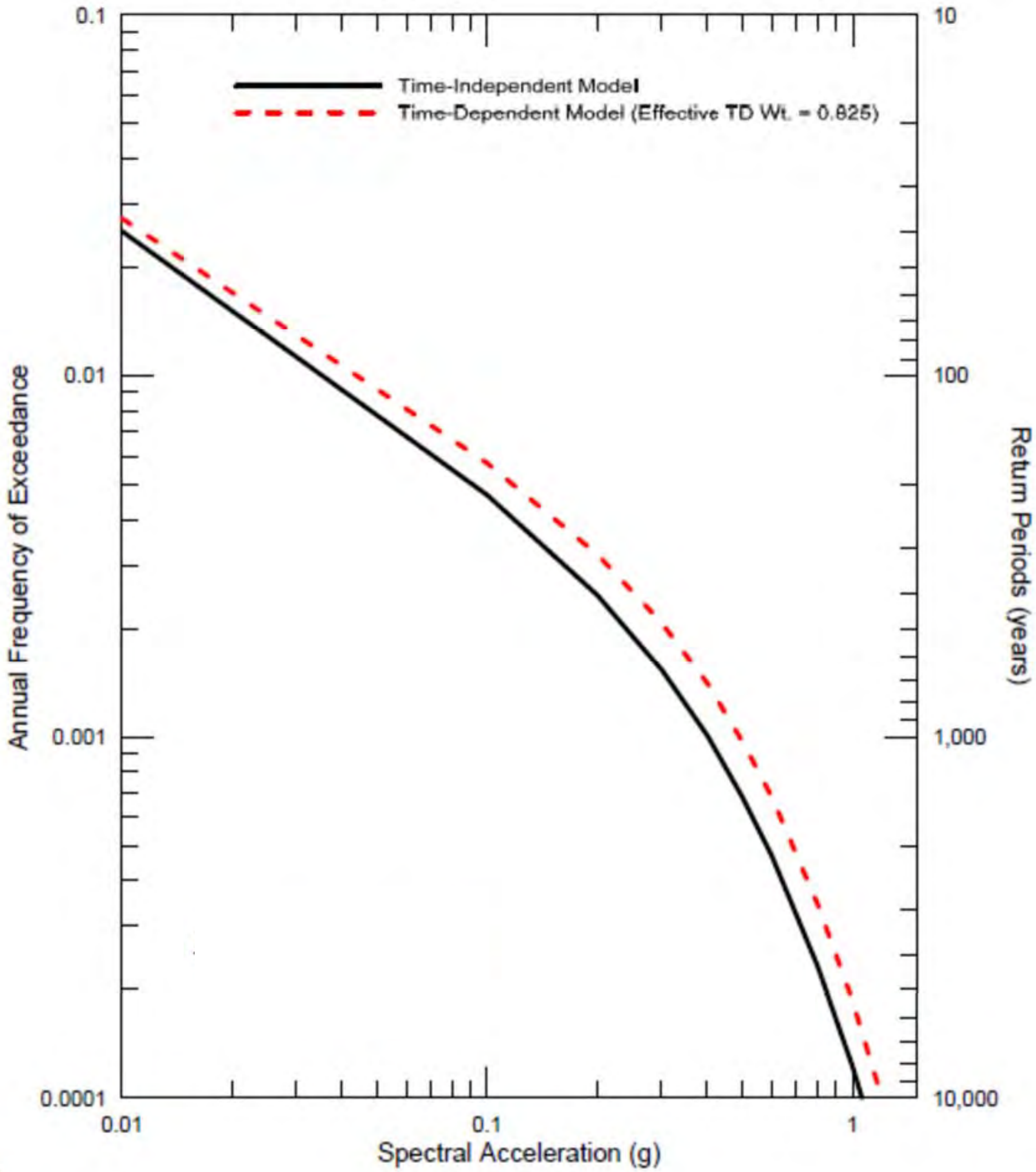
Salt Lake City, Utah

- 2,475-yr Return Period 1.0 Sec SA
  - TI: 0.46 g
  - TD: 0.56 g
- V_S30 = 760 m/sec
- NGA-West2 GMM



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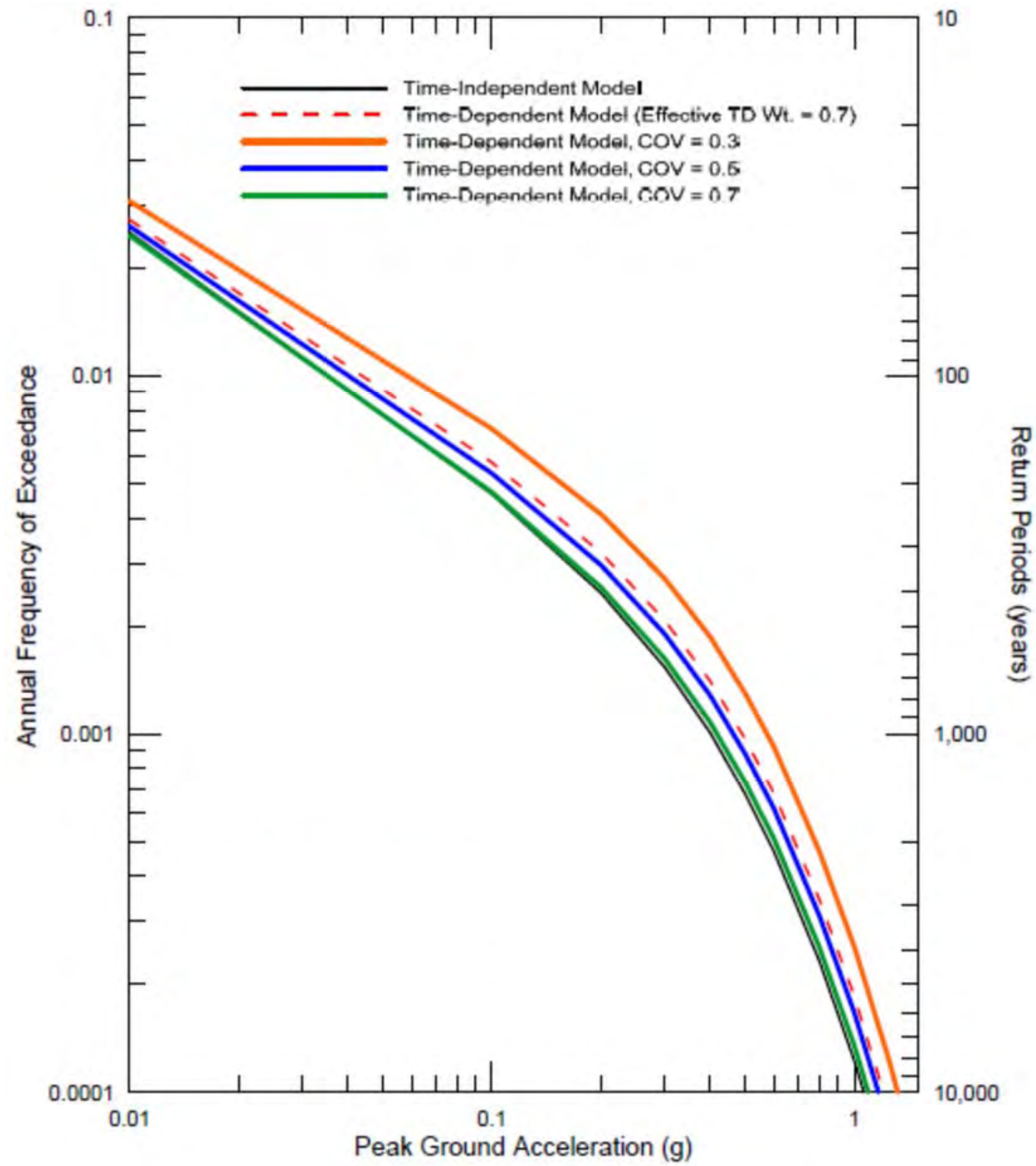
Salt Lake City, Utah

- 2,475-yr Return Period 1.0 sec SA

TI: 0.64 g

TD, COV=0.3: 0.85 g
TD, COV=0.5: 0.72 g
TD, COV=0.7: 0.66 g



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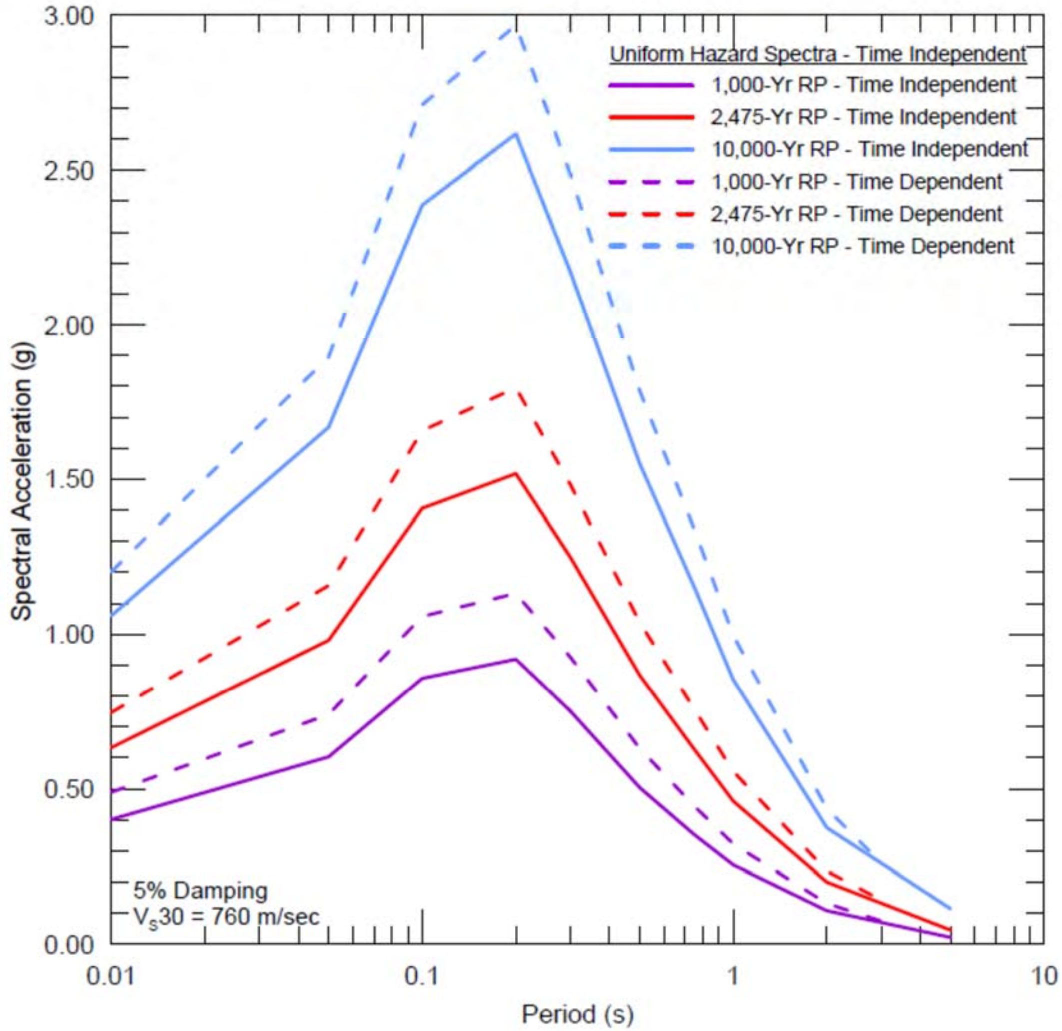
Salt Lake City, Utah

- 2,475-yr Return Period UHS

Time-Dependent UHS is 18-21% larger than Time-Independent



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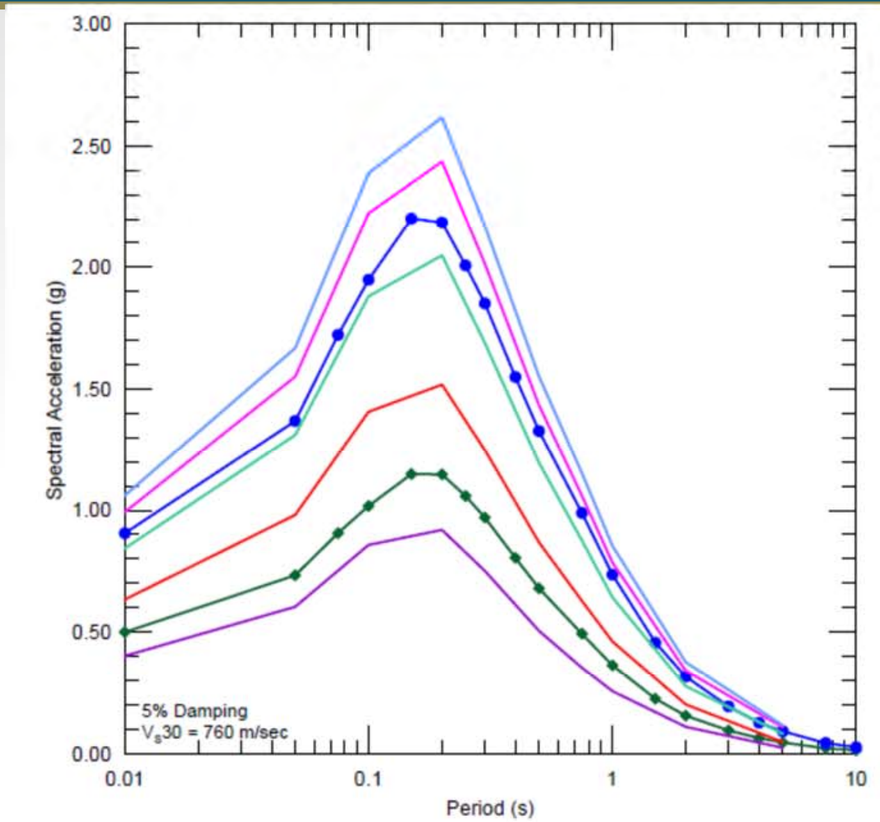
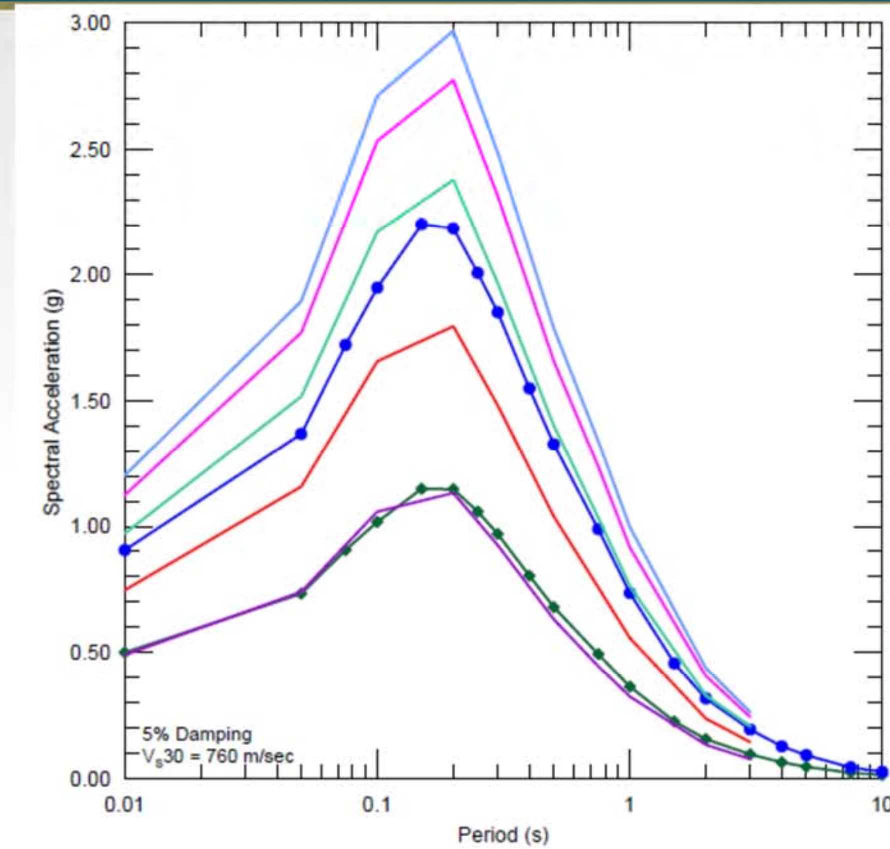
Comparison of Deterministic Spectrum with UHS – Salt Lake City Site





Uniform Hazard Spectra - Time Independent

- 1,000-Year Return Period
- 2,475-Year Return Period
- 5,000-Year Return Period
- 8,000-Year Return Period
- 10,000-Year Return Period

84th Percentile Deterministic Spectra

- Median, **M** 7.1 Wasatch Event
- 84th Percentile, **M** 7.1 Wasatch Event

Uniform Hazard Spectra - Time Dependent

- 1,000-Year Return Period
- 2,475-Year Return Period
- 5,000-Year Return Period
- 8,000-Year Return Period
- 10,000-Year Return Period

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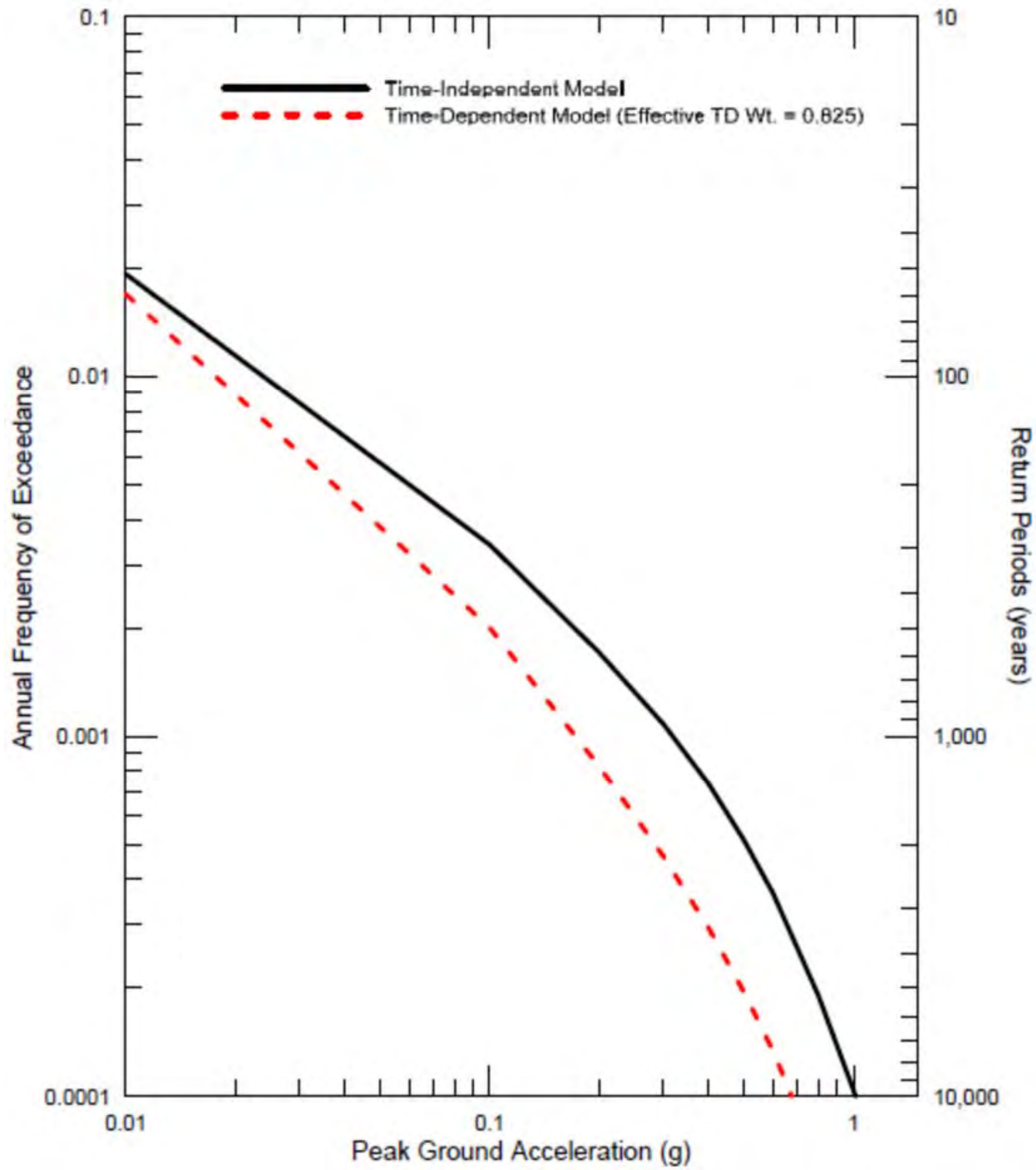
Nephi, Utah

- 2,475-yr Return Period PGA
  - TI: 0.57 g
  - TD: 0.33 g
- V_S30 = 760 m/sec
- NGA-West2 GMM



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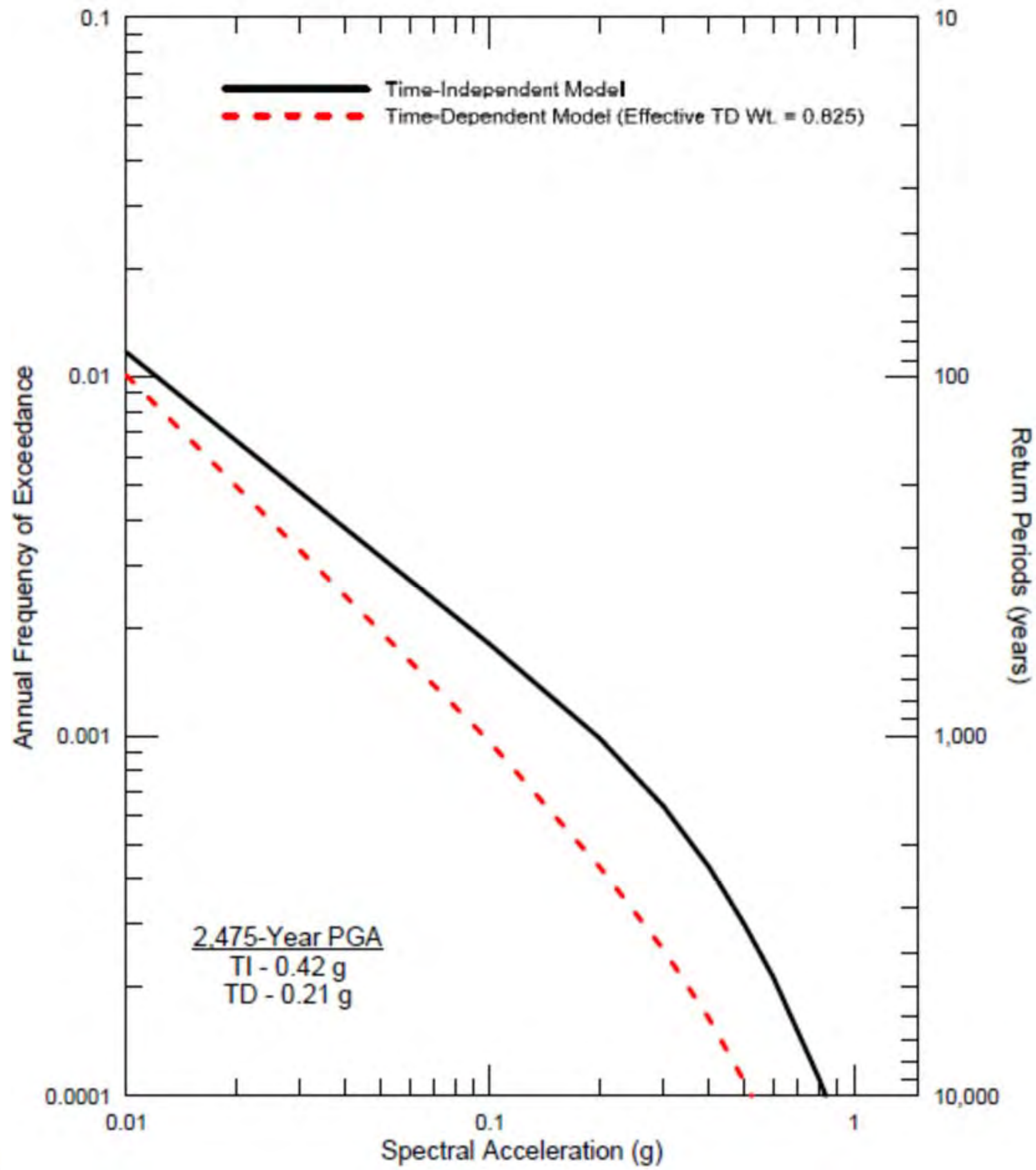
Nephi, Utah

- 2,475-yr Return Period 1.0 sec SA
  - TI: 0.42 g
  - TD: 0.21 g
- V_S30 = 760 m/sec
- NGA-West2 GMM



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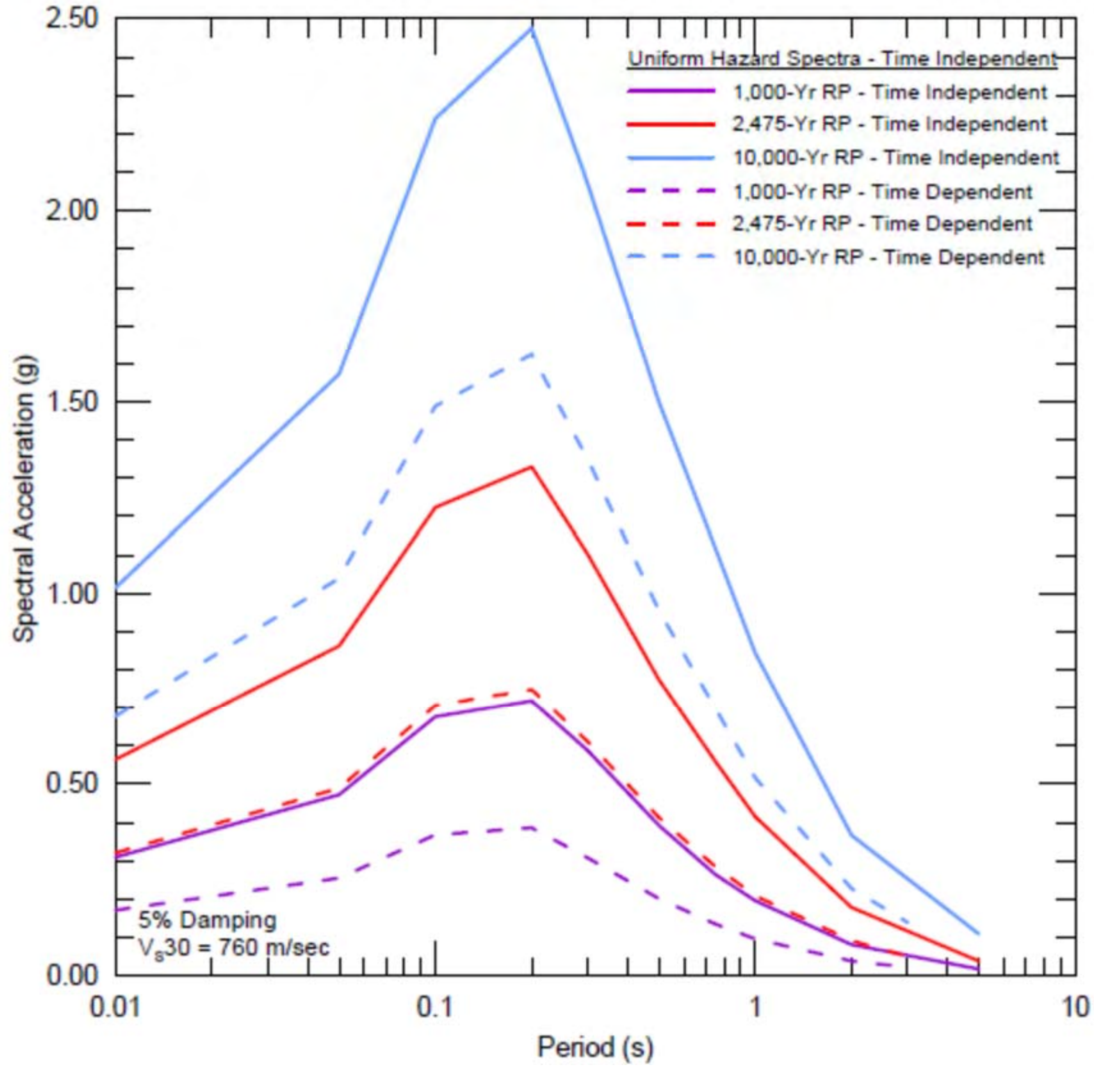
Nephi, Utah

- 2,475-yr Return Period UHS

Time-Dependent UHS is 43-50% smaller than Time-Independent



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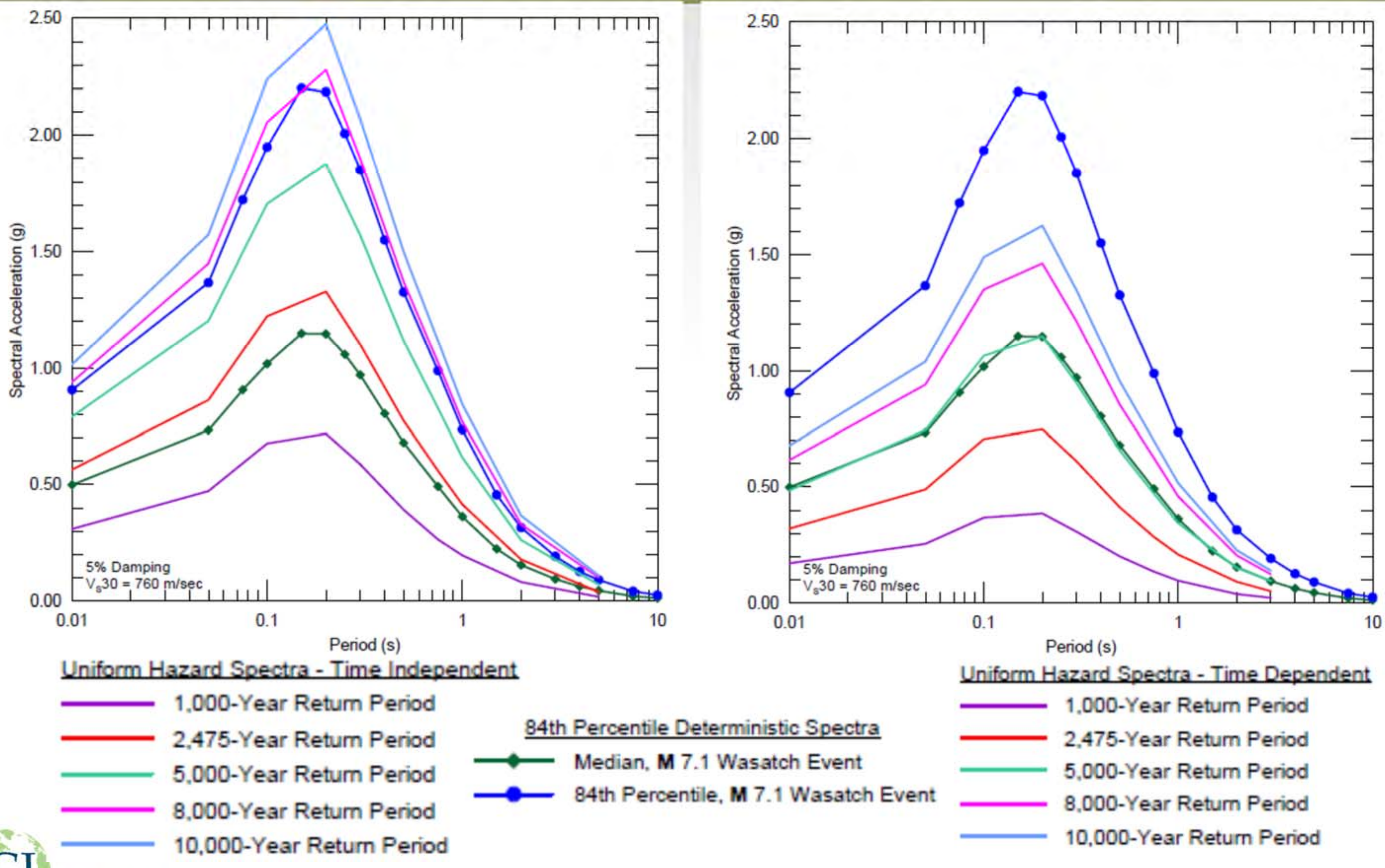
Comparison of Deterministic Spectrum with UHS – Nephi Site



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Conclusions

- Comparison of the time-dependent and time-independent hazard at three cities along the Wasatch Front show significant differences at a 2475-yr return period.

- These differences are due primarily to how the elapsed time since the MRE compares to the average recurrence intervals of the rupture scenarios particularly the single segment ruptures.

- Note that because there is a time-independent component in the time-dependent recurrence intervals, the time-dependent hazard estimates have large uncertainties.

- However, even given those uncertainties, the time-dependent hazard estimates need to be given strong consideration in structural design and safety analyses.

Thank You. Questions?