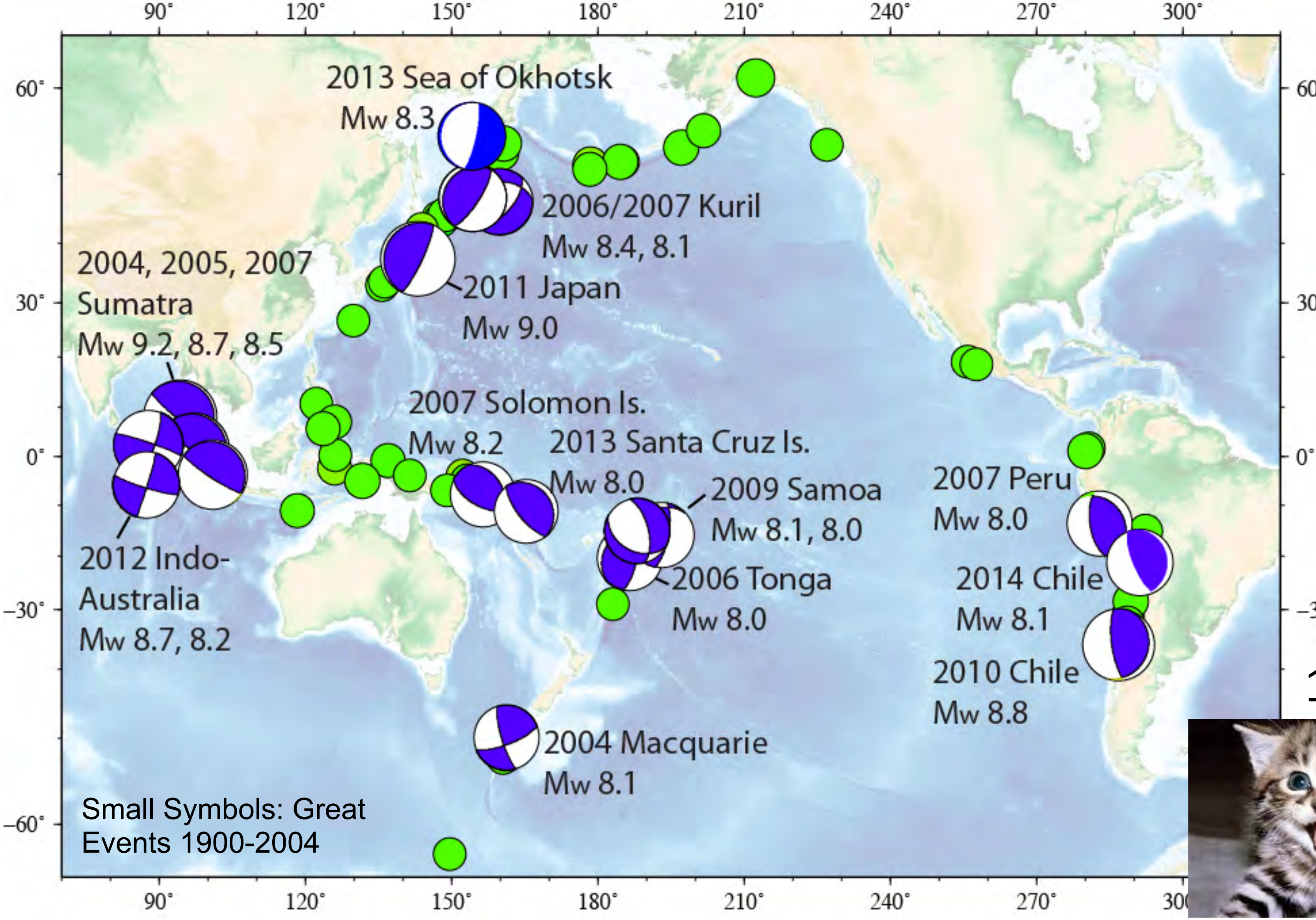
A GLOBAL SURGE OF TSUNAMIGENIC EARTHQUAKE RUPTURES AND HOW WE ARE QUANTIFYING THEM

Thorne Lay, University of California Santa Cruz

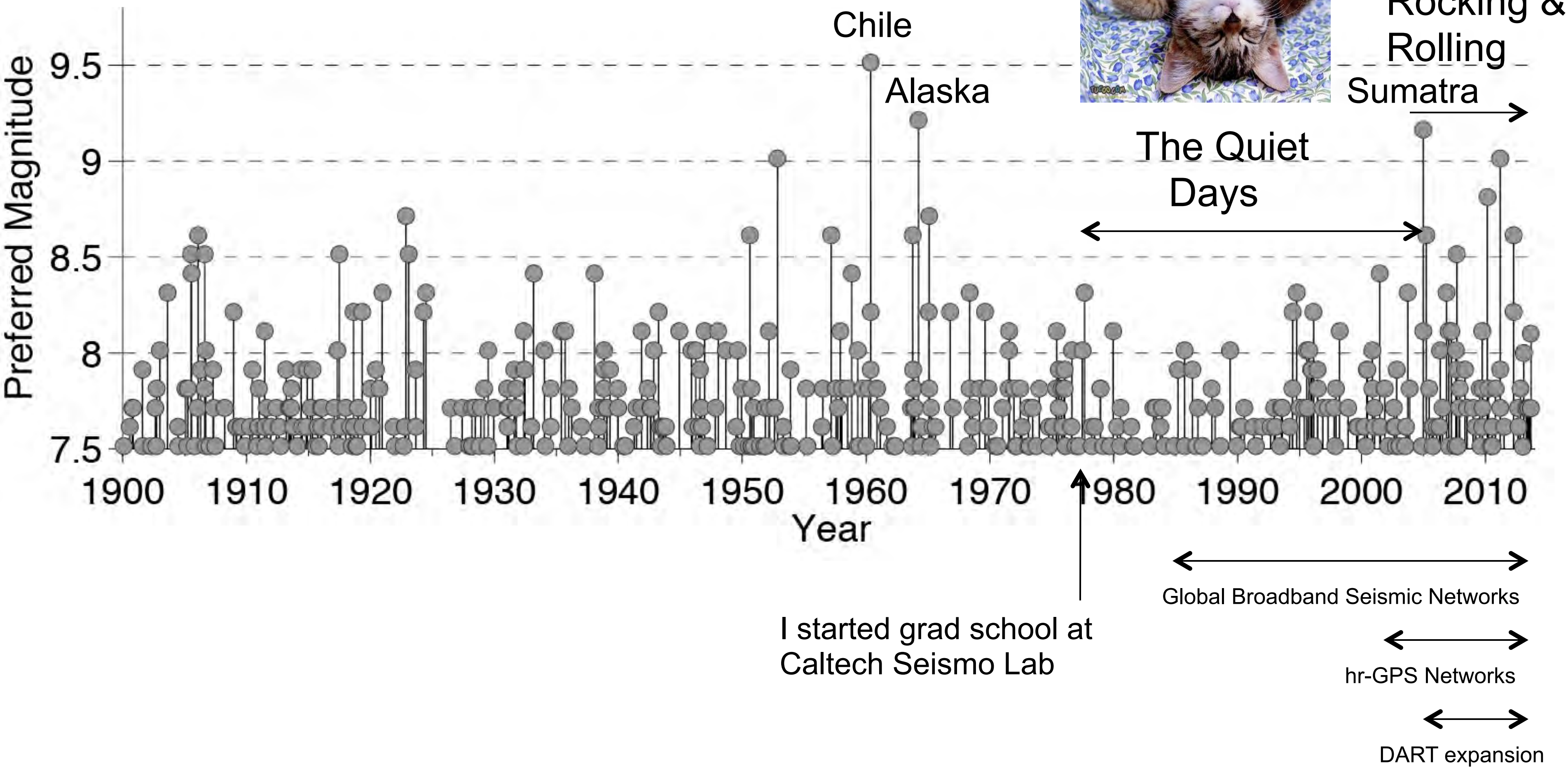
Last 10 yrs - 18 great earthquakes: rate 1.8/yr; rate over preceding century 0.7/yr



1.8/yr !

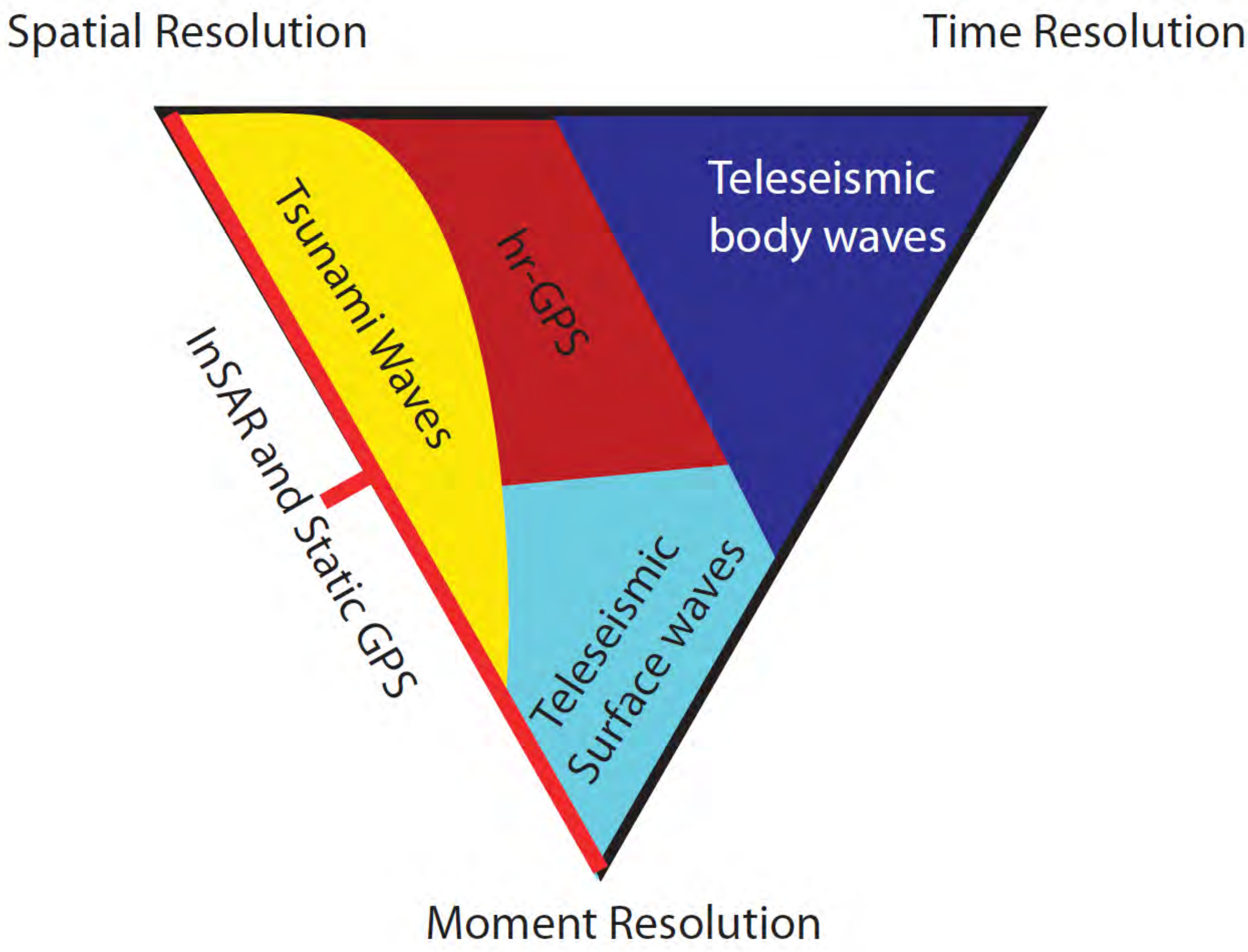
Great ($M_w \geq 8$) events from Dec. 2004-Apr. 2014

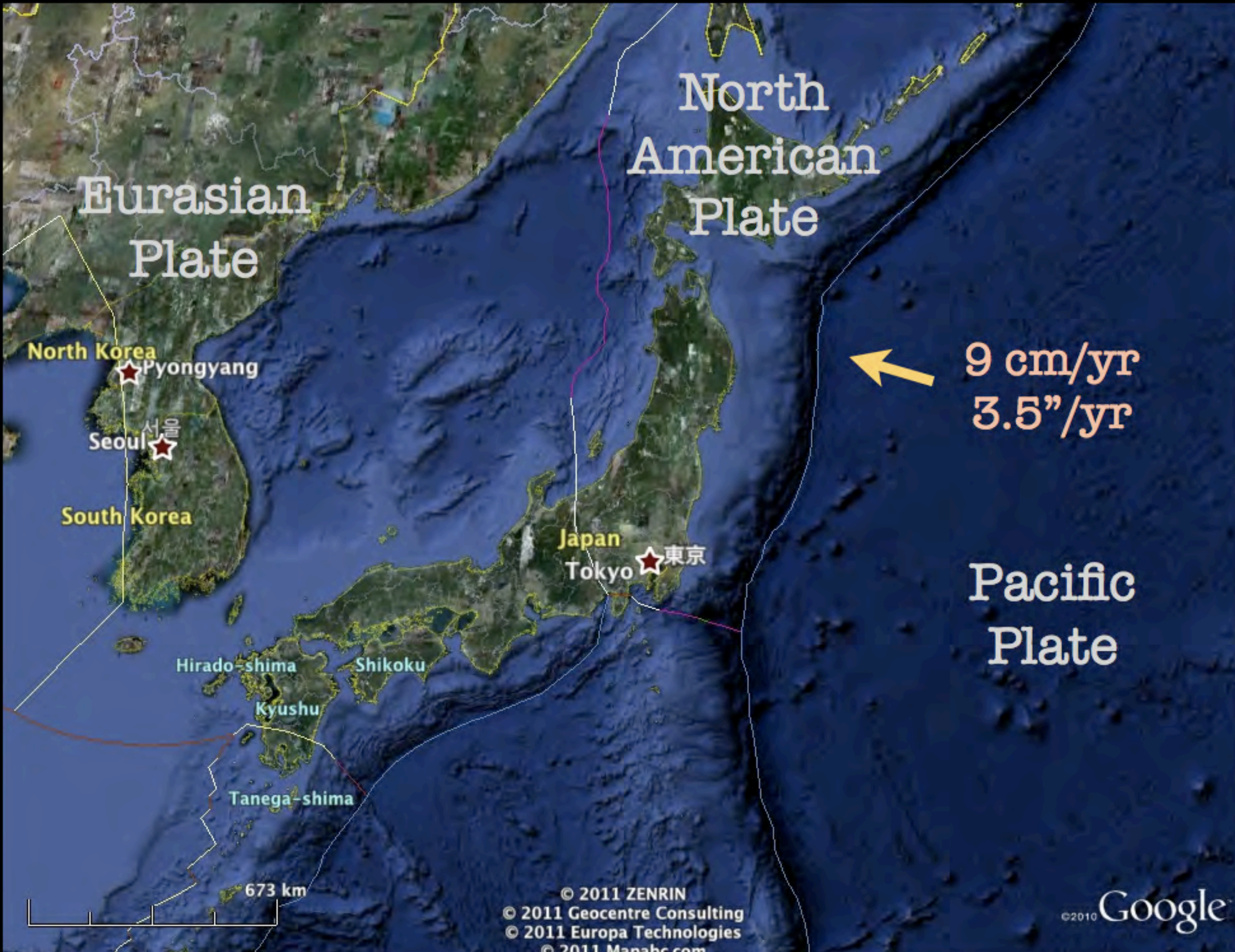
[Lay, 2014]



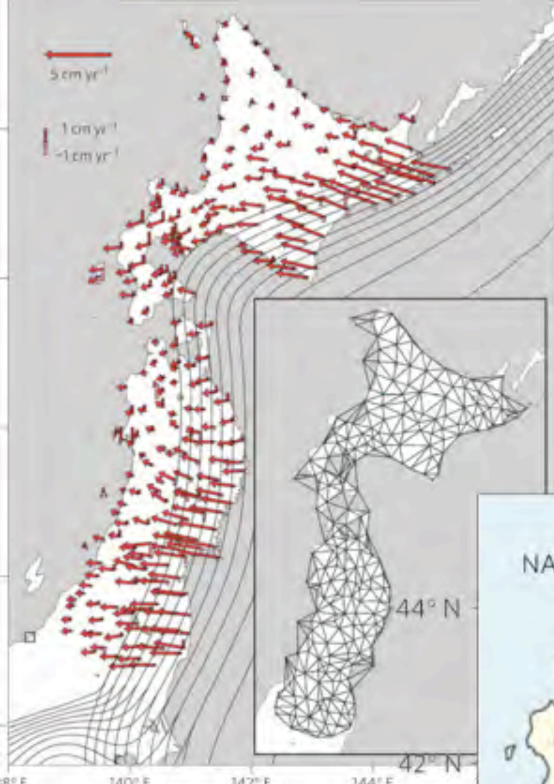
after, Ammon et al., SRL, 2010

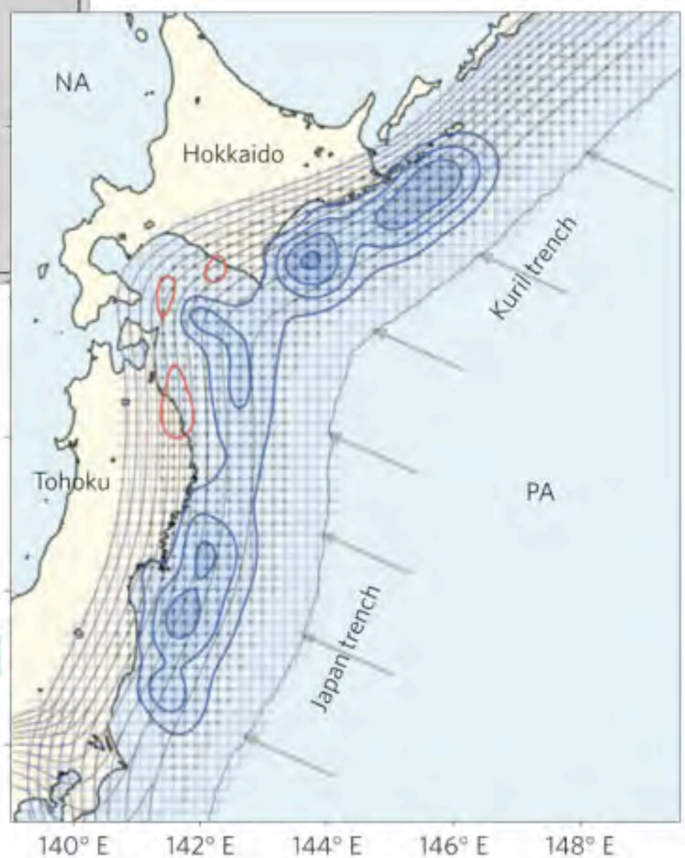
Resolutions of Joint inversion

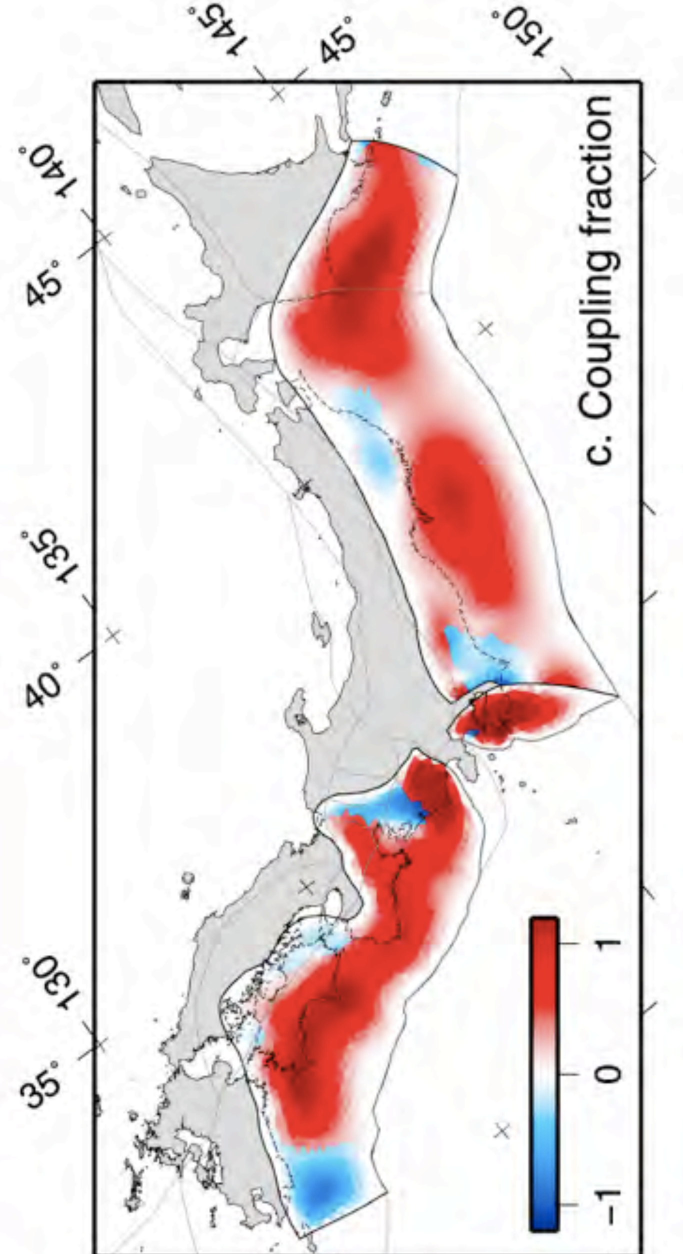




Eurasian Plate
North American Plate
Pacific Plate
9 cm/yr
3.5”/yr
North Korea
Pyongyang
Seoul
서울
South Korea
Japan
Tokyo
東京
Hirado-shima
Shikoku
Kyushu
Tanega-shima
673 km
© 2011 ZENRIN
© 2011 Geocentre Consulting
© 2011 Europa Technologies
© 2011 Mapabc.com
©2010 Google







nature geoscience LETTERS

Interplate seismogenic zones along the Kuril–Japan trench inferred from GPS data inversion

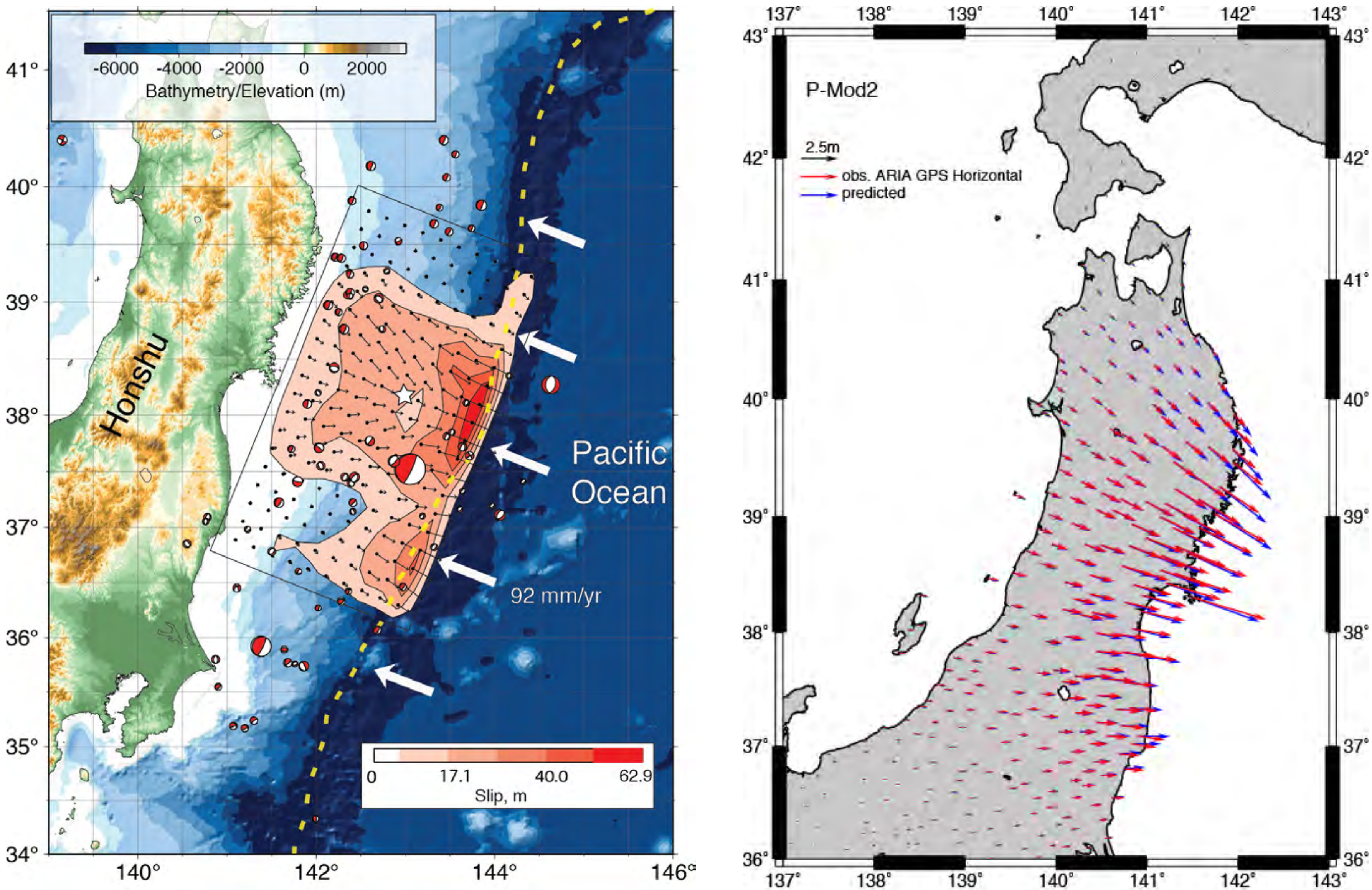
Chihiro Hashimoto, Akemi Noda, Takeshi Sagiya and Mitsuhiro Matsu'ura

Geodetic imaging of plate motions, slip rates, and partitioning of deformation in Japan

John P. Loveless[1] and Brendan J. Meade[1]

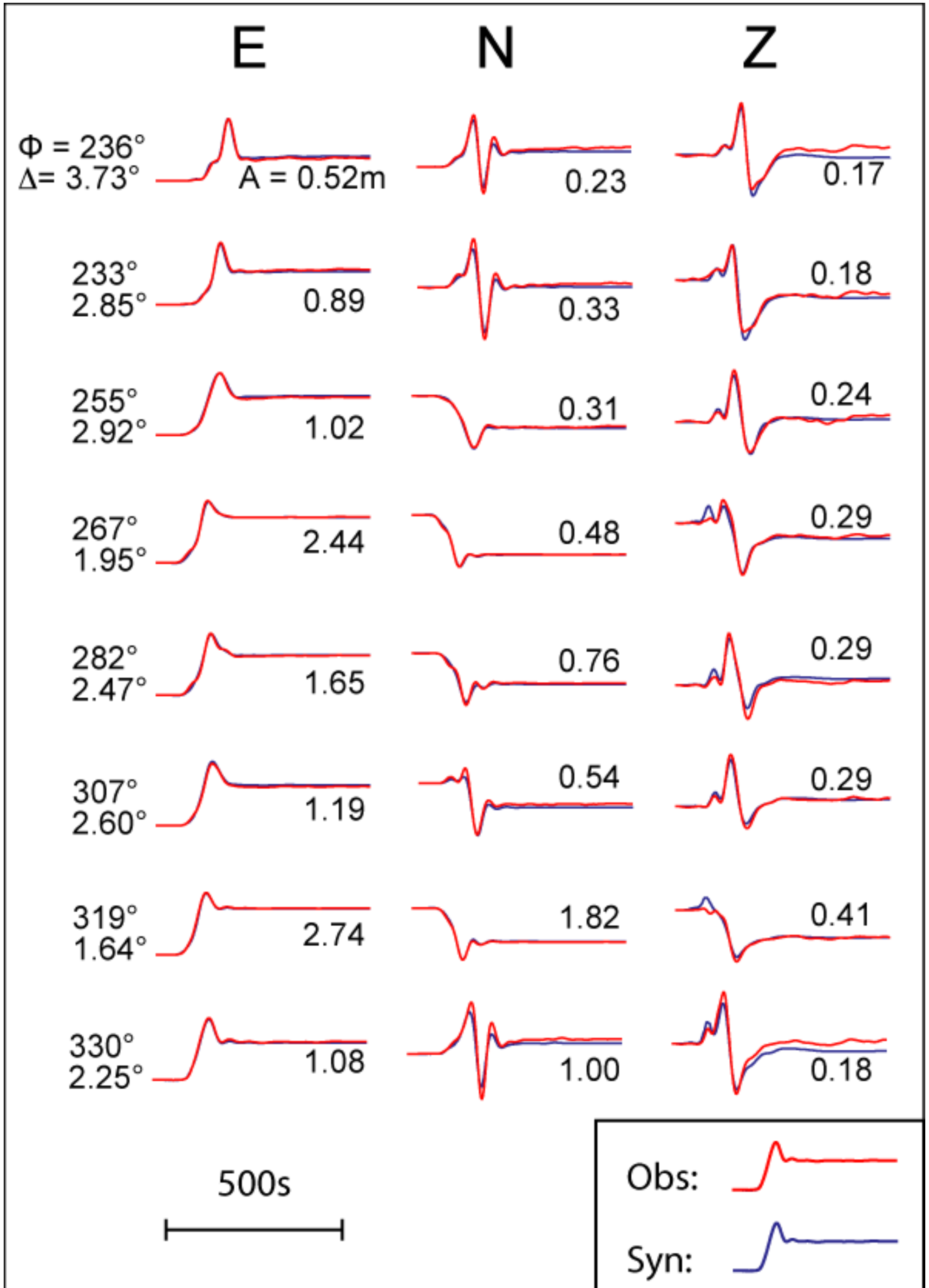
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, B02410, doi:10.1029/2008JB006248, 2010

ARIA Preliminary Coseismic Displacements from
March 11, 2011 Mw9.0 Sendai-Oki Earthquake
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
Horizontal
Displacement
1 m
130
135
140
145
45
40
35
30



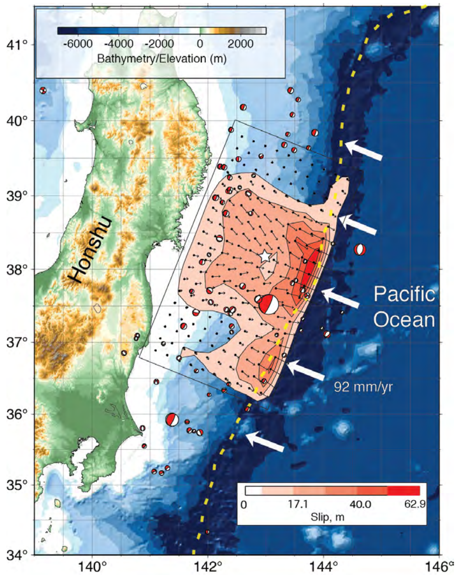
Aseismic model with near-trench slip can fit GPS statics well.
Quasi-seismogeodesy.

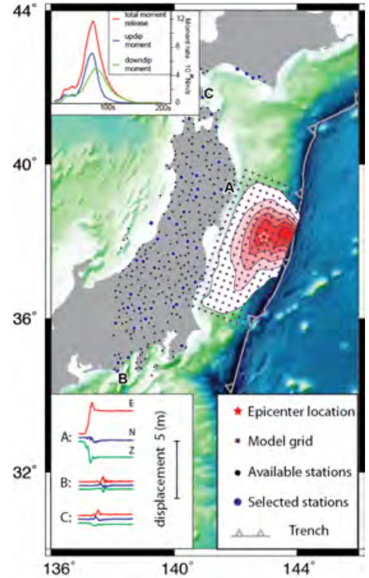
Lay et al., EPS, 2011

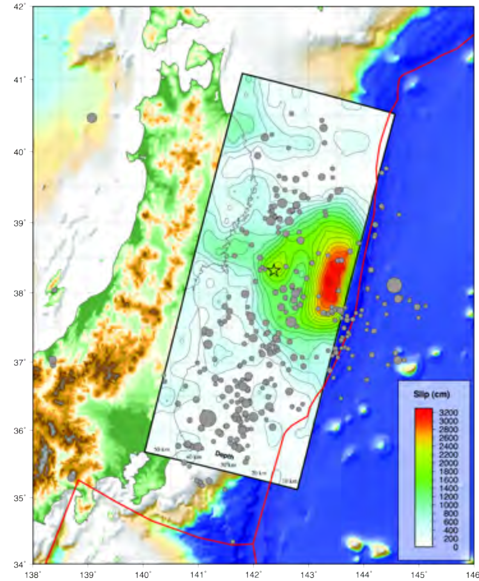


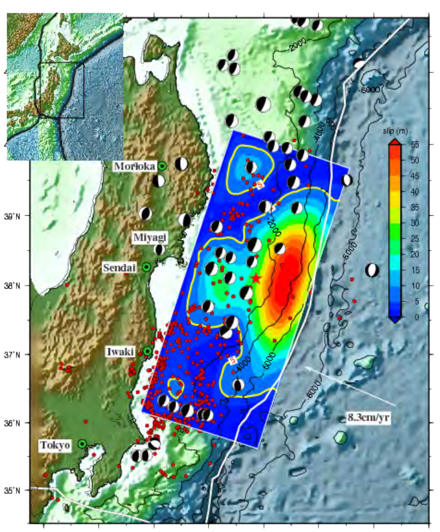
The GPS ground motions record both the arrivals of all seismic waves and the permanent deformations (offsets) of the ground.

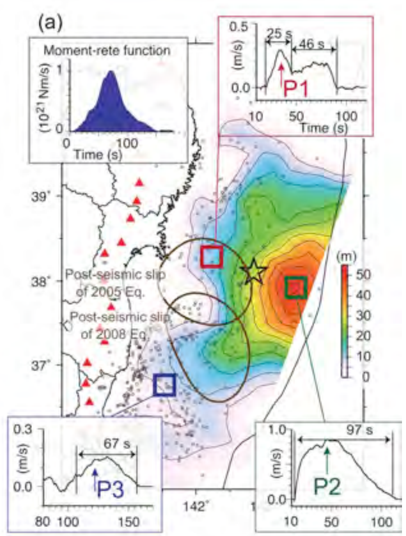
Yue and Lay, GRL, 2011

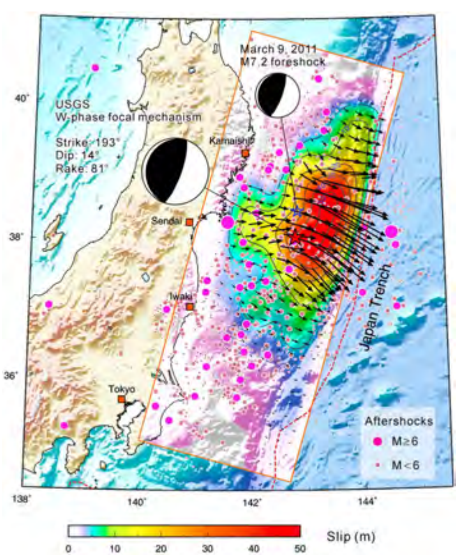






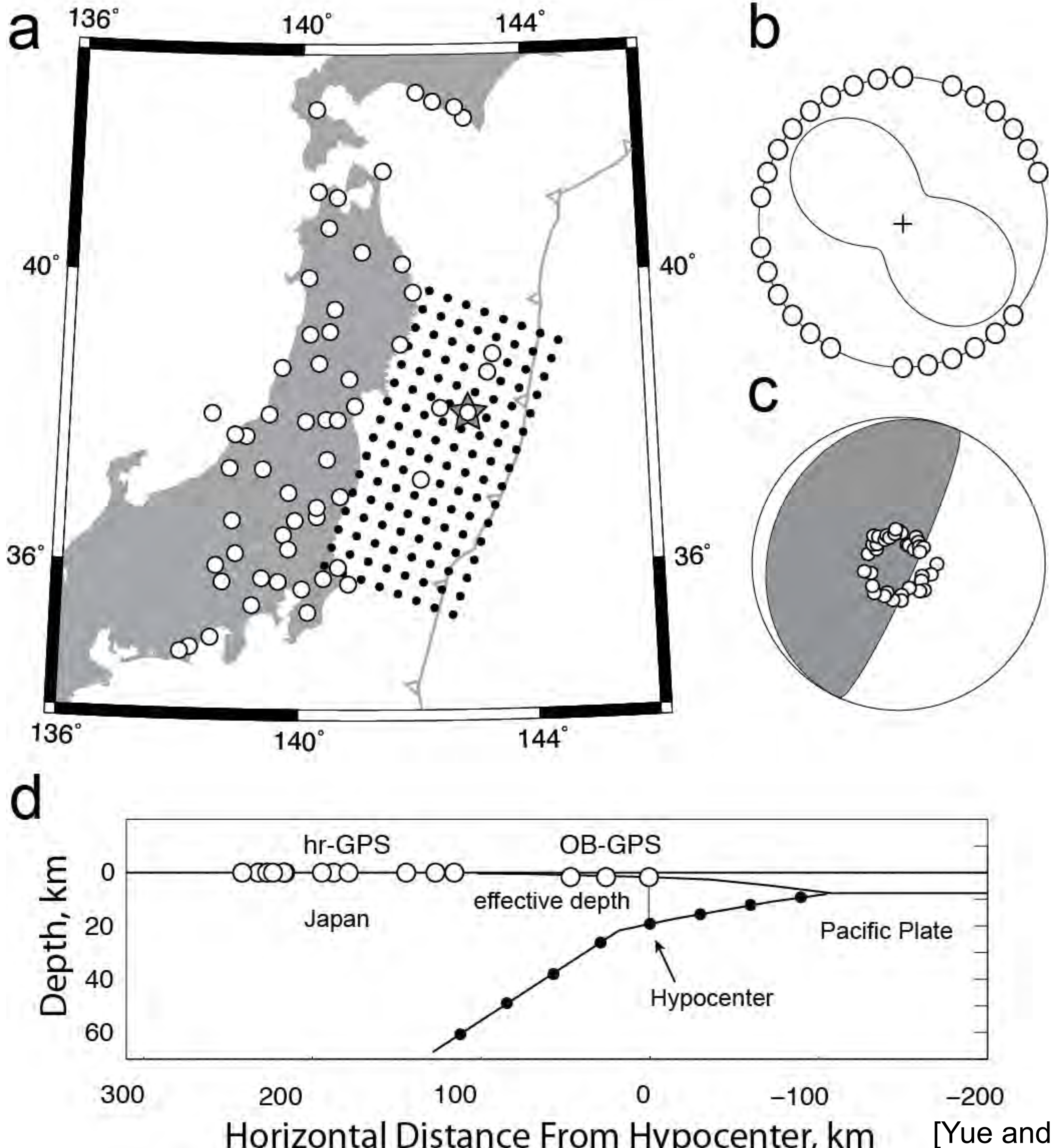




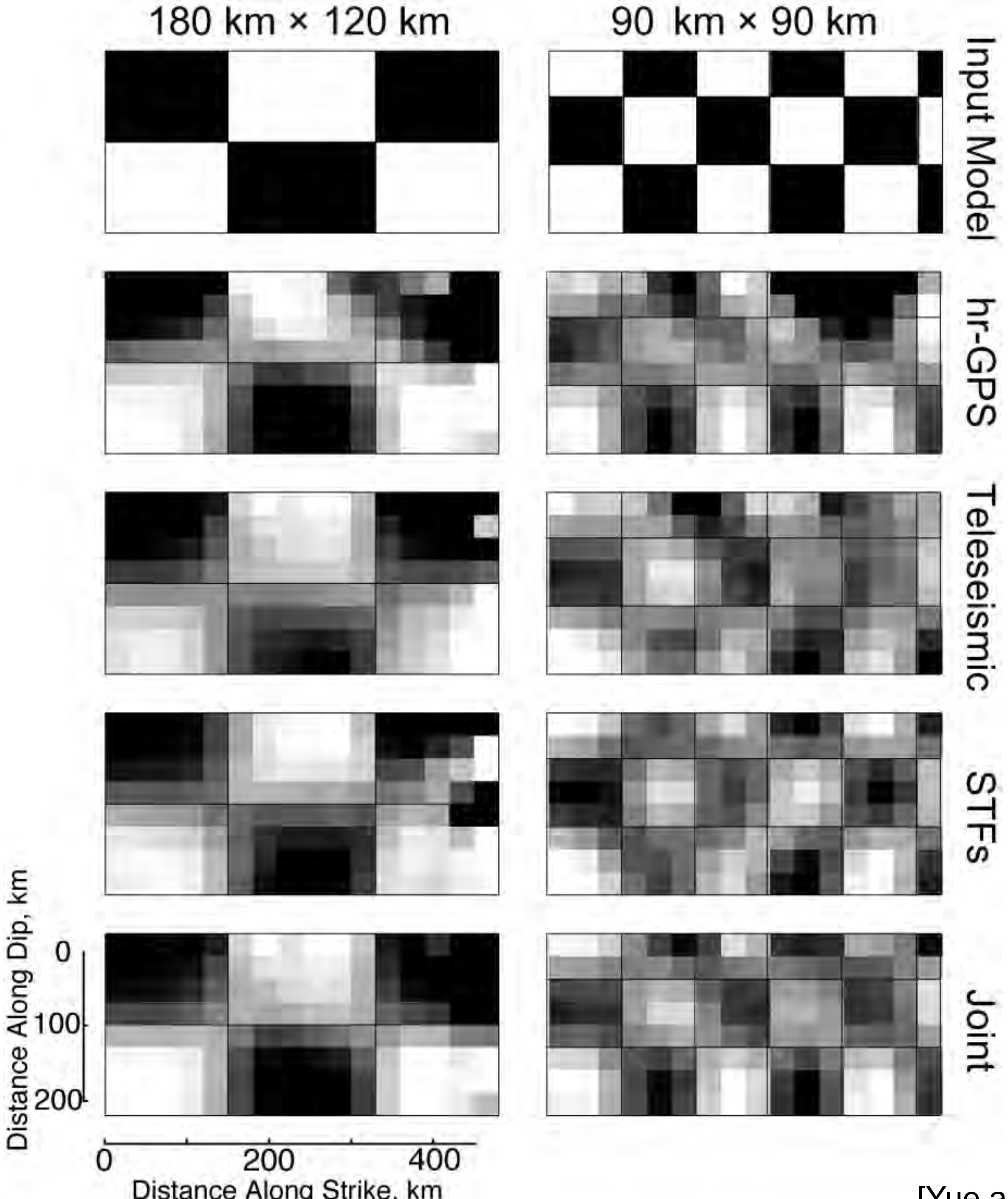


Many studies now confirm that slip in the uppermost 80 km of the megathrust is as much as 60-80 m.

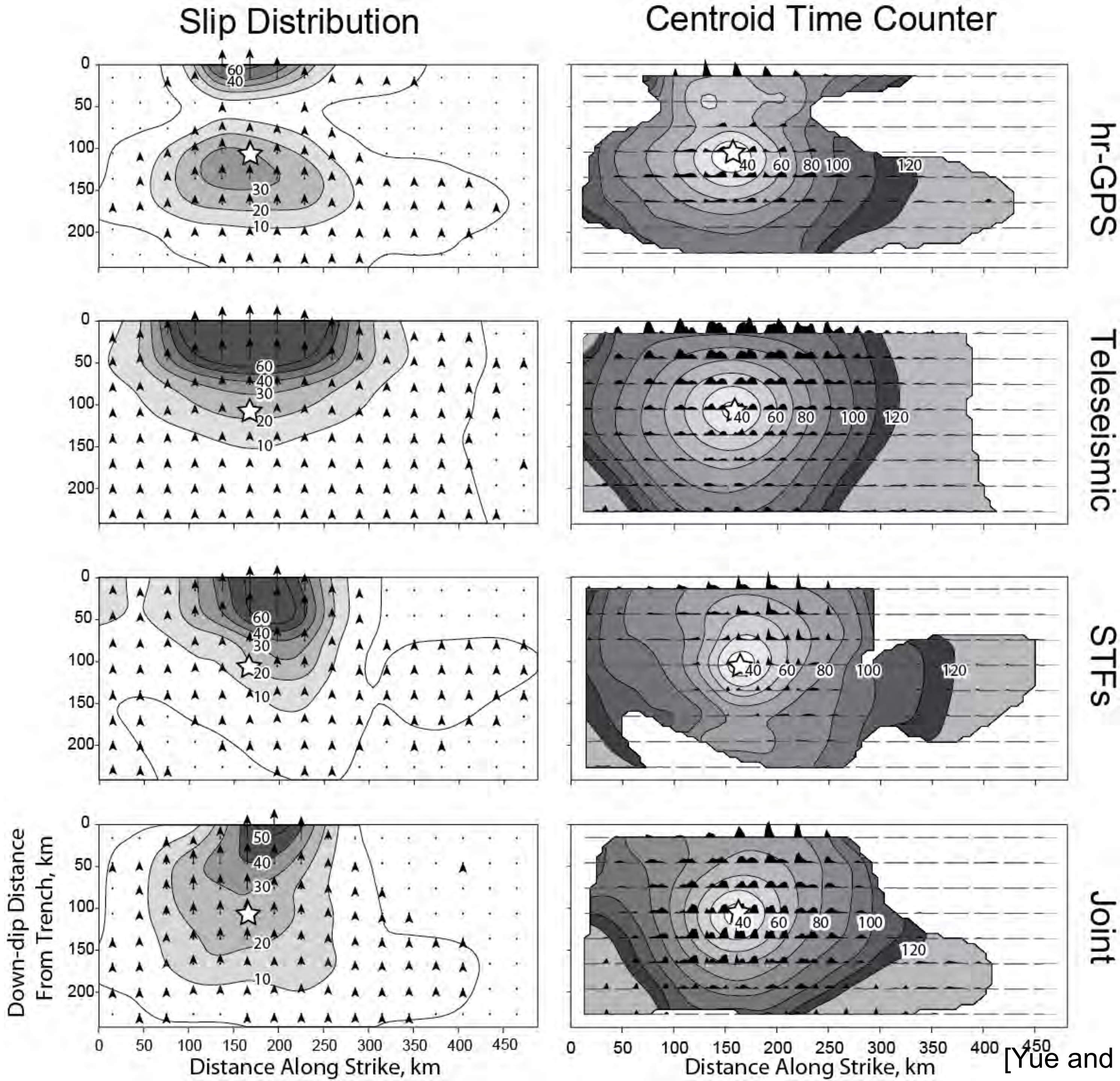
Shallow rupture resembles tsunami earthquake ruptures.



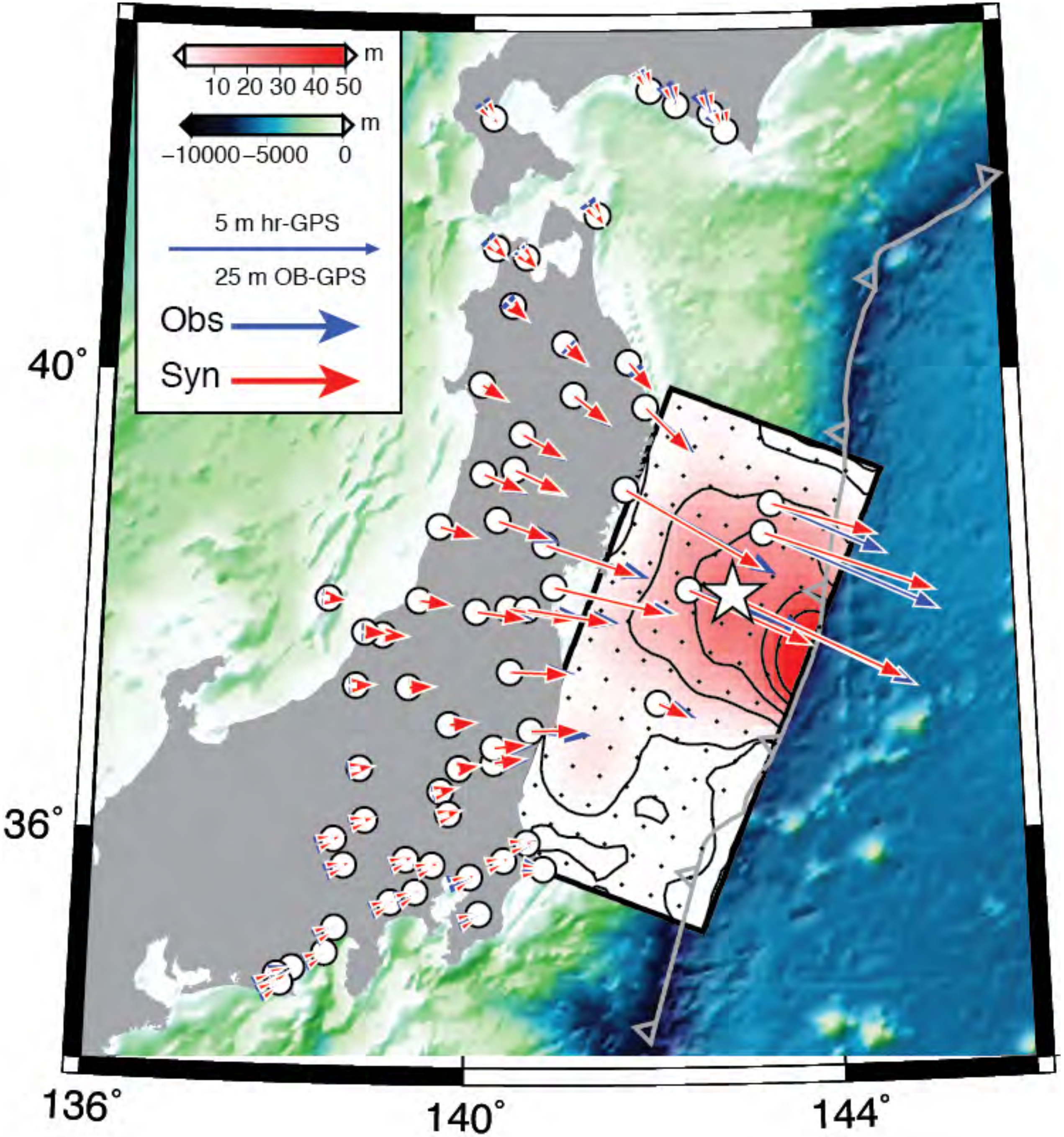
[Yue and Lay, 2013]



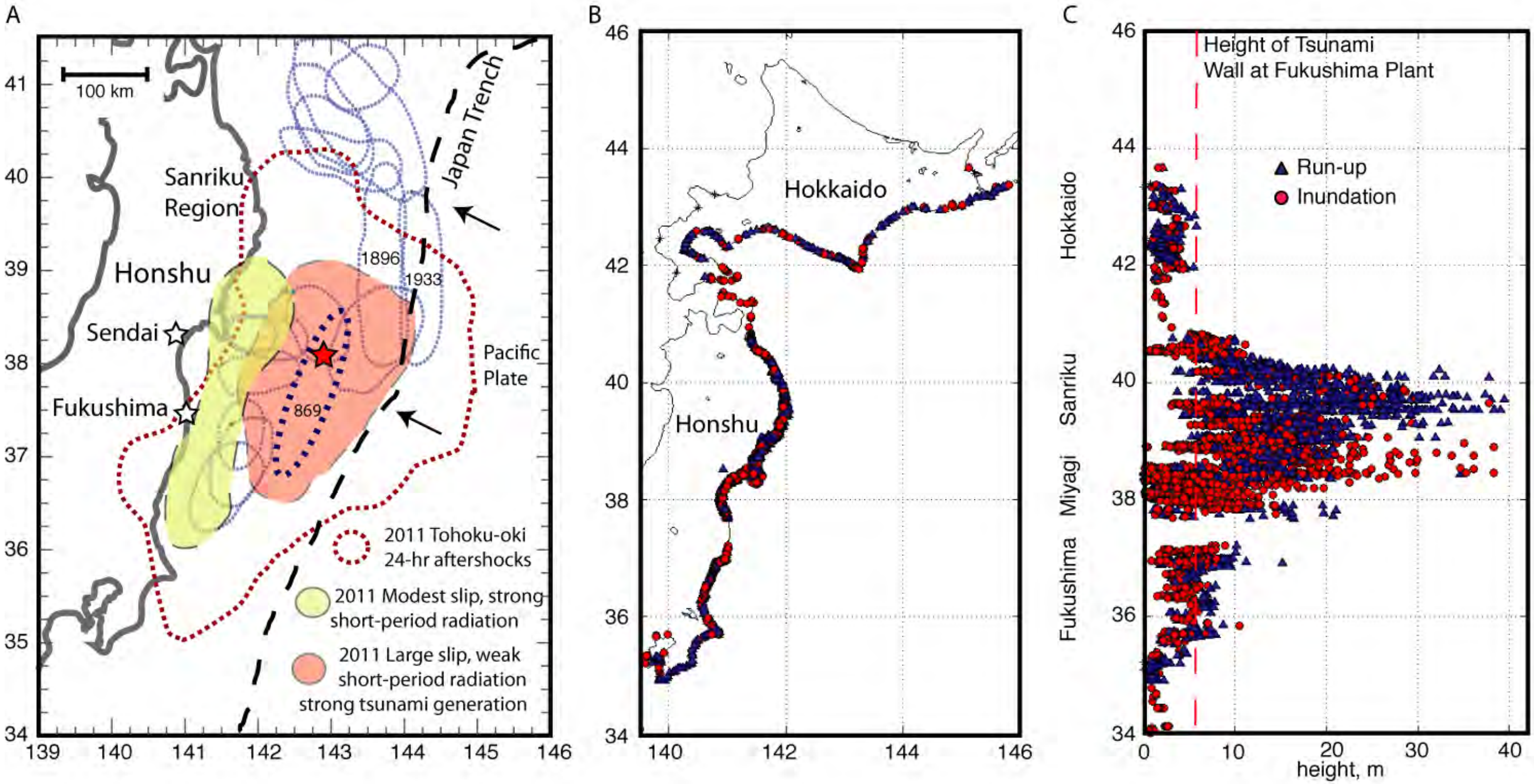
[Yue and Lay, 2013]



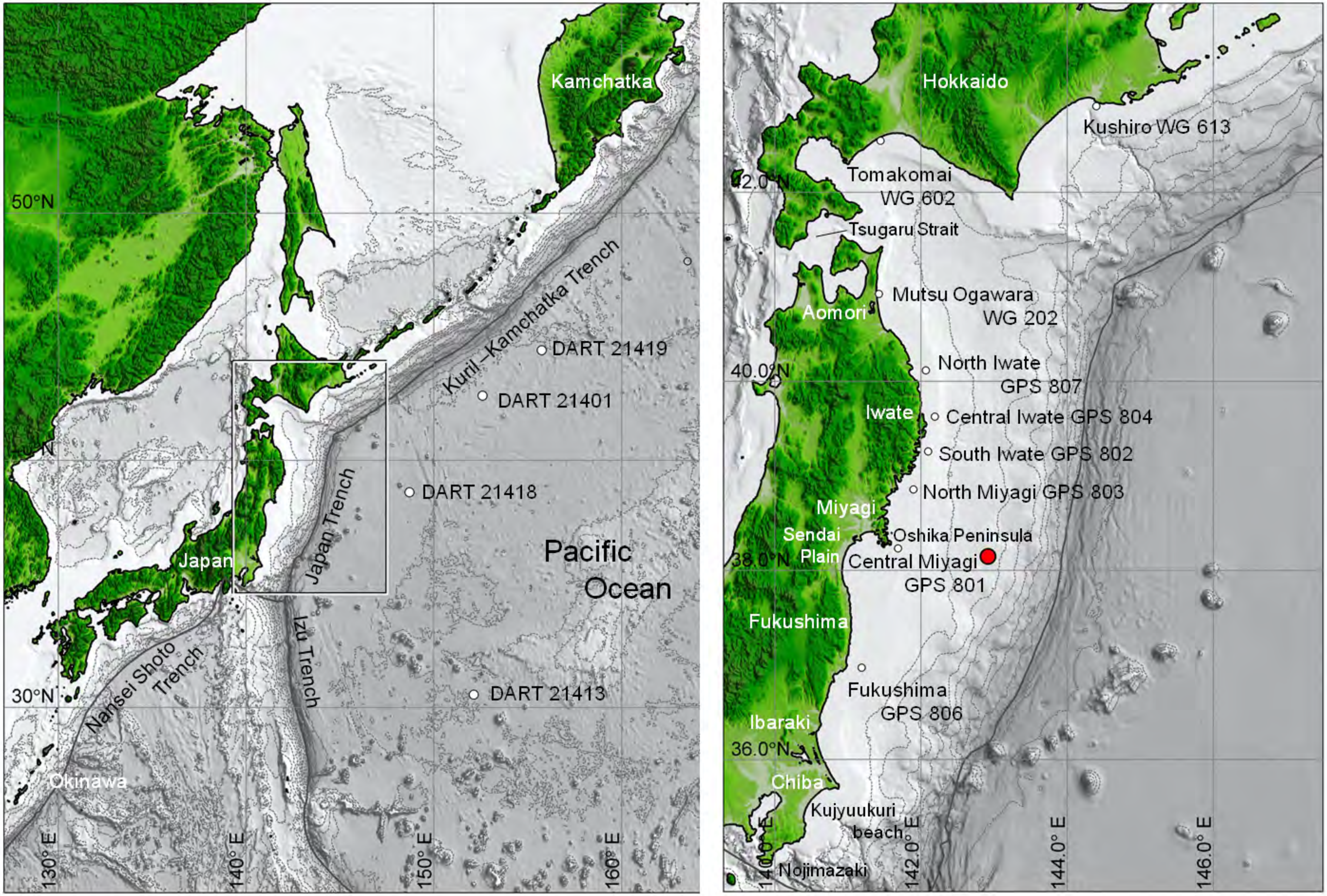
[Yue and Lay, 2013]



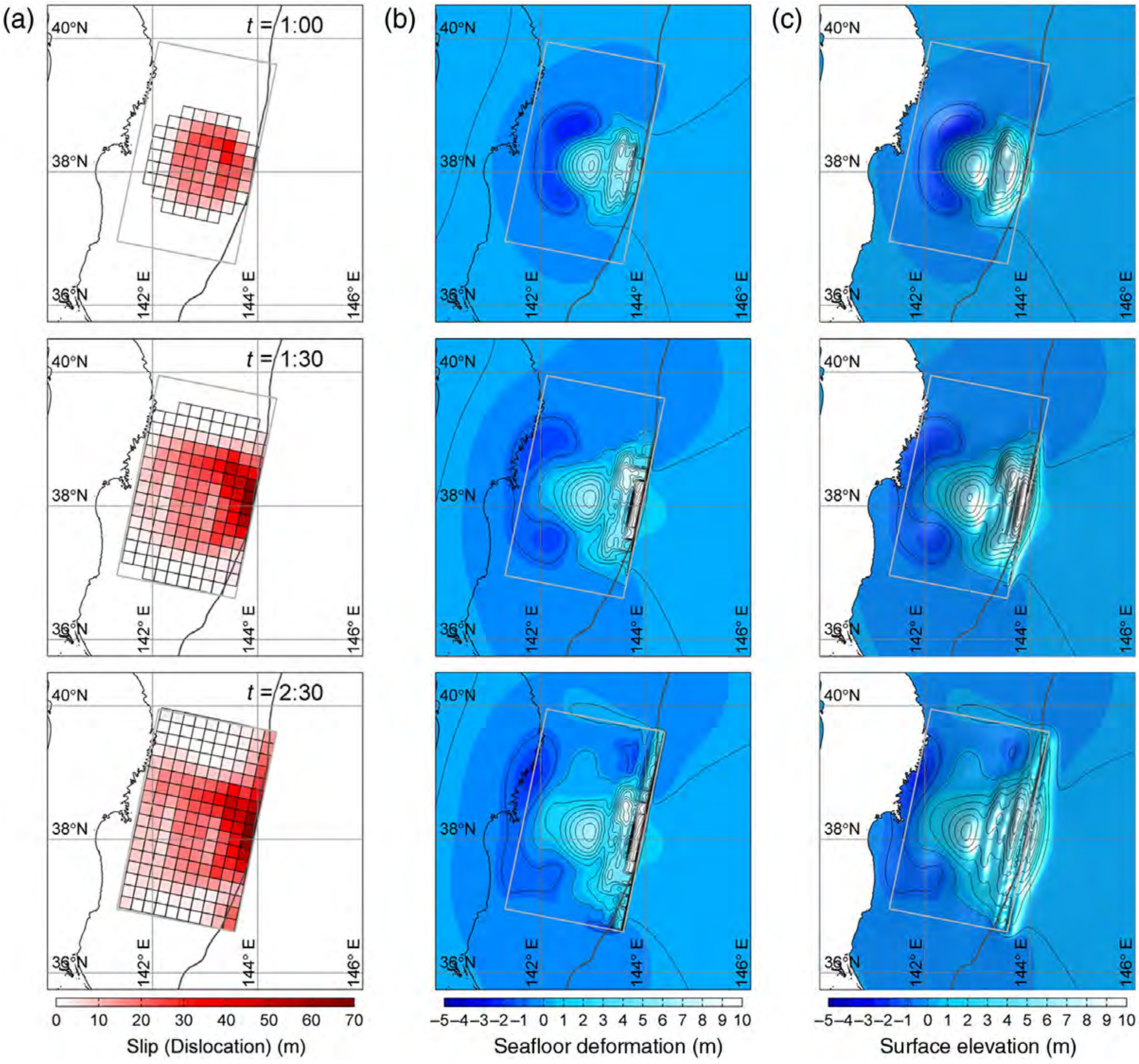
[Yue and Lay, 2013]



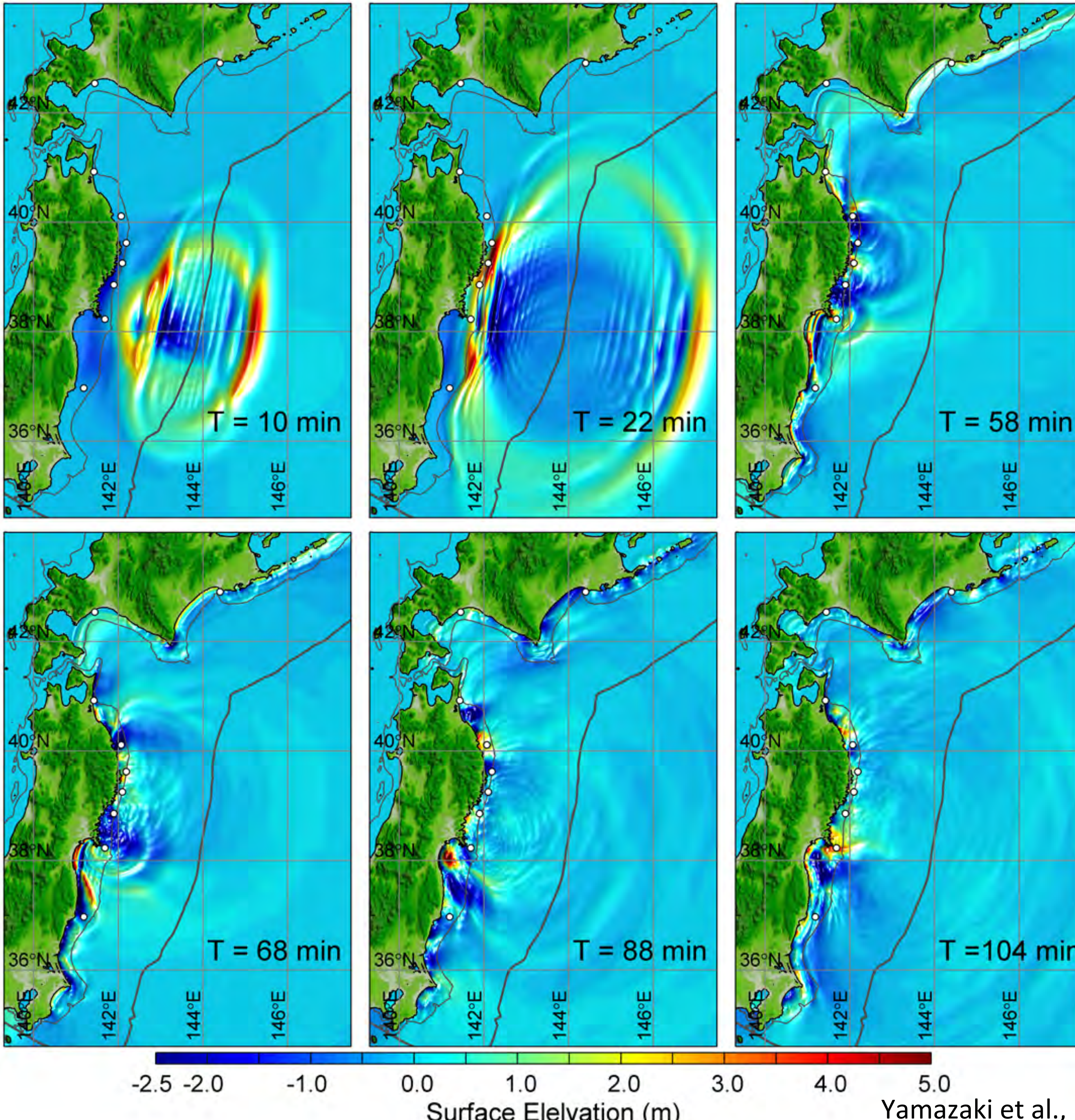
[Lay and Kanamori, 2012]



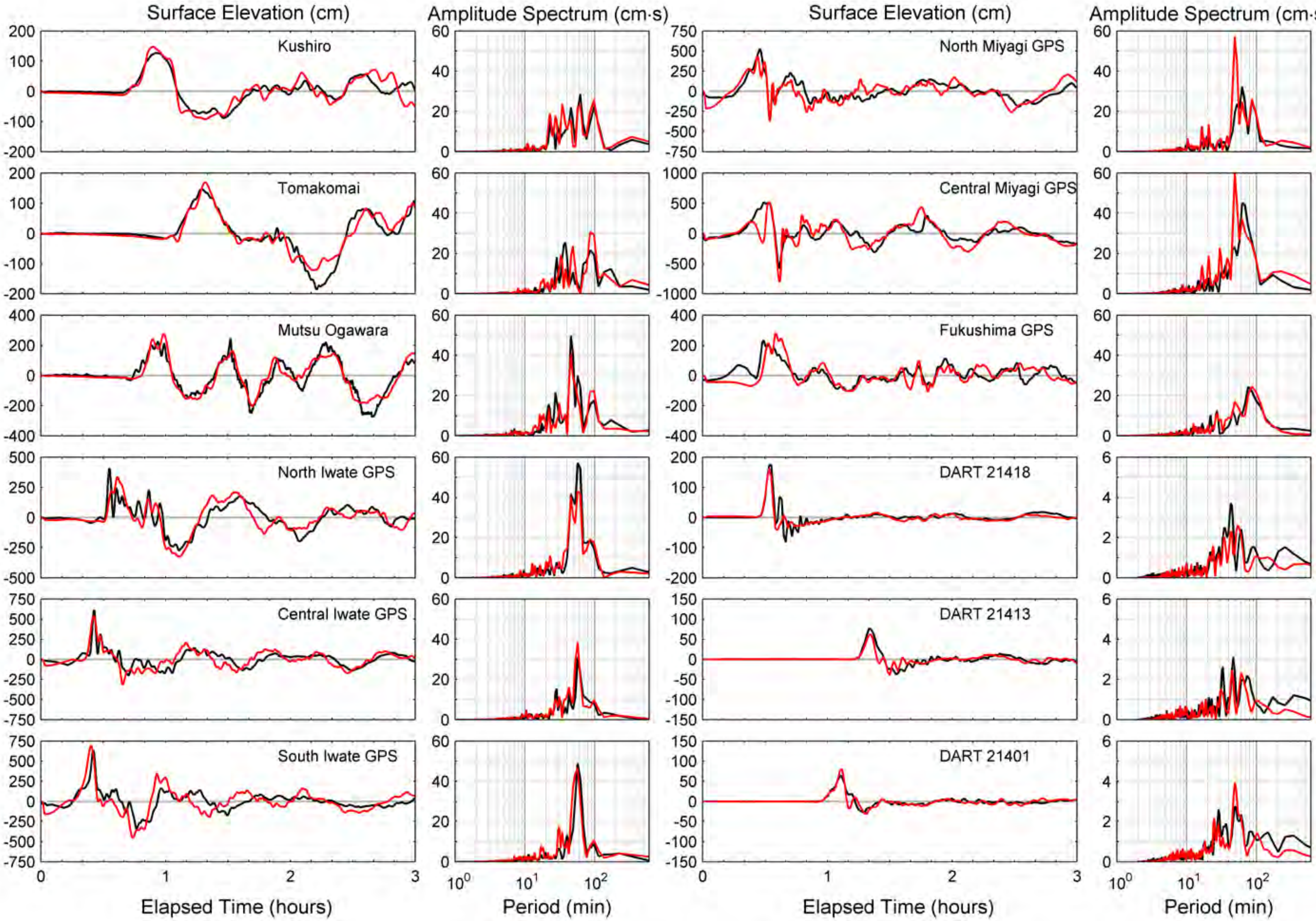
Yamazaki et al., BSSA, 2013



Yamazaki et al., BSSA, 2013

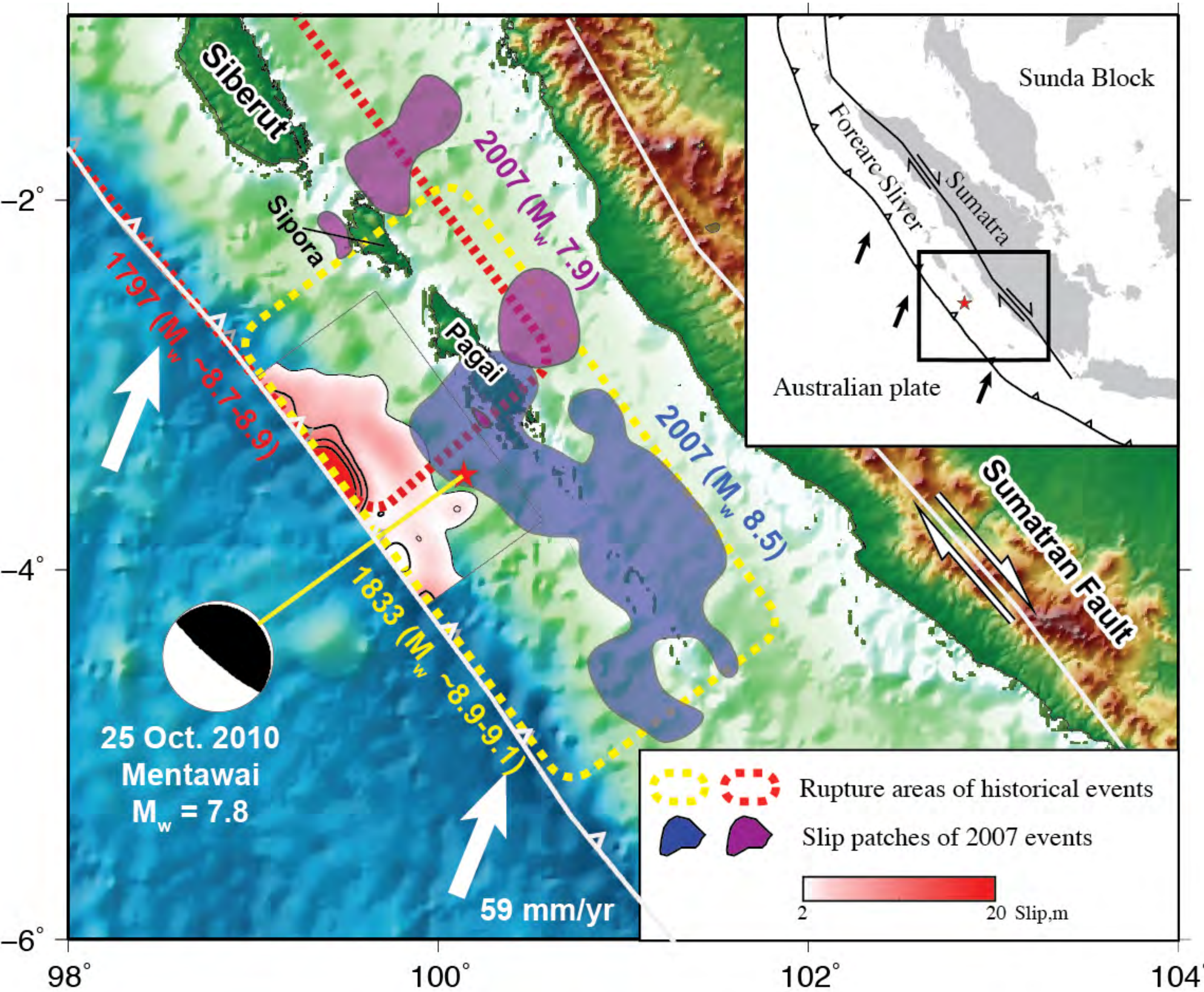


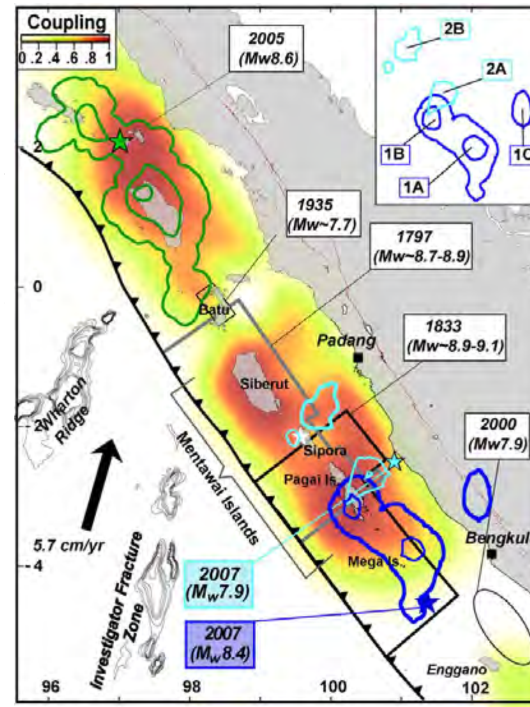
Yamazaki et al., BSSA, 2013



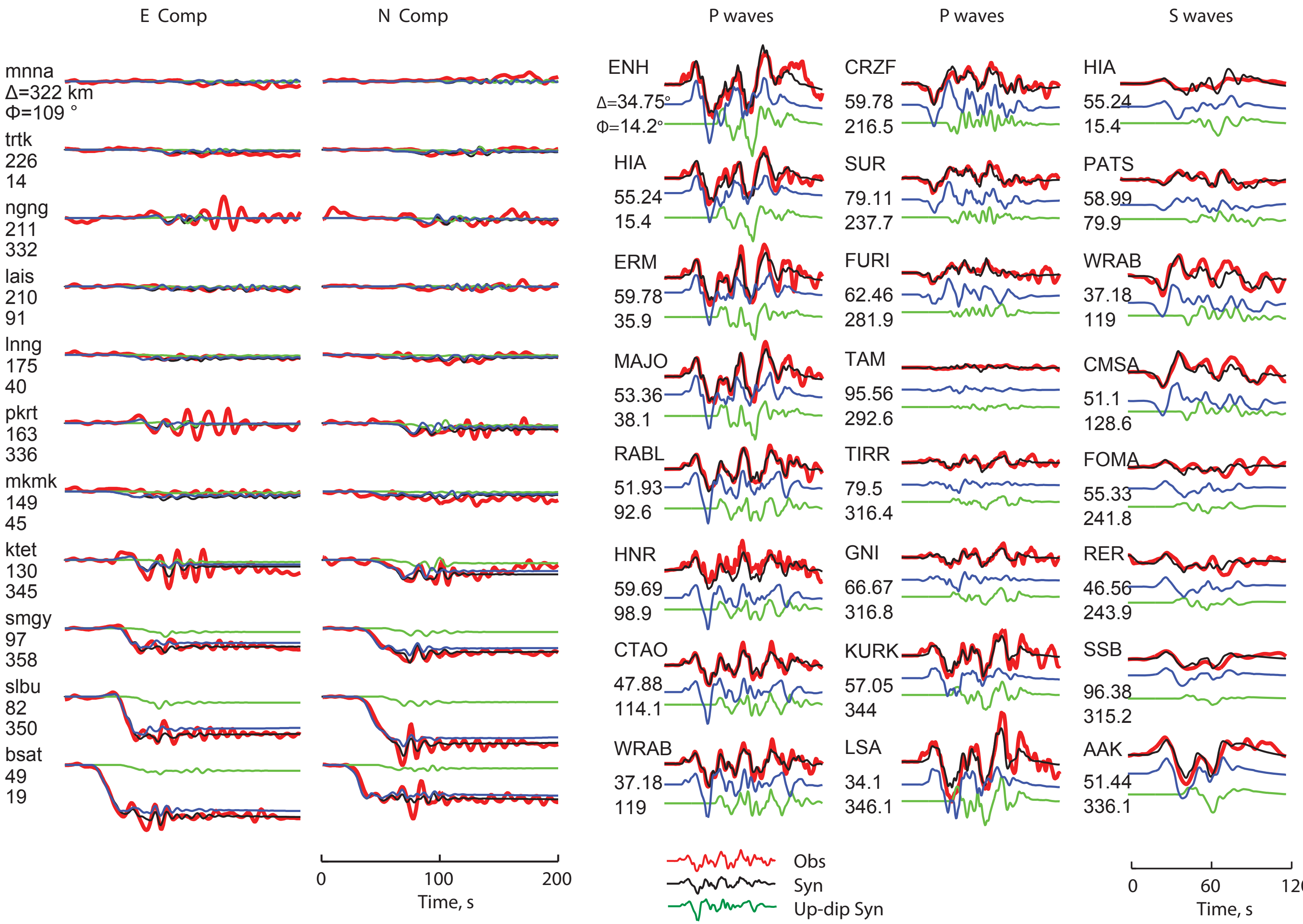
Yamazaki et al., BSSA, 2013

2010 Mentawai tsunami earthquake: Up-dip rupture from 2007 Sumatra events

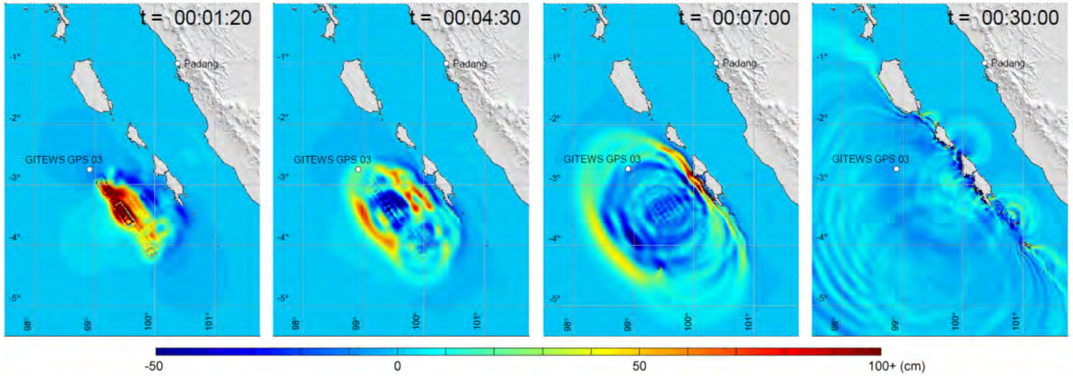




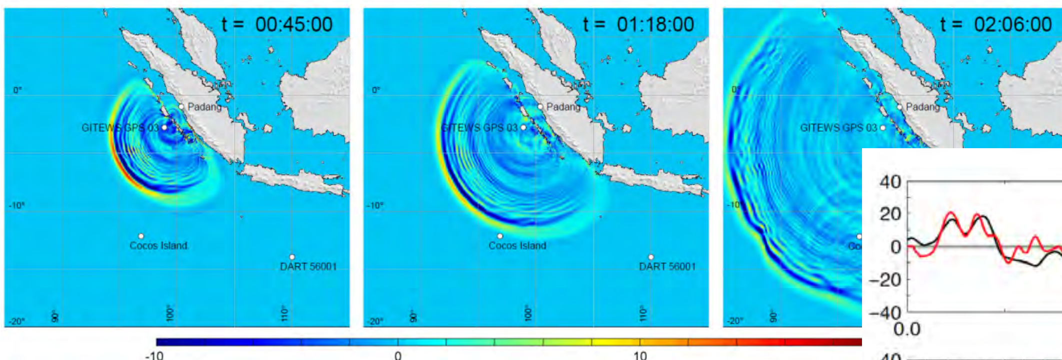
[Yue et al., 2014a]

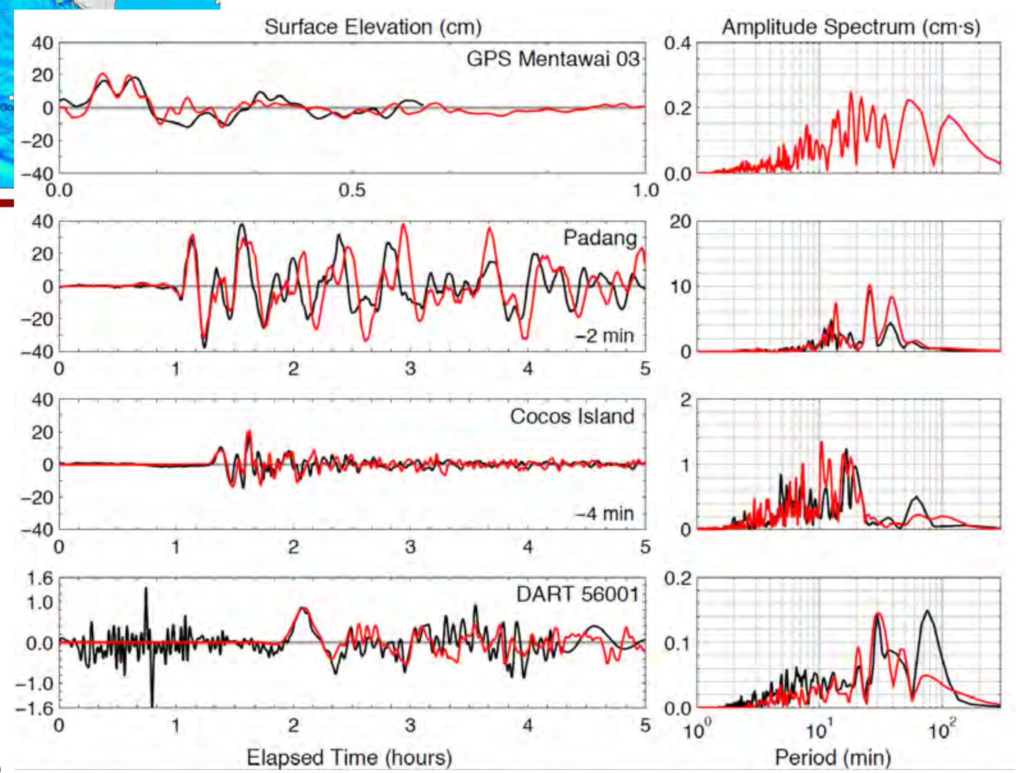


[Yue et al., 2014a]



Iterative modeling of tsunami dataset



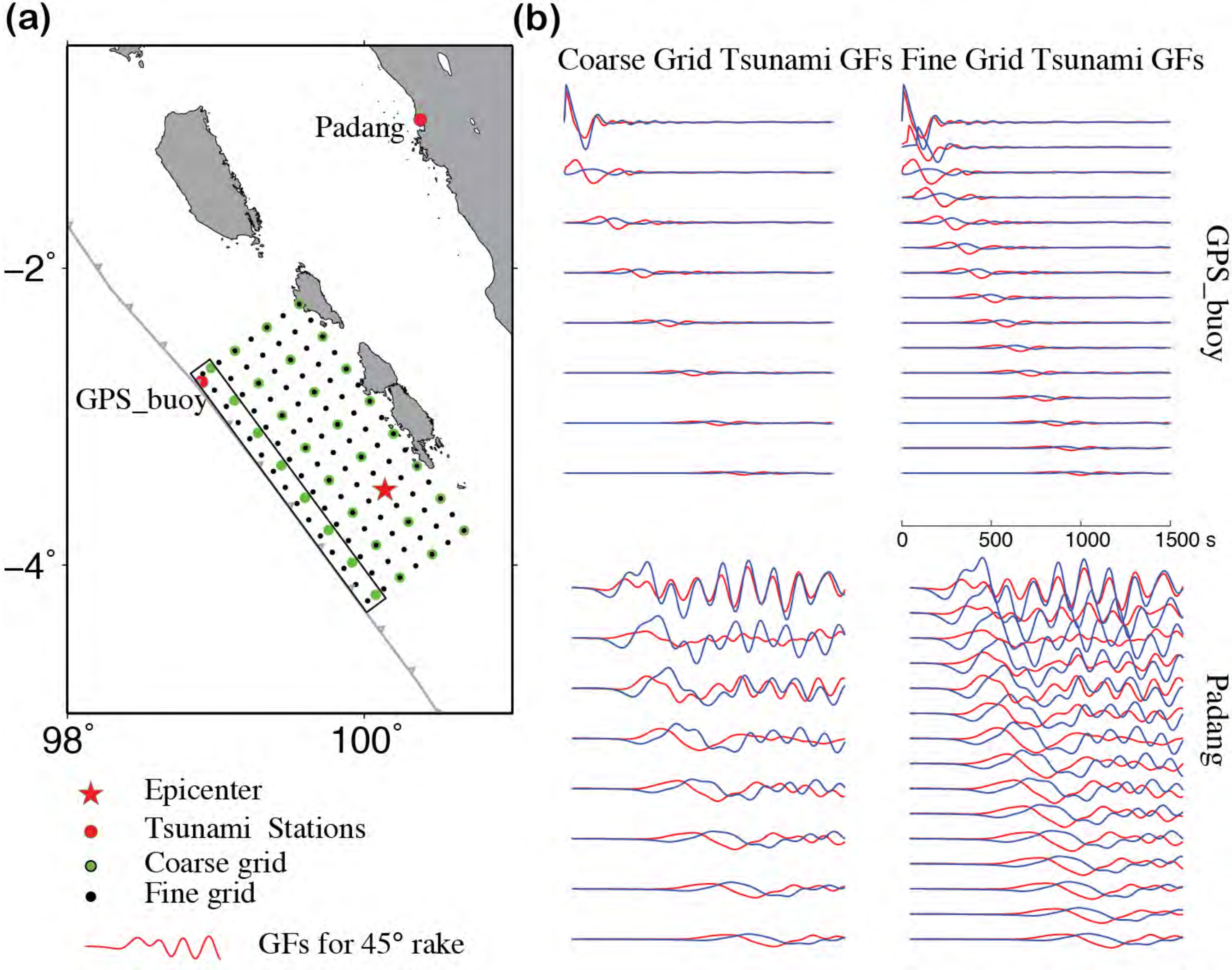


Relatively low propagation velocity of Tsunami waves

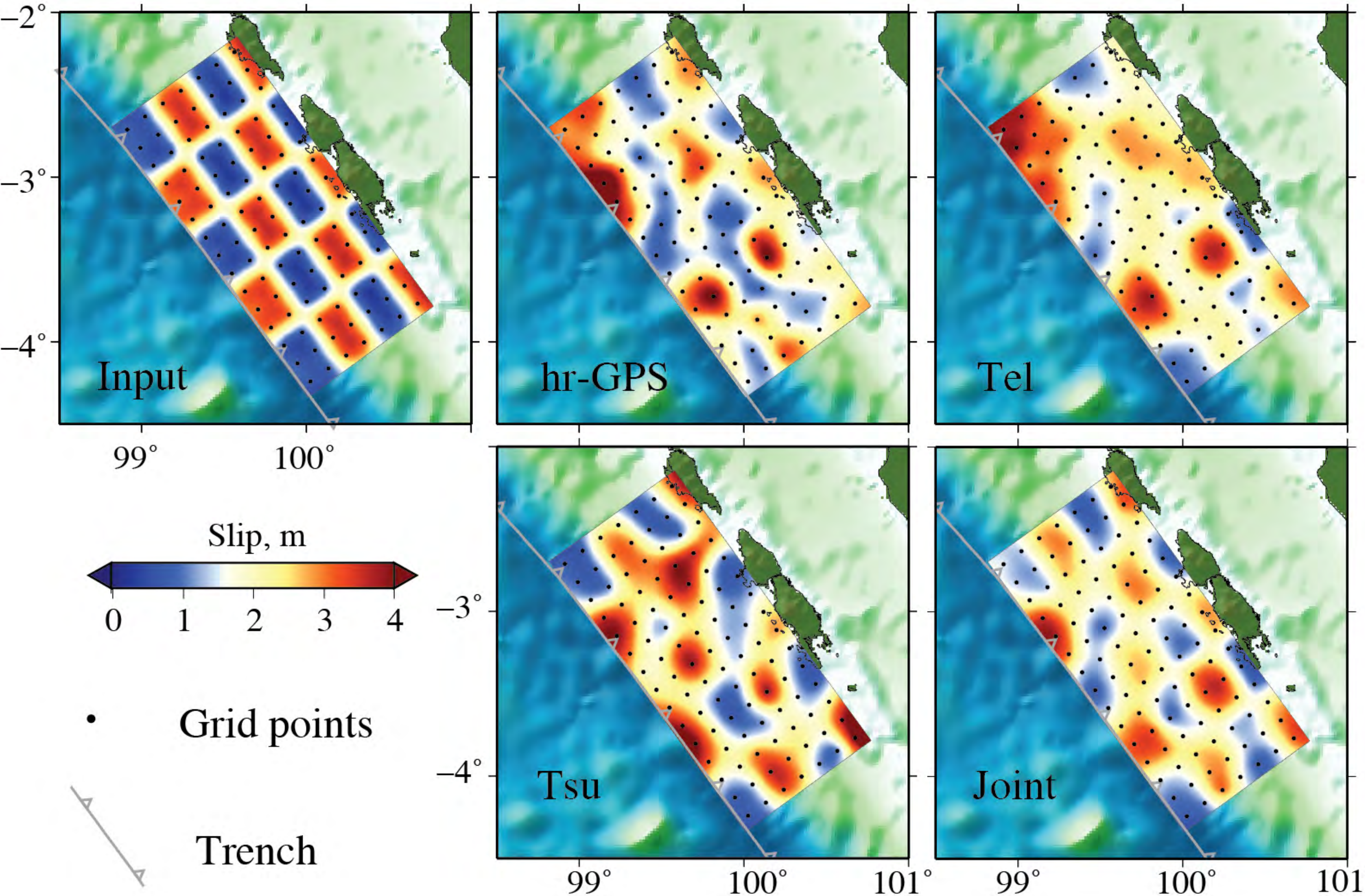
$v = \sqrt{gh}$ ~ 2o0 m/s

Arrivals of patches 40 km appart is separated by 200s

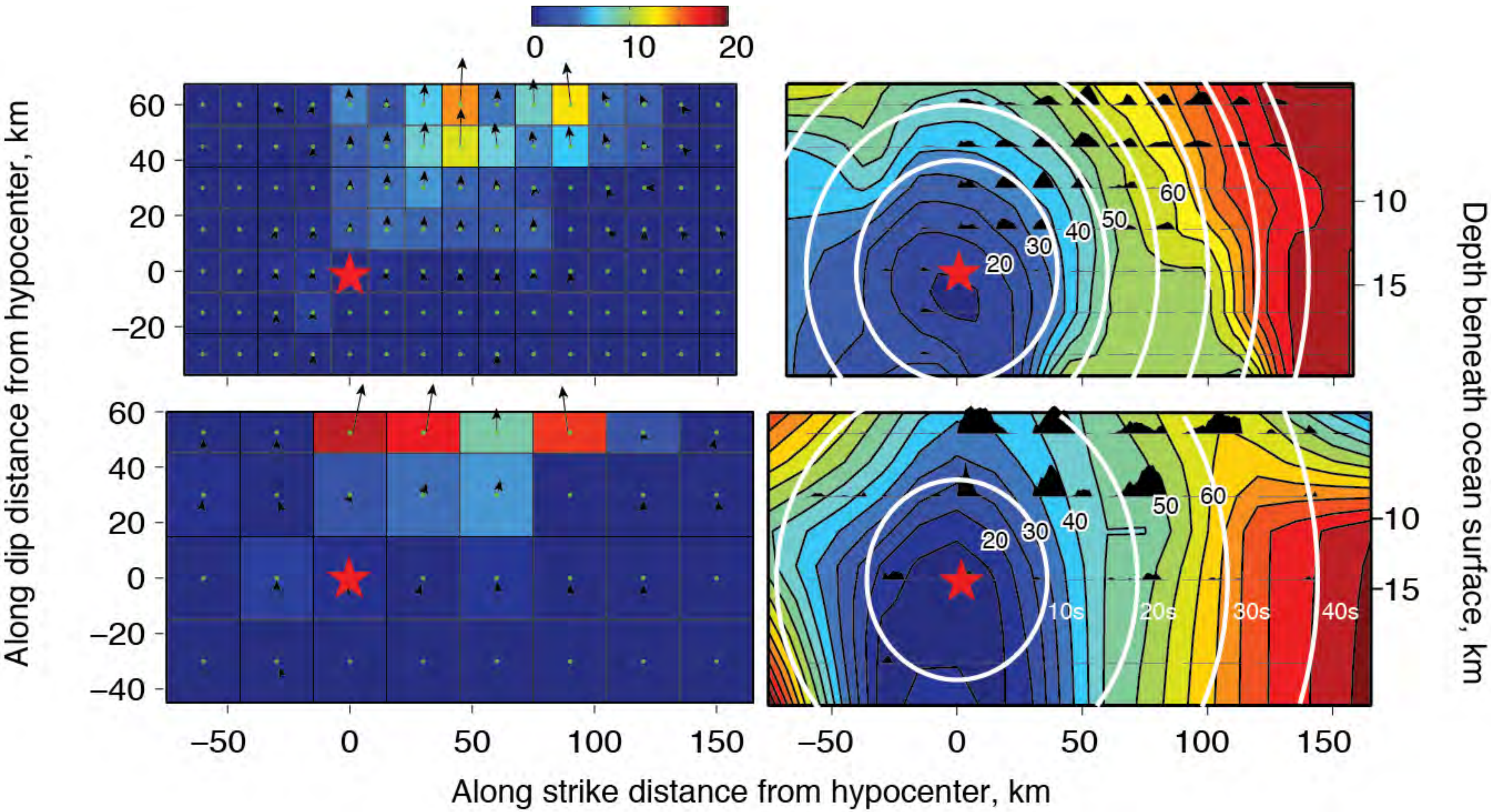
[Yue et al., 2014a]



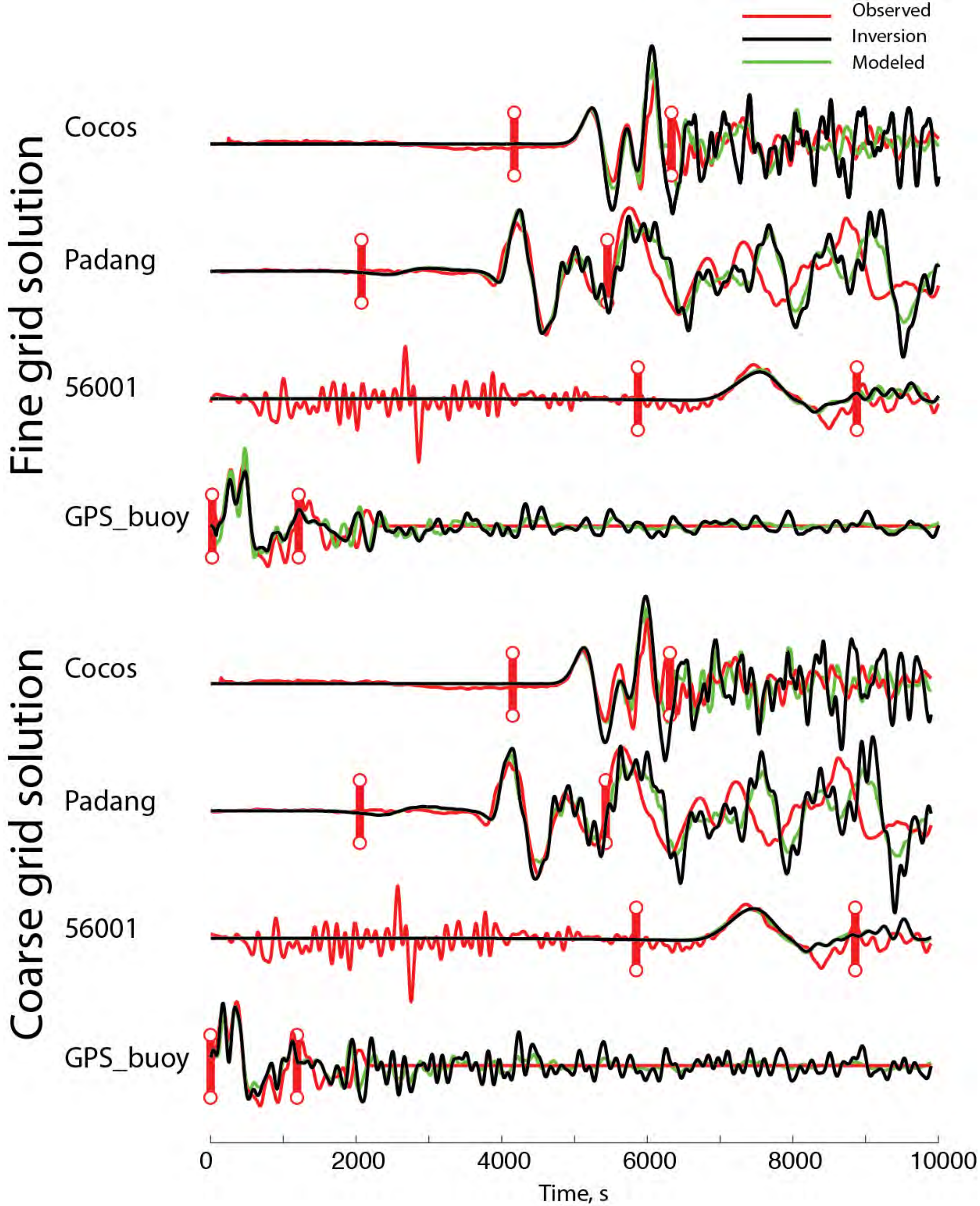
[Yue et al., 2014c]



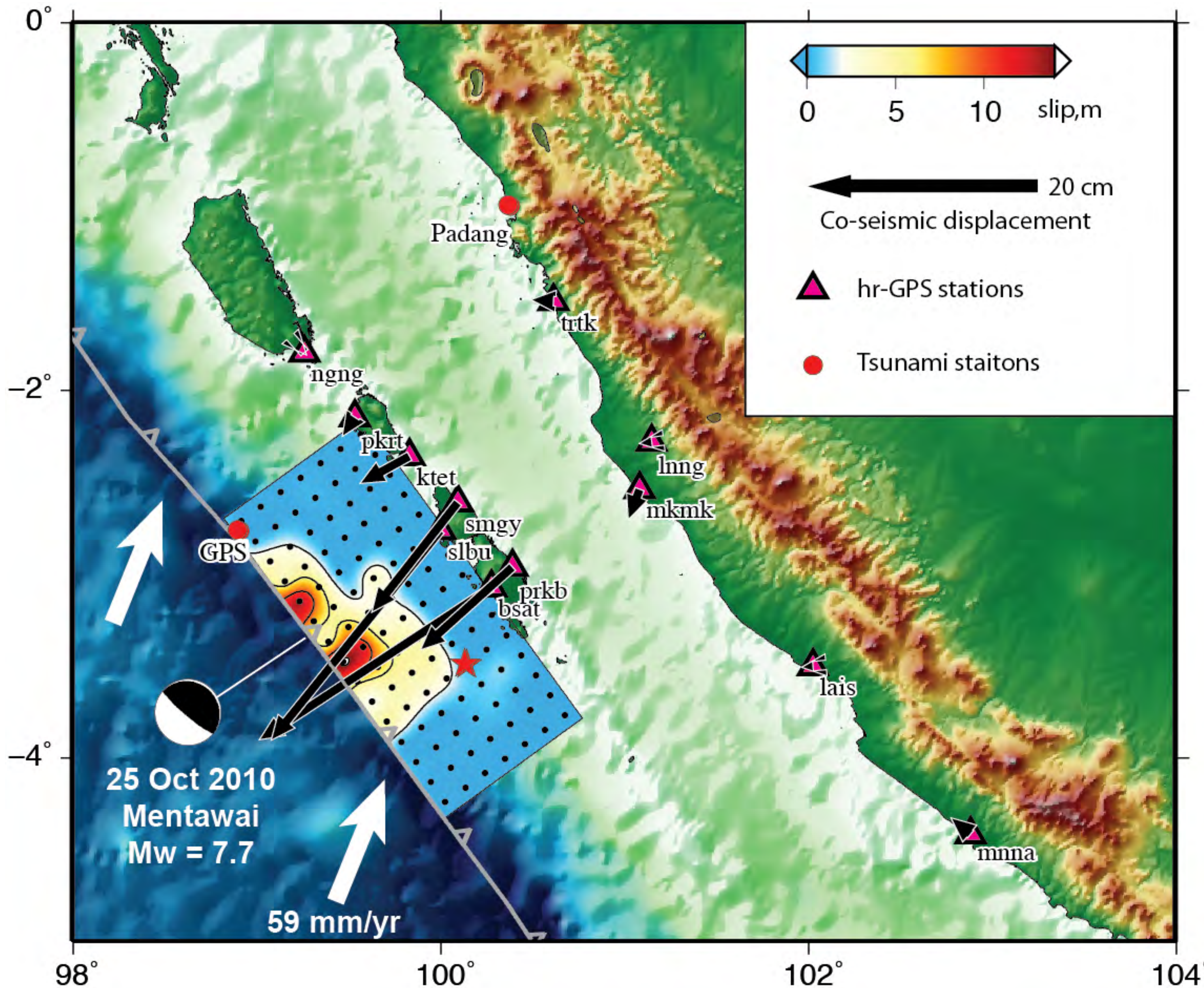
[Yue et al., 2014c]



[Yue et al., 2014c]



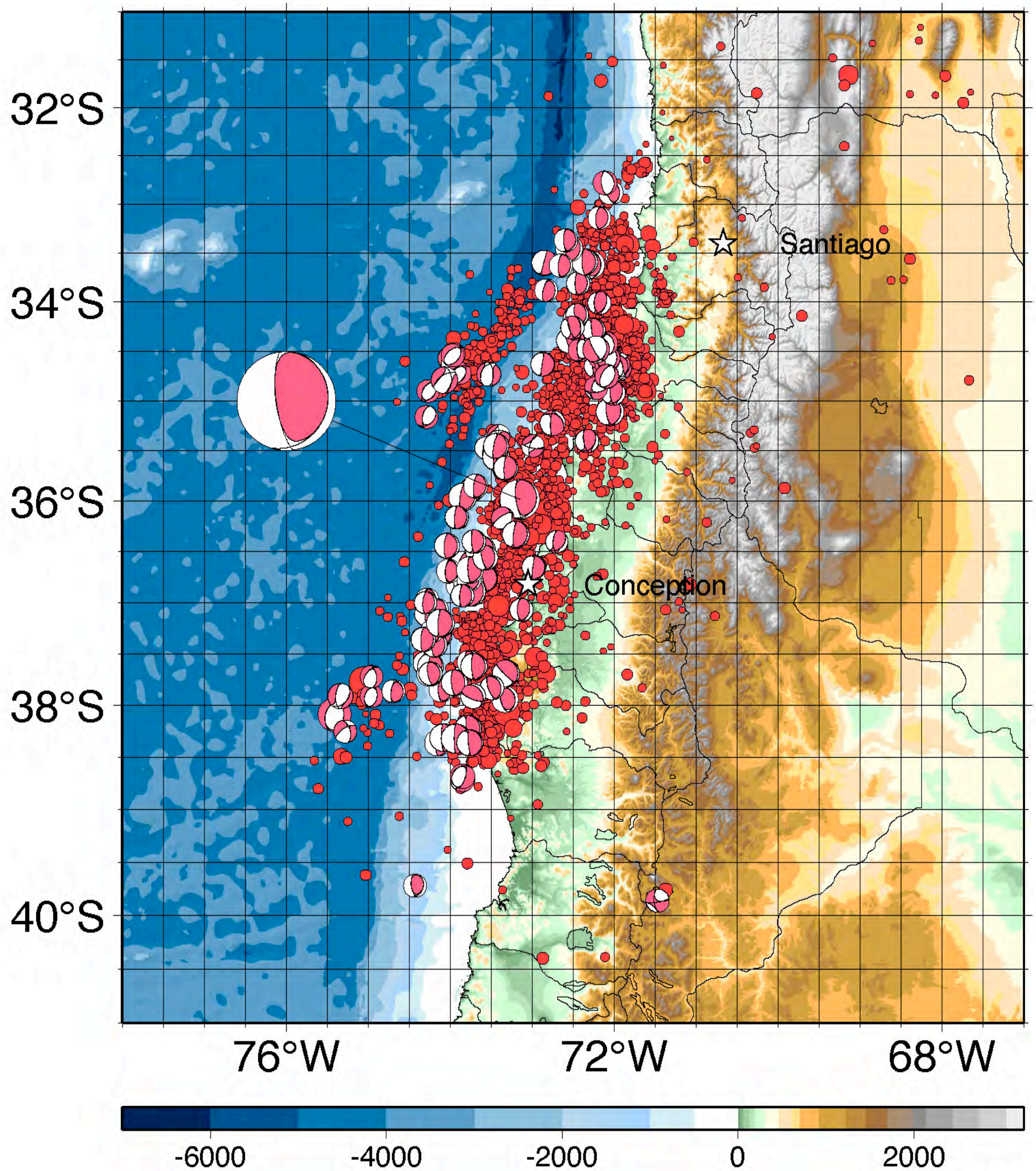
[Yue et al., 2014c]



[Yue et al., 2014c]

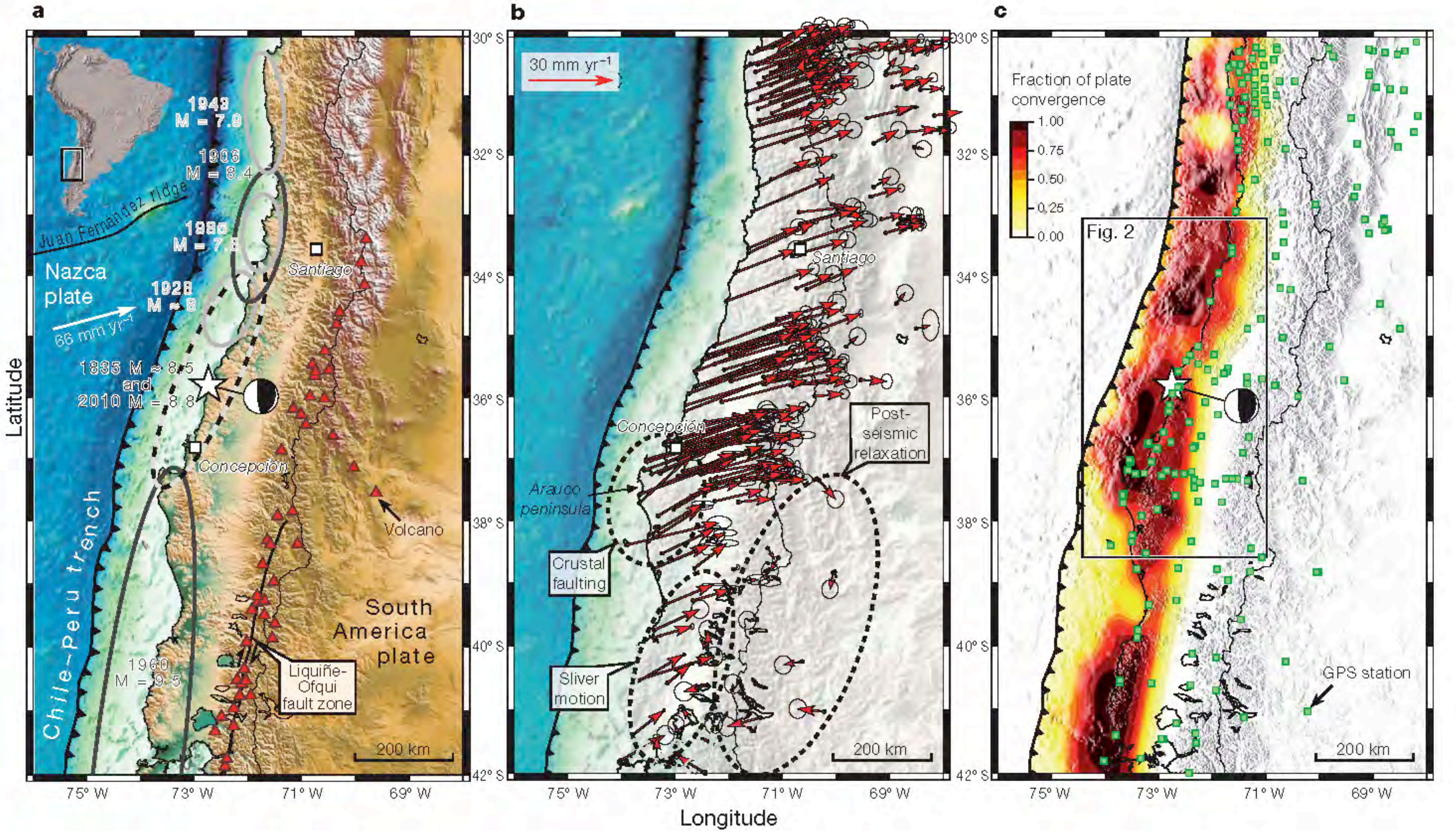
Feb. 27, 2010 Chile
M_w 8.8

Filling the 1835 seismic gap?
But it went well beyond that…



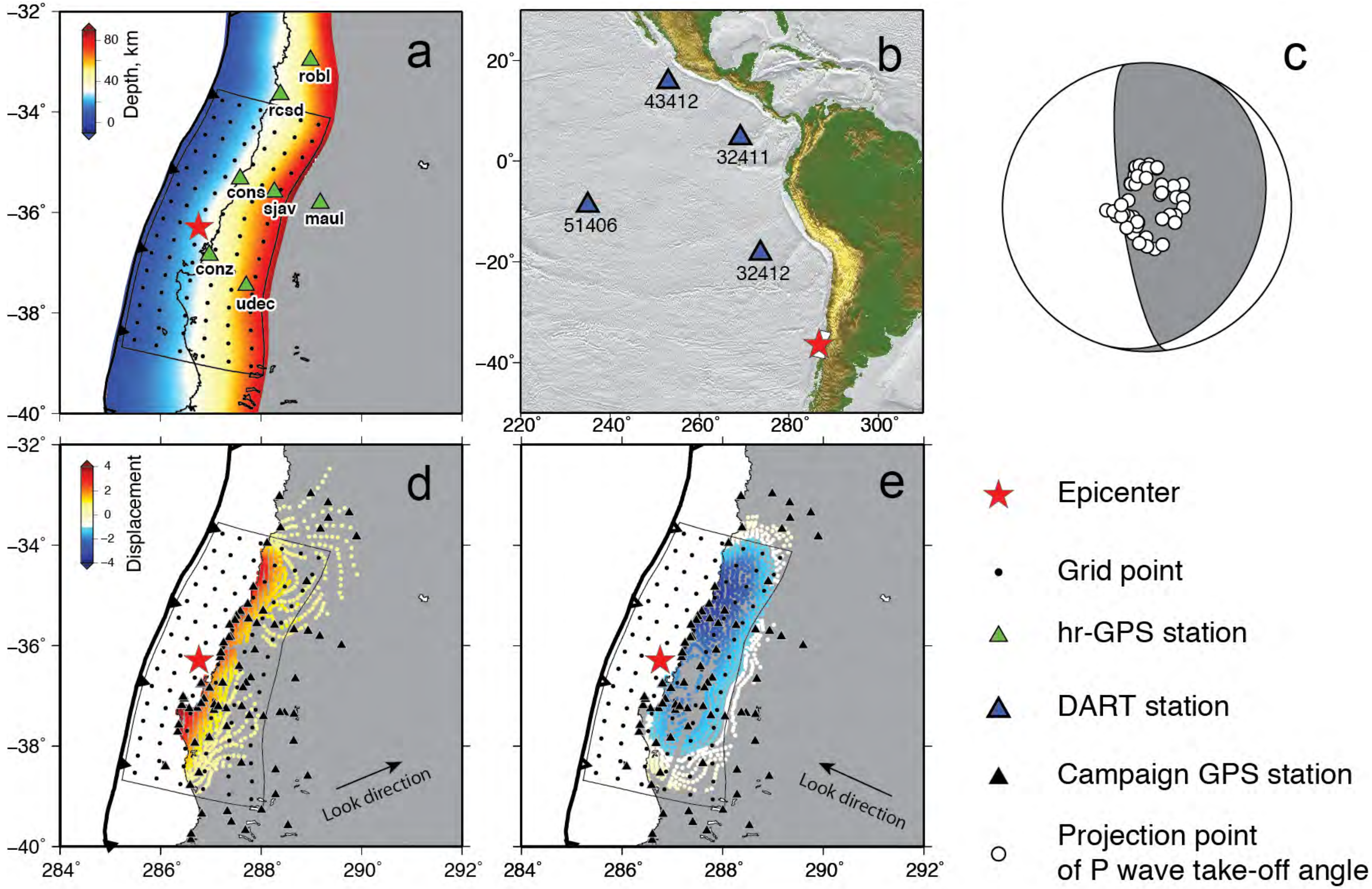
Updated From: Lay et al., GRL, 2010

Geodetic motions before Feb. 27, 2010 Chile

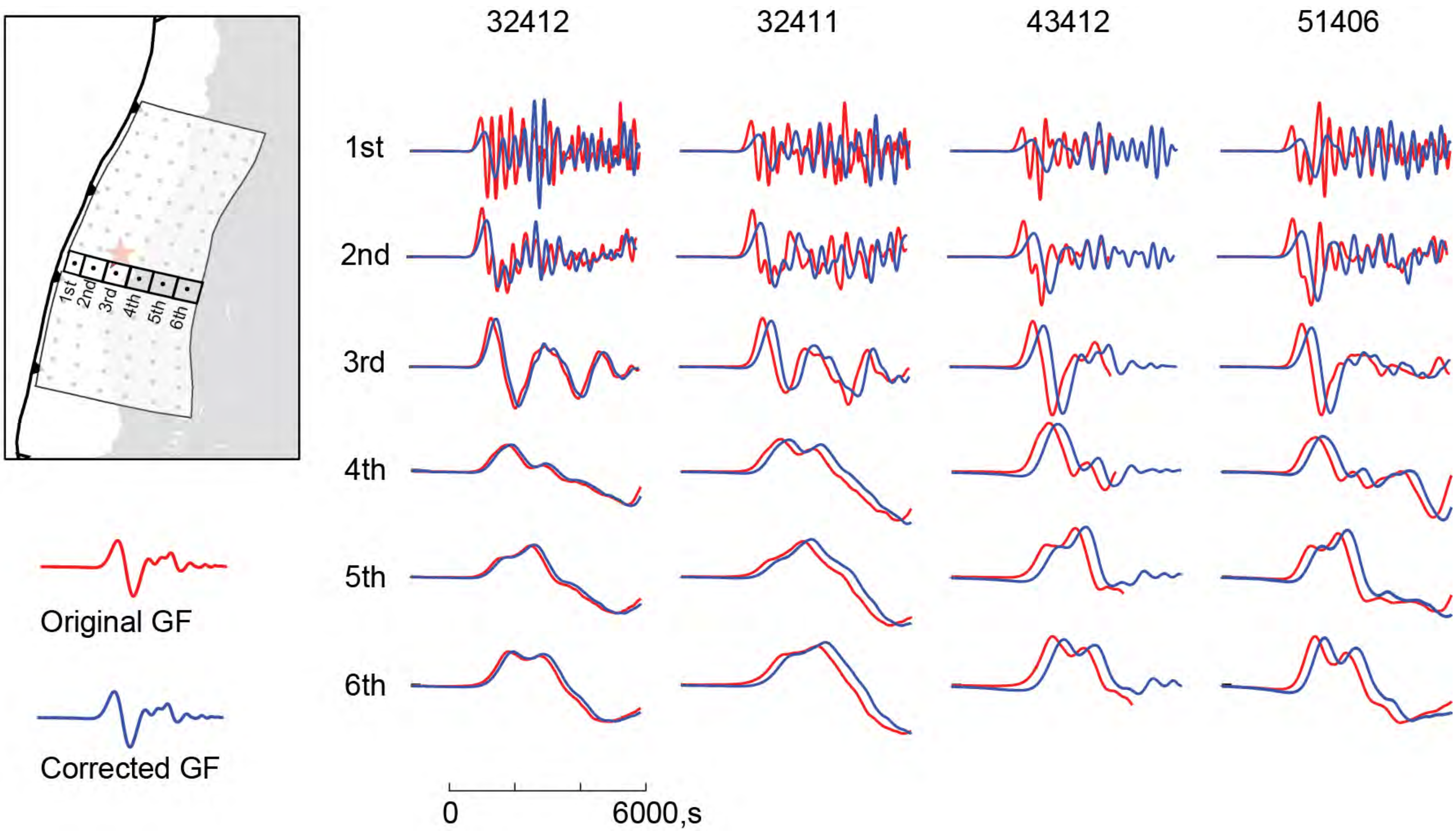


Moreno et al., Nature, 2010

Observations of 2010 M_w = 8.8 Maule earthquake

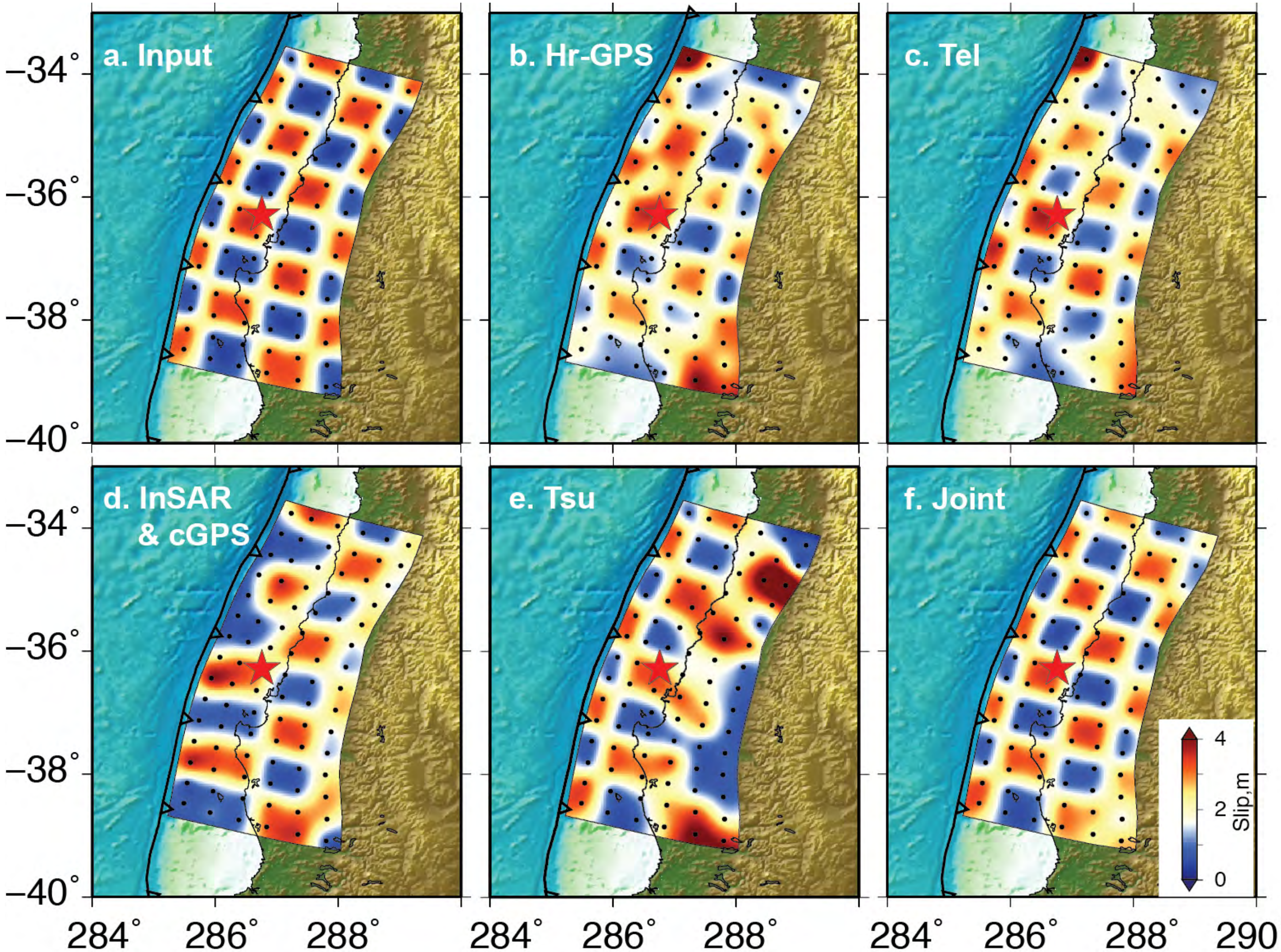


[Yue et al. 2014b]



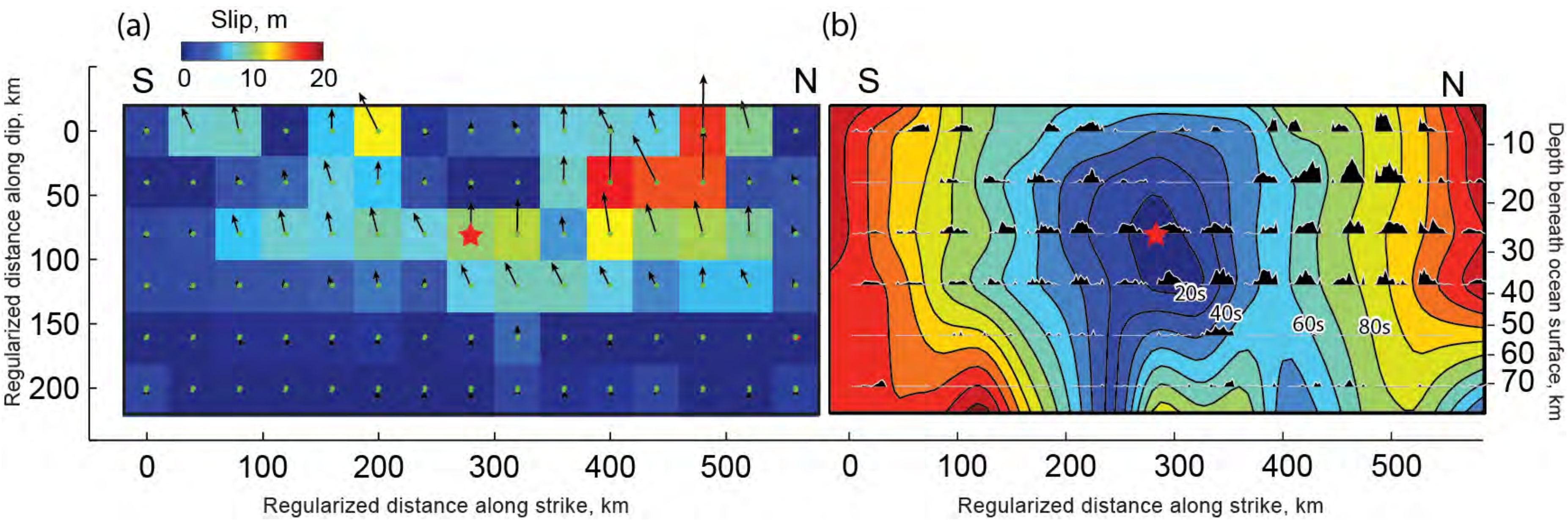
1st
2nd
3rd
4th
5th
6th
32412
32411
43412
51406
1st
2nd
3rd
4th
5th
6th
Original GF
Corrected GF
0
6000,s

Checker board test of each dataset and joint inversion

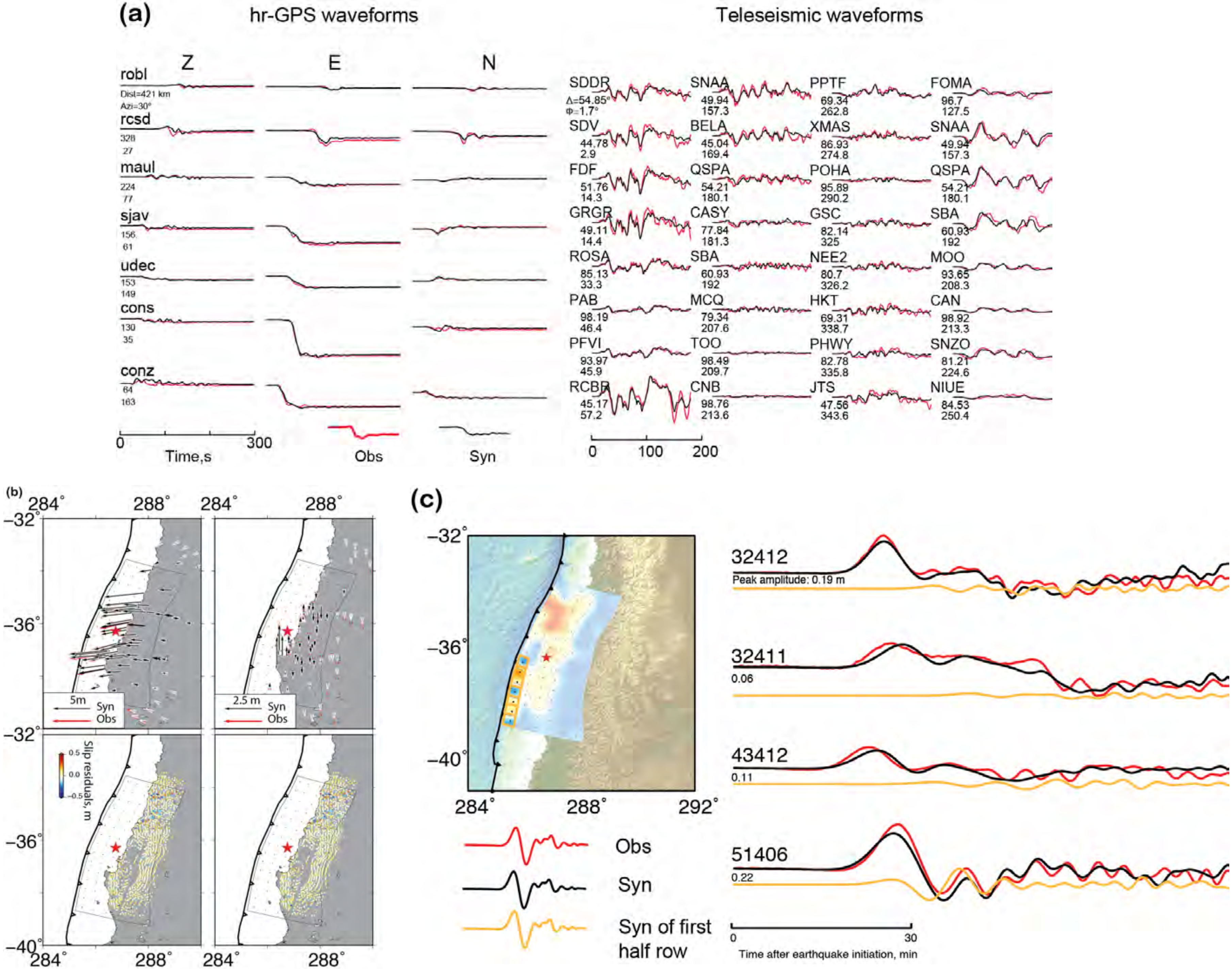


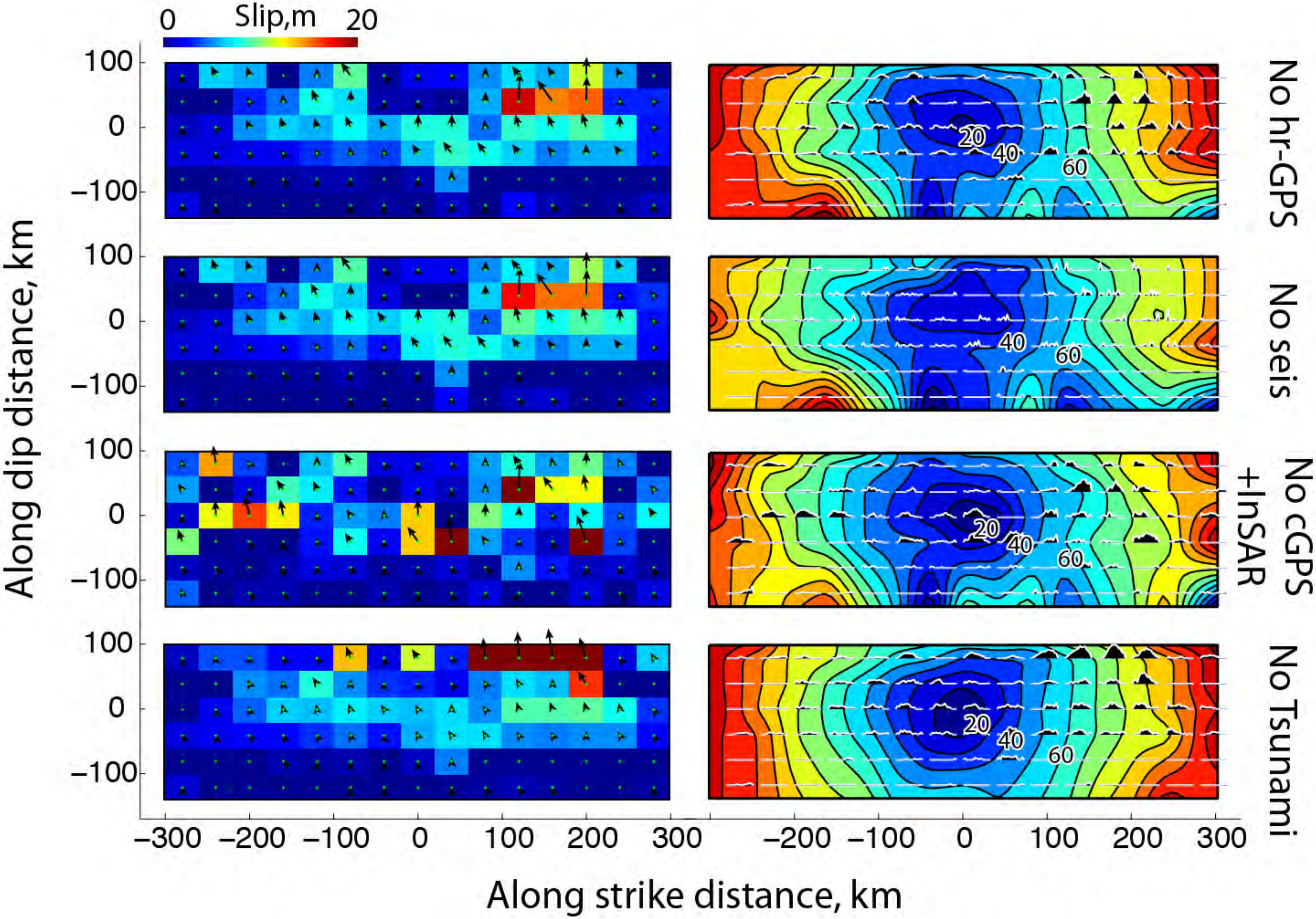
[Yue et al. 2014b]

Preferred rupture model of 2010 Maule earthquake

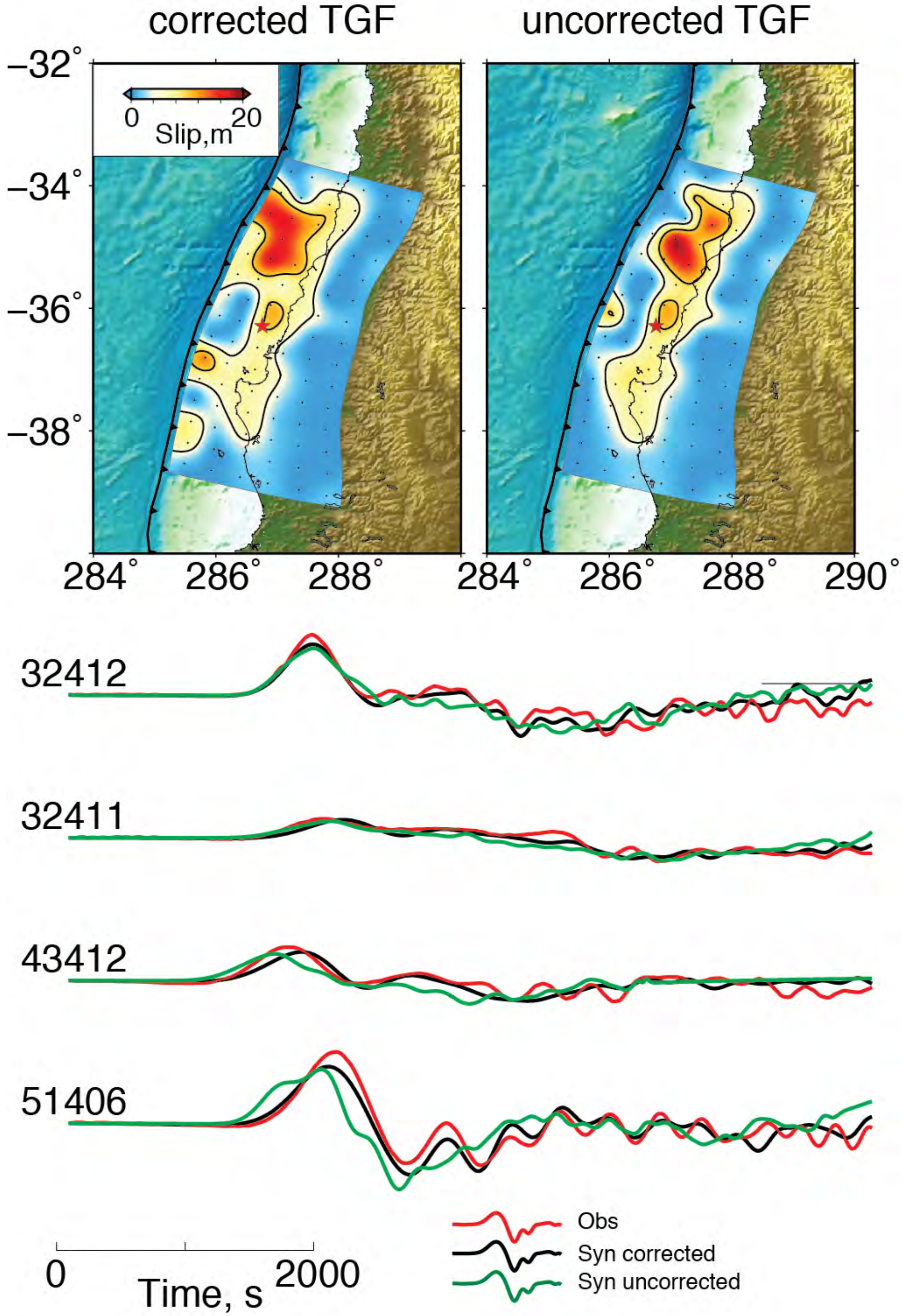


[Yue et al. 2014b]


(a)
hr-GPS waveforms
Teleseismic waveforms
Z
E
N
robl
Dist=421 km
Azi=30°
rcsd
328
27
maul
224
77
sjav
156
61
udec
153
149
cons
130
35
conz
64
163
0
Time,s
300
Obs
Syn
SDDR
Δ=54.85°
Φ=1.7°
SNAA
49.94
157.3
PPTF
69.34
262.8
FOMA
96.7
127.5
SDV
44.78
2.9
BELA
45.04
169.4
XMAS
86.93
274.8
SNAA
49.94
157.3
FDF
51.76
14.3
QSPA
54.21
180.1
POHA
95.89
290.2
QSPA
54.21
180.1
GRGR
49.11
14.4
CASY
77.84
181.3
GSC
82.14
325
SBA
60.93
192
ROSA
85.13
33.3
SBA
60.93
192
NEE2
80.7
326.2
MOO
93.65
208.3
PAB
98.19
46.4
MCQ
79.34
207.6
HKT
69.31
338.7
CAN
98.92
213.3
PFVI
93.97
45.9
TOO
98.49
209.7
PHWY
82.78
335.8
SNZO
81.21
224.6
RCBR
45.17
57.2
CNB
98.76
213.6
JTS
47.56
343.6
NIUE
84.53
250.4
0
100
200
(b)
284°
288°
-32°
-36°
-40°
5m
2.5 m
Syn
Obs
Slip residuals, m
0.5
0.0
-0.5
(c)
-32°
-36°
-40°
284°
288°
292°
Obs
Syn
Syn of first half row
32412
Peak amplitude: 0.19 m
32411
0.06
43412
0.11
51406
0.22
0
30
Time after earthquake initiation, min

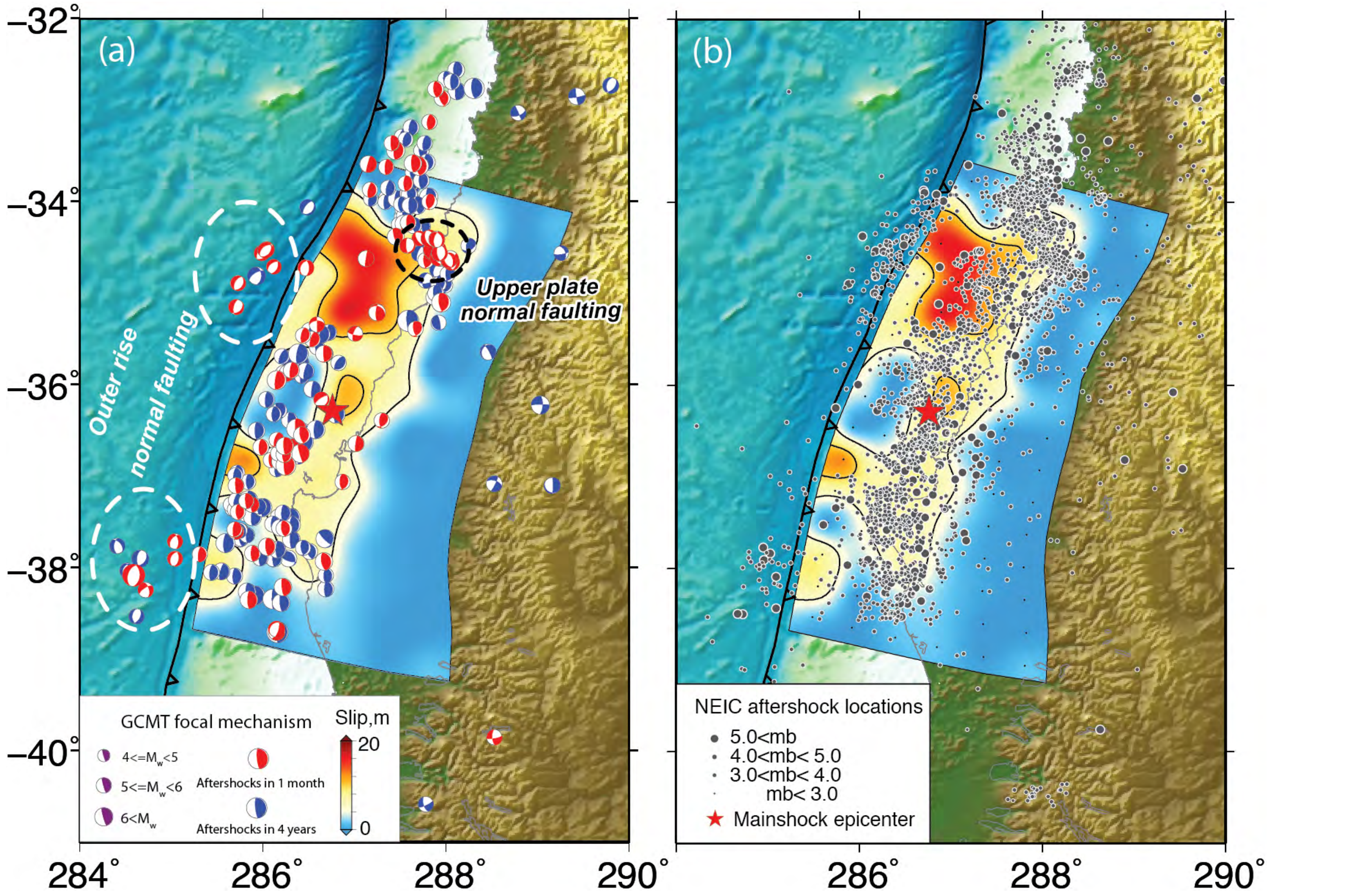


0
Slip,m
20
100
0
−100
Along dip distance, km
20
40
60
No hr-GPS
No seis
No cGPS +InSAR
No Tsunami
−300
−200
−100
0
100
200
300
Along strike distance, km



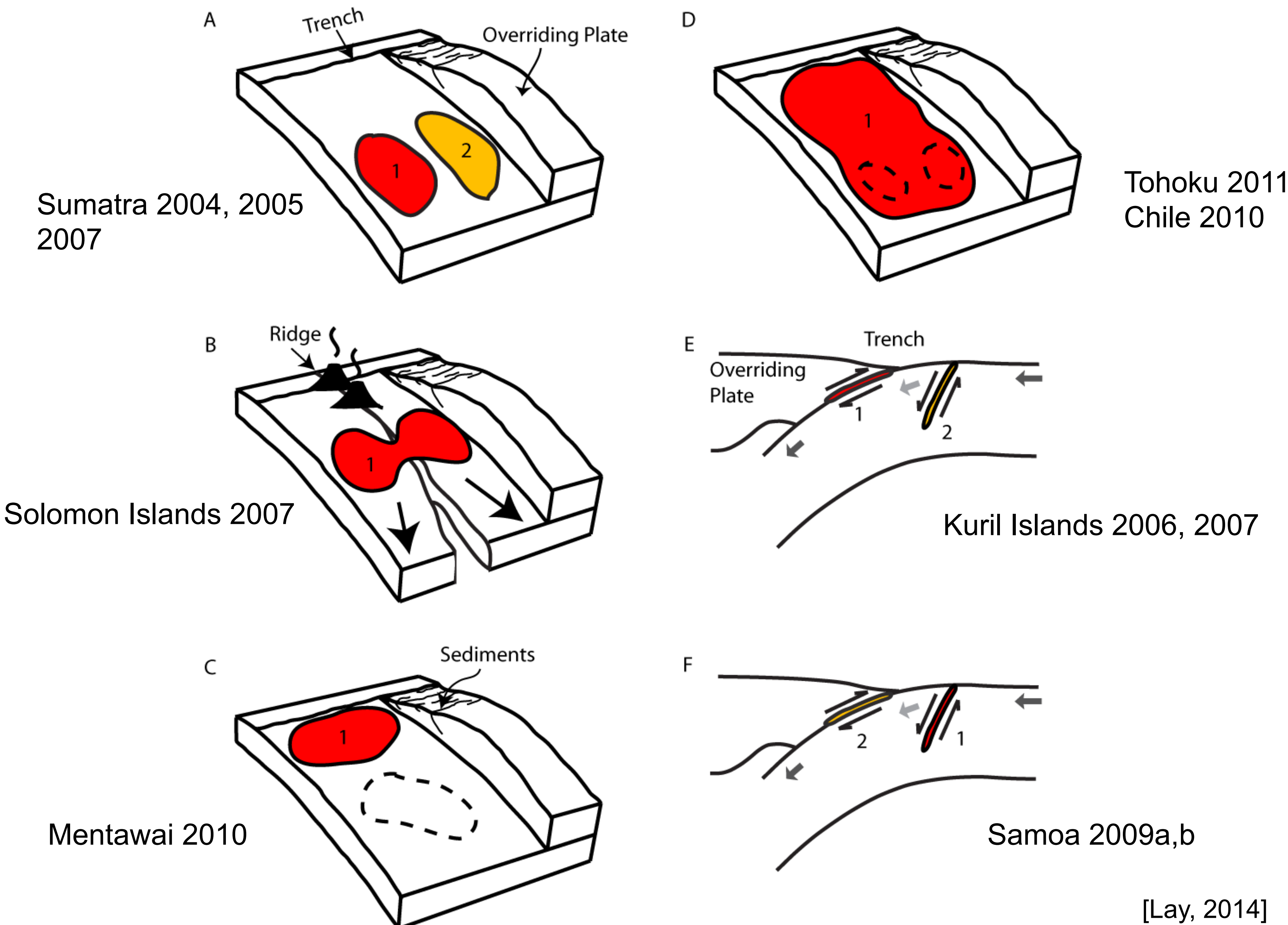
corrected TGF
uncorrected TGF
0
20
Slip,m
−32°
−34°
−36°
−38°
284°
286°
288°
284°
286°
288°
290°
32412
32411
43412
51406
0
2000
Time, s
Obs
Syn corrected
Syn uncorrected

Complementary pattern with the aftershock distribution



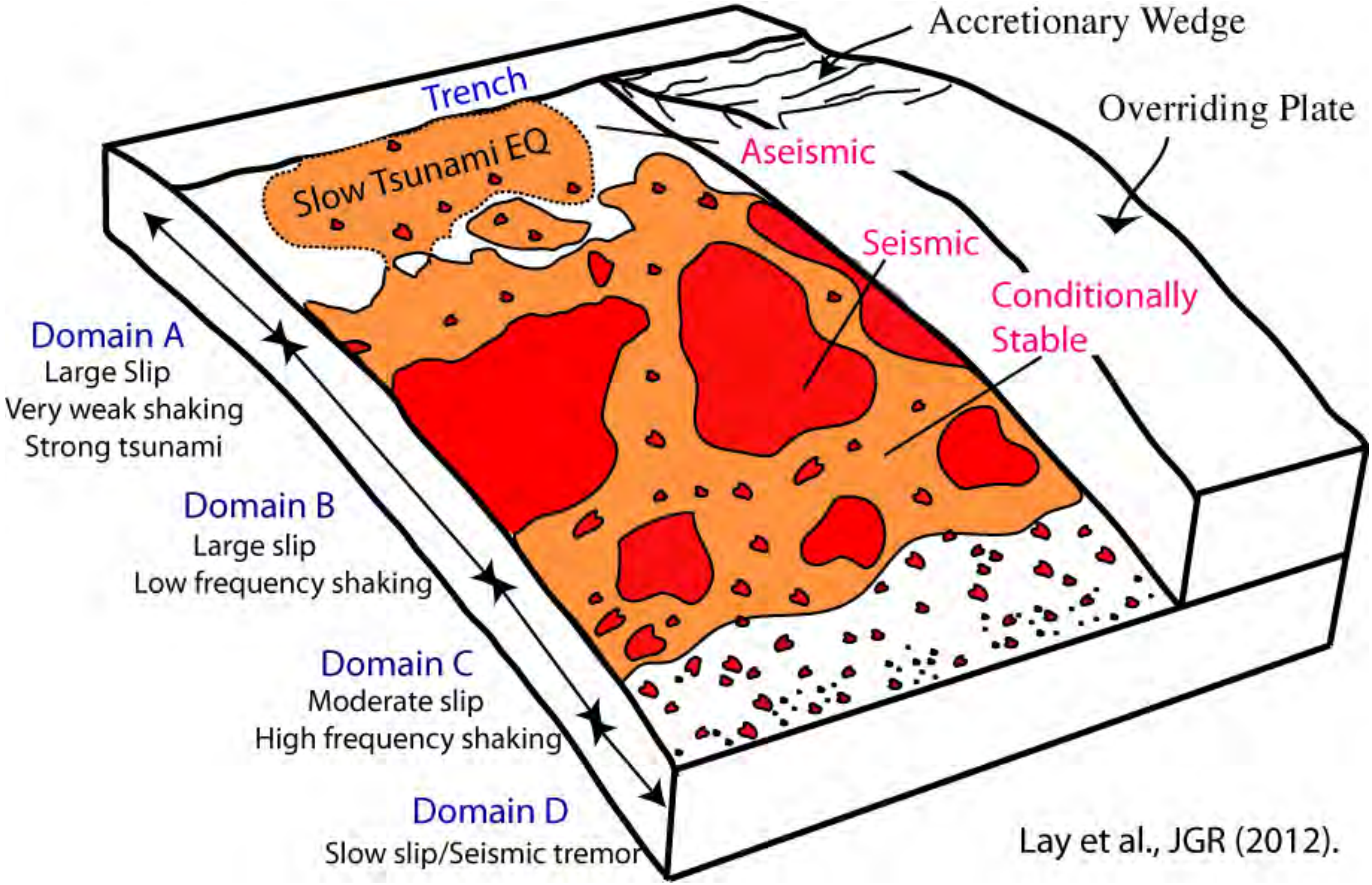
[Yue et al. 2014b]

Great Earthquake Scenarios



[Lay, 2014]

Variable frictional properties seem ubiquitous



Lay et al., JGR (2012).

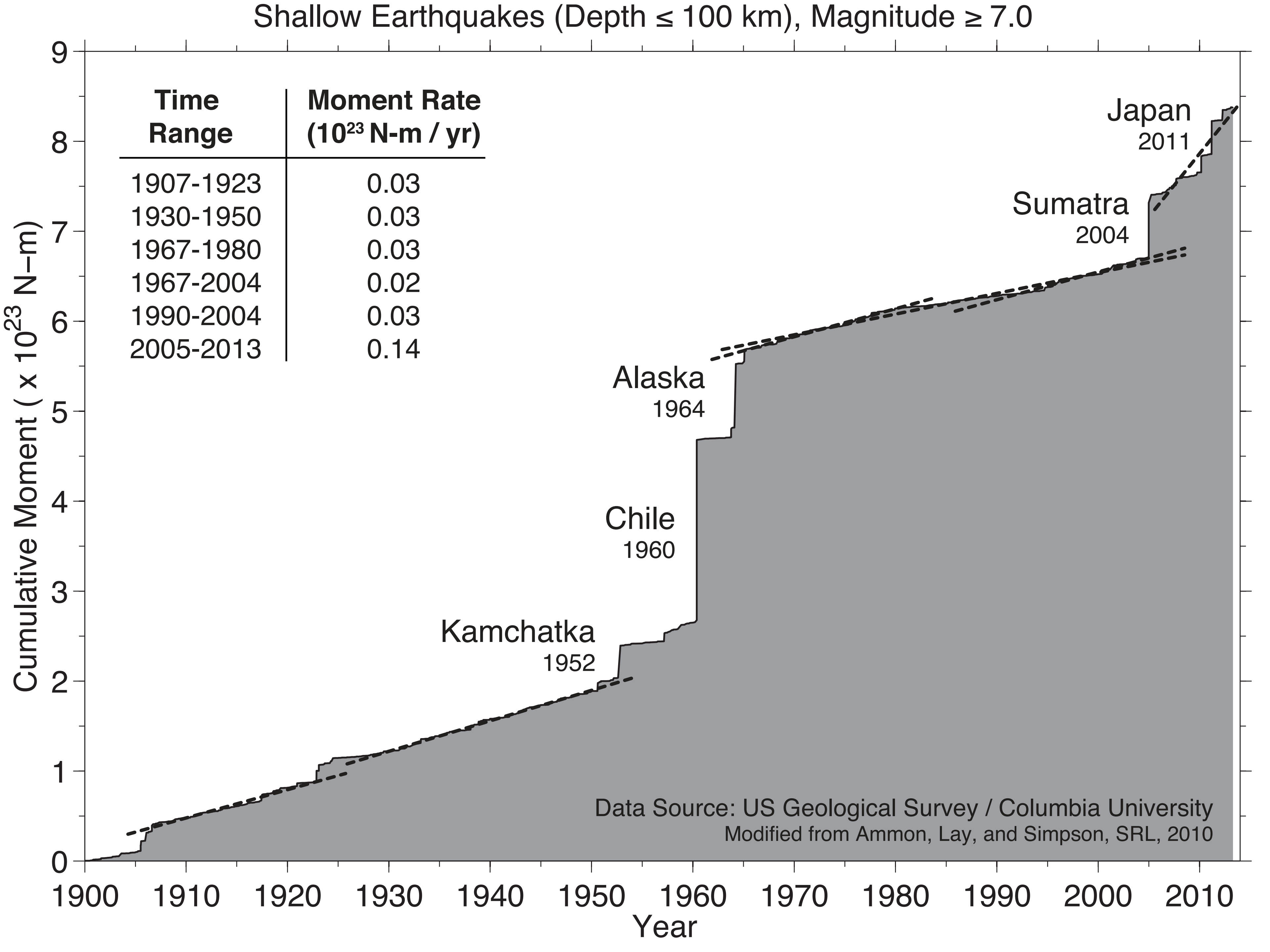
Conclusions

Great earthquake ruptures and associated pre-seismic and post-seismic are now being quantified in unprecedented detail.

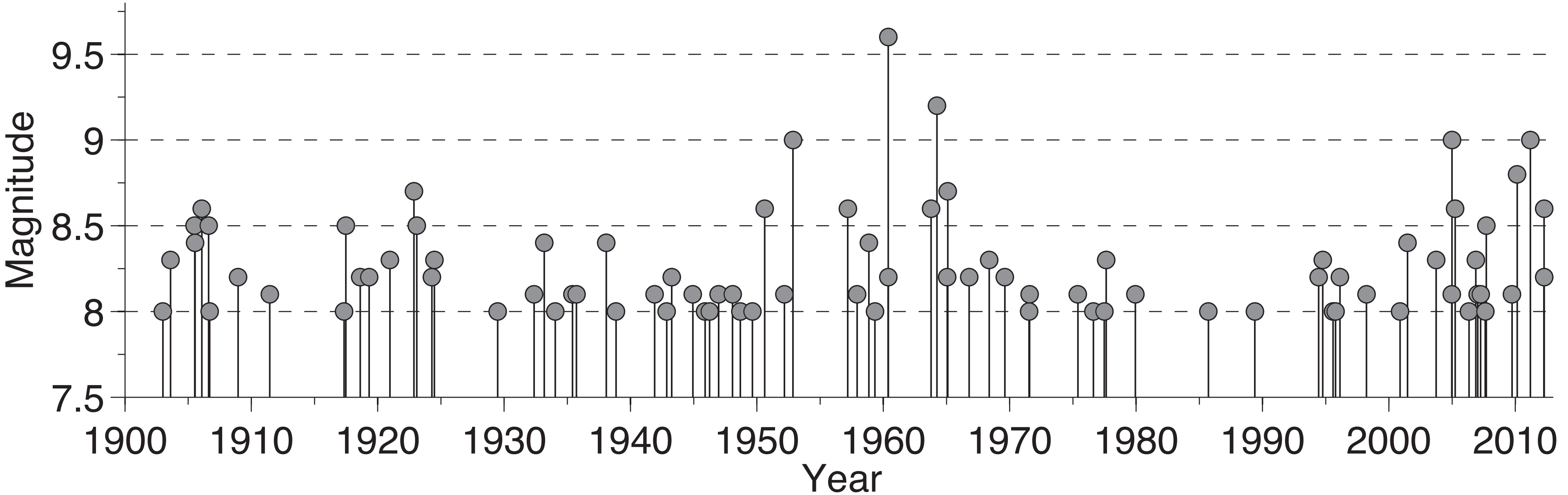
This results from systematic deployment of global seismic, geodetic, and tsunami instrumentation that is largely openly available, in parallel with extensive development of finite-faulting inversion capabilities for all wavefields.

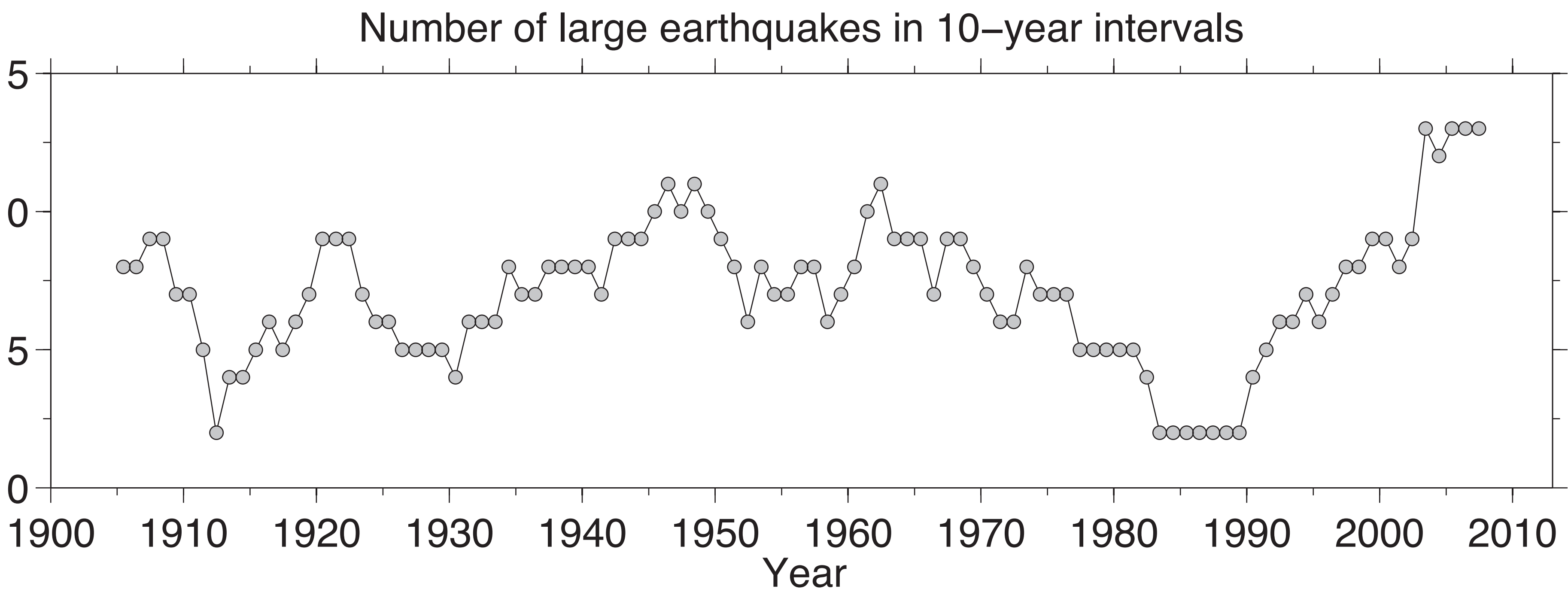
Comprehensive modeling of all ground motions, including dynamic and static three-component motions is viable and yields best constrained solutions.

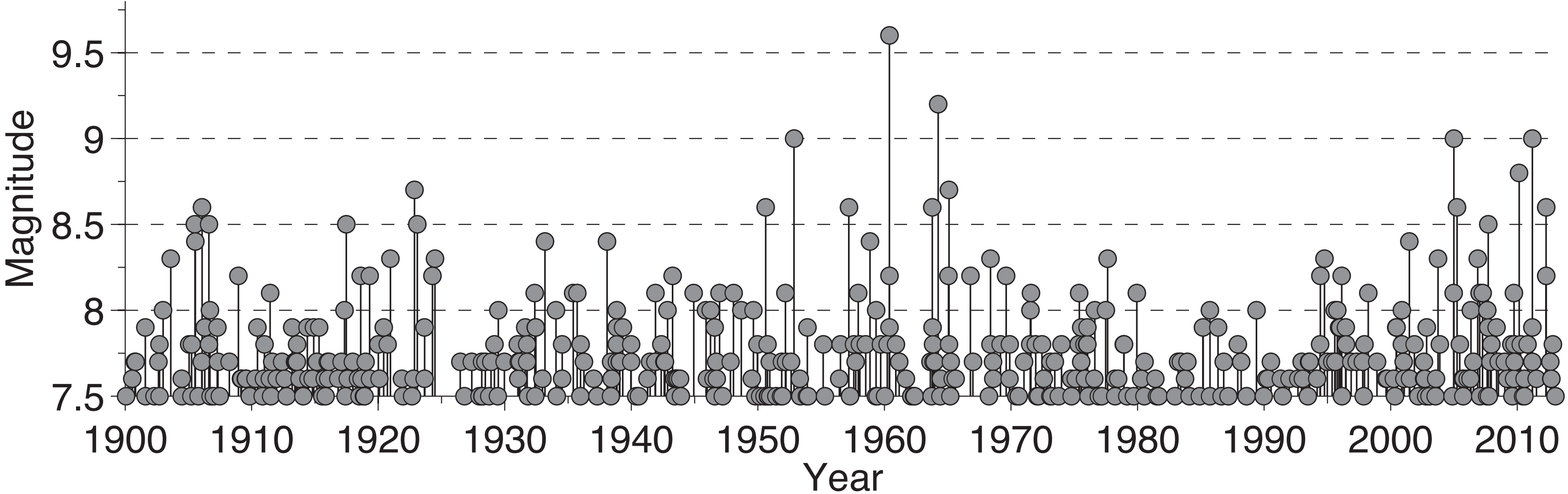
We need to prepare for future great earthquakes



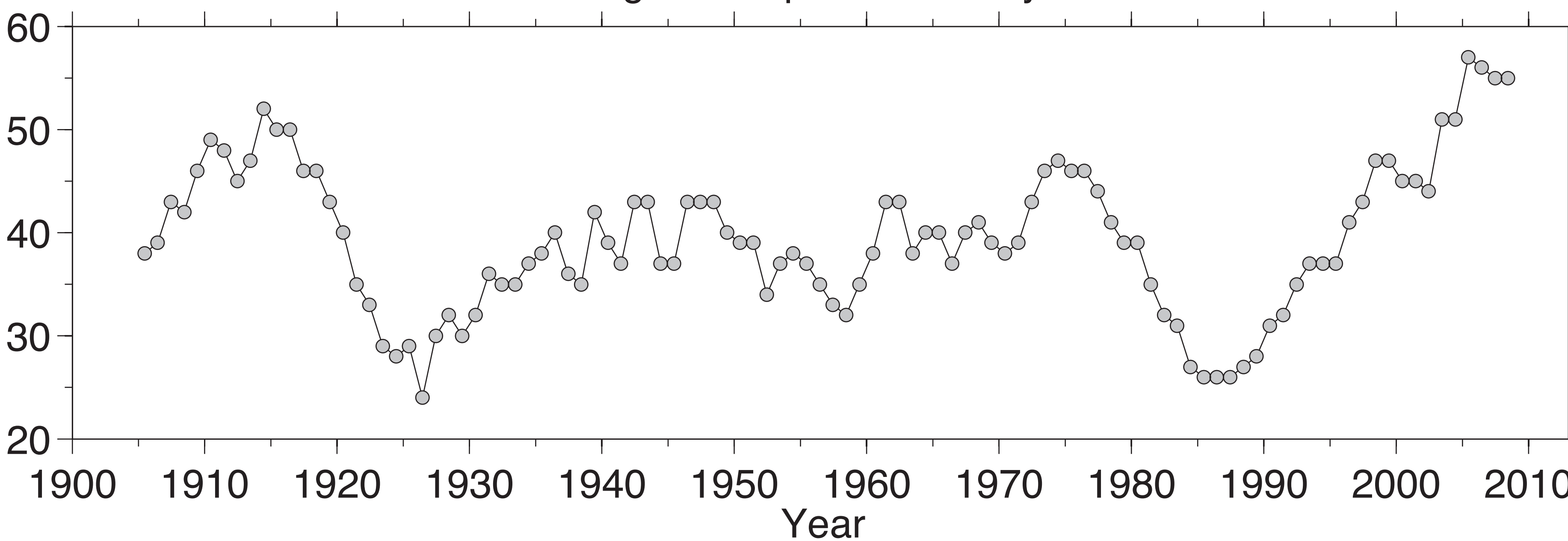
Shallow Earthquakes (Depth ≤ 100 km), Magnitude ≥ 7.0
Time Range
Moment Rate (10^23 N-m / yr)
1907-1923 0.03
1930-1950 0.03
1967-1980 0.03
1967-2004 0.02
1990-2004 0.03
2005-2013 0.14
Japan 2011
Sumatra 2004
Alaska 1964
Chile 1960
Kamchatka 1952
Cumulative Moment (x 10^23 N–m)
Year
Data Source: US Geological Survey / Columbia University
Modified from Ammon, Lay, and Simpson, SRL, 2010

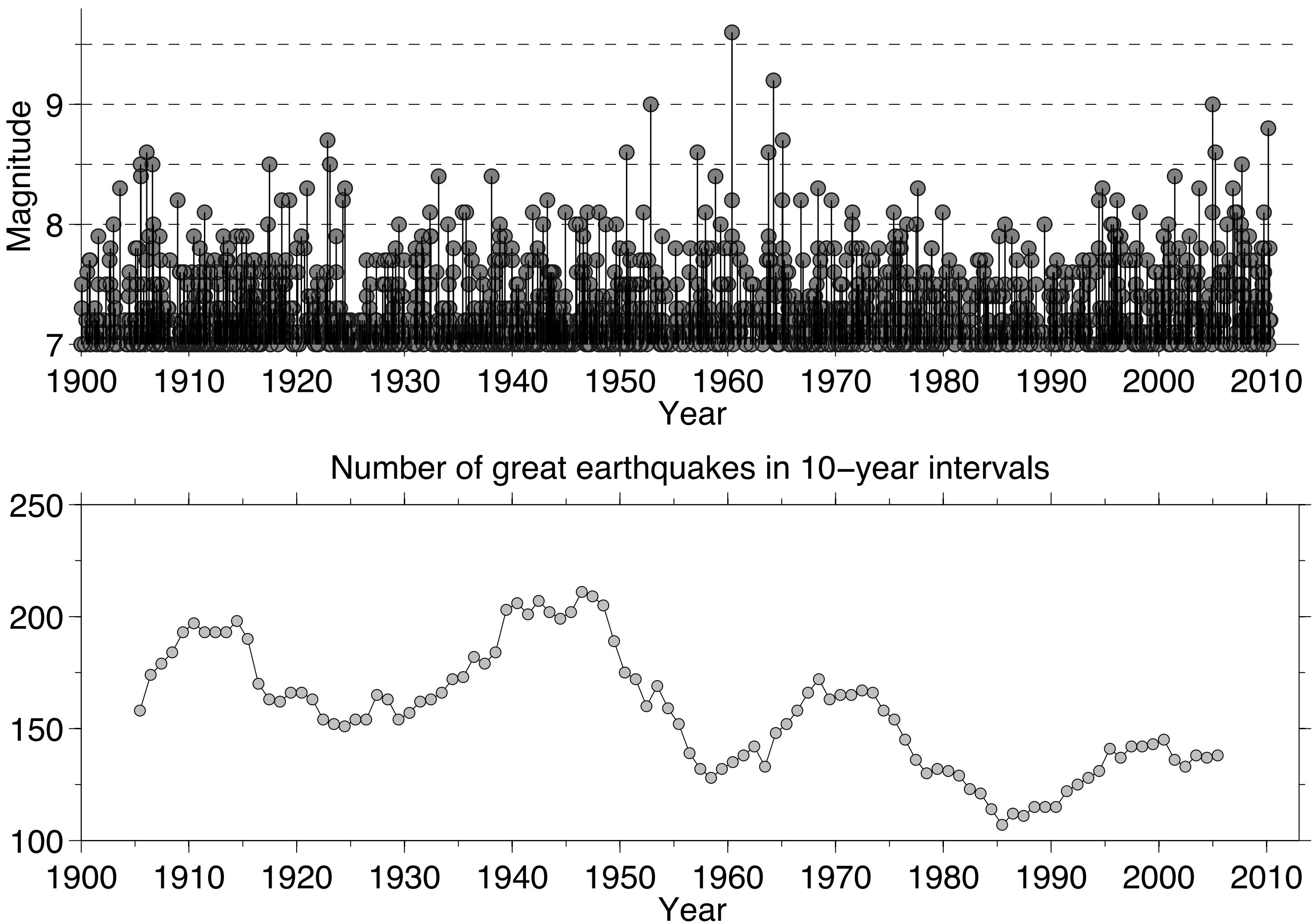

Magnitude
9.5
9
8.5
8
7.5
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year


Number of large earthquakes in 10−year intervals
15
10
5
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year



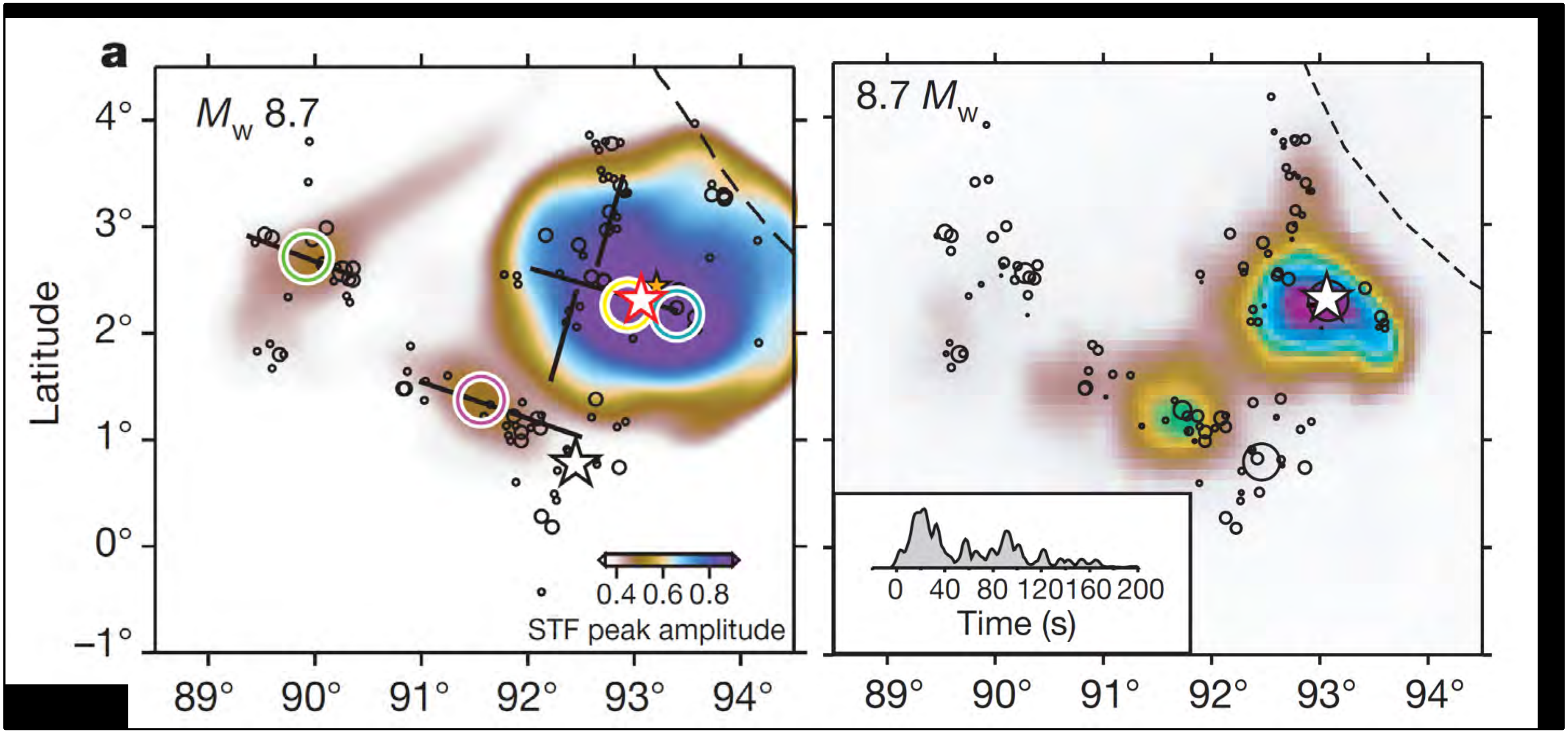
Number of large earthquakes in 10−year intervals





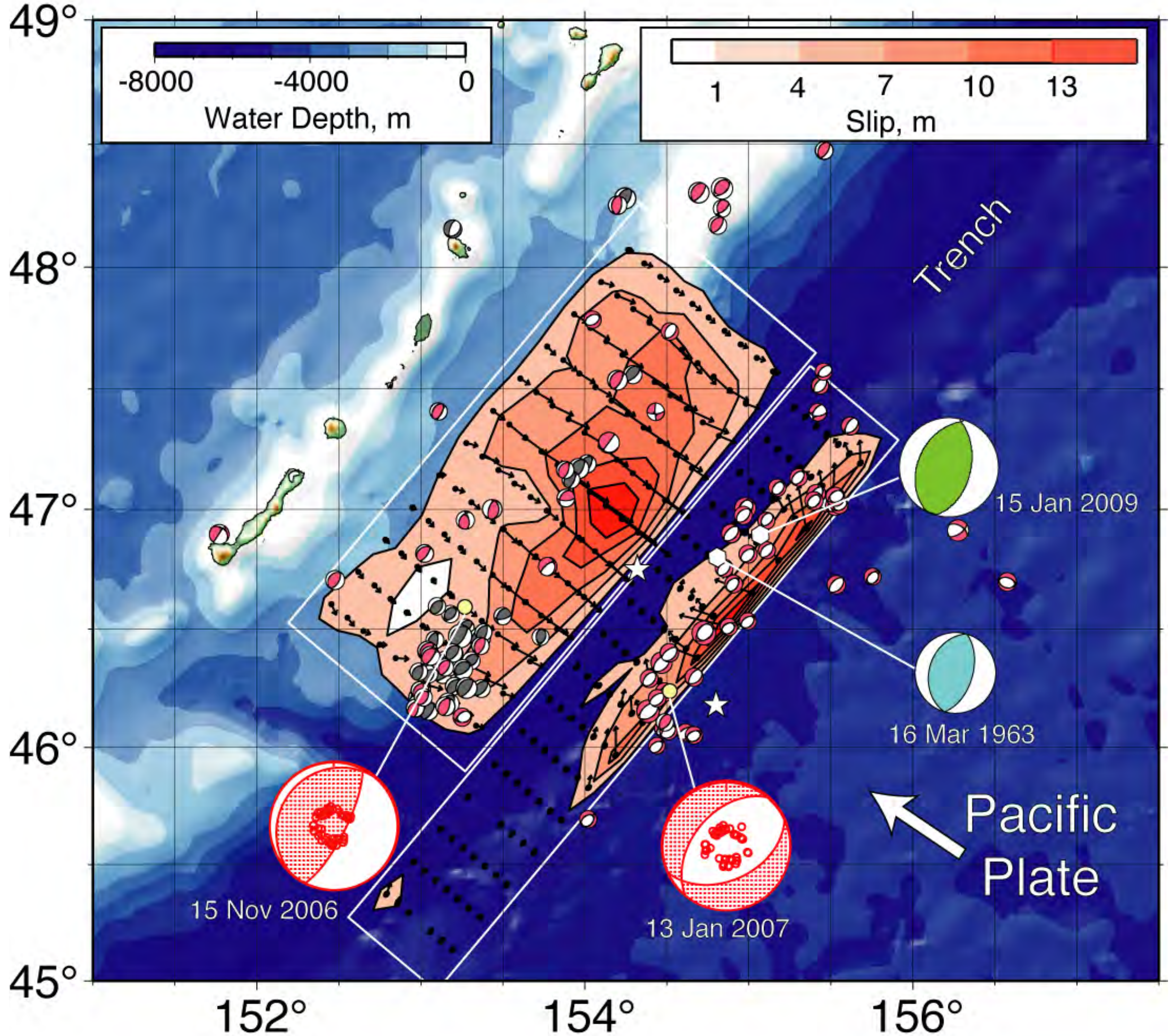
From: Ammon, Lay, Simpson, 2010

Beam-forming using teleseismic body waves and surface wave source time functions



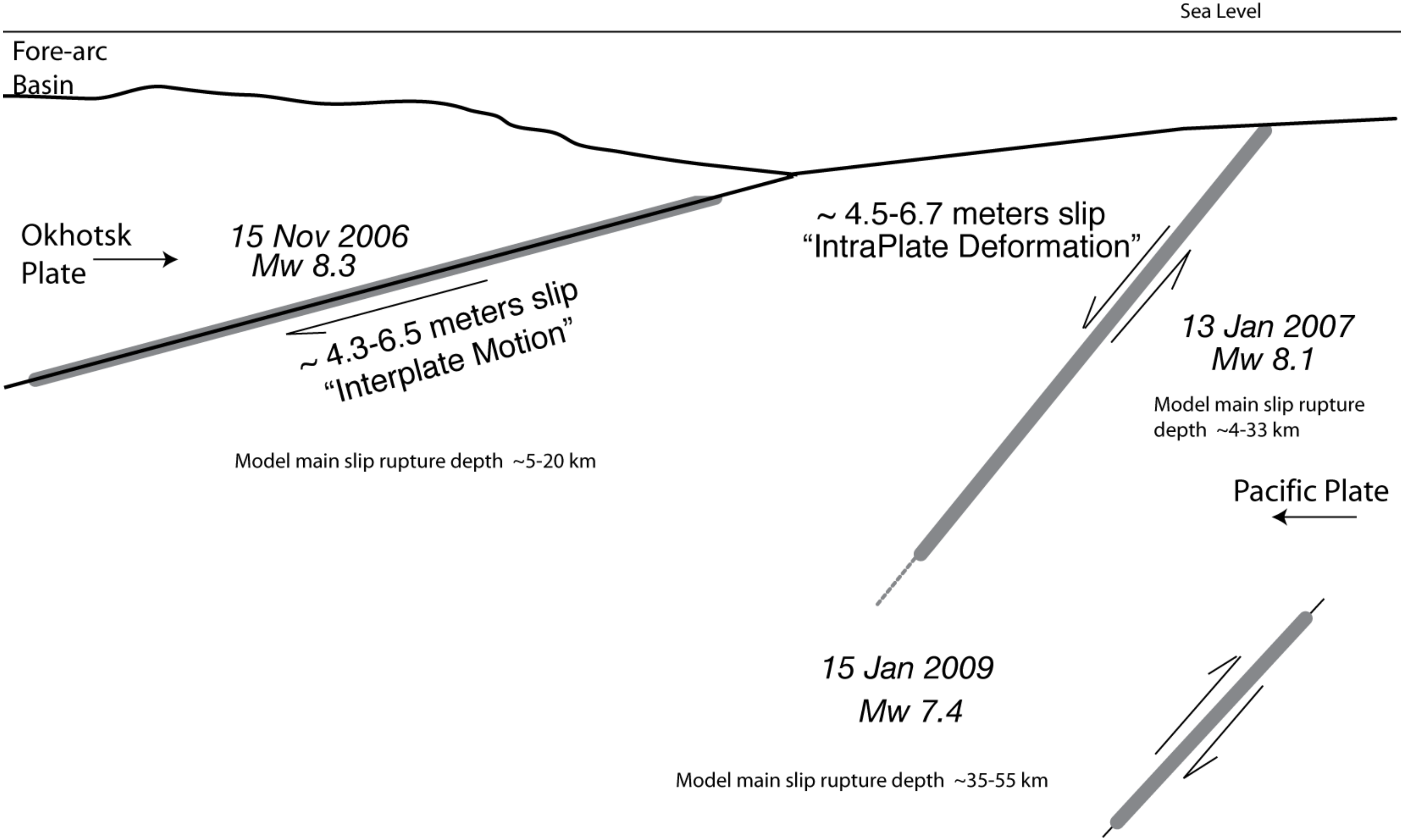
(Yue et al. 2012)

2006-2007 Kuril Doublet: Mw 8.1 normal after Mw 8.4 thrust. Trench-slope stress cycled from compressional to extensional to compressional

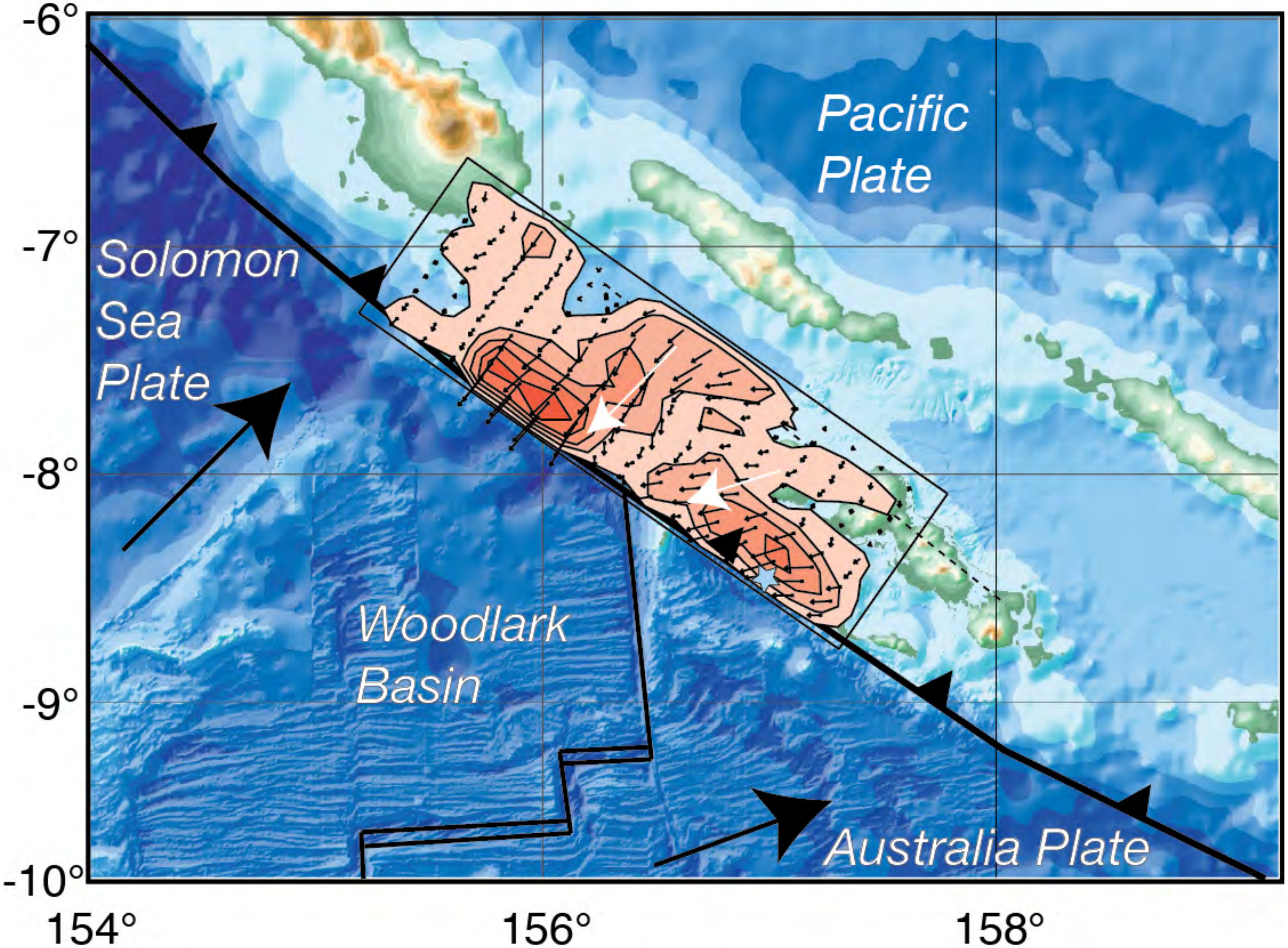


Lay et al., JGR (2009)

Kuril Islands Great Doublet



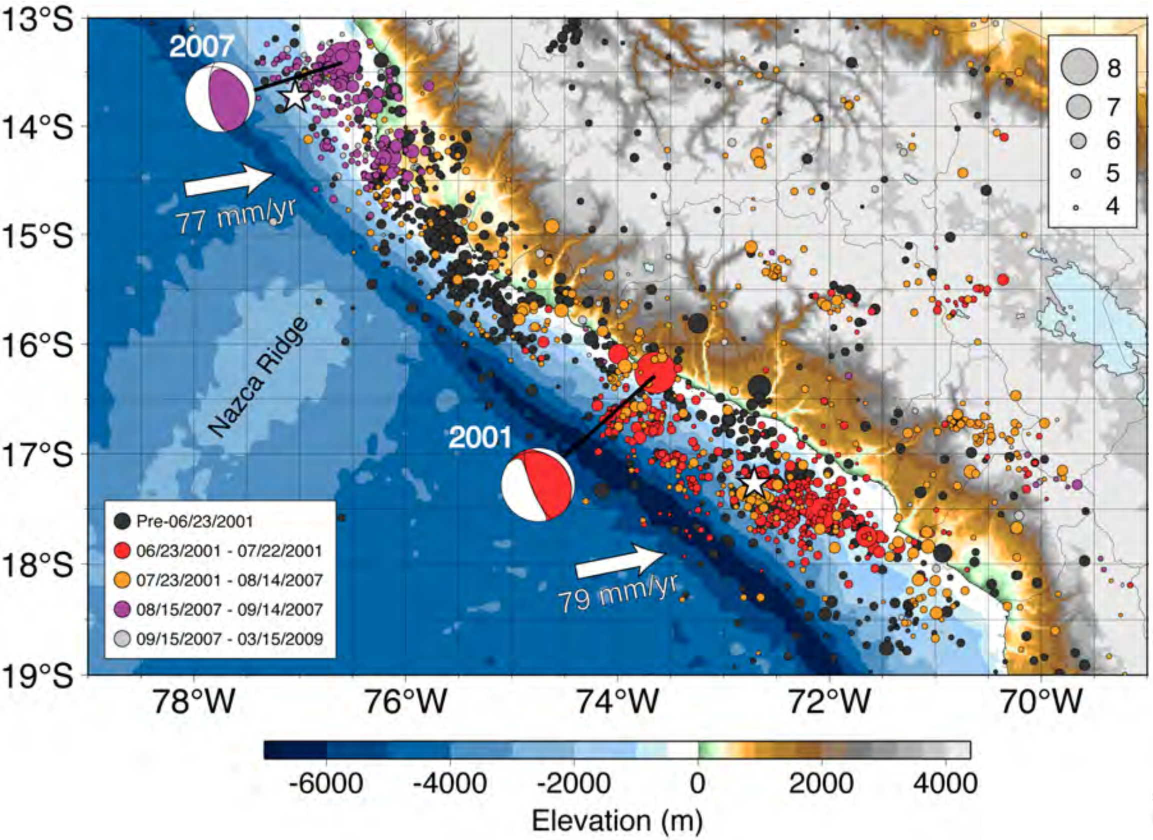
Lay et al., JGR (2009)

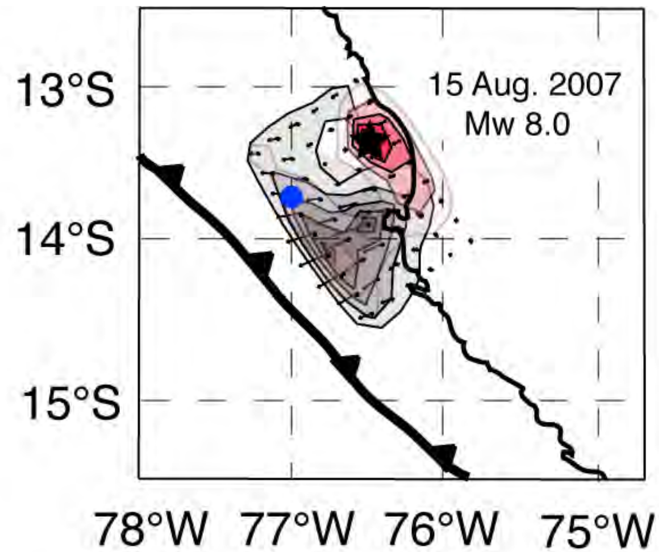


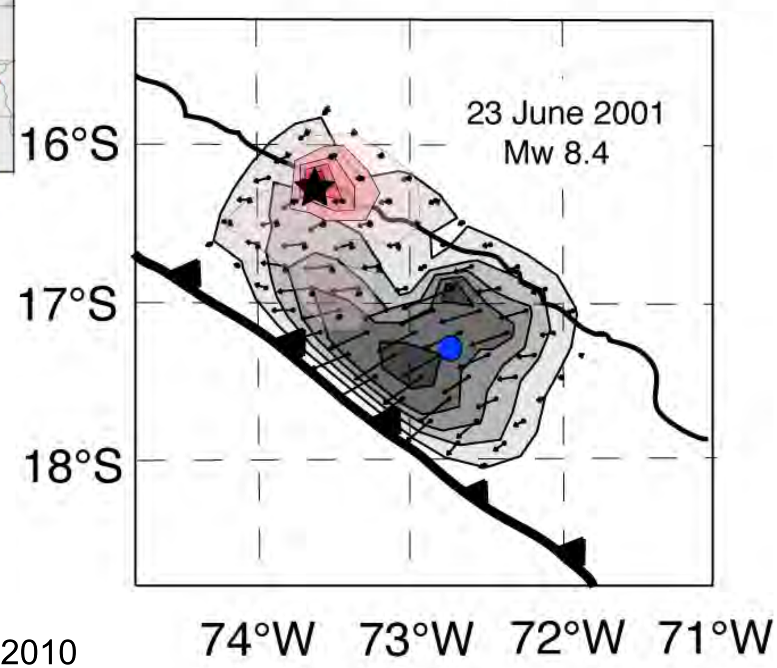
Furlong et al., Science (2009)

April 1, 2007 Solomon Islands Earthquake M_w=8.1
Rupture Across a Triple Junction

Great events along southern Peru megathrust: Ruptures triggering large second rupture with complex expansion.





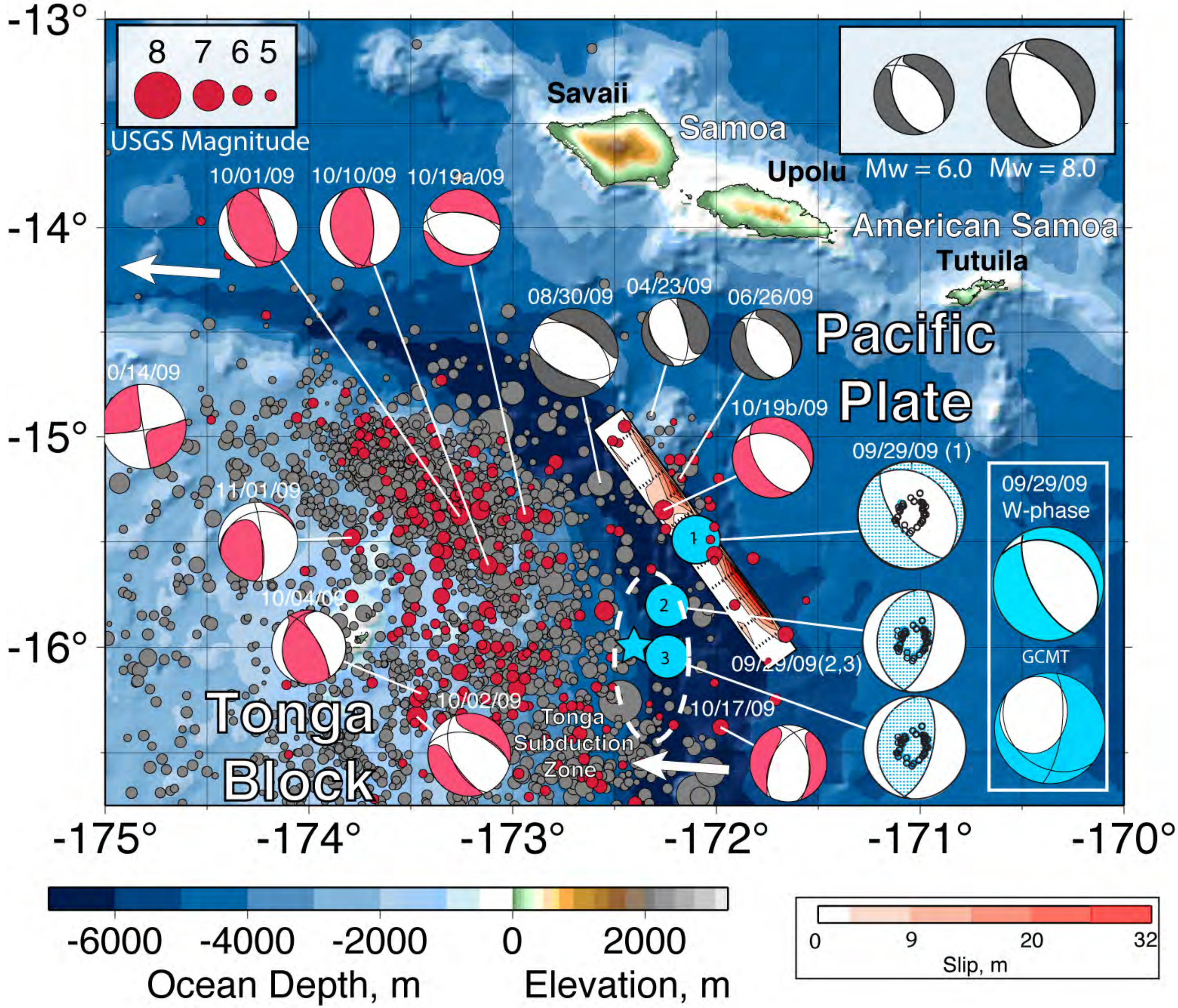


2001 Peru (M_w 8.4) – Initial 7.5 triggers rupture of 8.4 on ~Rayleigh wave arrival

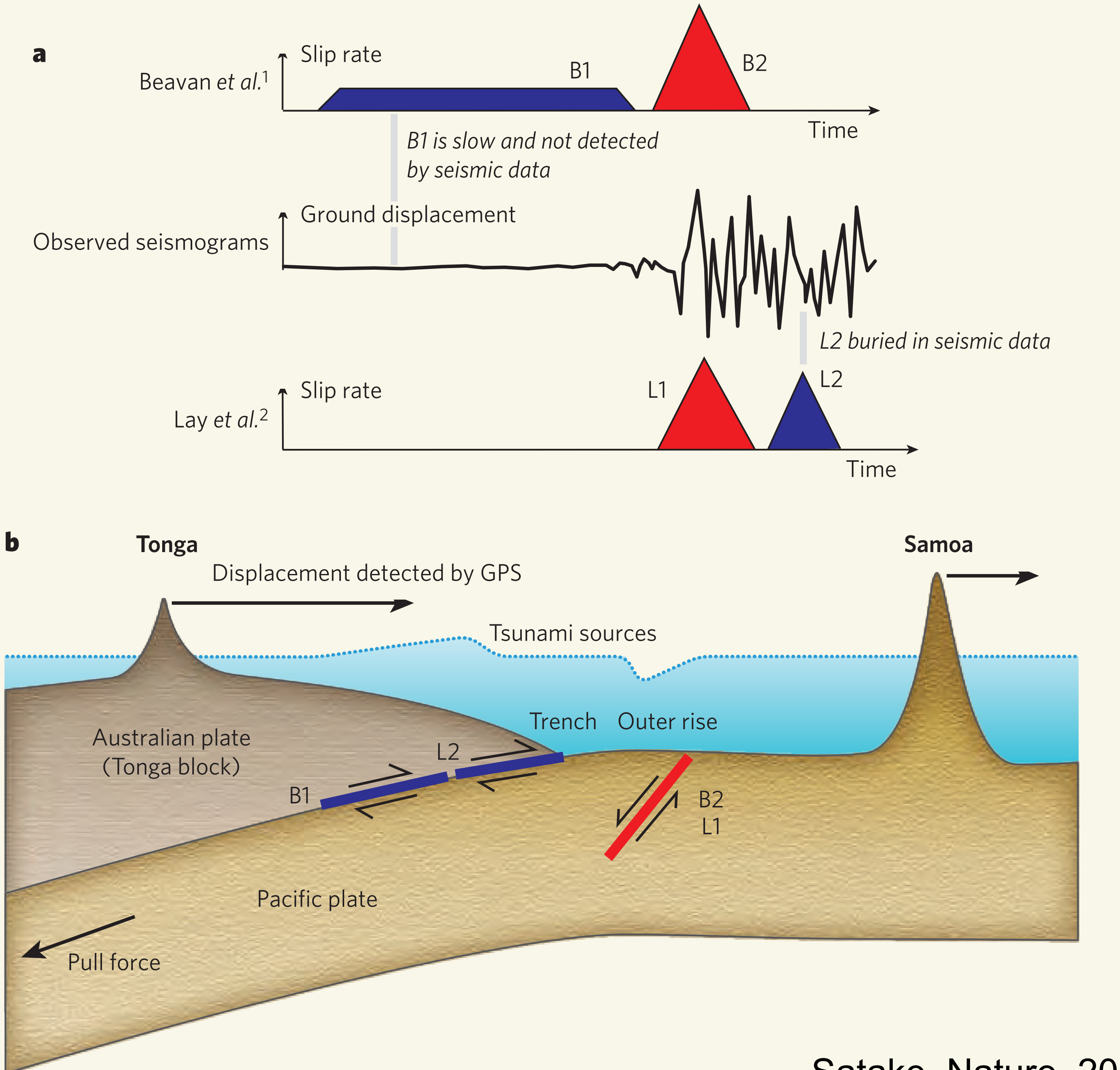
2007 Peru (M_w 8.0) – Initial 7.8 triggers rupture of 8.1 after ~60 s hiatus`

Lay, et al., BSSA, 2010

2009 Samoa-Tonga Triggered Doublet (M_w 8.0, 8.0)

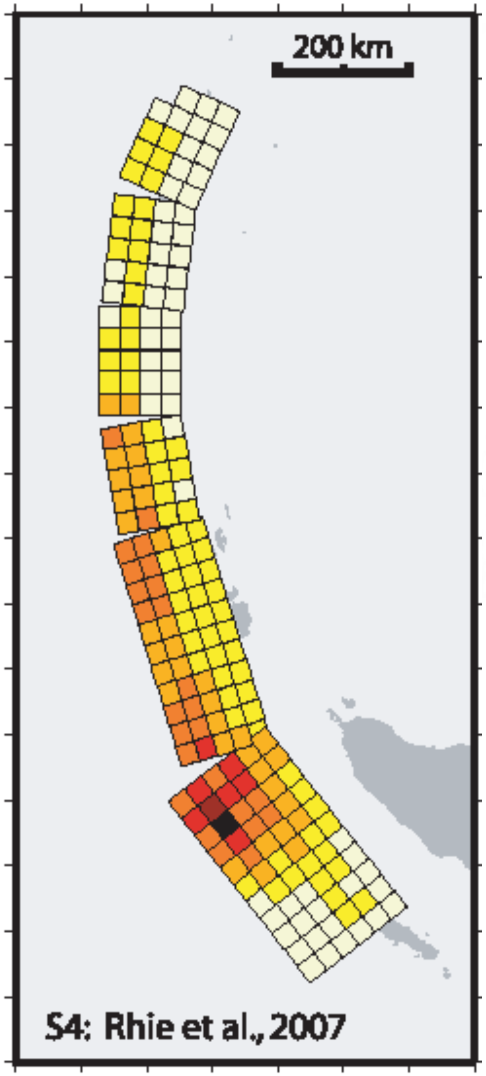


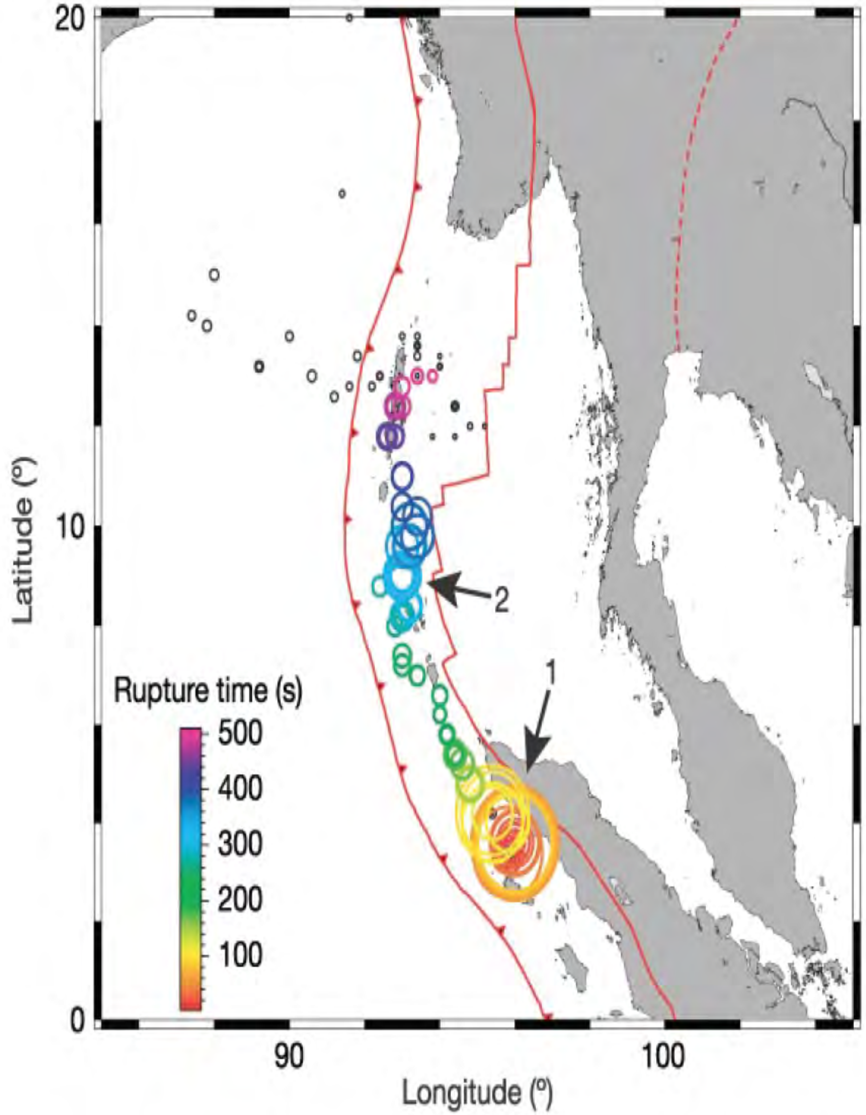
Lay et al., Nature (2010)



Satake, Nature, 2010

Models for 2004 Sumatra





2004 Sumatra was the first event for which back-projection of dense network signals to image coherent sources of short-period radiation was performed (by Ishii et al. 2005, and Krüger and Ohrnberger, 2005). Slip and short-period coherent power do NOT correlate spatially in detail.

2004 prompted geophysicists to 'tune-up' algorithms to handle very long duration, extended fault. Solutions developed using seismic, geodetic, tsunami, and joint data sets came out after several months/years. Initiated upgrade of DART system in Pacific.

Recent Huge Events With "Surprises"

2004 Sumatra M_w 9.2; ruptures 1300+ km long, massive tsunami
2005 M_w 8.7, 2007 8.5, 7.9 'clustered' events along Sumatra

2006 Kuril M_w 8.4 thrust; triggers 2007 Kuril M_w 8.1 normal

2007 Peru M_w 8.0 devastates Pisco; triggered by 7.8 initial rupture

2007 Solomon Island M_w 8.2; rupture across triple junction

2008 Wenchuan M_w 7.9; unexpected thrusting

2009 Samoa M_w 8.1 normal faulting; triggers Tonga M_w 8.0 thrust

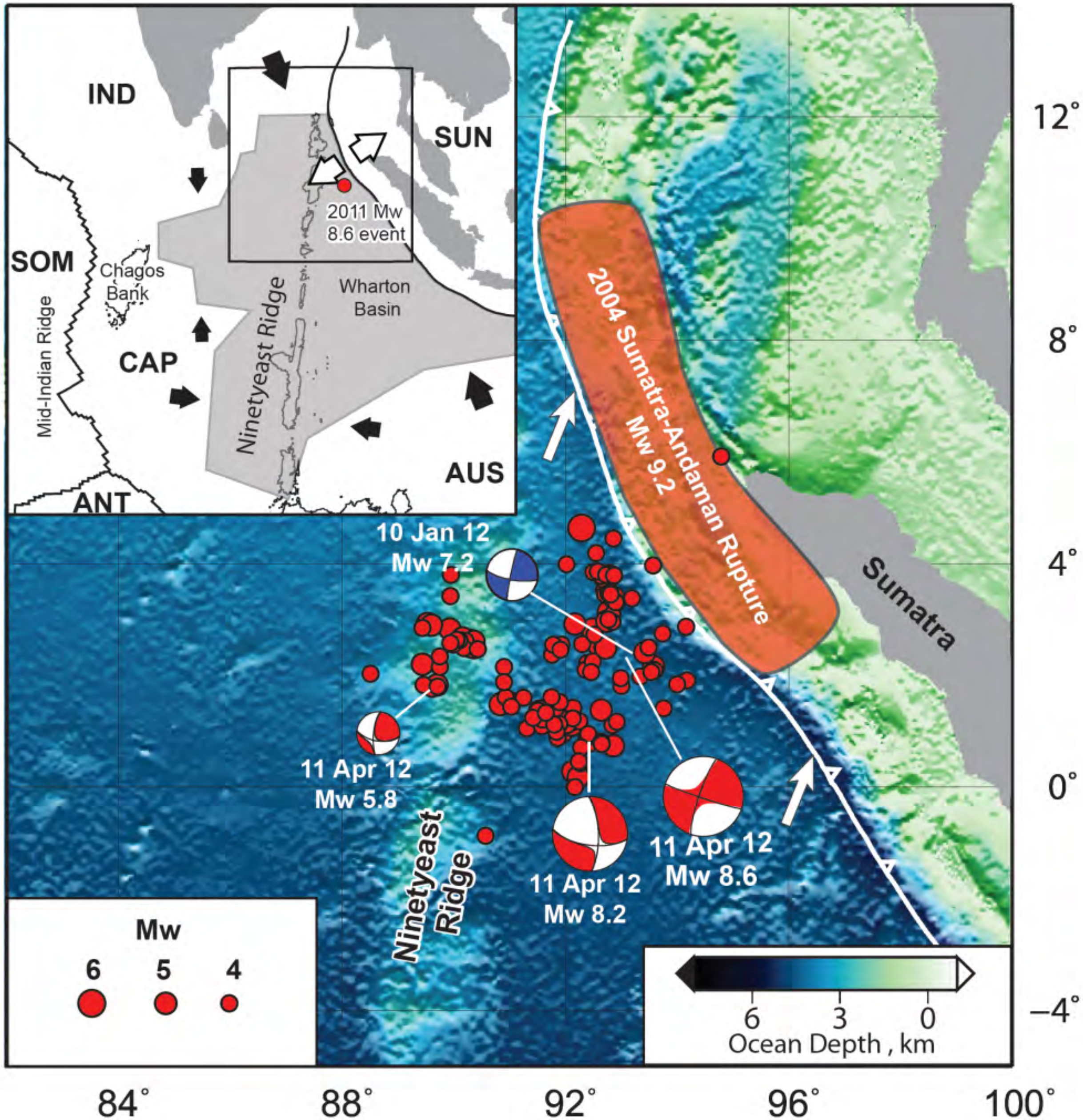
2010 Chile M_w 8.8 ruptures beyond "Darwin Gap"

2010 Mentawai M_w 7.8 tsunami earthquake updip of 2007 8.5/7.9 Sumatra

2011 Tohoku M_w 9.0 ruptures entire megathrust, slip up to 60 m

2012 Indo-Australia M_w 8.7, 8.2 ruptures 5 fault grid- largest intraplate strike-slip

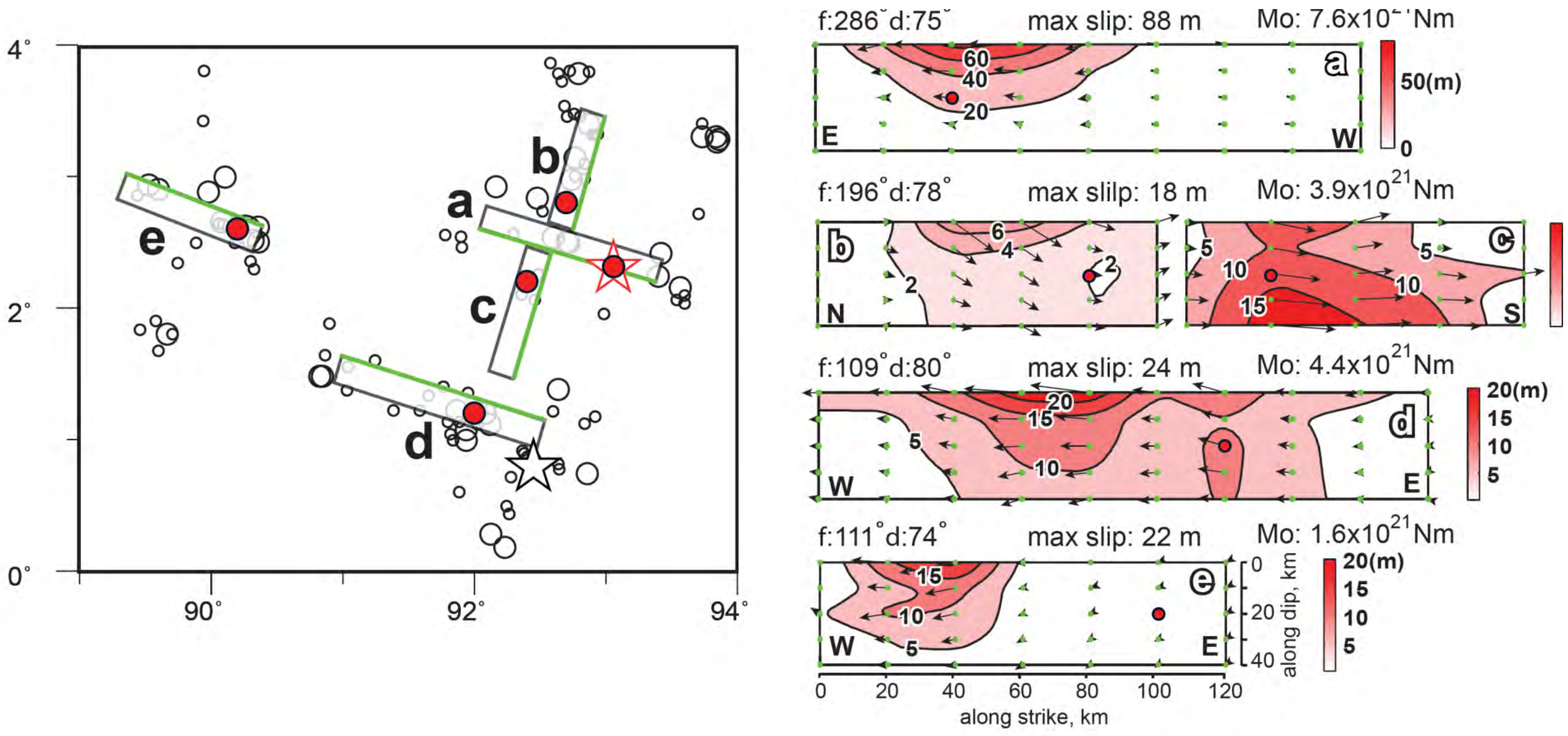
2013 Sea of Okhotsk M_w 8.3 largest/longest/most energy deep earthquake ever



- 1. The largest (Mw=8.6) strike slip event seismically recorded.
- 2. The largest intra-plate event seismically recorded.
- 3. Complex faulting-5 faults involved.
- 4. Complex aftershock location.

[Yue et al., 2012]

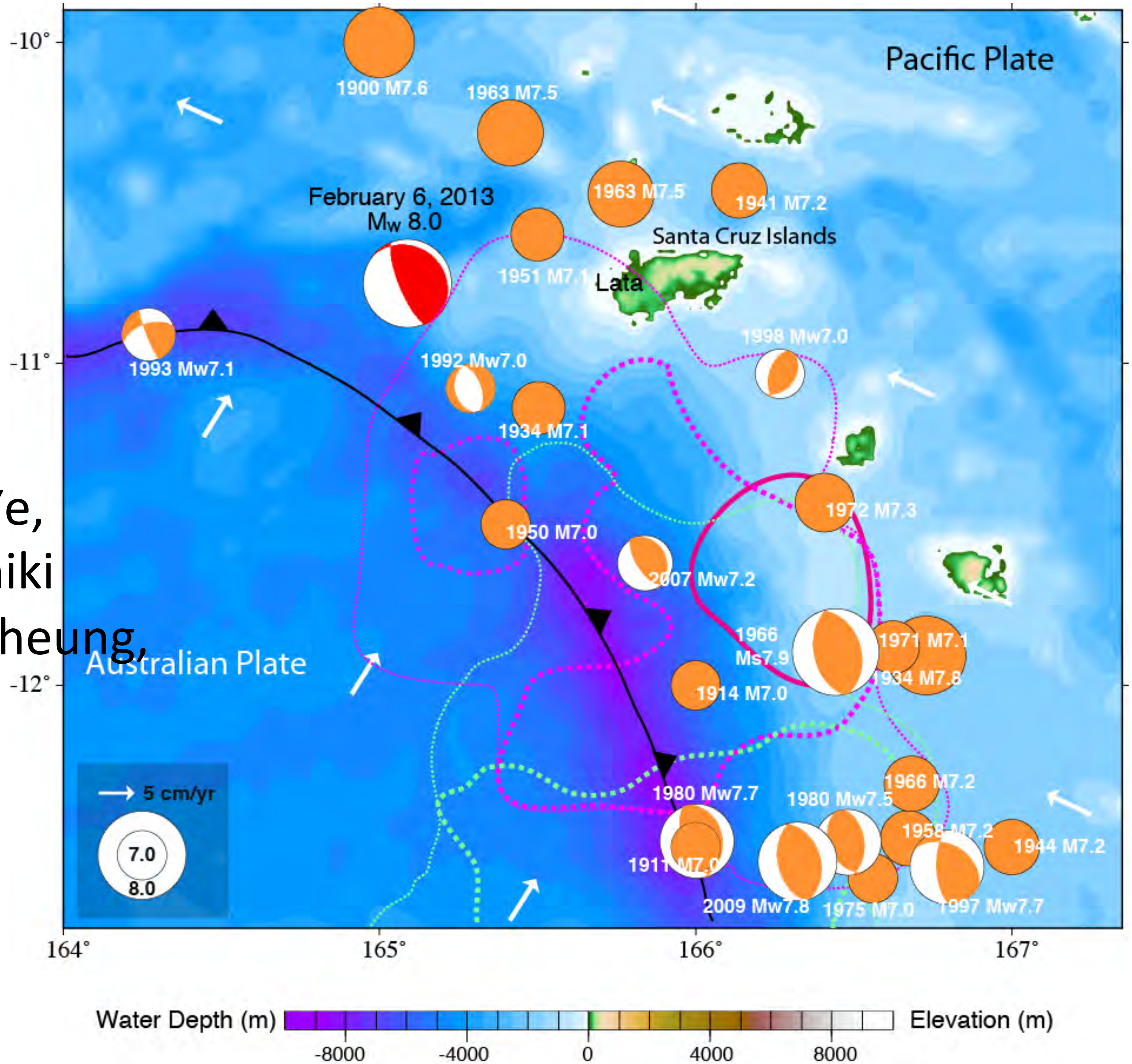
Finite fault model on multiple fault segments



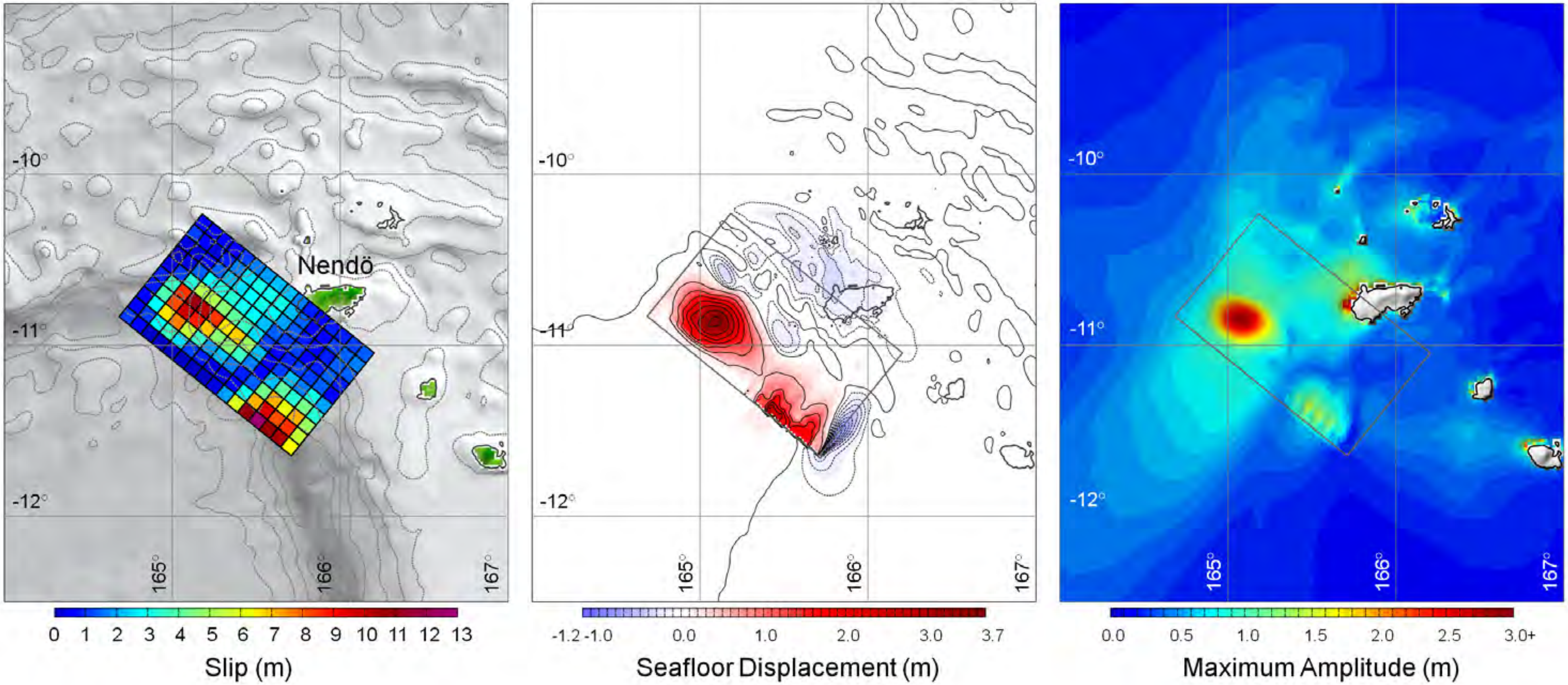
[Yue et al., 2012]

The February 6, 2013 M_w 8.0 Santa Cruz Islands earthquake and Tsunami

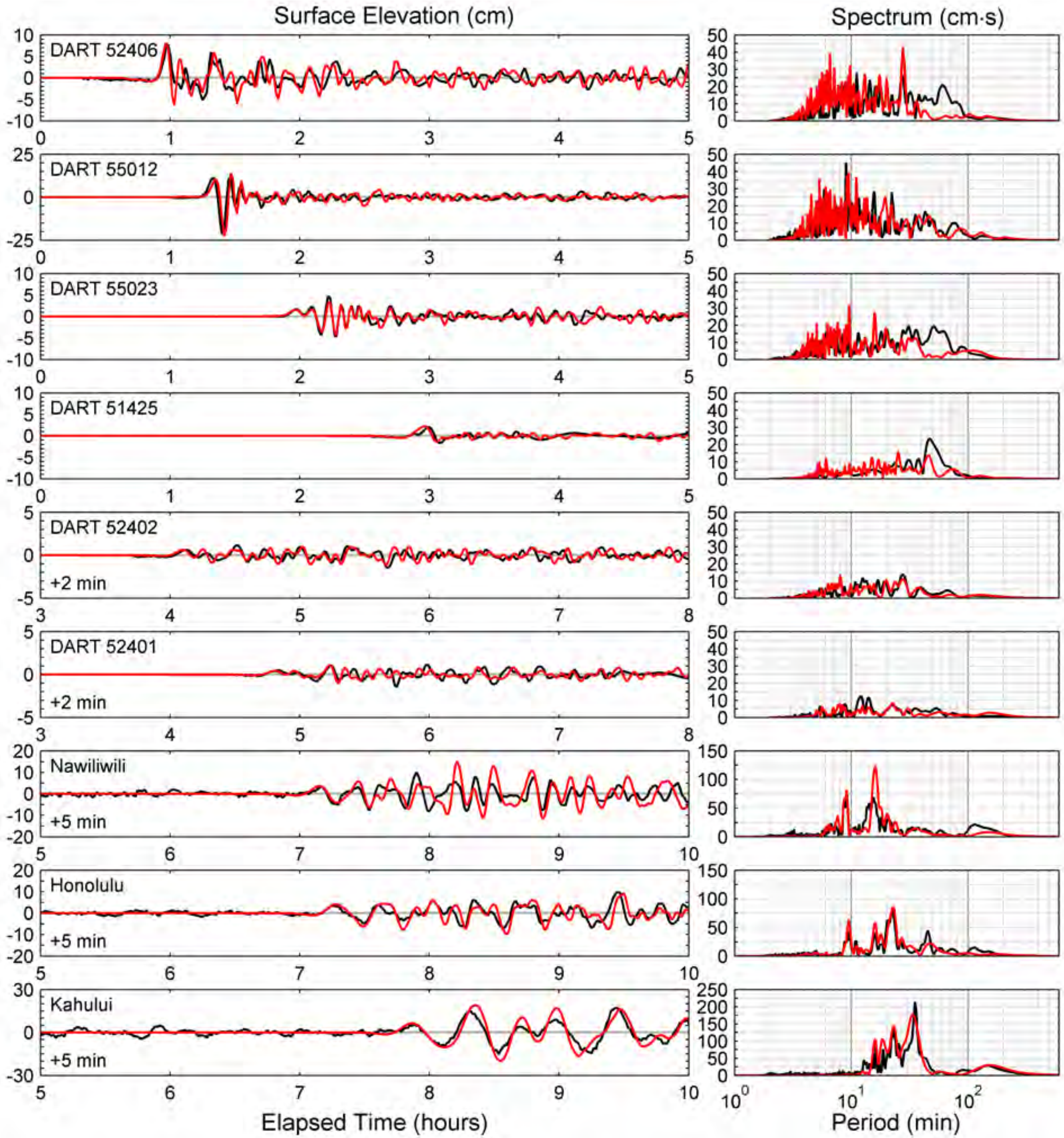
Thorne Lay, Lingling Ye, Hiroo Kanamori, Yoshiki Yamazaki, Kwok Fai Cheung, Charles J. Ammon



Lay et al., Tectonophysics, 2013

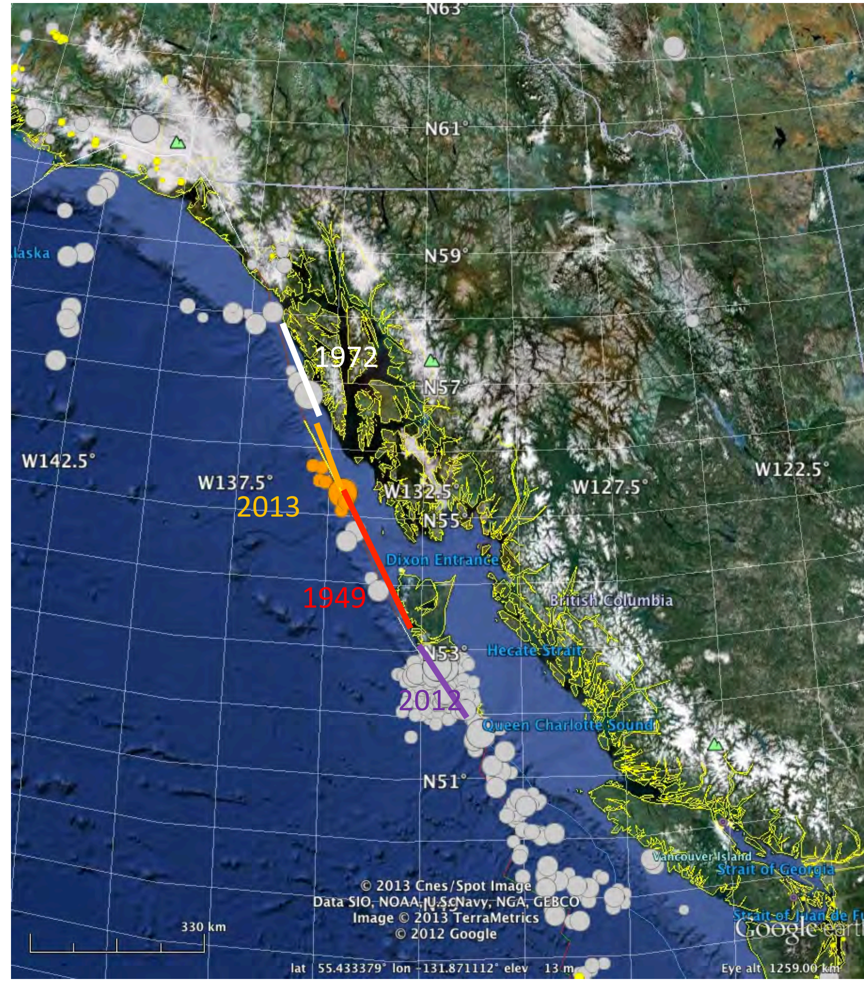


Lay et al., Tectonophysics, 2013



Lay et al., Tectonophysics, 2013

The October 28, 2012 M_w 7.8 Haida Gwaii Underthrusting Earthquake and Tsunami: Slip Partitioning Along the Queen Charlotte Fault Transpressional Plate Boundary



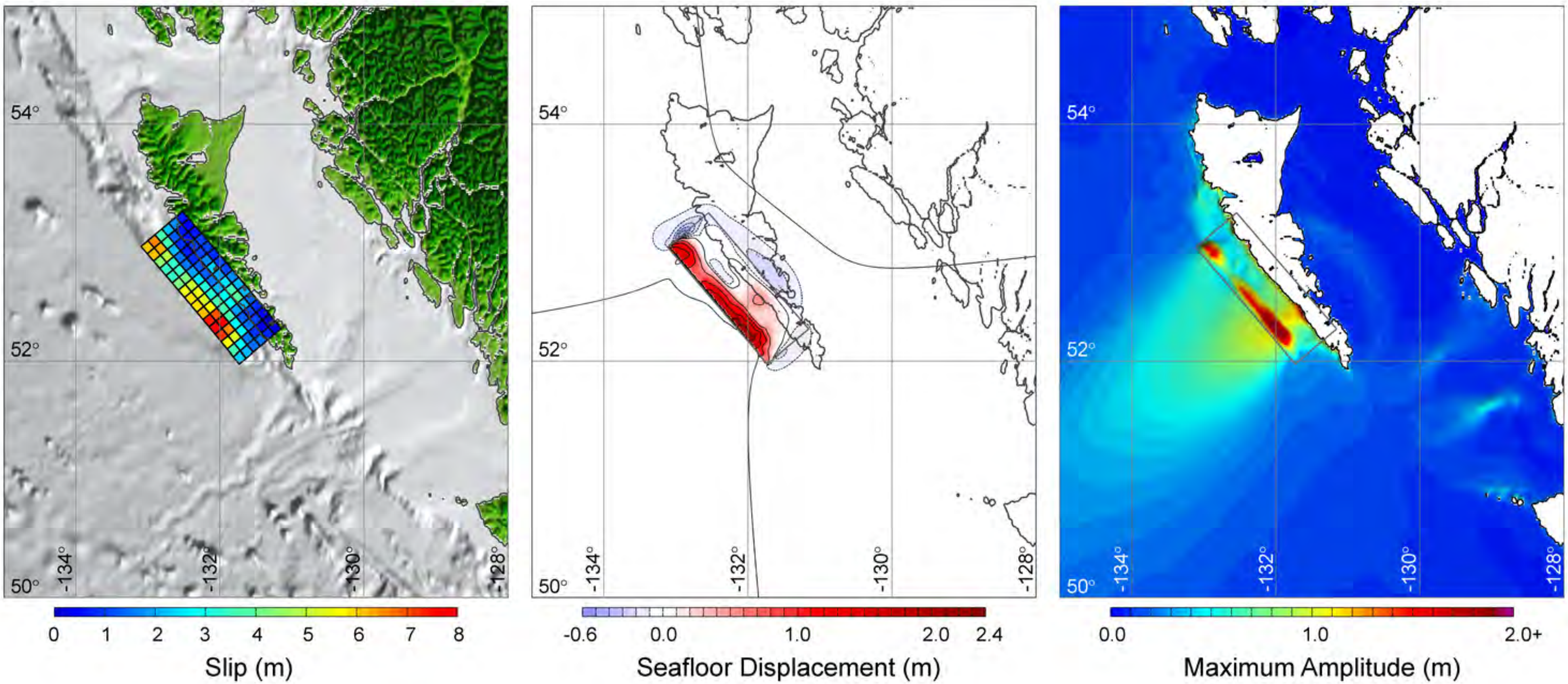
T. Lay, UCSC

w/ L. Ye, H. Kanamori, Y. Yamazaki, K. F. Cheung, K. D. Koper, K. B. Kwong

Hadia Gwaii Final Slip Model

Surface Vertical Displacement

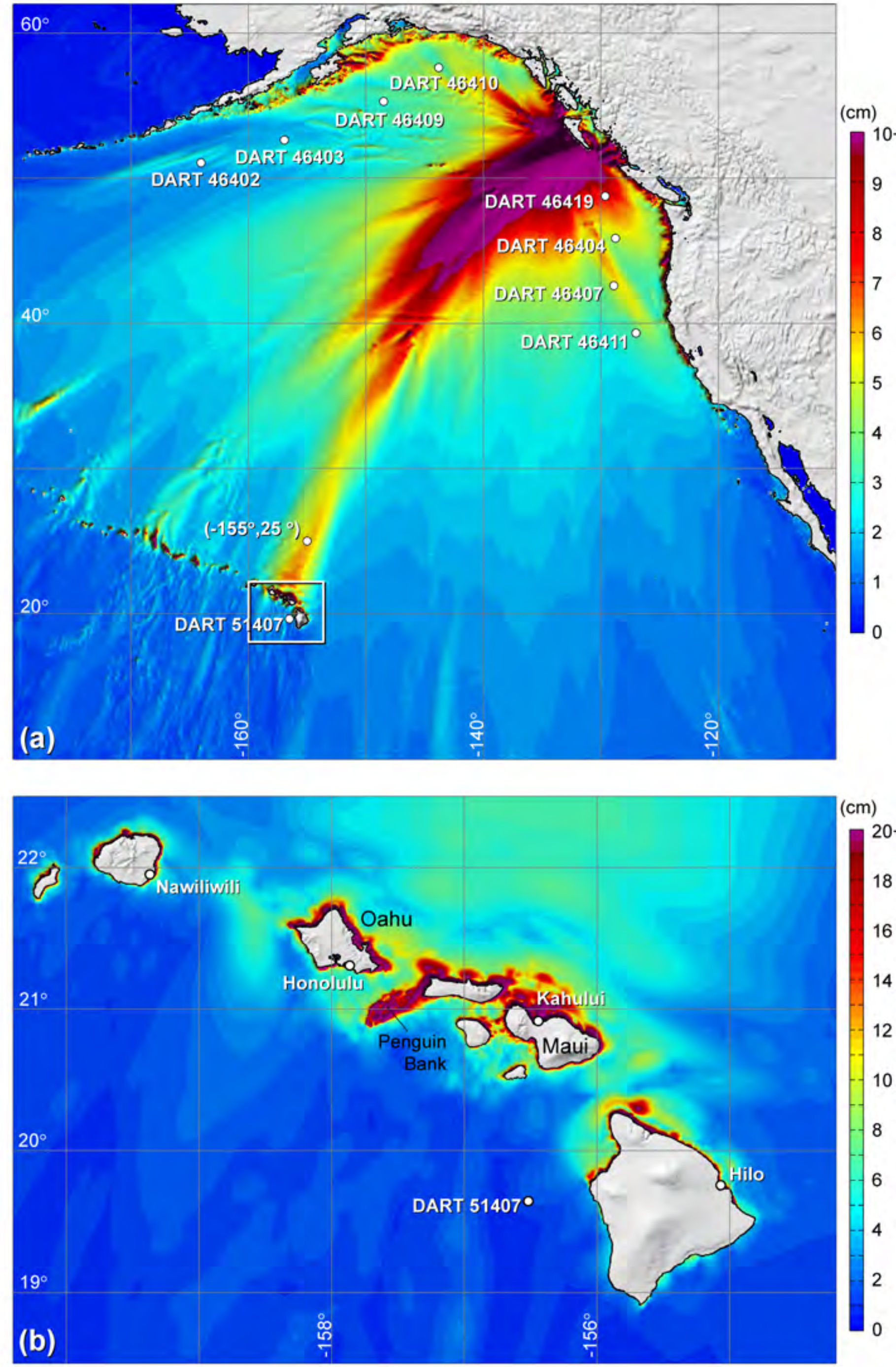
Local Peak Tsunami



Local tsunami is reported to have Up to 8-9 m run-up in some inlets.

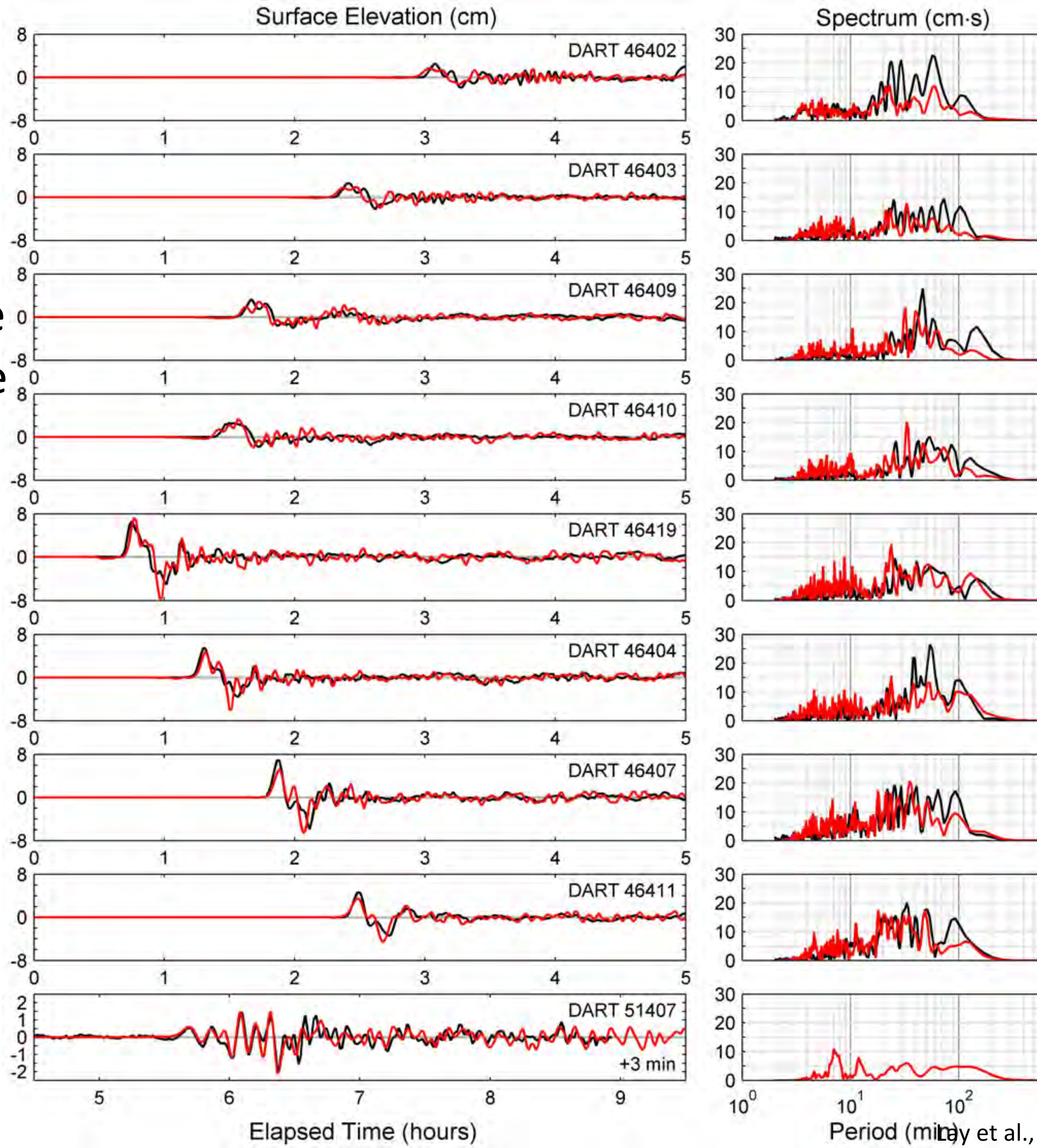
(Lay et al., EPSL, 2013)

Sea Surface Peak Amplitudes for preferred model from iterative seismic/tsunami modeling. NOAA DART buoys give excellent deep water tsunami records along Alaska/Aleutians and to the south, as well as near Hawaii. also have good quality tide-gauge recordings in Hawaii.

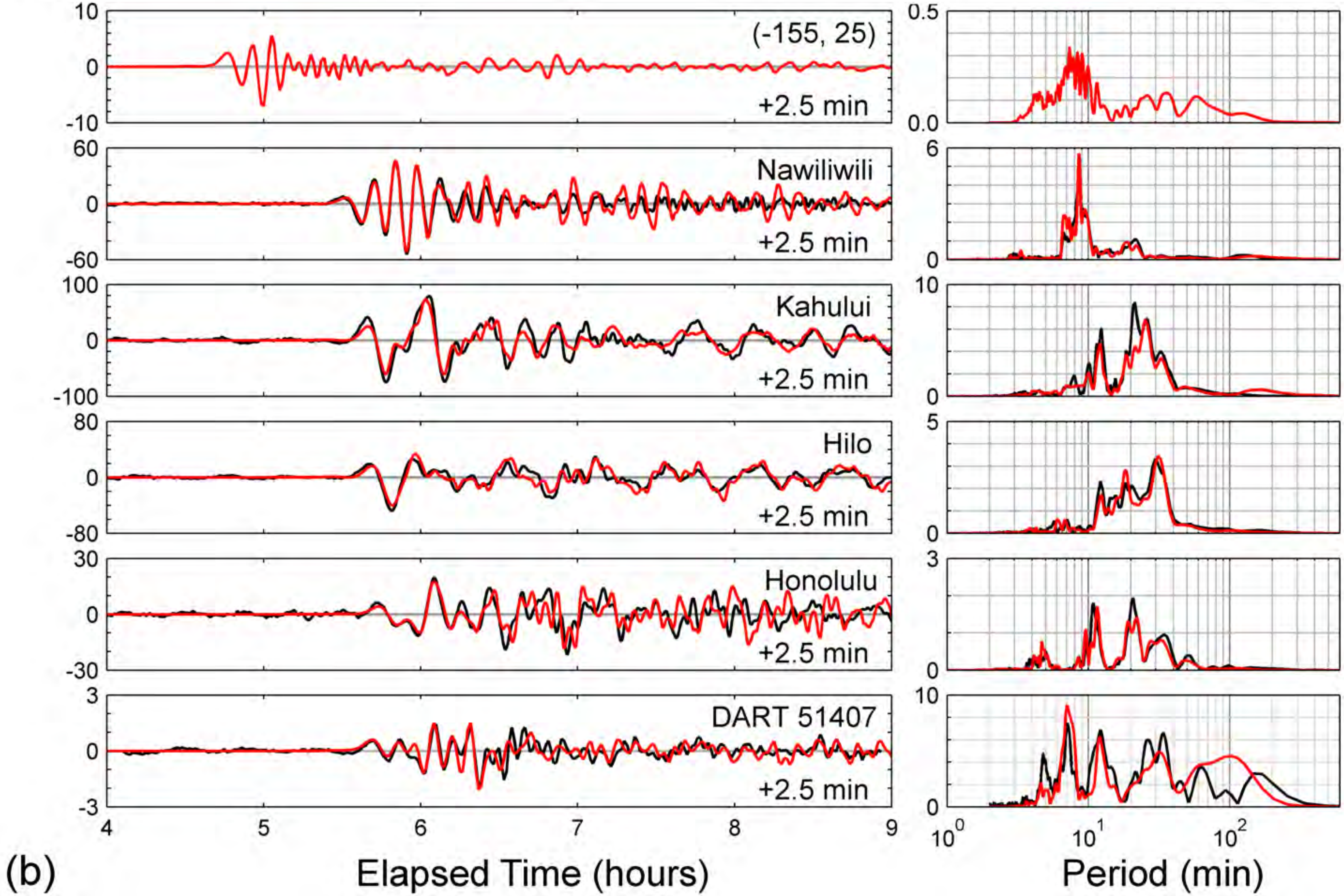


(Lay et al., EPSL, 2013)

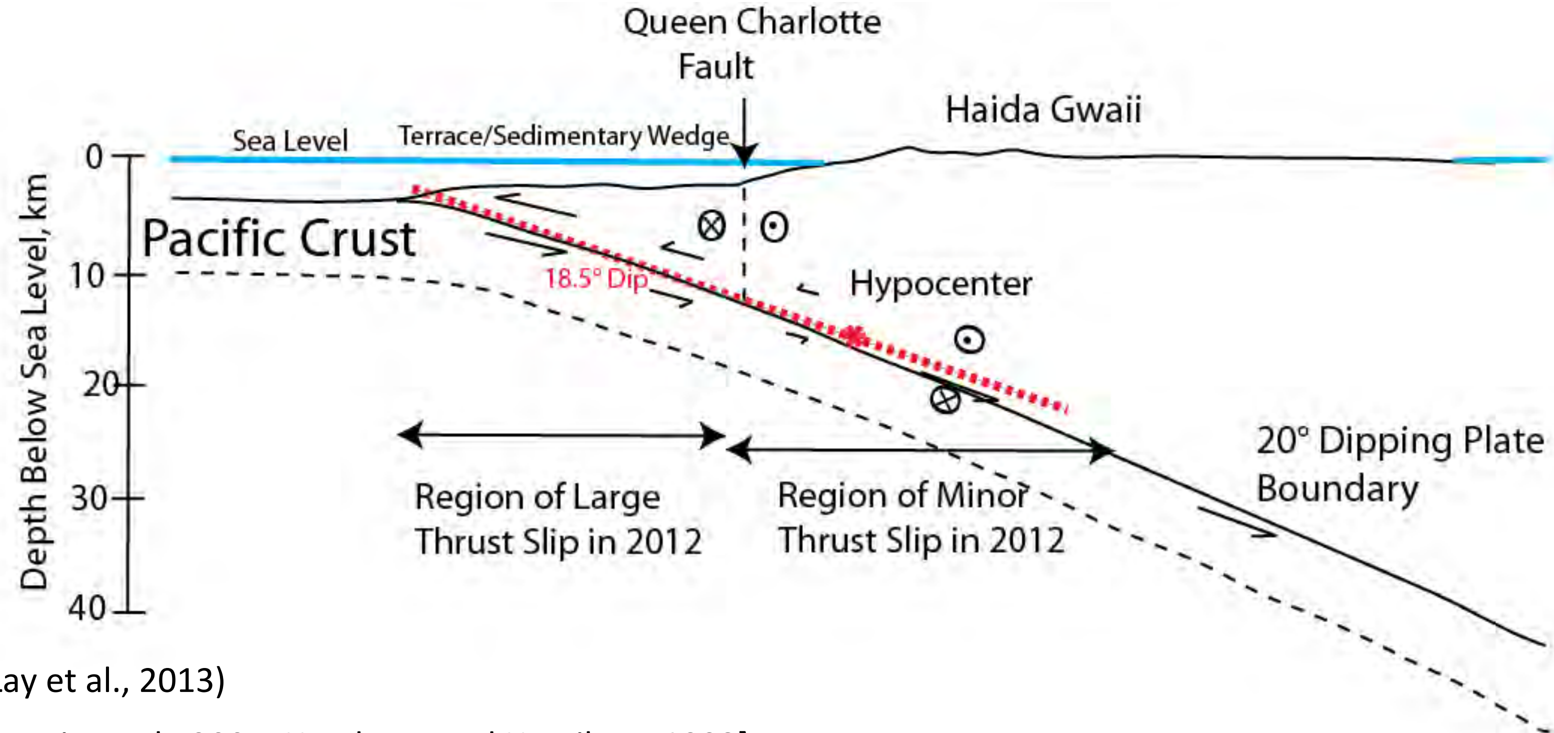
DART data and model predictions in red for the final iterative model.



Lay et al., EPSL, 2013

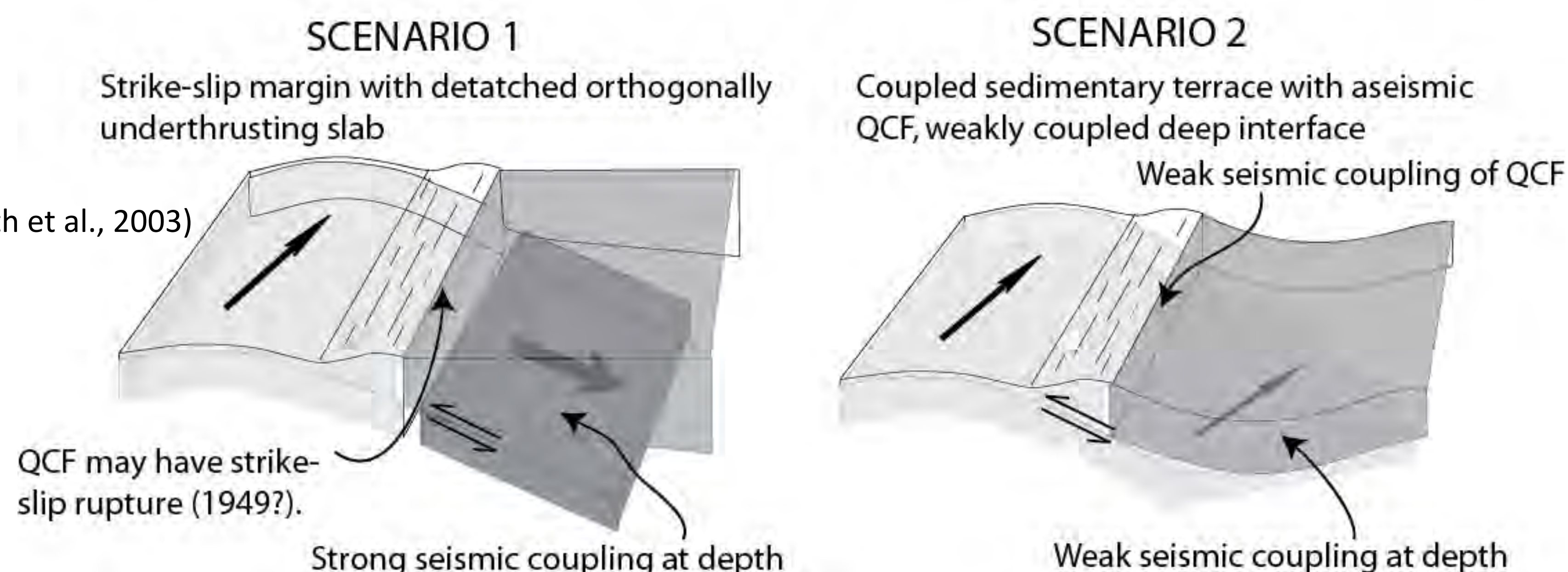


(Lay et al., EPSL, 2013)



(Lay et al., 2013)

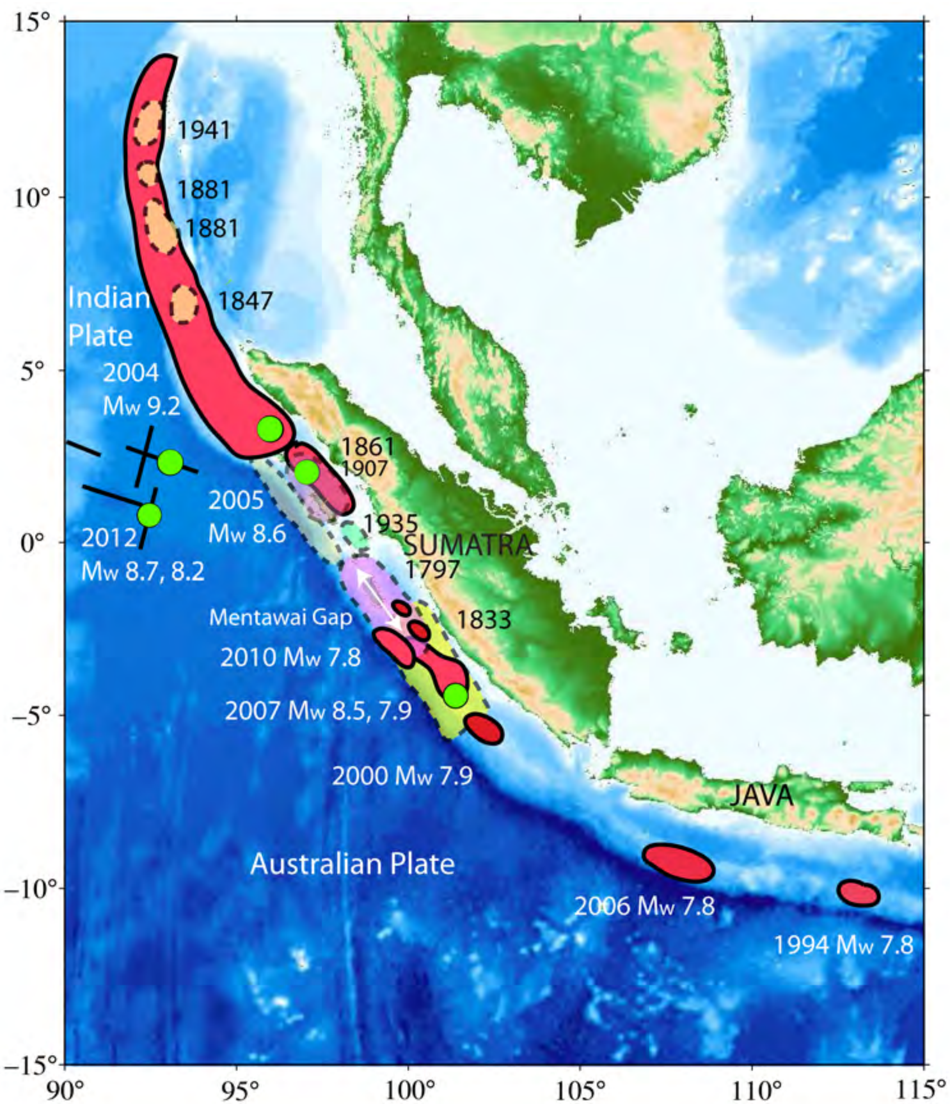
[after Bustin et al., 2007; Hyndman and Hamilton, 1993]



(Smith et al., 2003)

(Lay et al., EPSL, 2013)

Sumatra-Sunda



[Lay, 2014]

Struck by a ‘cluster’ of great/very large earthquakes since 2004.

Dec. 26, 2004 – ‘unexpected’ northward extension to Andaman Islands. 9.2

March 2005 – adjacent ‘aftershock’. 8.6

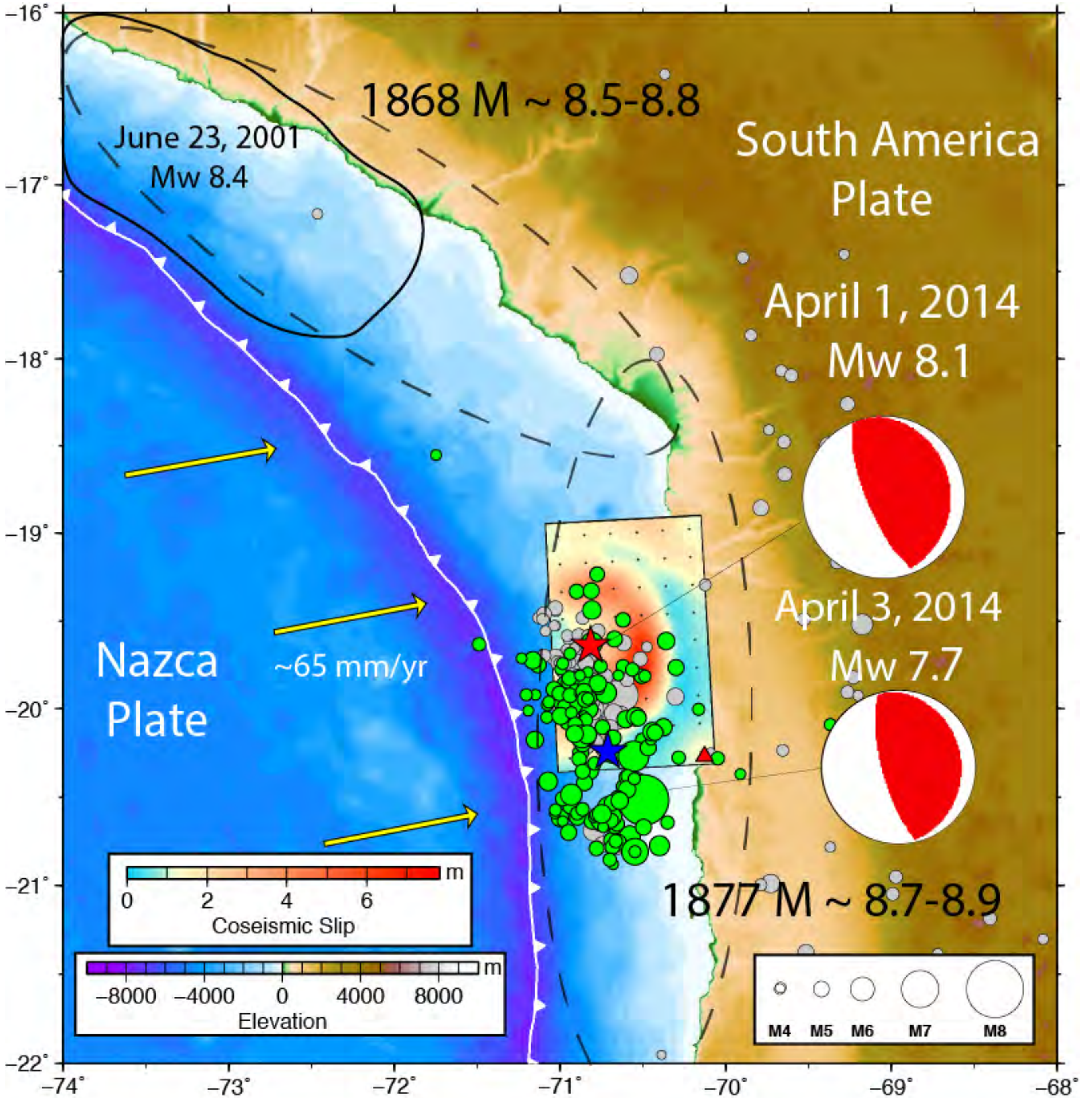
July 2006 – Java tsunami earthquake. 7.8

Sept. 2007 – Kepulauan pair. 8.5, 7.9

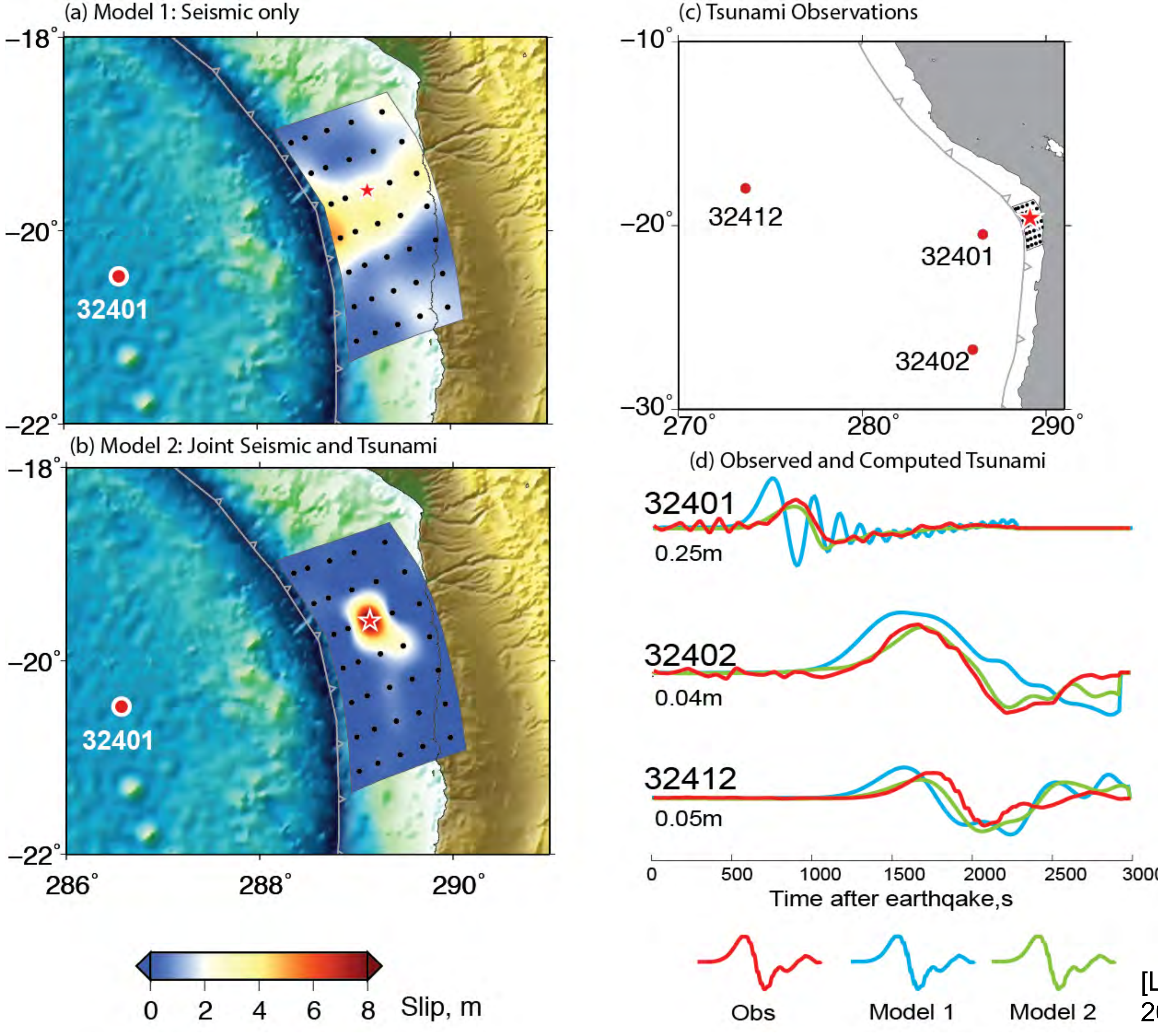
Oct. 2010 – Mentawai tsunami earthquake. 7.8

Similar to Alaska-Aleutians sequence of 1946, 1957, 1964, 1965

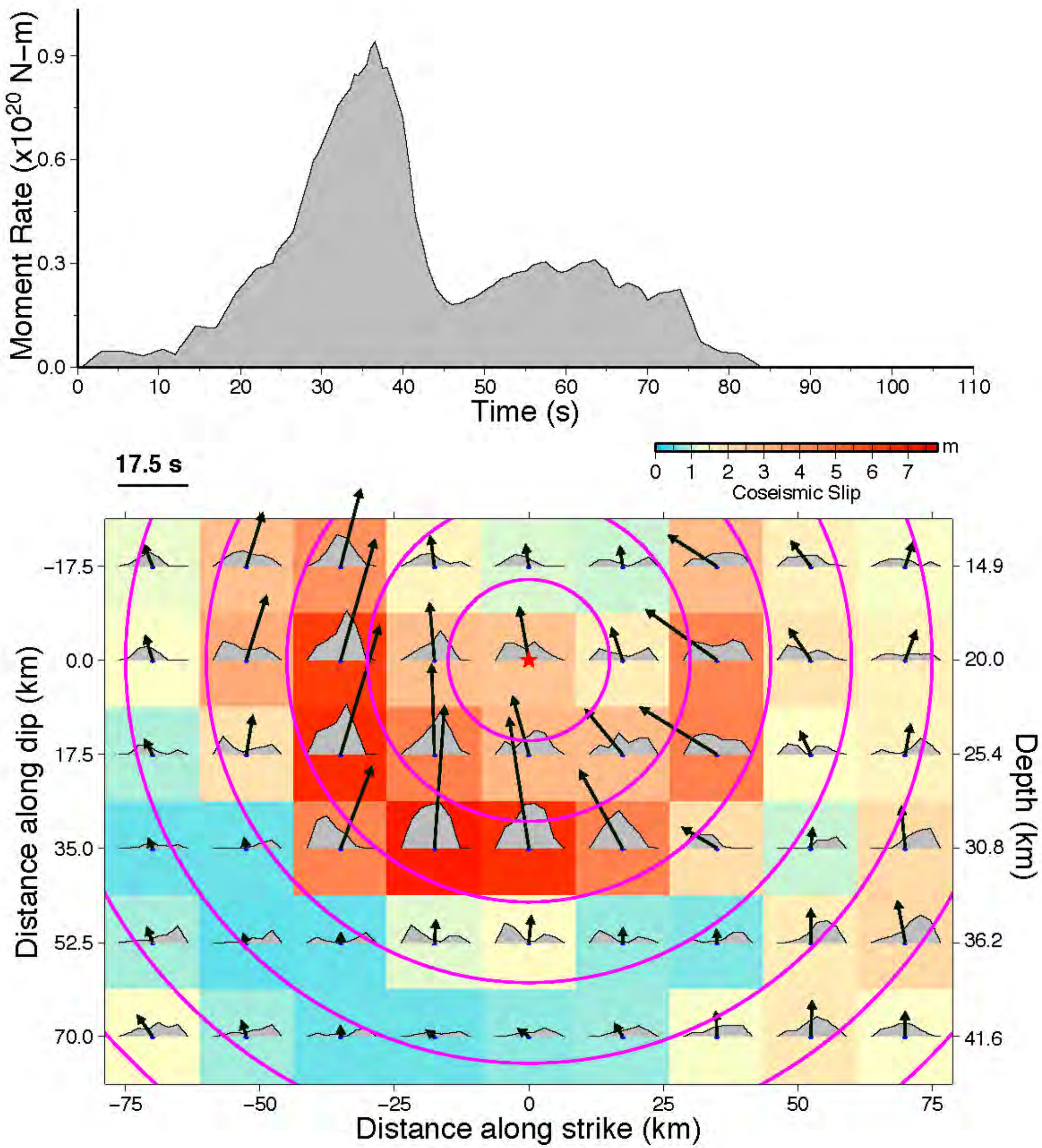
Where will the next one be? - 1797 ‘gap’? Sumatran Fault? Sumba potential?



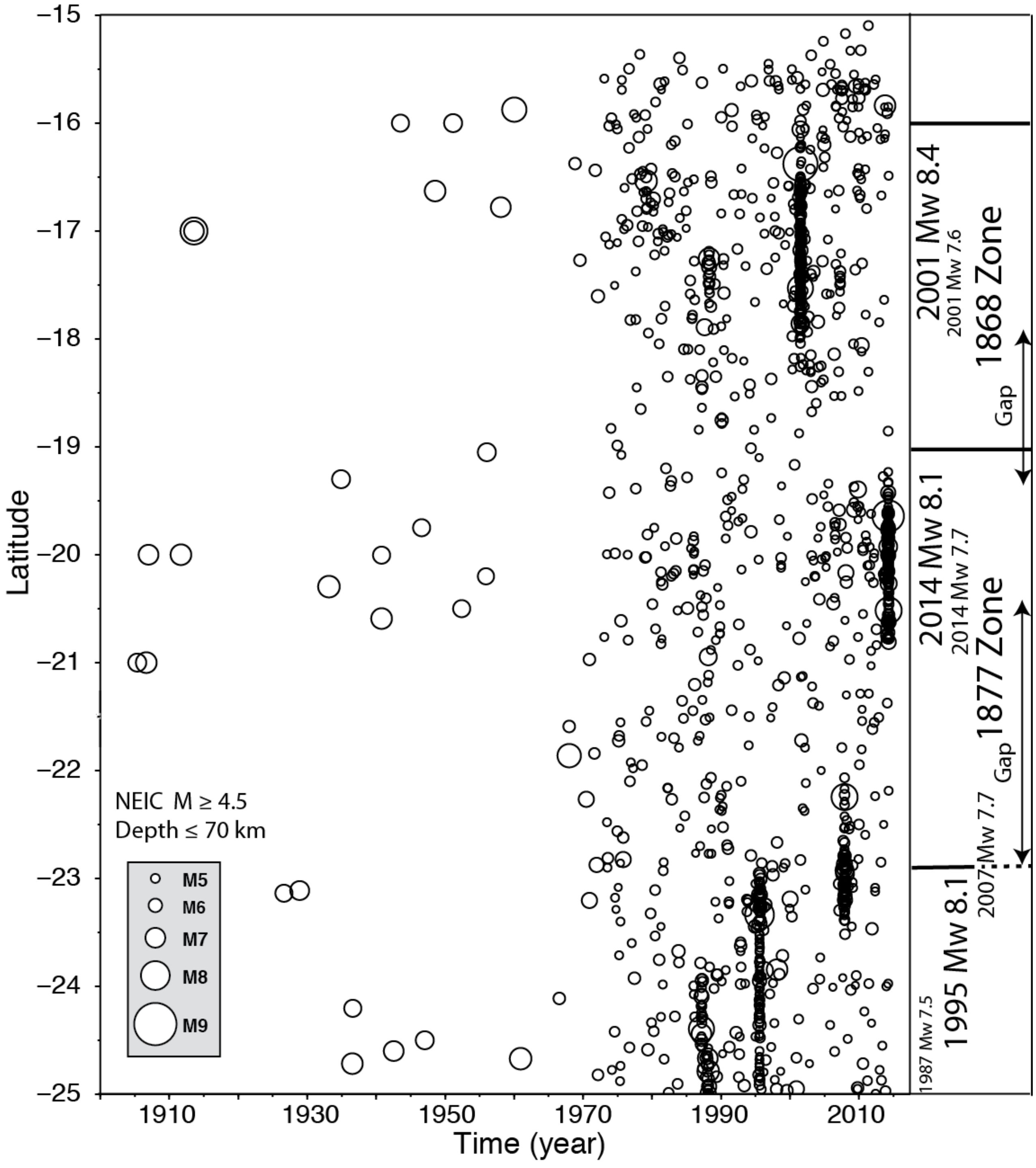
[Lay et al., 2014]



[Lay et al., 2014]

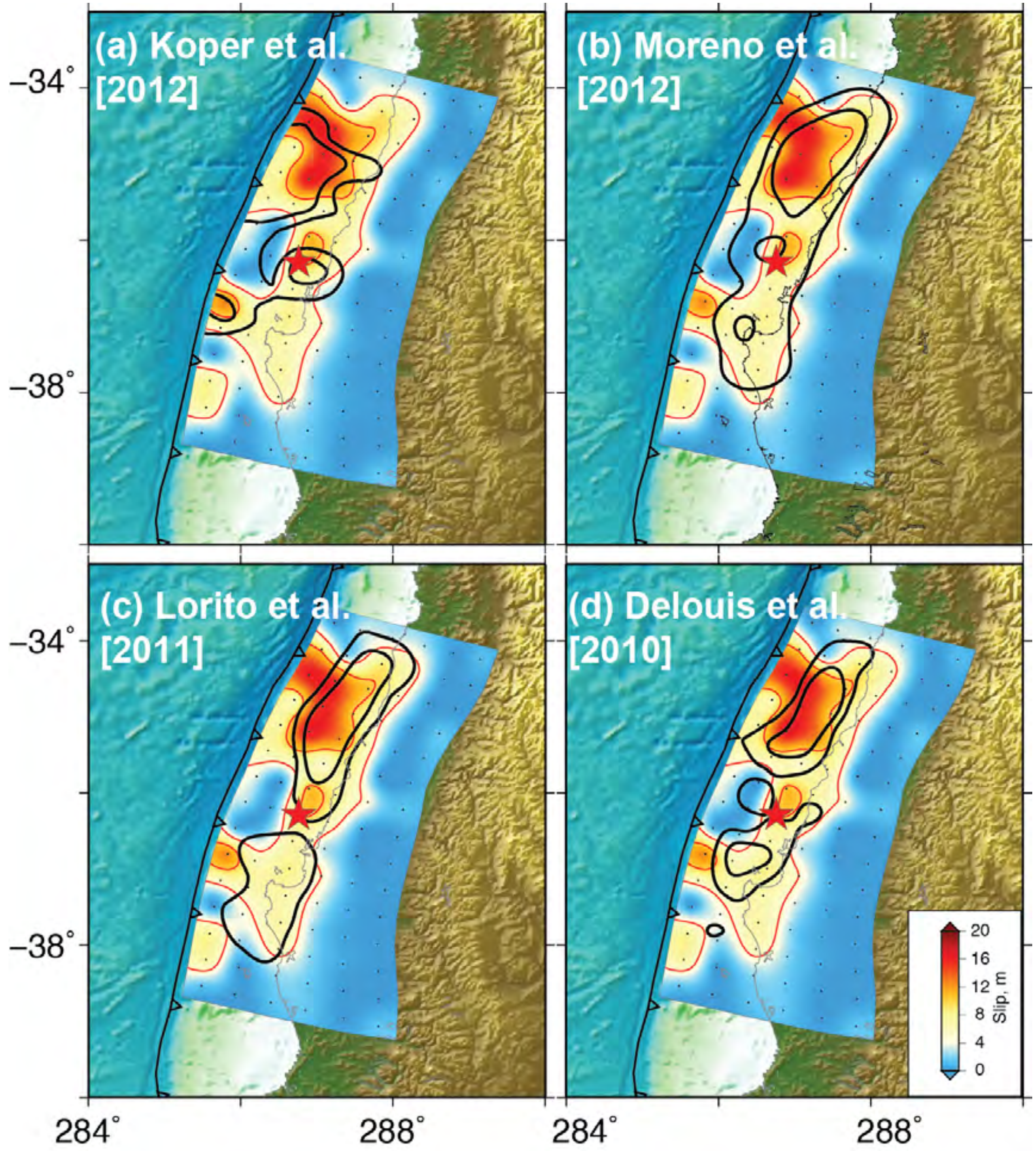


[Lay et al., 2014]

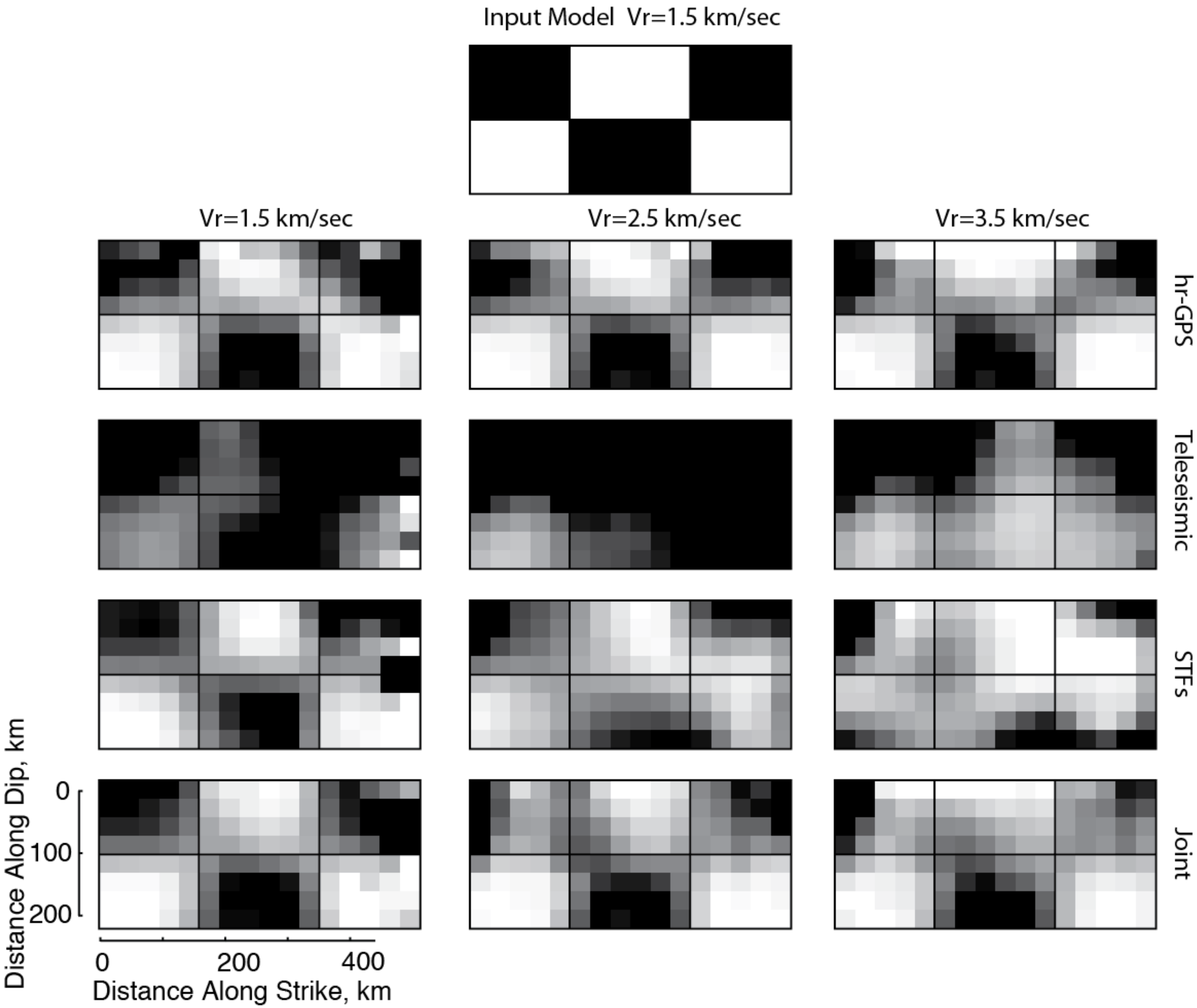


[Lay et al., 2014]

Differences from previous inversion results



[Yue et al. 2014b]



[Yue and Lay, 2013]

Earthquake	Year	Used Dataset						Publications
		Hr-GPS	Teleseismic	STF/ surface waves	Static GPS	InSAR / Landsat	Tsunami	
Tohoku	2011	x	x	x			○	Yue and Lay, 2011,2013 Yamazaki et al, 2011
Indo-Australia	2012	x	x	x				Yue et al, 2012; Hill et al, in prep
Costa Rica	2012	x	x	x	x			Yue et al, 2013a
Craig	2013	x	x	x				Yue et al, 2013b
Mentawai	2010	x	x				○	Yue et al, 2014a
Iquique	2014		x				x	Lay et al, 2014
Maule	2010	x	x			x	x	Yue et al, 2014b
Pakistan	2013		x			x		Sun et al, in prep

Note:
- **x** indicates datasets used in inversion
- ○ Indicatesdataset compared with forward modeling