Simulated motions validation and acceptance criteria for ground motion databases

The Southern California Validation Experience

Ricardo Taborda

PEER

2024 PEER - LBNL Workshop

Simulated Ground Motions for the San Francisco Bay Area

January 18-19, 2024

BERKELEY LAB

The Southern California Validation Experience

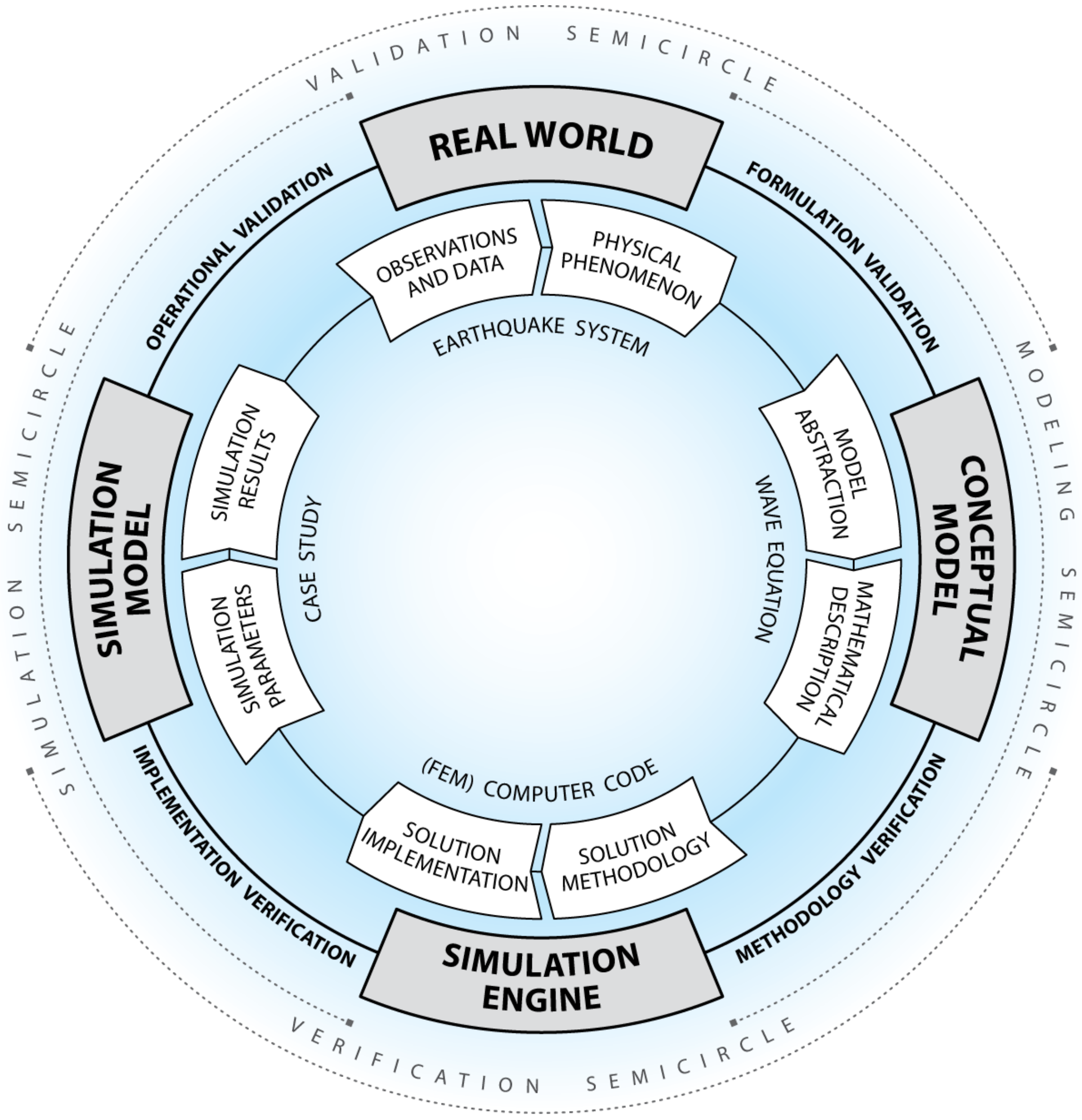
Event scenario

» TeraShake	Independent	N/A
» ShakeOut	Coordinated	Verification
» Chino Hills	Independent	Validation
» La Habra	Coordinated	Verification and validation
» BBP	Coordinated	Verification and validation
» CyberShake	Coordinated	Validation
» Others		

Factors

» Modeling scope	Physics
» Minimum velocity	Resolution
» Maximum frequency	Resolution
» Velocity model	Accuracy, resolution, uncertainty
» Source model	Accuracy, resolution, uncertainty
» Attenuation model	Approach, model, uncertainty
» Implementations	Numerical accuracy and computational efficiency

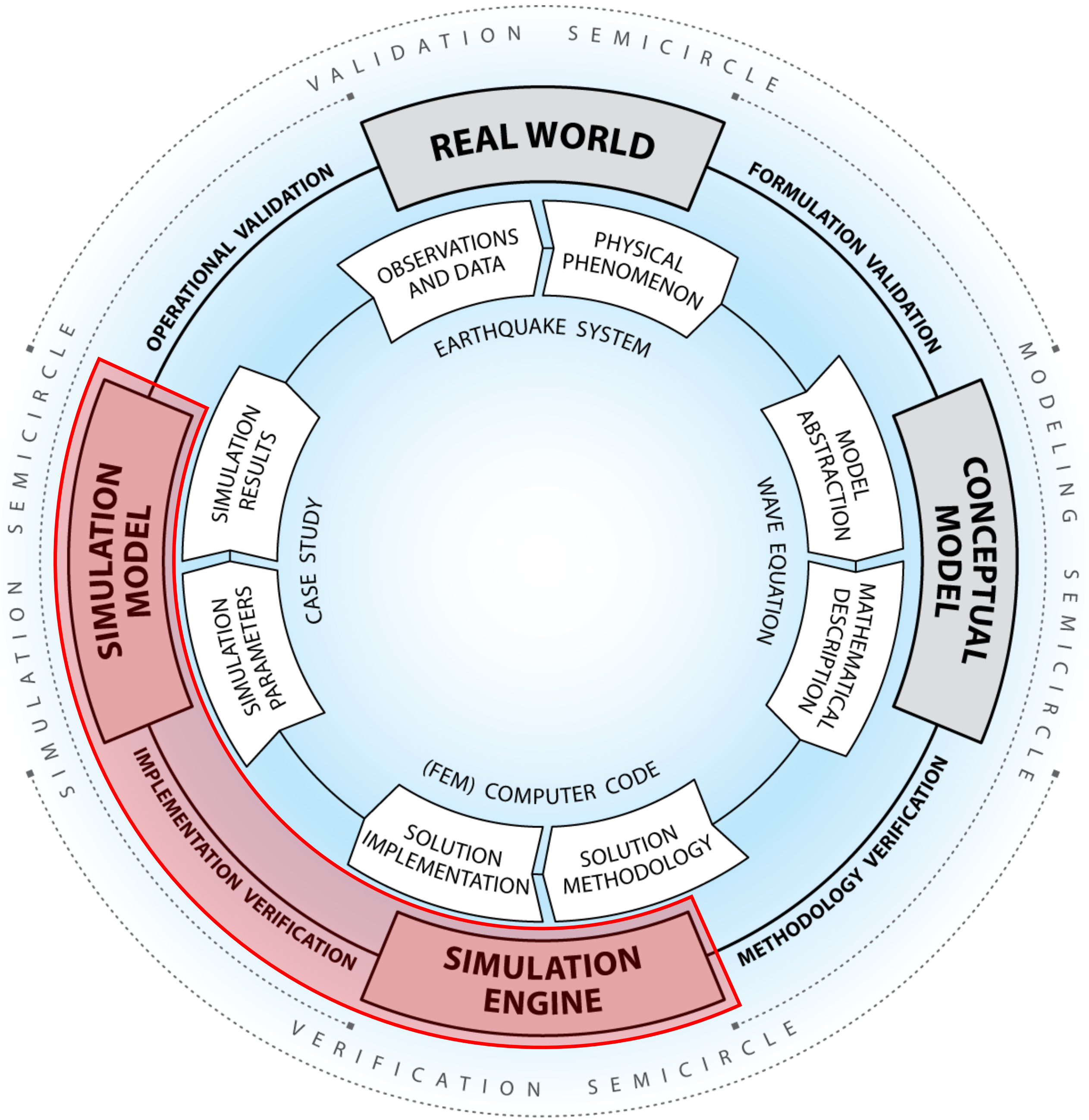
Verification and **Validation**



R. Taborda (2008)

Operational **Validation**

- Level of agreement between synthetics and actual data
- Comparison of simulations with observations



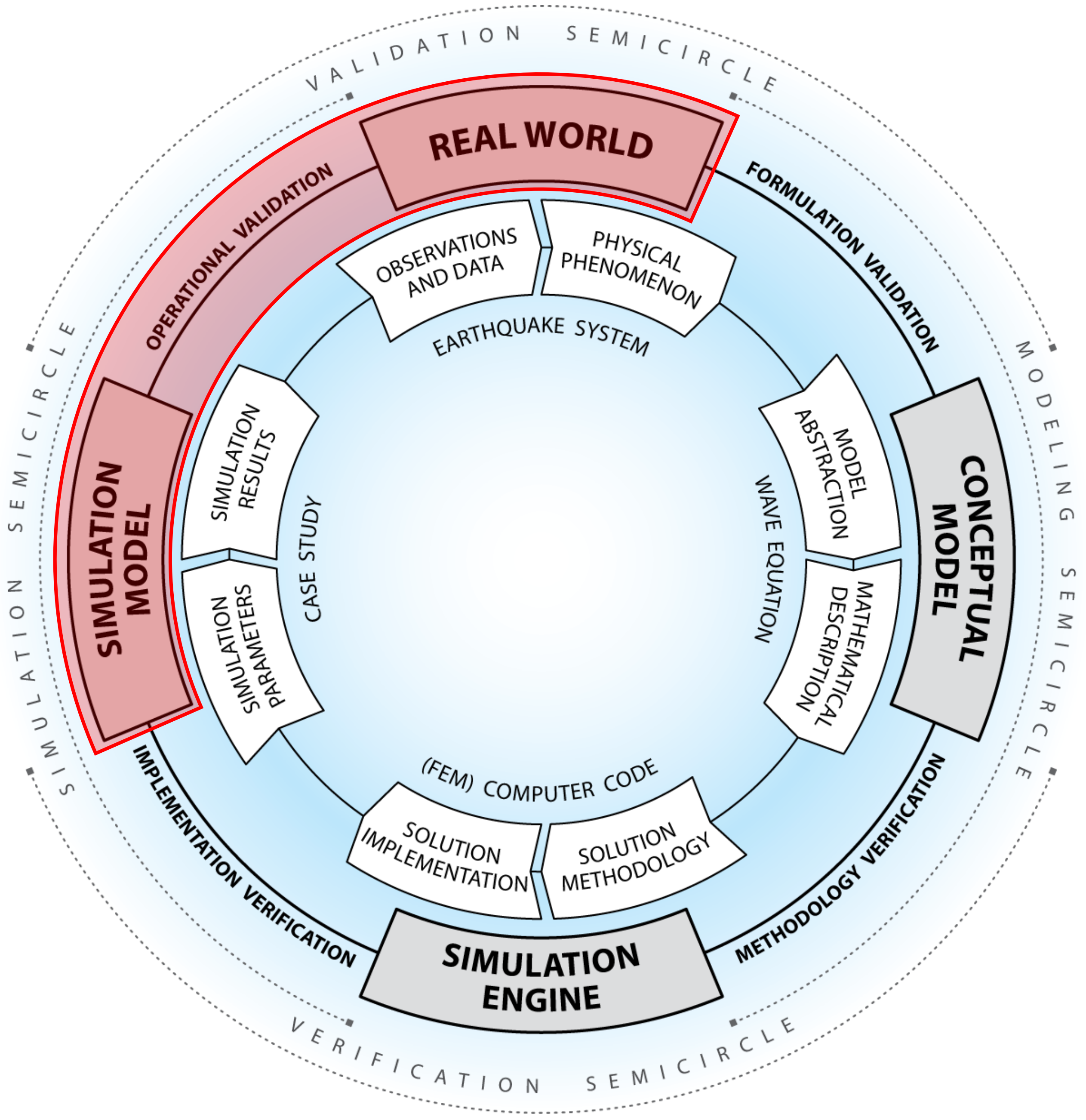
Implementation **Verification**

- Correctness of the implementation of a simulation scheme
- Comparison of simulations with exact or alternative solutions

R. Taborda (2008)

Operational **Validation**

- Level of agreement between synthetics and actual data
- Comparison of simulations with observations



Implementation **Verification**

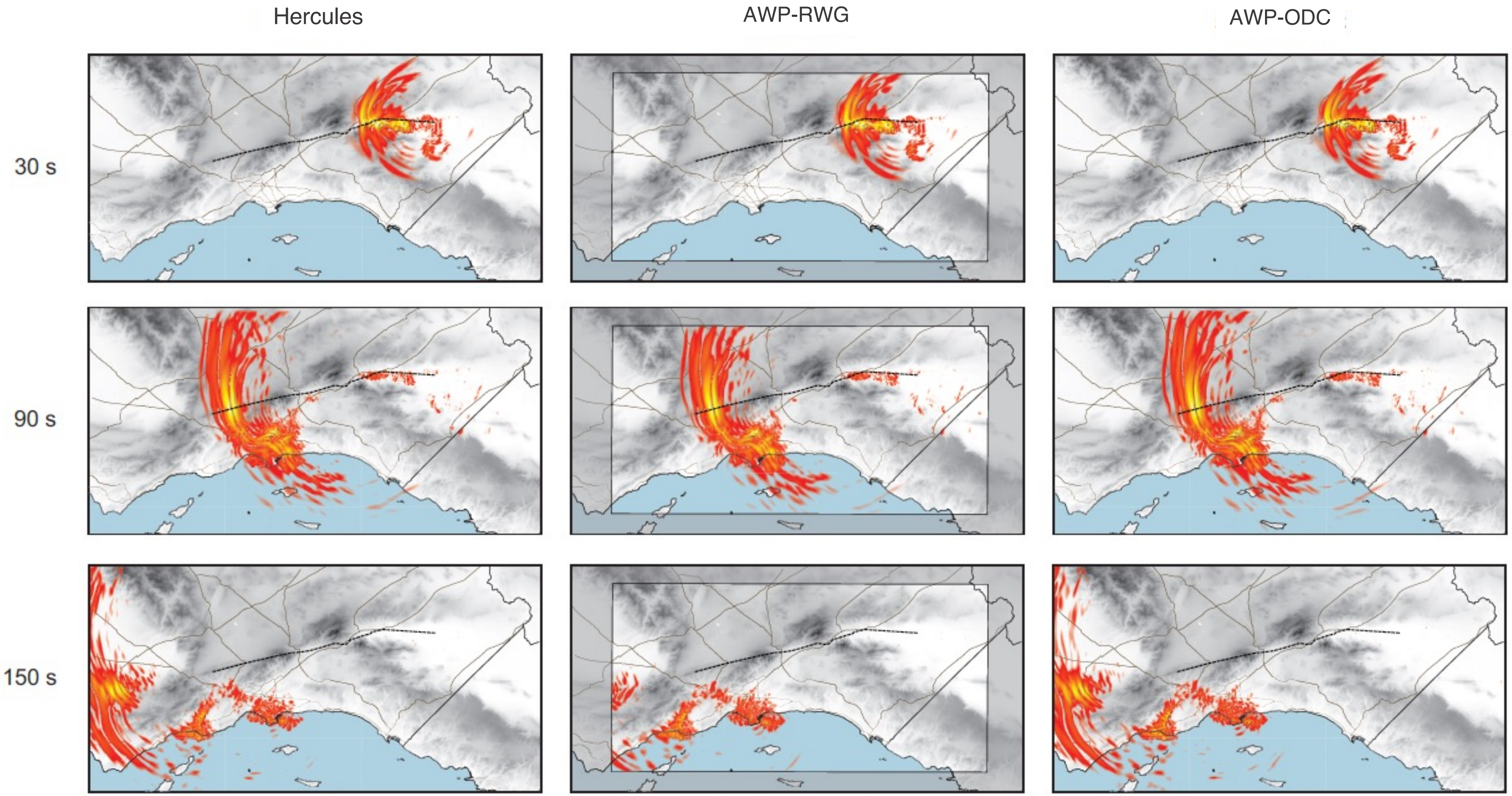
- Correctness of the implementation of a simulation scheme
- Comparison of simulations with exact or alternative solutions

R. Taborda (2008)

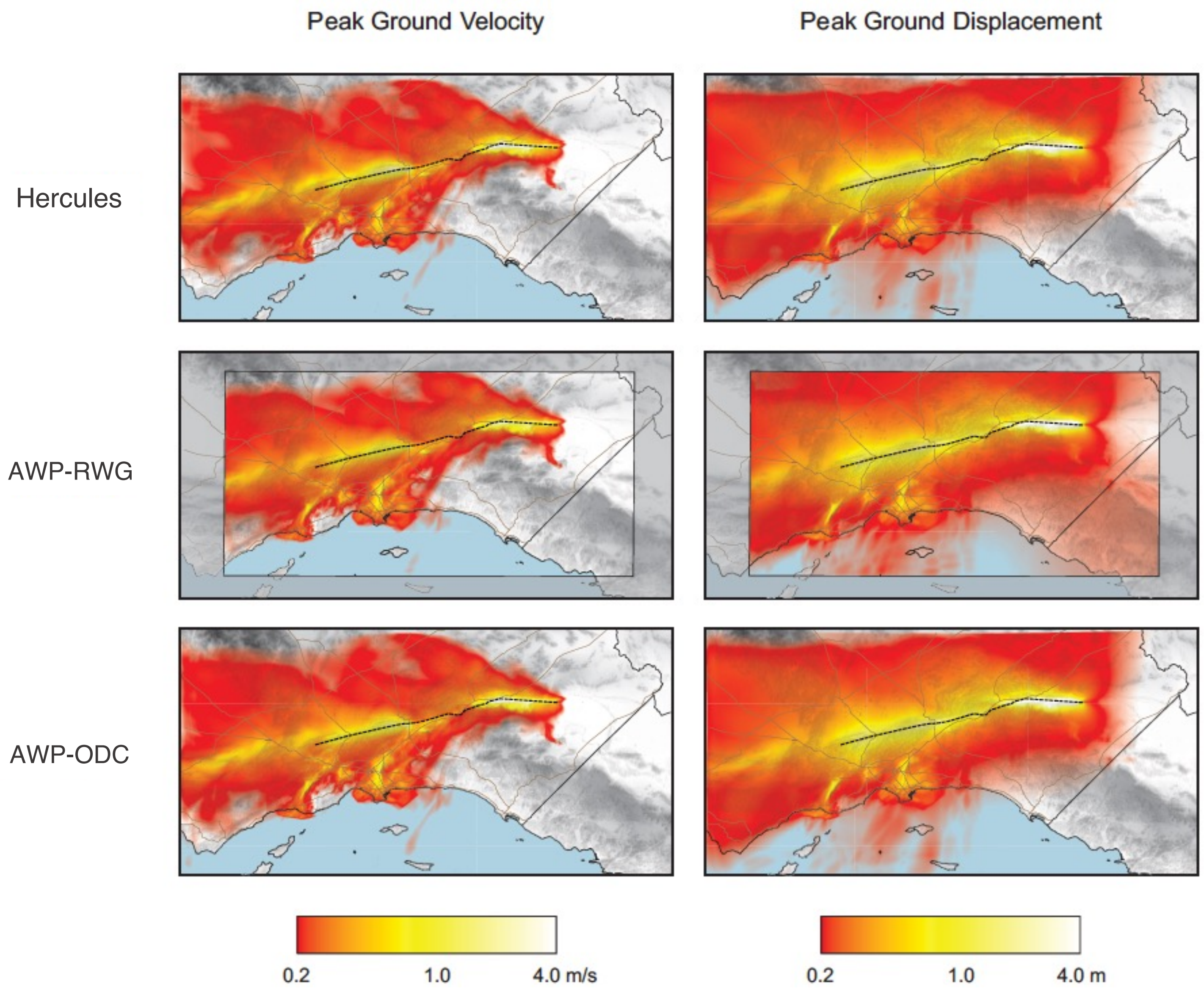
Legacy of the ShakeOut **verification** exercise

Bielak et al. (GJI, 2010)

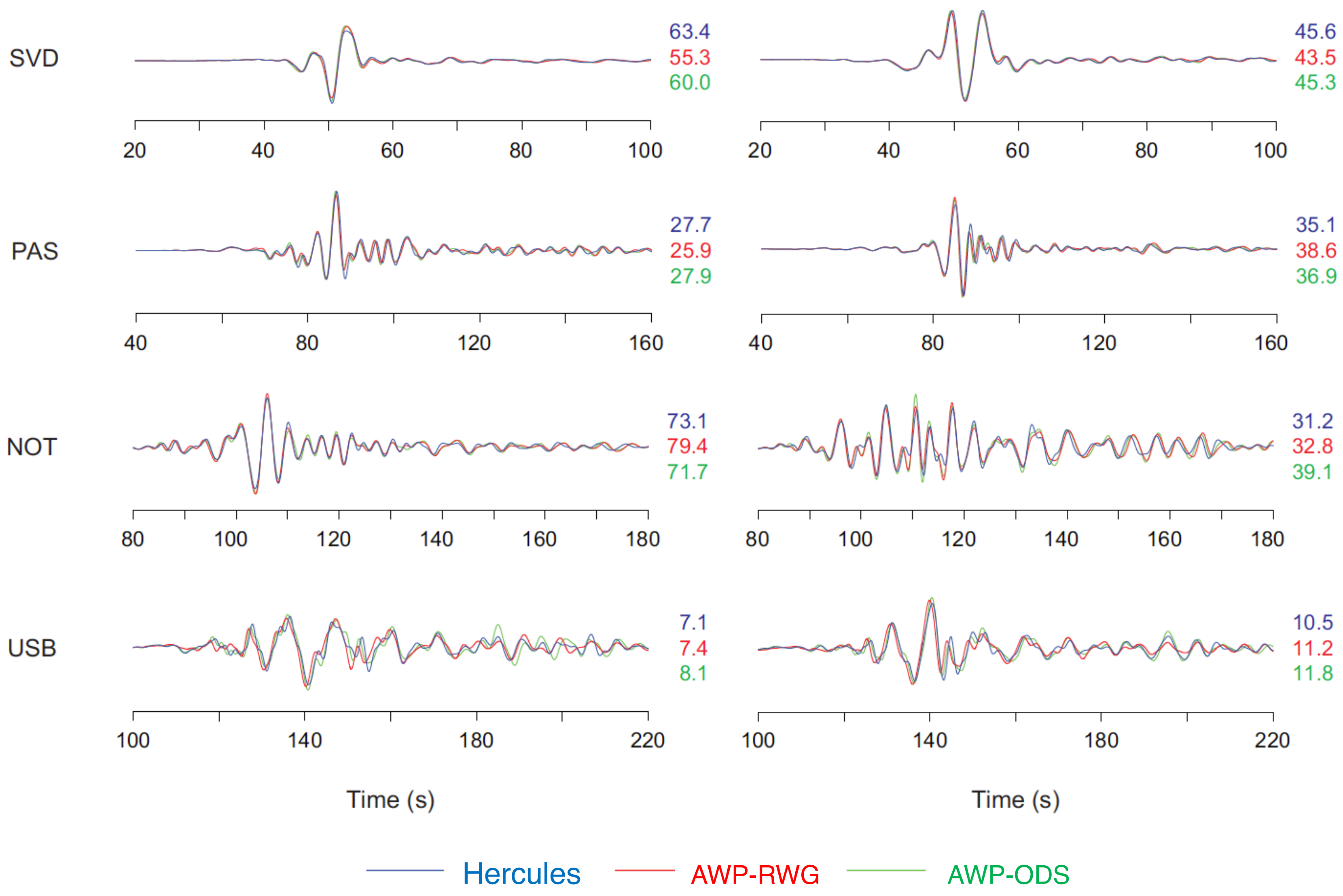
Qualitative verification



Qualitative verification



Qualitative verification



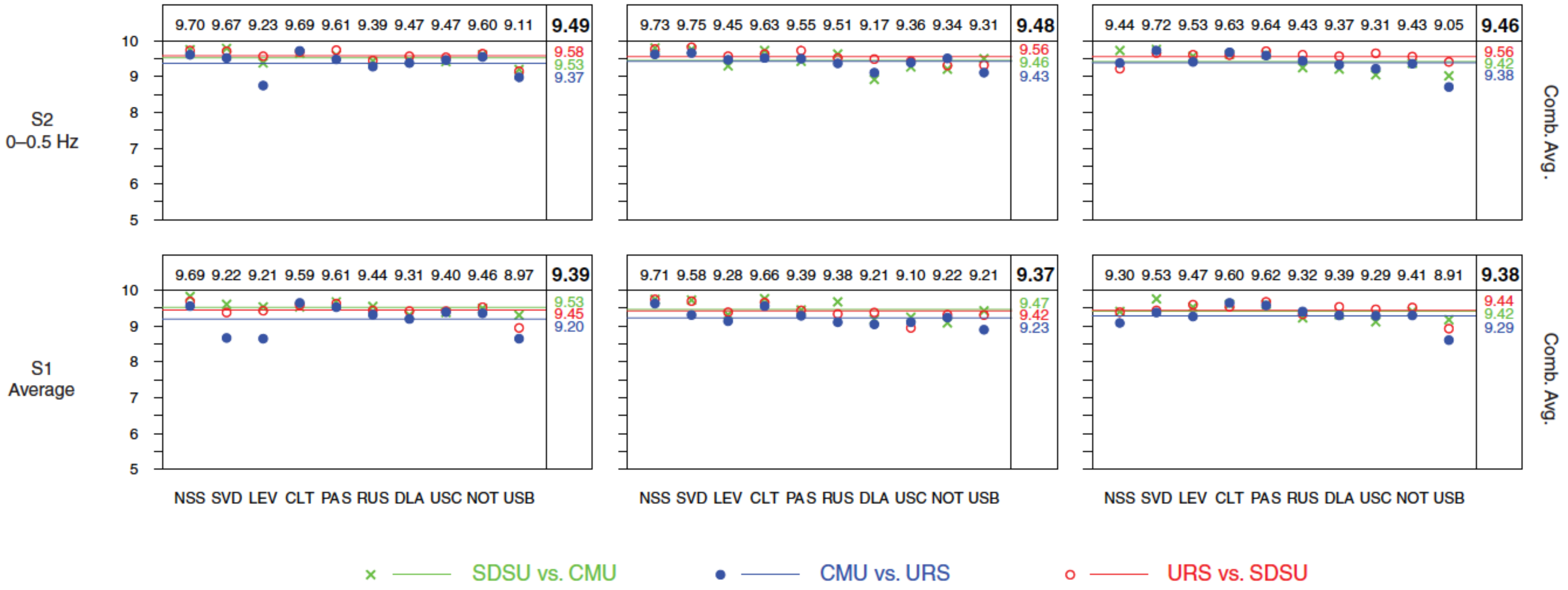
Quantitative comparisons

Goodness-of-fit (GOF) metrics

Cross Correlation	Arias Intensity	Energy Integral	Duration	8 – 10 Excellent
	PGA	PGV	PGD	6 – 8 Good
		Fourier Spectrum	Response Spectrum	4 – 6 Fair
				0 – 4 Poor

- Wiggle-by-wiggle
  - Kristekova et al. (2006, 2008)
- Signal metrics
  - Anderson (2004)
- Others

Quantitative verification



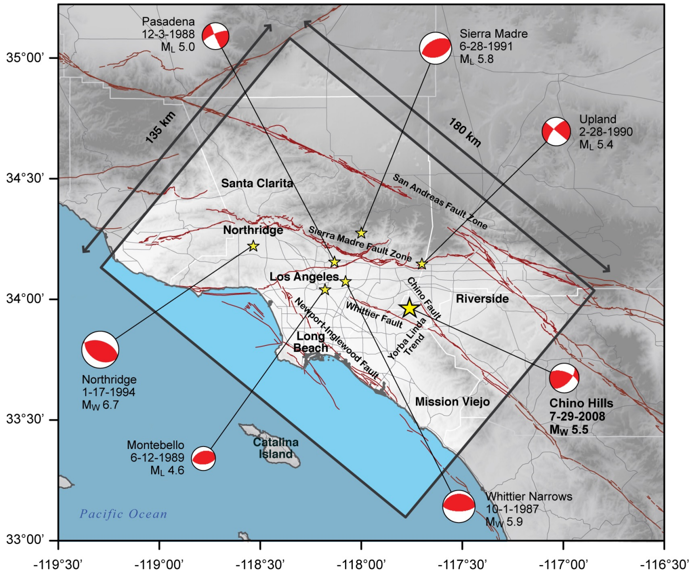
Validation

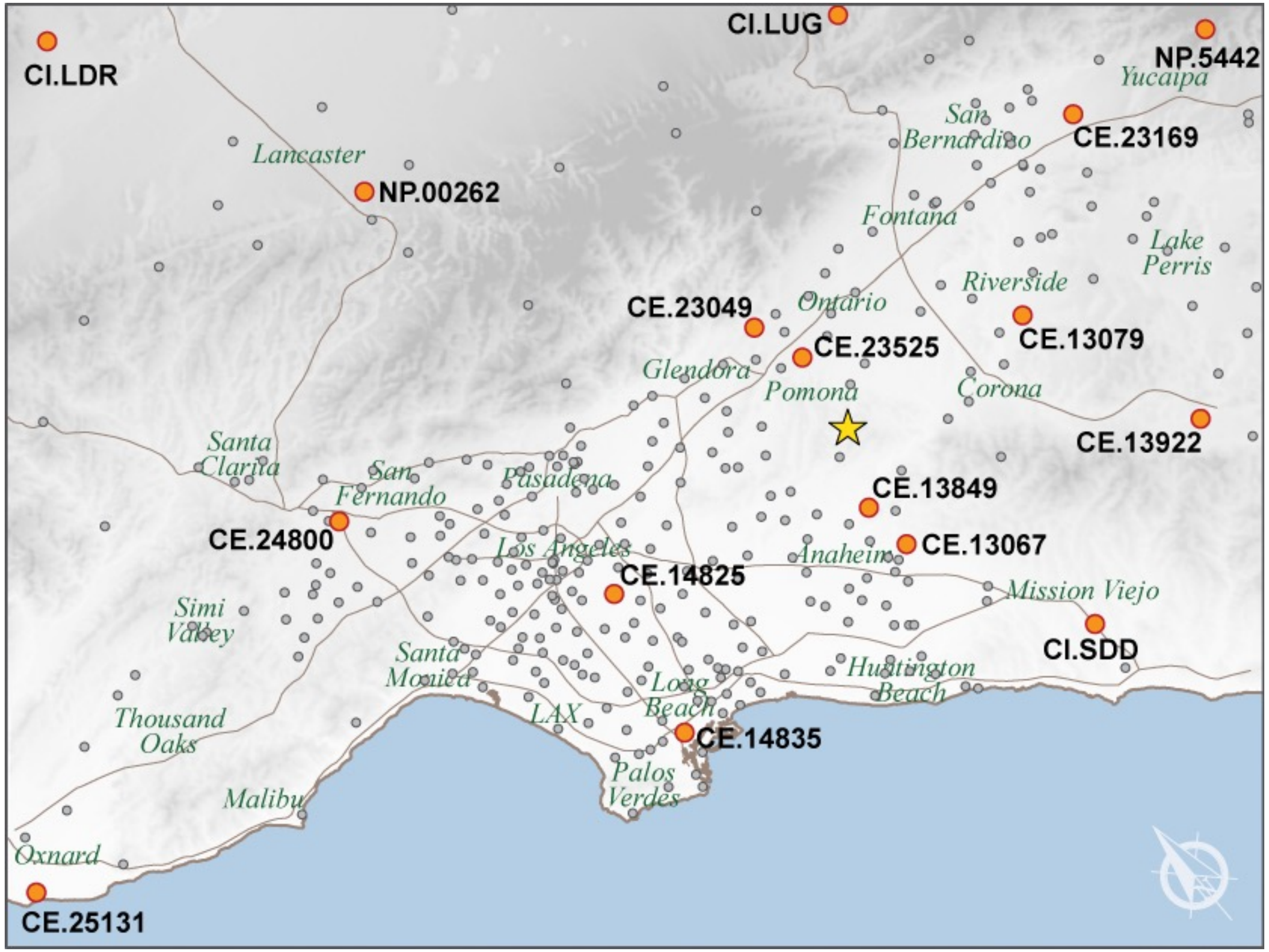
2008 Mw 5.4 Chino Hills earthquake

Taborda and Bielak (BSSA, 2013)
Taborda and Bielak (BSSA, 2014)

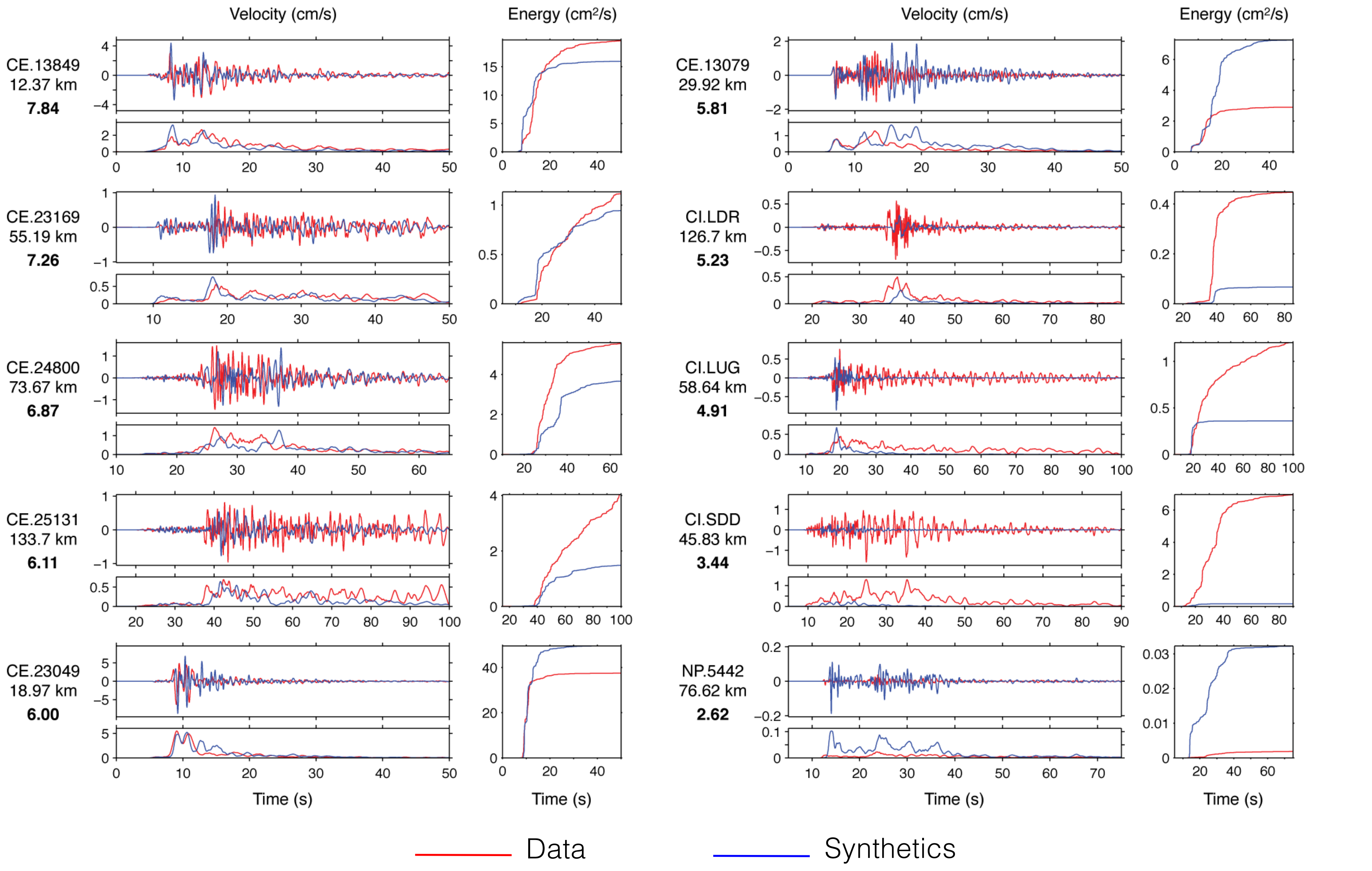
2008 Mw 5.4 Chino Hills earthquake verification and validation

- 4 Hz
- 200 m/s
- 300+ observations

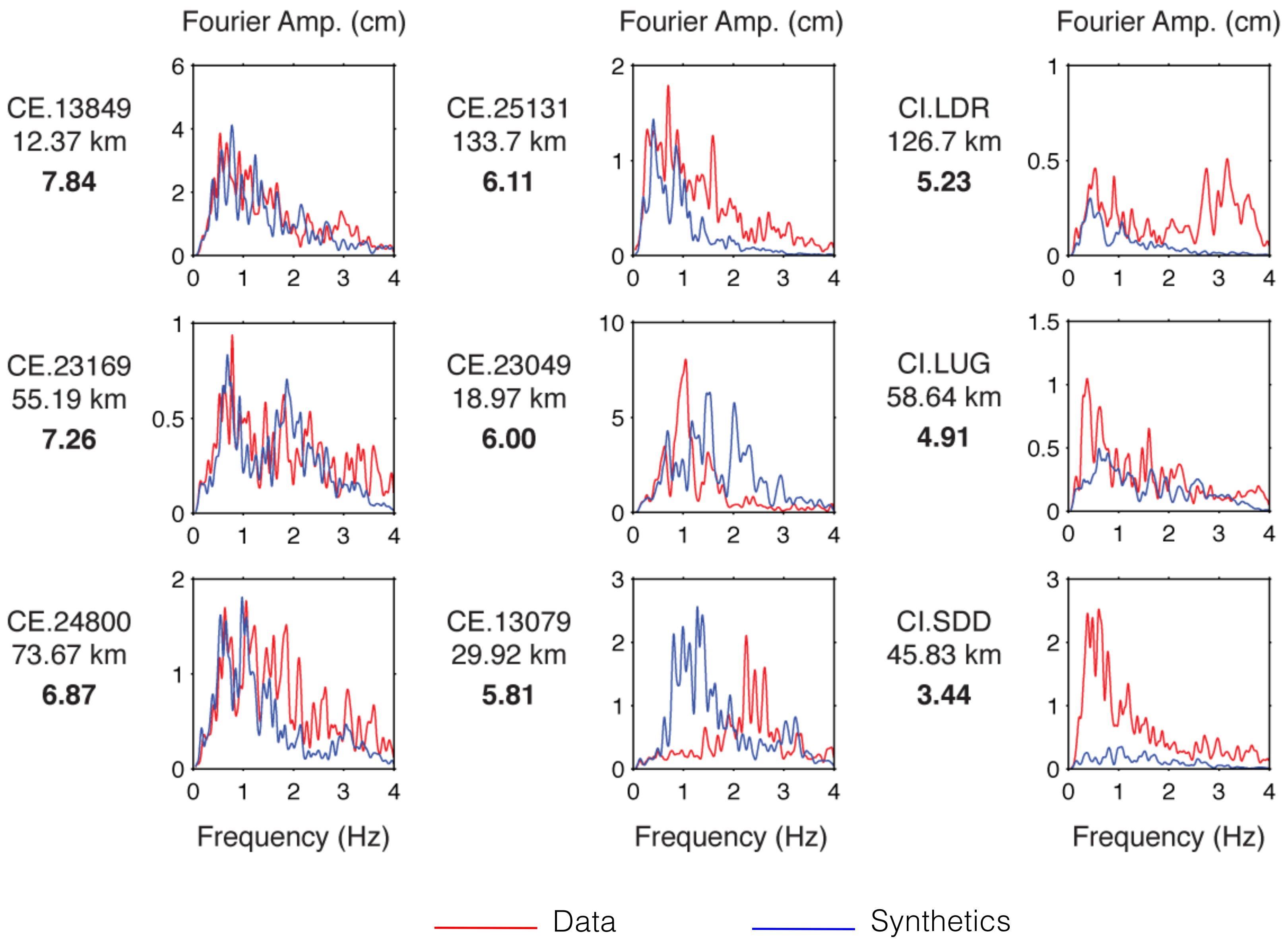




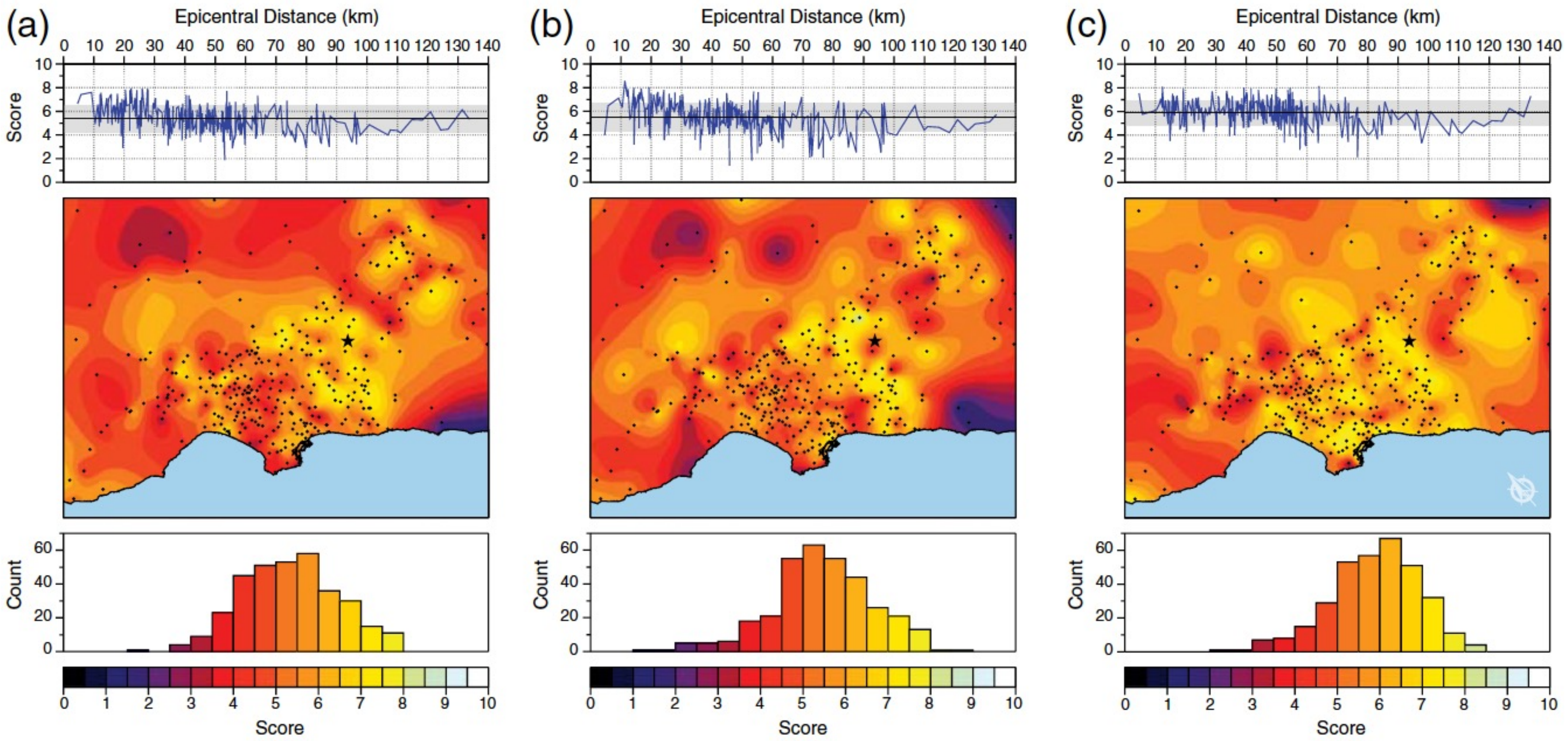
Validation: time series and energy integral



Validation: Fourier spectra



GOF maps (components of motion)

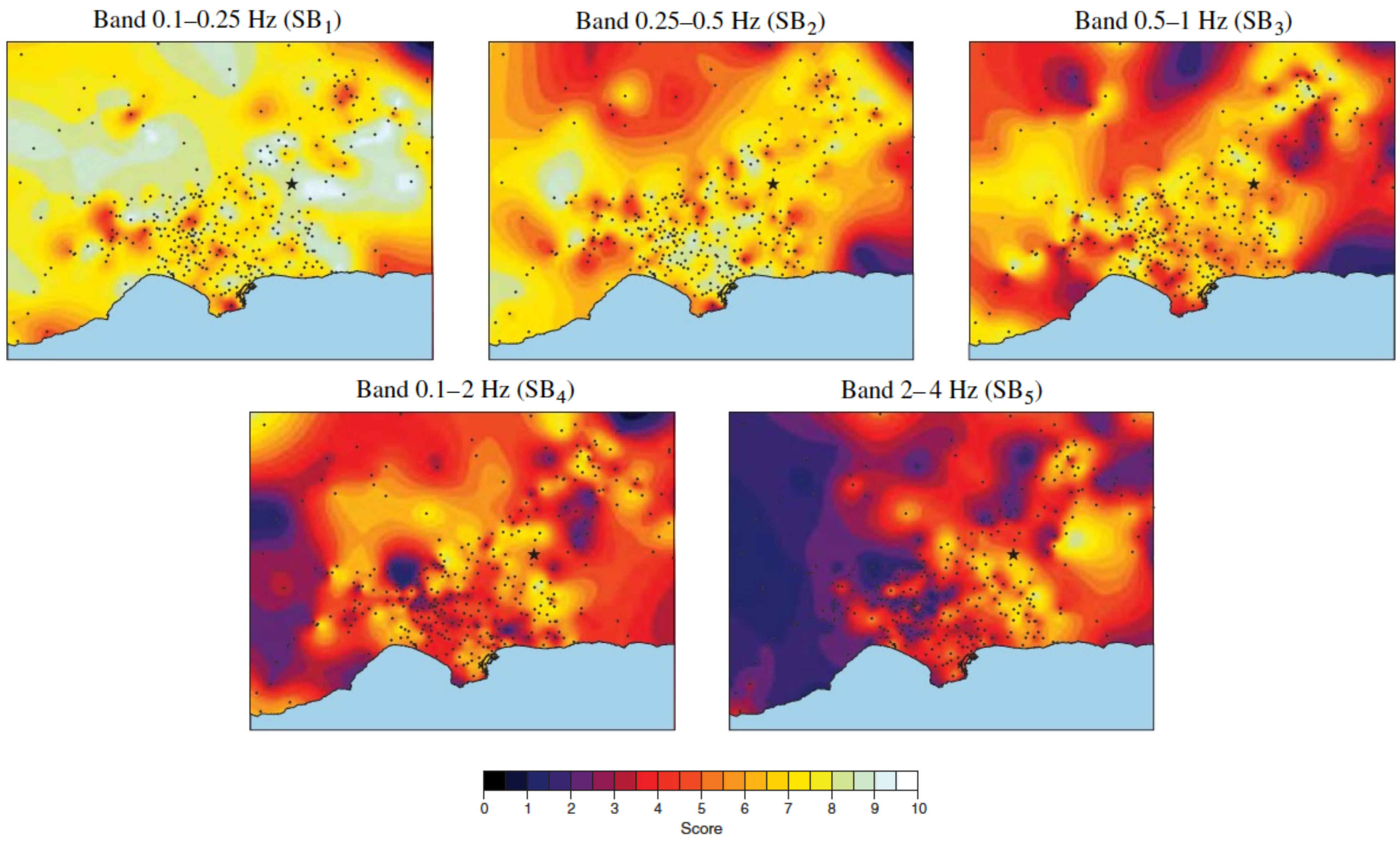


S1 in NS

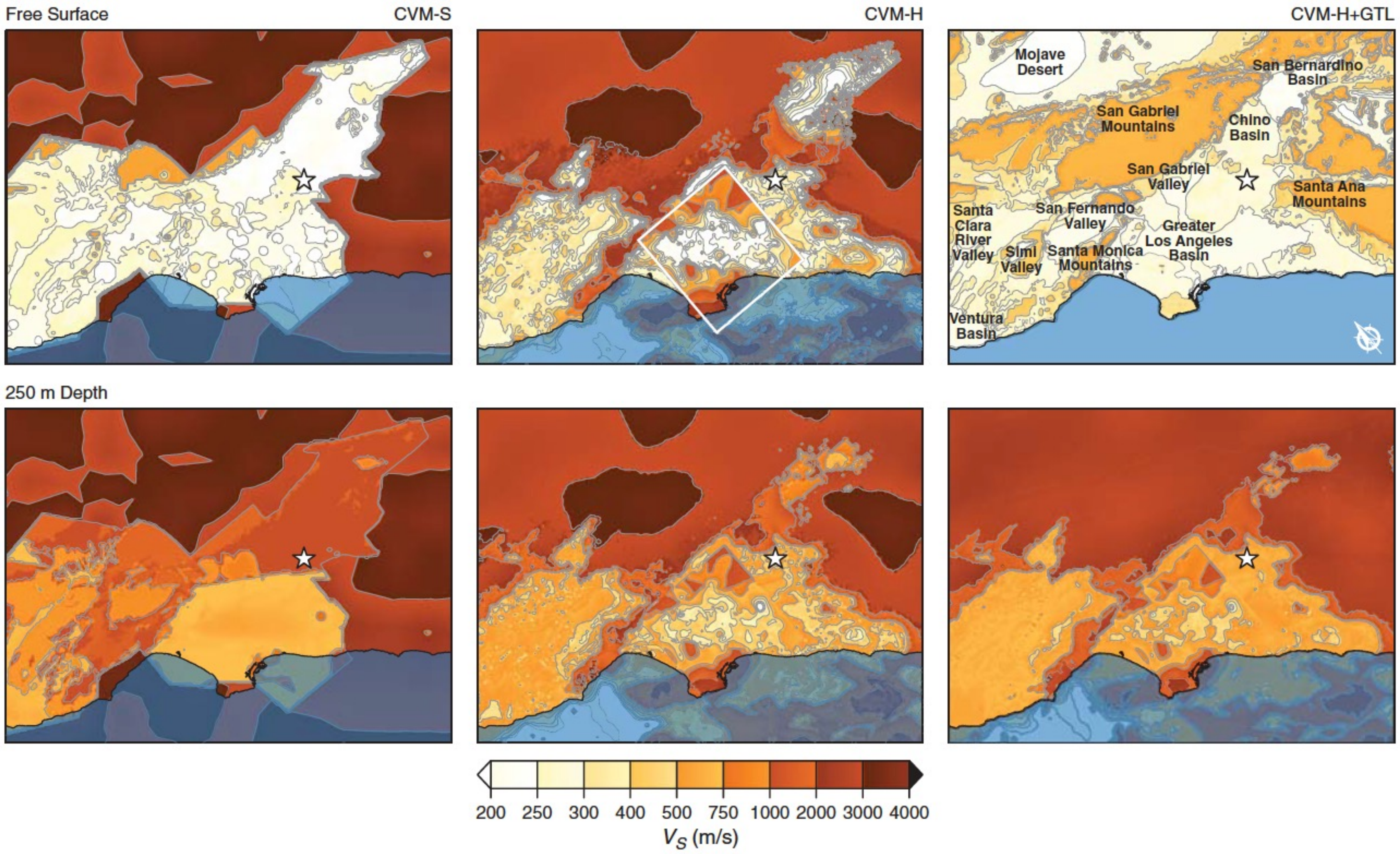
S1 in EW

S1 in UD

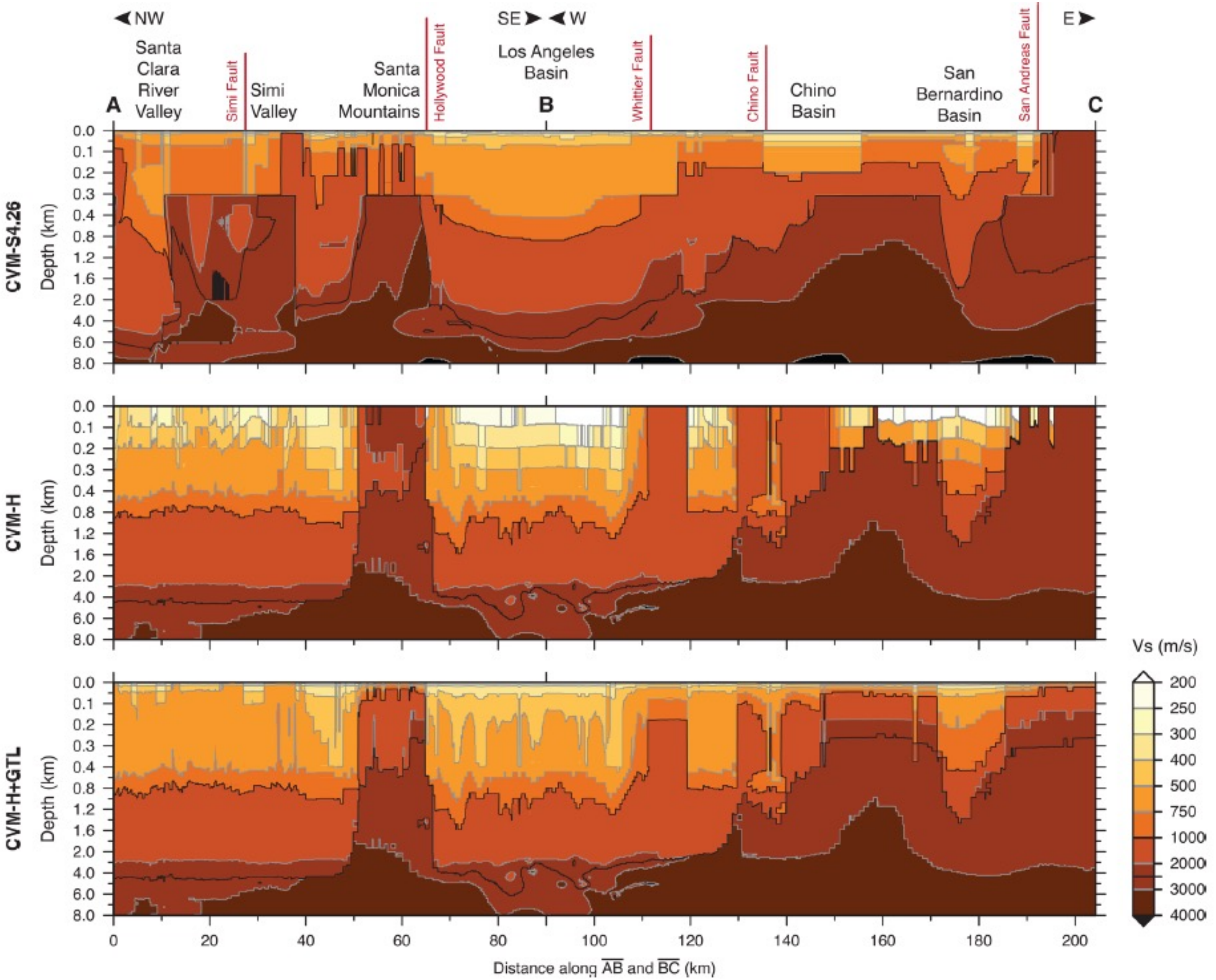
GOF maps (frequency bands)



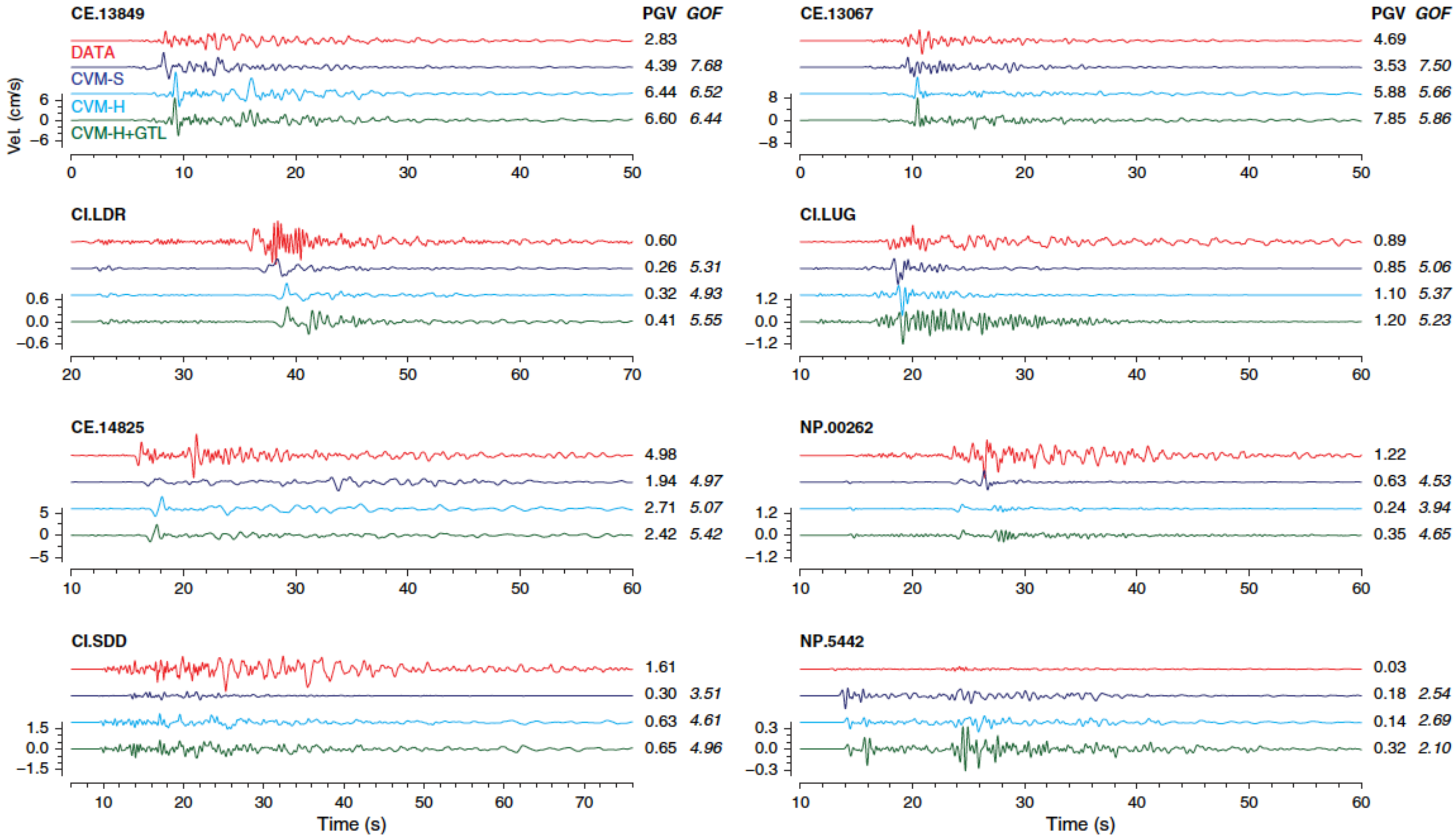
Influence of seismic velocity models



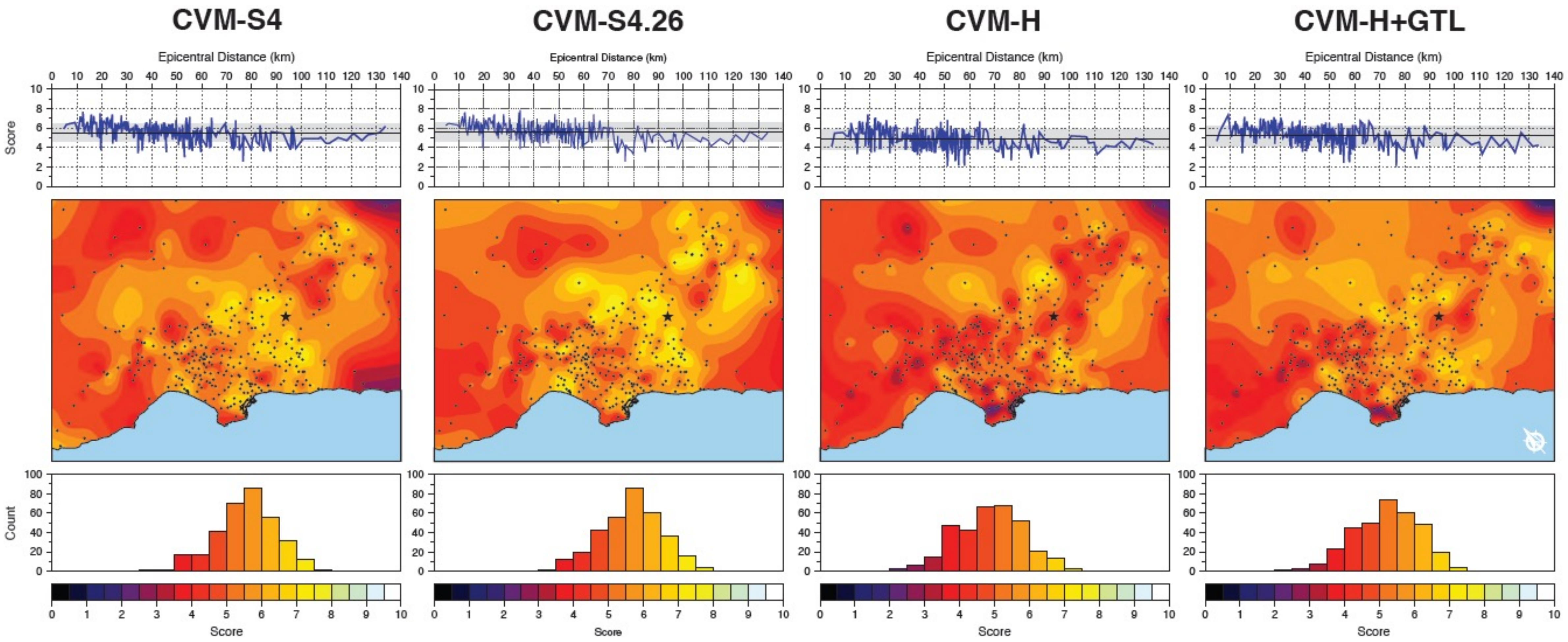
Influence of seismic velocity models



Influence of seismic velocity models on synthetics

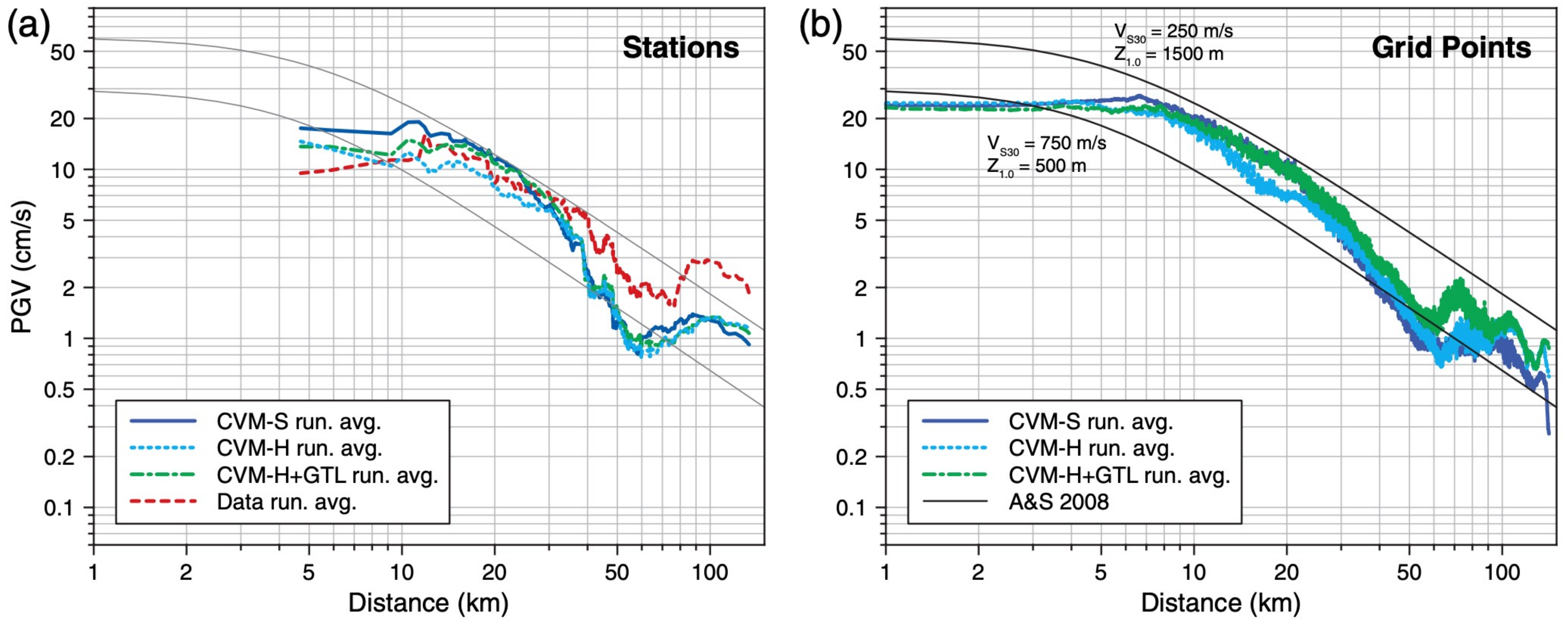


Influence of seismic velocity models on validation results

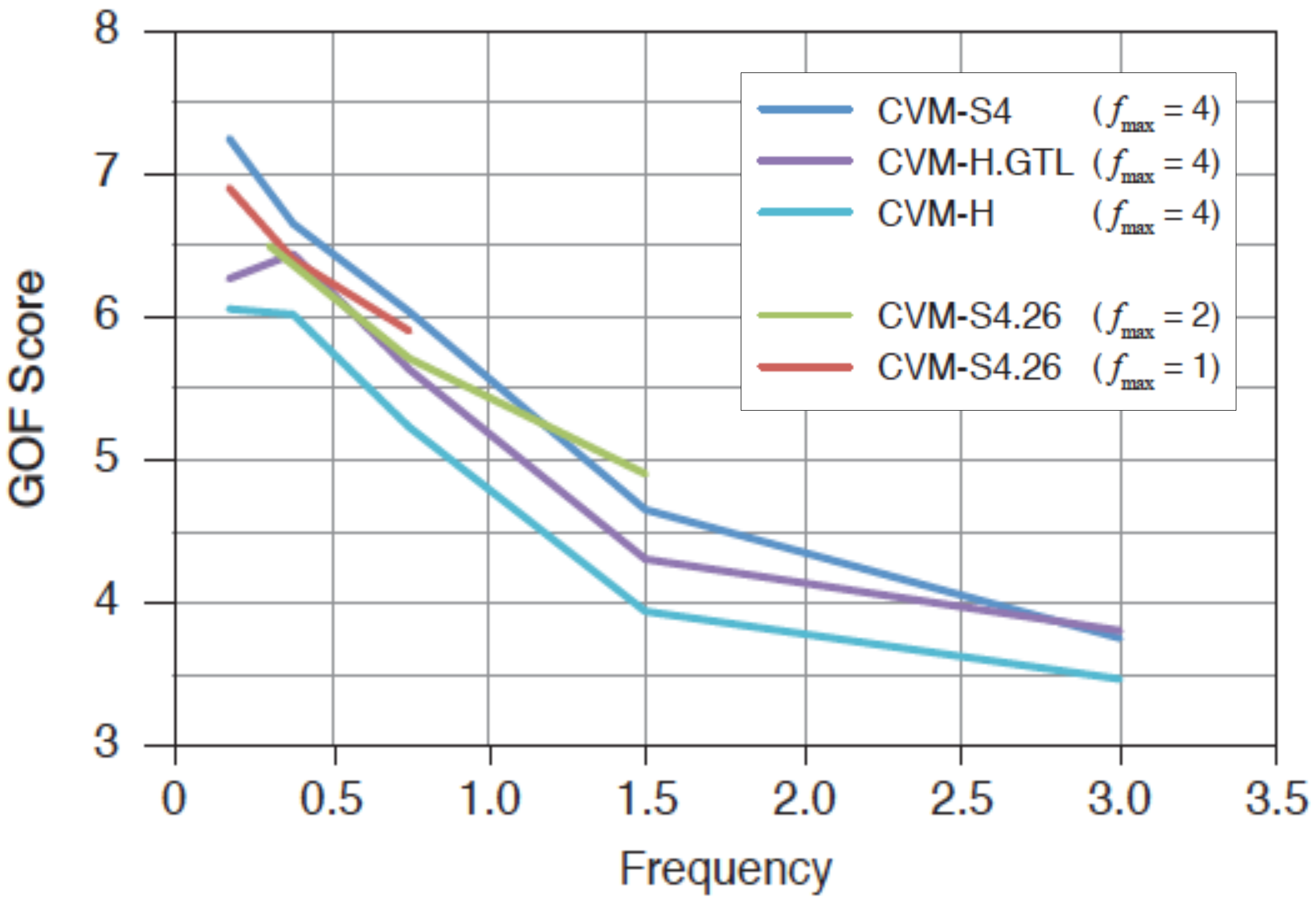


Taborda and Bielak (BSSA, 2014)

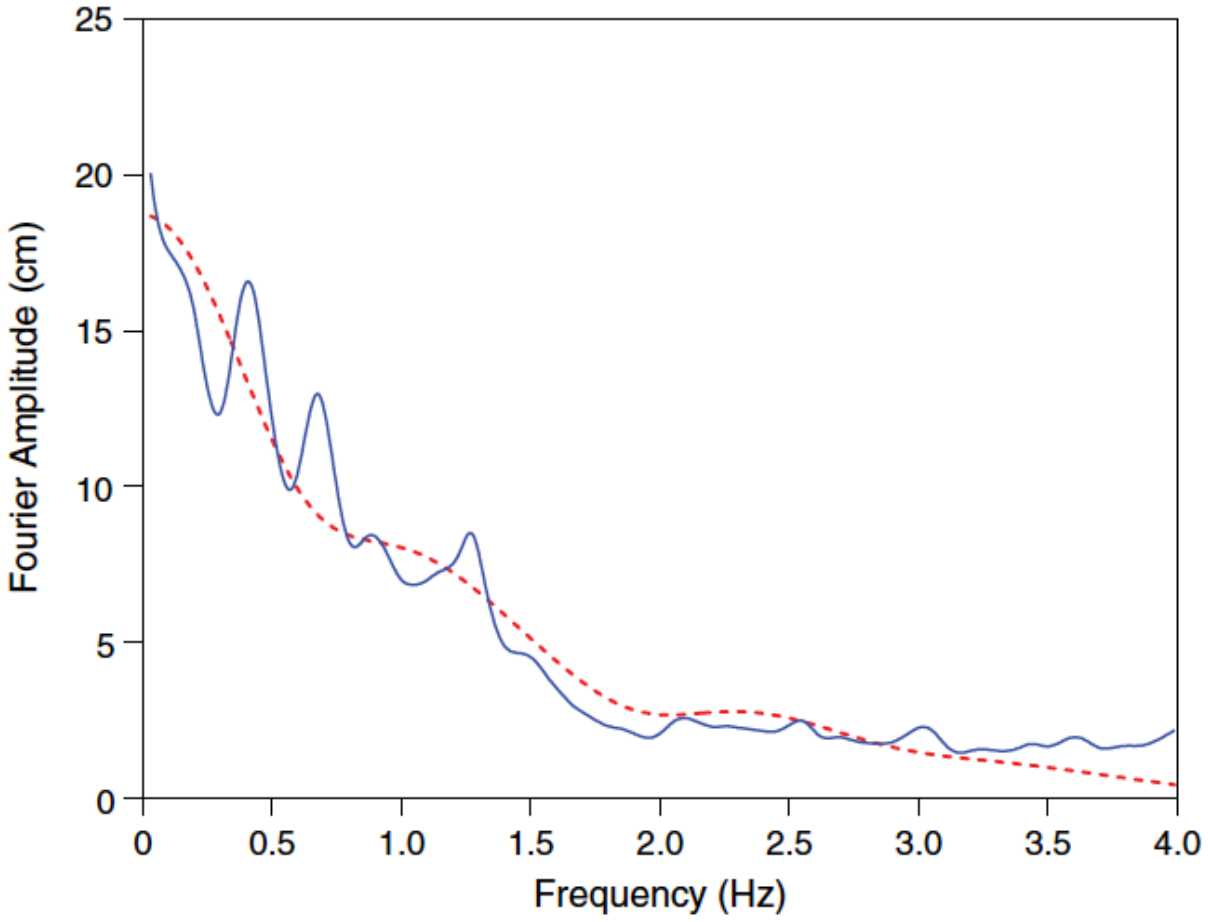
Validation in terms of attenuation



Taborda and Bielak (BSSA, 2014)



8
7
6
5
4
3
GOF Score
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Frequency
CVM-S4 (f_{max} = 4)
CVM-H.GTL (f_{max} = 4)
CVM-H (f_{max} = 4)
CVM-S4.26 (f_{max} = 2)
CVM-S4.26 (f_{max} = 1)



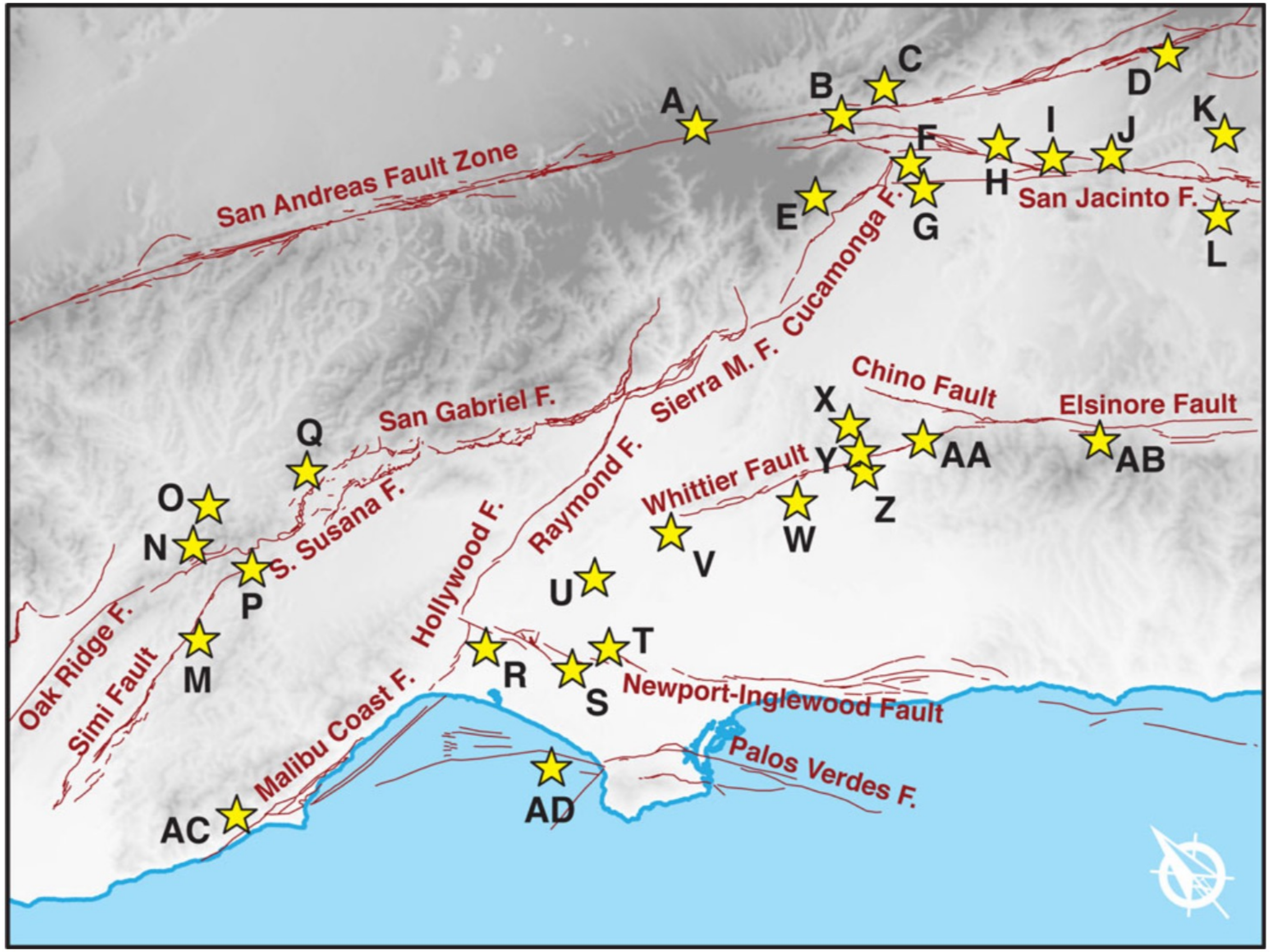
Fourier Amplitude (cm)
25
20
15
10
5
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Frequency (Hz)

Validation

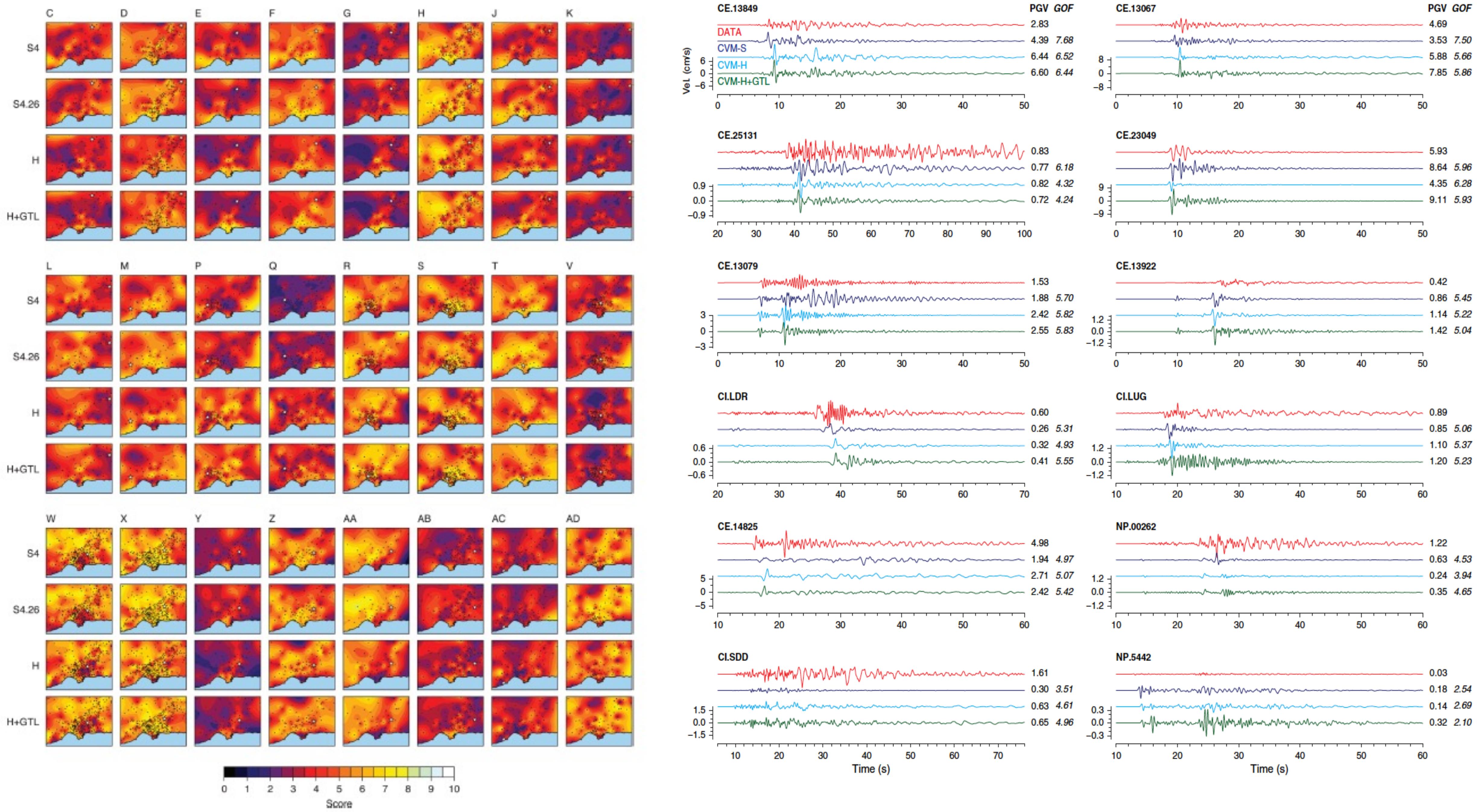
Multiple events in the greater L.A. region

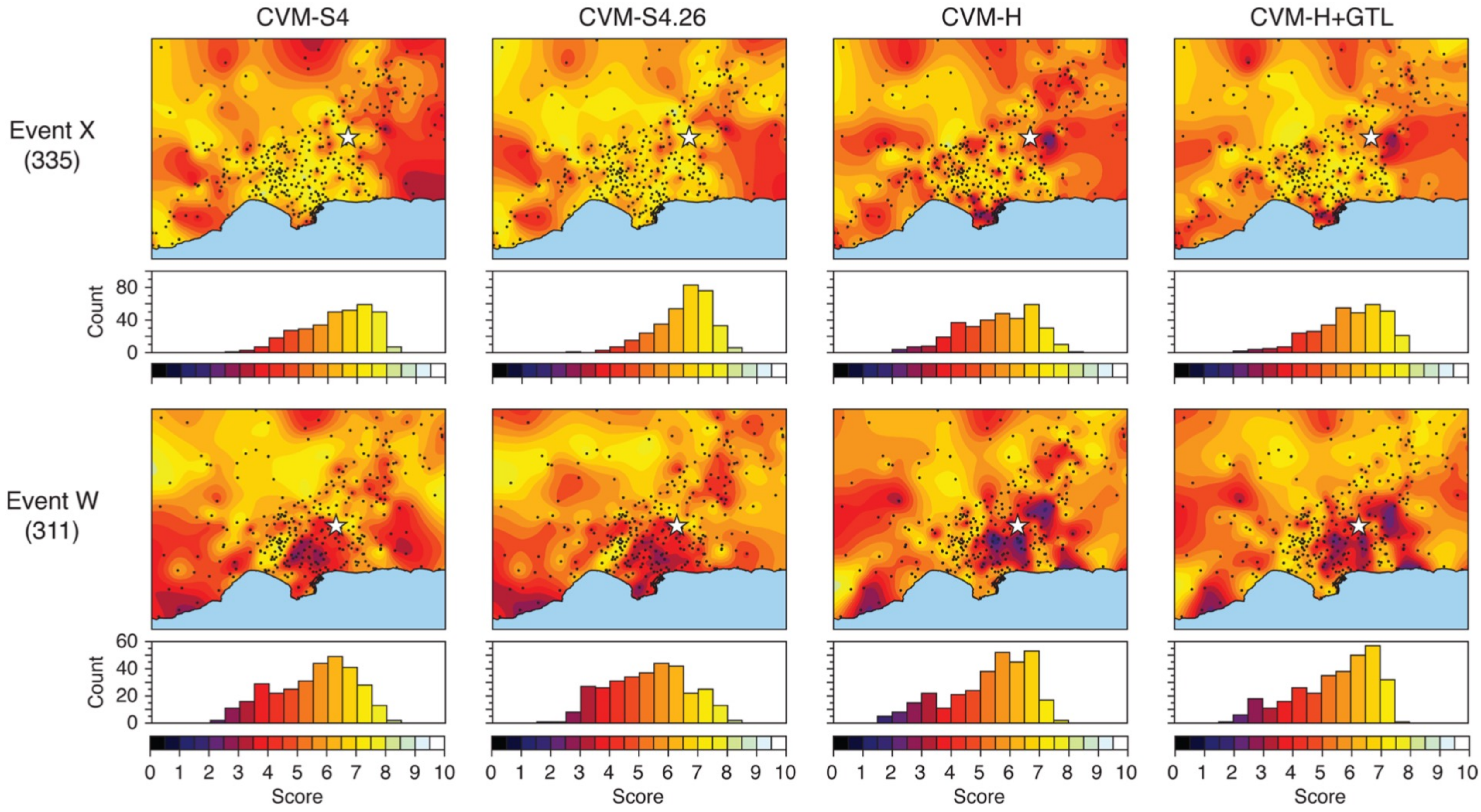
Taborda et al. (GJI, 2016)

Multiple events
and additional models
(CVM-S4, CVM-S4.26.M01, CVM-H, CVM-H+GTL)

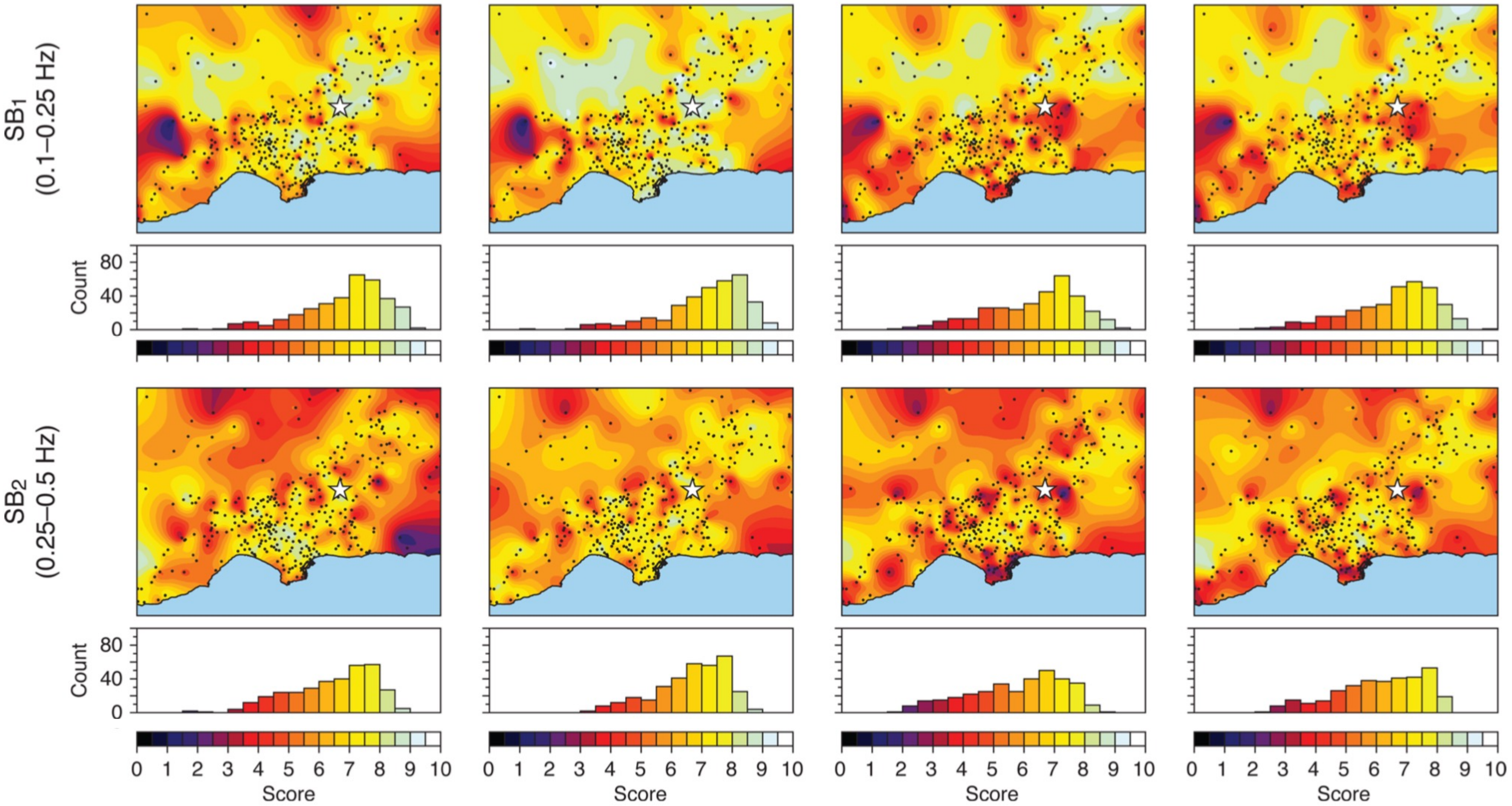


Code	Earthquake name	Mw	Depth (m)	Strike/Dip/Rake	Date (yyy/mm/dd)
A	Wrightwood	4.40	8.99	285/57/86	1998/08/20
B	NW of Devore	3.79	10.91	98/58/68	2001/07/19
C	NNE of Devore	3.72	7.18	344/69/-33	2009/08/01
D	Yucaipa	4.88	11.61	75/59/55	2005/06/16
E	N of Rancho Cucamonga	3.60	4.92	54/69/16	2006/11/04
F	2002 Fontana	3.74	6.54	233/72/-28	2002/07/25
G	2005 Fontana	4.42	4.15	222/88/-25	2005/01/06
H	San Bernardino	4.45	14.22	87/70/28	2009/01/09
I	N of Loma Linda	4.37	15.36	270/90/-6	2000/02/21
J	Redlands	4.10	8.53	33/46/-68	2010/02/13
K	2010 Beaumont	4.28	13.93	234/89/9	2010/01/16
L	2006 Beaumont	3.90	11.53	45/31/-25	2006/07/10
M	Simi Valley	3.59	13.81	234/62/60	2003/10/29
N	WSW of Valencia	3.90	14.21	83/62/57	2002/01/29
O	N of Pico Canyon	3.98	11.53	287/55/54	1999/07/22
P	Chatsworth	4.66	7.58	82/27/51	2007/08/09
Q	Newhall	3.86	3.59	236/58/33	2012/10/28
R	Beverly Hills	4.24	7.90	262/81/4	2001/09/09
S	Inglewood Area	4.70	13.86	243/60/25	2009/05/18
T	NW of Compton	3.98	31.13	116/68/71	2001/10/28
U	Downtown Los Angeles	3.77	9.53	125/49/79	1999/06/29
V	Whittier Narrows	4.44	18.85	282/36/73	2010/03/16
W	La Habra	5.10	5.00	239/70/38	2014/03/29
X	Chino Hills	5.39	14.70	47/51/32	2008/07/29
Y	2002 Yorba Linda	4.75	12.92	34/84/-10	2002/09/03
Z	2009 Yorba Linda	3.98	4.23	208/65/26	2009/04/24
AA	ESE of Yorba Linda	3.64	3.59	56/65/37	2001/04/13
AB	Lake Elsinore	4.73	12.60	65/59/58	2007/09/02
AC	Westlake Village	4.42	14.17	254/73/30	2009/05/02
AD	Hermosa Beach	3.69	11.23	57/41/54	2010/06/07

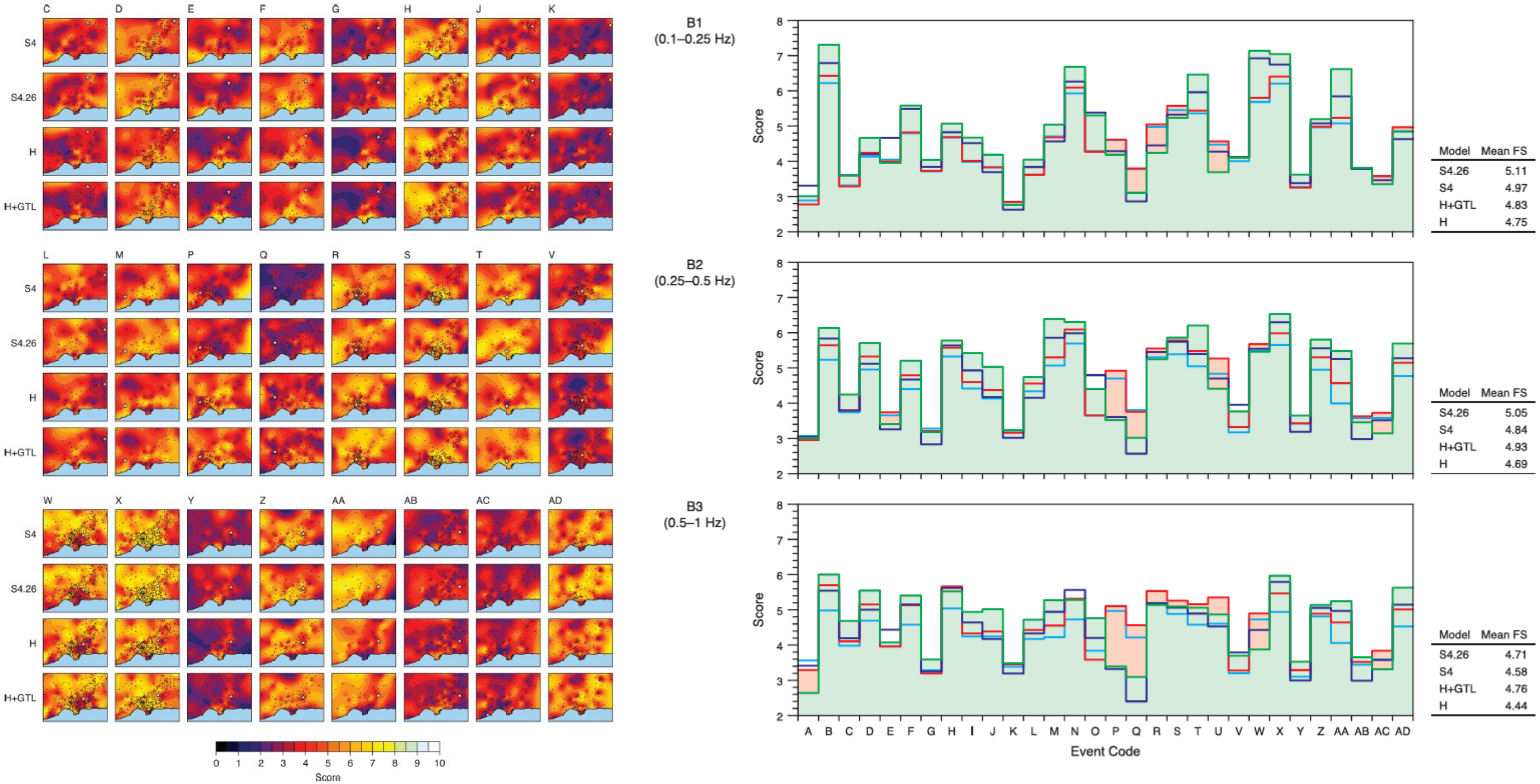

C D E F G H J K
S4
S4.26
H
H+GTL
L M P Q R S T V
W X Y Z AA AB AC AD
0 1 2 3 4 5 6 7 8 9 10
Score
PGV GOF
CE.13849
DATA 2.83
CVM-S 4.39 7.68
CVM-H 6.44 6.52
CVM-H+GTL 6.60 6.44
Vel. (cm/s)
CE.13067
4.69
3.53 7.50
5.88 5.66
7.85 5.86
CE.25131
0.83
0.77 6.18
0.82 4.32
0.72 4.24
CE.23049
5.93
8.64 5.96
4.35 6.28
9.11 5.93
CE.13079
1.53
1.88 5.70
2.42 5.82
2.55 5.83
CE.13922
0.42
0.86 5.45
1.14 5.22
1.42 5.04
CI.LDR
0.60
0.26 5.31
0.32 4.93
0.41 5.55
CI.LUG
0.89
0.85 5.06
1.10 5.37
1.20 5.23
CE.14825
4.98
1.94 4.97
2.71 5.07
2.42 5.42
NP.00262
1.22
0.63 4.53
0.24 3.94
0.35 4.65
CI.SDD
1.61
0.30 3.51
0.63 4.61
0.65 4.96
NP.5442
0.03
0.18 2.54
0.14 2.69
0.32 2.10
Time (s)



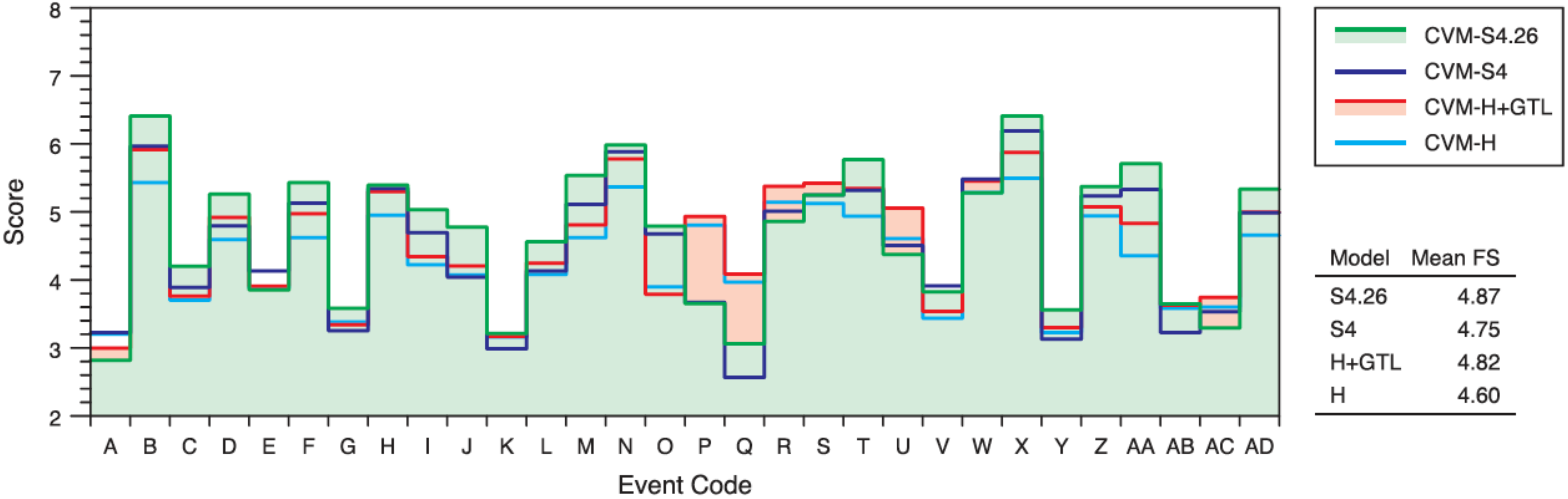
CVM-S4
CVM-S4.26
CVM-H
CVM-H+GTL
Event X
(335)
Event W
(311)
Count
0
20
40
60
80
0 1 2 3 4 5 6 7 8 9 10
Score



SB1 (0.1–0.25 Hz)
SB2 (0.25–0.5 Hz)
Count
0
40
80
0 1 2 3 4 5 6 7 8 9 10
Score



Taborda et al. (GJI, 2016)

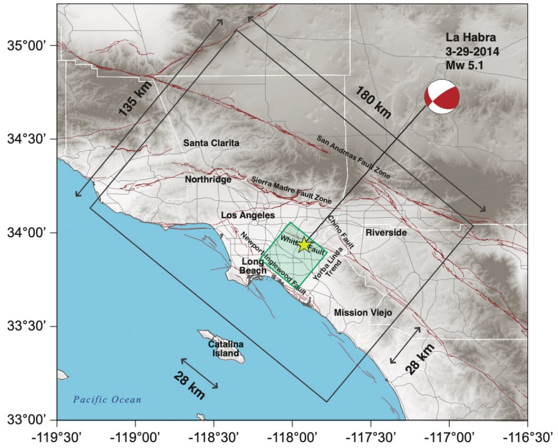


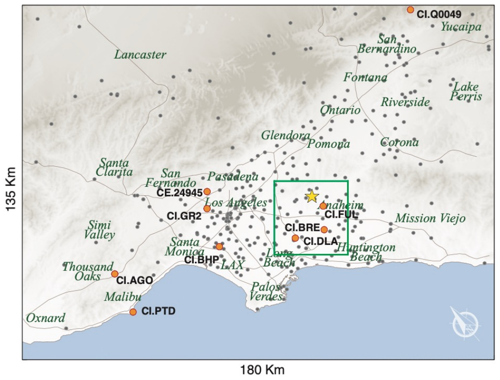
Model	Mean FS
S4.26	4.87
S4	4.75
H+GTL	4.82
H	4.60

Verification and Validation

2014 Mw 5.1 La Habra earthquake

Taborda et al. (SCEC, 2016)





Name: La Habra
Date: 03-29-2014
Time: 04:09:42.97
Magnitude: Mw 5.1

Longitude: 117.930°
Latitude: 33.922°
Depth: 5.0 km

Strike/Dip/Rake: 239/70/38
(Lee et al., 2014)

Large Simulation Domain:
180 km x 135 km x 61.875 km

Small Simulation Domain
(green box):
28 km x 28 km x 14 km

Large Domain Bounding Box:
-119.288842°, 34.120549°
-118.354016°, 35.061096°
-116.846030°, 34.025873°
-117.780976°, 33.096503°

Rotation Angle: 39.9°

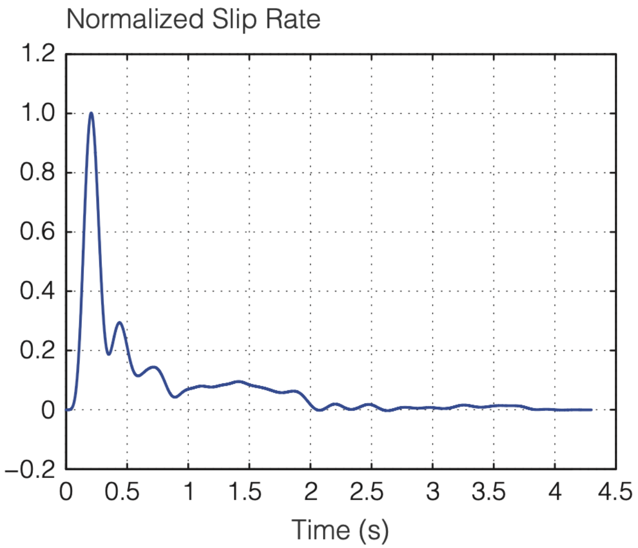
Avail. Records: 350+ stations

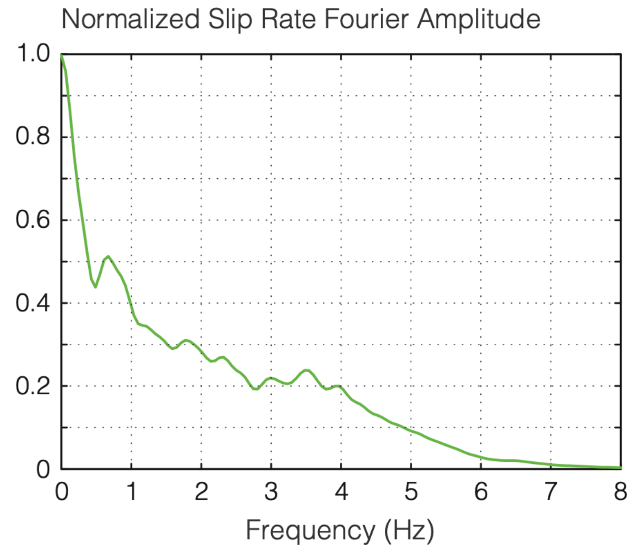
FEM Hercules
FDM AWP-ODC
FDM AWP-RWG
F-K L. Zhu

Domain Size	Velocity Model	Attenuation	Source	Code Completion
Large	Halfspace	None (Elastic)	Point Source	
Large	1D Crustal Model	None (Elastic)	Point Source	
Large	1D Crustal Model	Freq. Indep. Q	Point Source	
Large	1D Crustal Model	Freq. Dep. Q	Point Source	
Large	3D Crustal Model	Freq. Indep. Q	Point Source	
Small	3D Crustal Model	Freq. Indep. Q	Point Source	
Small	3D Crustal Model	Freq. Indep. Q	Finite F. (Wei)	
Small	3D Crustal Model	Freq. Indep. Q	Finite F. (G&P)	
Large	3D Crustal Model	Freq. Indep. Q	Finite Fault	
Large	3D Crustal Model	Freq. Dep. Q	Finite Fault	

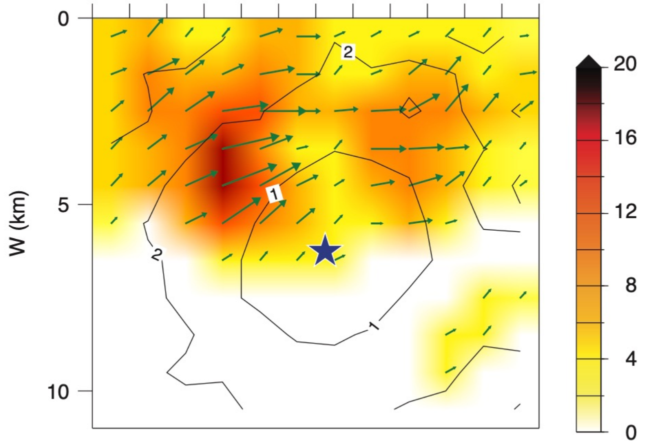
Used in validation

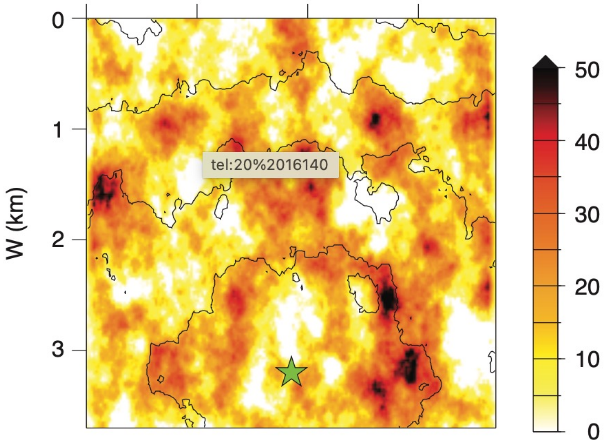
Point Source Model

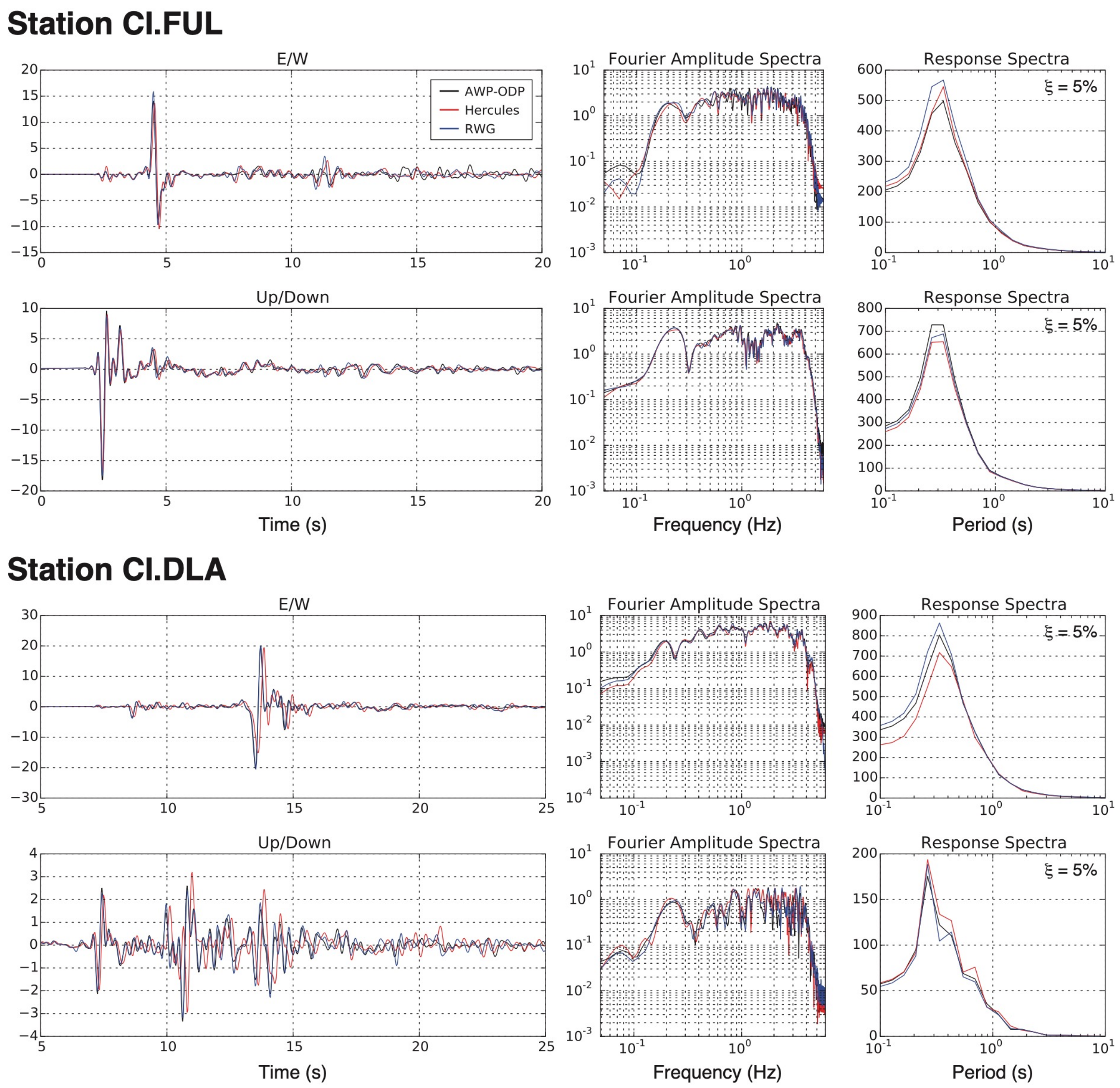




Finite Fault Models

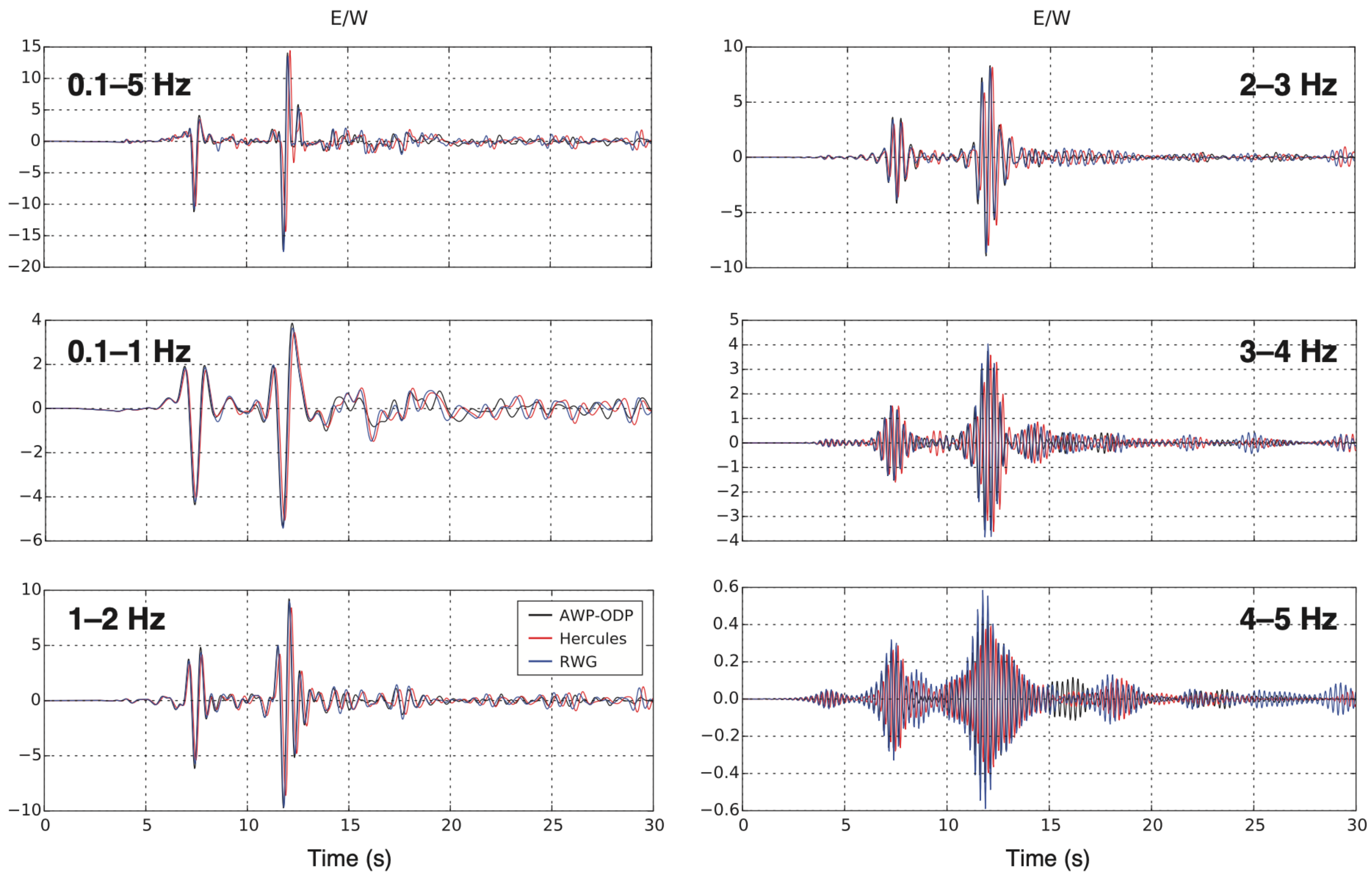


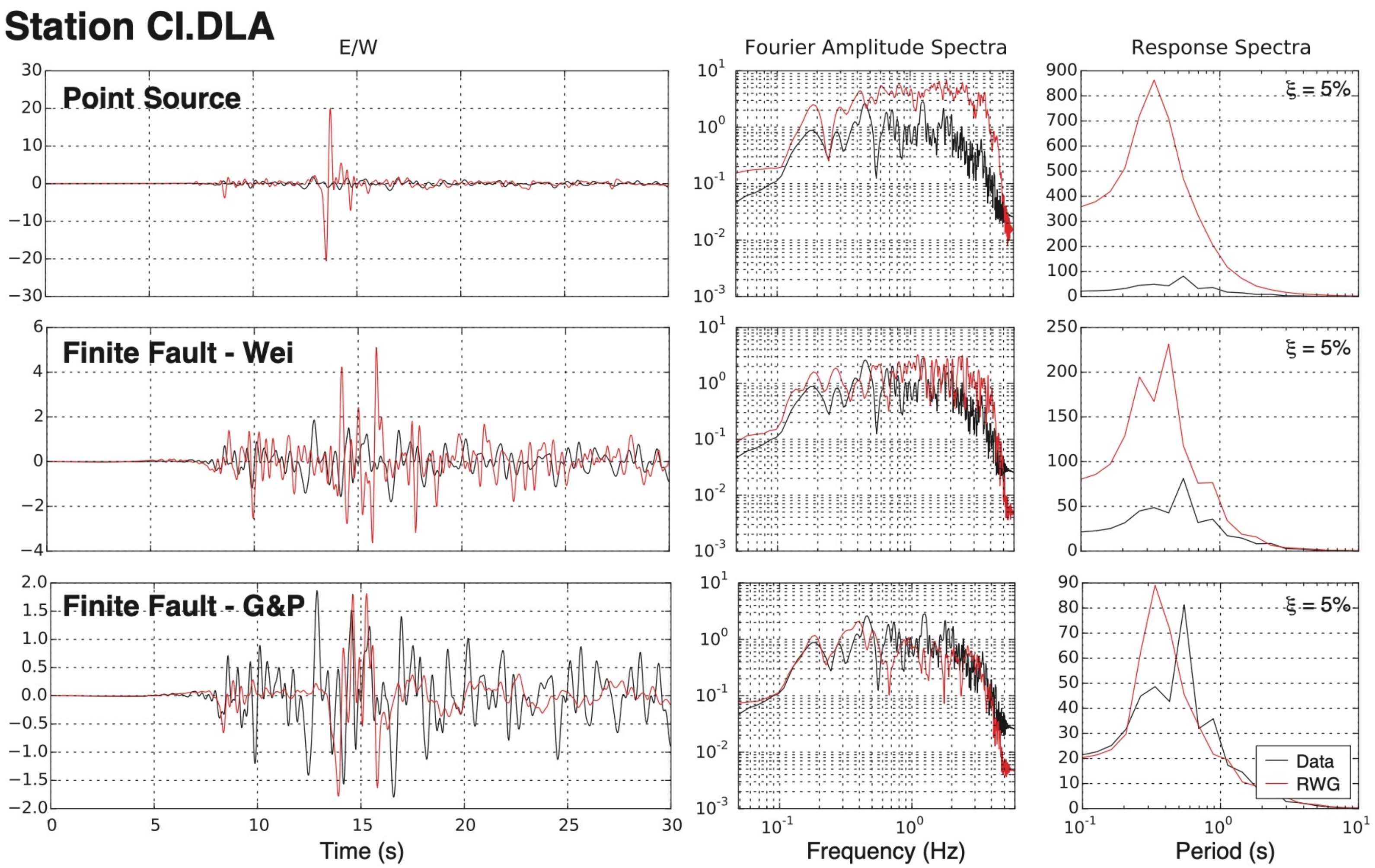




Station CI.FUL
E/W
Fourier Amplitude Spectra
Response Spectra
AWP-ODP
Hercules
RWG
ξ = 5%
Up/Down
Time (s)
Frequency (Hz)
Period (s)
Station CI.DLA

Station CI.BRE – Filtered





Station CI.DLA
E/W
Fourier Amplitude Spectra
Response Spectra
Point Source
Finite Fault - Wei
Finite Fault - G&P
ξ = 5%
Data
RWG
Time (s)
Frequency (Hz)
Period (s)

Validation

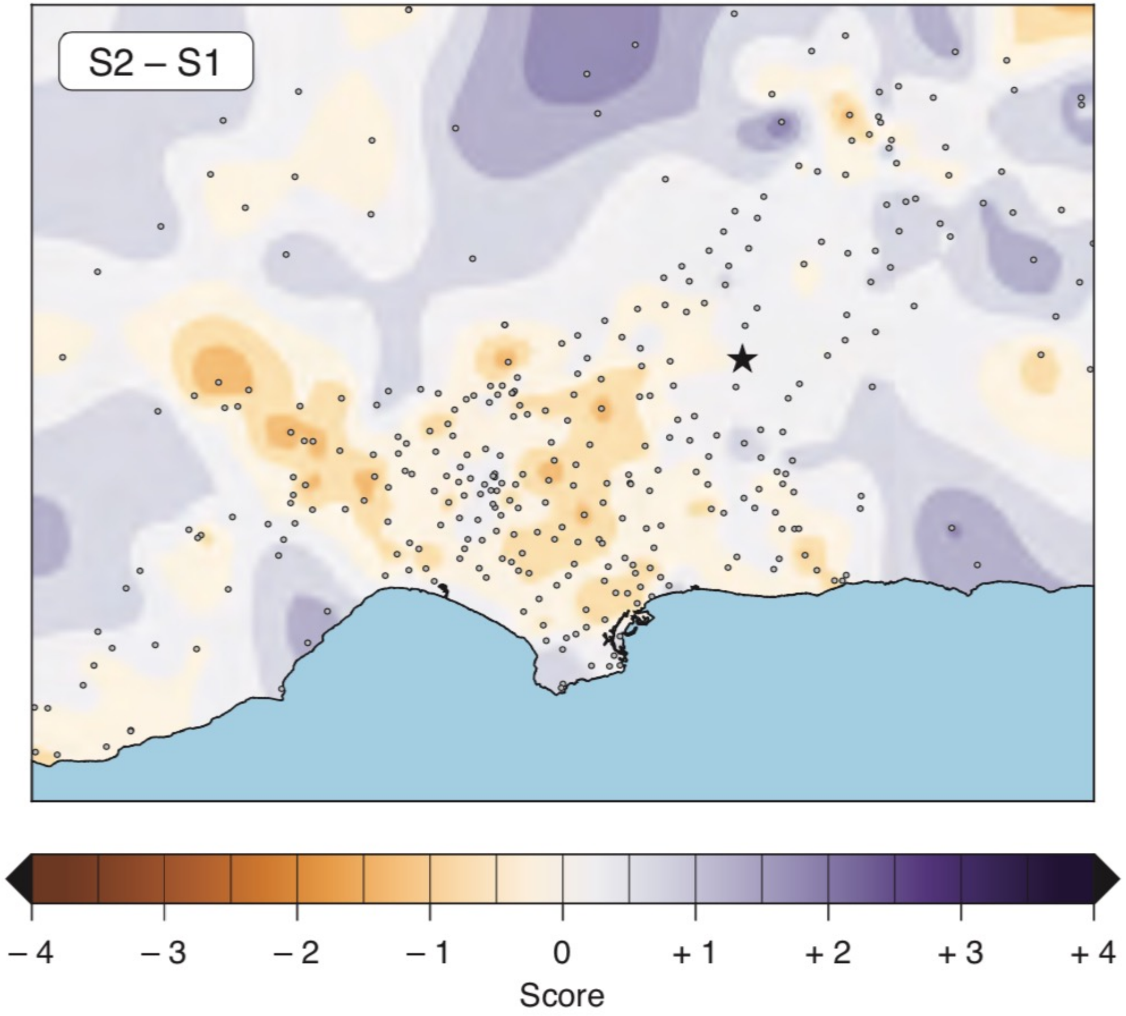
Multiple factors and complexity levels

Taborda et al. (WCEE, 2017)

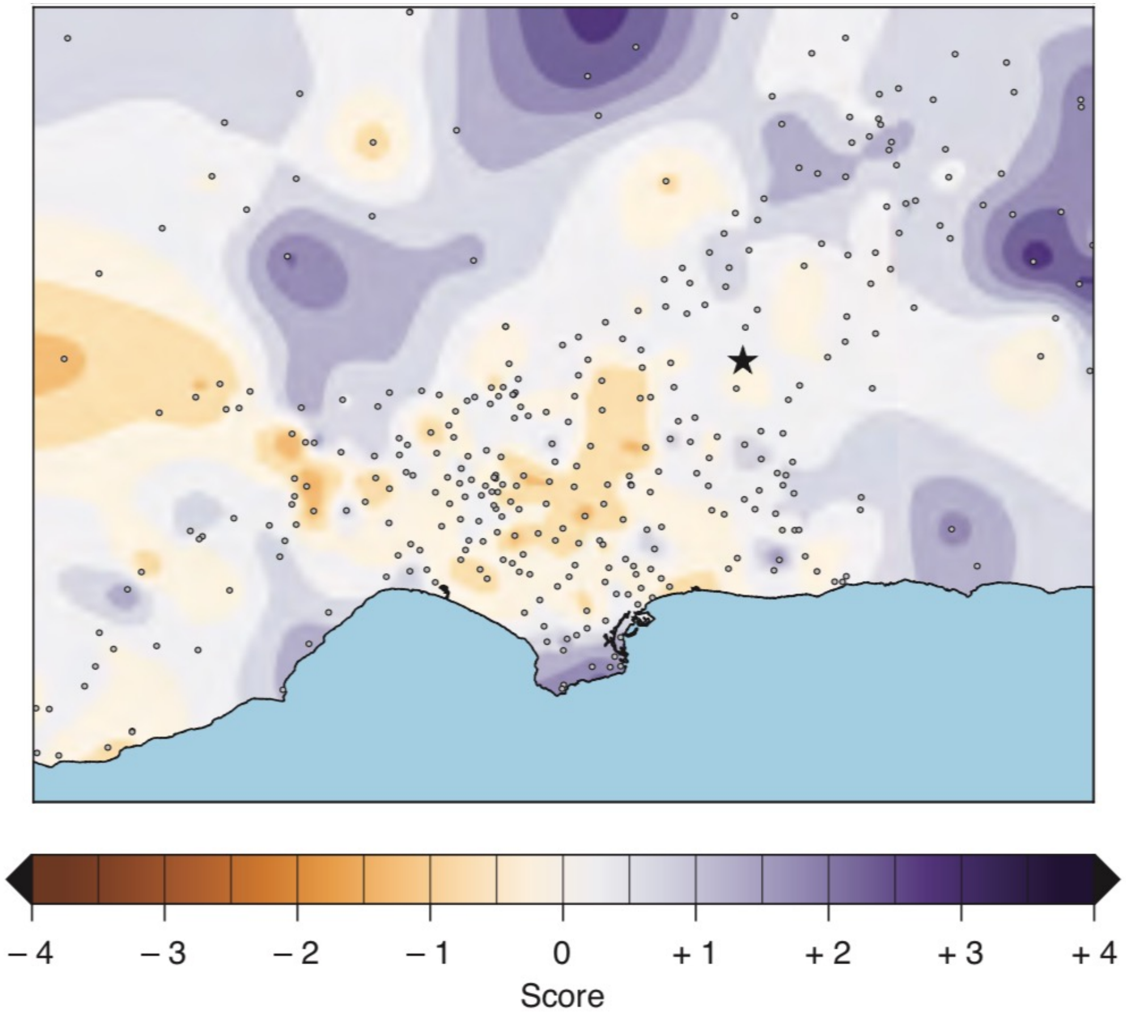
Sim. ID	**CVM-S**		**$V_{S\min}$**		**Pts. per wavelength**		**α in $Q_S = \alpha V_S$**		**λ in $Q(f) = Q_O f^{\lambda}$**			**Source**		**Magnitude**		
	4	**4.26**	**200**	**500**	**10**	**20**	**50**	**100**	**0 (a)**	**0 (b)**	**0.8 (b)**	**Point**	**Ext.**	**5.4**	**5.45**	**5.5**
S1	•			•	•		•		•			•		•		
S2		•		•	•		•		•			•		•		
S3		•		•	•			•	•			•		•		
S4		•	•		•			•	•			•		•		
S5		•	•		•			•	•				•	•		
S6		•	•		•			•		•			•	•		
S7		•	•		•			•			•		•	•		
S8		•		•		•		•		•			•	•		
S9		•		•		•		•			•		•	•		
S10		•		•	•			•	•				•	•		
S11		•		•	•			•		•			•	•		
S12		•		•	•			•		•			•		•	
S13		•		•	•			•		•			•			•

(a) This corresponds to the attenuation model BKT2, which is frequency independent.
(b) This corresponds to the attenuation model BKT3, which can be frequency dependent if $\lambda \neq 0$.

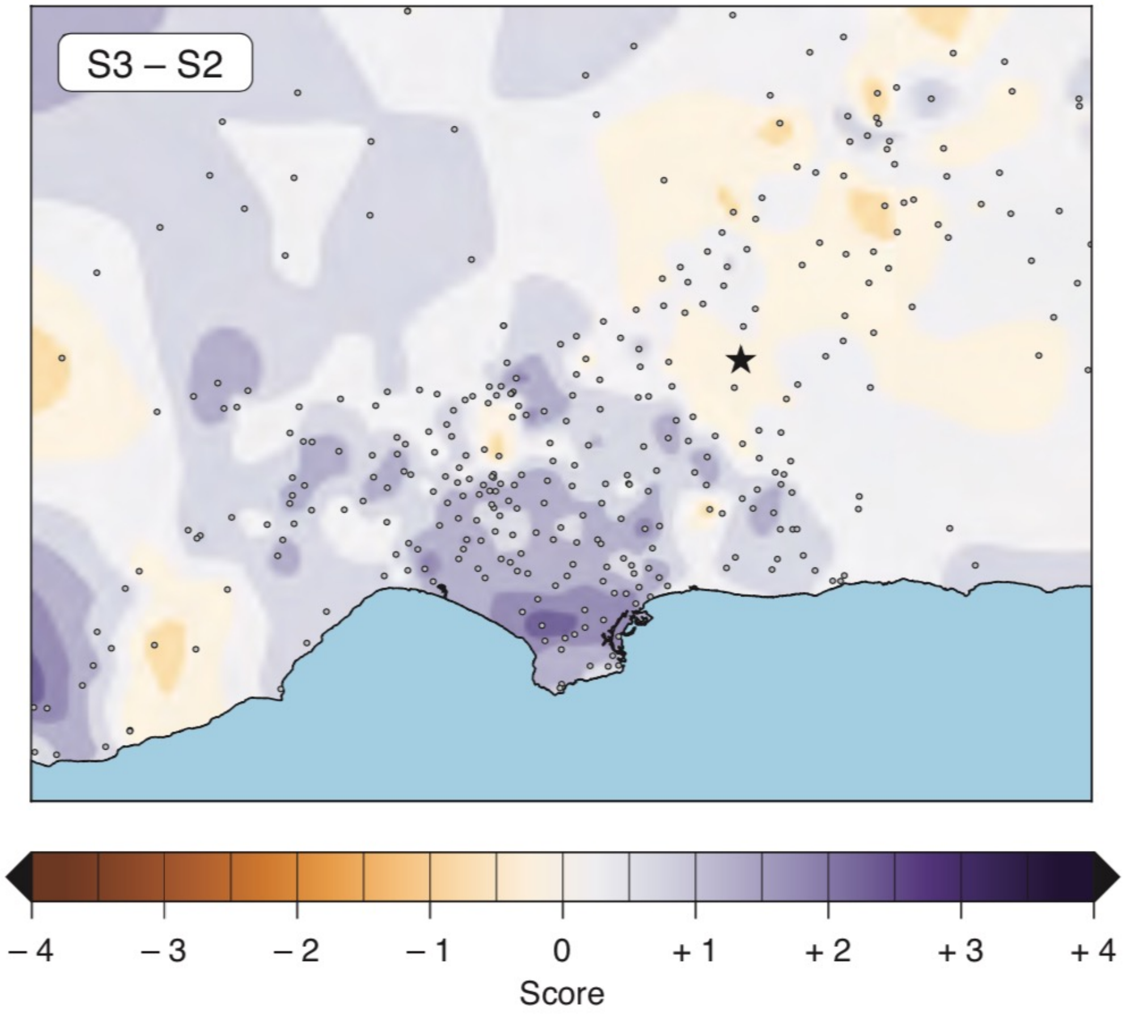
CVM-S4.26.M01 vs. CVM-S4 (1@1 Hz CH-PS)



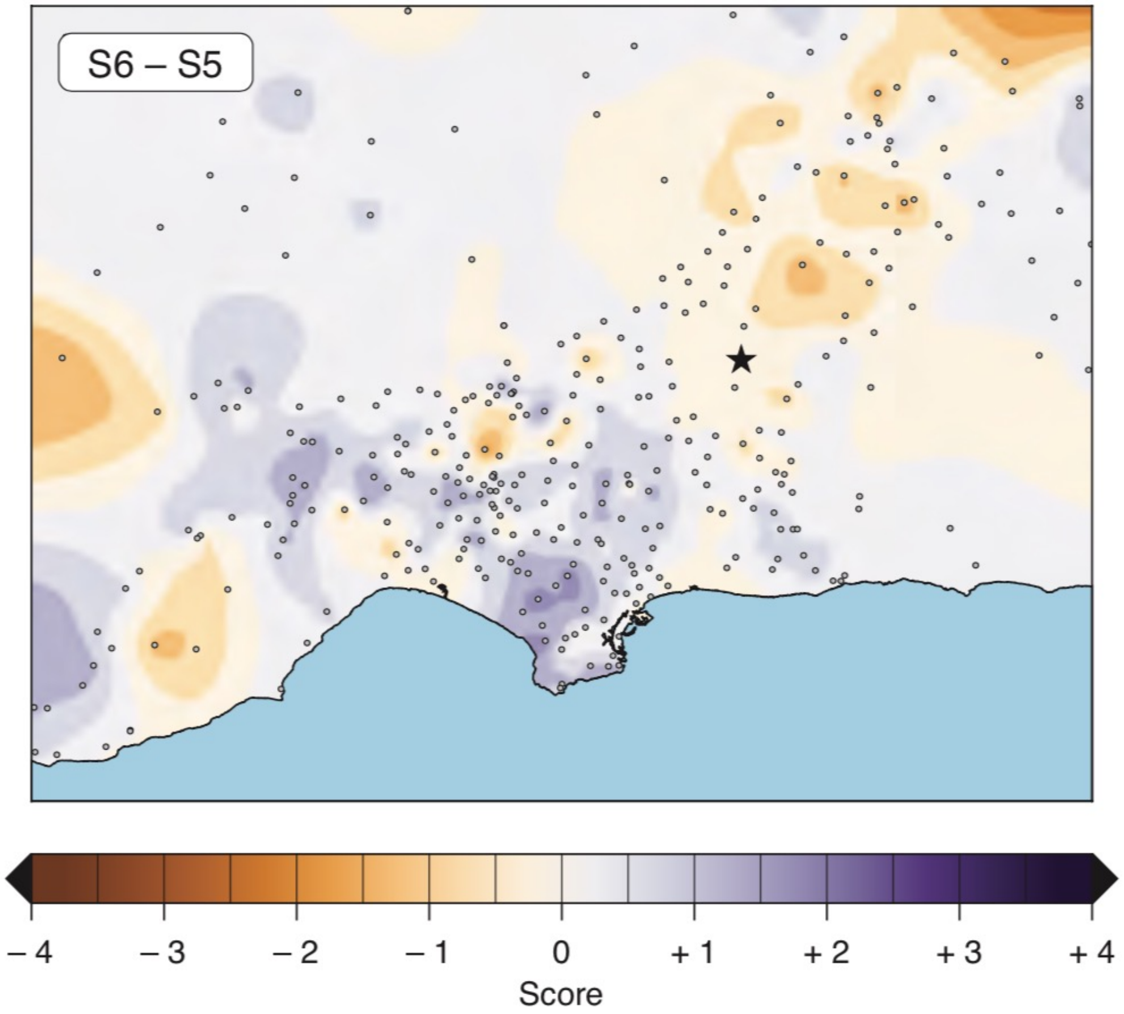
CVM-S4.26.M01 vs. CVM-S4 (1@4 Hz CH-ES)



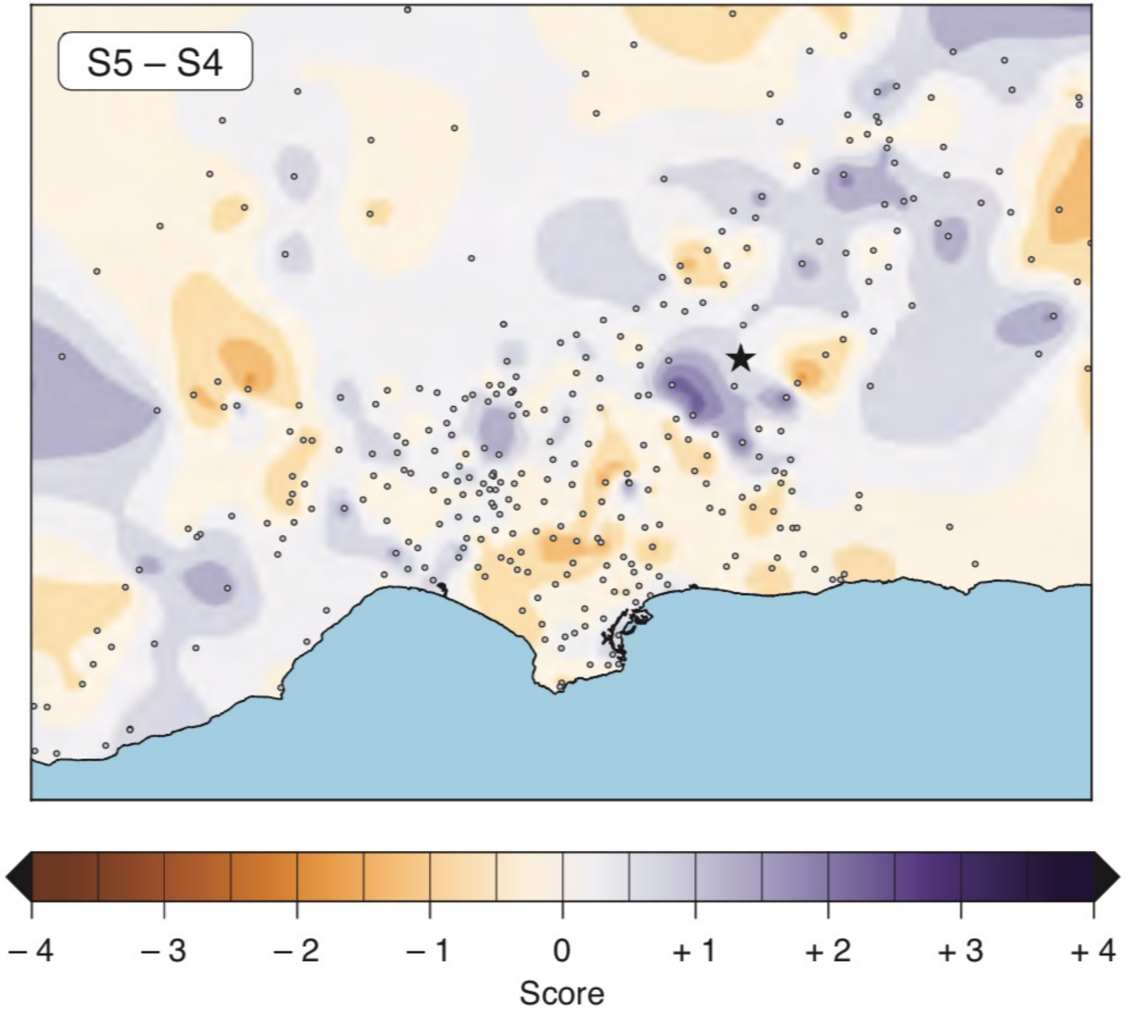
Q as 100Vs vs. 50Vs (at 1 Hz for CH-PS)



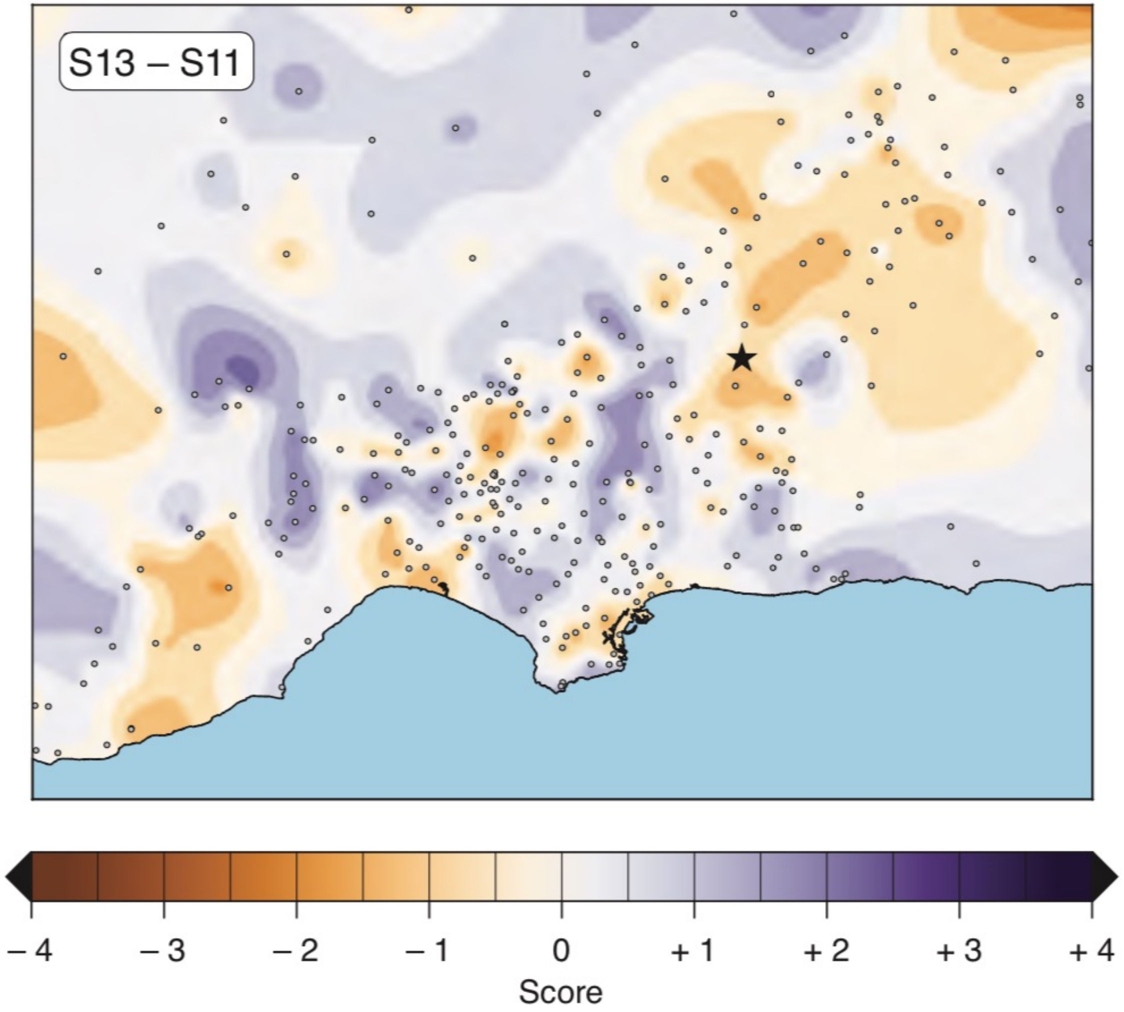
BKT3 vs. BKT2 modeling (at 1 Hz for CH-PS)



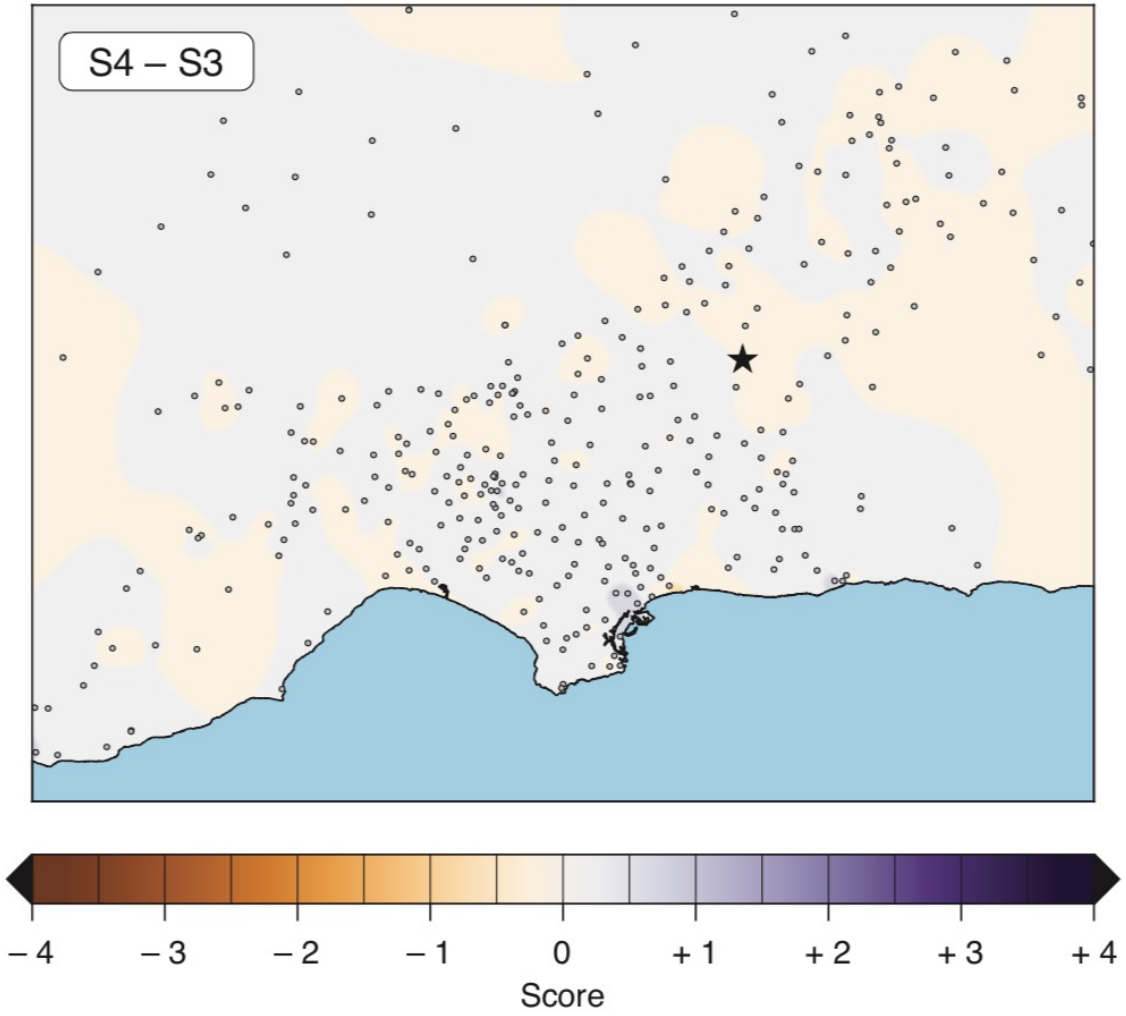
Extended vs. point source (at 1 Hz for CH-PS)



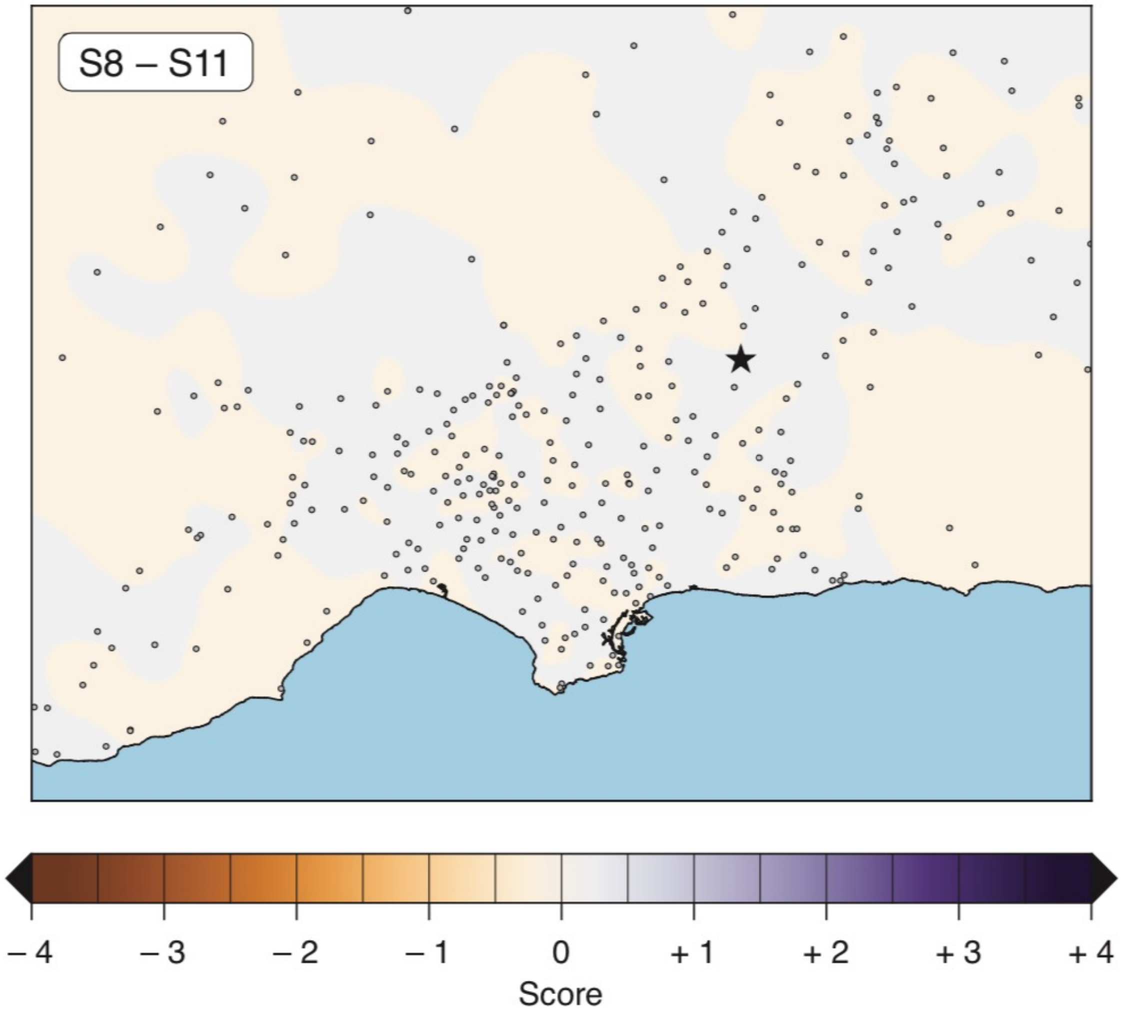
Varying to Mw 5.5 vs. 5.4 (at 1 Hz for CH-PS)



200 m/s vs. 500 m/s (at 1 Hz for CH-PS)



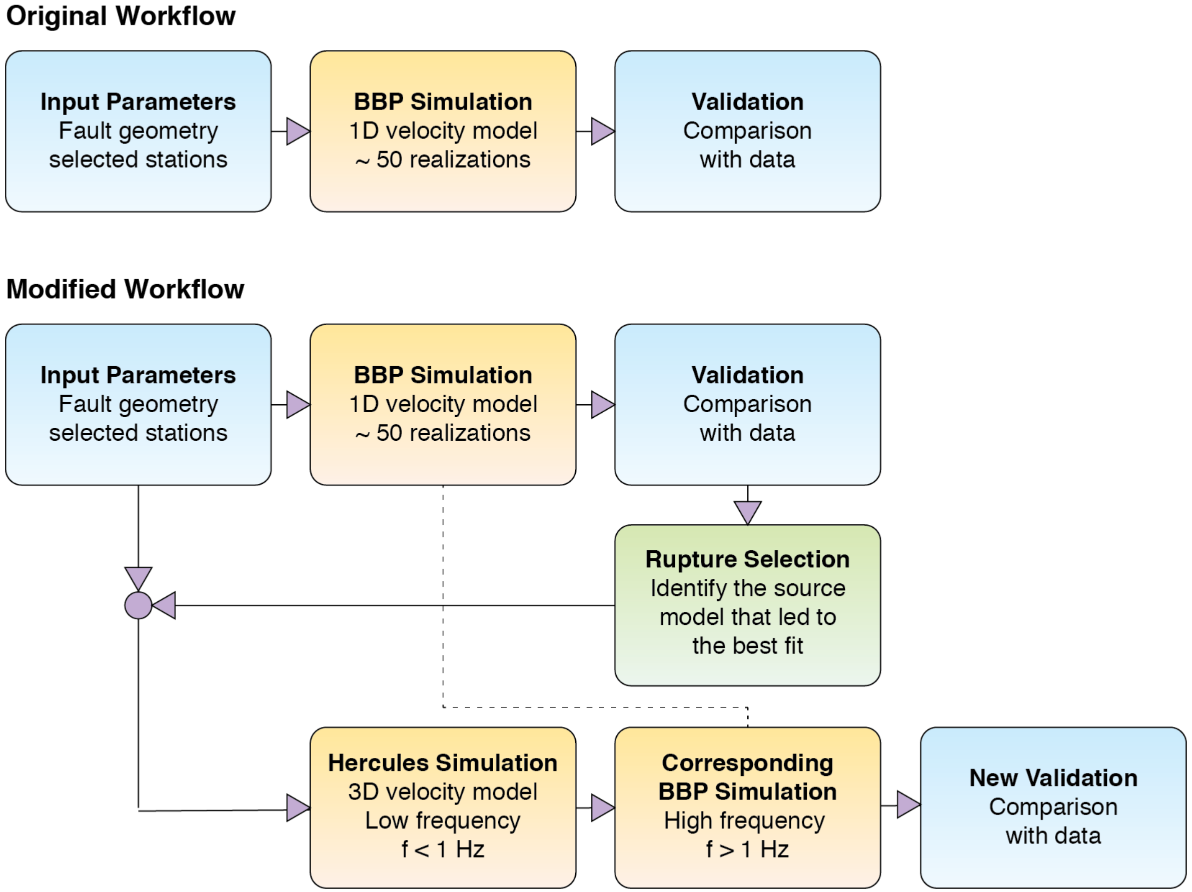
10 PPWL vs. 20 PPWL (at 1 Hz for CH-PS)

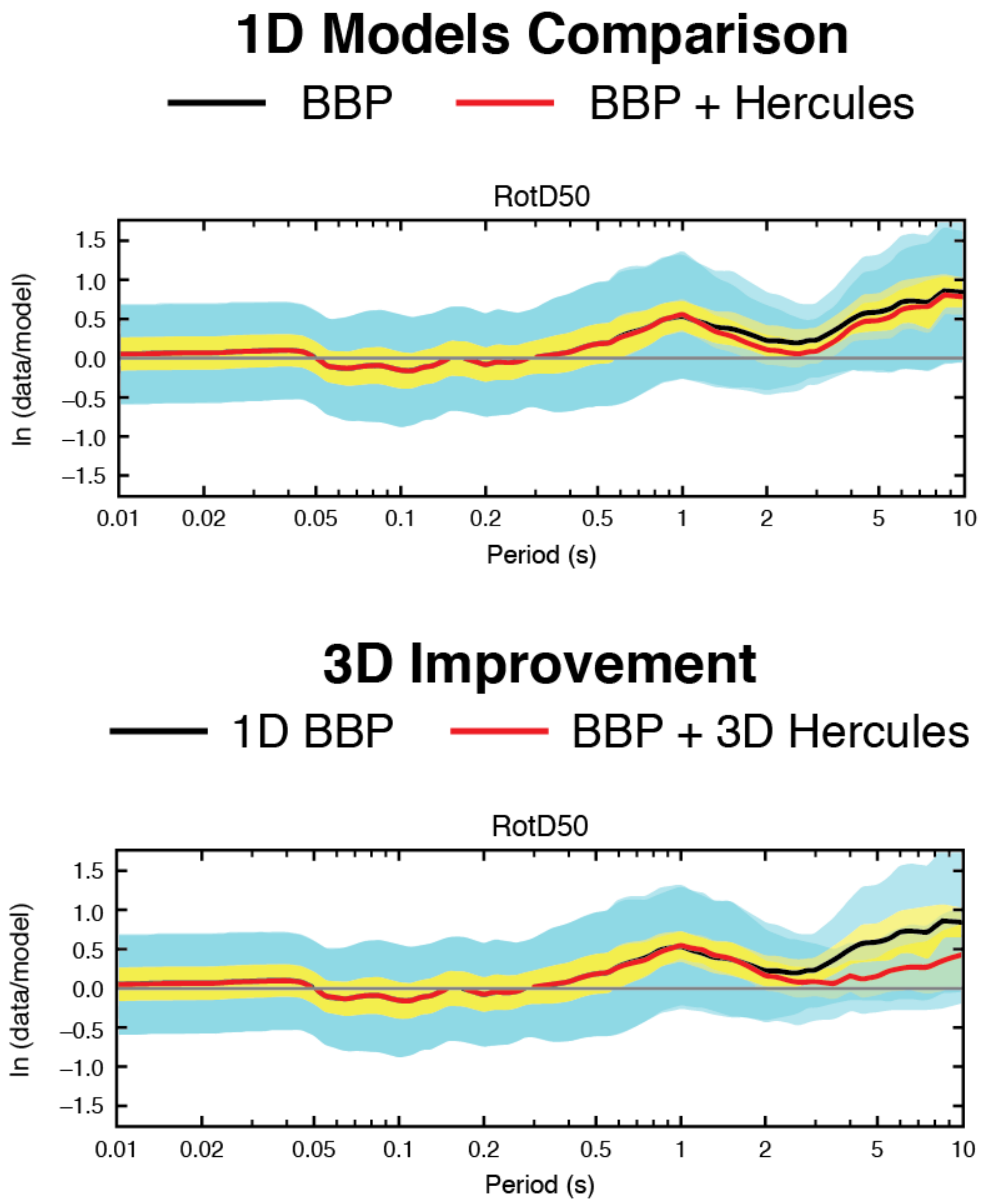


Other considerations

Purpose and intended use, hybrid approaches, metrics
topography, plasticity and nonlinearity, built Environment, …

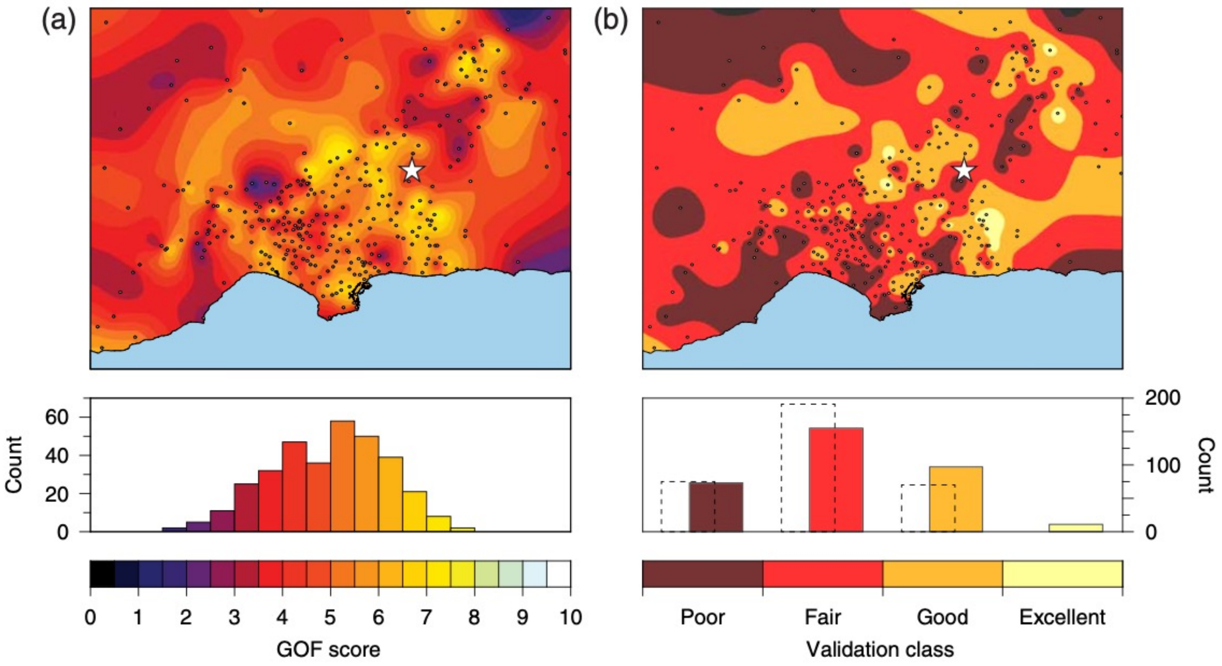
Integrating 1D BBP and 3D Simulations

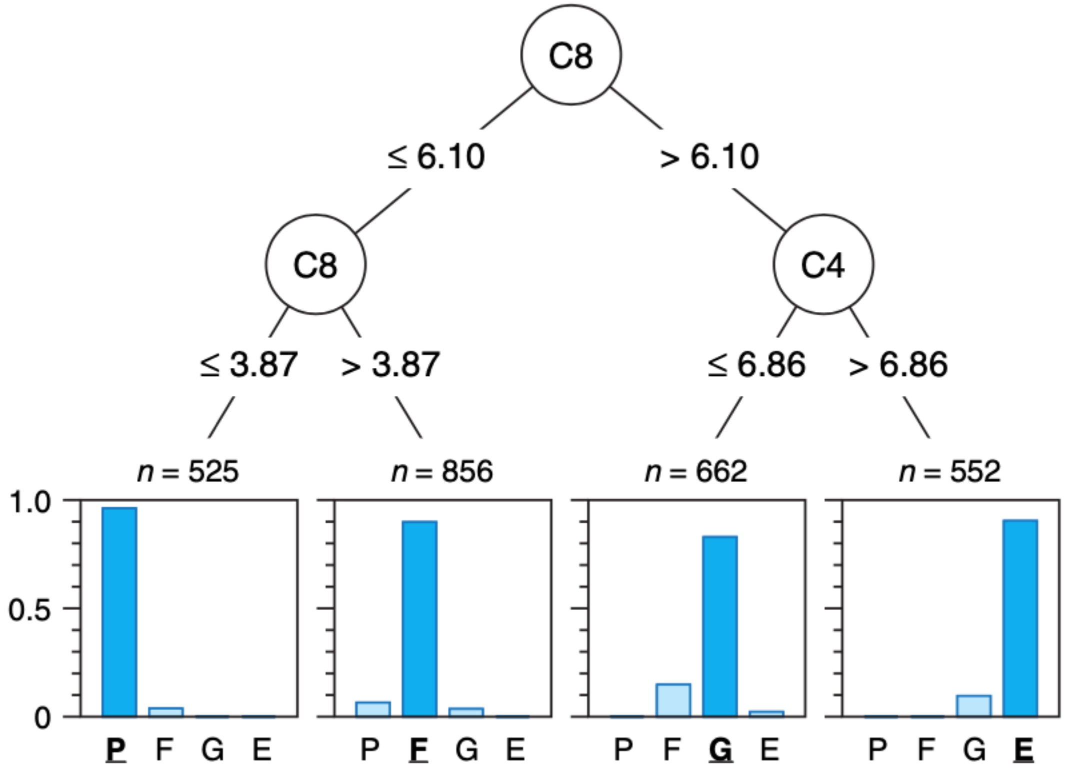




Taborda et al. (SCEC, 2014)

Alternatives to reduce validation post-processing



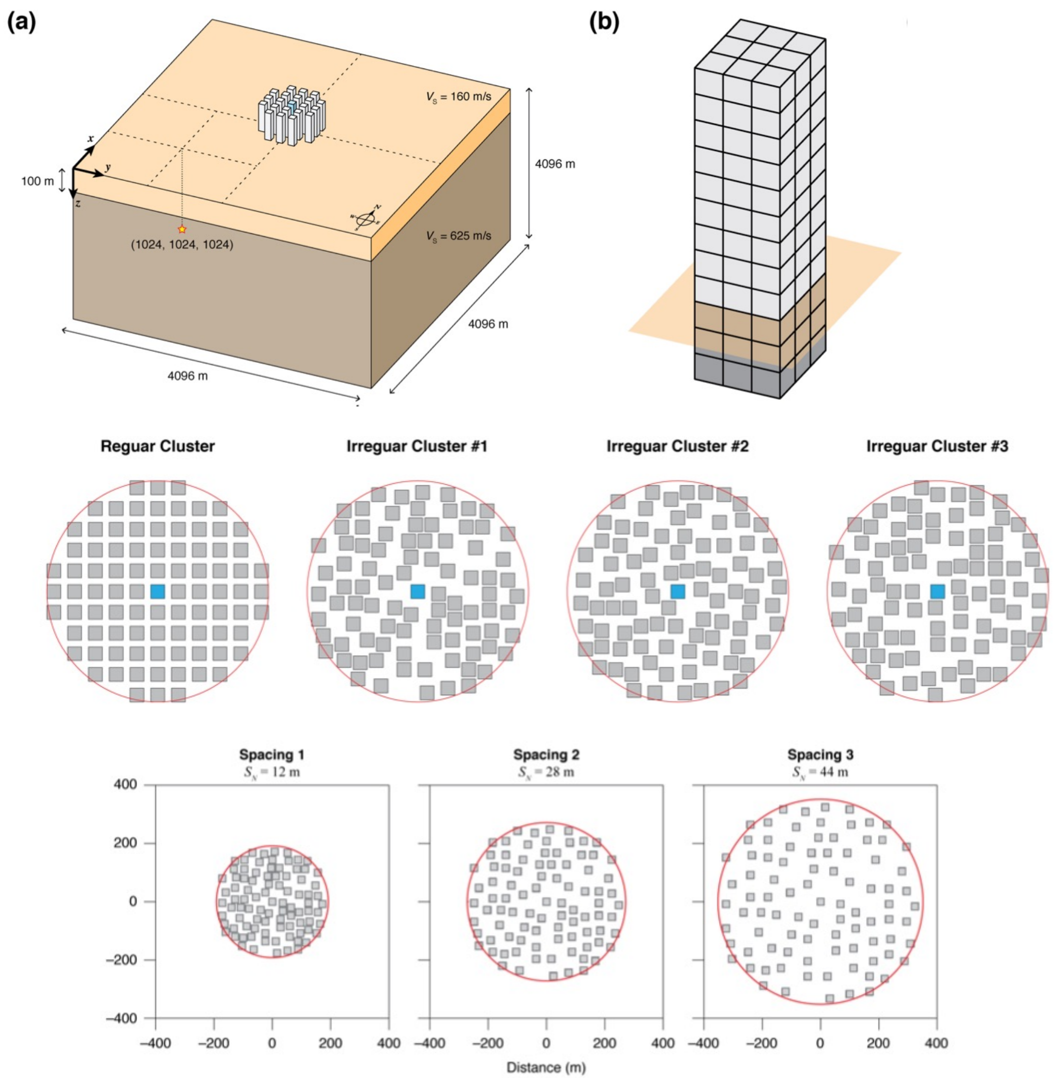


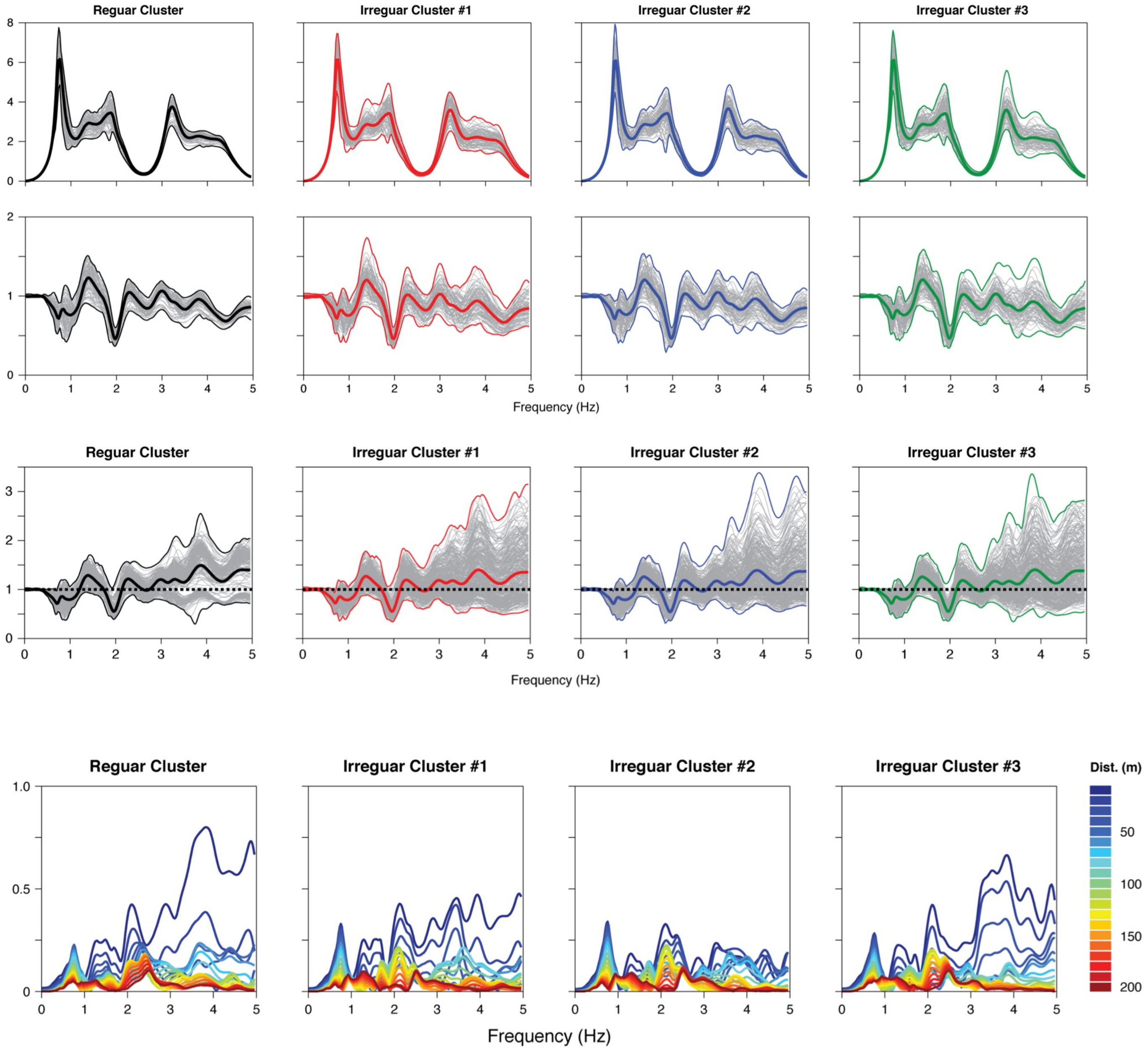
» C8: Response spectra

» C4: Energy

Khoshnevis and Taborda (BSSA, 2018)

Attempts to understand effects of urban environments





Taborda and Isbiliroglu (USGS, 2018)

In closing…

» Velocity model	Matters a lot – perhaps the most.
» Minimum Vs	Matters provided the resolution of the model and that of the simulation are worth the computational effort.
» Numerical resolution	Matters a lot for verification, but it may not matter that much for validation
» Attenuation model	Matters significantly, especially for far field analysis and higher frequencies.
» Source model	Matters more than one would think of. Even for small earthquakes. Even at some distance (low vs high frequencies, near vs far field.)
» Source uncertainty	Can make a significant difference.
» Nonlinear soil	Matter a lot. Mostly local. But it may impact regional response to an extent we do not fully understand for now.
» Topography	We know it matters but cannot fully characterize it for synthesis at regional scale just yet.
» Site-city interaction	We do not fully understand yet.

» Inversions: For better velocity models, thus other information.

» Energy losses: Anelasticity and nonlinearities of engineering interest.

» Variability: Anything that increases it matters at higher frequency (e.g., topography).

» Uncertainty: Simulations / workflows that can carry forward information about uncertainty.

» Workflows: In the form of automated simulations that can be repeated systematically.

Thank you

Simulated motions validation and acceptance criteria for ground motion databases

The Southern California Validation Experience

Ricardo Taborda