Key Word: **Path Calibration**

High Resolution Finite Fault Inversions for M>4.8 Earthquakes in the 2012 Brawley Swarm

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@Palm Spring

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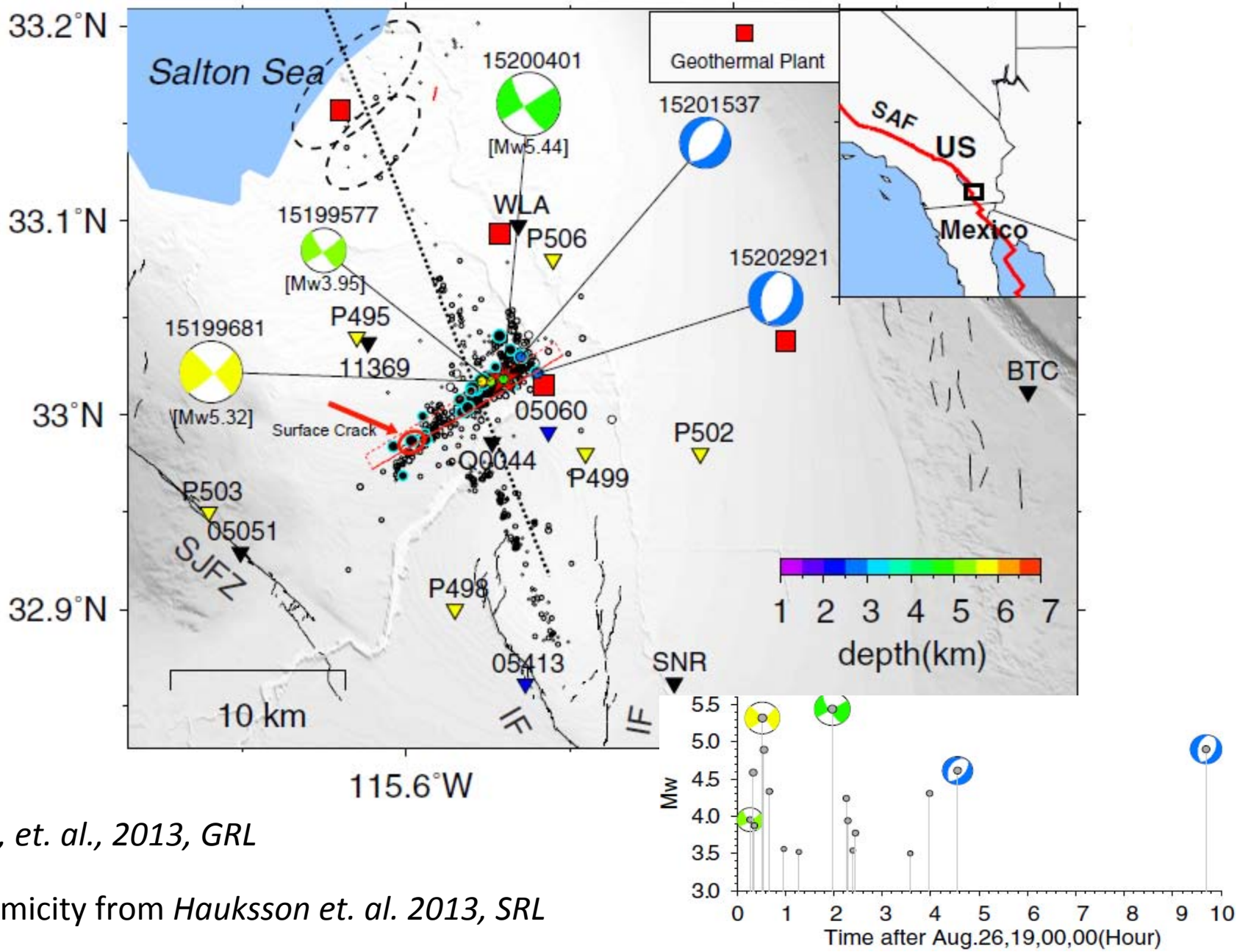
Outline

- Overview of the 2012 Brawley swarm
- Path calibration from the Mw3.9 earthquake
- Waveform inversion of the M>5 events up to 3Hz
- Complementary slip distribution (triggering?)
- Two shallow (depth ~ 2.0km) normal earthquakes: seismological, field observation and geodetic evidence
- Joint inversion for the Mw4.9 normal earthquake
- Conclusion

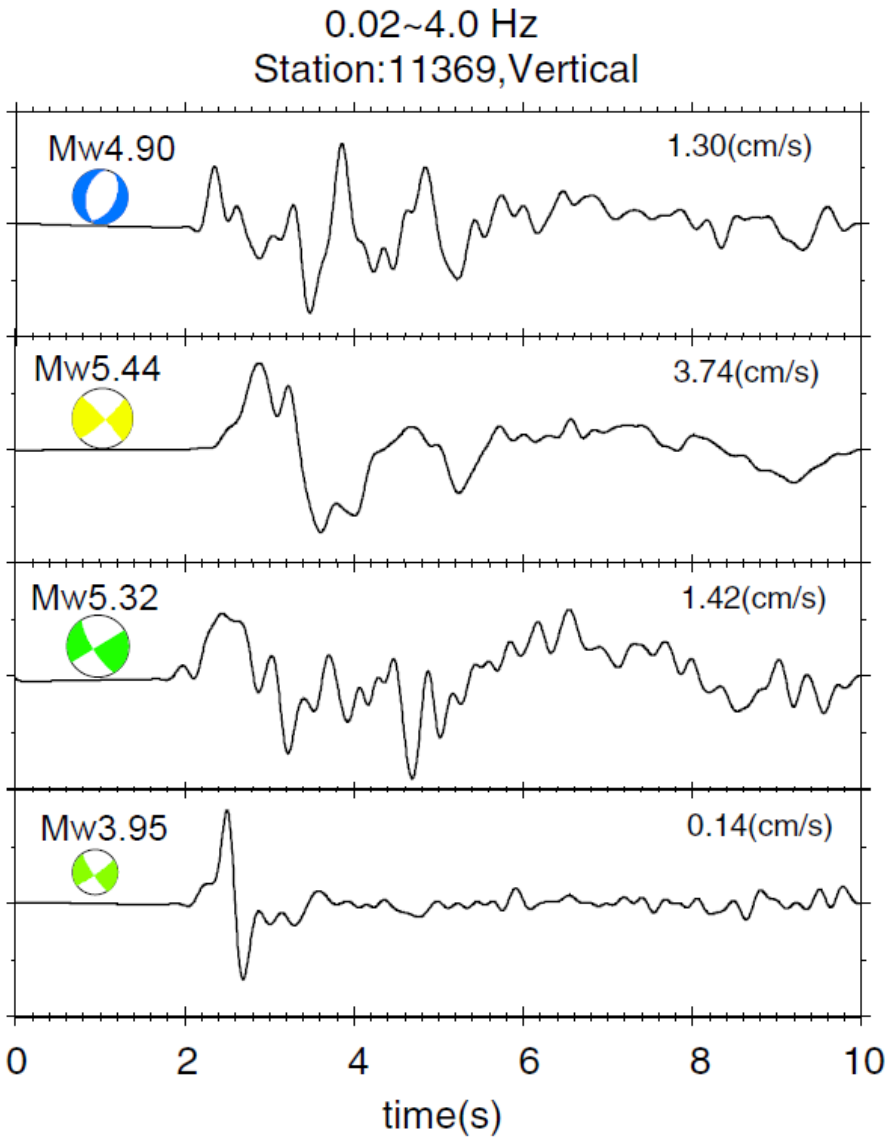
Overview

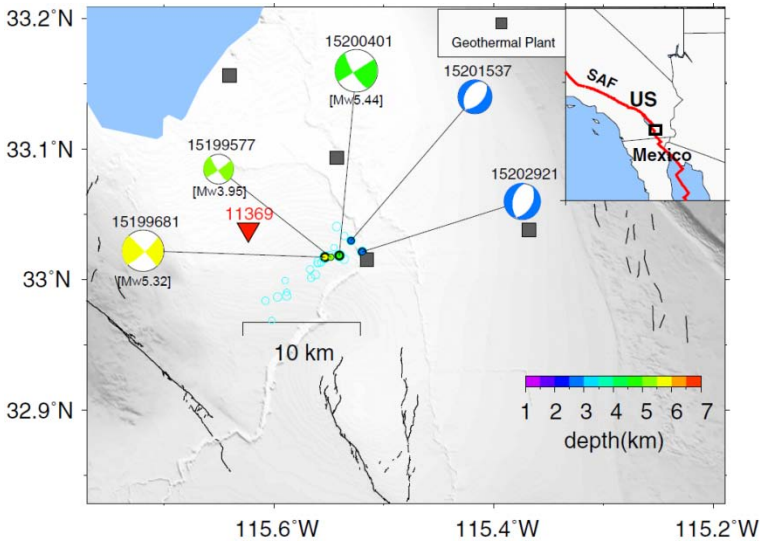


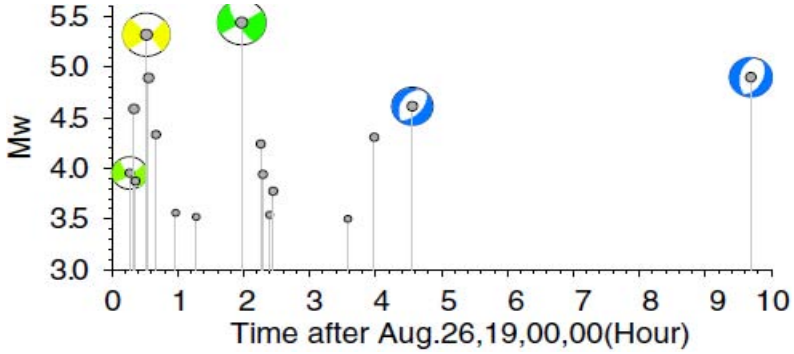
Wei, et. al., 2013, GRL

Seismicity from *Hauksson et. al. 2013, SRL*

Waveform Complexity







Finite Fault Inversion Method

We need a layered crustal model to calculate synthetic seismogram:

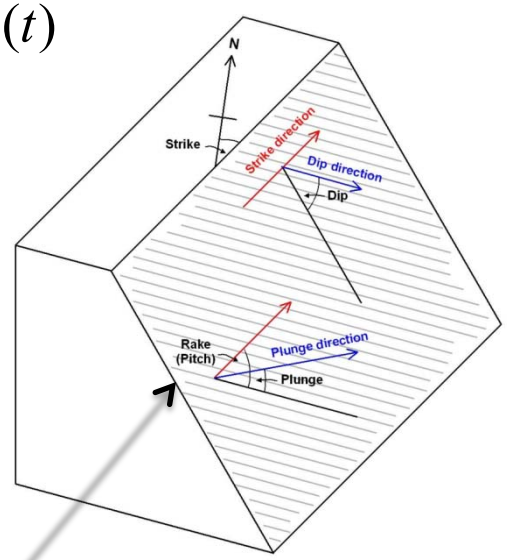
$$u(t) = \sum_{j=1}^{n}\sum_{k=1}^{m} D_{jk}[\cos(\lambda_{jk})Y_{jk}^{1}(v_{jk},t) + \sin(\lambda_{jk})Y_{jk}^{2}(v_{jk},t)]\&_{jk}(t)$$

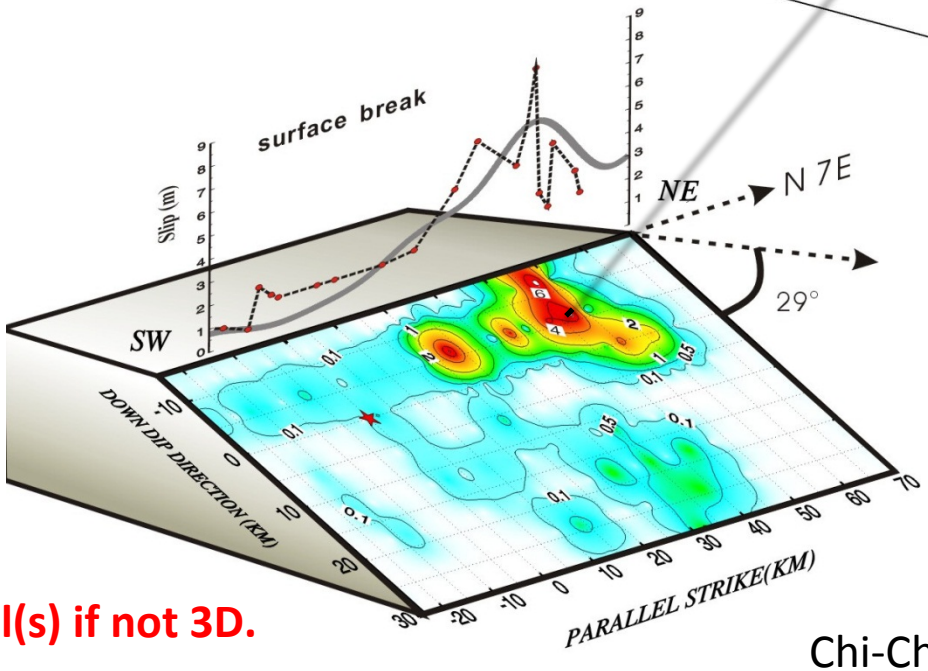
$u(t)$: *Green's Function*

A simulated annealing algorithm is used to simultaneously invert for the:

slip amplitude,
slip direction,
rise time,
rupture velocity

Ji et. al., 2002a, *BSSA*





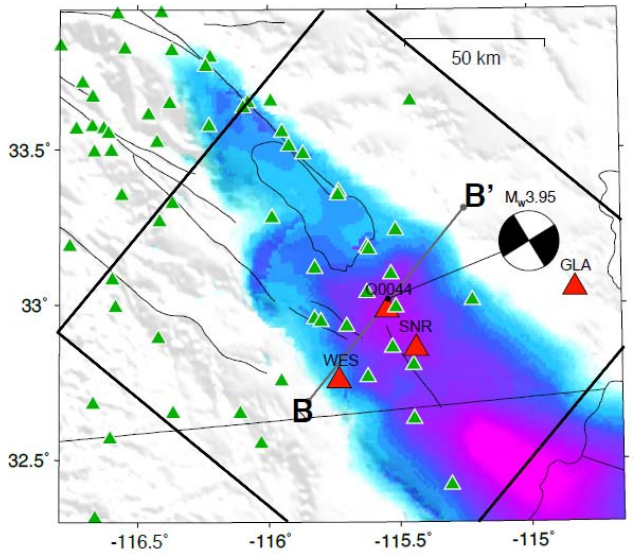
We need 1D velocity model(s) if not 3D.

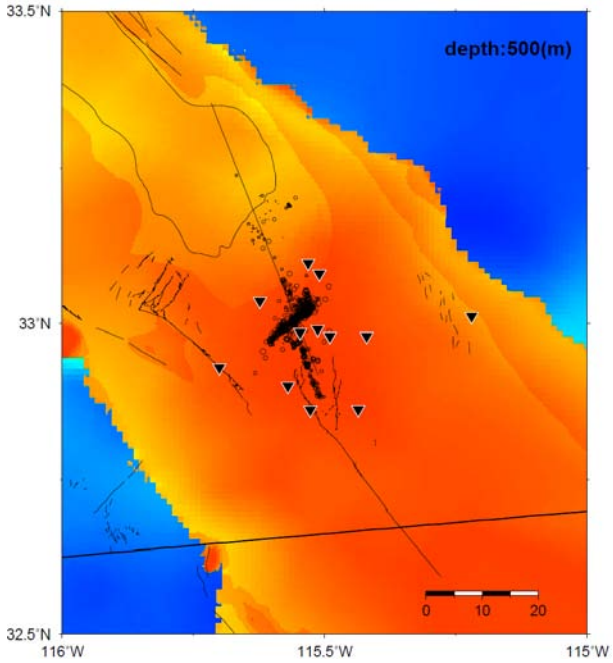
Chi-Chi Earthquake

3D velocity model: CVM-H-11.9.0

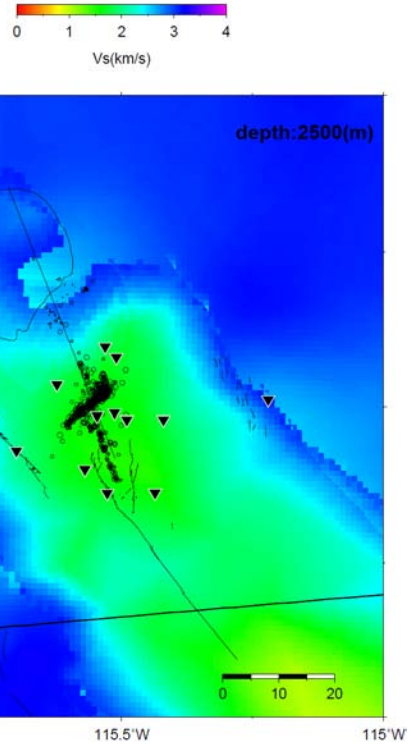
- Basin Thickness
- 2D horizontal cuts

Earthquake depth: ~5km

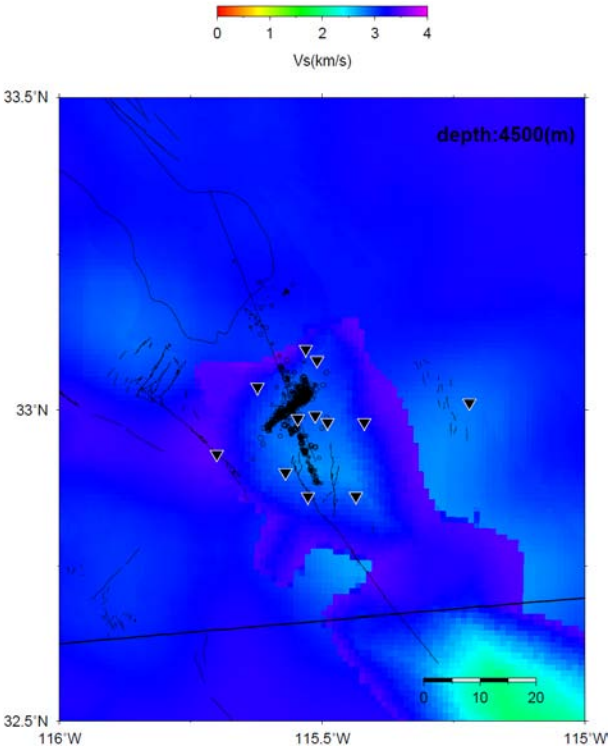




D=0.5km

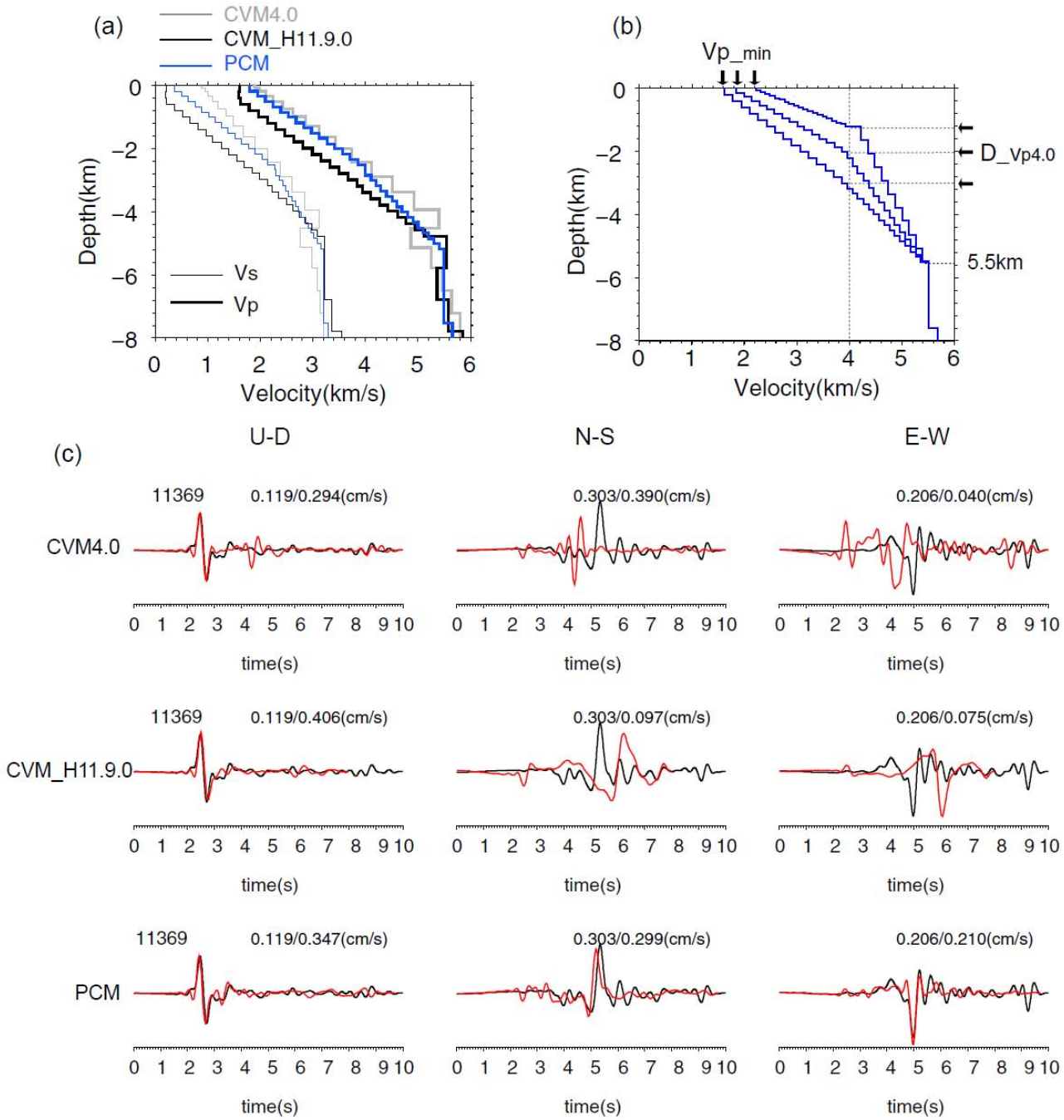


D=2.5km



D=4.5km

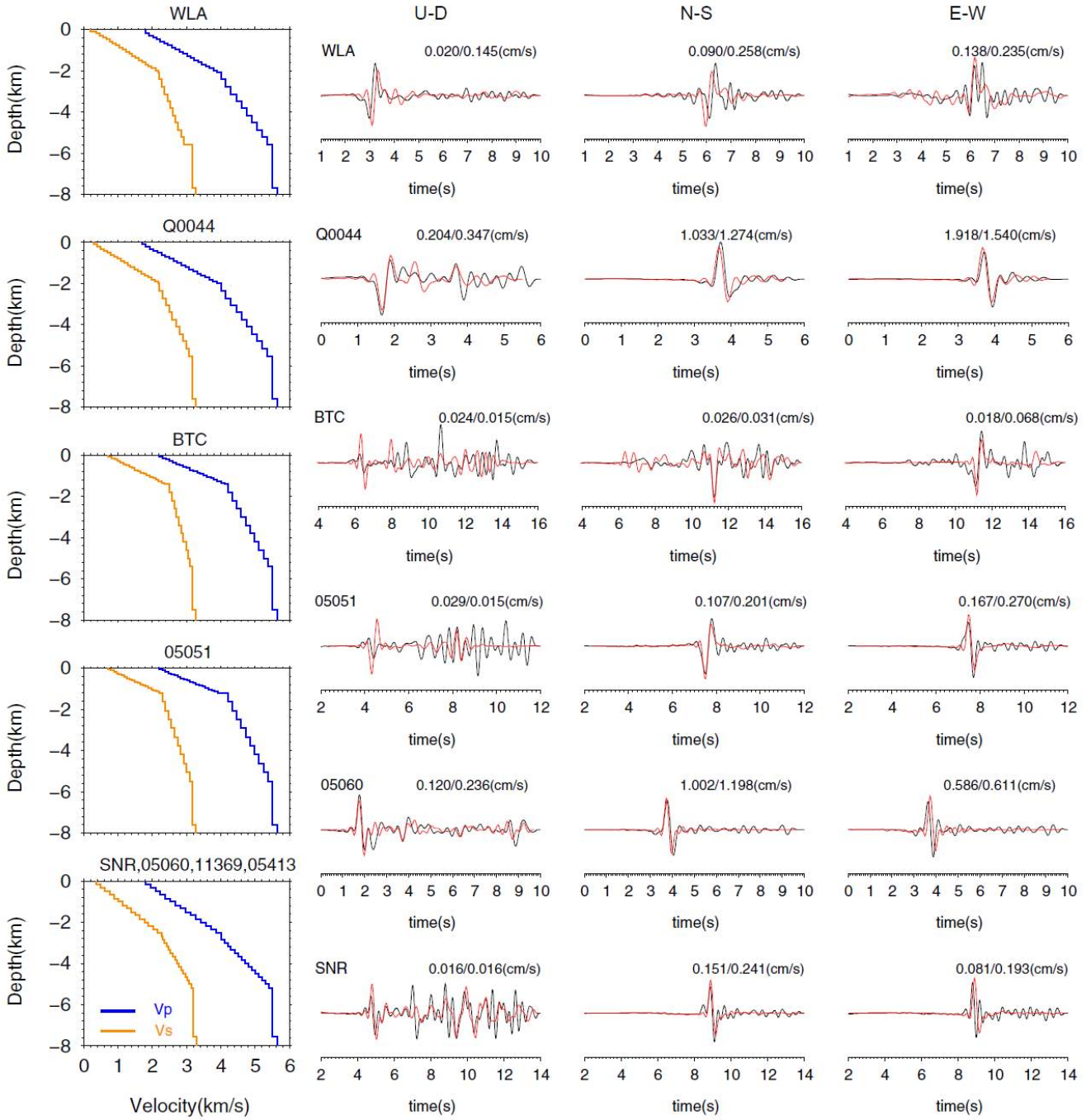
Path Calibration using the Mw3.9 Event



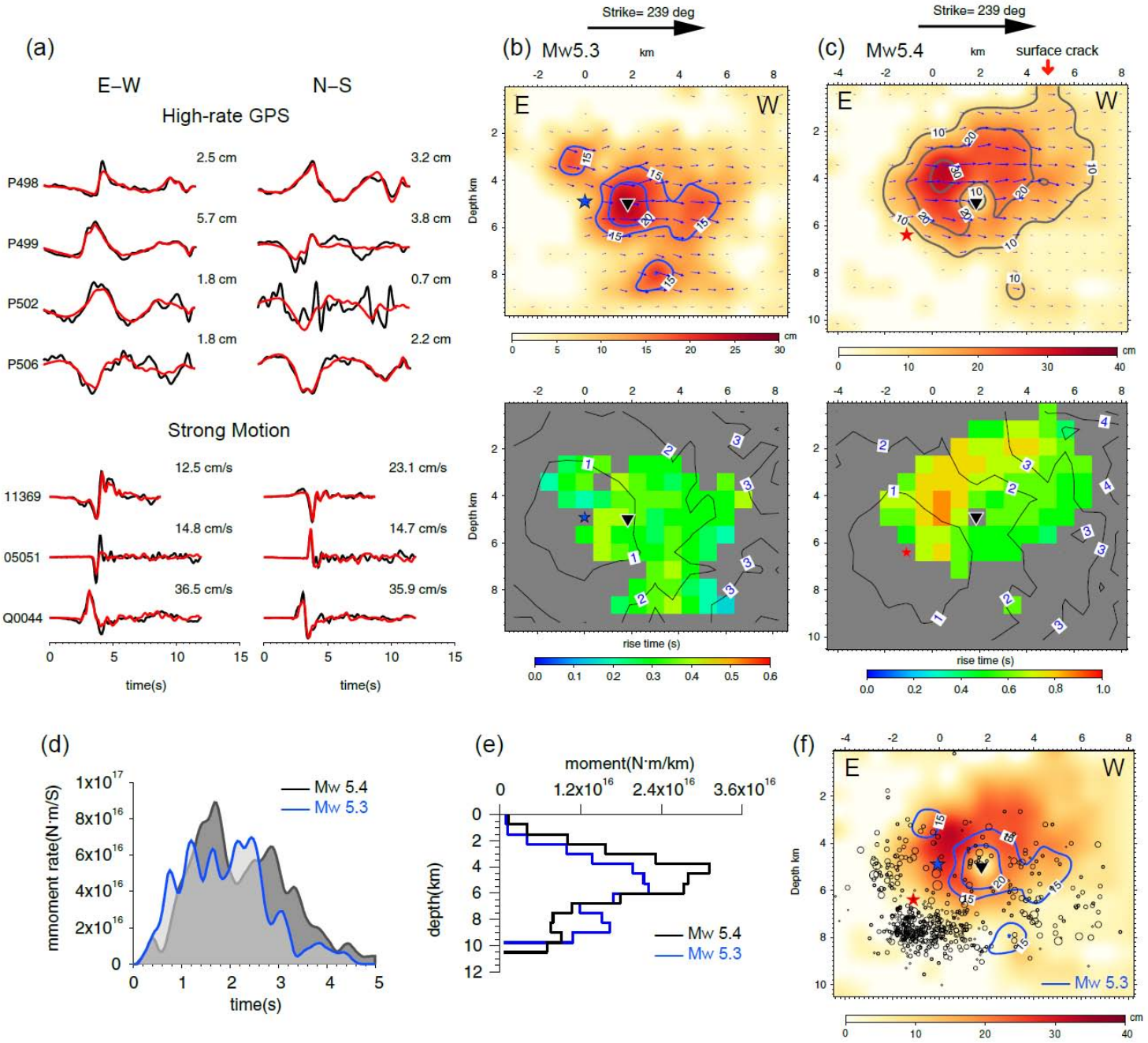
Vs = (Vp – 1.36)/1.16
for Vp < 4.0km/s

Brocher, 2005, BSSA

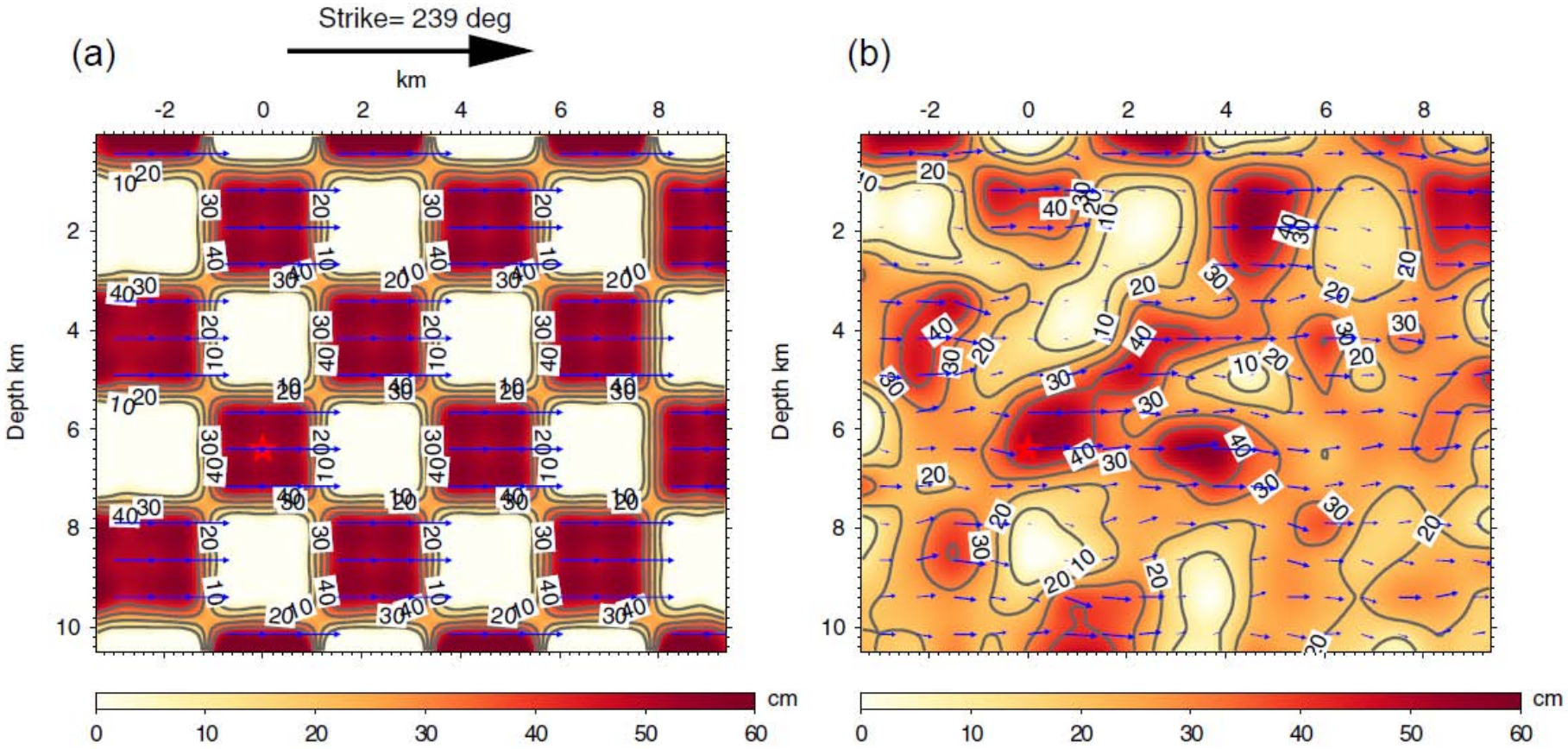
frequency band:
0.05 ~ 3 Hz


WLA
Q0044
BTC
05051
SNR,05060,11369,05413
Depth(km)
Vp
Vs
Velocity(km/s)
U-D
N-S
E-W
WLA
0.020/0.145(cm/s)
0.090/0.258(cm/s)
0.138/0.235(cm/s)
Q0044
0.204/0.347(cm/s)
1.033/1.274(cm/s)
1.918/1.540(cm/s)
BTC
0.024/0.015(cm/s)
0.026/0.031(cm/s)
0.018/0.068(cm/s)
05051
0.029/0.015(cm/s)
0.107/0.201(cm/s)
0.167/0.270(cm/s)
05060
0.120/0.236(cm/s)
1.002/1.198(cm/s)
0.586/0.611(cm/s)
SNR
0.016/0.016(cm/s)
0.151/0.241(cm/s)
0.081/0.193(cm/s)
time(s)

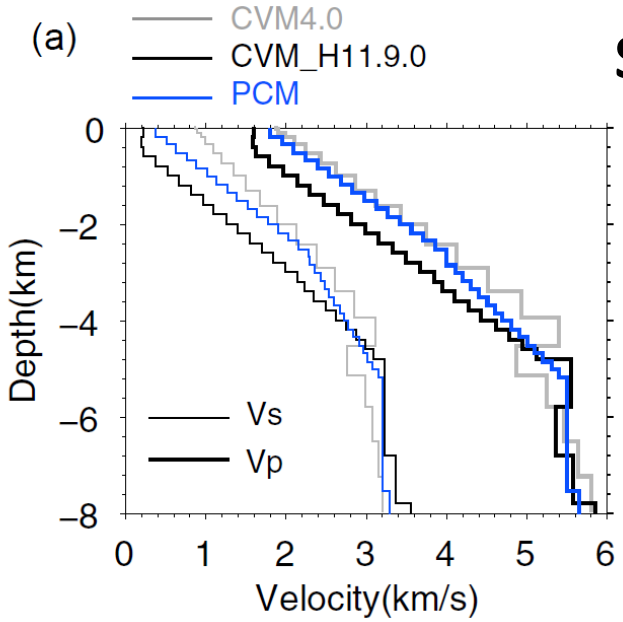
Inversion results



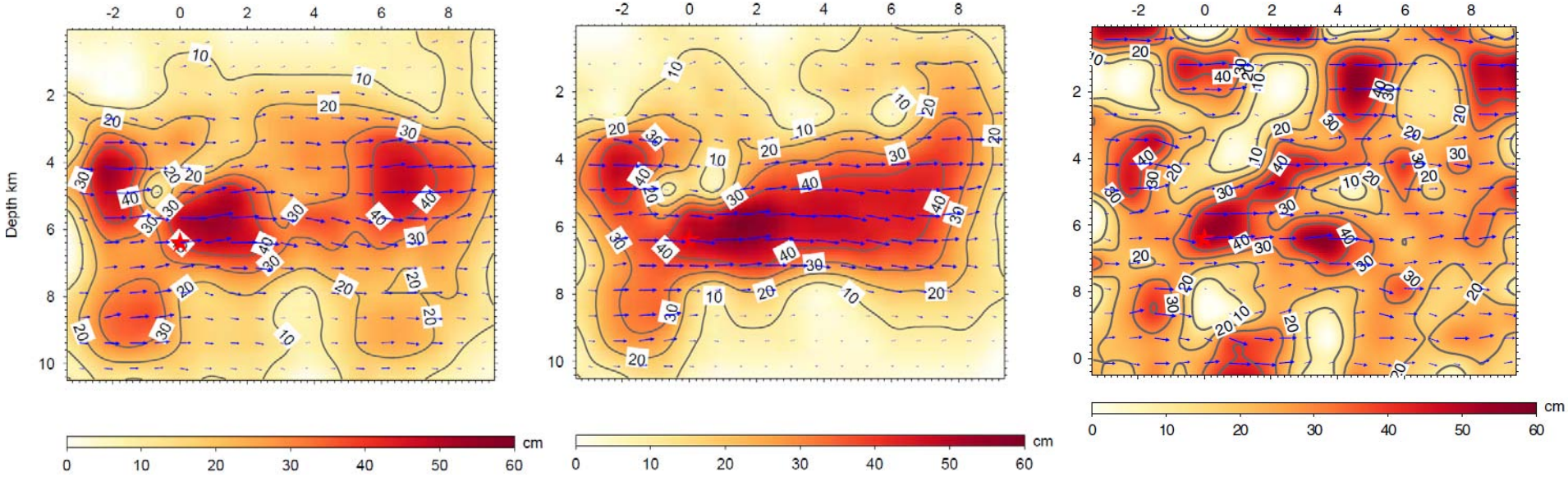
Resolution of the data set



Sensitivity for velocity structure



Model used to generate synthetic data: **PCM**

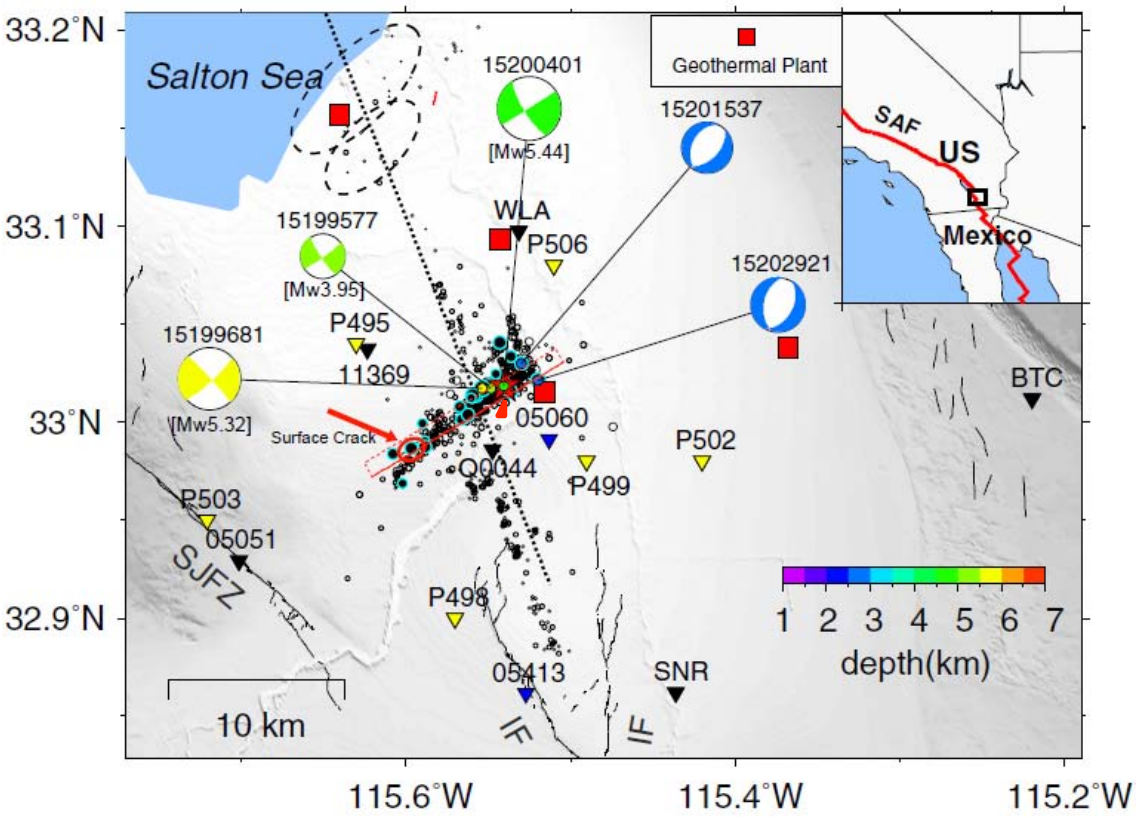


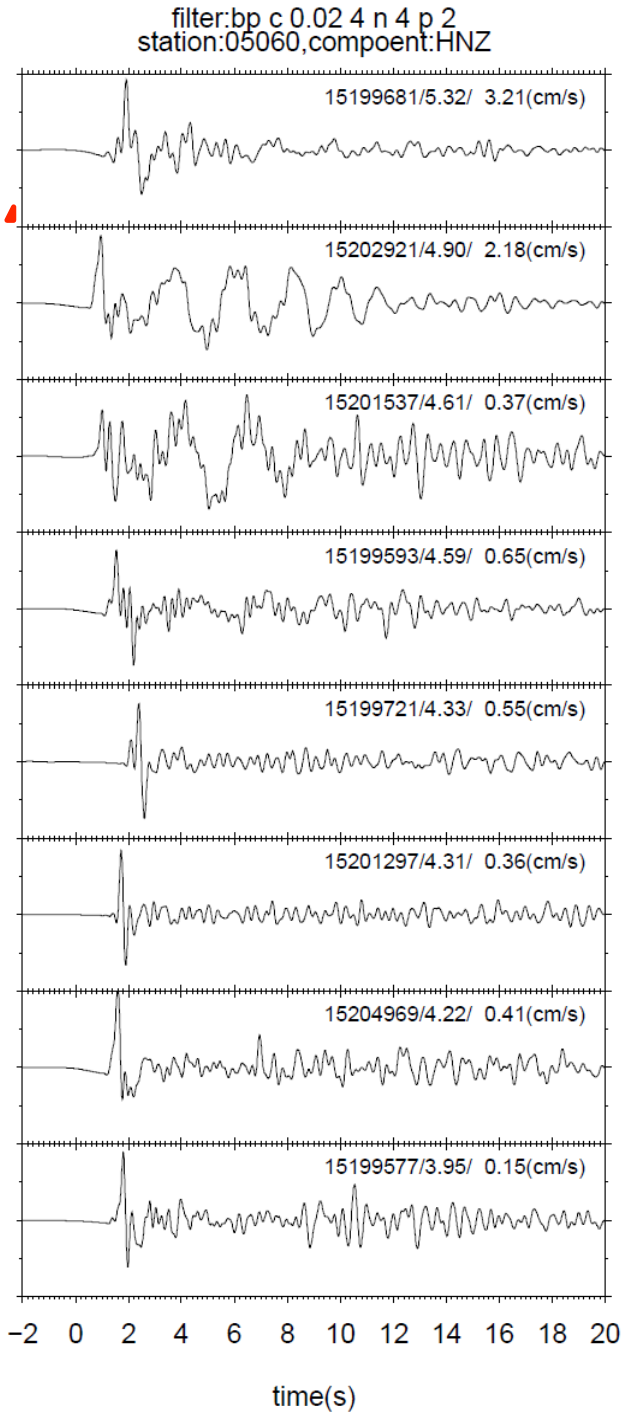
CVM4.0

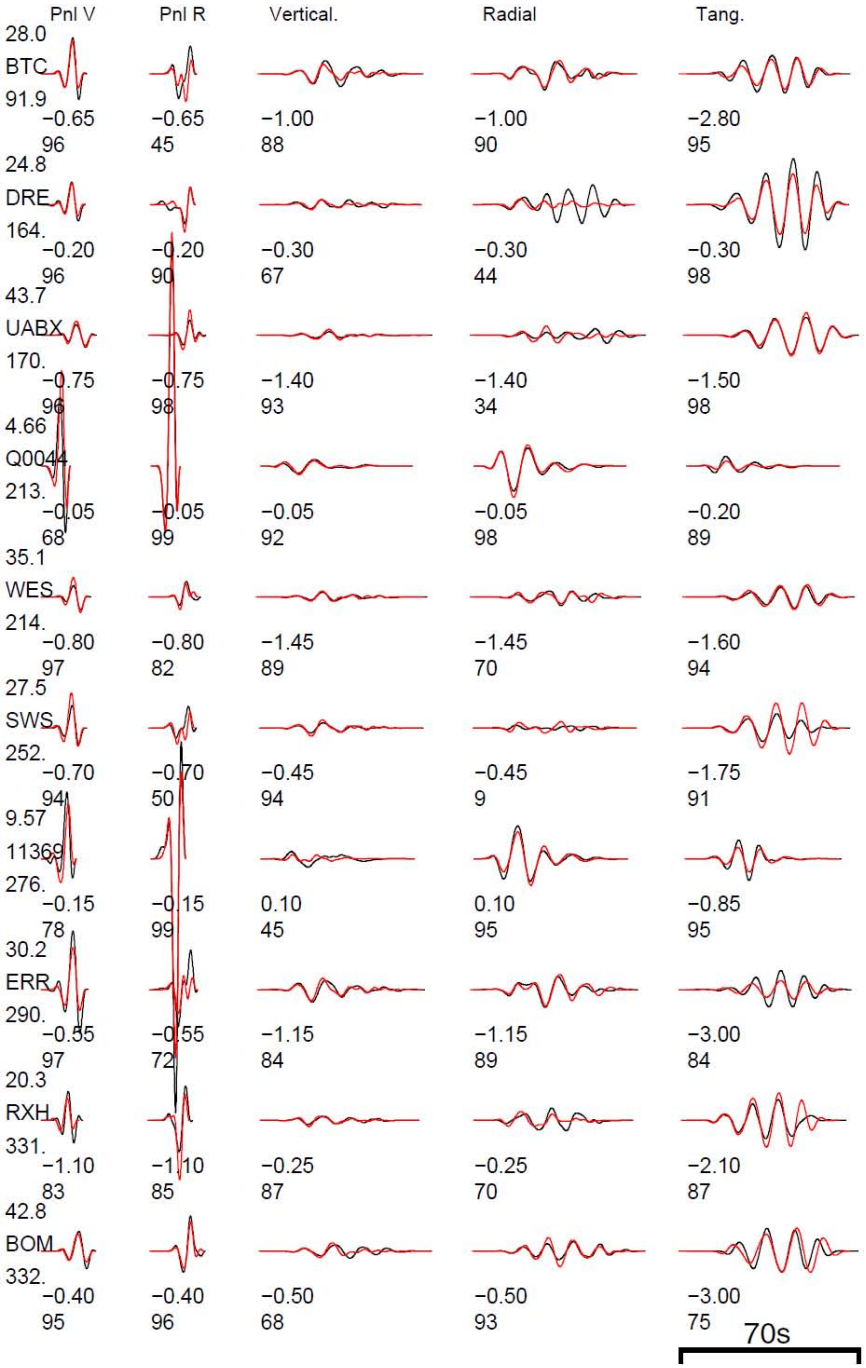
CVMH_11.9.0

PCM

Normal Events

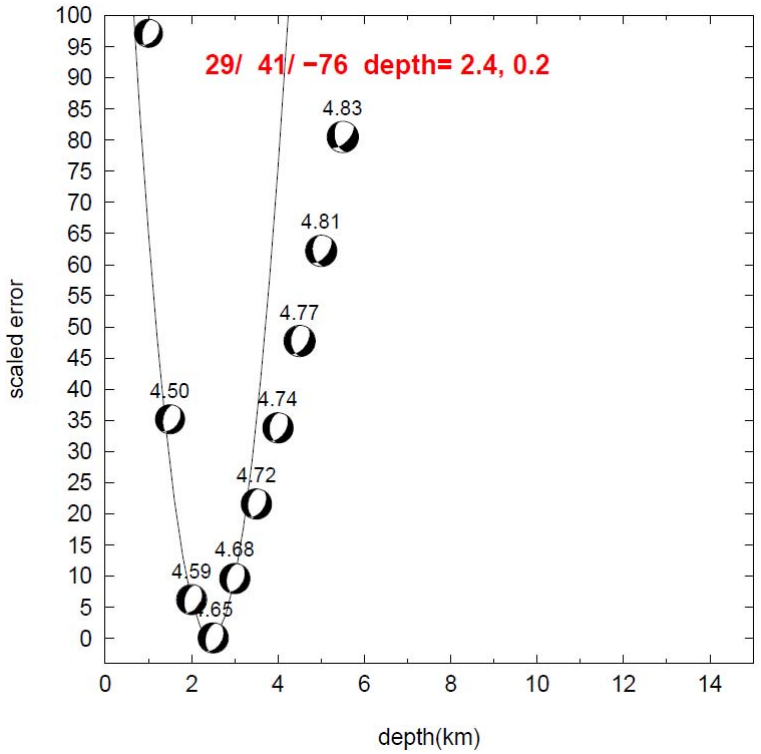




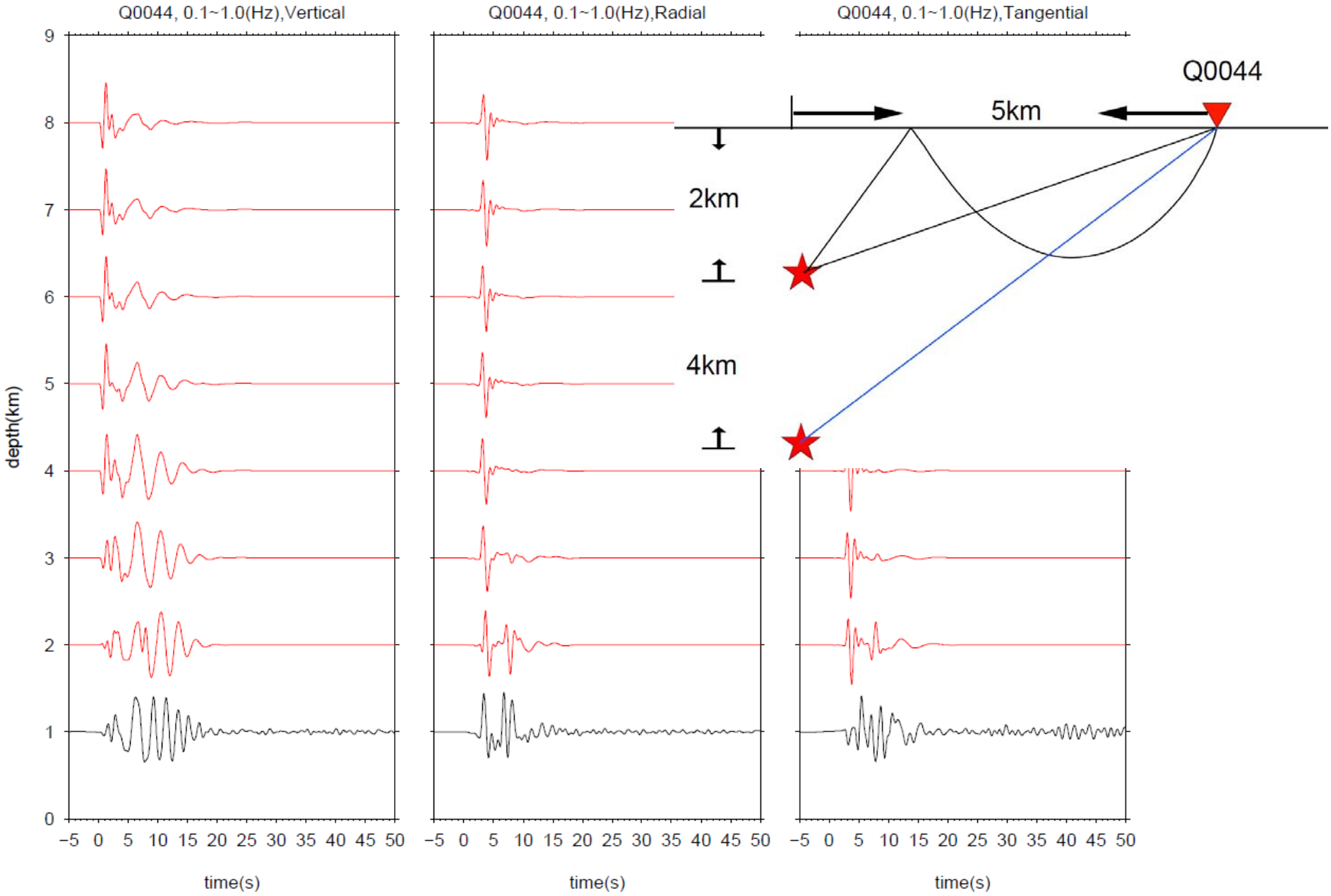


Point source double-couple moment tenor

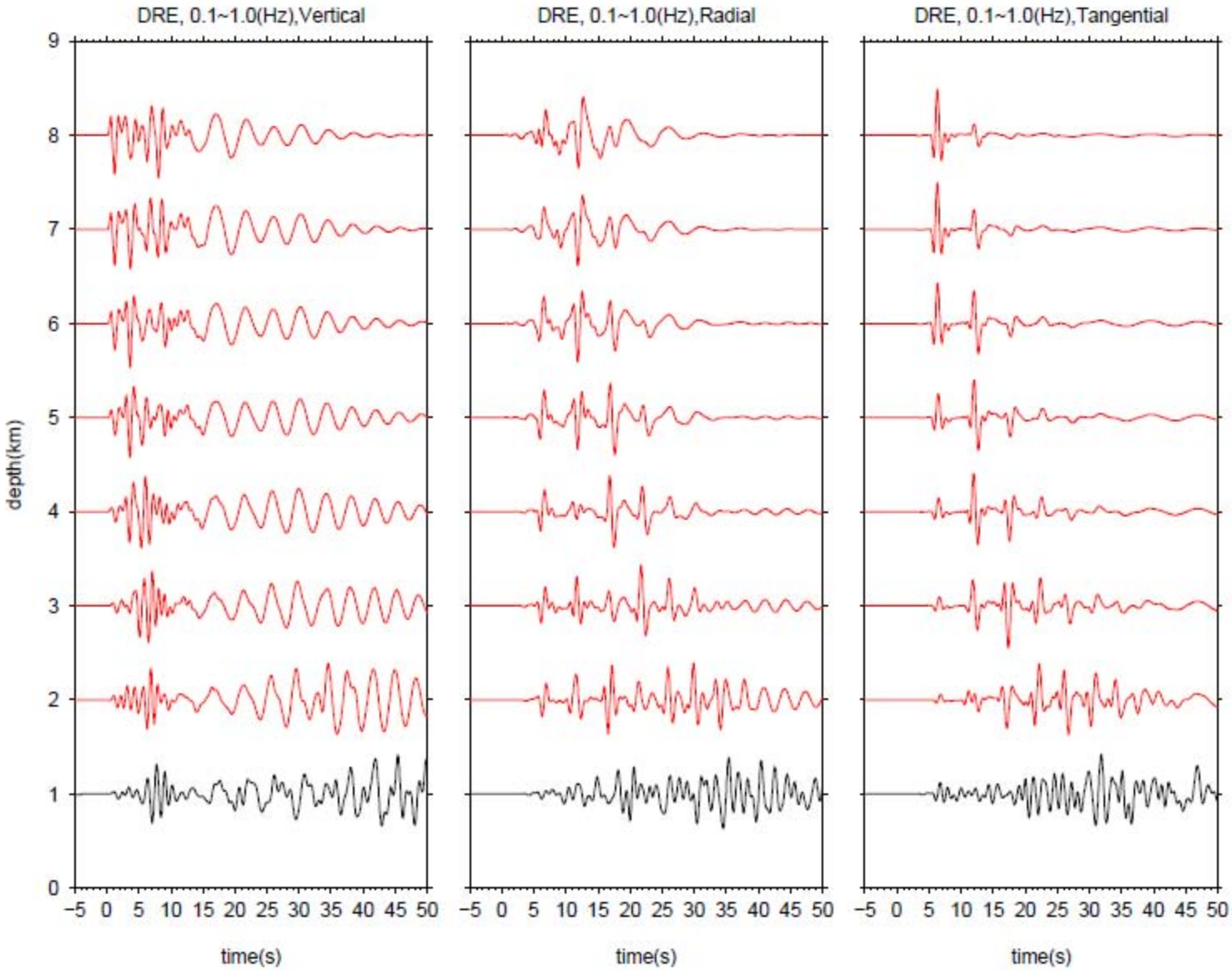
Event 15202921 Model SNRmod4_2.5 FM 29 41 −76 rms 8.567e−02 3915 ERR 0 0 1
Frequency band for Pnl: 0.05 ~ 0.20(Hz) Frequency band for Surface Wave: 0.05 ~ 0.10(Hz)



Waveform inversions at different frequency bands show similar results

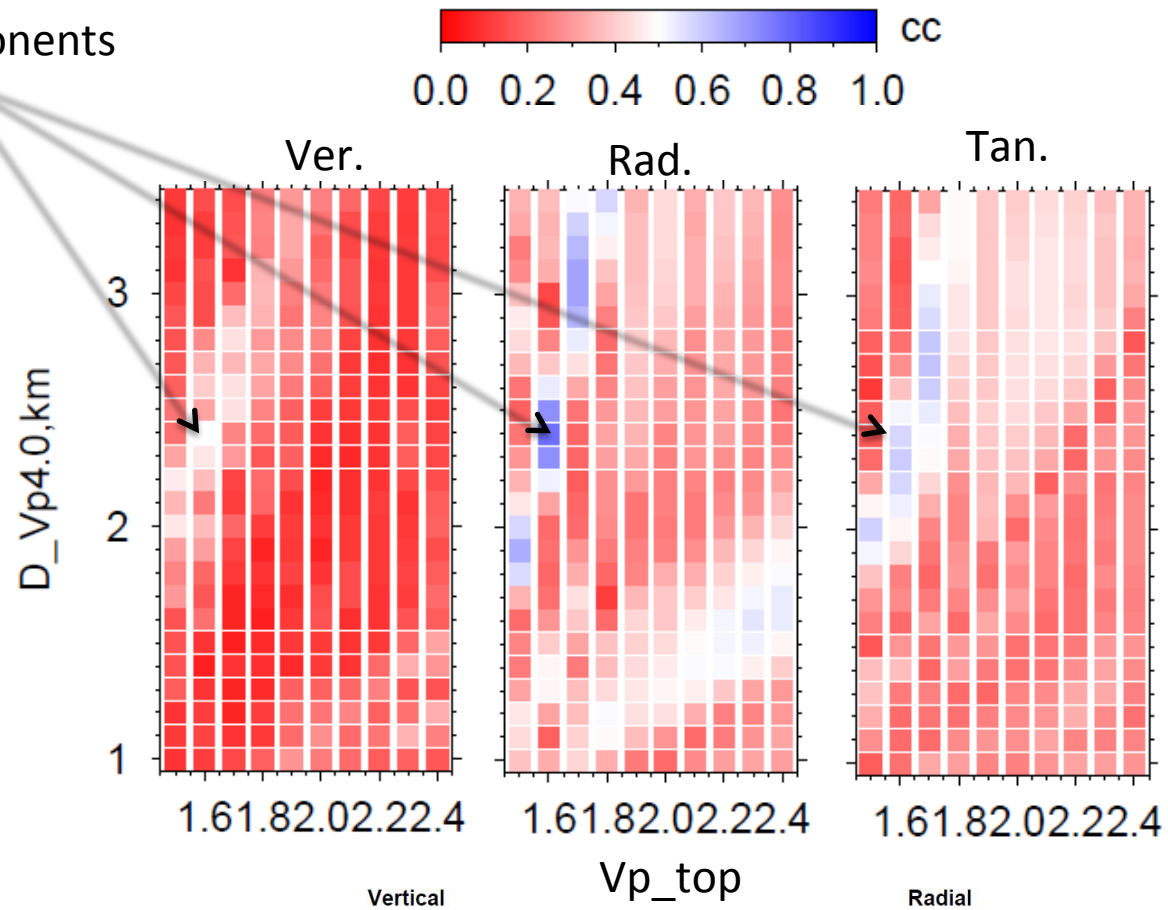

Q0044, 0.1~1.0(Hz),Vertical
Q0044, 0.1~1.0(Hz),Radial
Q0044, 0.1~1.0(Hz),Tangential
depth(km)
time(s)
time(s)
time(s)
Q0044
5km
2km
4km

DRE at 30km

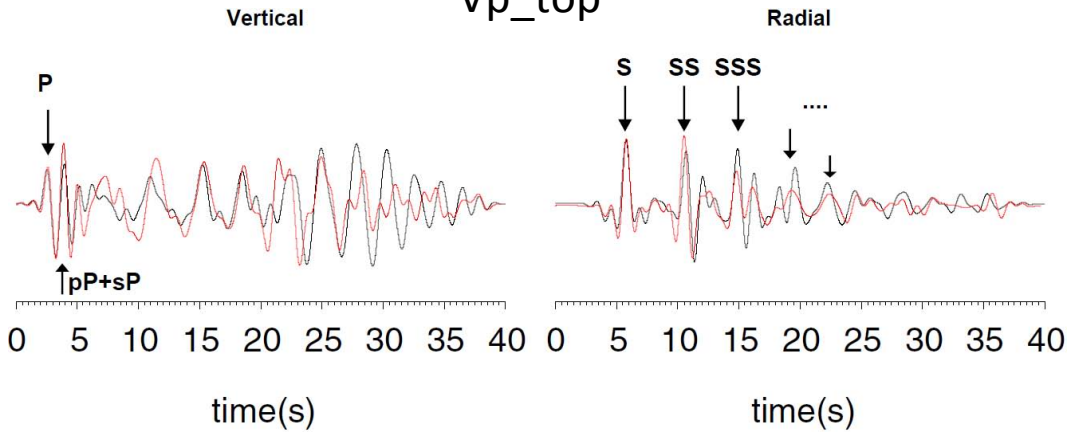

DRE, 0.1~1.0(Hz),Vertical
DRE, 0.1~1.0(Hz),Radial
DRE, 0.1~1.0(Hz),Tangential
depth(km)
0
1
2
3
4
5
6
7
8
9
−5 0 5 10 15 20 25 30 35 40 45 50
time(s)

Only a small window fits all components

Grid Search result using the M4.6 event

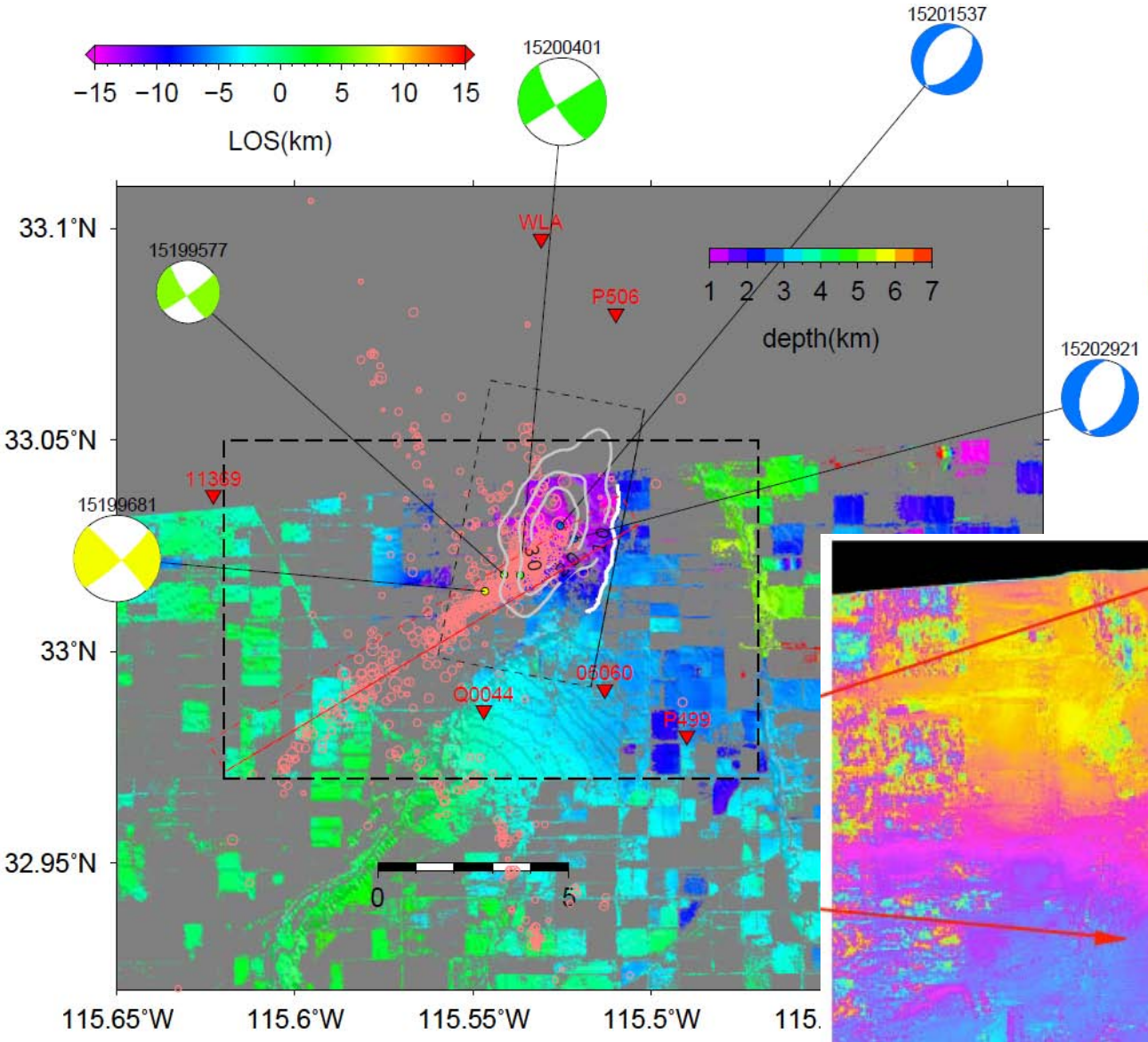


Station: 11369

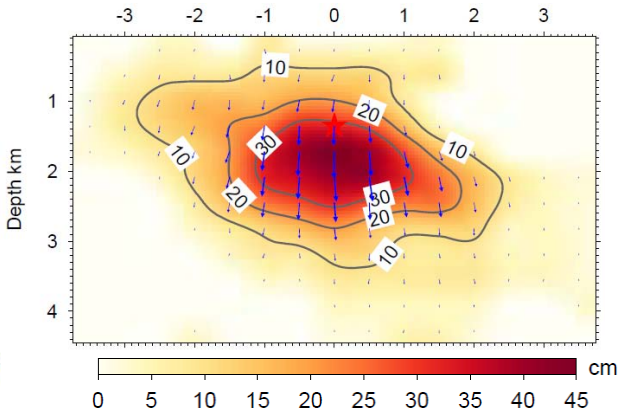


1Hz Velocity

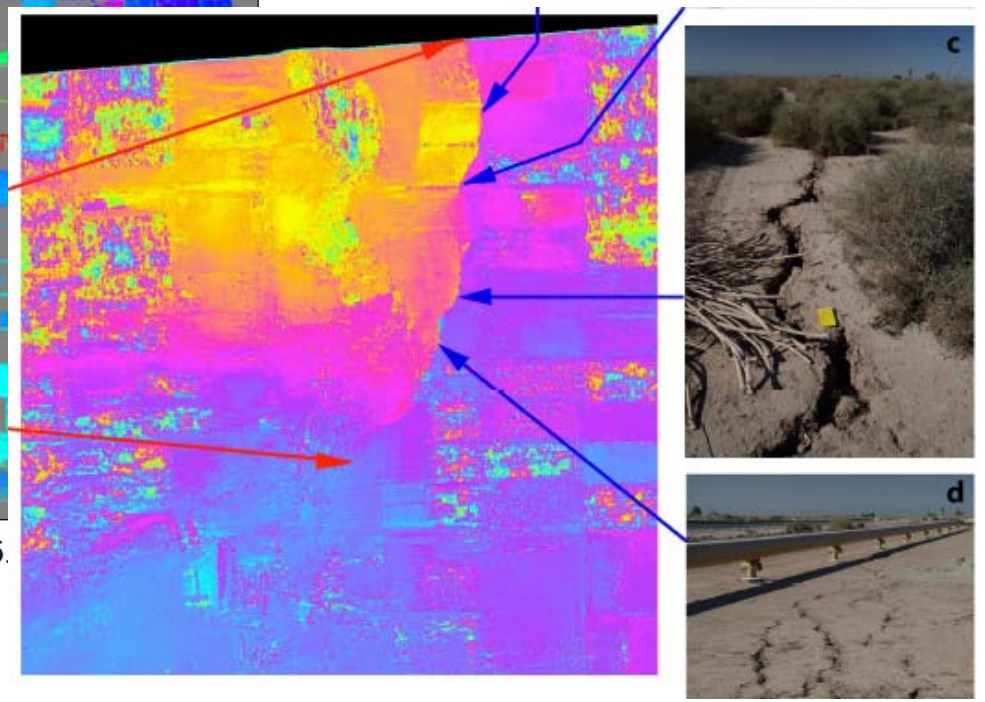
UAVSAR data (RPI 265) and field observation



Static only inversion

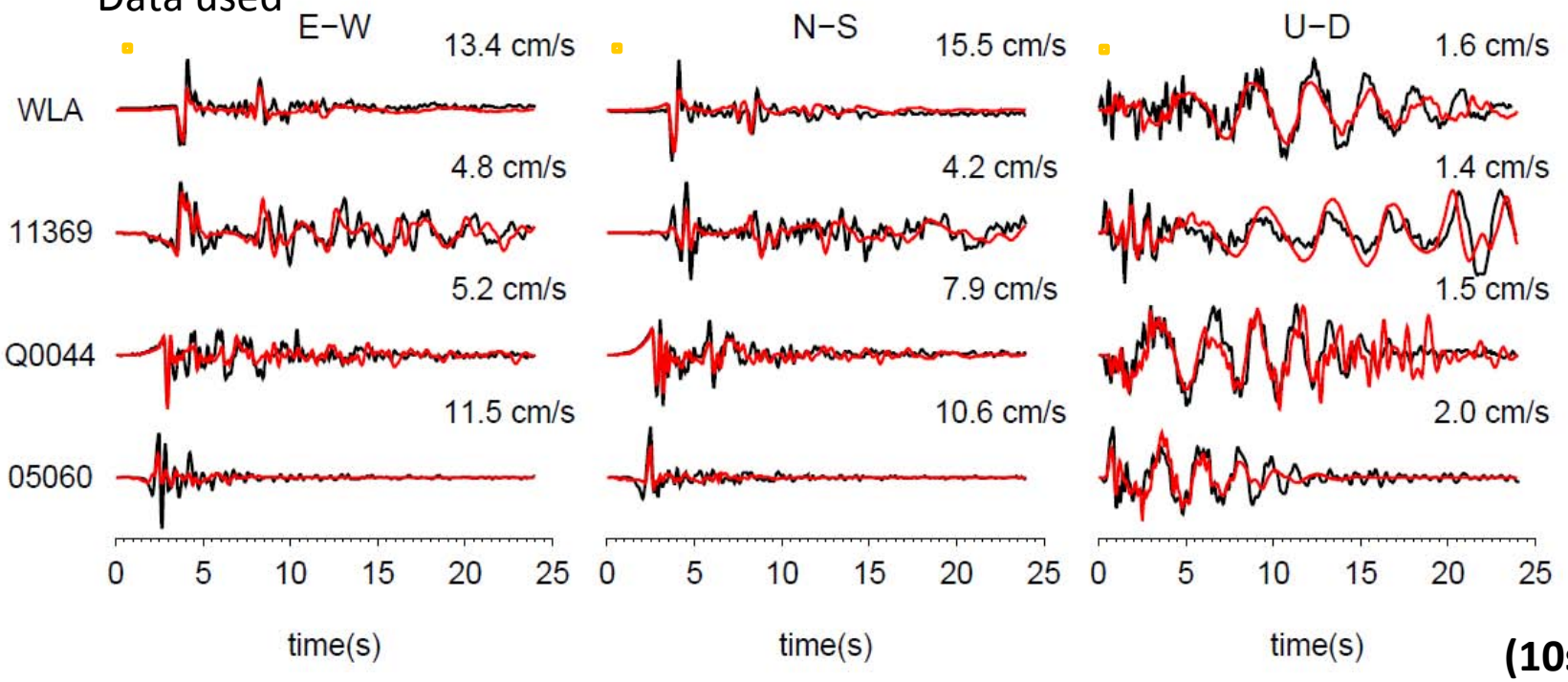


Poster: 058 (by Ken Hudnut)

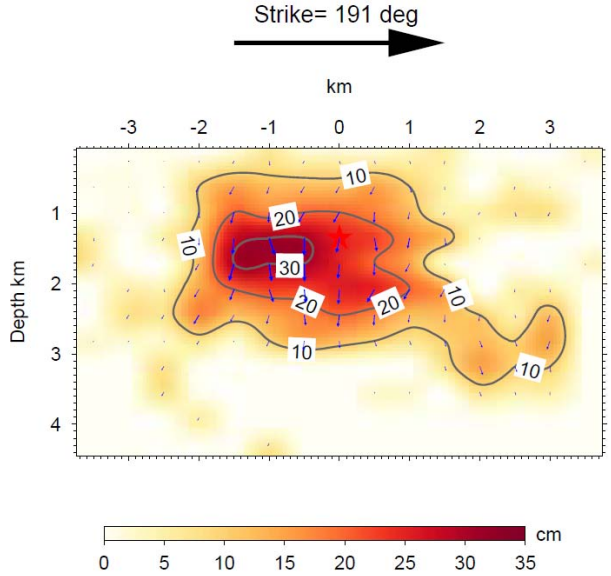


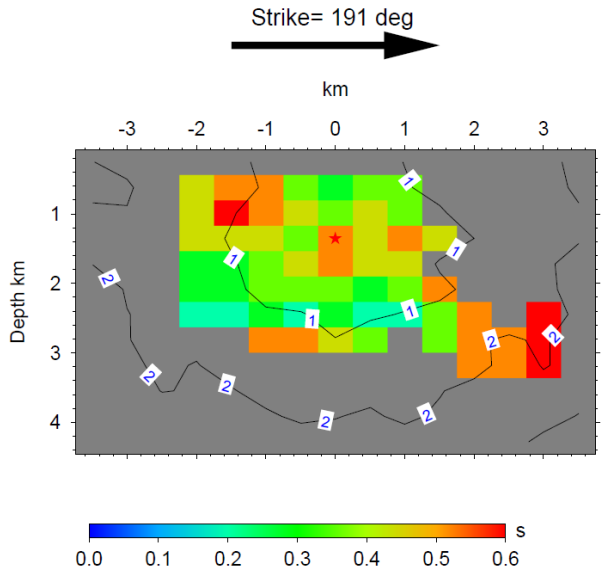
Strong motion waveform fits and prediction

Data used

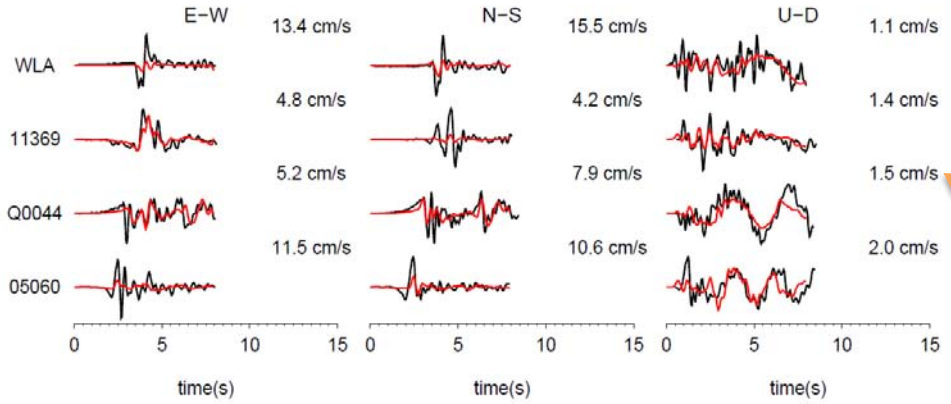


(10s~4Hz)

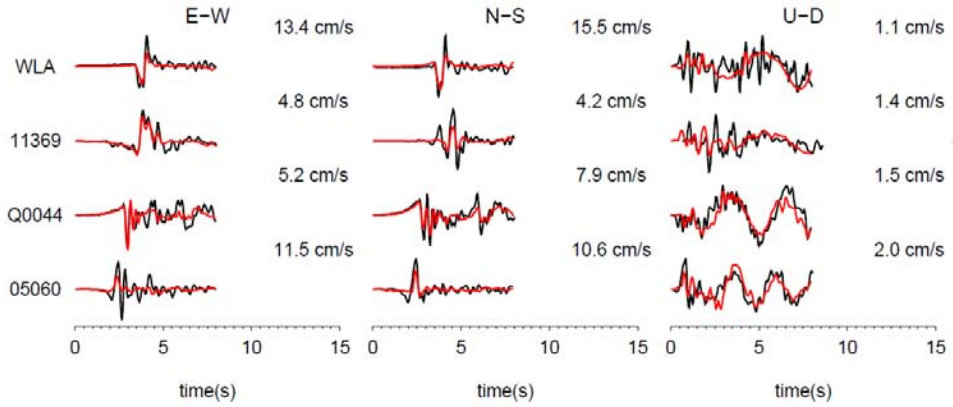




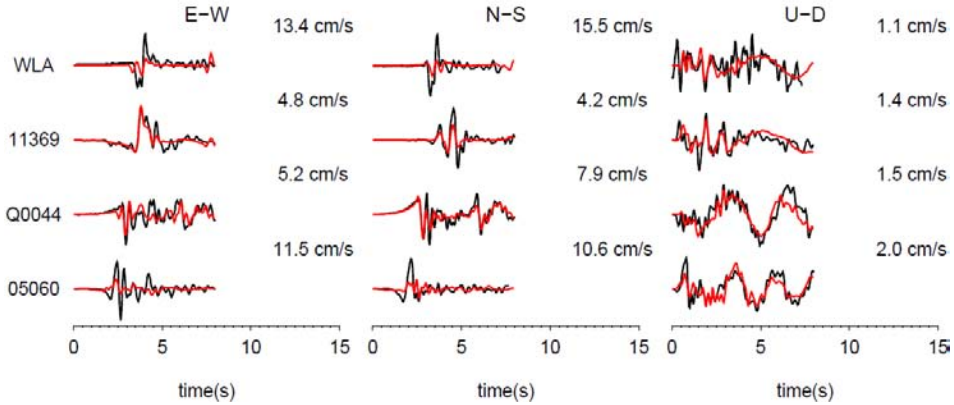
Vr=1.25km/s



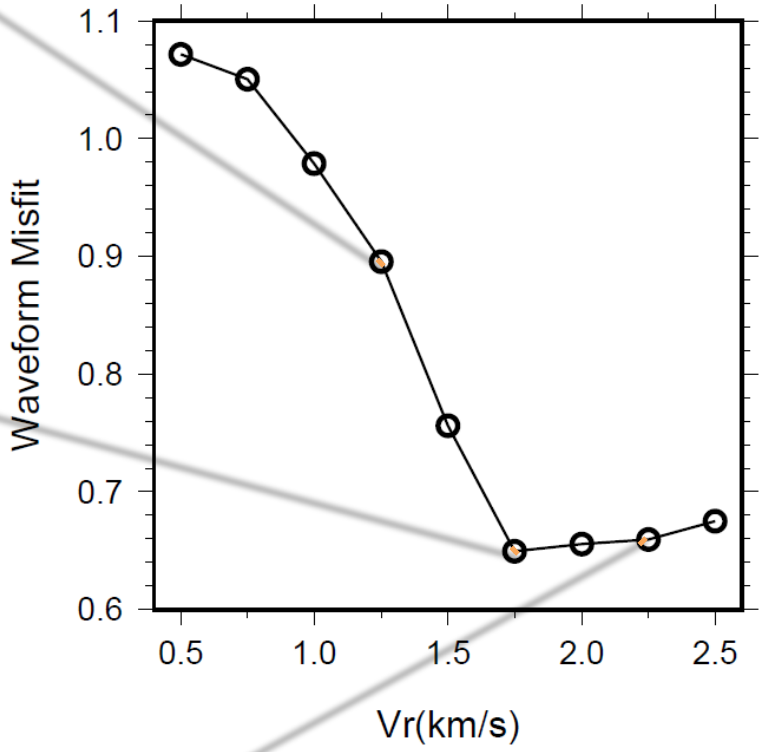
Vr=1.75km/s



Vr=2.25km/s

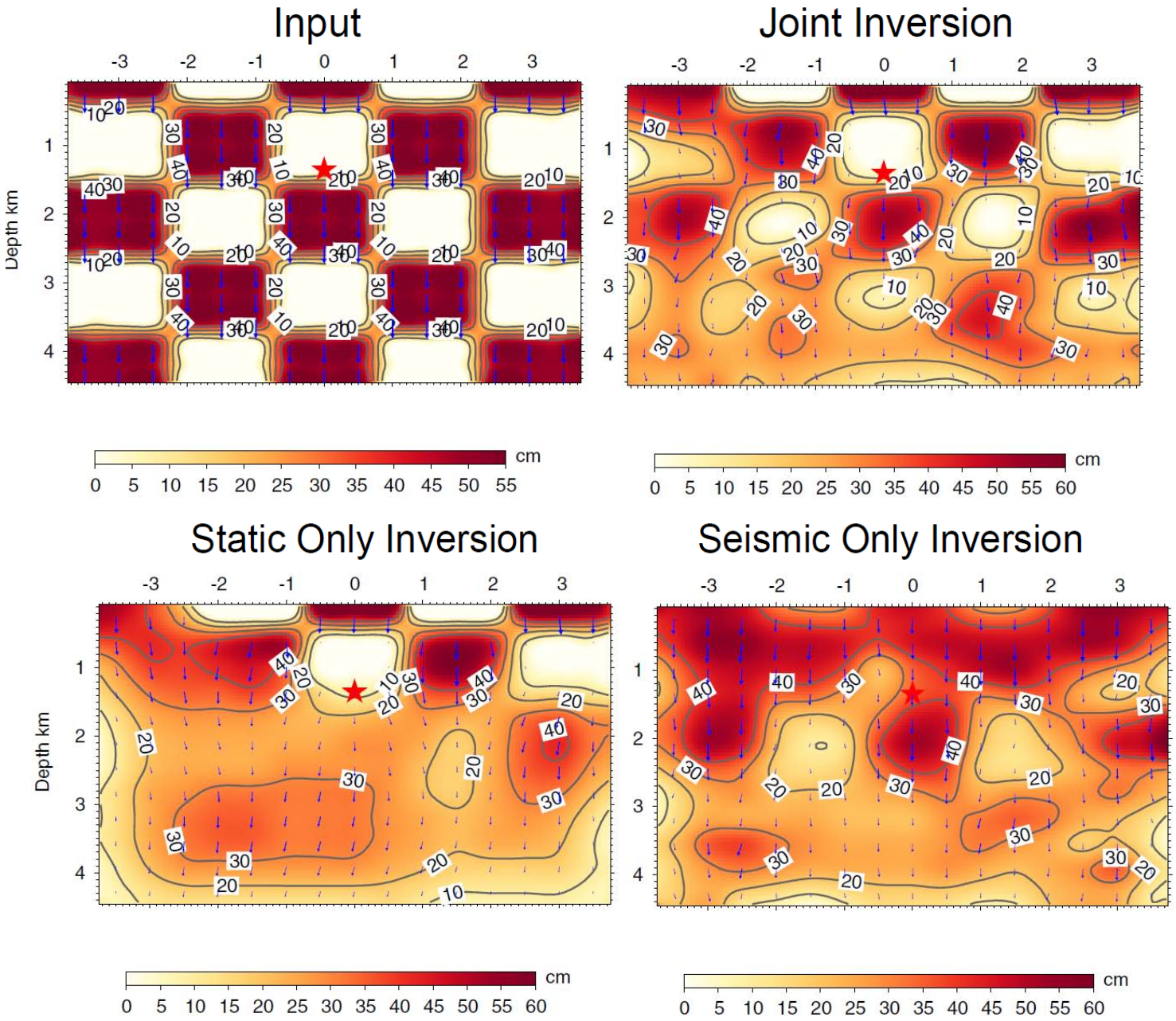


Rupture Velocity



Enough redundancy is set for the rise time

Resolution tests

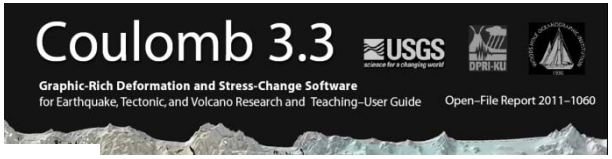


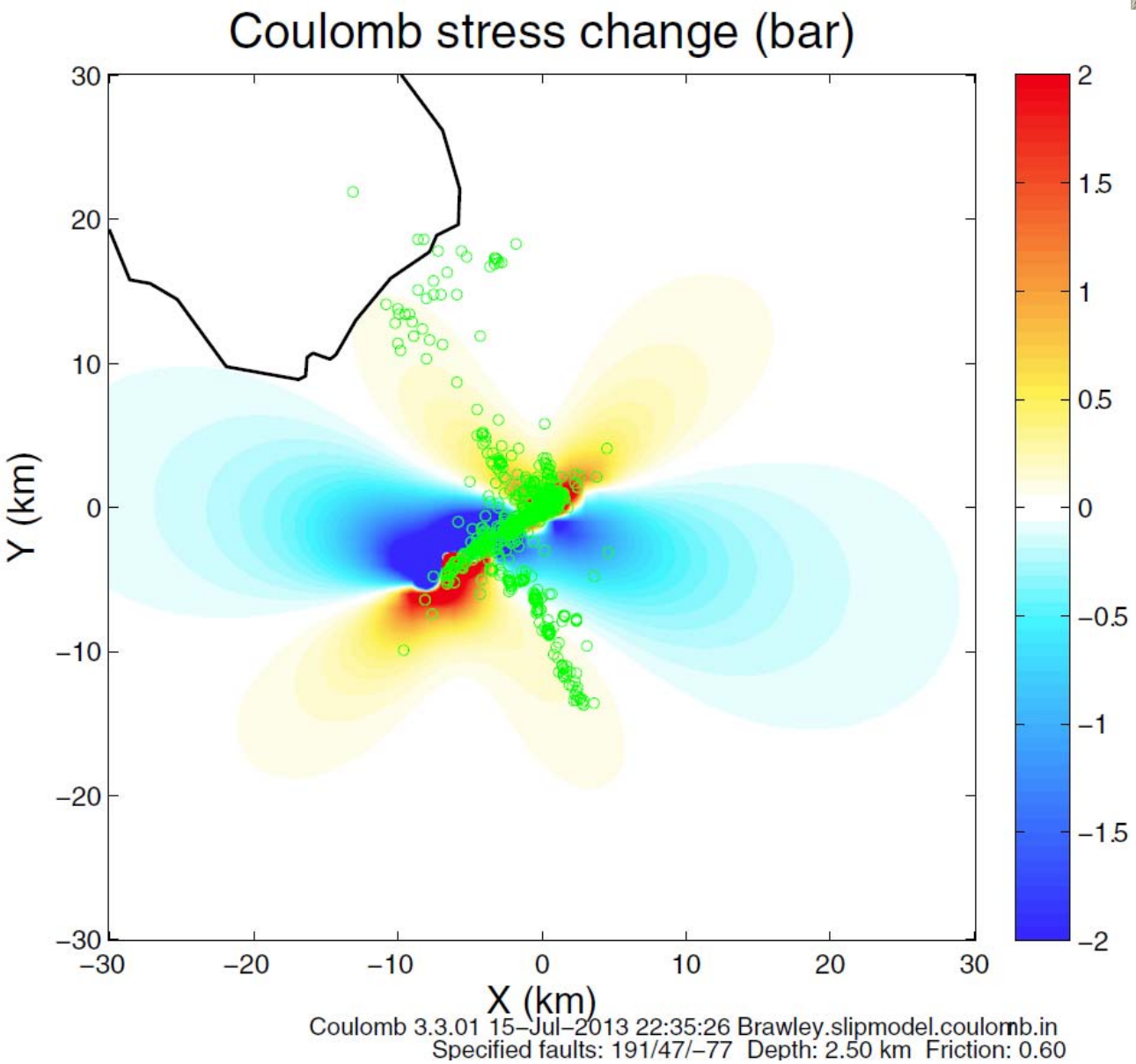
Conclusion

- Path calibrations are needed for high resolution finite fault inversions.
- M5.3 and M5.4 events have complementary slip distribution. (Similar result for the recent Mw8.3 Sea of Okhotsk Earthquake obtained with teleseismic path calibrations, poster number: 091)
- The shallow M4.9 normal earthquake has a centroid depth of ~2.0km and average rupture speed is 1.75km/s. (more details see poster: 058)

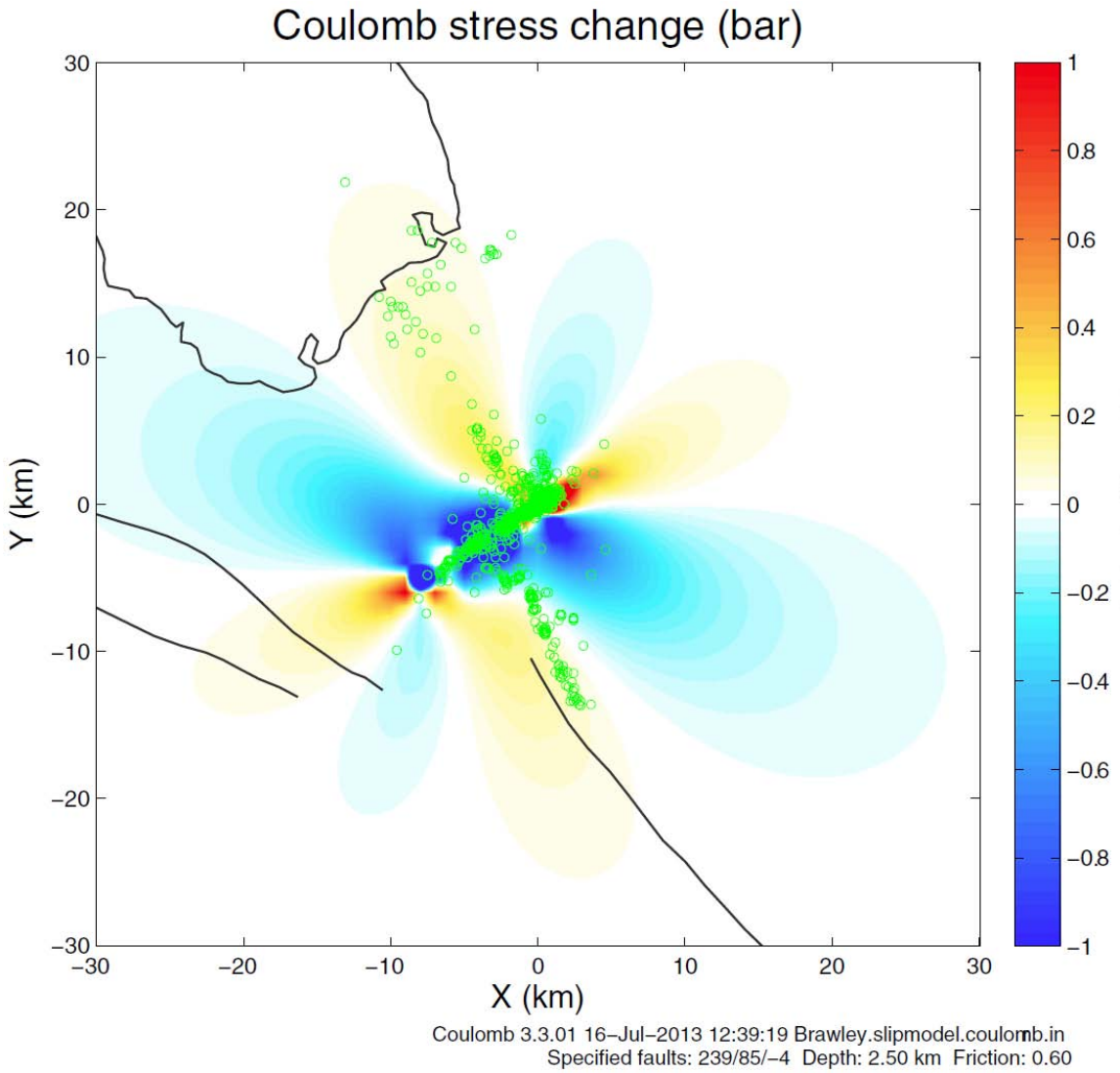
Thanks for your attention!

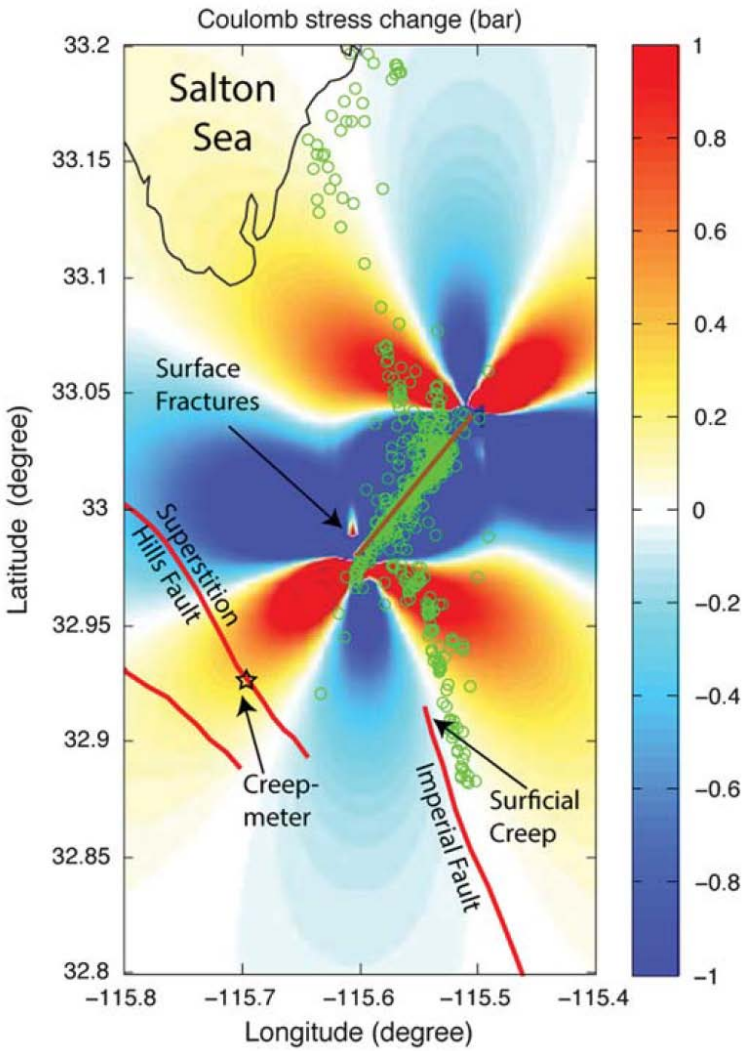
Normal Faulting



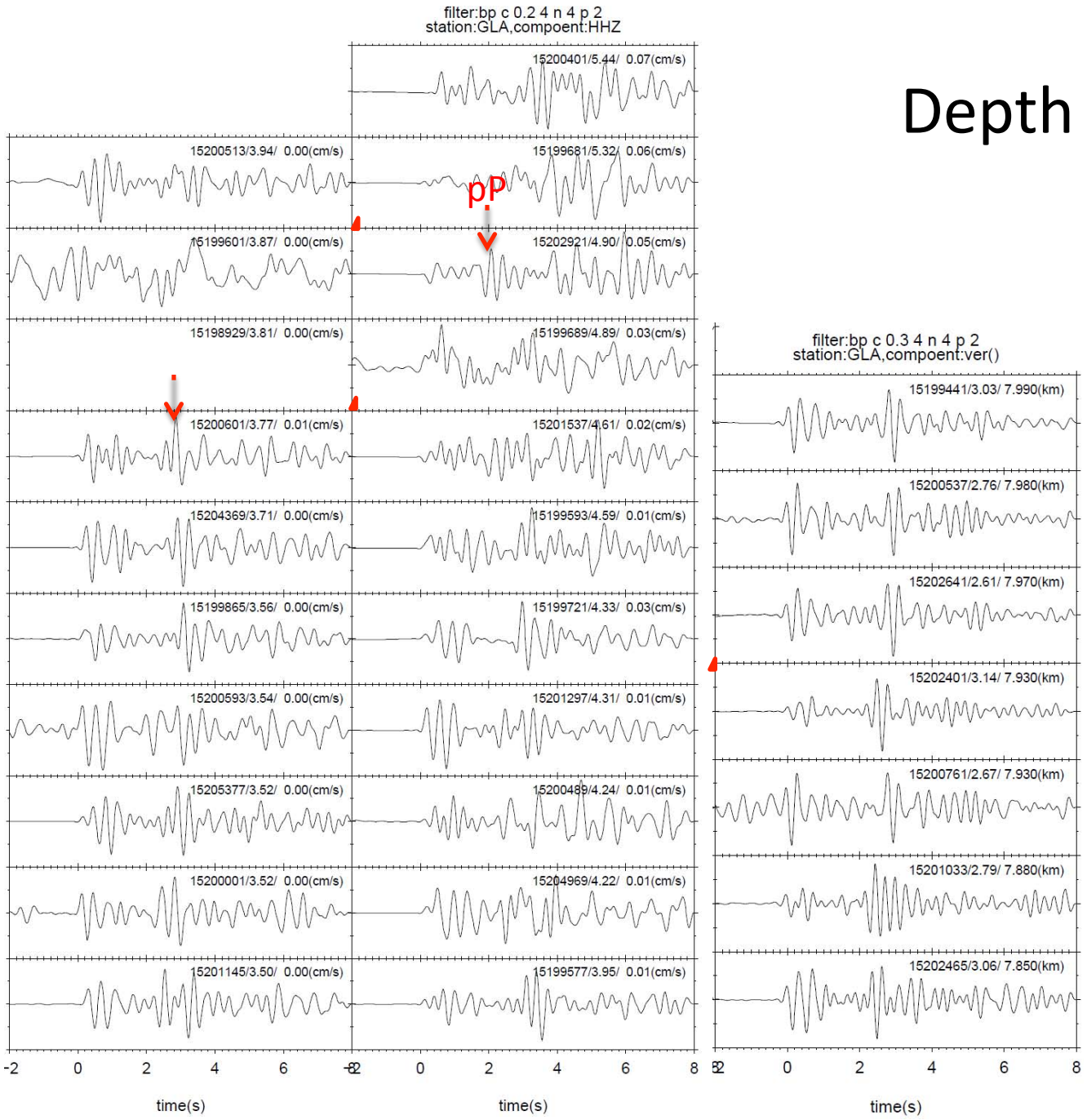


Strike-Slip Faulting





Hauksson et. al., 2013

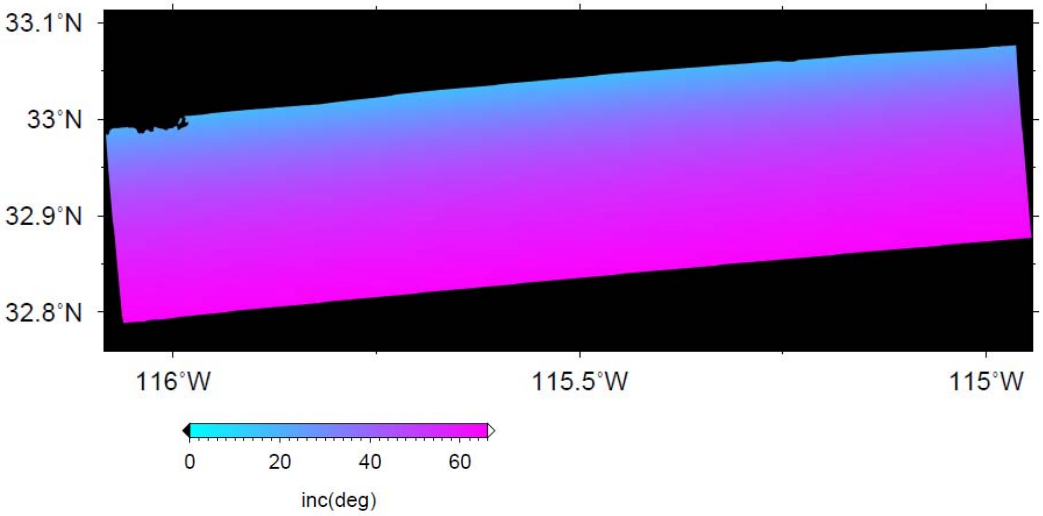


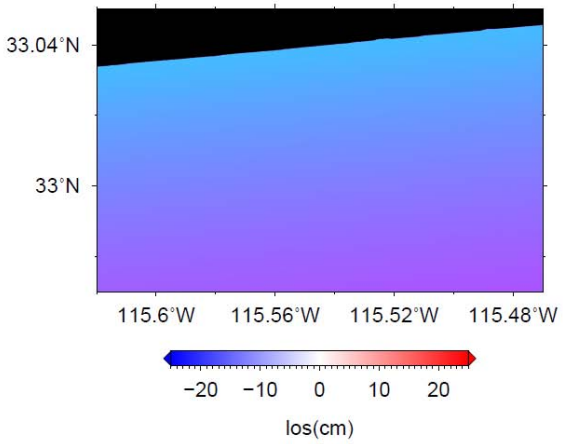
Depth Phases

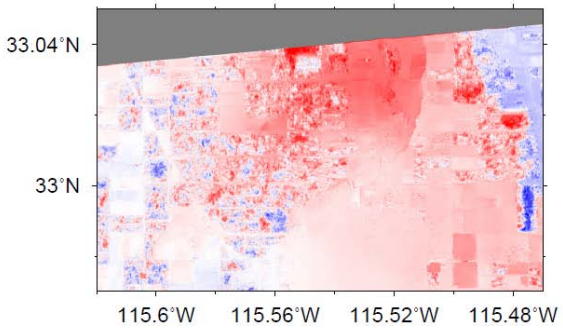
Time table (PCM)

Dep(km)	Tp(s)	Ts(s)
1.00	0.469	1.609
1.50	0.646	2.008
2.00	0.800	2.314
2.50	0.935	2.562
3.01	1.059	2.779
3.51	1.176	2.981
4.01	1.285	3.169
4.51	1.387	3.346
5.01	1.484	3.512
7.54	1.945	4.305
9.74	2.334	4.974
11.9	2.712	5.625

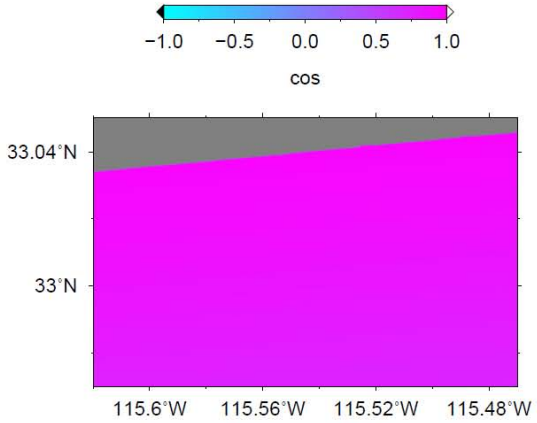
Looking Angle



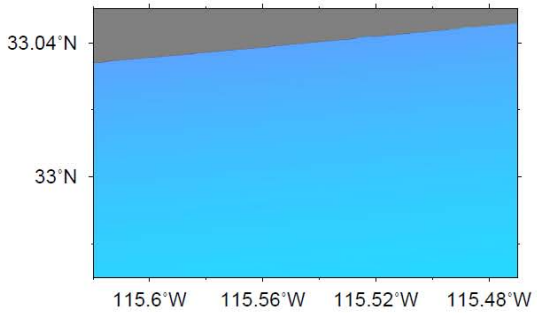




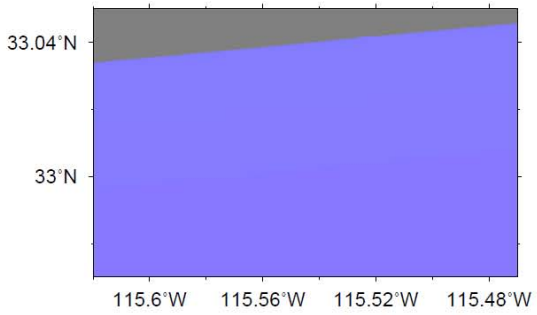
Direction Cosine



U-D

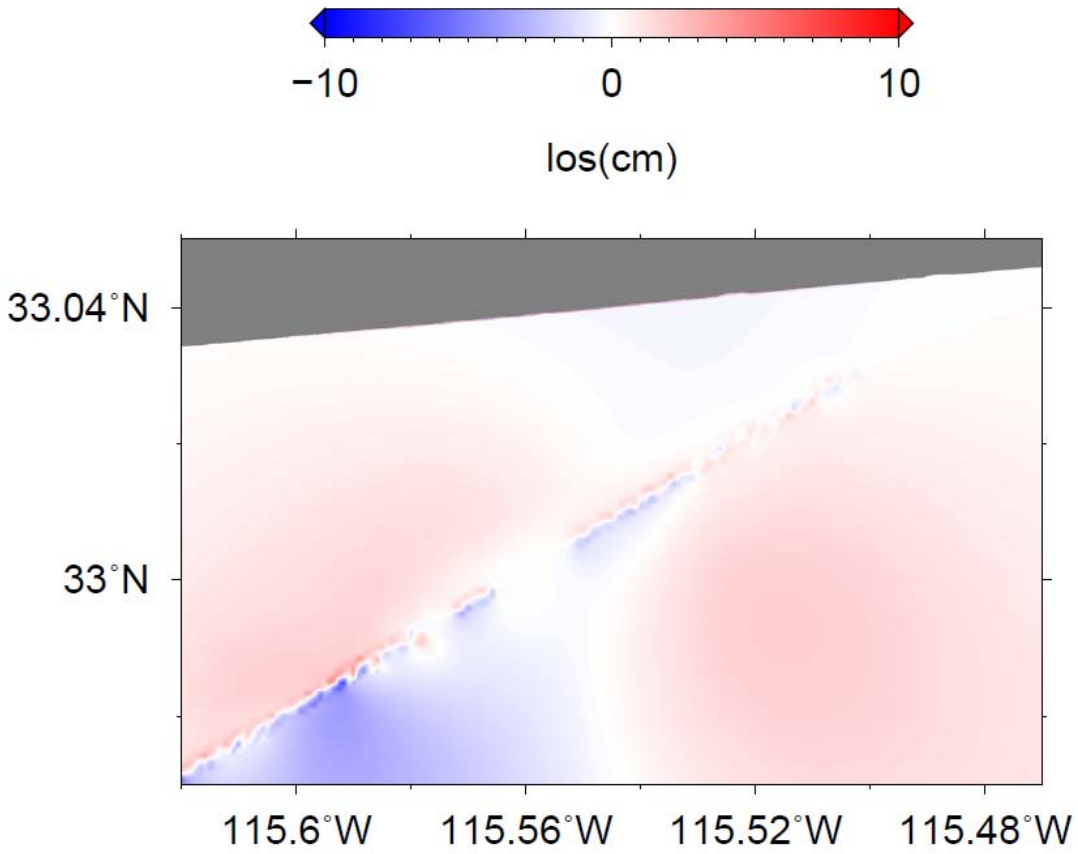


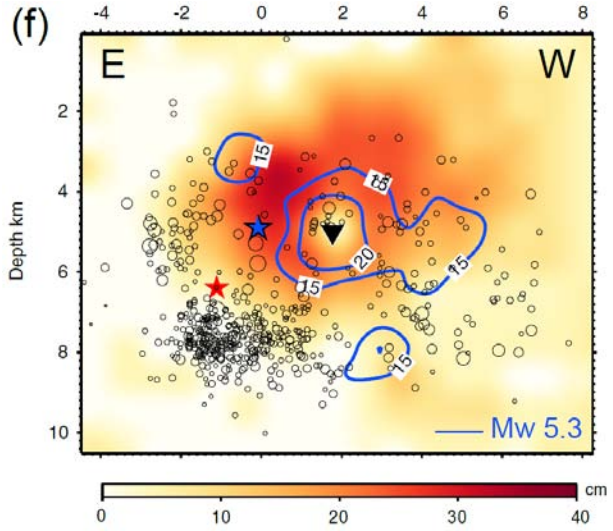
N-S



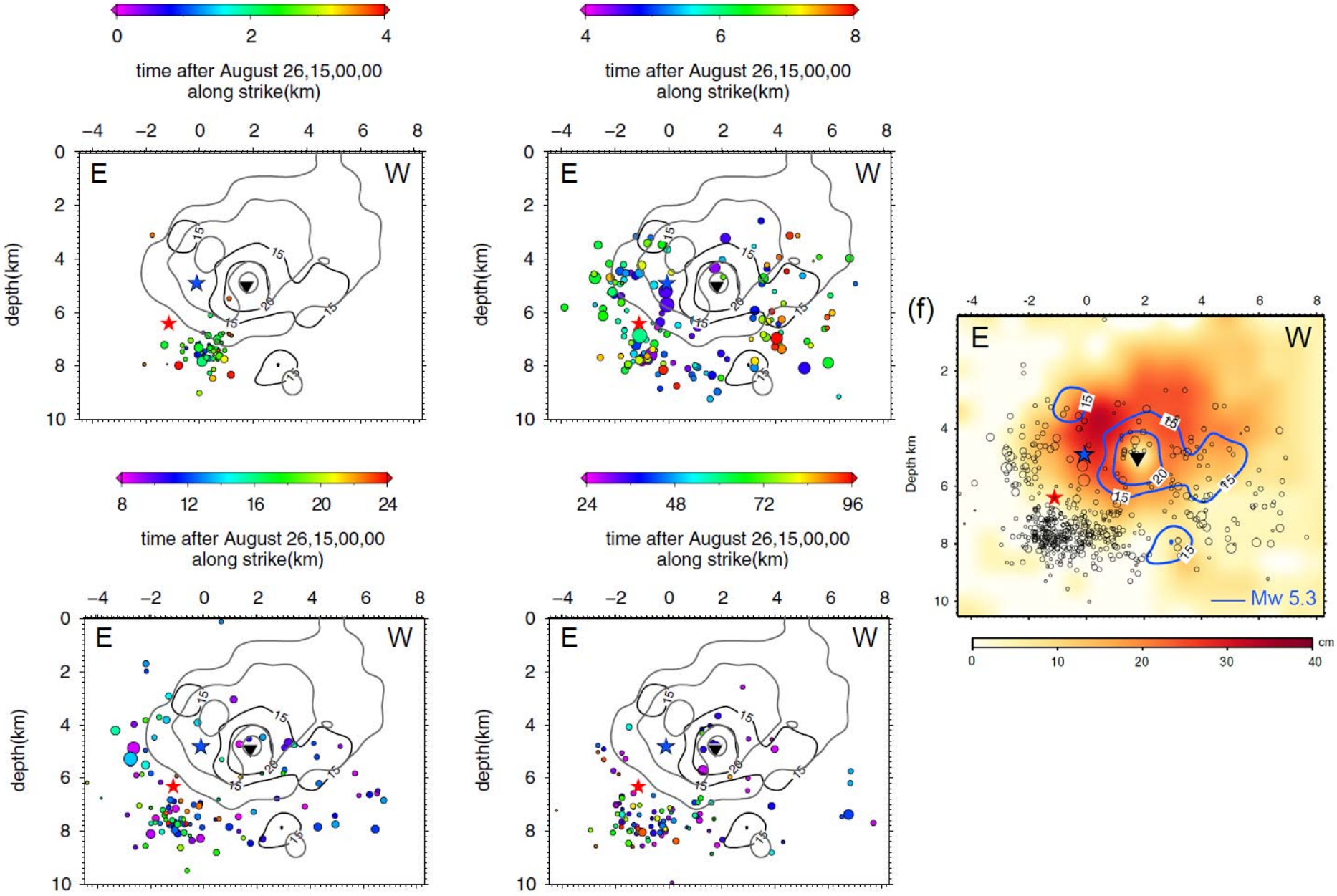
E-W

LOS prediction from the slip models of M5.4 and M5.3





4 Days Seismicity



North Brawley Operations

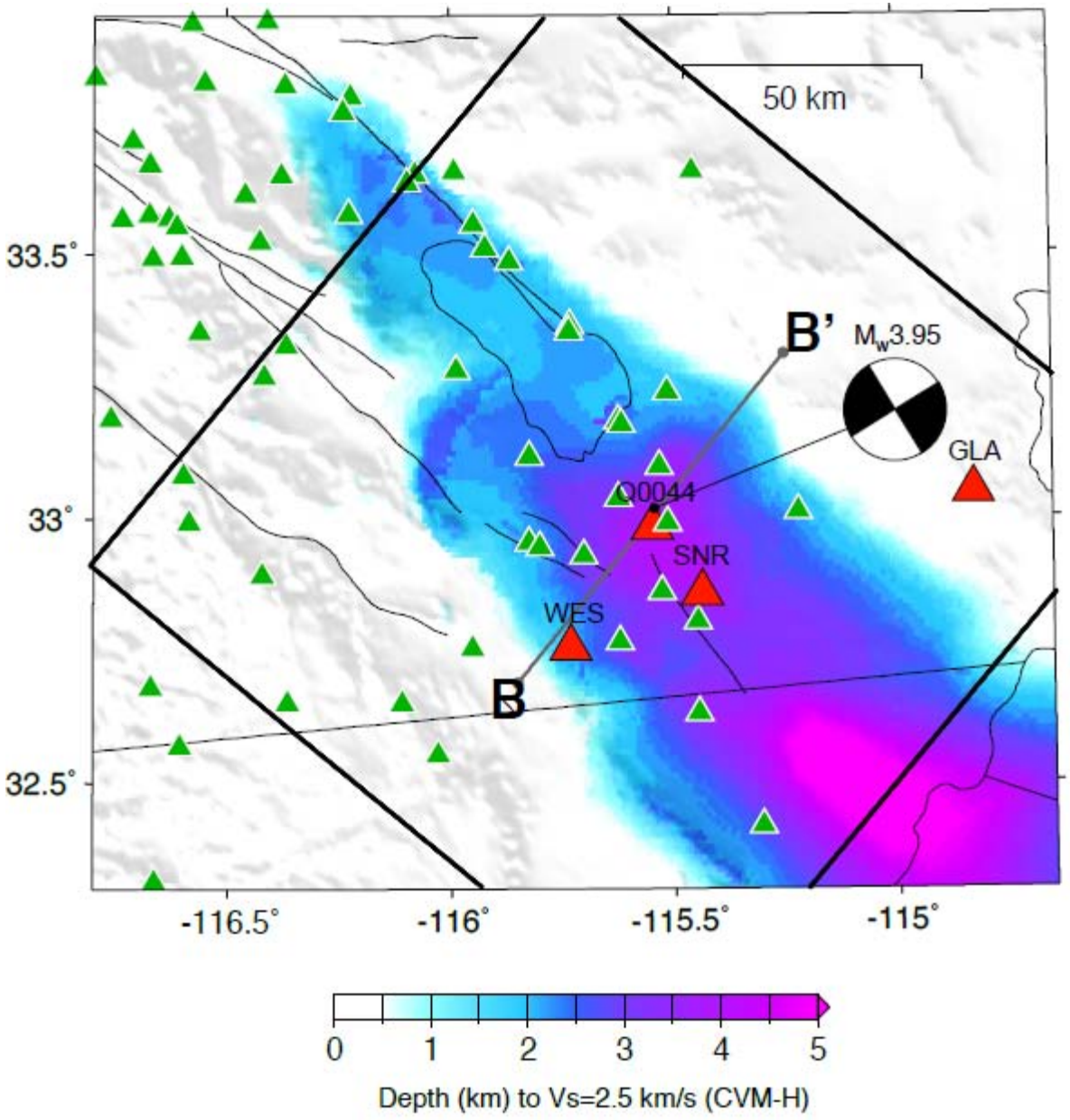
- North Brawley: 49.9 MW net - 2009
  - Currently operating at approximately 33 net MW
- Annual Volume of Fluid Produced: 57,000 million gallons
- Annual Volume of Fluid Injected: 53,000 million gallons
- 19 injection wells
  - Average well depth 3900 feet
  - Injection all < 3500 feet
  - Deepest injection at ~6000 feet
- Salinity: Average 40,000 ppm (TDS)
- Binary Fluid Injection Temperature: 150 F
  - Temperature in the Injection Zone : 150 to 410 F
- Injection Rate: Average is 525 gpm
- Injection Pressure: Average is 330 psig
- Not allowed to exceed fracture gradient at shallowest perforations

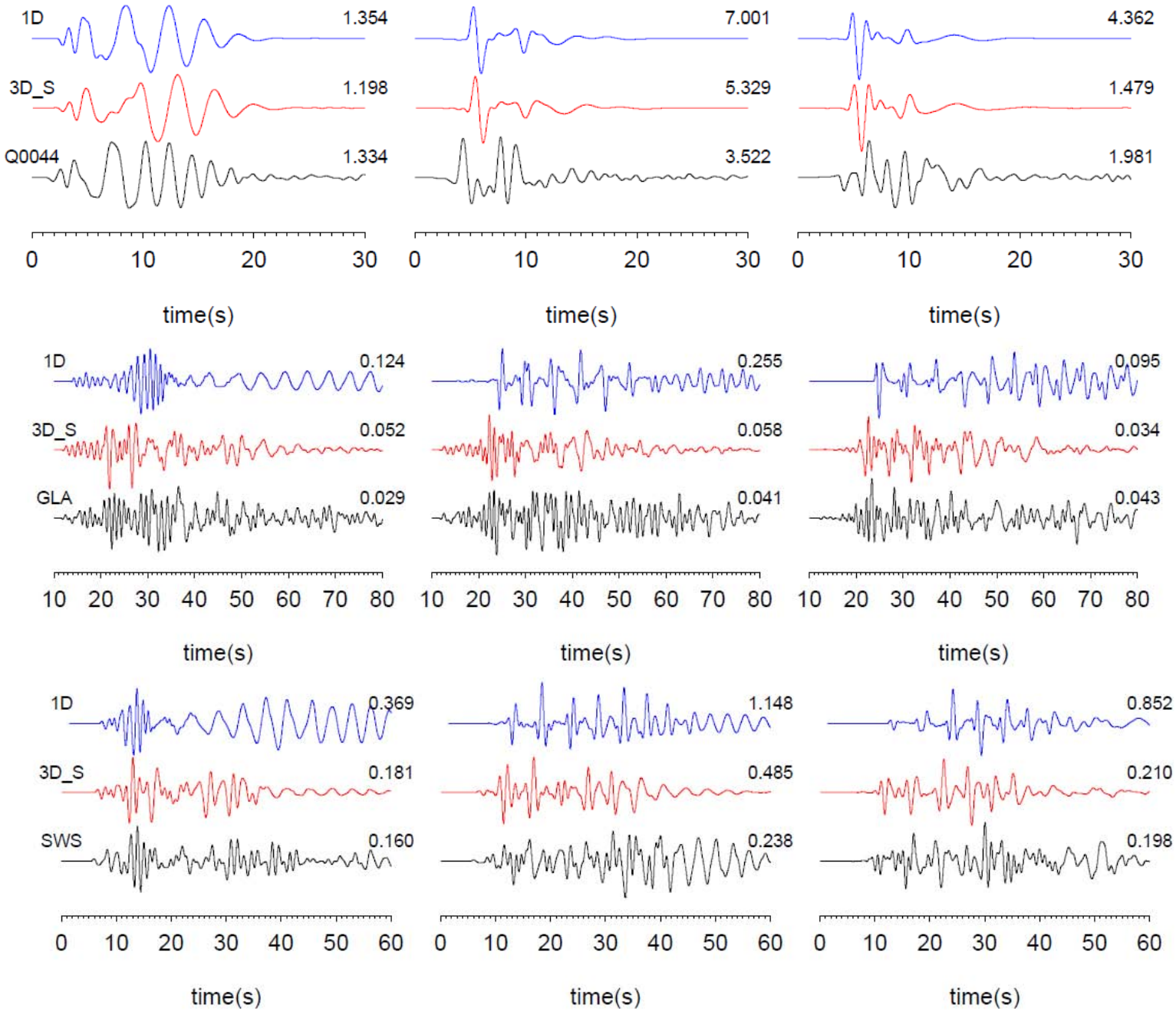
North Brawley Seismic Array and Wells

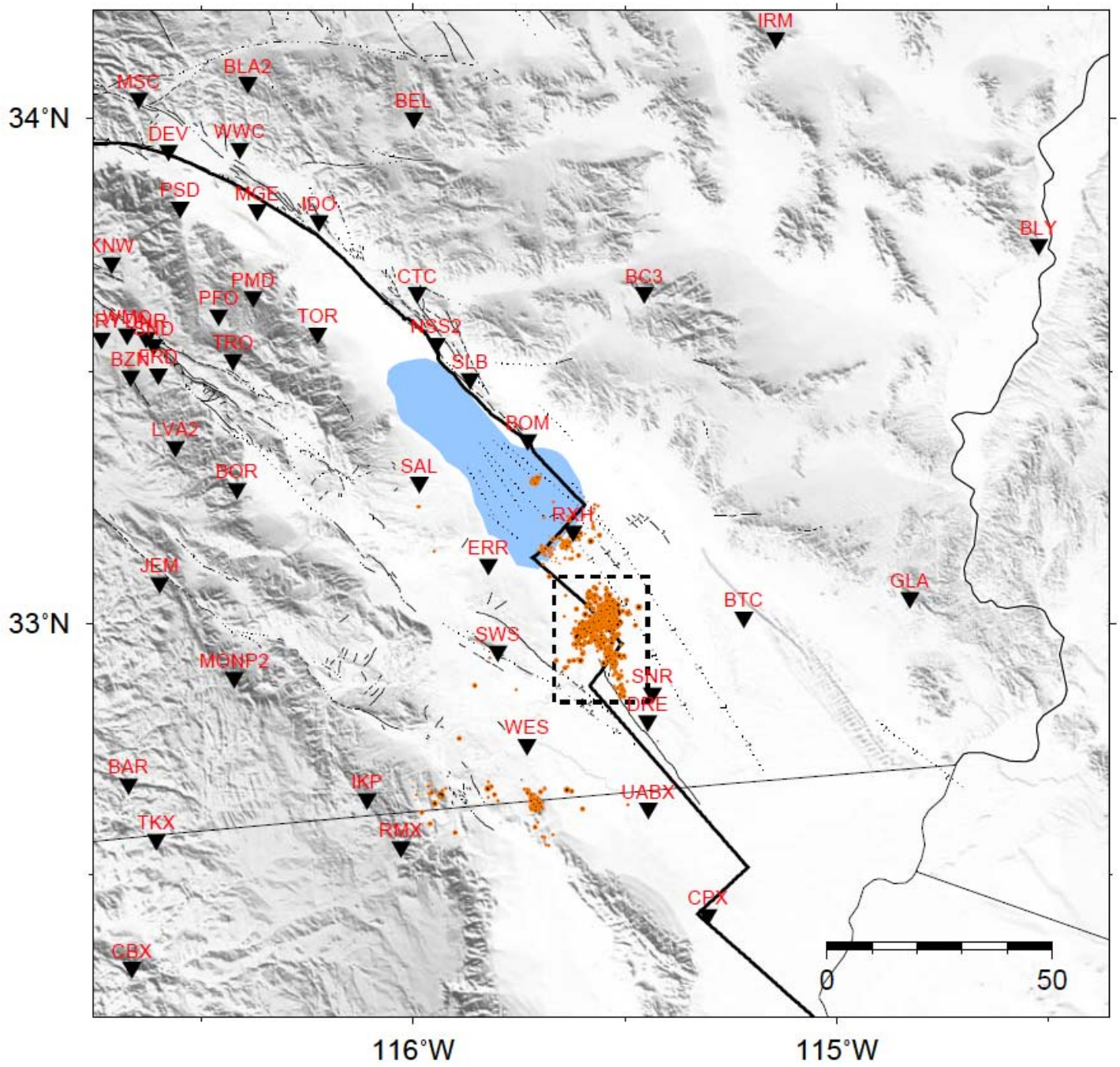
Production wells: RED

Injection wells: BLUE

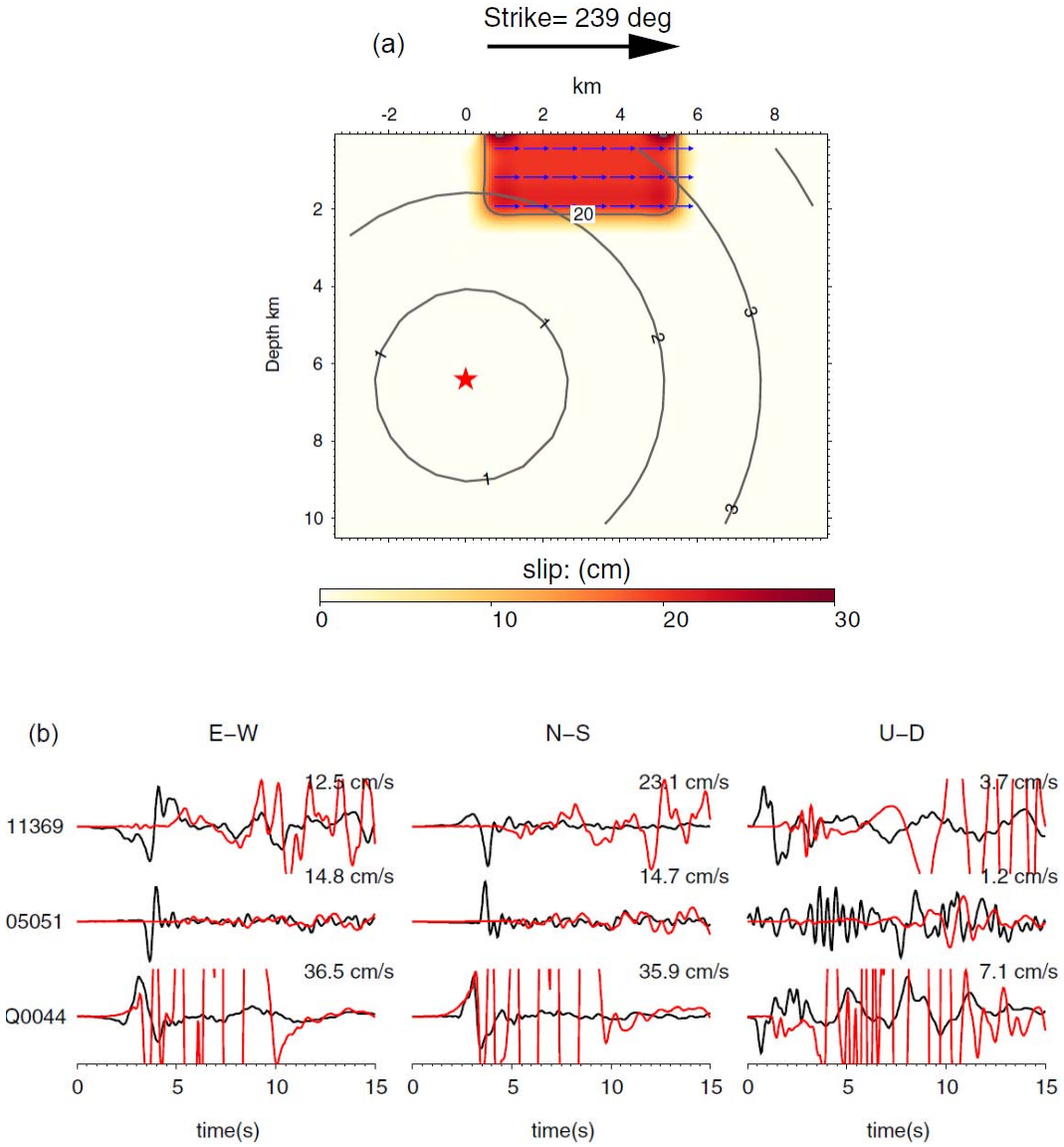
Seismic Stations: YELLOW


50 km
33.5°
33°
32.5°
-116.5°
-116°
-115.5°
-115°
B'
B
M_w3.95
GLA
Q0044
SNR
WES
0
1
2
3
4
5
Depth (km) to Vs=2.5 km/s (CVM-H)

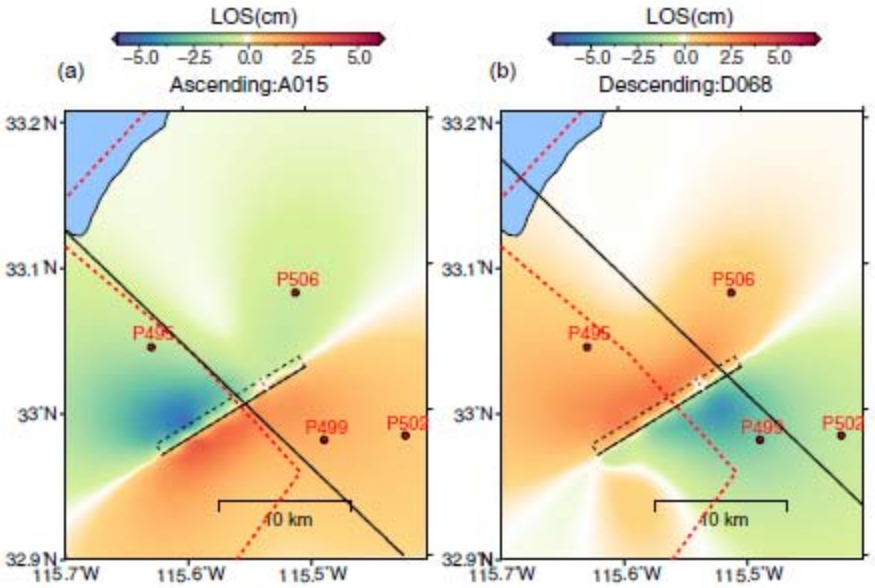

1D
1.354
3D_S
1.198
Q0044
1.334
7.001
5.329
3.522
4.362
1.479
1.981
0 10 20 30
time(s)
1D
0.124
3D_S
0.052
GLA
0.029
0.255
0.058
0.041
0.095
0.034
0.043
10 20 30 40 50 60 70 80
time(s)
1D
0.369
3D_S
0.181
SWS
0.160
1.148
0.485
0.238
0.852
0.210
0.198
0 10 20 30 40 50 60
time(s)

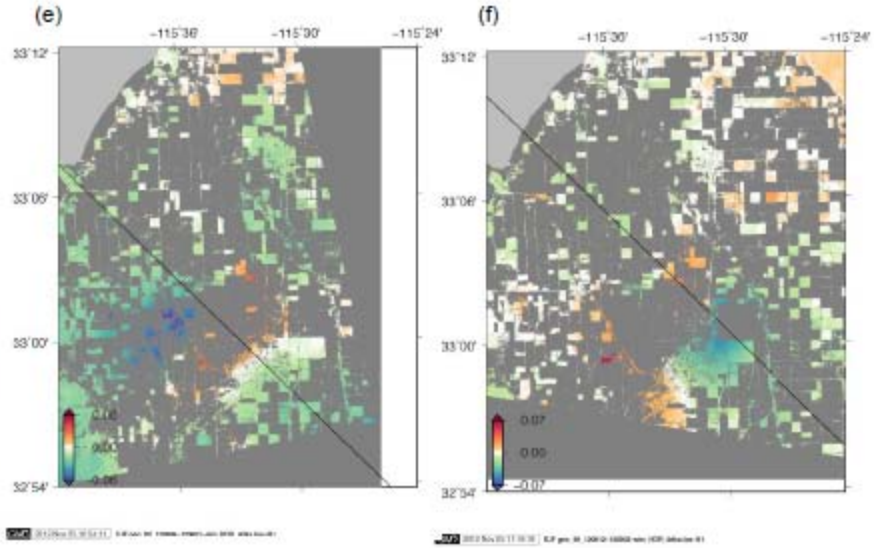

IRM
BLA2
MSC
BEL
DEV
WWC
PSD
MGE
IDO
BLY
KNW
CTC
BC3
PMD
PFO
TOR
NSS2
TRO
SLB
BOM
LVA2
SAL
BOR
RXH
ERR
JEM
GLA
BTC
SWS
MONP2
SNR
DRE
WES
BAR
IKP
UABX
TKX
RMX
CBX
CBX
34°N
33°N
116°W
115°W
0
50

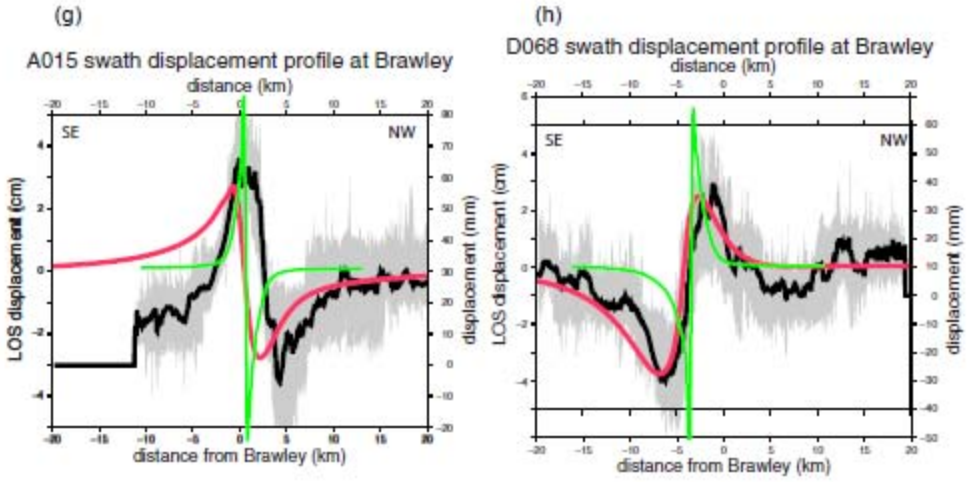
Synthetics test



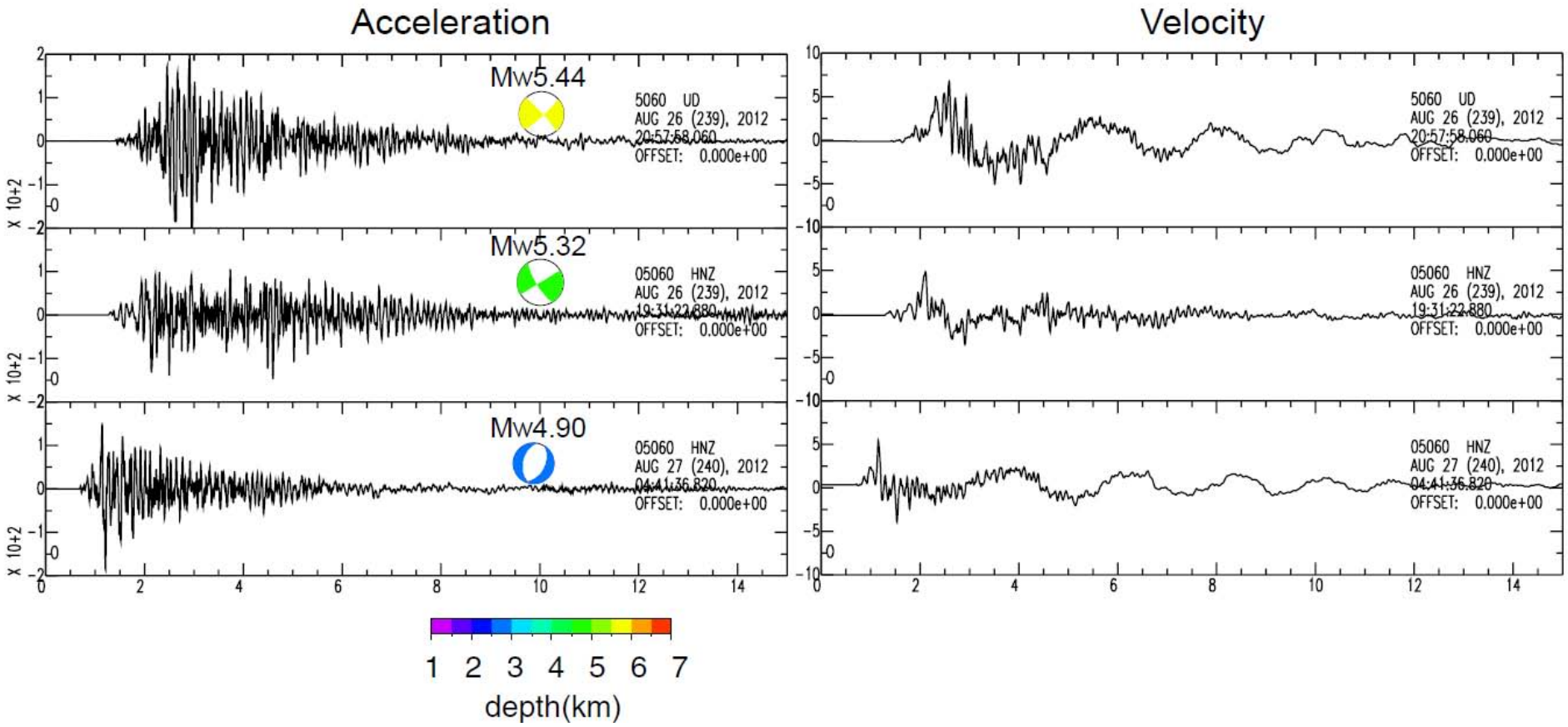
InSAR observations



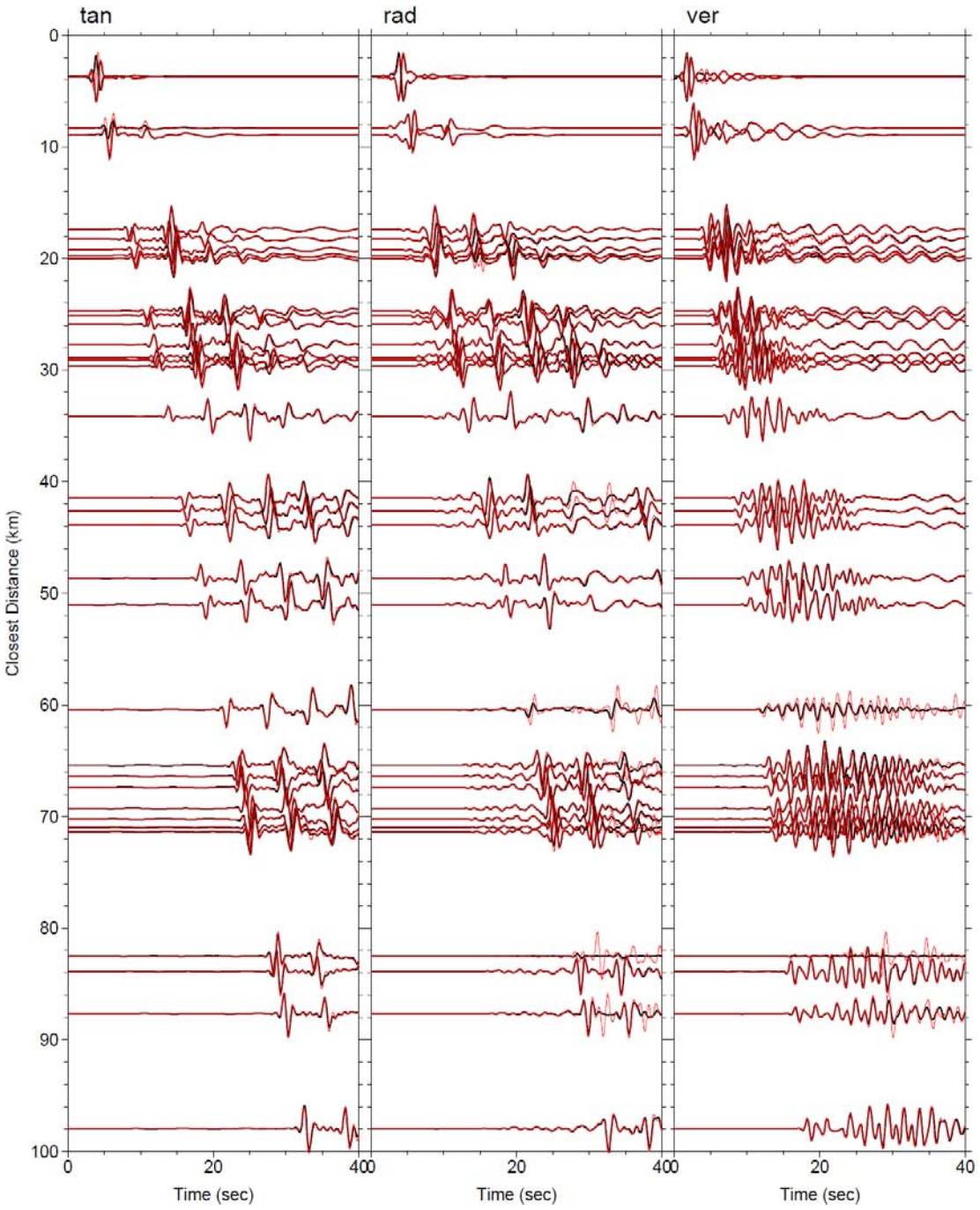


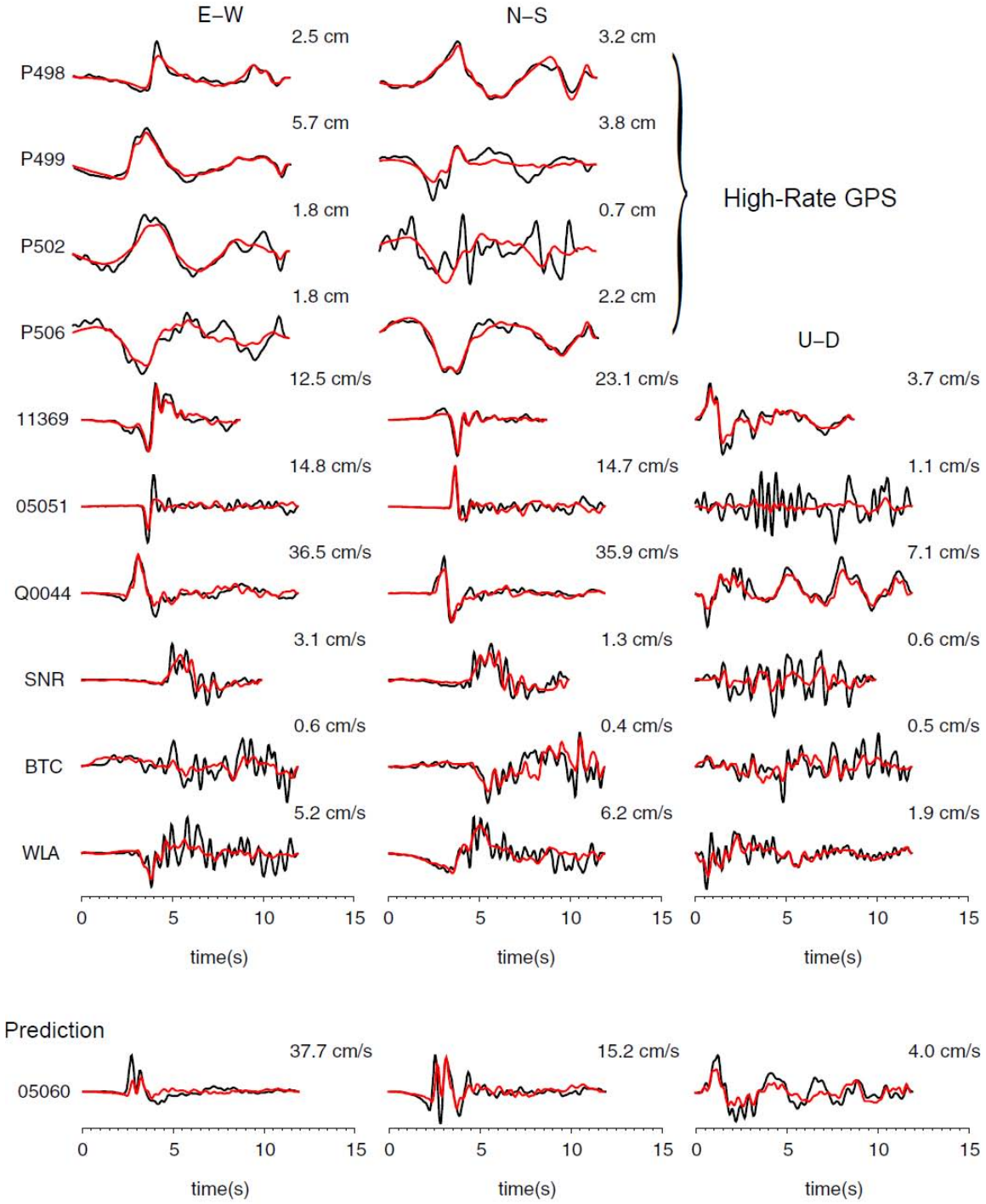


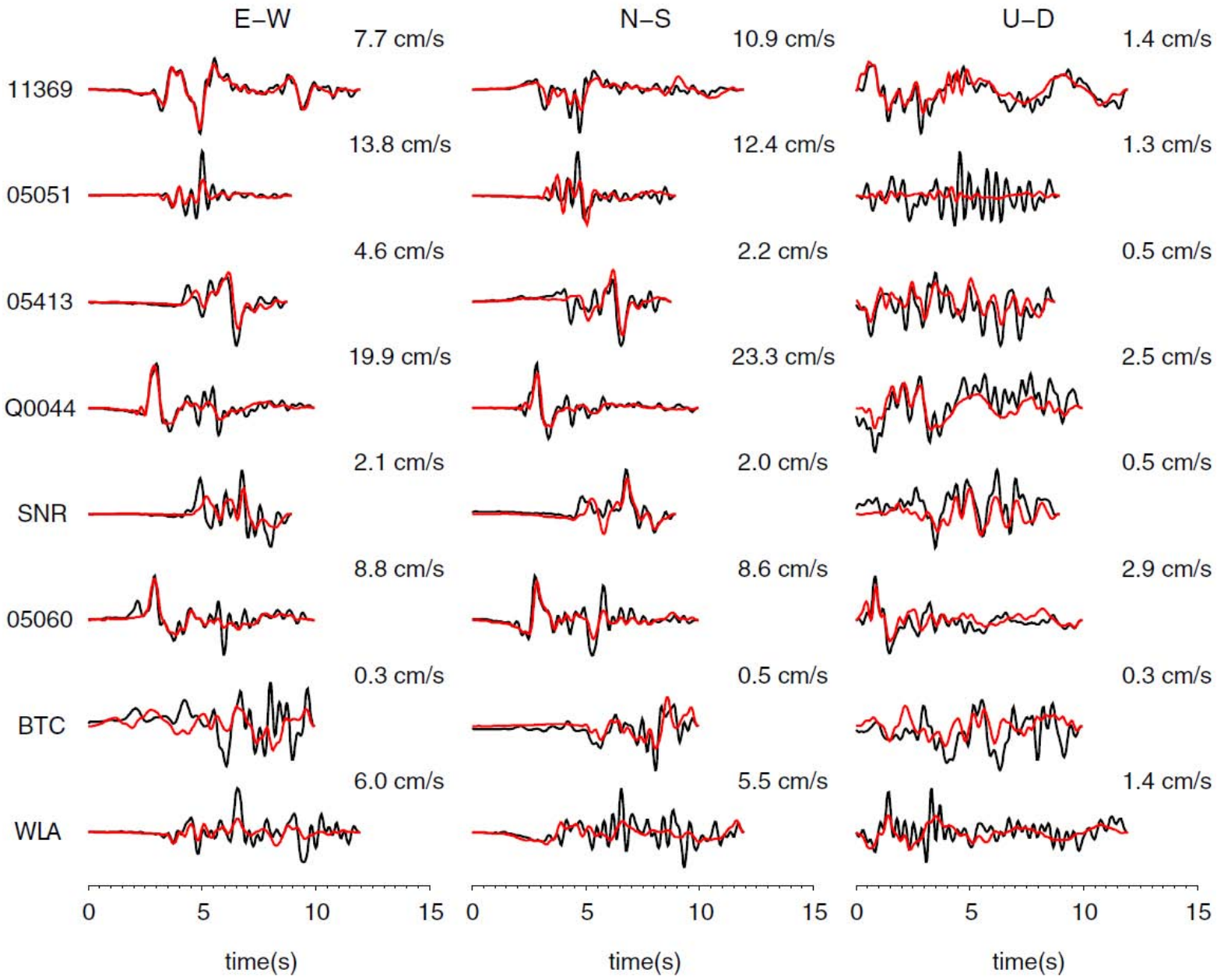
station 05060, U-D component, ~4km to the southeast of the epicenter



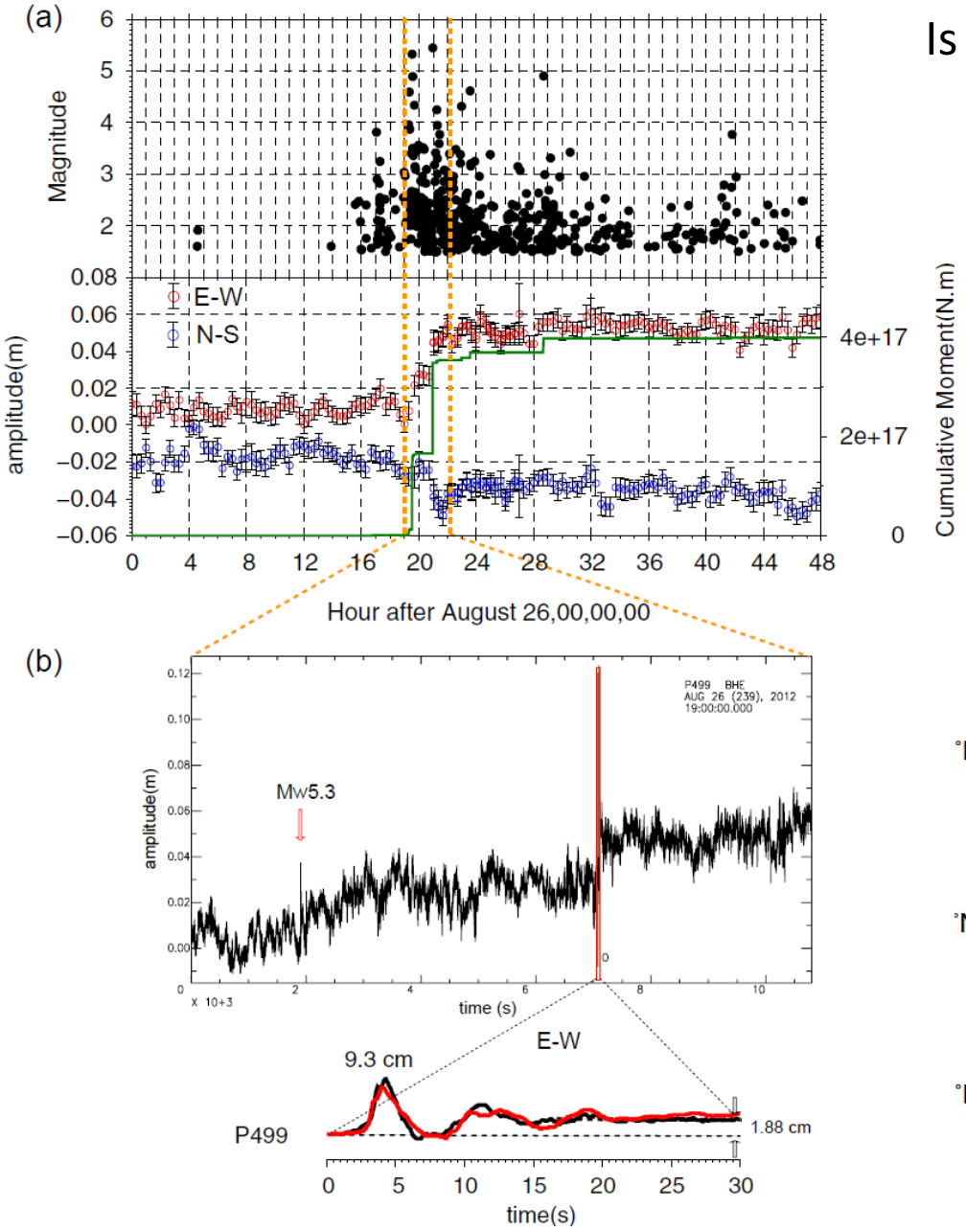
FK FD validation

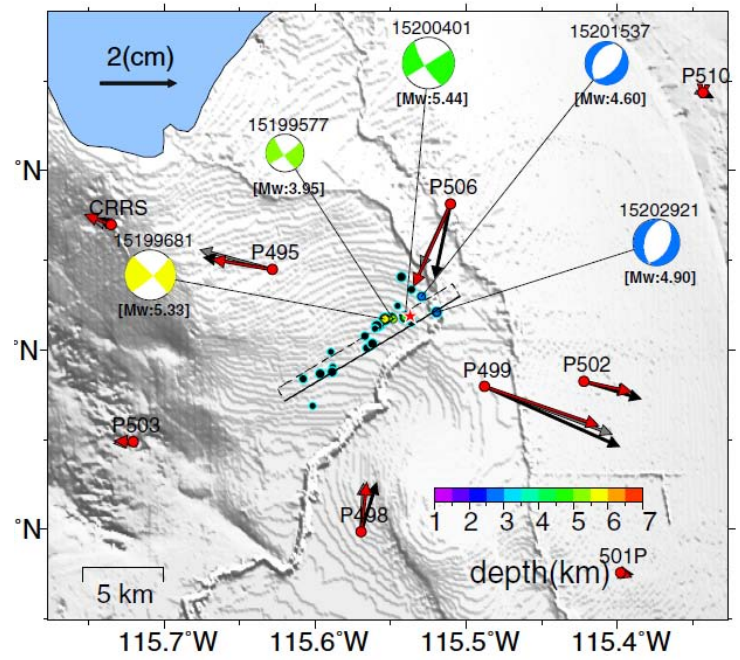



E–W
N–S
U–D
High-Rate GPS
P498
P499
P502
P506
11369
05051
Q0044
SNR
BTC
WLA
Prediction
05060
2.5 cm
3.2 cm
5.7 cm
3.8 cm
1.8 cm
0.7 cm
1.8 cm
2.2 cm
12.5 cm/s
23.1 cm/s
3.7 cm/s
14.8 cm/s
14.7 cm/s
1.1 cm/s
36.5 cm/s
35.9 cm/s
7.1 cm/s
3.1 cm/s
1.3 cm/s
0.6 cm/s
0.6 cm/s
0.4 cm/s
0.5 cm/s
5.2 cm/s
6.2 cm/s
1.9 cm/s
37.7 cm/s
15.2 cm/s
4.0 cm/s
0
5
10
15
time(s)


E–W
N–S
U–D
11369
05051
05413
Q0044
SNR
05060
BTC
WLA
7.7 cm/s
13.8 cm/s
4.6 cm/s
19.9 cm/s
2.1 cm/s
8.8 cm/s
0.3 cm/s
6.0 cm/s
10.9 cm/s
12.4 cm/s
2.2 cm/s
23.3 cm/s
2.0 cm/s
8.6 cm/s
0.5 cm/s
5.5 cm/s
1.4 cm/s
1.3 cm/s
0.5 cm/s
2.5 cm/s
0.5 cm/s
2.9 cm/s
0.3 cm/s
1.4 cm/s
0
5
10
15
time(s)

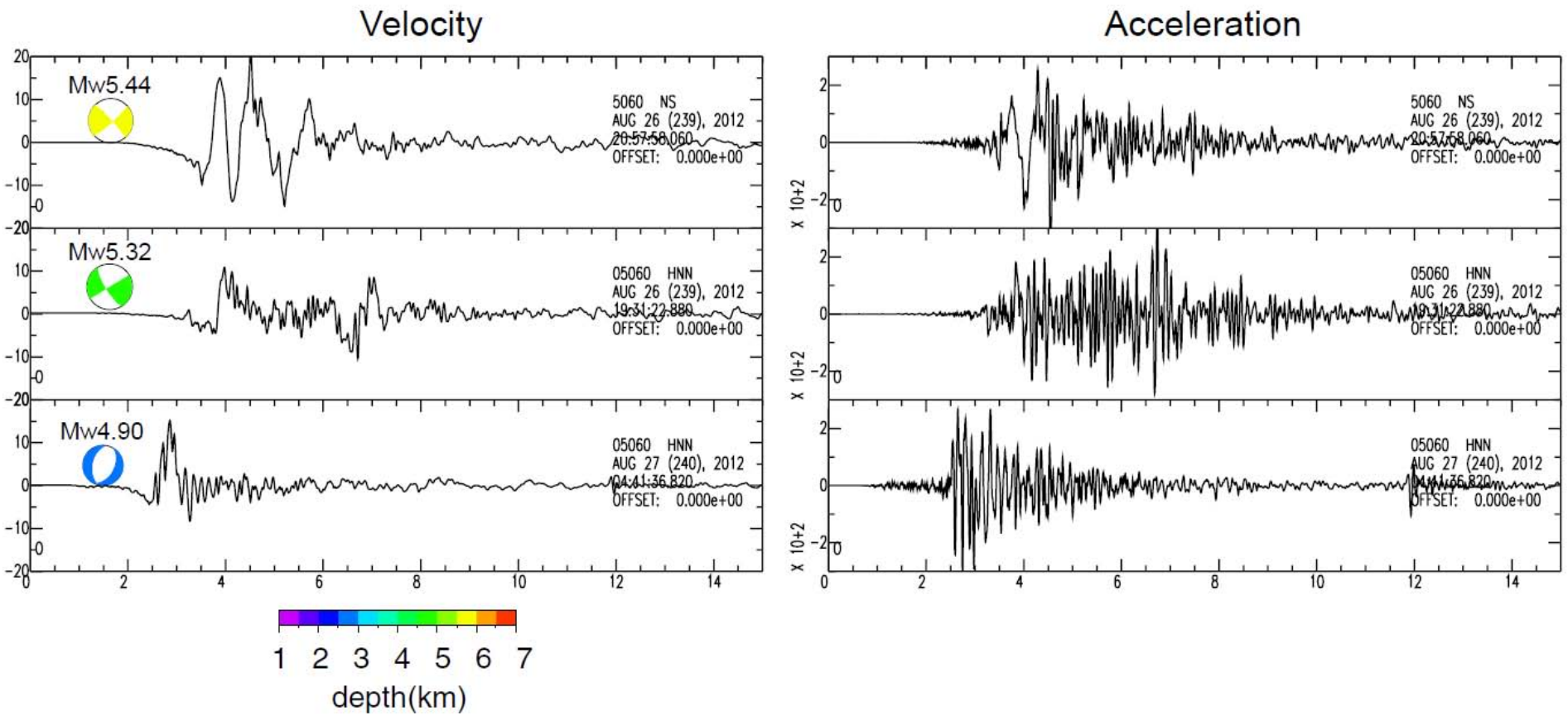
Is there large amount of aseismic slip?



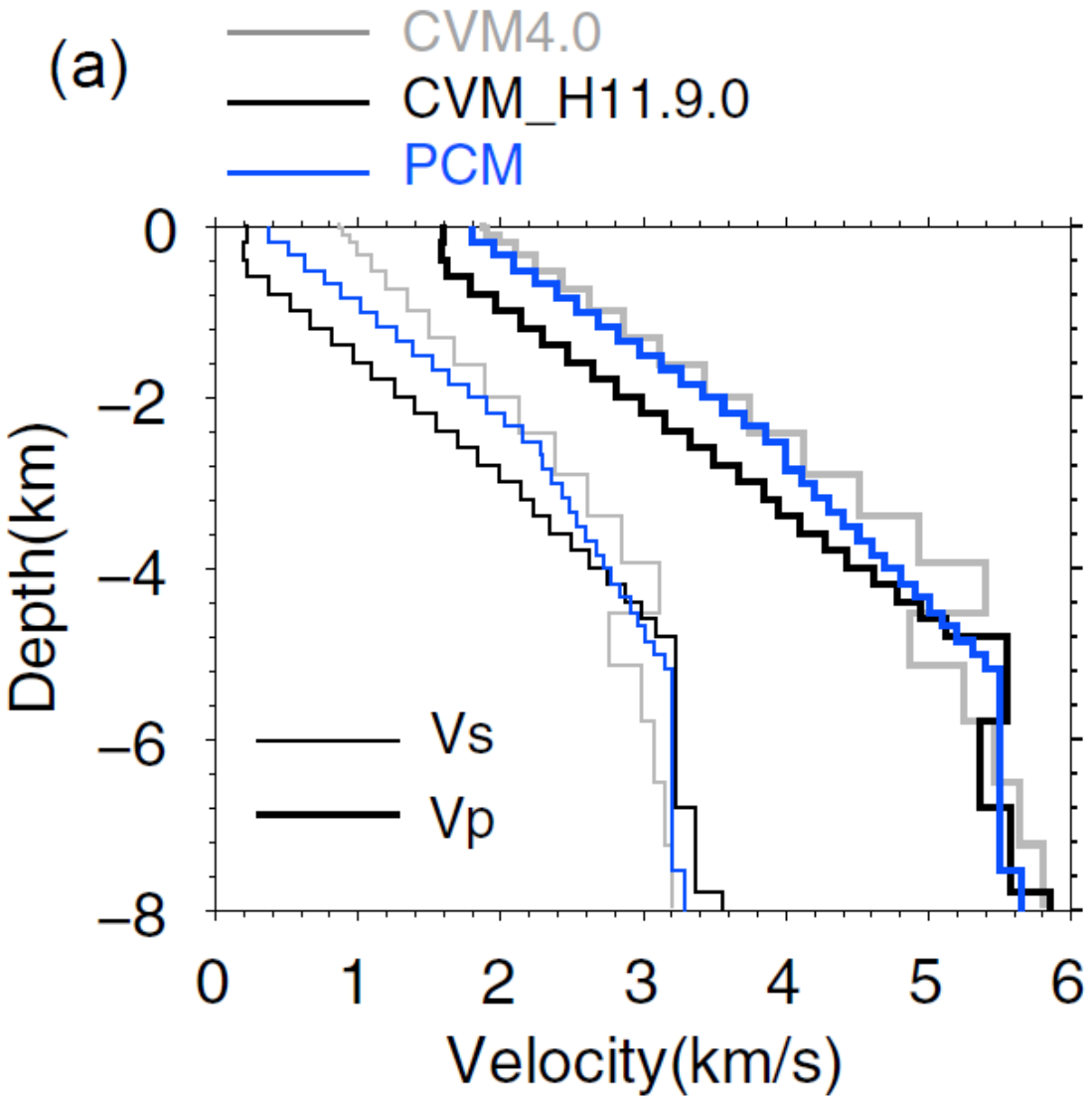


static offset is pure prediction

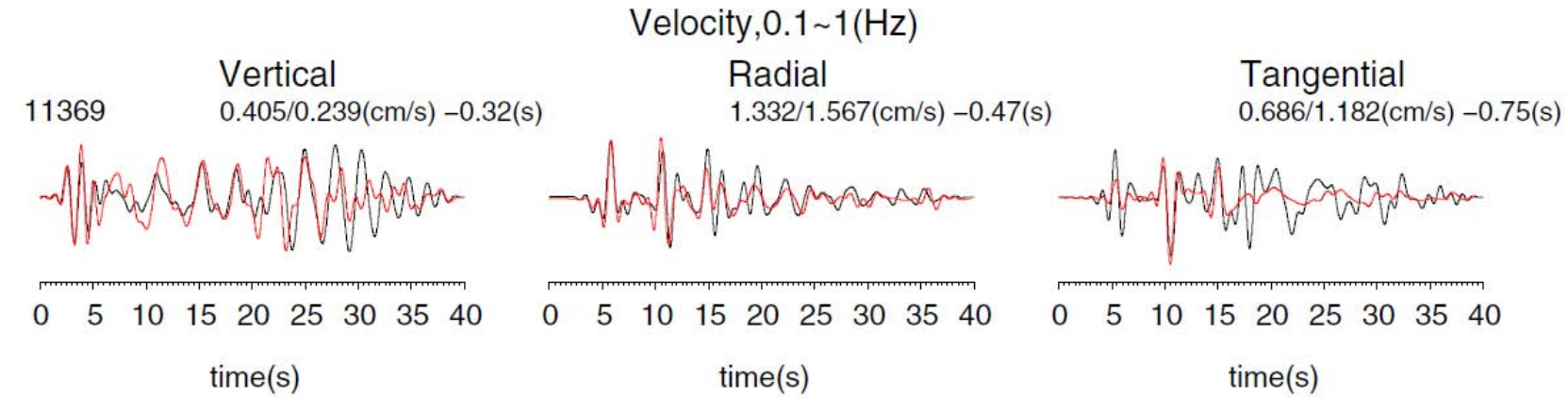
station 05060, N-S component, ~4km to the southeast of the epicenter

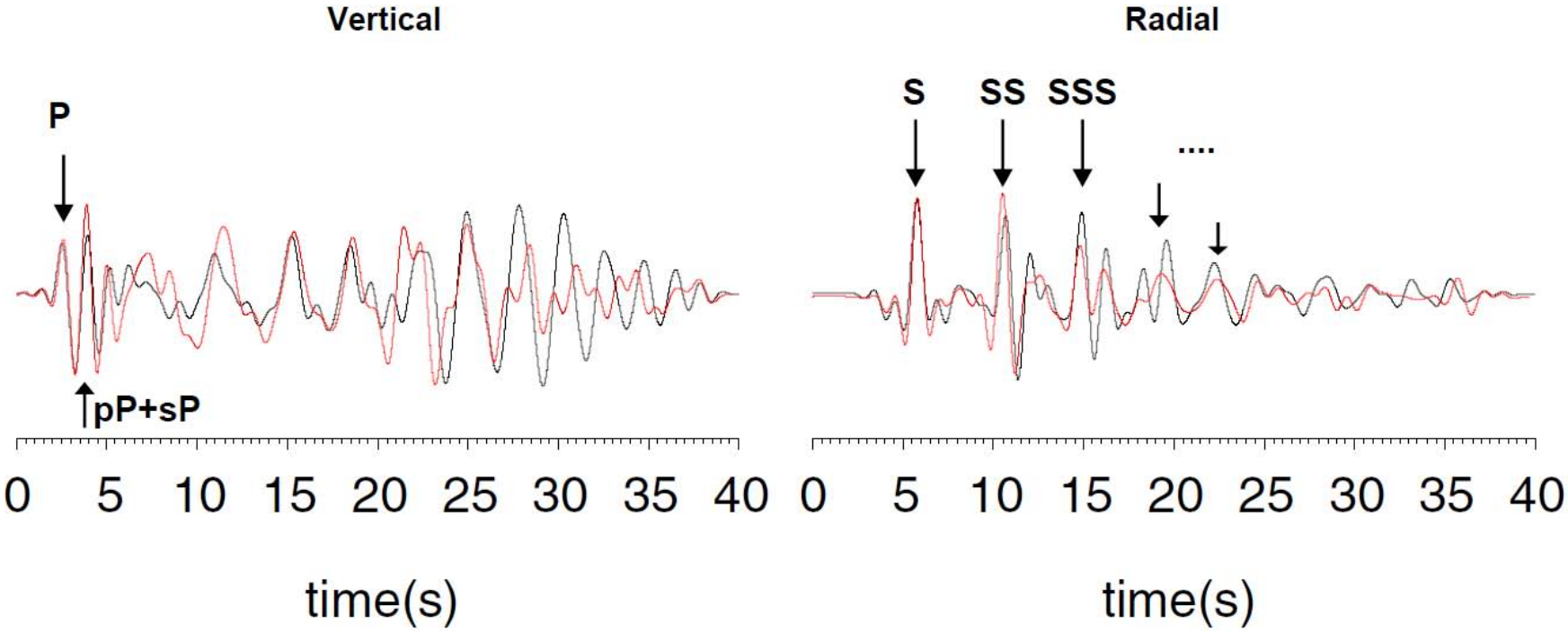


Velocity Model

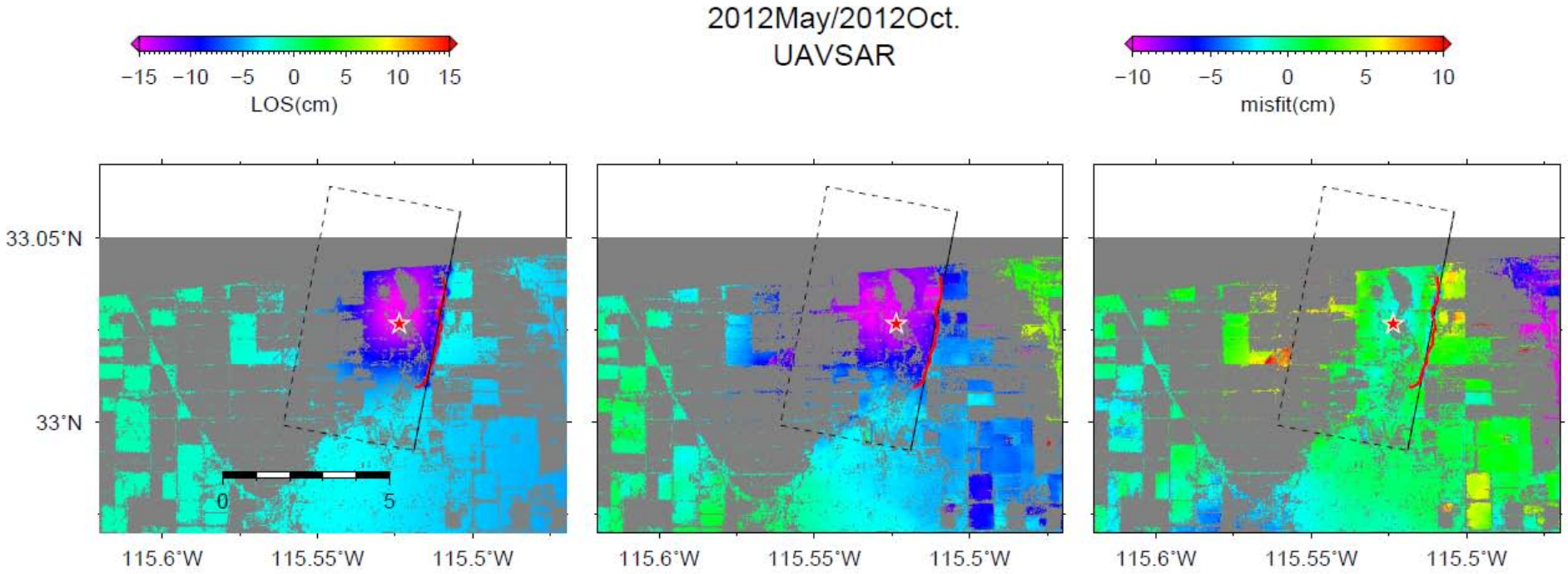


11369 waveform prediction for the shallow normal earthquake (M4.6)





UAVSAR 265


2012May/2012Oct.
UAVSAR
−15 −10 −5 0 5 10 15
LOS(cm)
−10 −5 0 5 10
misfit(cm)
33.05°N
33°N
0
5
115.6°W
115.55°W
115.5°W
115.6°W
115.55°W
115.5°W
115.6°W
115.55°W
115.5°W