A GLOBAL SURGE OF GREAT EARTHQUAKES AND WHAT WE ARE LEARNING FROM THEM

Thorne Lay, University of California Santa Cruz

Plate boundaries are a planet-wide network of faults where most earthquakes and volcanoes are located.

Earthquake Explanation

- An earthquake is the process of sudden, shearing displacement on a fault (a surface of contact between two rock masses) combined with resultant vibrations (seismic waves)

- Earthquakes ‘catch up’ with prior large-scale crustal motions: strain and stress in rock change (reduce)

- Earthquakes are frictional sliding instabilities. Repeated stick-slip behavior is observed. Friction depends on pressure, temperature, fluids, slip velocity, fault history, and material properties in the fault zone.

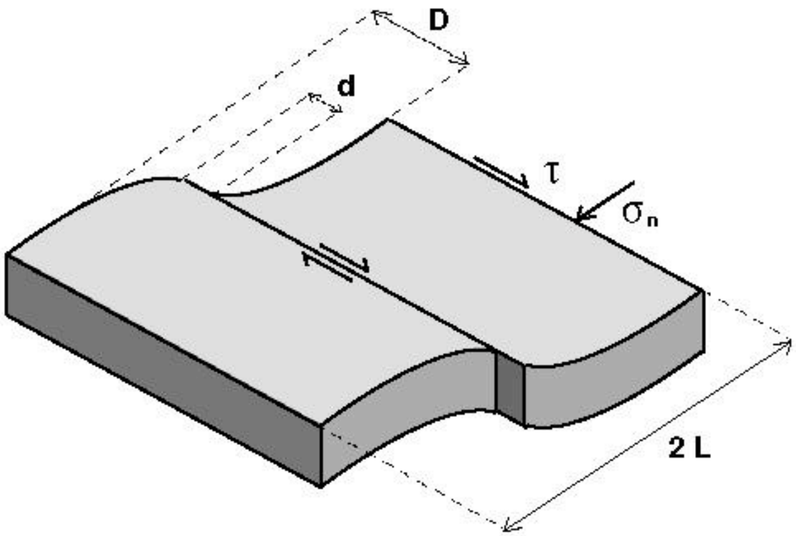


Figure 13 - Peltzer et al., 1998

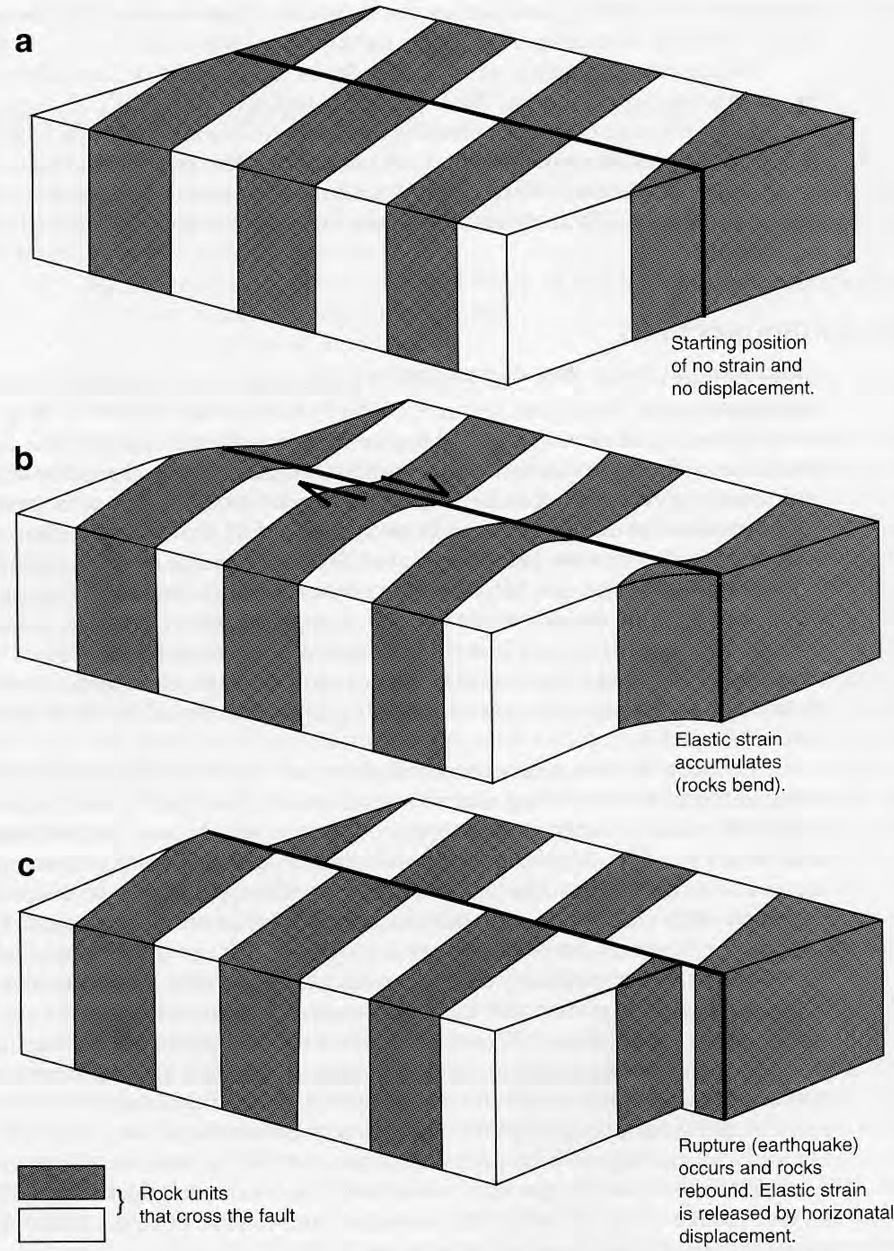
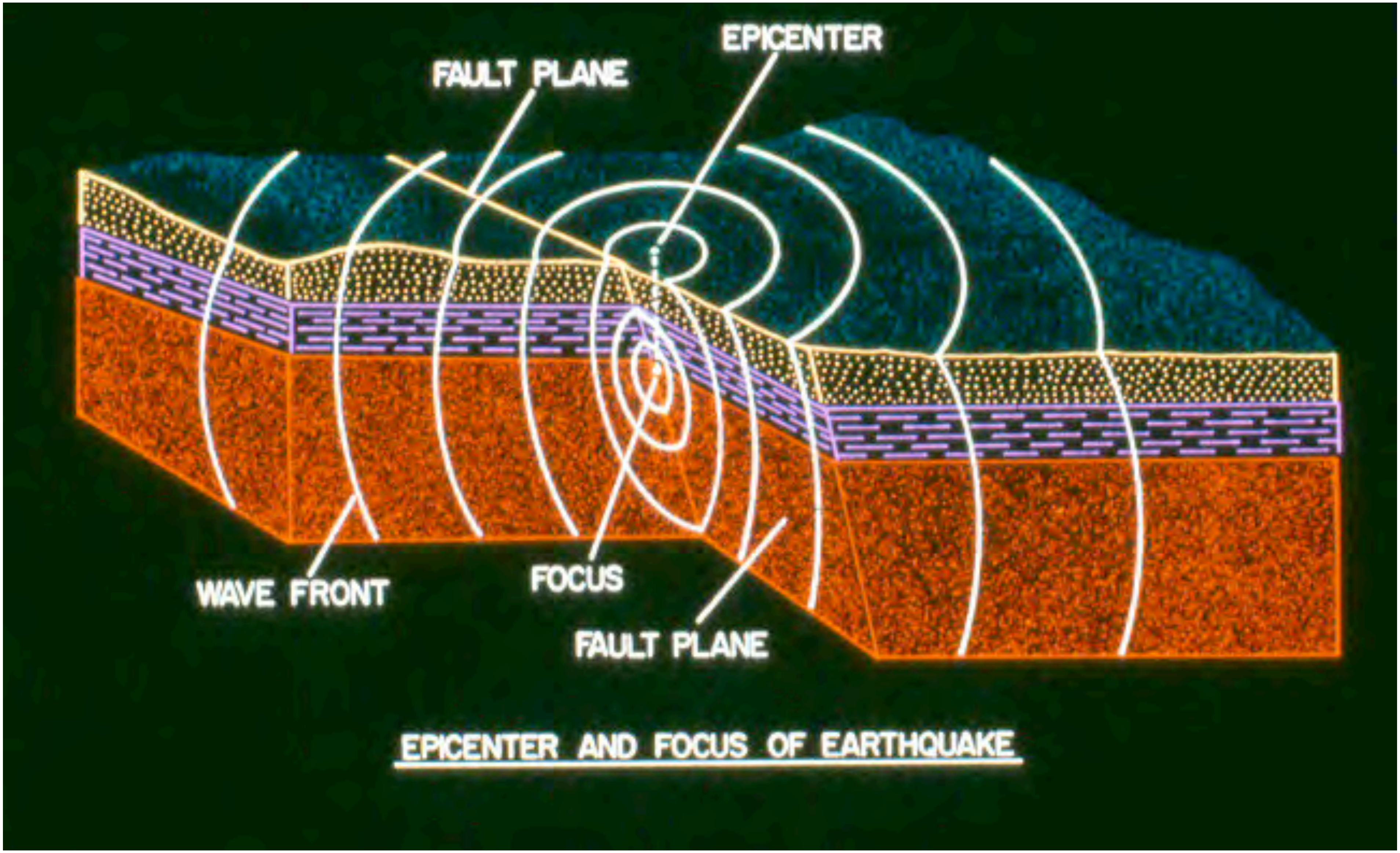
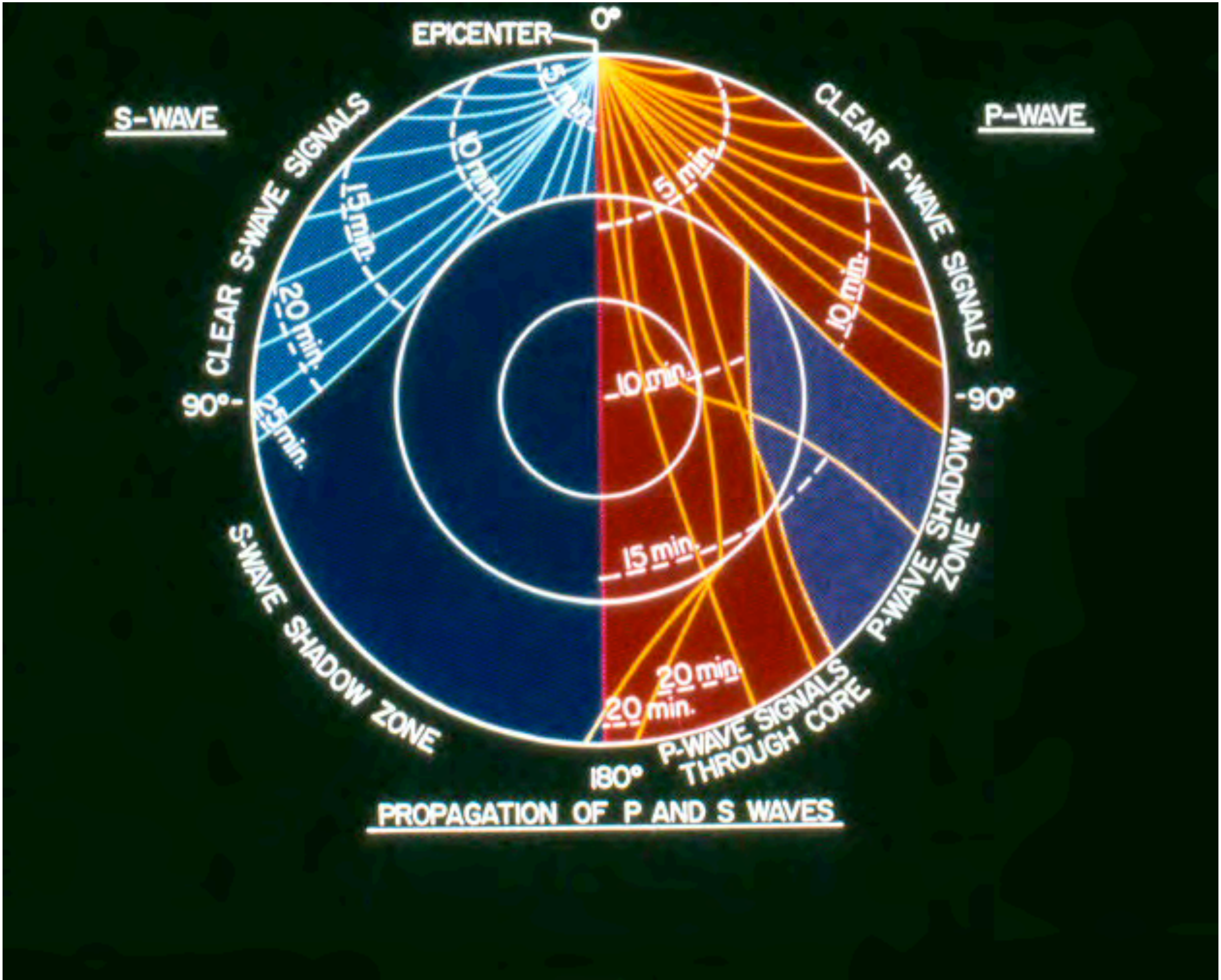


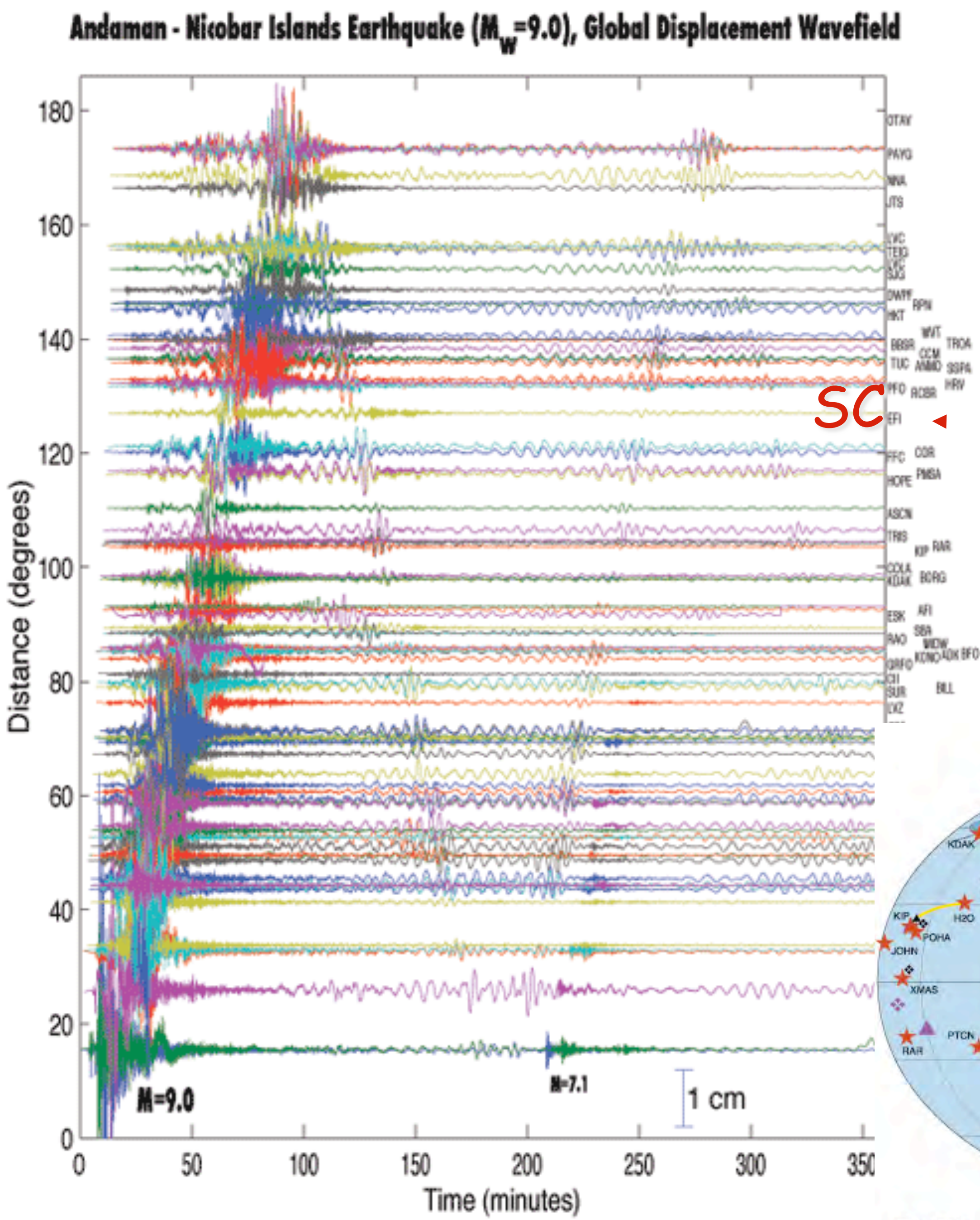
Figure 1.27 Idealized block diagrams illustrating the earthquake cycle and elastic rebound. (a) Beginning position with no strain or displacement. (b) After accumulation of elastic strain. (c) Following earthquake and rupture. (Courtesy of F. Duennebier.)


EPICENTER
FAULT PLANE
WAVE FRONT
FOCUS
FAULT PLANE
EPICENTER AND FOCUS OF EARTHQUAKE

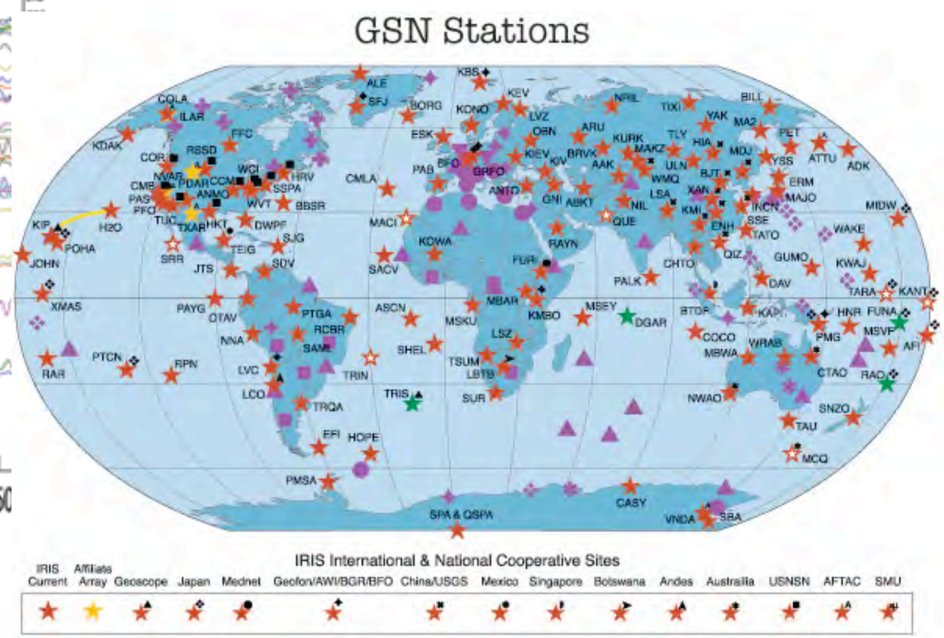


EPICENTER
0°
S-WAVE
P-WAVE
CLEAR S-WAVE SIGNALS
CLEAR P-WAVE SIGNALS
5 min.
10 min.
15 min.
20 min.
25 min.
90°
-90°
S-WAVE SHADOW ZONE
P-WAVE SHADOW ZONE
P-WAVE SIGNALS THROUGH CORE
180°
PROPAGATION OF P AND S WAVES

Waveforms from the Global Seismographic Network (GSN) of the Sumatra Earthquake

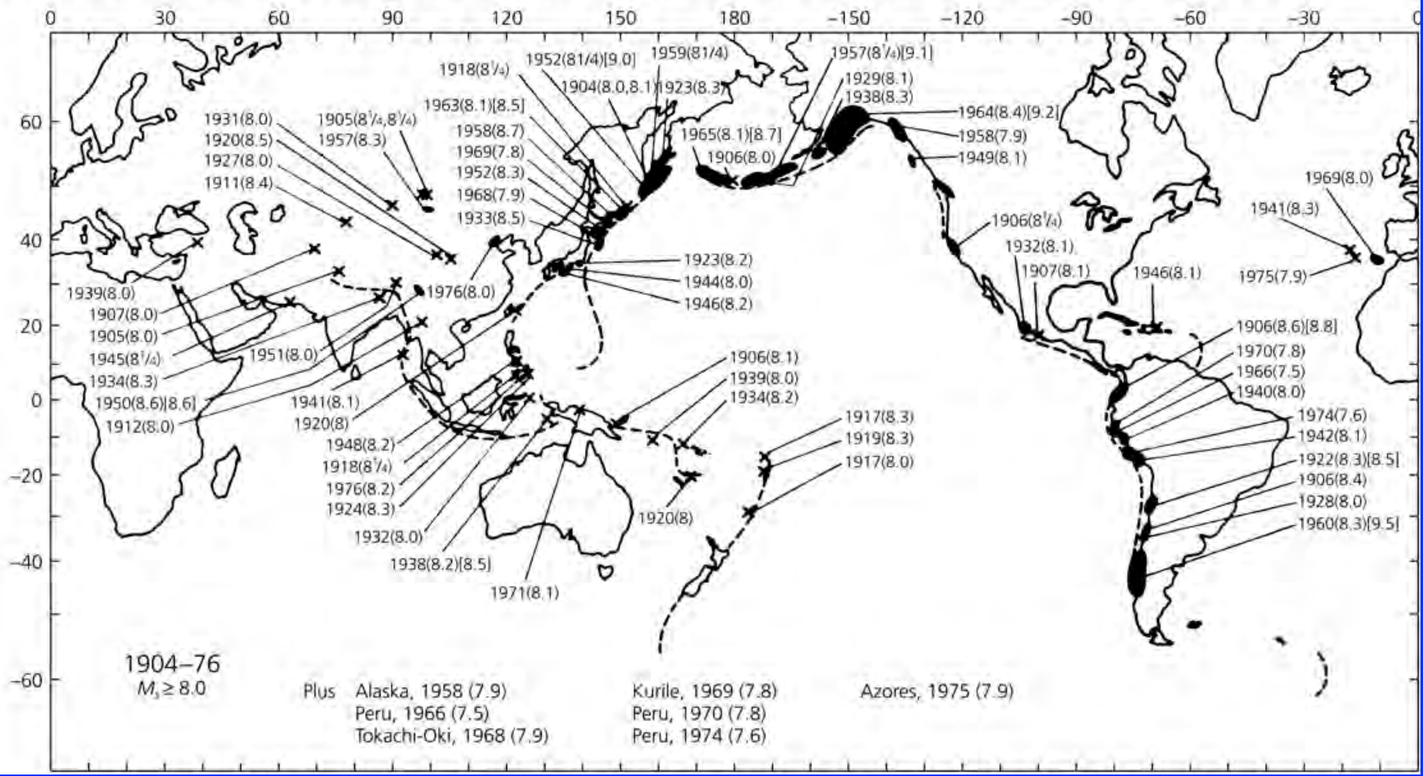


A record section plot of vertical displacements of the Earth's surface recorded by seismometers around the world. Time is on the horizontal axis, and vertical displacements of the Earth on the vertical axis.



MOST OF THE LARGEST EARTHQUAKES ARE AT SUBDUCTION ZONES AND RESULT FROM THRUST FAULTING AT THE PLATE INTERFACE

Figure 5.4-24: Locations of the largest earthquakes during 1904-1976.



Kanamori, 1978

Much of what is known about the geometry and mechanics of the interaction between plates at subduction zones comes from the distribution and focal mechanisms of shallow earthquakes at the interface between the plates

EARTHQUAKE CYCLE

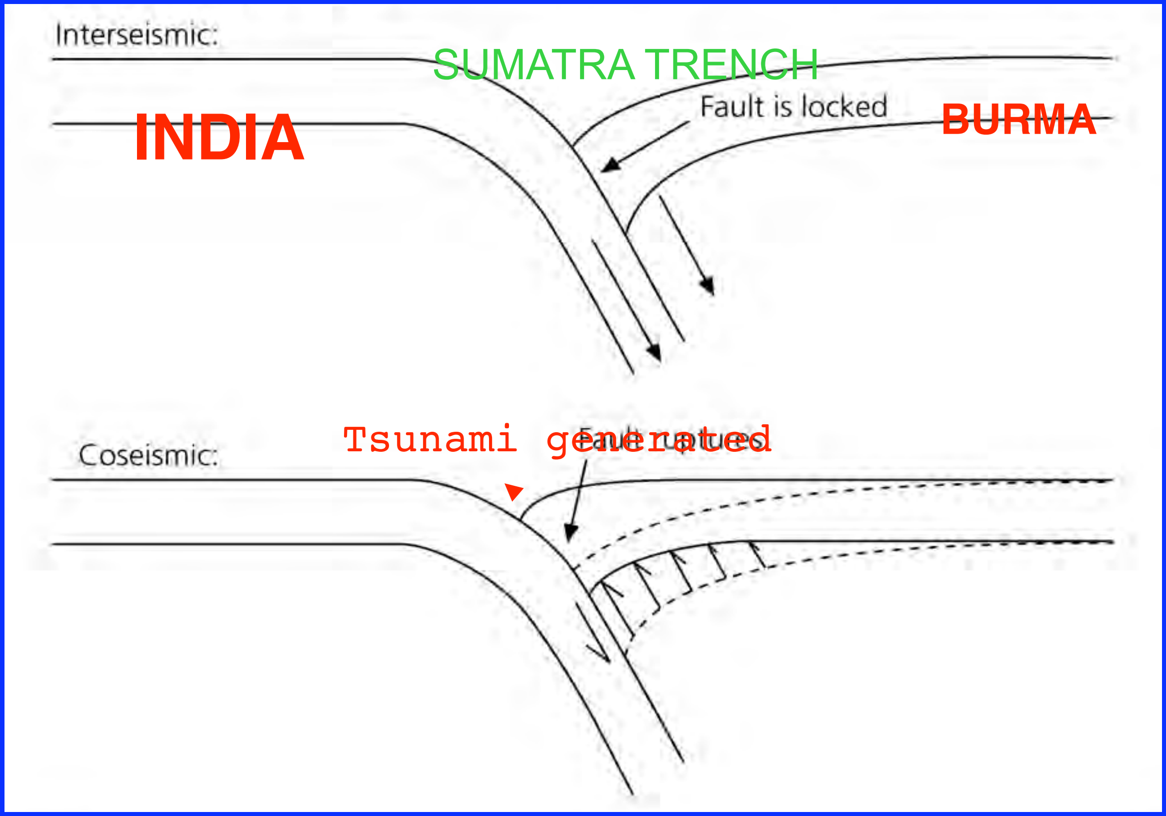
INTERSEISMIC:

India subducts beneath Burma at about 20 mm/yr

Fault interface is locked

EARTHQUAKE (COSEISMIC):

Fault interface slips, overriding plate rebounds, releasing accumulated motion and generating tsunami

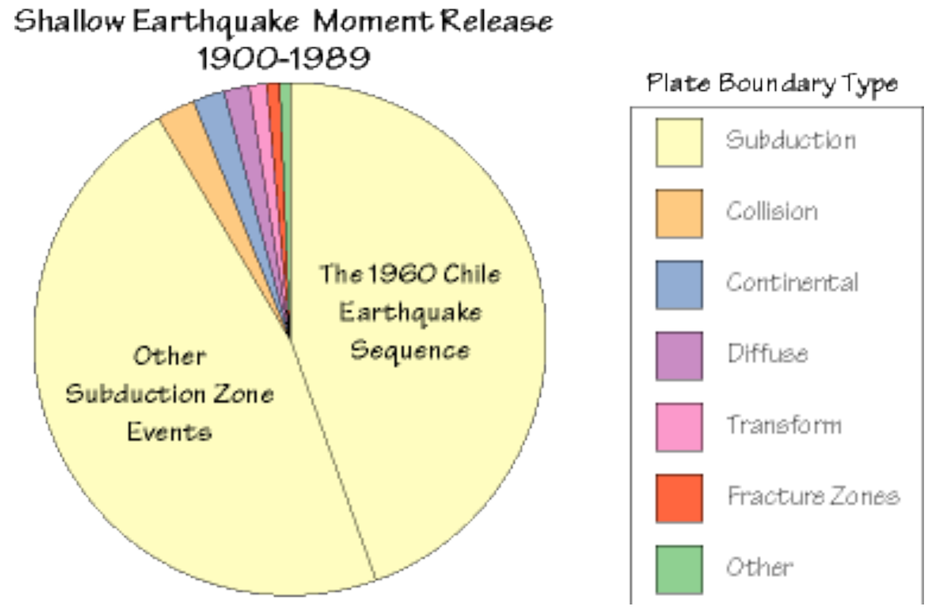


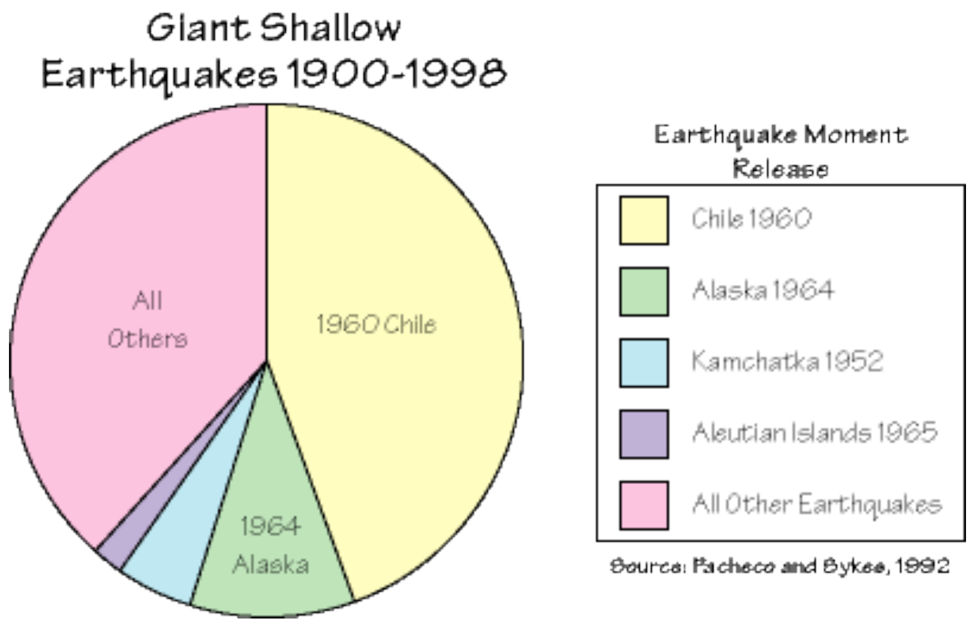
Stein & Wysession, 2003 4.5-14

HOW OFTEN:

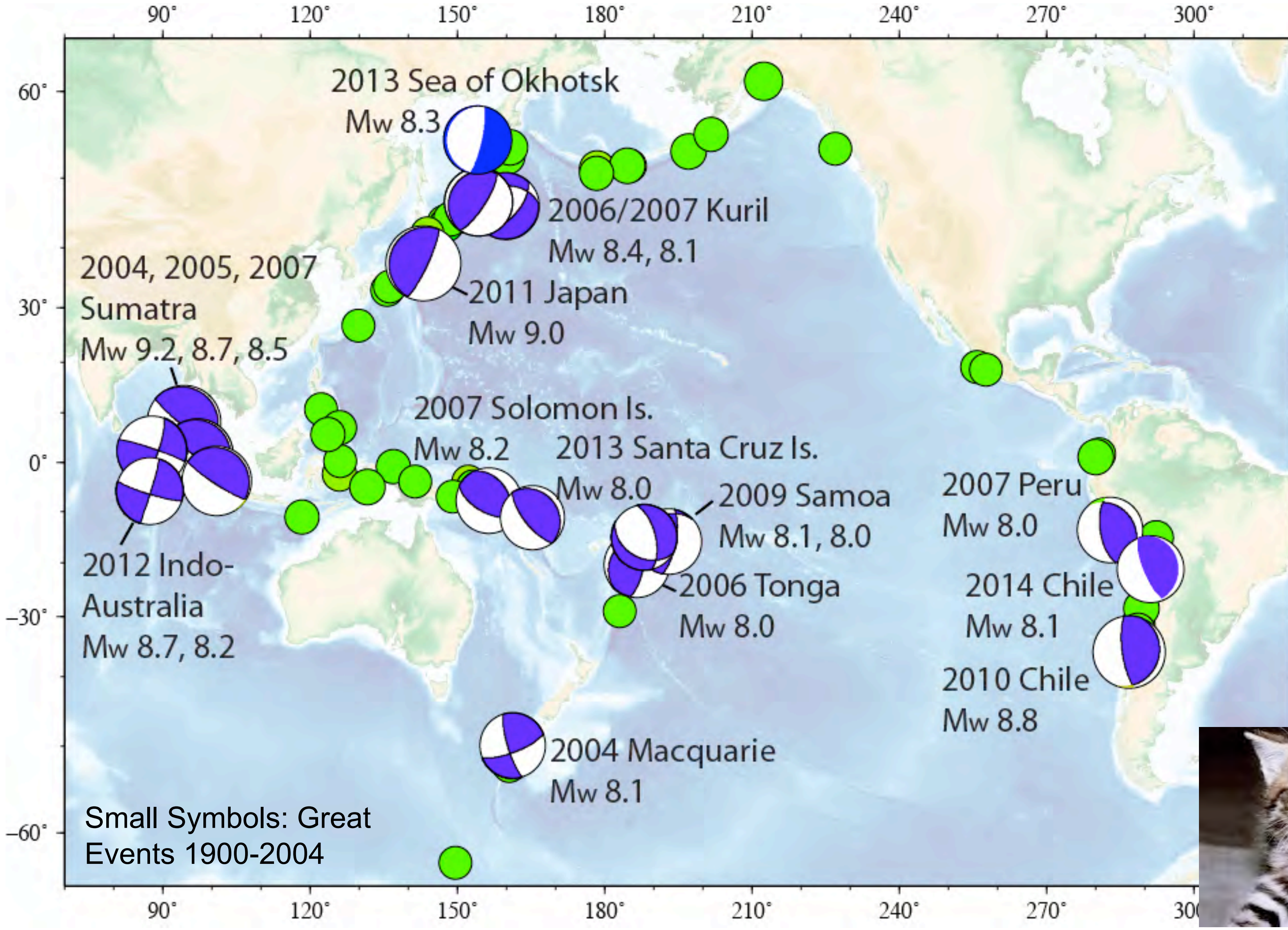
Fault slipped ~ 10 m --> 10000 mm / 20 mm/yr = 500 yr
Longer if some slip is aseismic

Faults aren't exactly periodic, likely because chaotic nature of rupture controls when large earthquakes occur

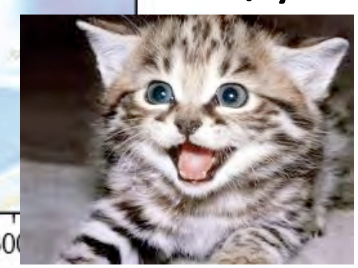

Shallow Earthquake Moment Release
1900-1989
The 1960 Chile
Earthquake
Sequence
Other
Subduction Zone
Events
Plate Boundary Type
Subduction
Collision
Continental
Diffuse
Transform
Fracture Zones
Other


Giant Shallow
Earthquakes 1900-1998
All
Others
1960 Chile
1964
Alaska
Earthquake Moment
Release
Chile 1960
Alaska 1964
Kamchatka 1952
Aleutian Islands 1965
All Other Earthquakes
Source: Pacheco and Sykes, 1992

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

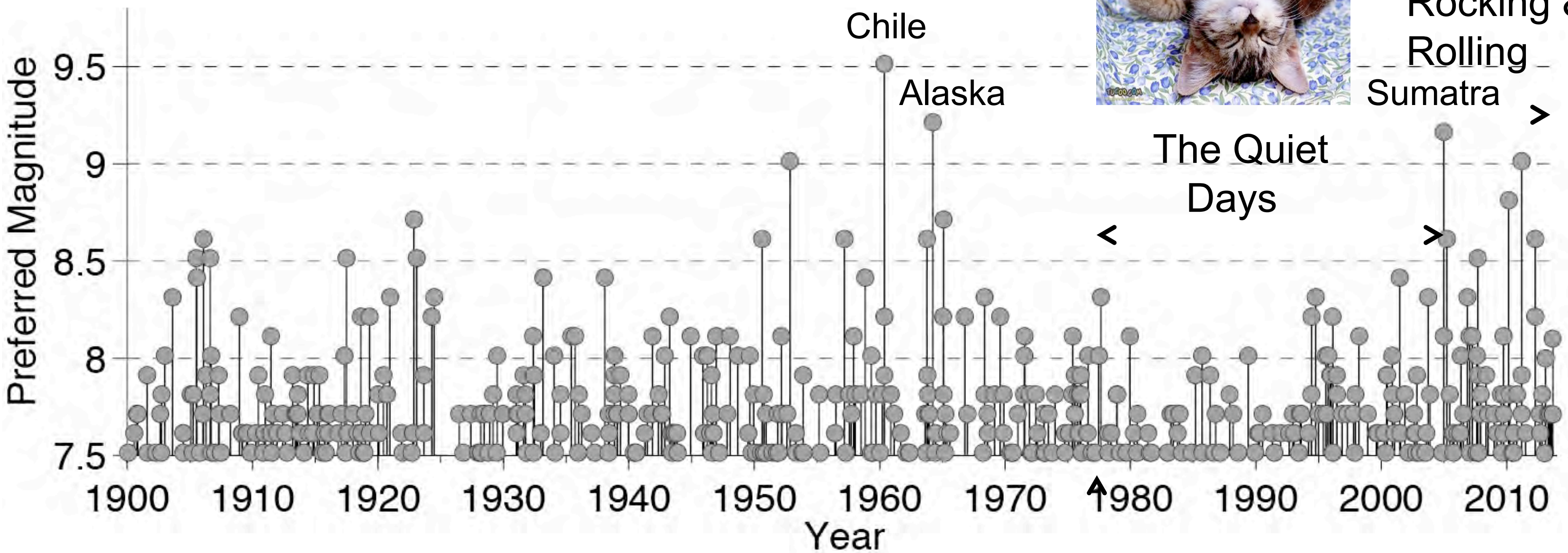


1.8/yr !



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

[Lay, 2014]



Global Broadband Seismic Networks

hr-GPS Networks

DART expansion

I started grad school at
Caltech Seismo Lab

after, Ammon et al., SRL, 2010

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"

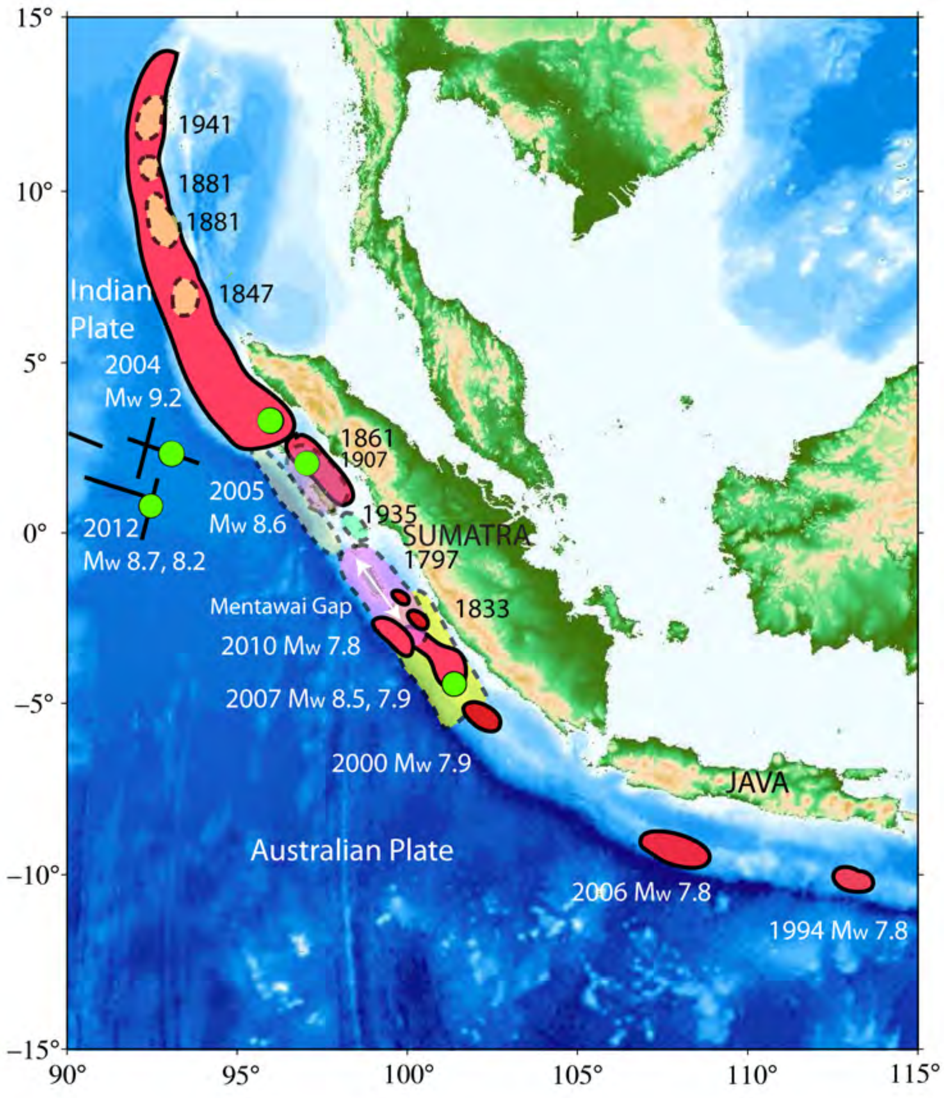
2010 Mentawai M_w 7.8 tsunami earthquake updip of 2007 8.5/7.9 Sumatra

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

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

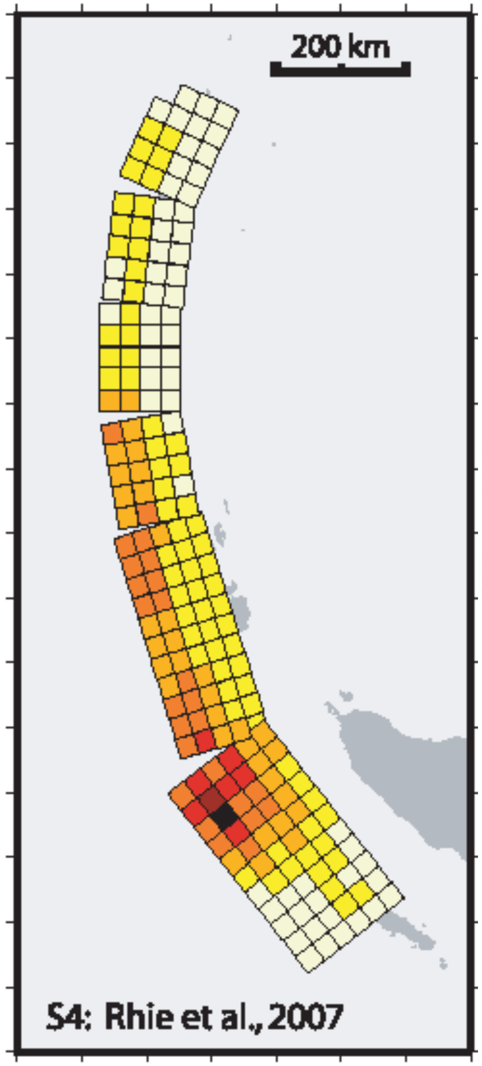
Sept. 2007 – Kepulauan pair. 8.5, 7.9

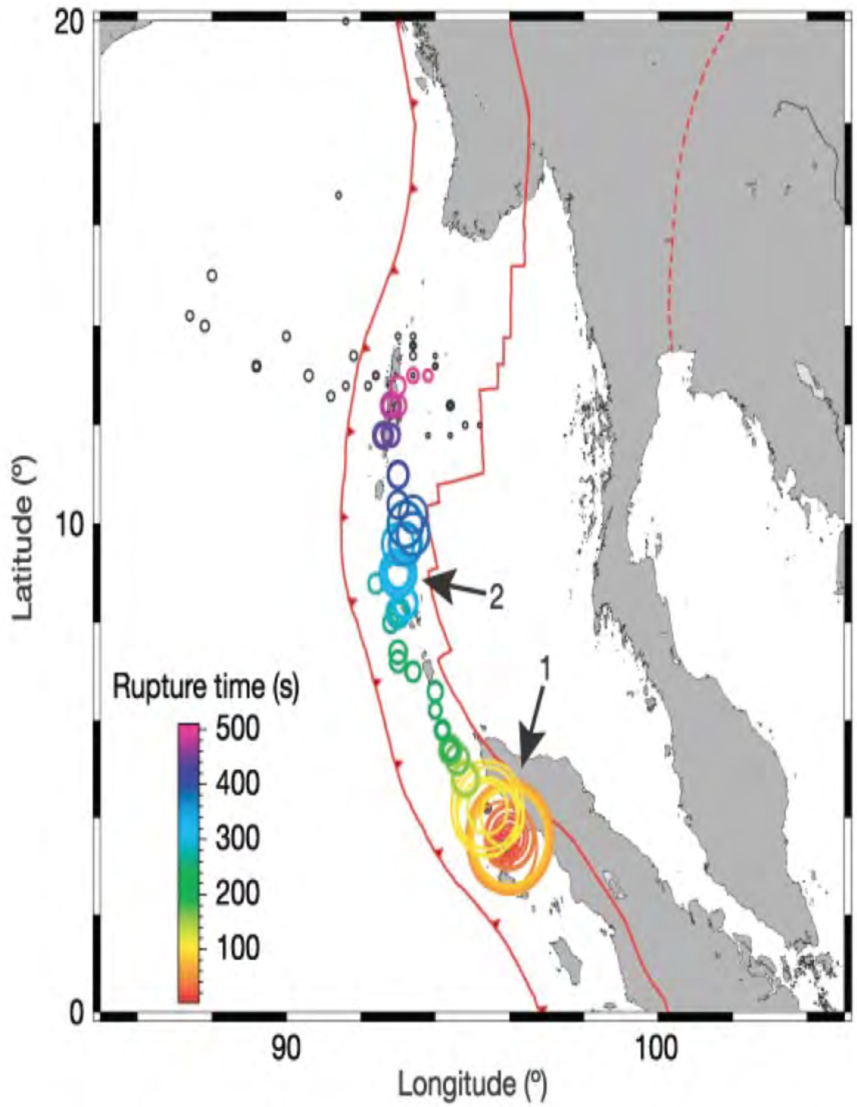
Oct. 2010 – Mentawai tsunami earthquake. 7.8

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

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

Models for 2004 Sumatra

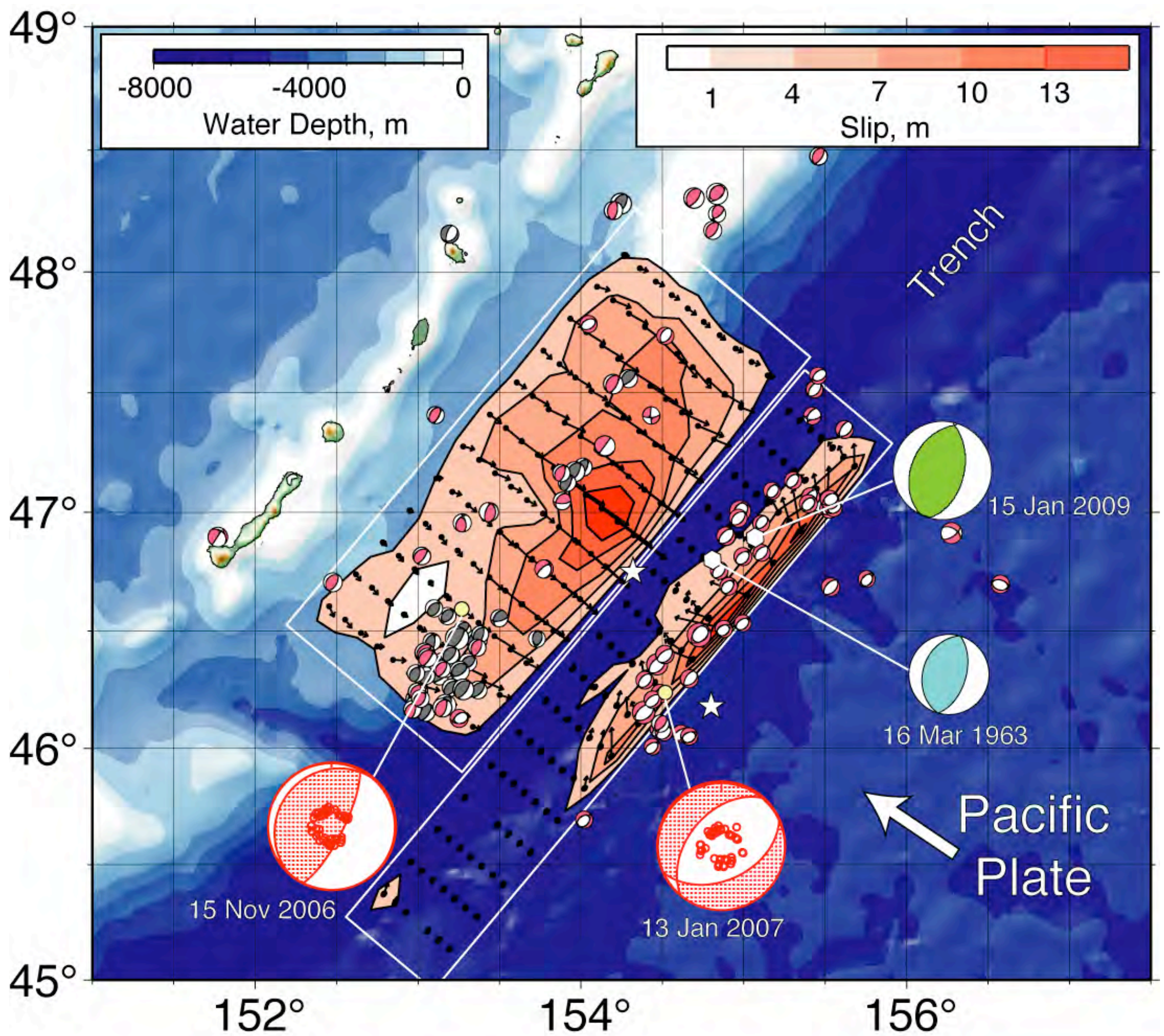




2004 Sumatra was the first event for which back-projection of dense network signals to image coherent sources of short-period radiation was performed (by Ishii et al. 2005, and Krüger and Ohrnberger, 2005). Slip and short-period coherent power do NOT correlate spatially in detail.

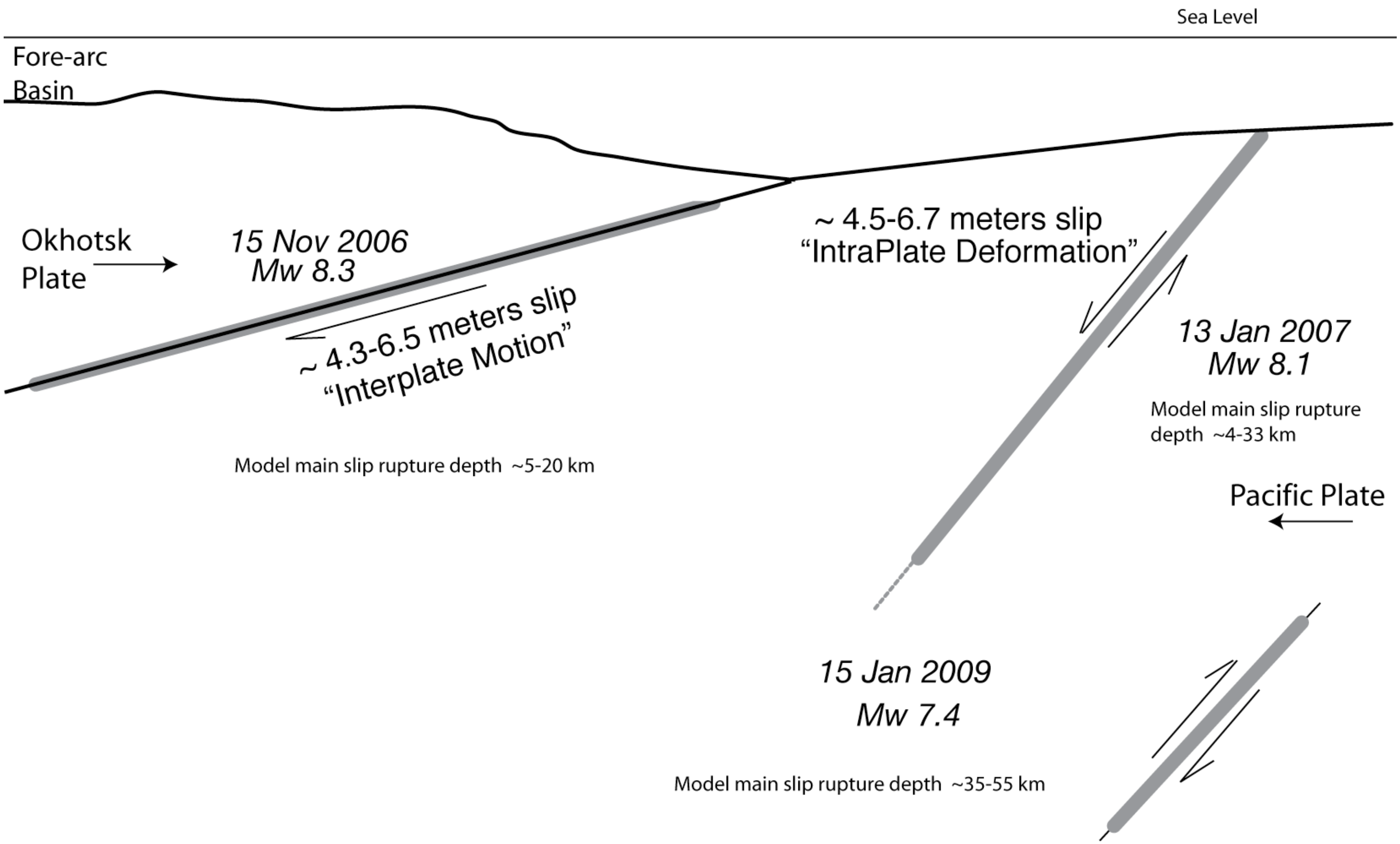
2004 prompted geophysicists to ‘tune-up’ algorithms to handle very long duration, extended fault. Solutions developed using seismic, geodetic, tsunami, and joint data sets came out after several months/years. Initiated upgrade of DART system in Pacific.

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

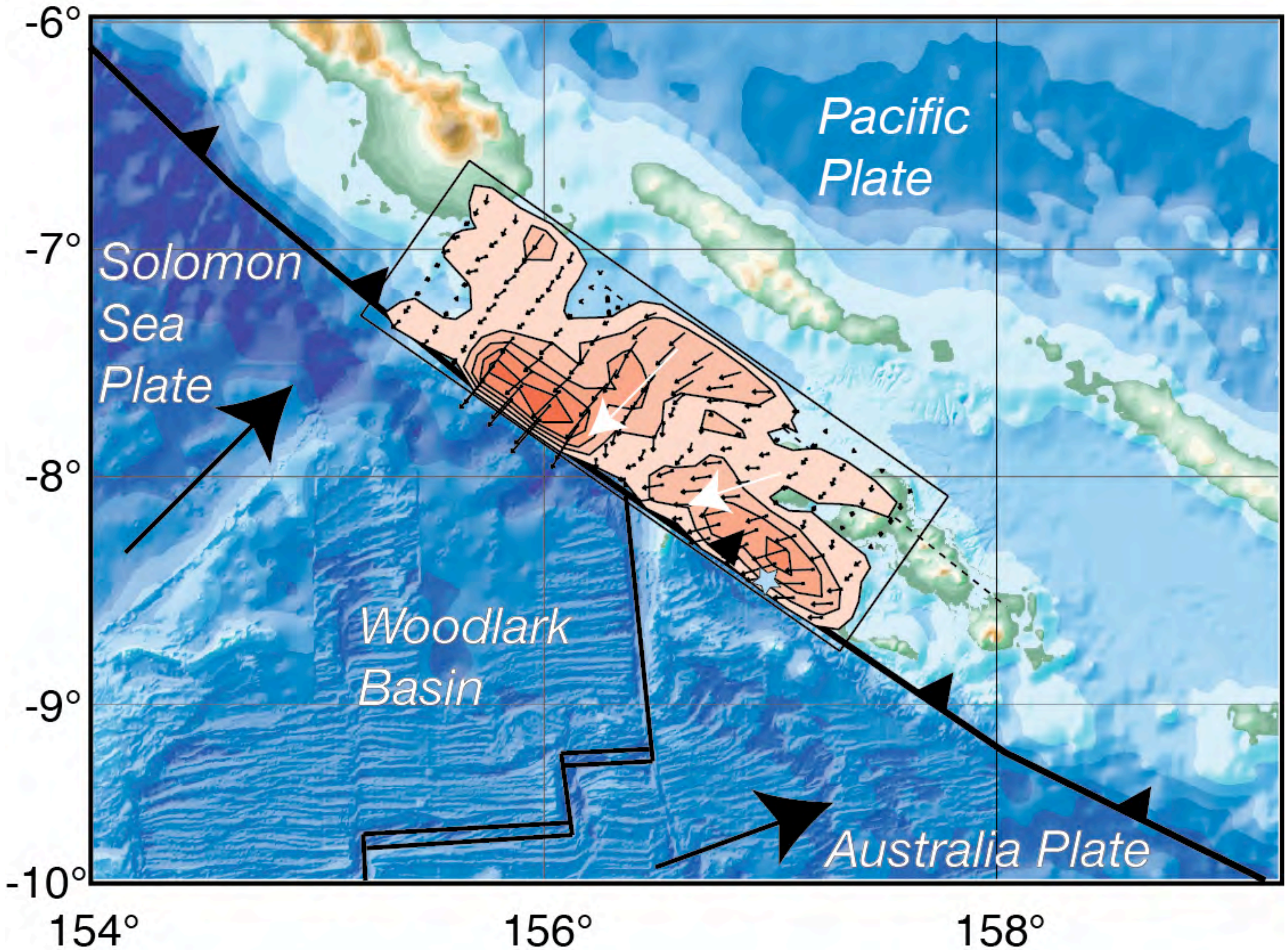


Lay et al., JGR (2009)

Kuril Islands Great Doublet



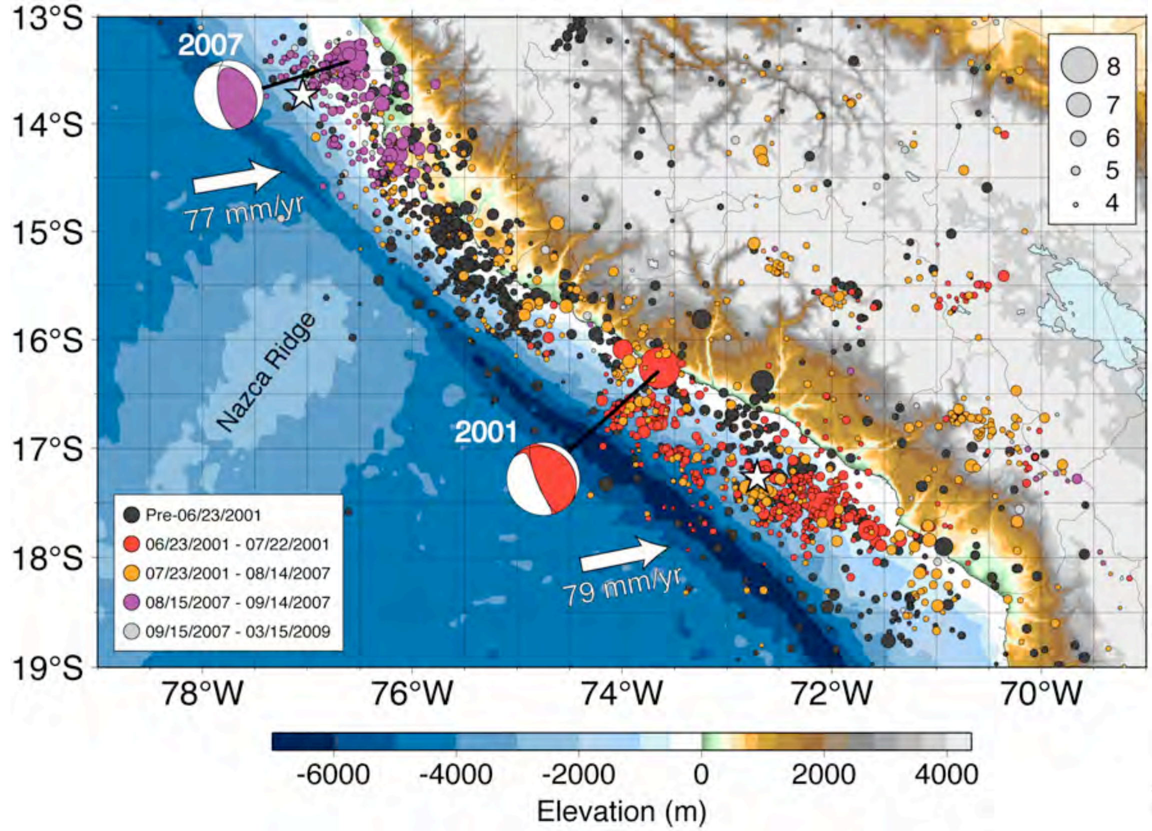
Lay et al., JGR (2009)

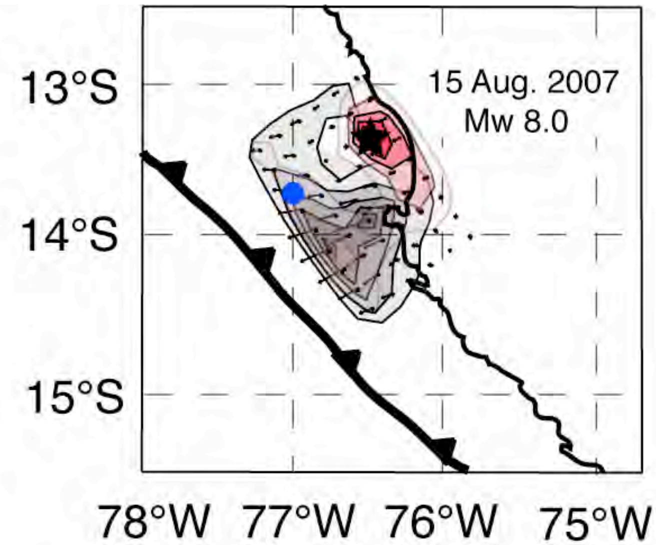


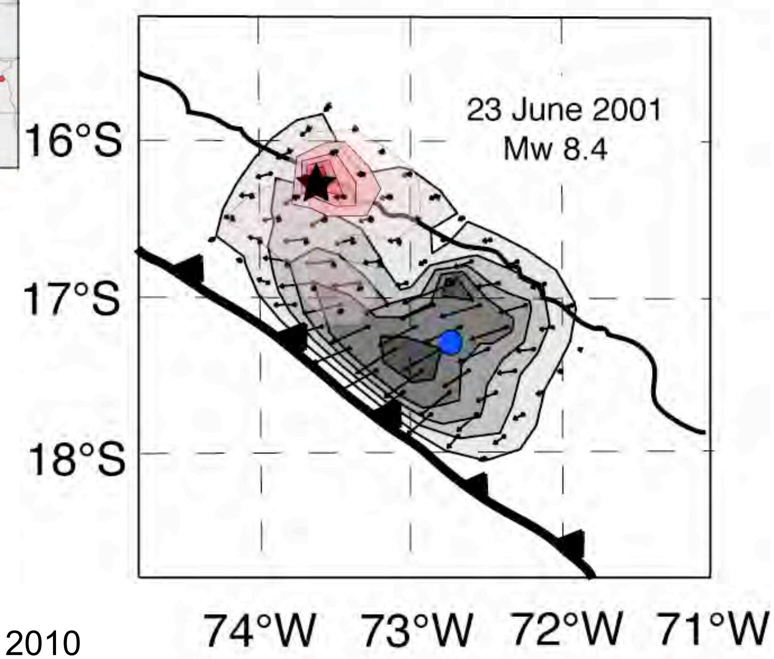
Furlong et al., Science (2009)

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.





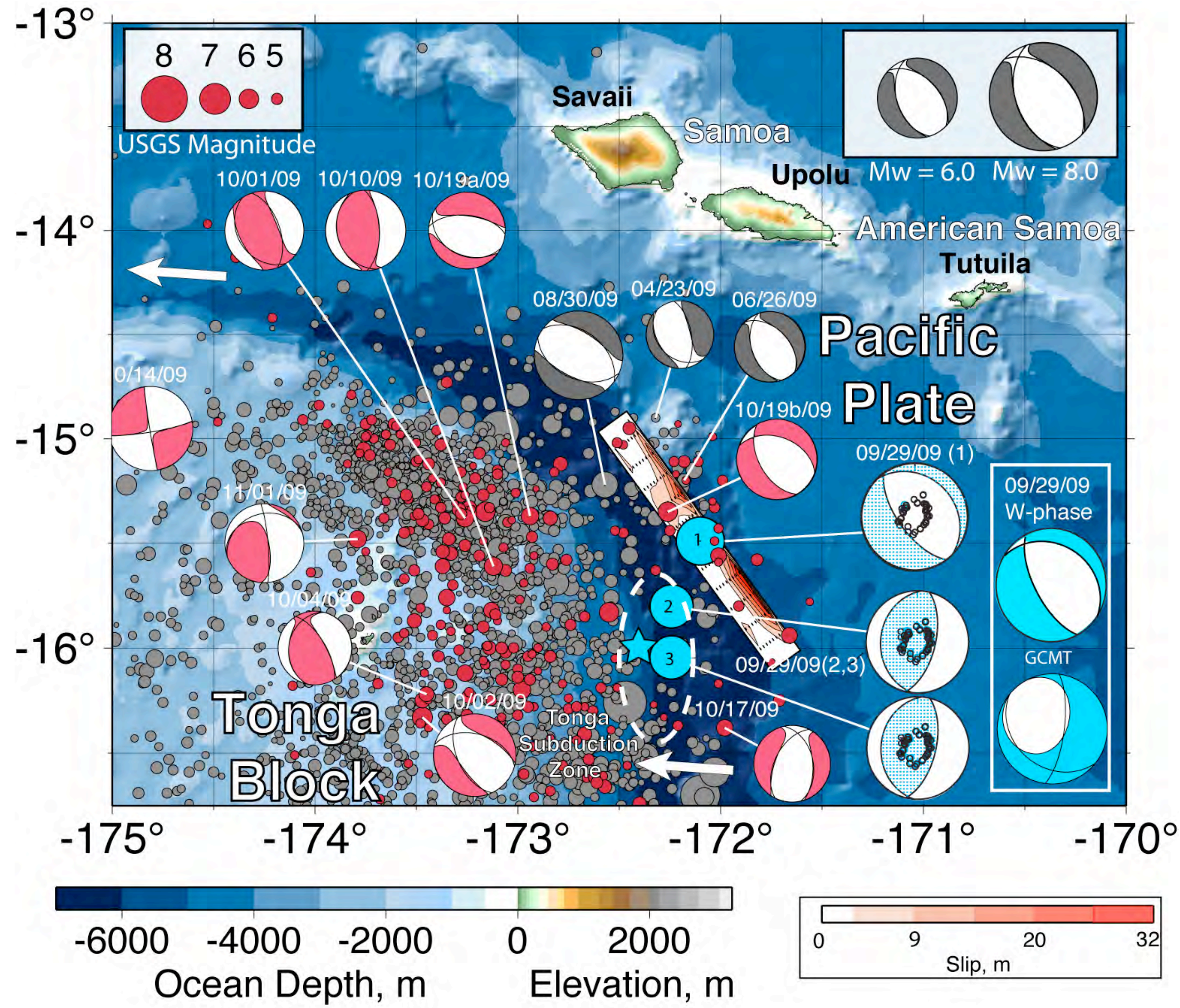


2001 Peru (M_w 8.4) – Initial 7.5 triggers rupture of 8.4 on ~Rayleigh wave arrival

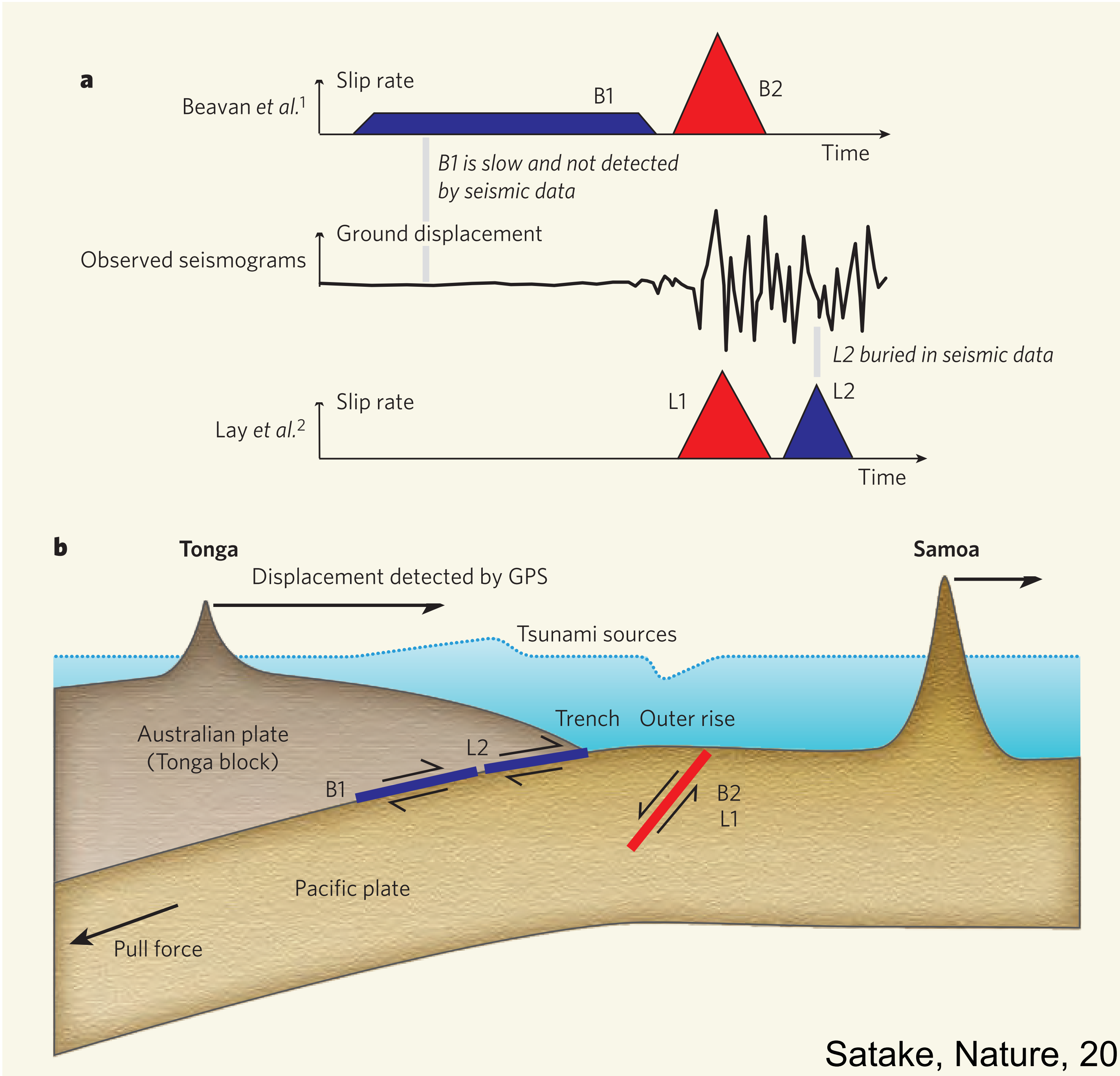
2007 Peru (M_w 8.0) – Initial 7.8 triggers rupture of 8.1 after ~60 s hiatus`

Lay, et al., BSSA, 2010

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

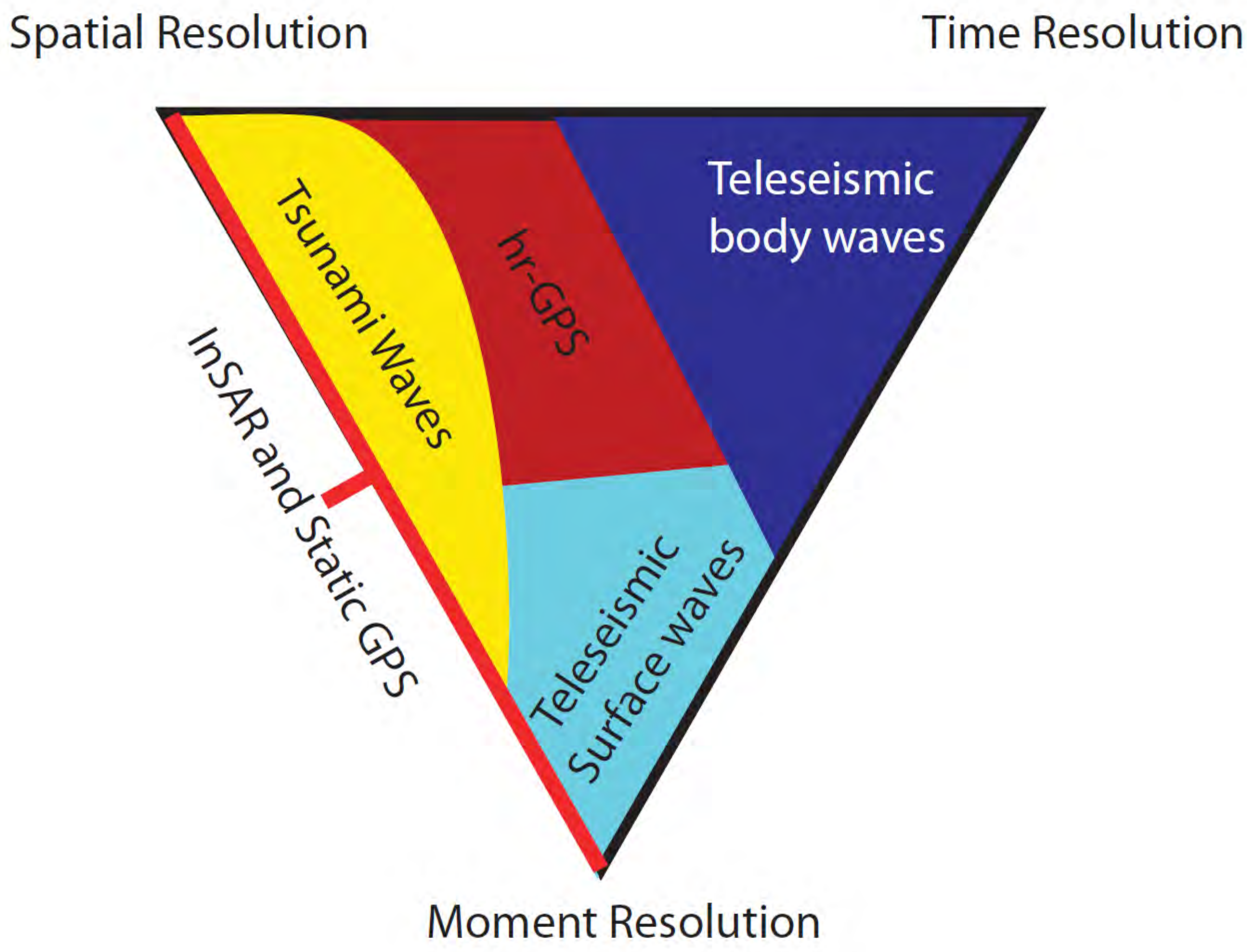


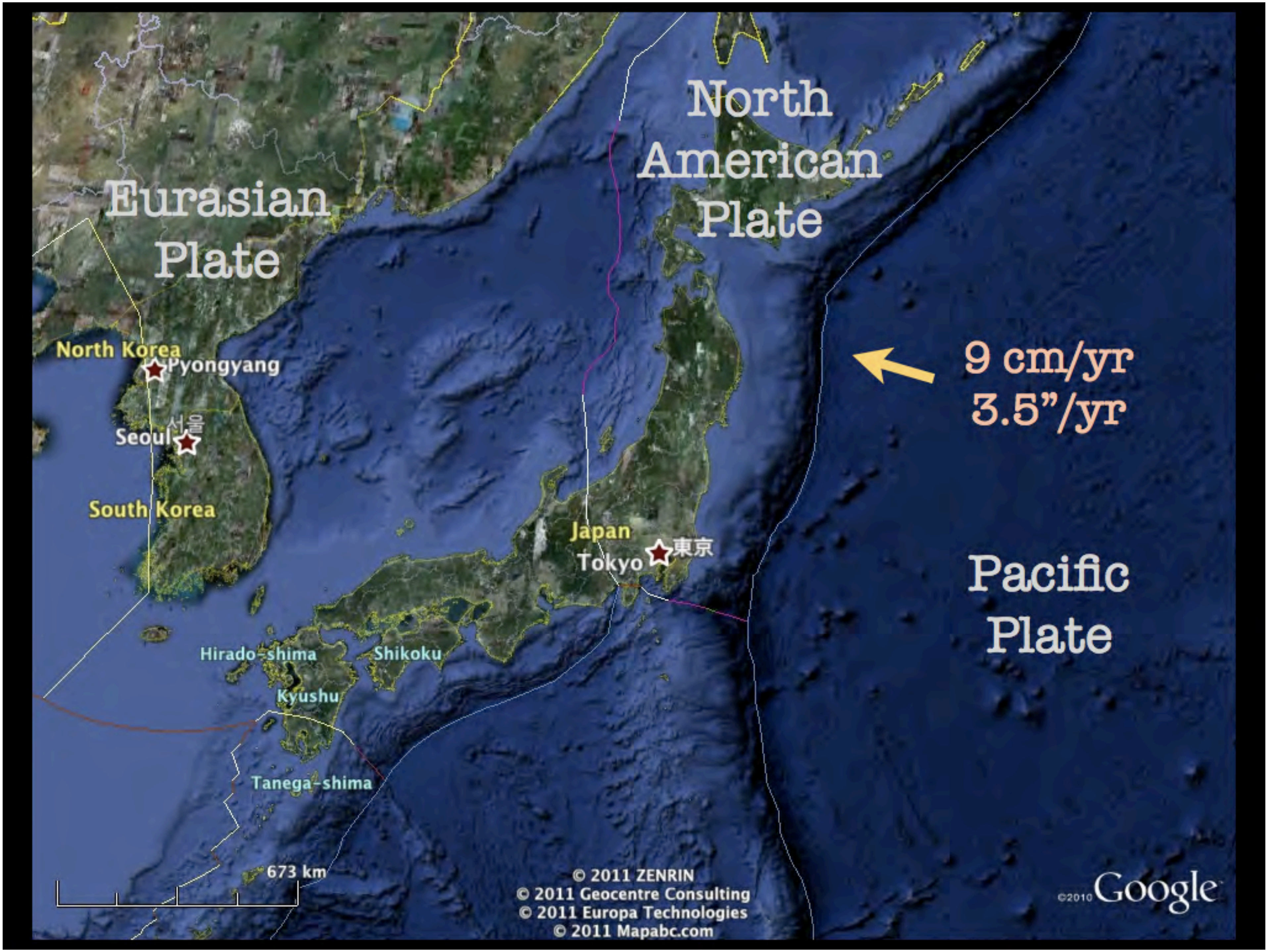
Lay et al., Nature (2010)



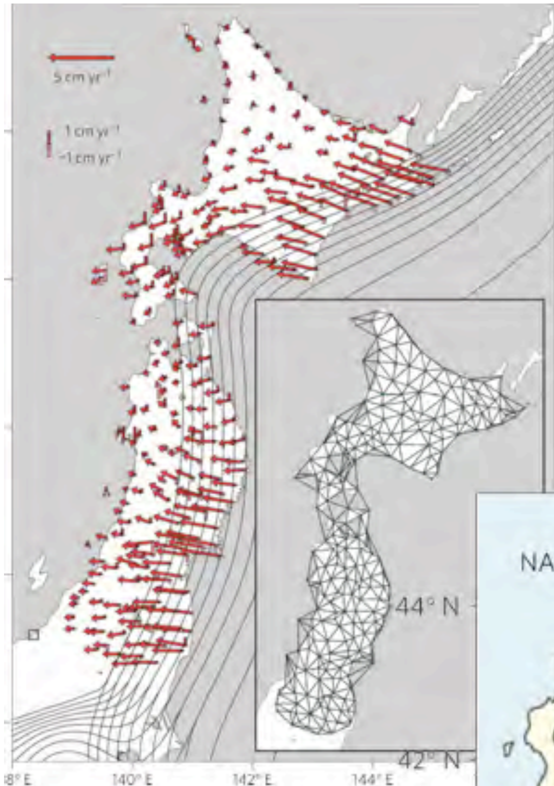
Satake, Nature, 2010

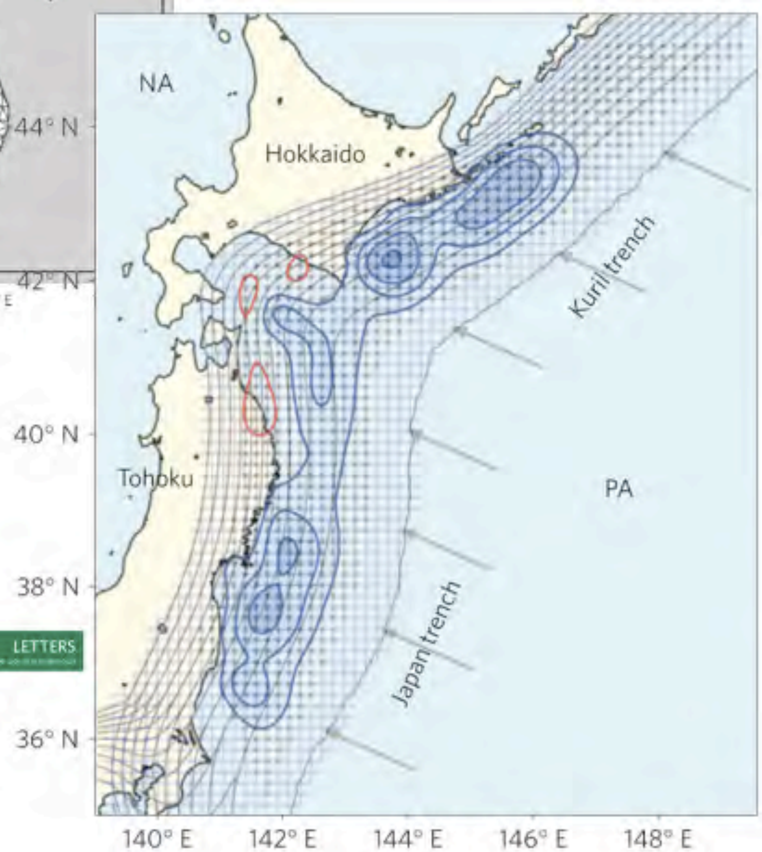
Resolutions of Joint inversion





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

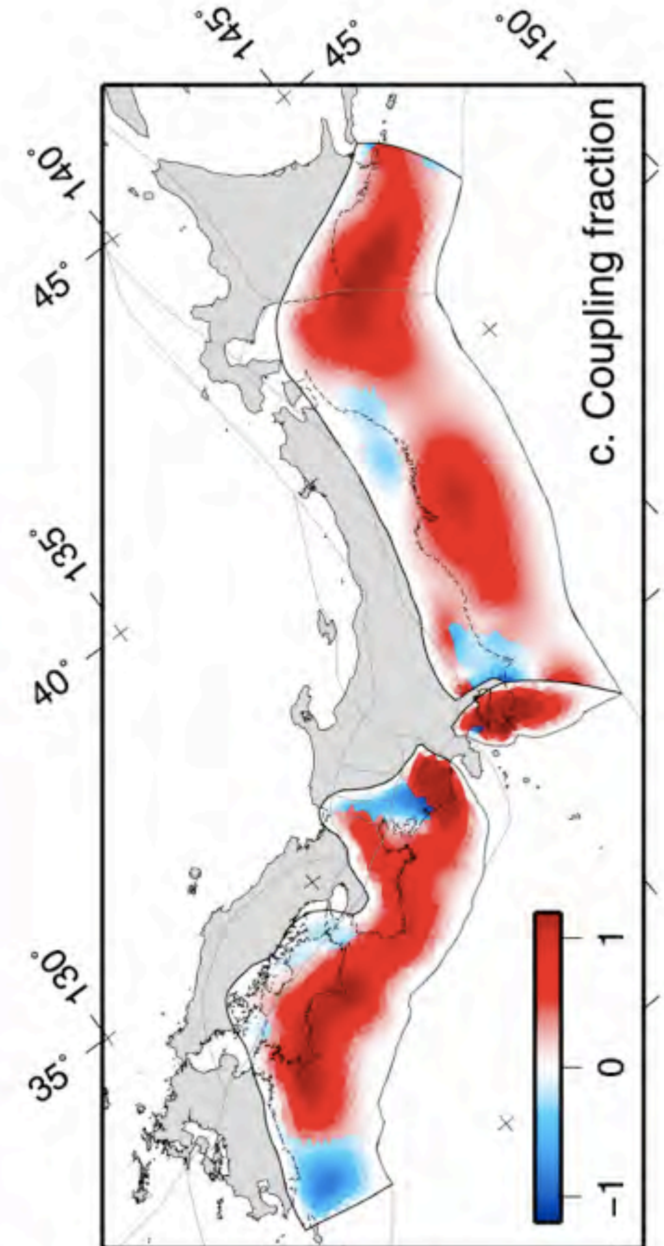




nature geoscience | LETTERS

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

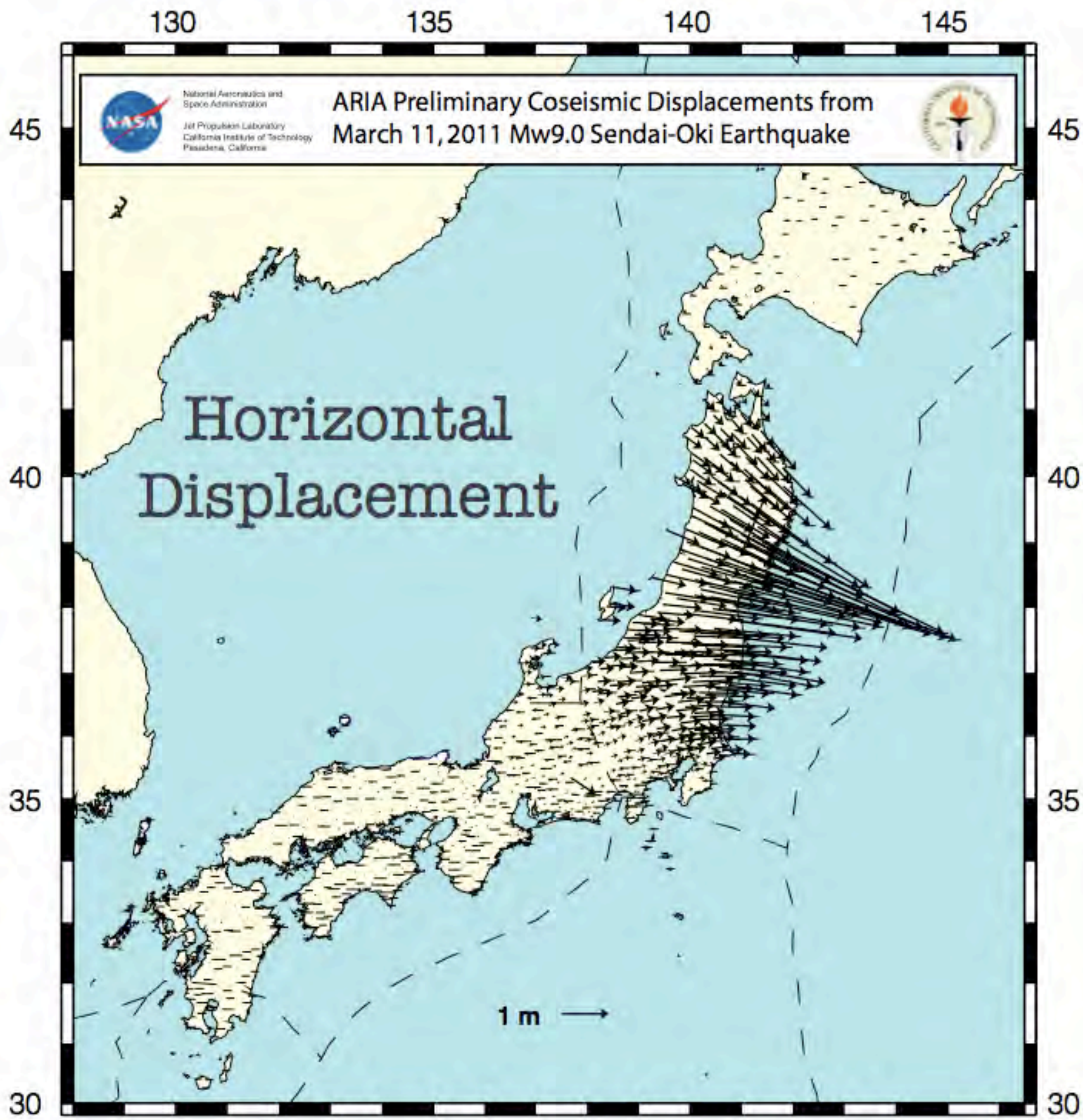
Chihiro Hashimoto[1]*, Akemi Noda[1], Takeshi Sagiya[2] and Mitsuhiro Matsu'ura[1]



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



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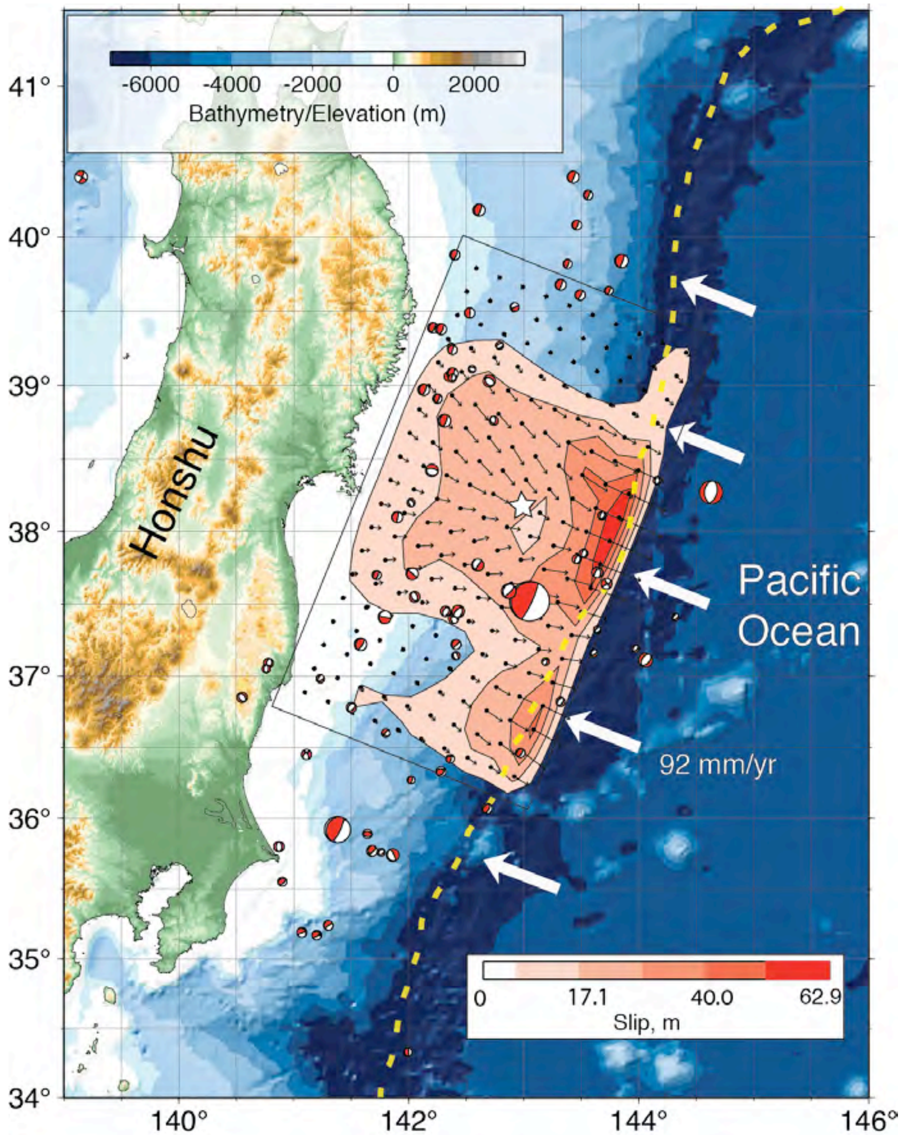
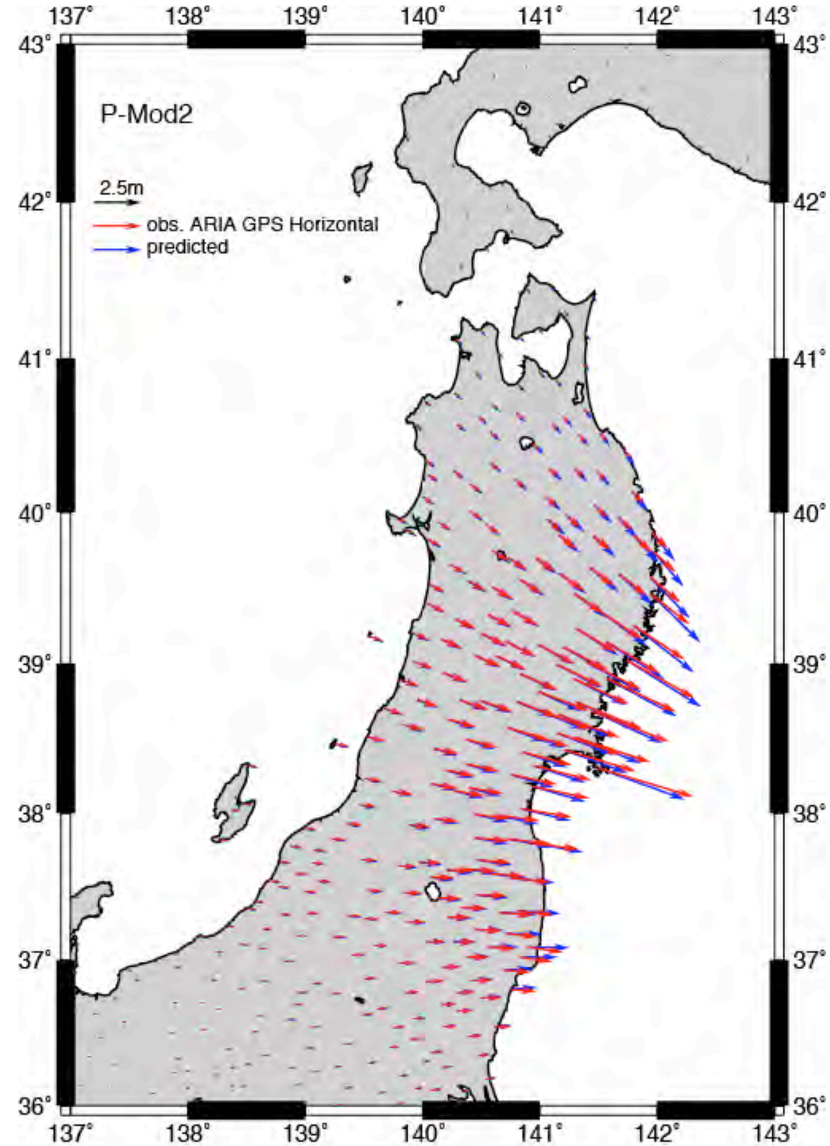
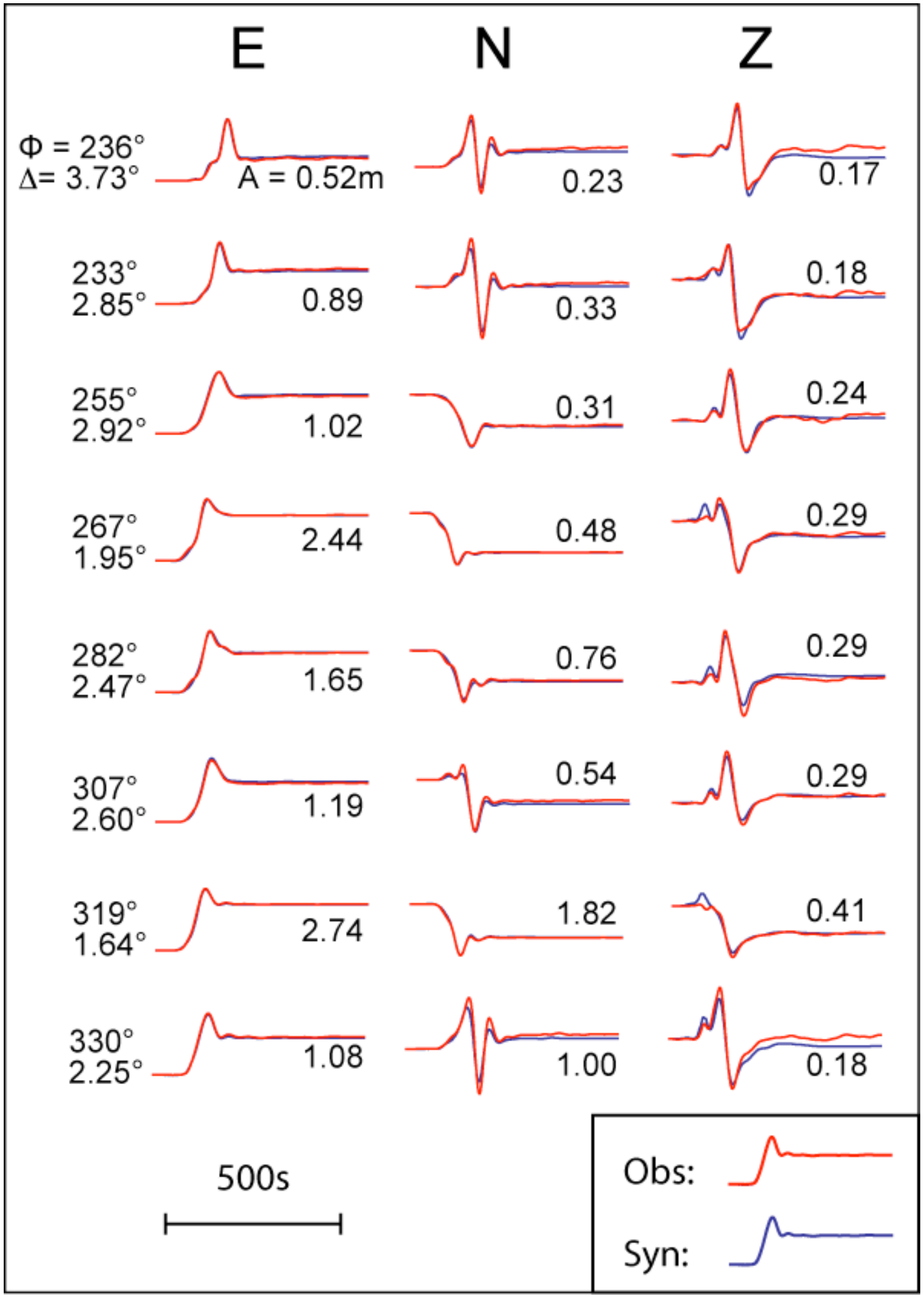
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
ARIA Preliminary Coseismic Displacements from
March 11, 2011 Mw9.0 Sendai-Oki Earthquake
Horizontal
Displacement
1 m





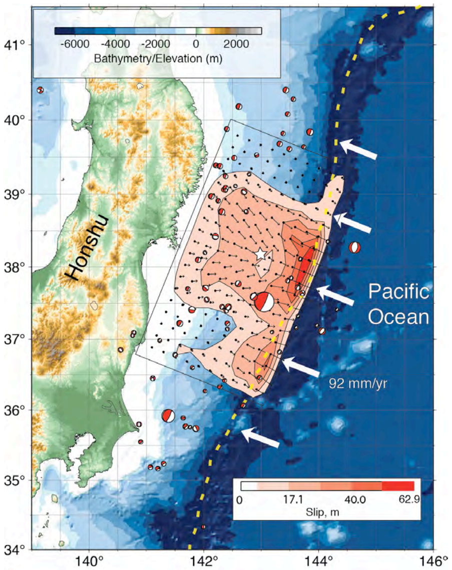
Aseismic model with near-trench slip can fit GPS statics well.
Quasi-seismogeodesy.

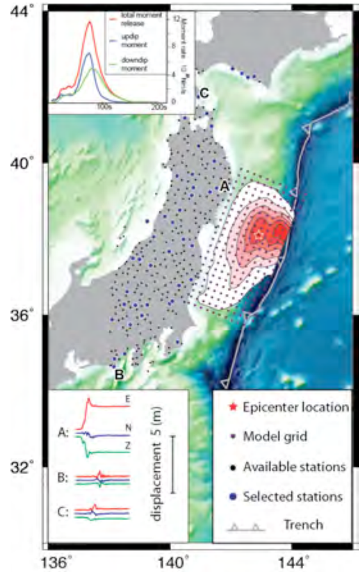
Lay et al., EPS, 2011

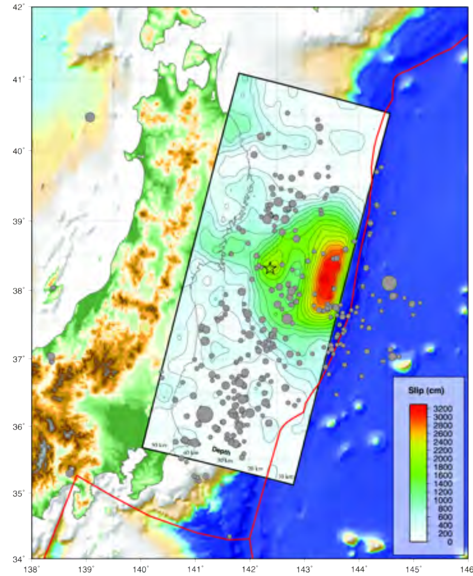


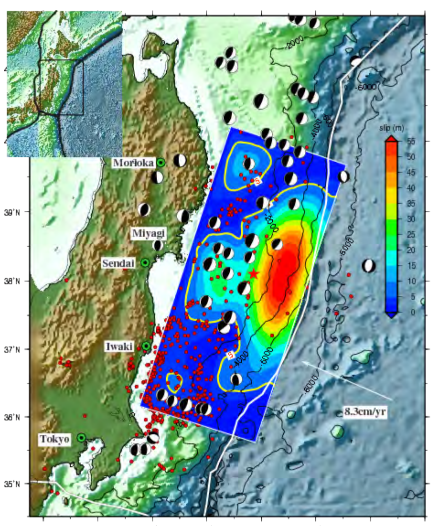
The GPS ground motions record both the arrivals of all seismic waves and the permanent deformations (offsets) of the ground.

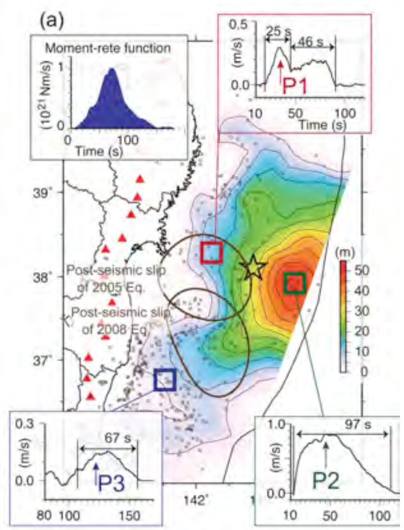
Yue and Lay, GRL, 2011

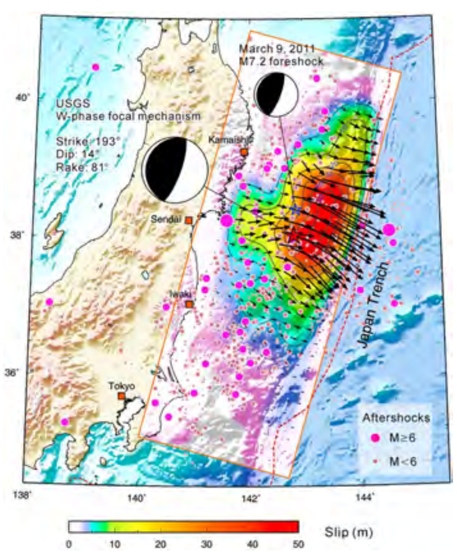






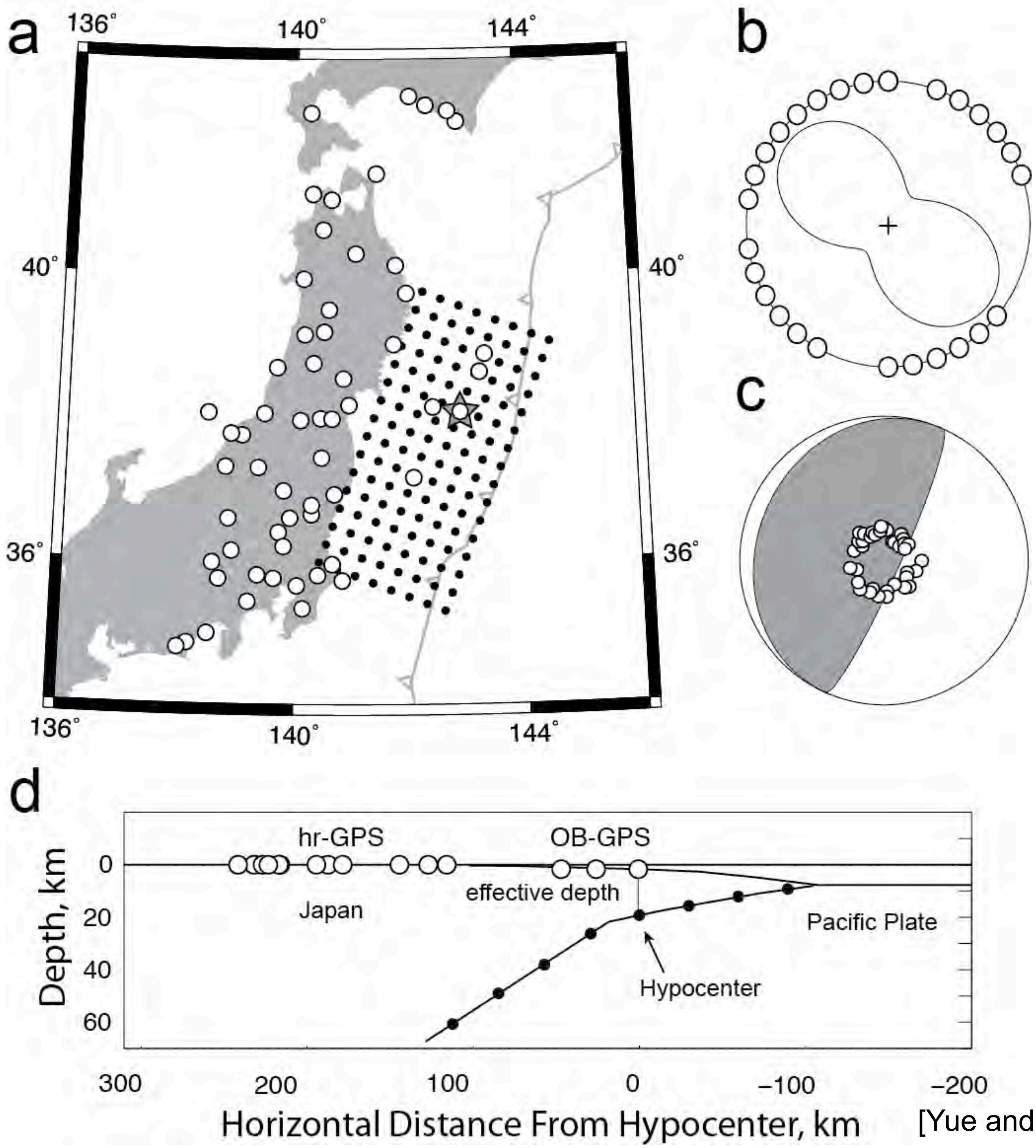




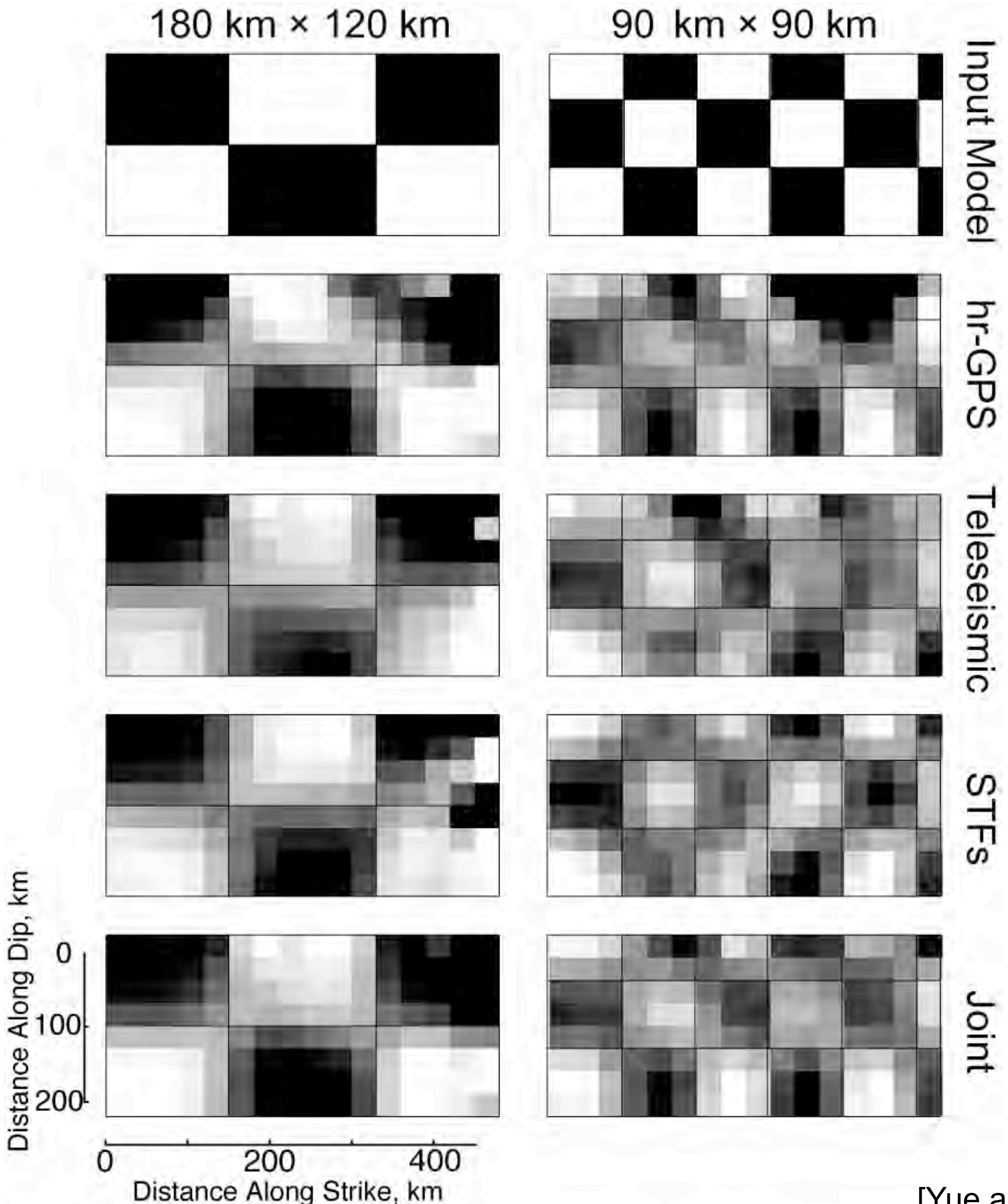


Many studies now confirm that slip in the uppermost 80 km of the megathrust is as much as 60-80 m.

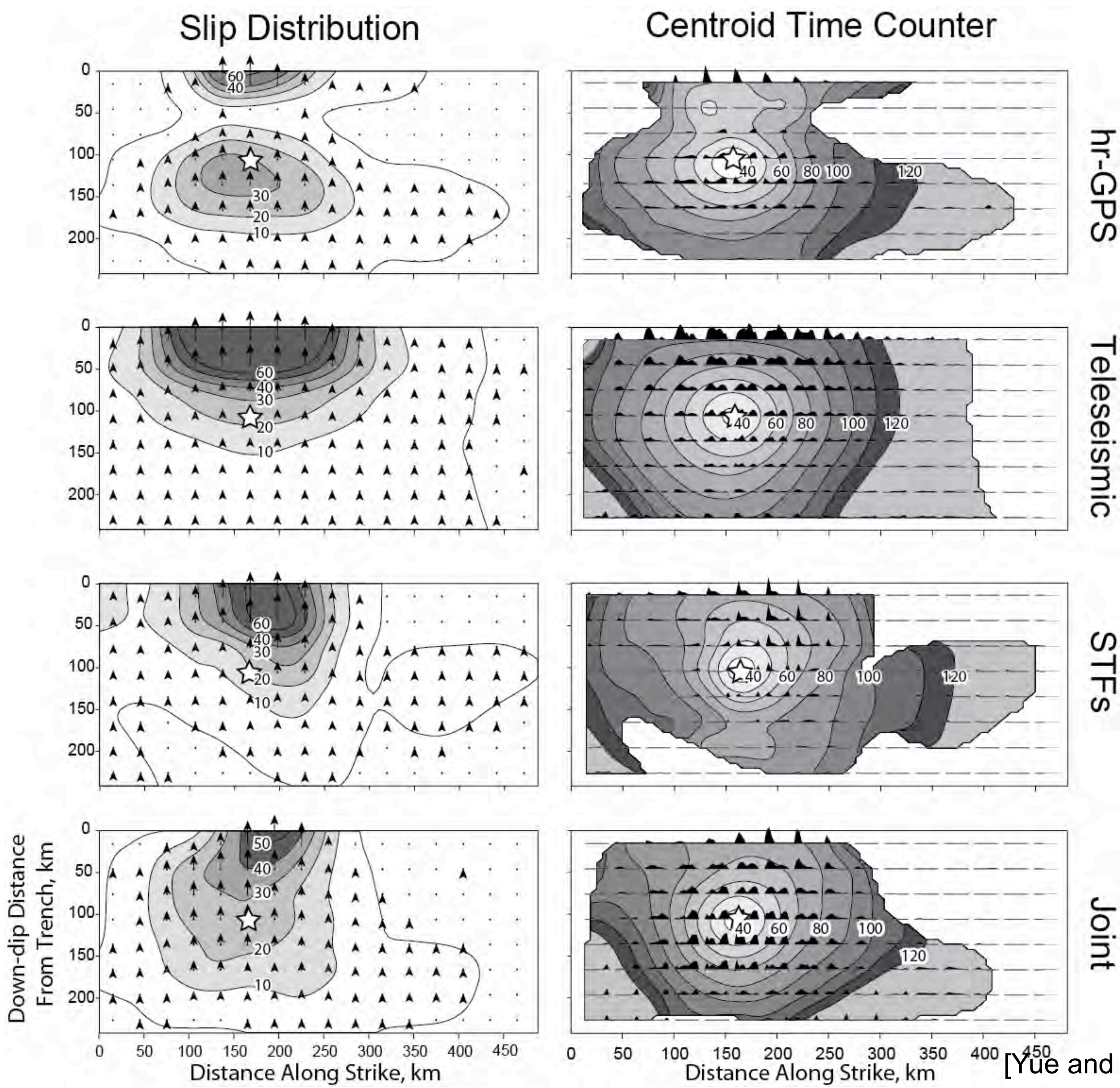
Shallow rupture resembles tsunami earthquake ruptures.



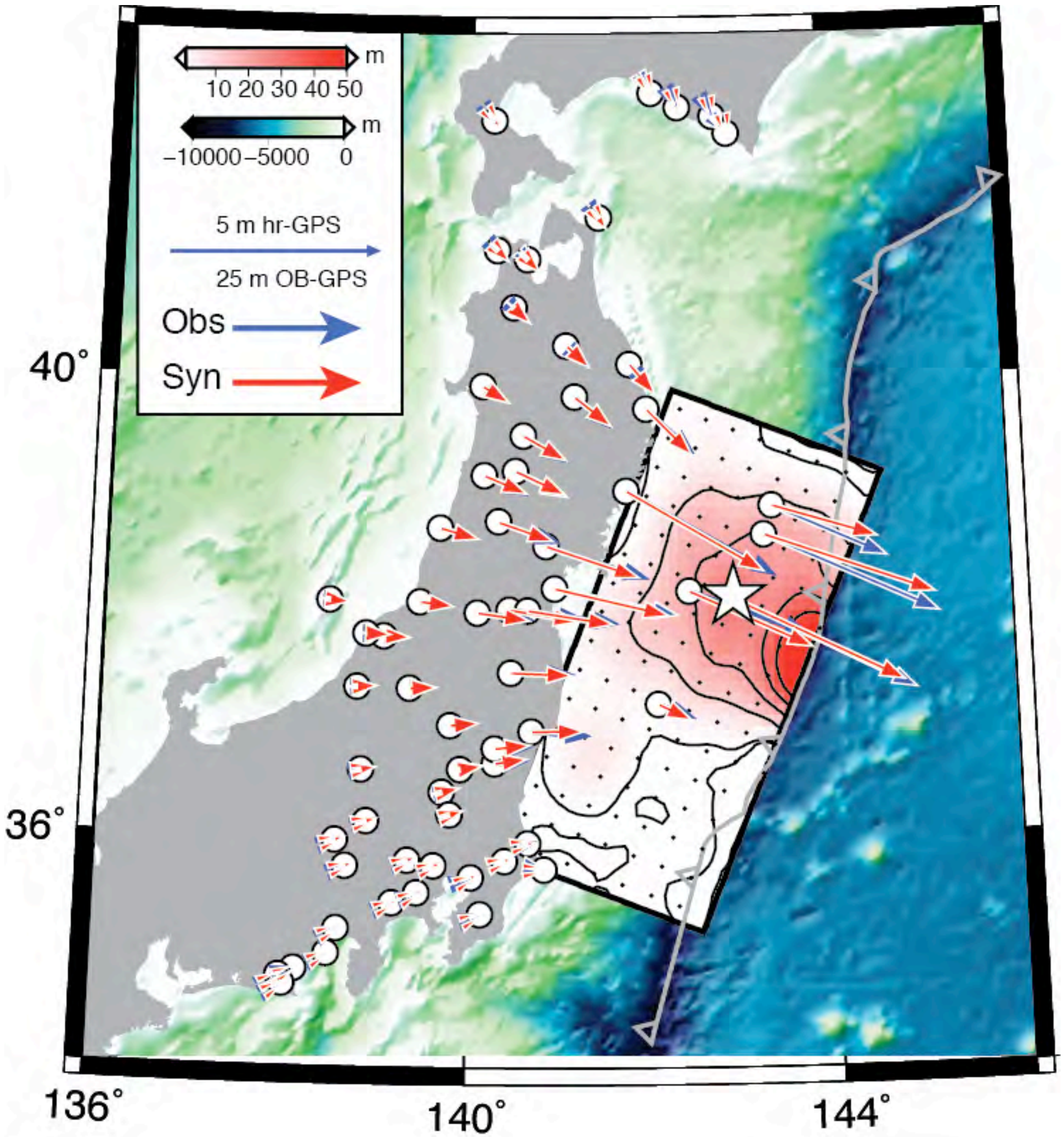
[Yue and Lay, 2013]



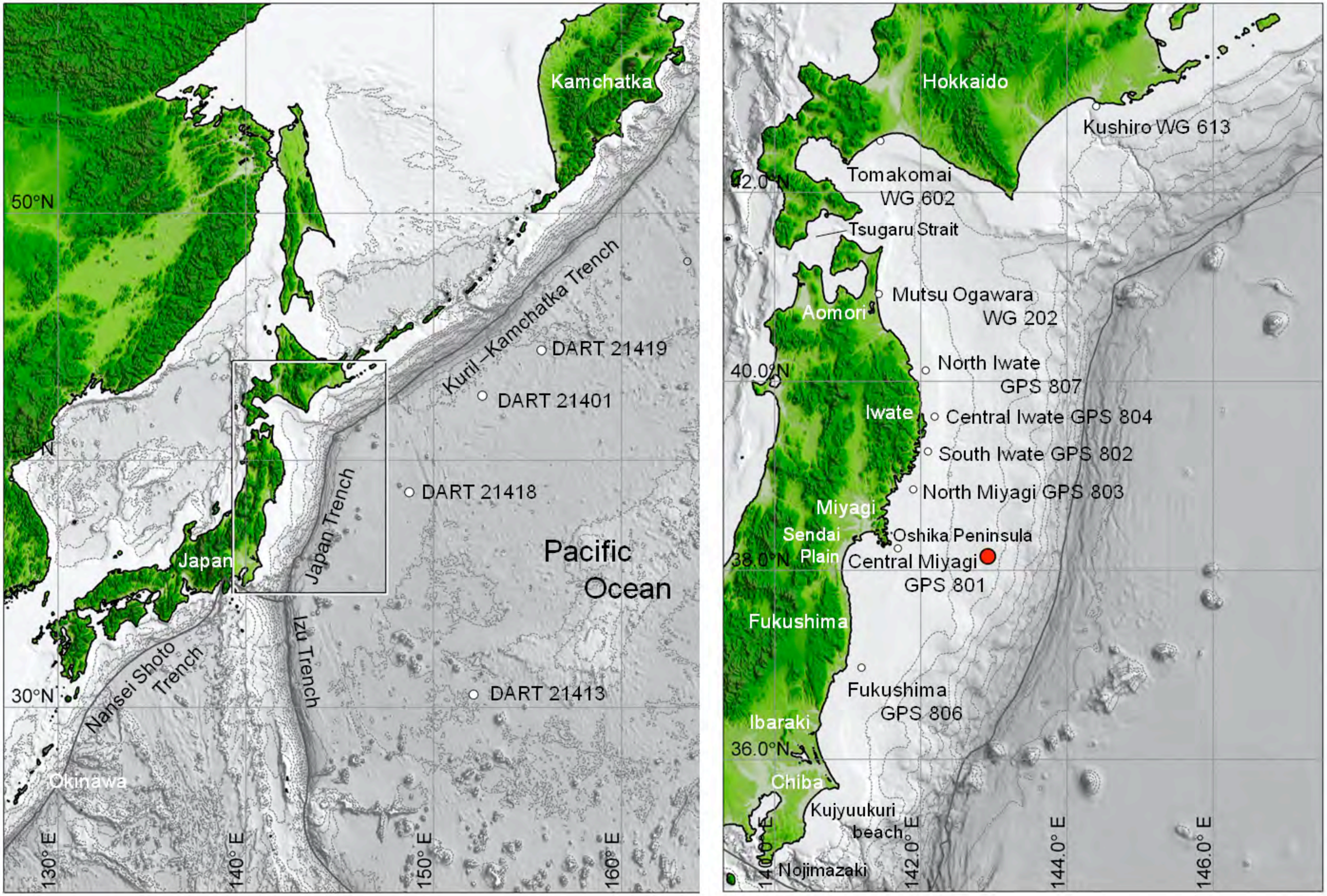
[Yue and Lay, 2013]



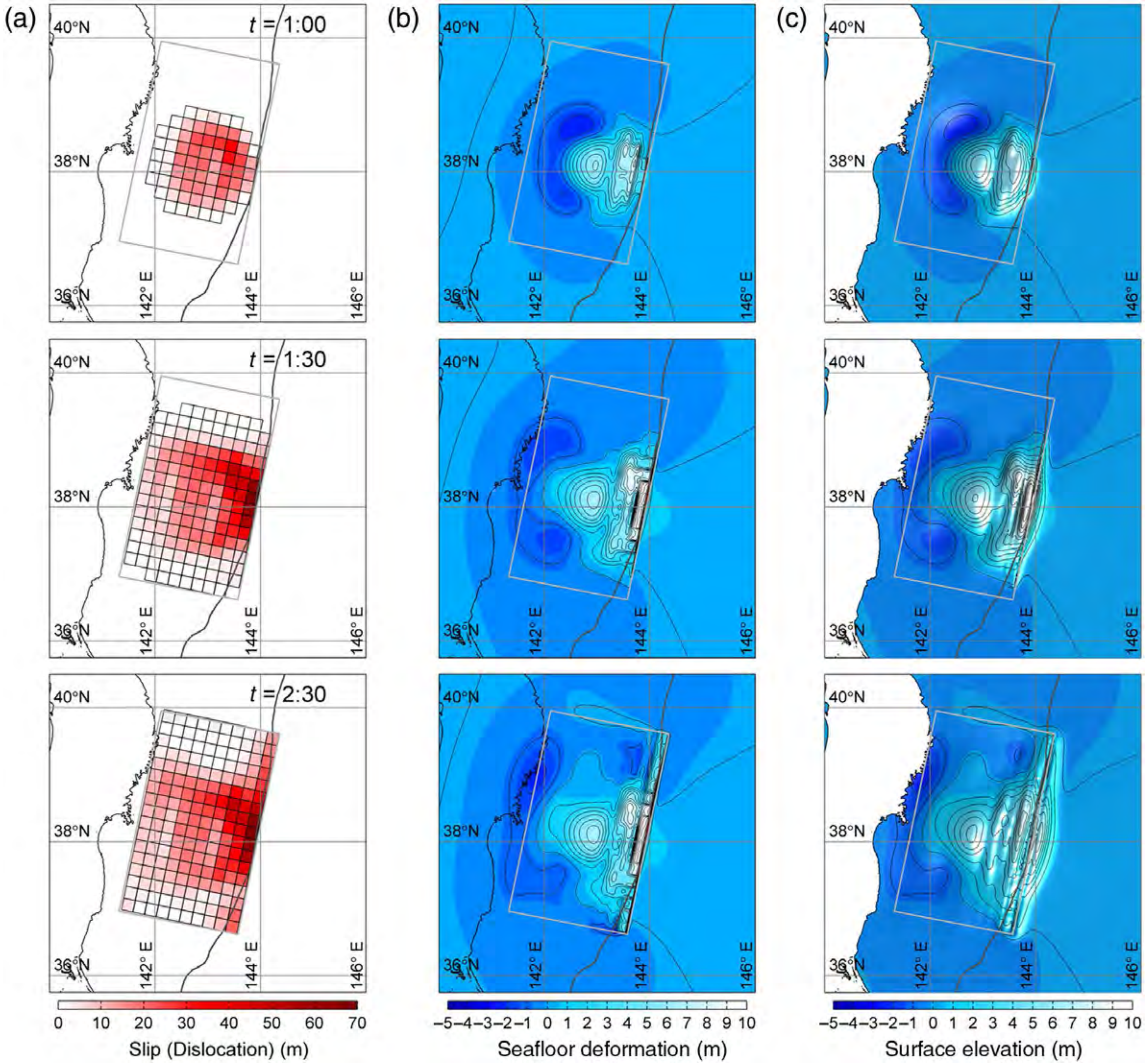
[Yue and Lay, 2013]



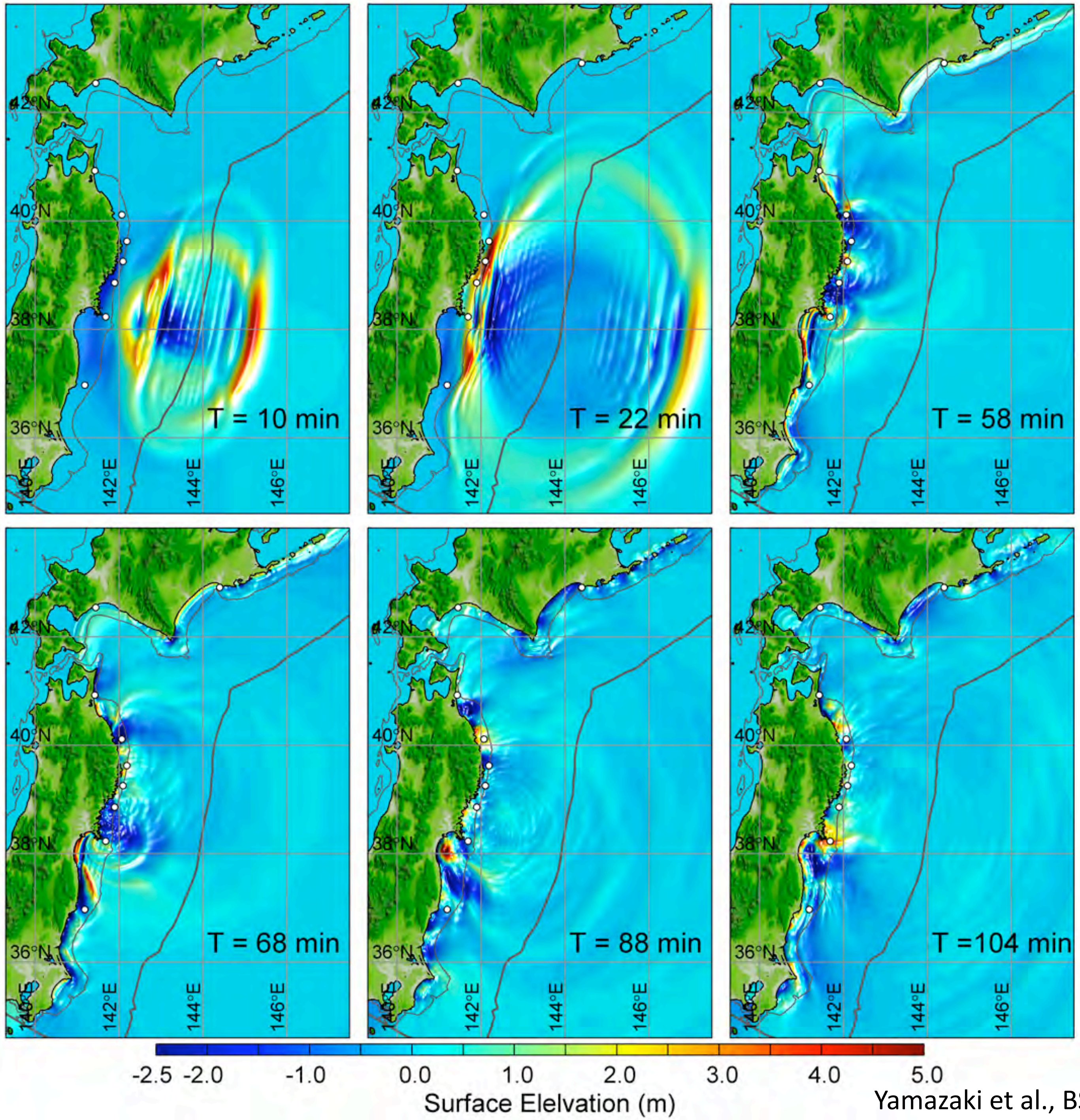
[Yue and Lay, 2013]



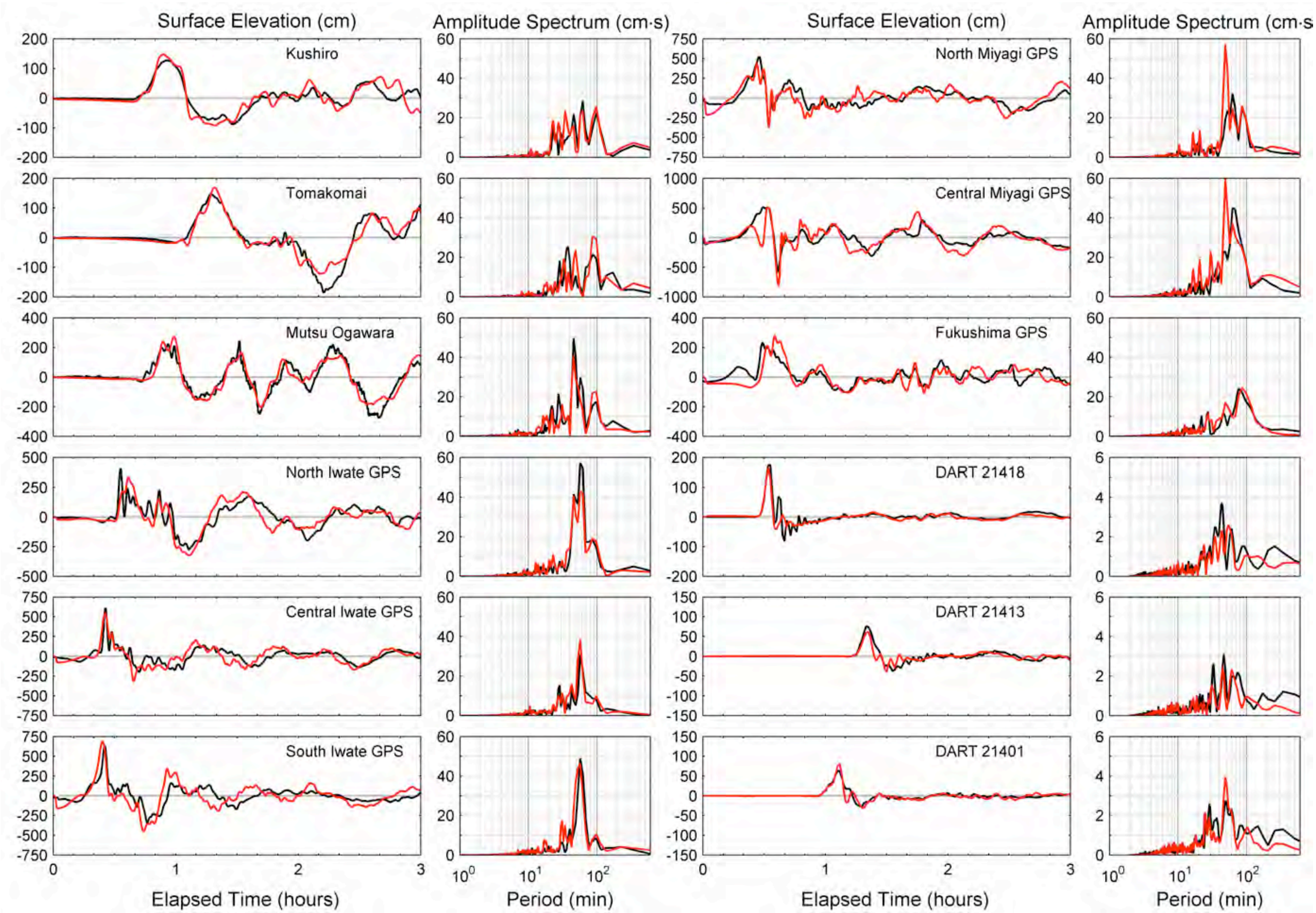
Yamazaki et al., BSSA, 2013



Yamazaki et al., BSSA, 2013

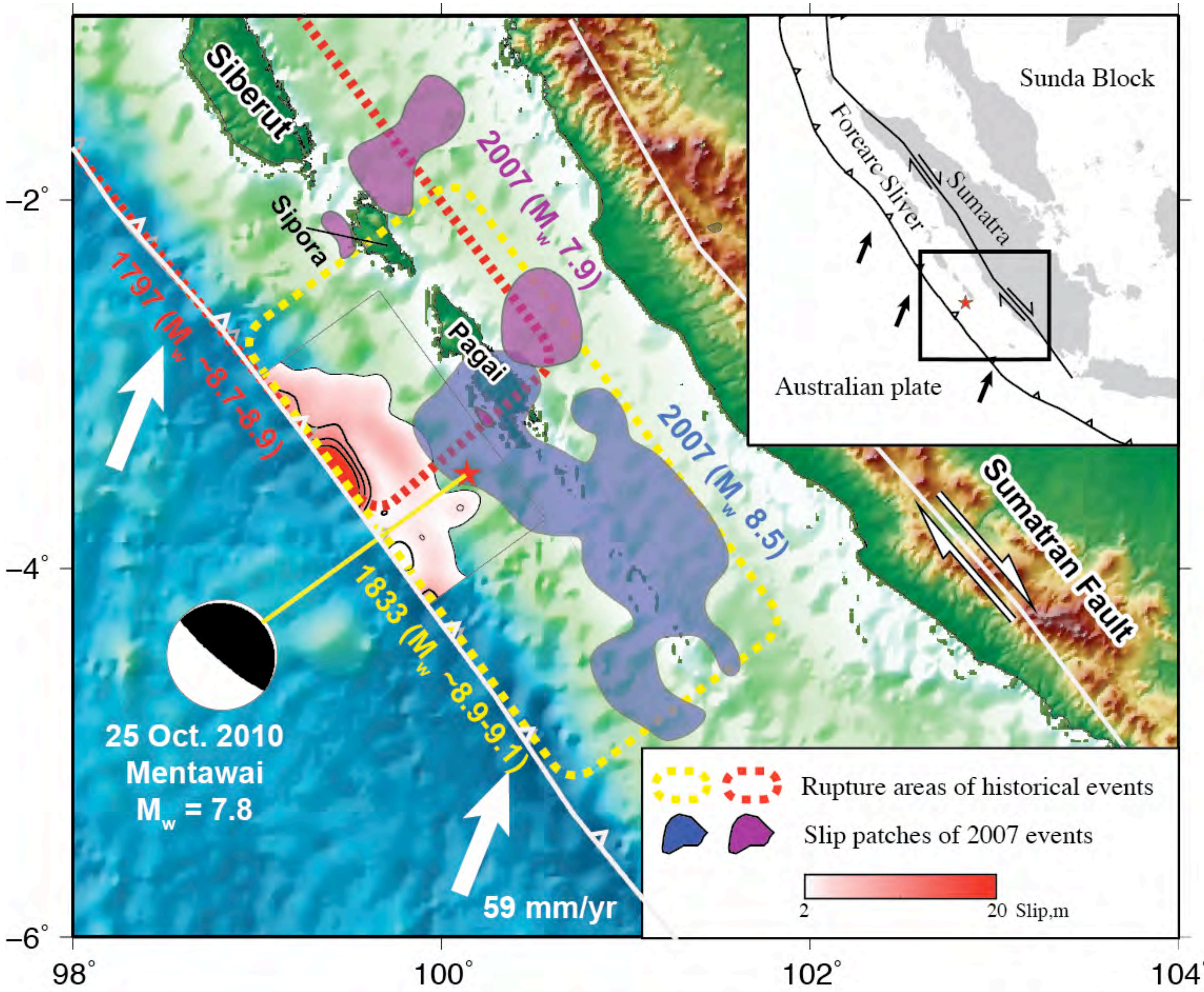


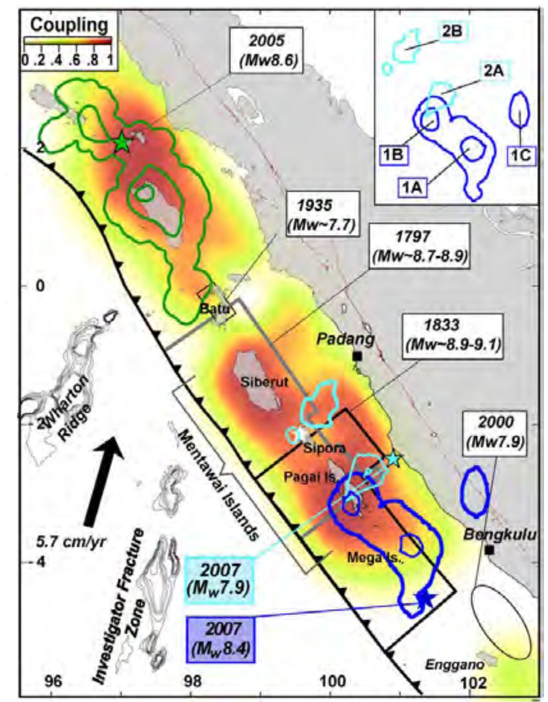
Yamazaki et al., BSSA, 2013



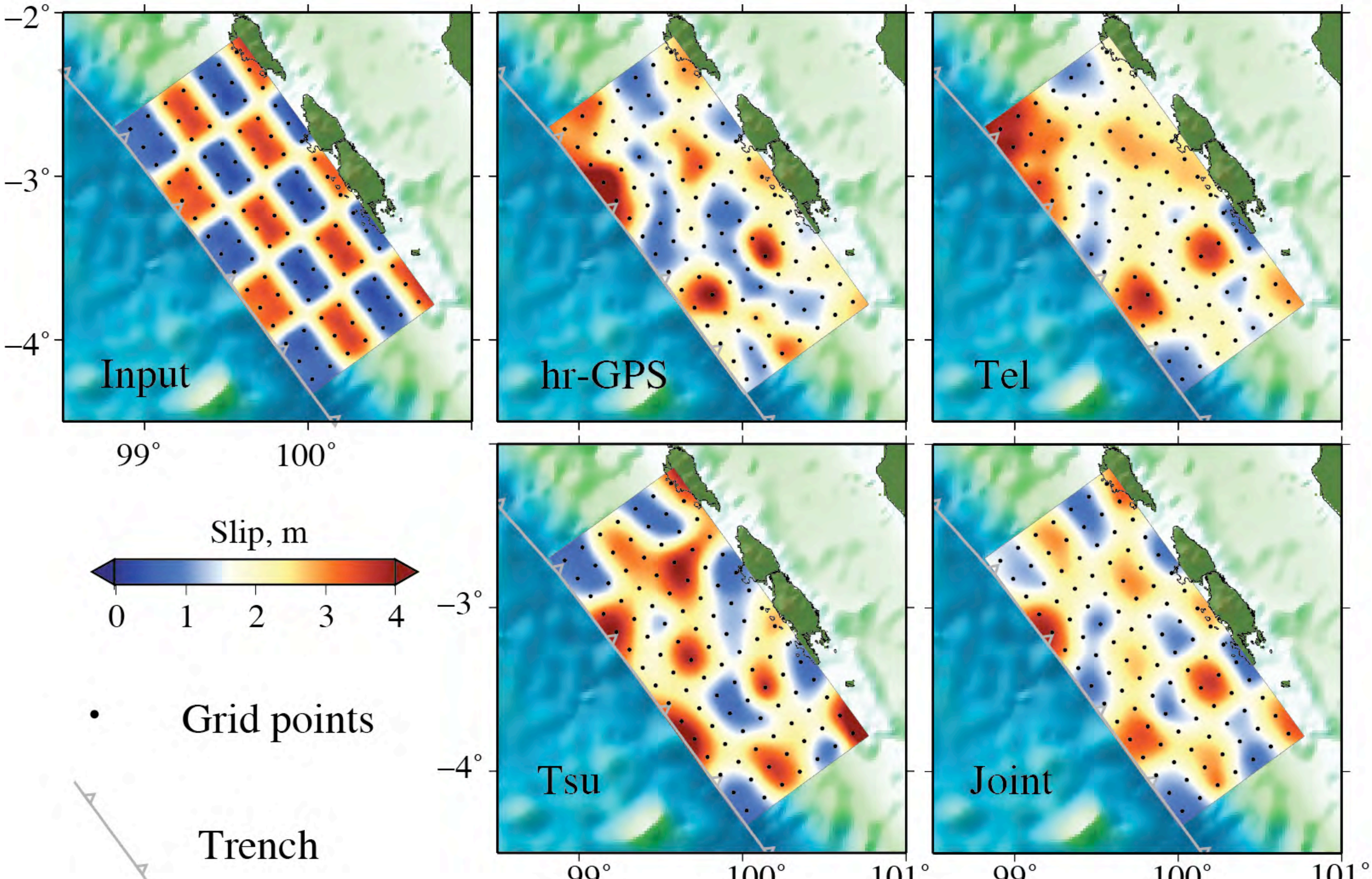
Yamazaki et al., BSSA, 2013

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

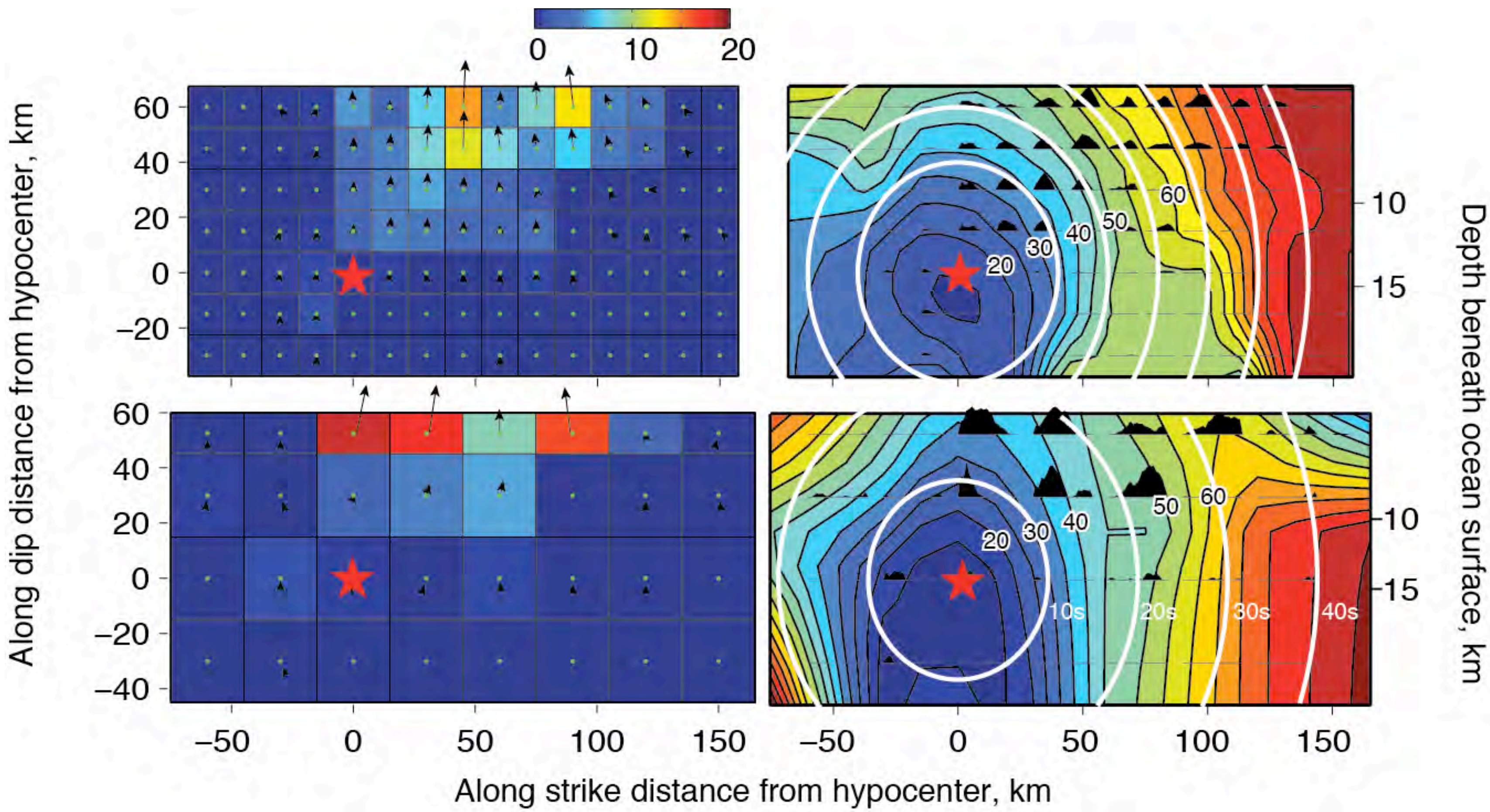




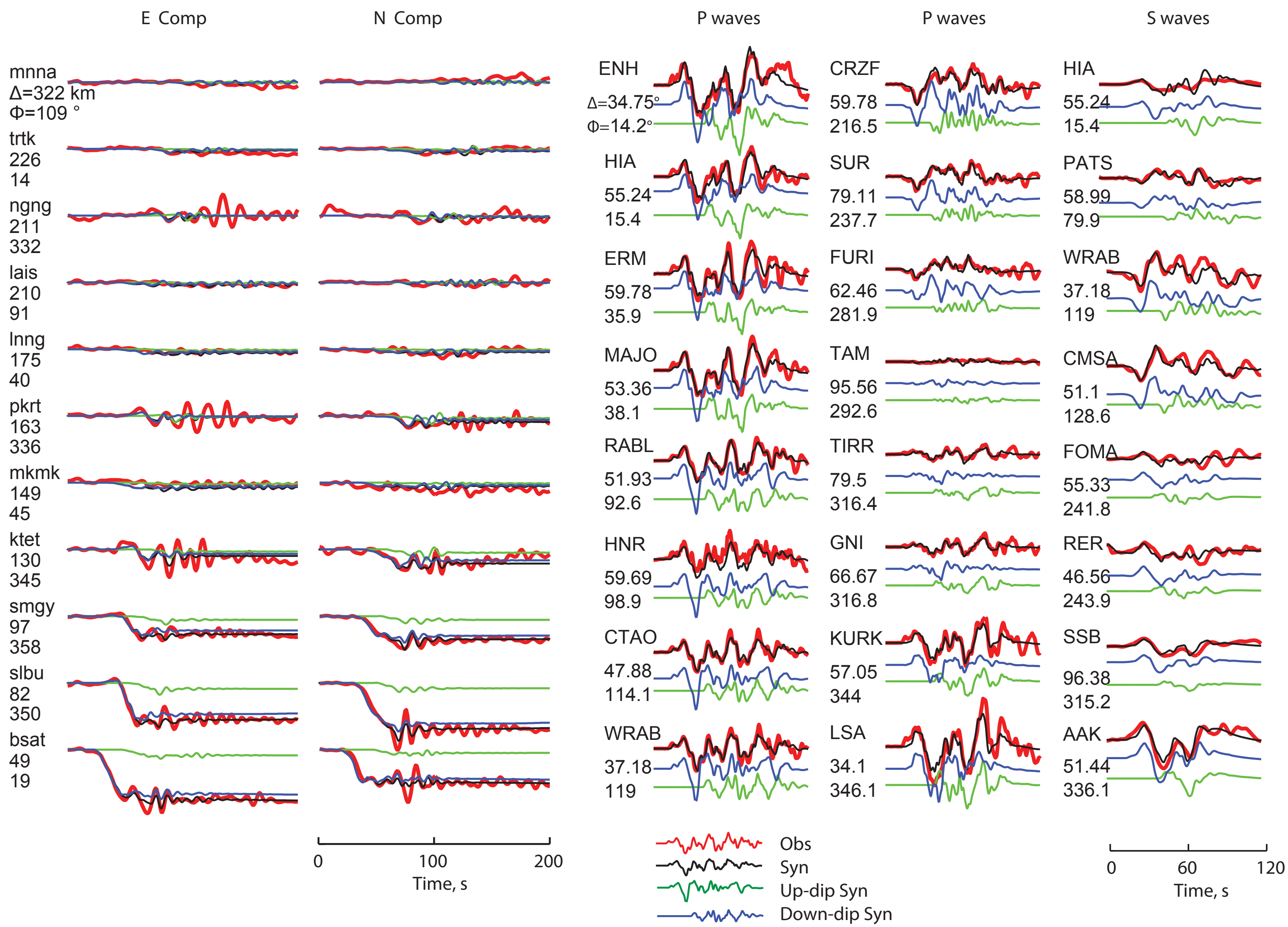
[Yue et al., 2014a]



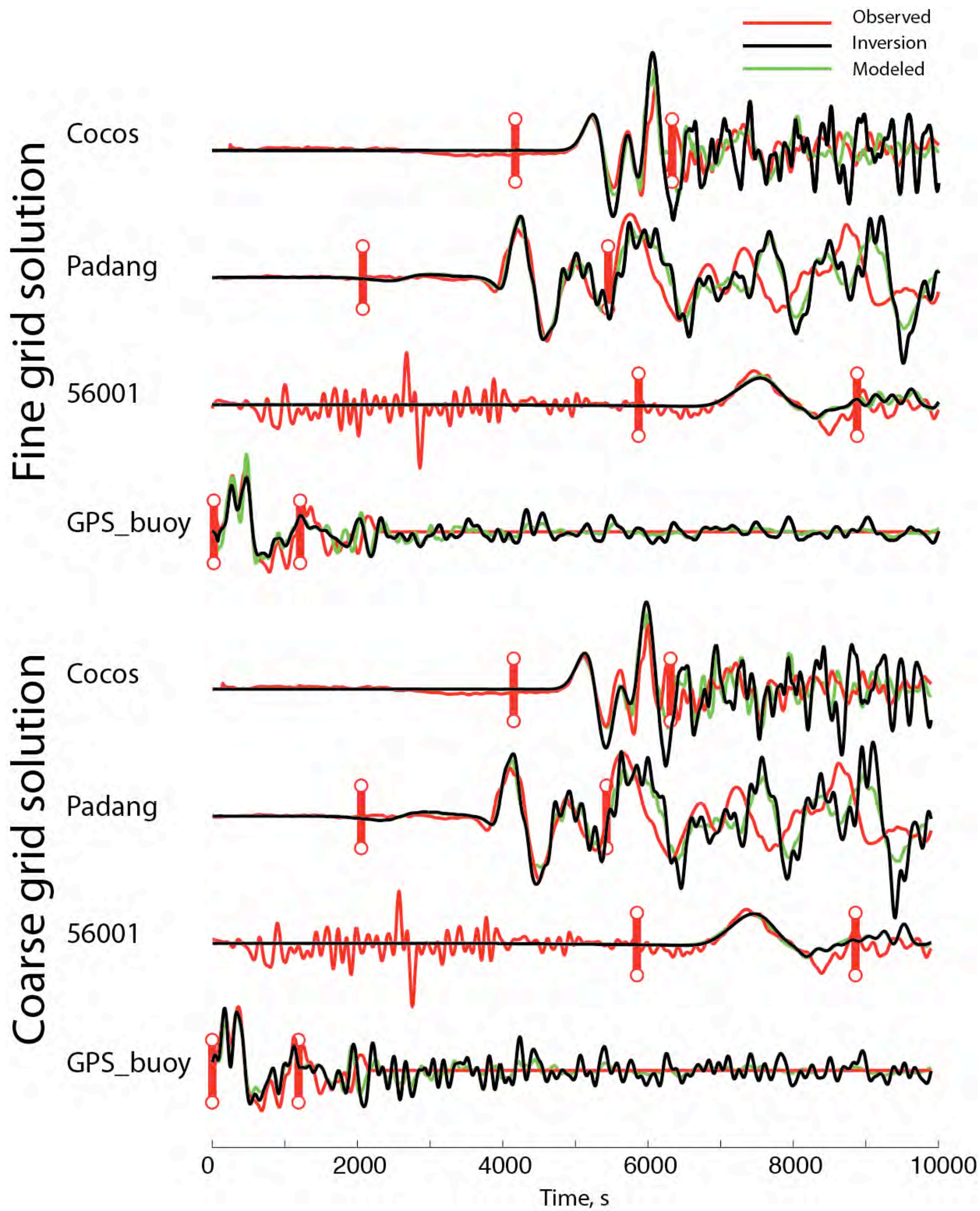
[Yue et al., 2014c]



[Yue et al., 2014c]



[Yue et al., 2014a]



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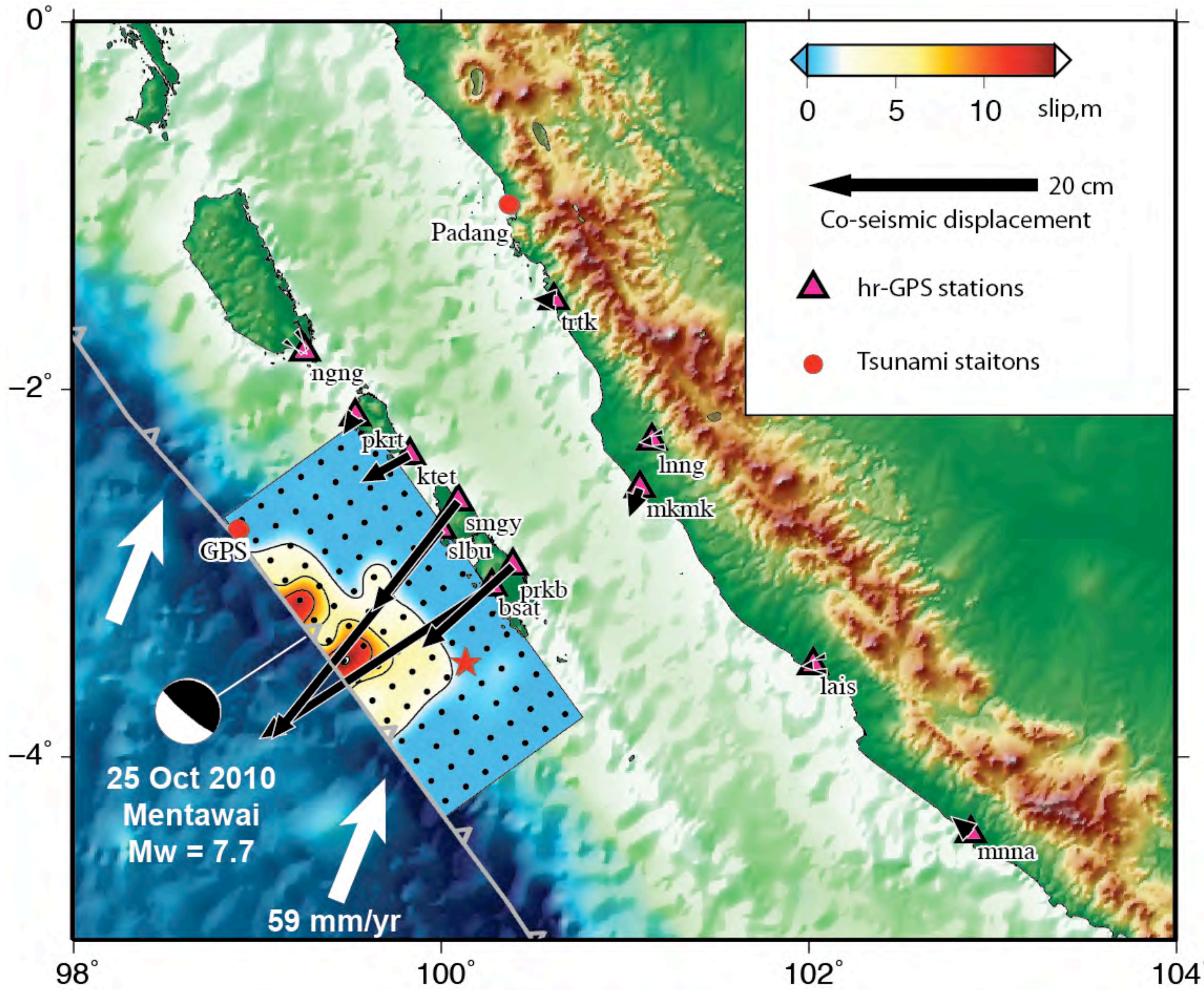
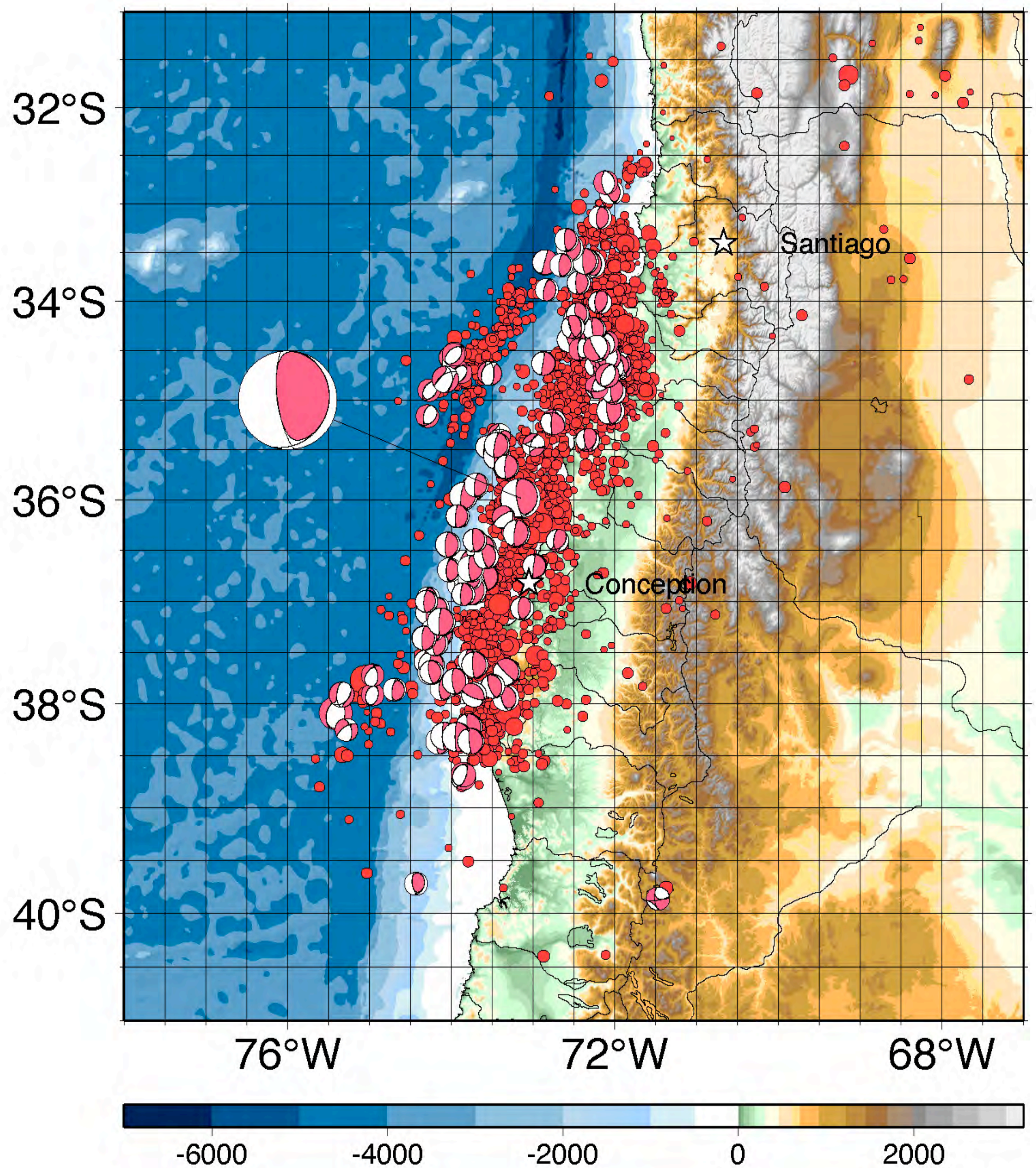


[Yue et al., 2014c]

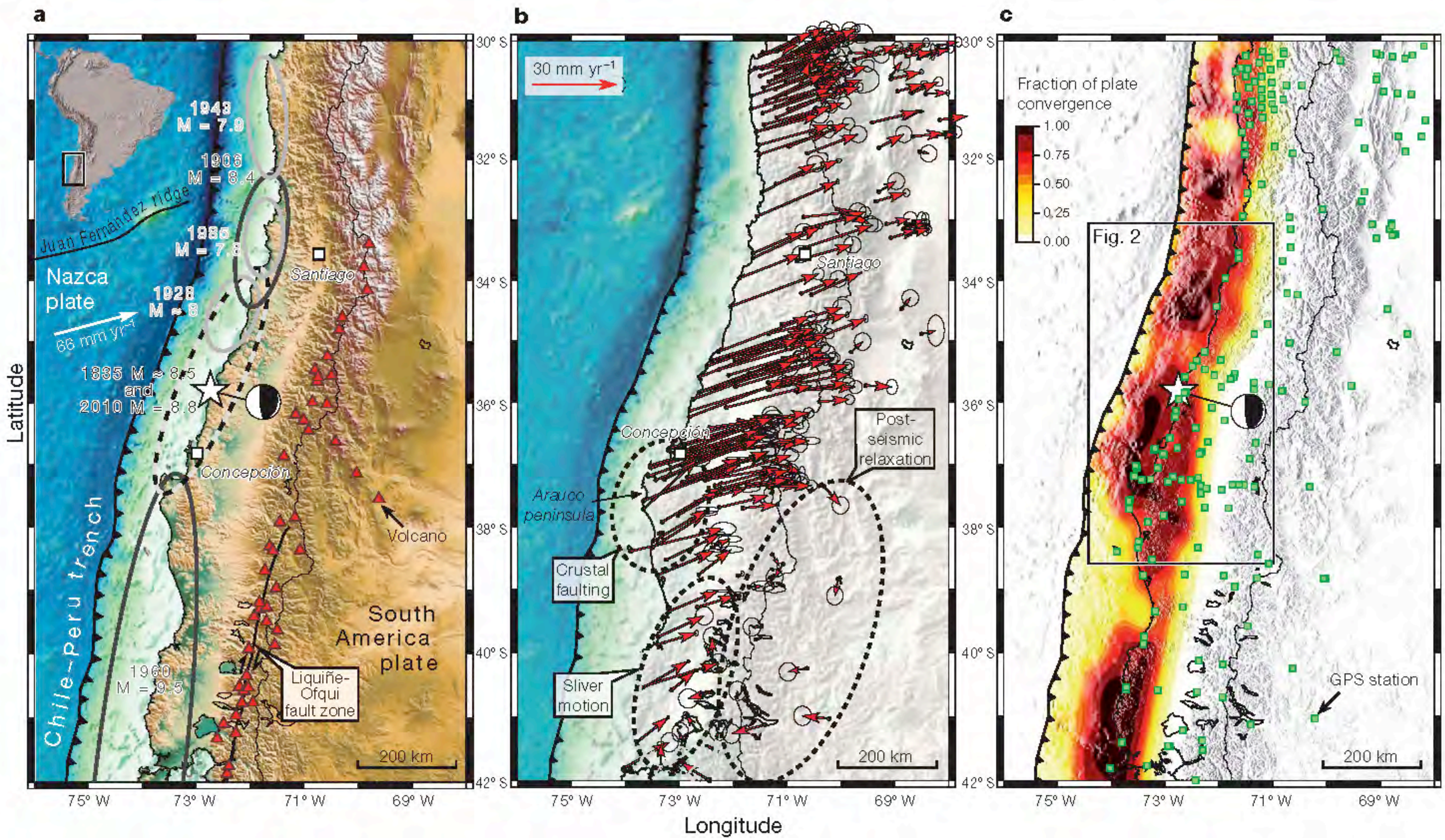
Feb. 27, 2010 Chile
M_w 8.8

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



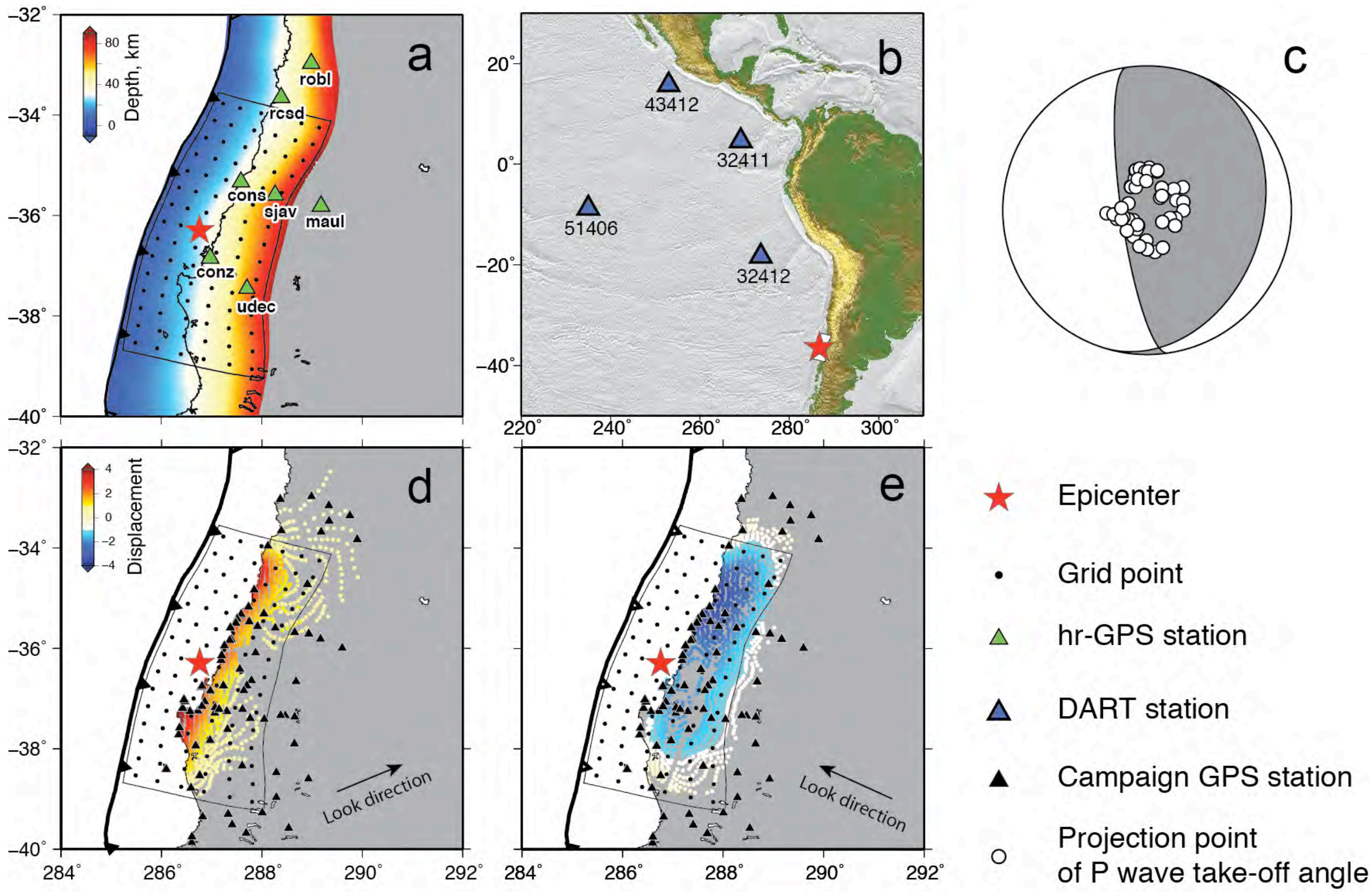
Updated From: Lay et al., GRL, 2010

Geodetic motions before Feb. 27, 2010 Chile



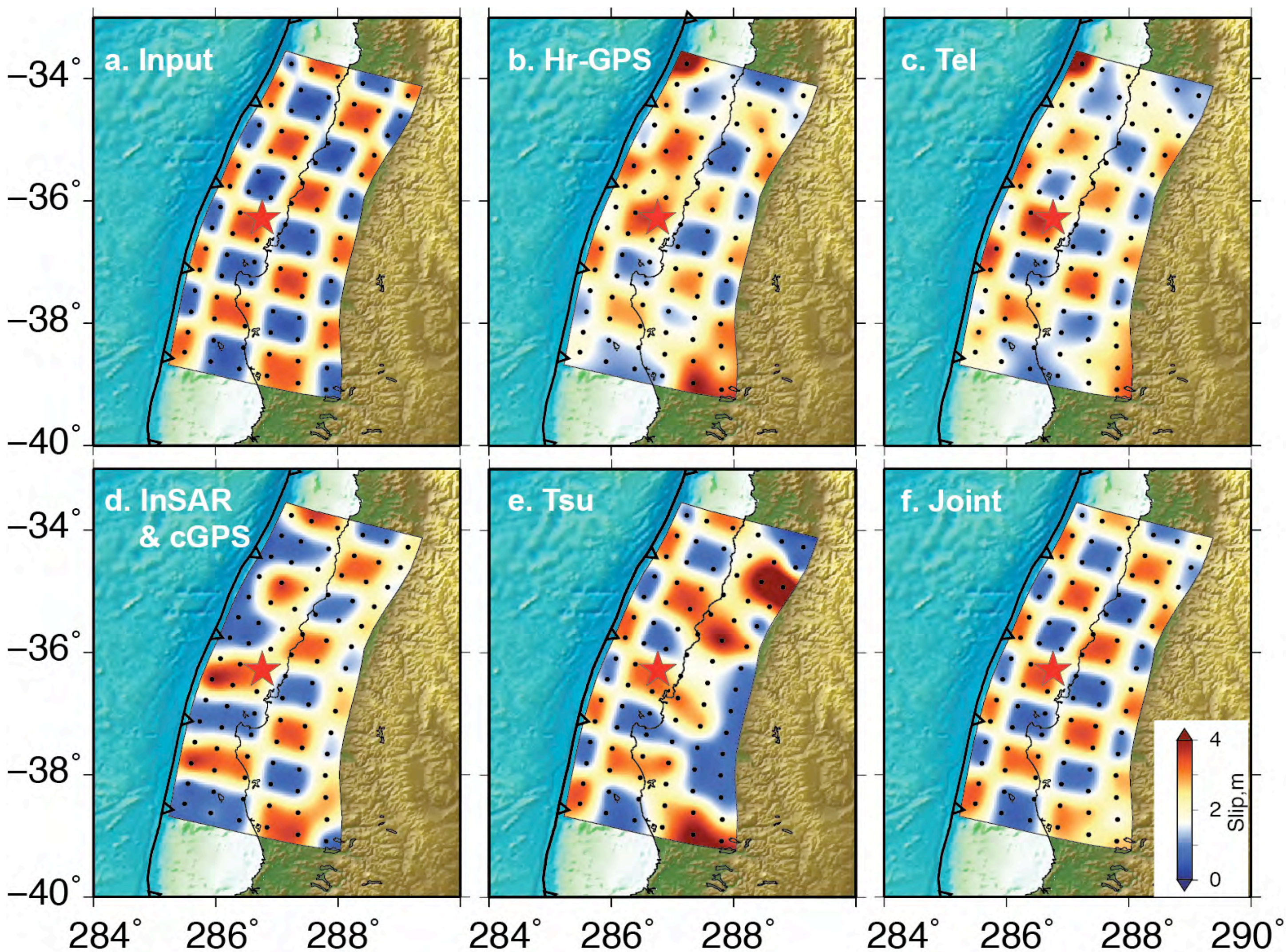
Moreno et al., Nature, 2010

Observations of 2010 M_w = 8.8 Maule earthquake



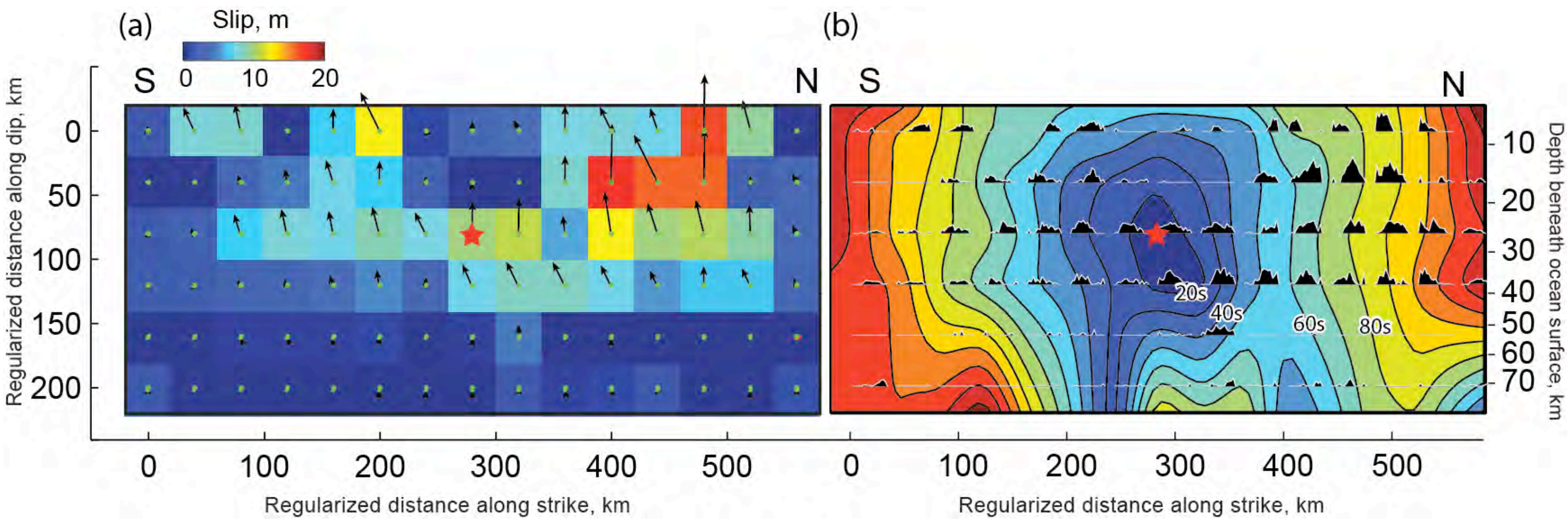
[Yue et al. 2014b]

Checker board test of each dataset and joint inversion

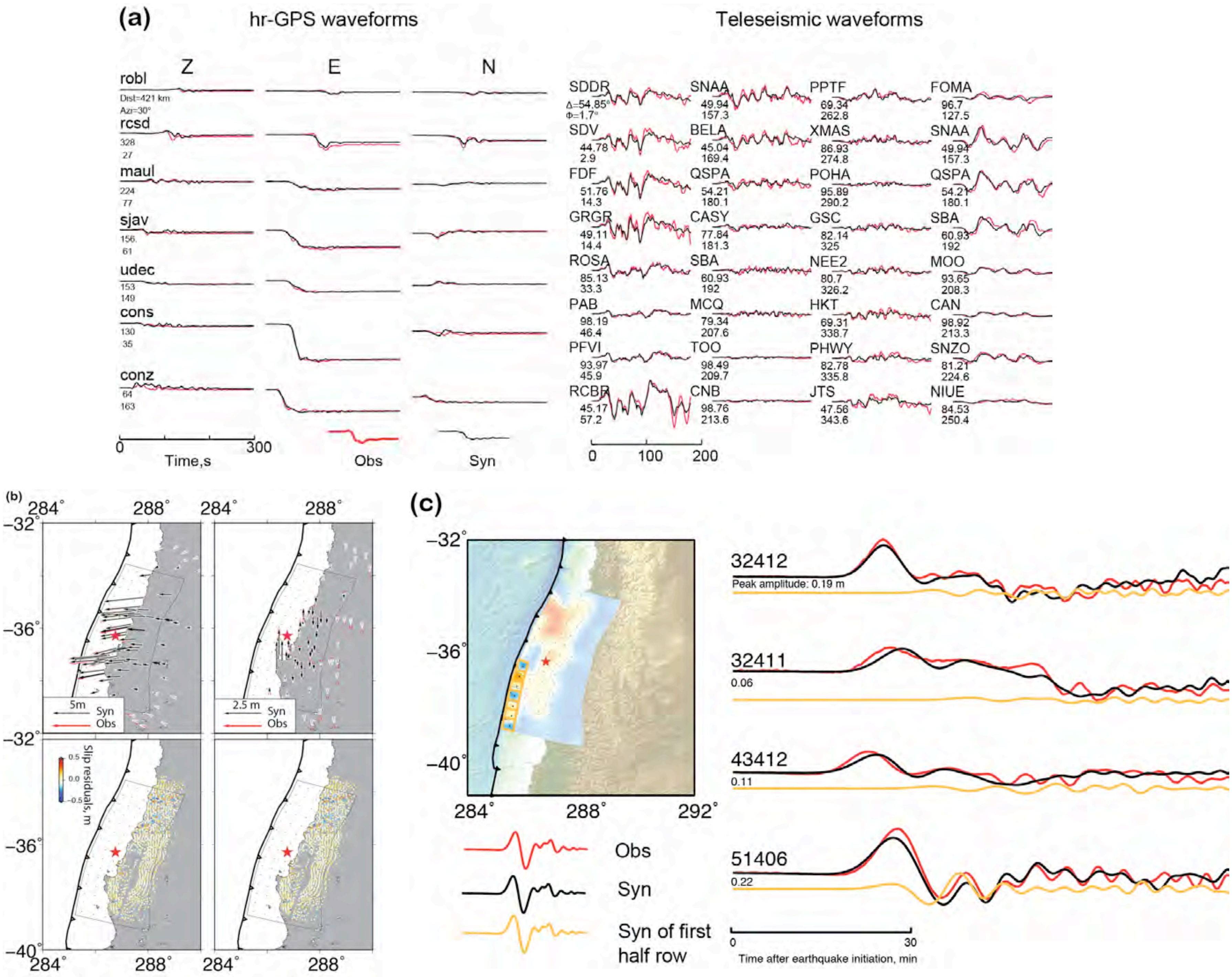


[Yue et al. 2014b]

Preferred rupture model of 2010 Maule earthquake

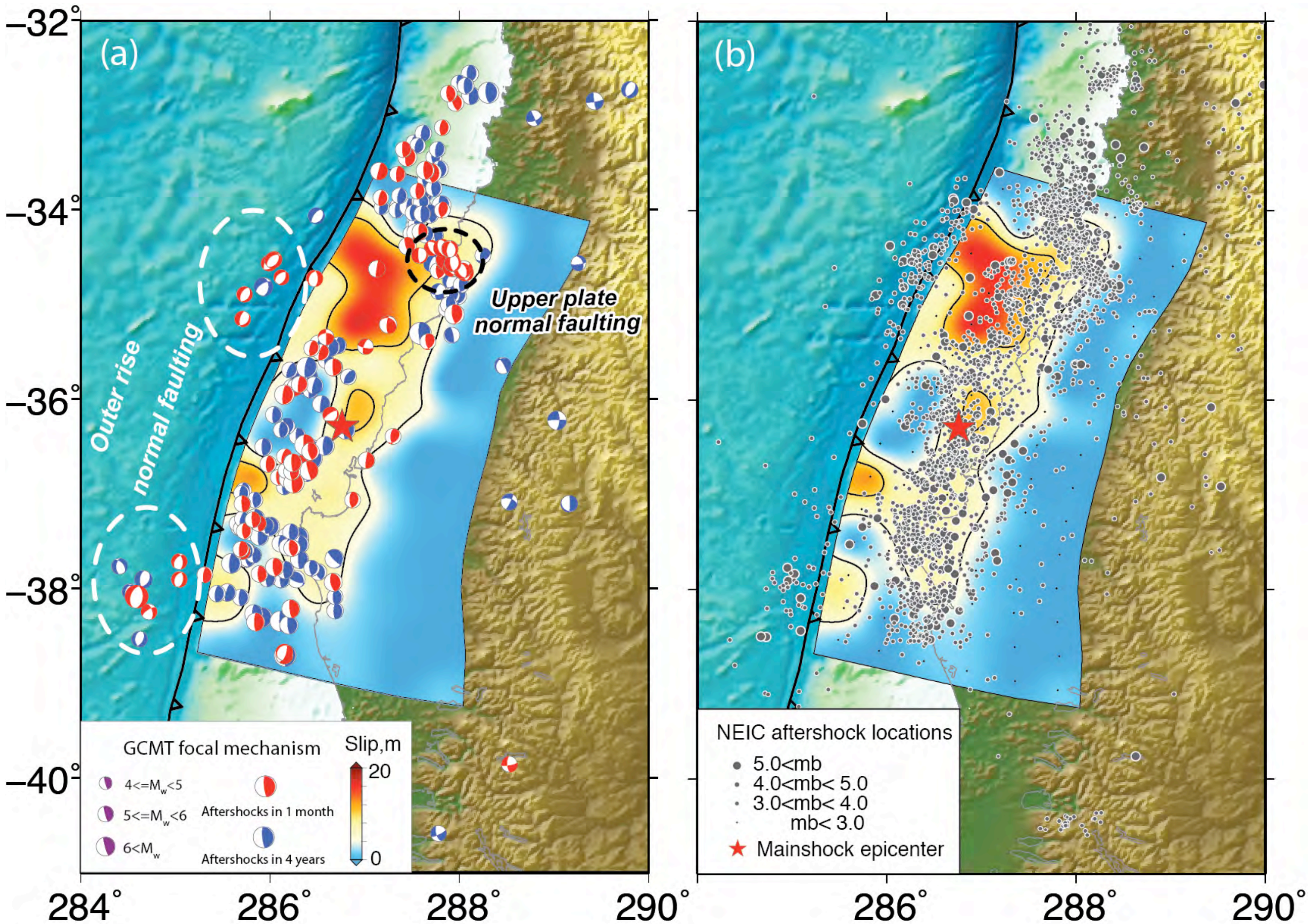


[Yue et al. 2014b]



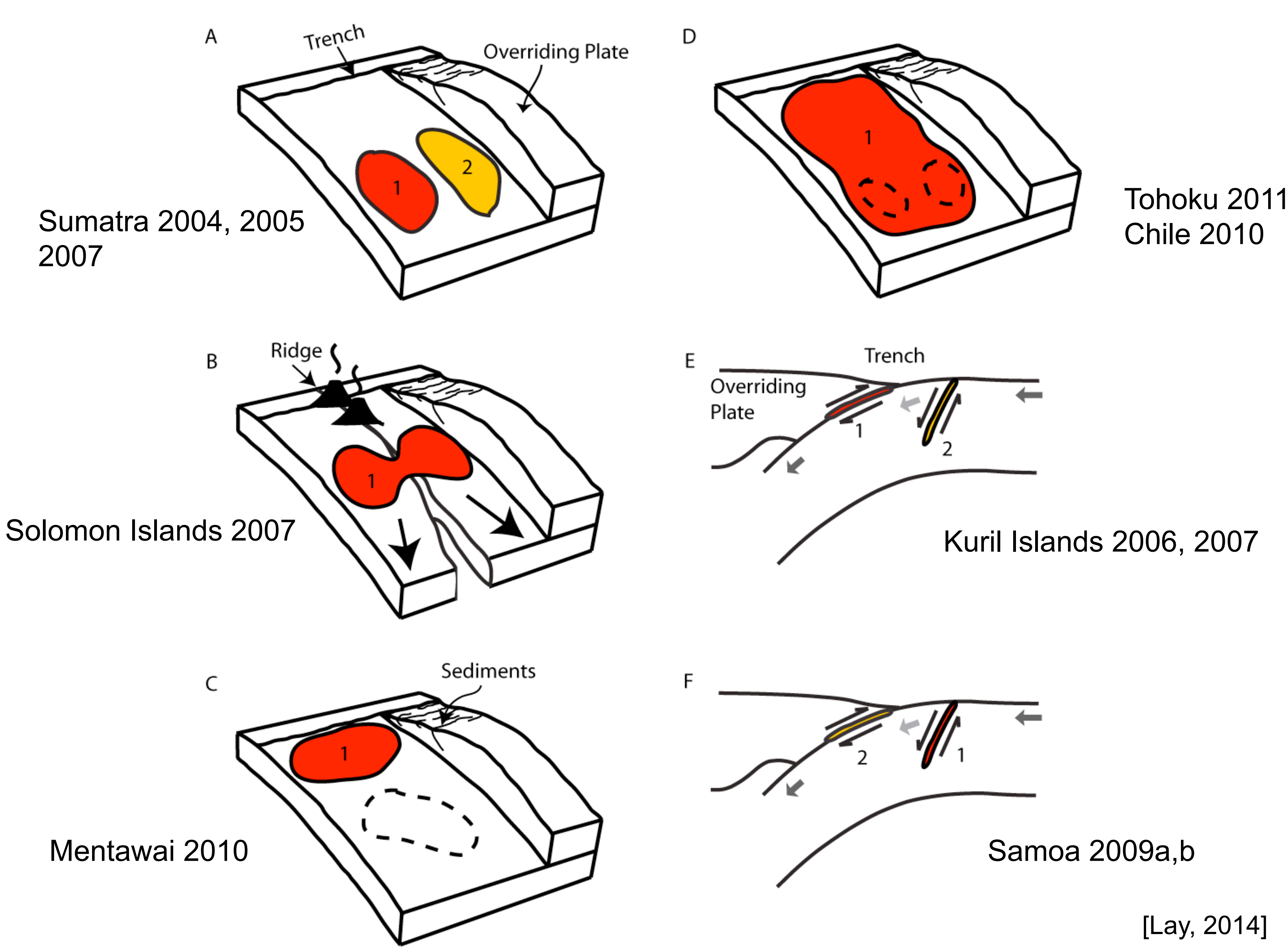
(a)
hr-GPS waveforms
Teleseismic waveforms
Z
E
N
robl
Dist=421 km
Azi=30°
rcsd
328
27
maul
224
77
sjav
156
61
udec
153
149
cons
130
35
conz
64
163
0
300
Time,s
Obs
Syn
SDDR
Δ=54.85°
Φ=1.7°
SNAA
49.94
157.3
PPTF
69.34
262.8
FOMA
96.7
127.5
SDV
44.78
2.9
BELA
45.04
169.4
XMAS
86.93
274.8
SNAA
49.94
157.3
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°
284°
288°
−32°
−36°
5m
Syn
Obs
2.5 m
Syn
Obs
−32°
Slip residuals, m
0.5
0.0
−0.5
−36°
−40°
284°
288°
284°
288°
(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

Complementary pattern with the aftershock distribution



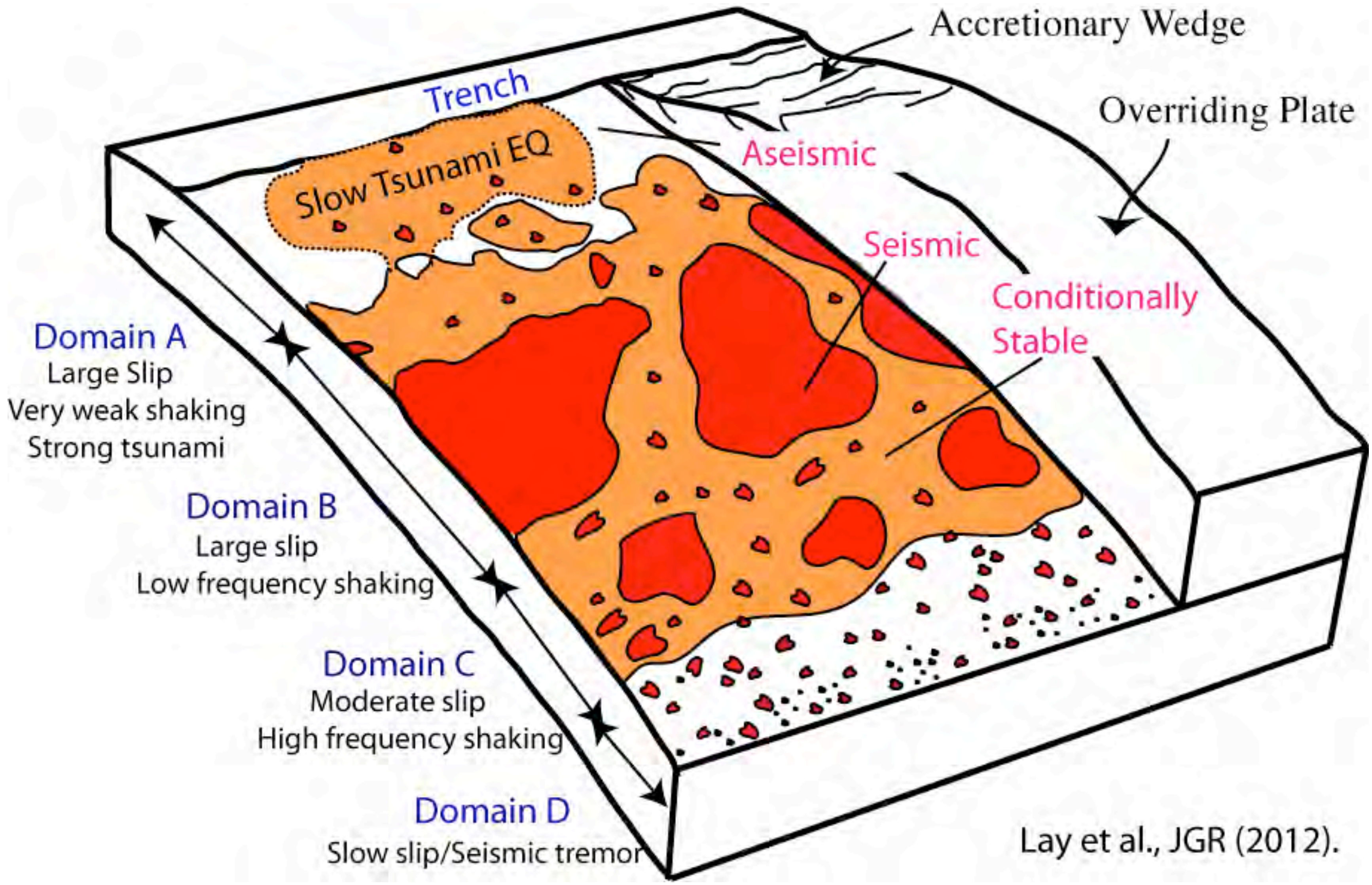
[Yue et al. 2014b]

Great Earthquake Scenarios



[Lay, 2014]

Variable frictional properties seem ubiquitous



Lay et al., JGR (2012).

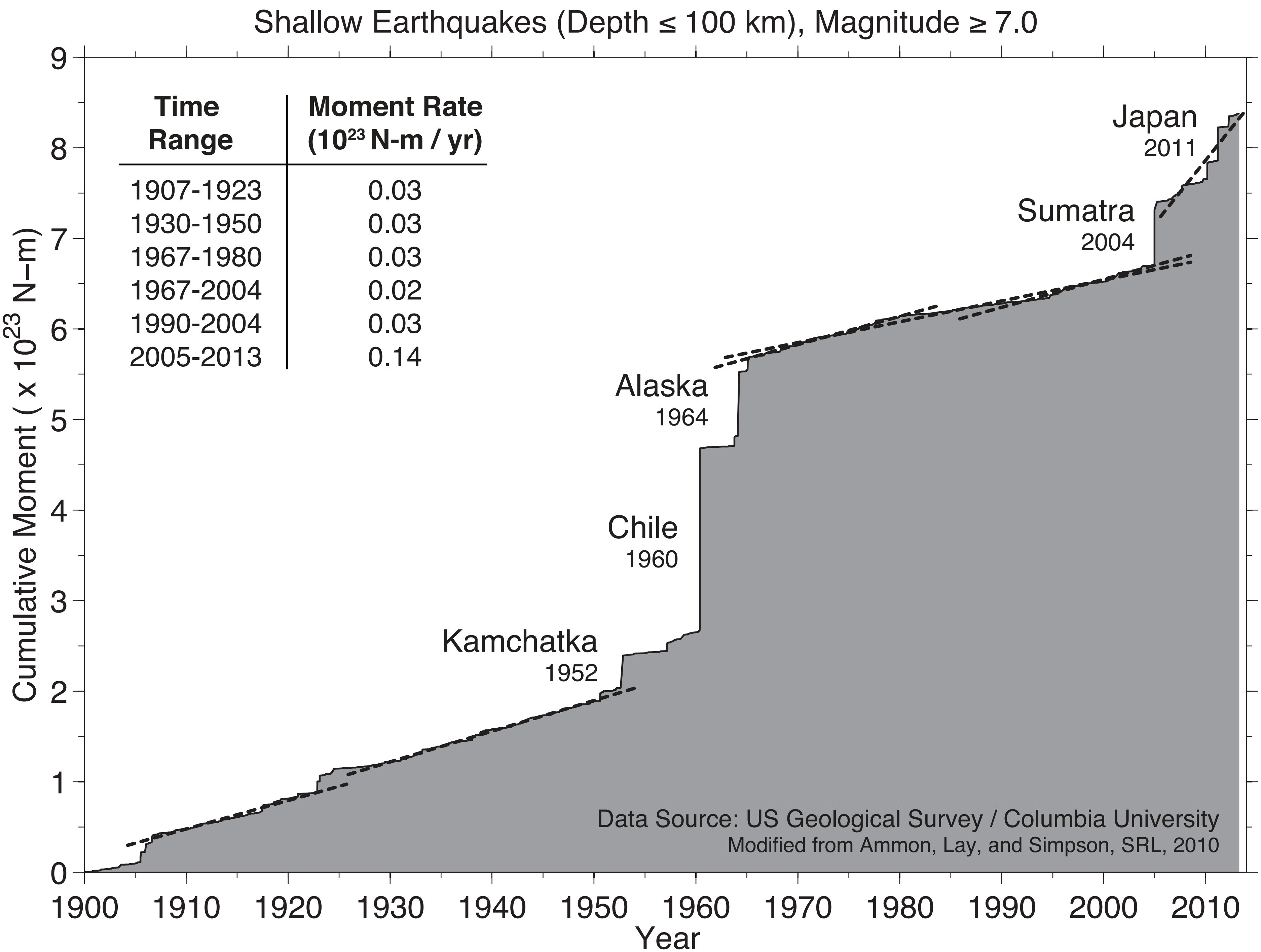
Conclusions

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

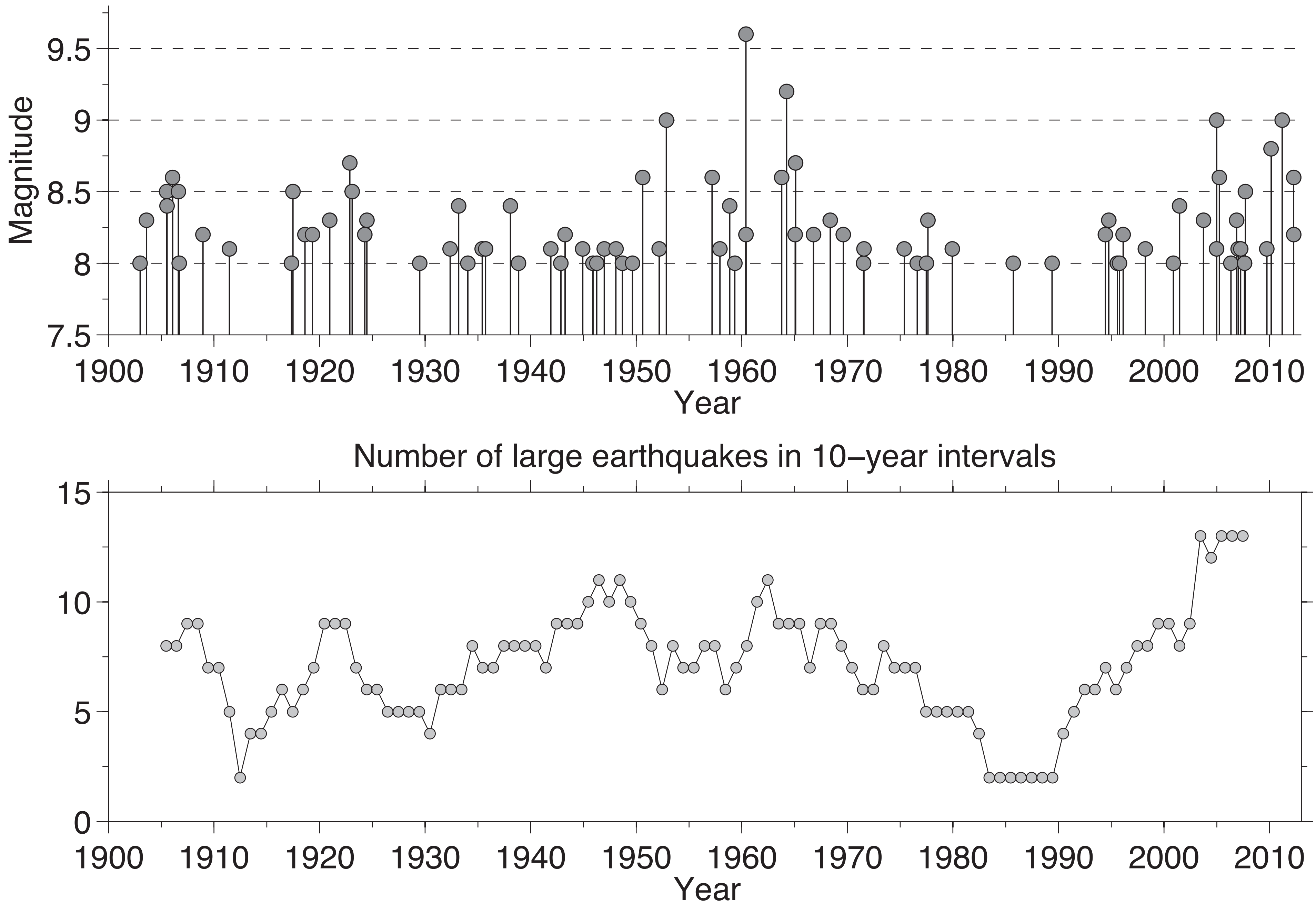
This results from systematic deployment of global seismic, geodetic, and tsunami instrumentation that is largely openly available, in parallel with extensive development of finite-faulting inversion capabilities for all wavefields.

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

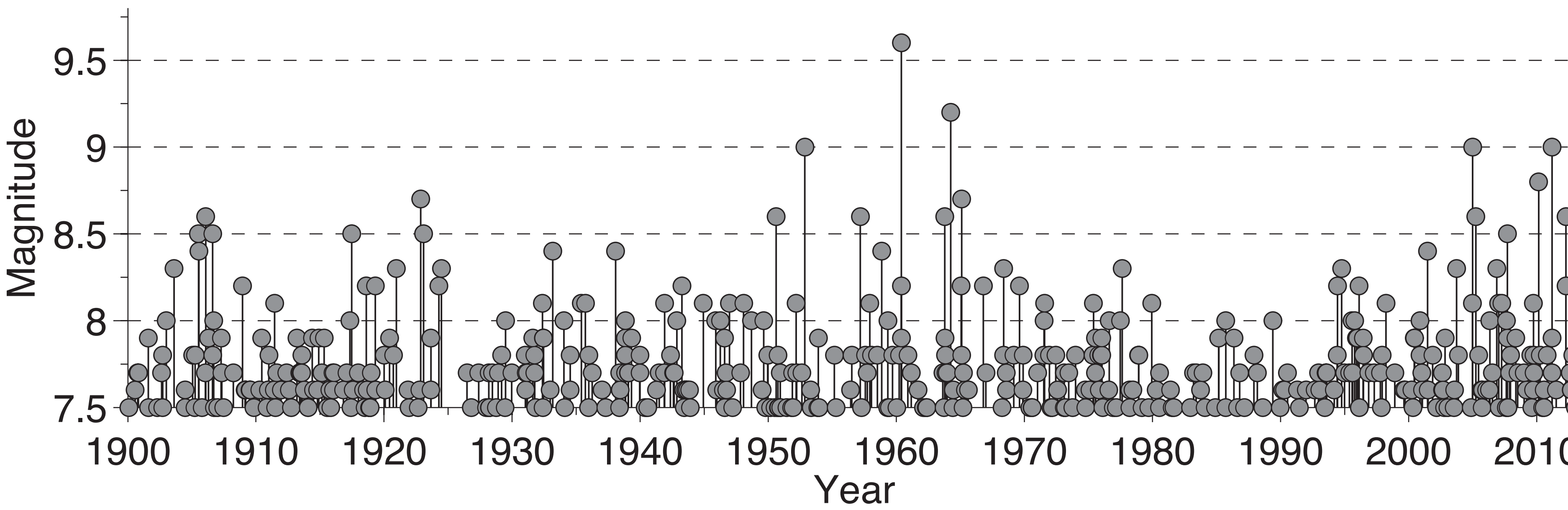
We need to prepare for future great earthquakes



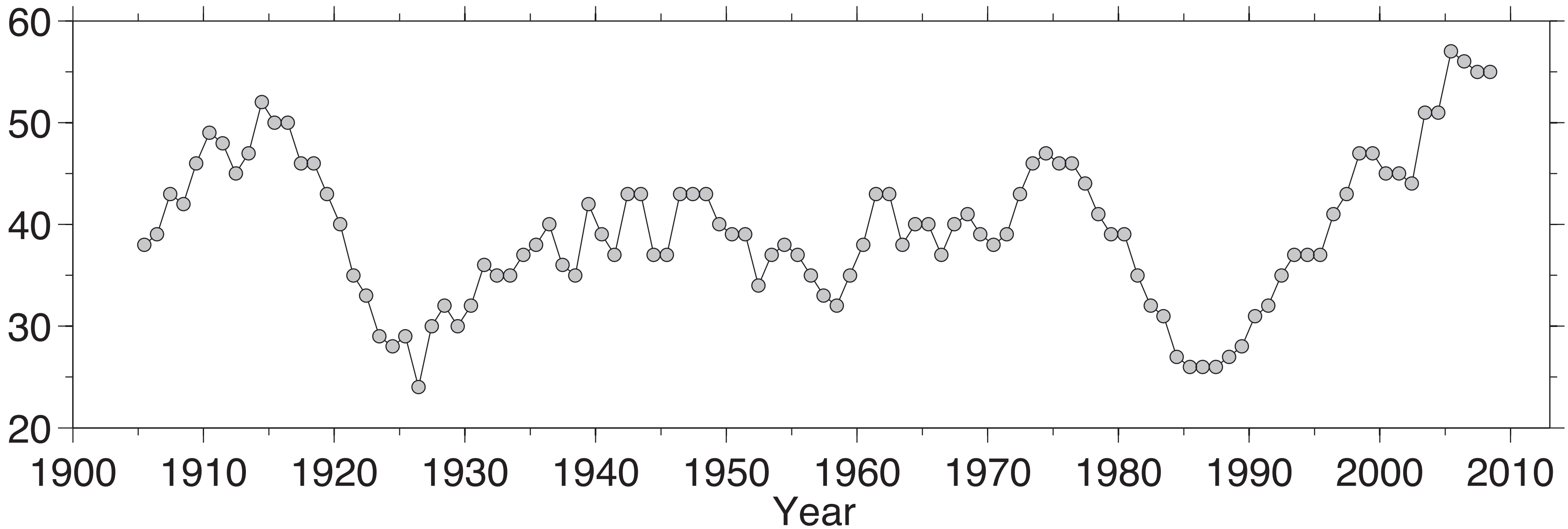
Shallow Earthquakes (Depth ≤ 100 km), Magnitude ≥ 7.0
Time Range
Moment Rate (10^{23} N-m / yr)
1907-1923 0.03
1930-1950 0.03
1967-1980 0.03
1967-2004 0.02
1990-2004 0.03
2005-2013 0.14
Japan 2011
Sumatra 2004
Alaska 1964
Chile 1960
Kamchatka 1952
Cumulative Moment (x 10^{23} N–m)
Year
Data Source: US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

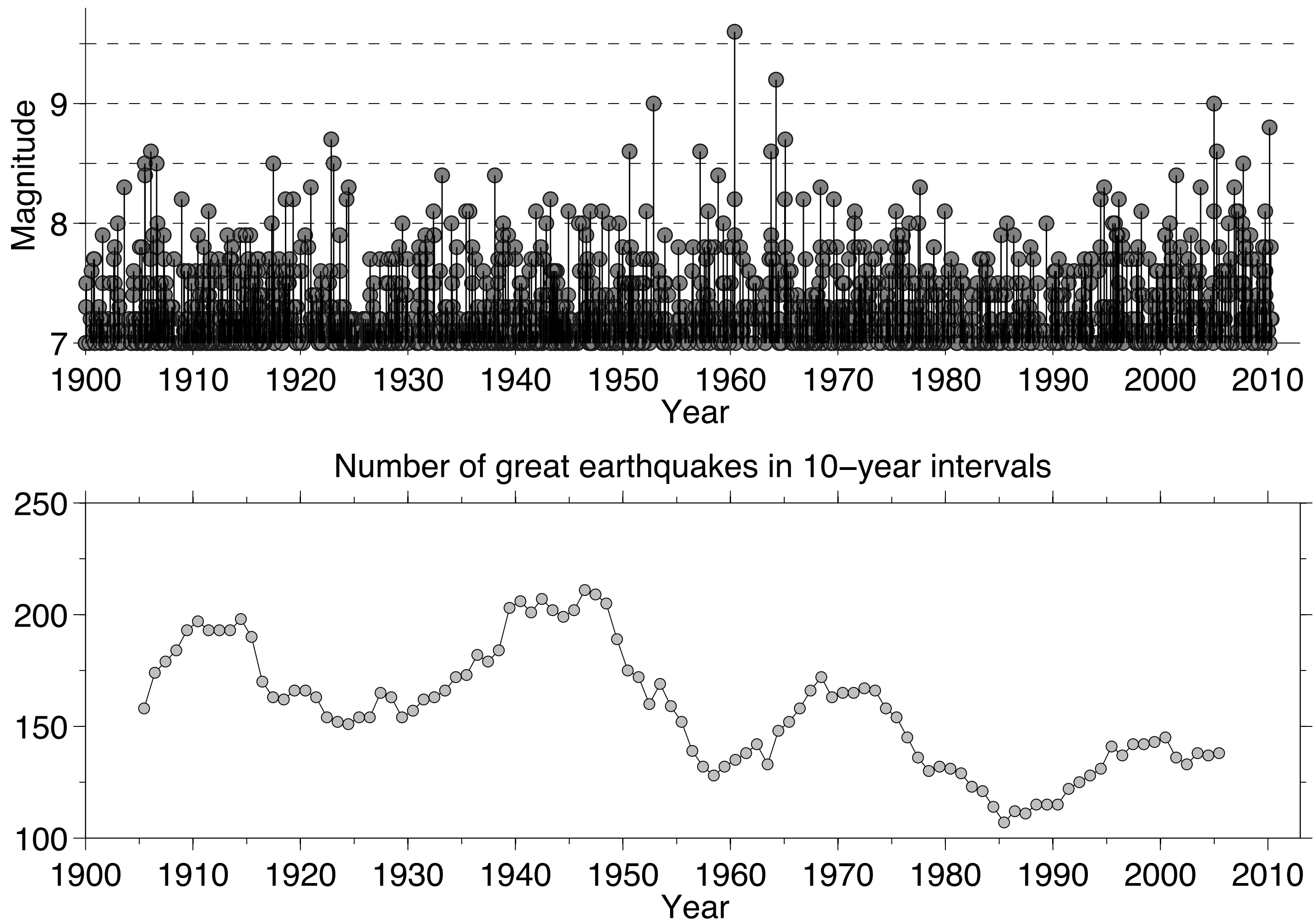


Magnitude
9.5
9
8.5
8
7.5
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
Number of large earthquakes in 10−year intervals
15
10
5
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

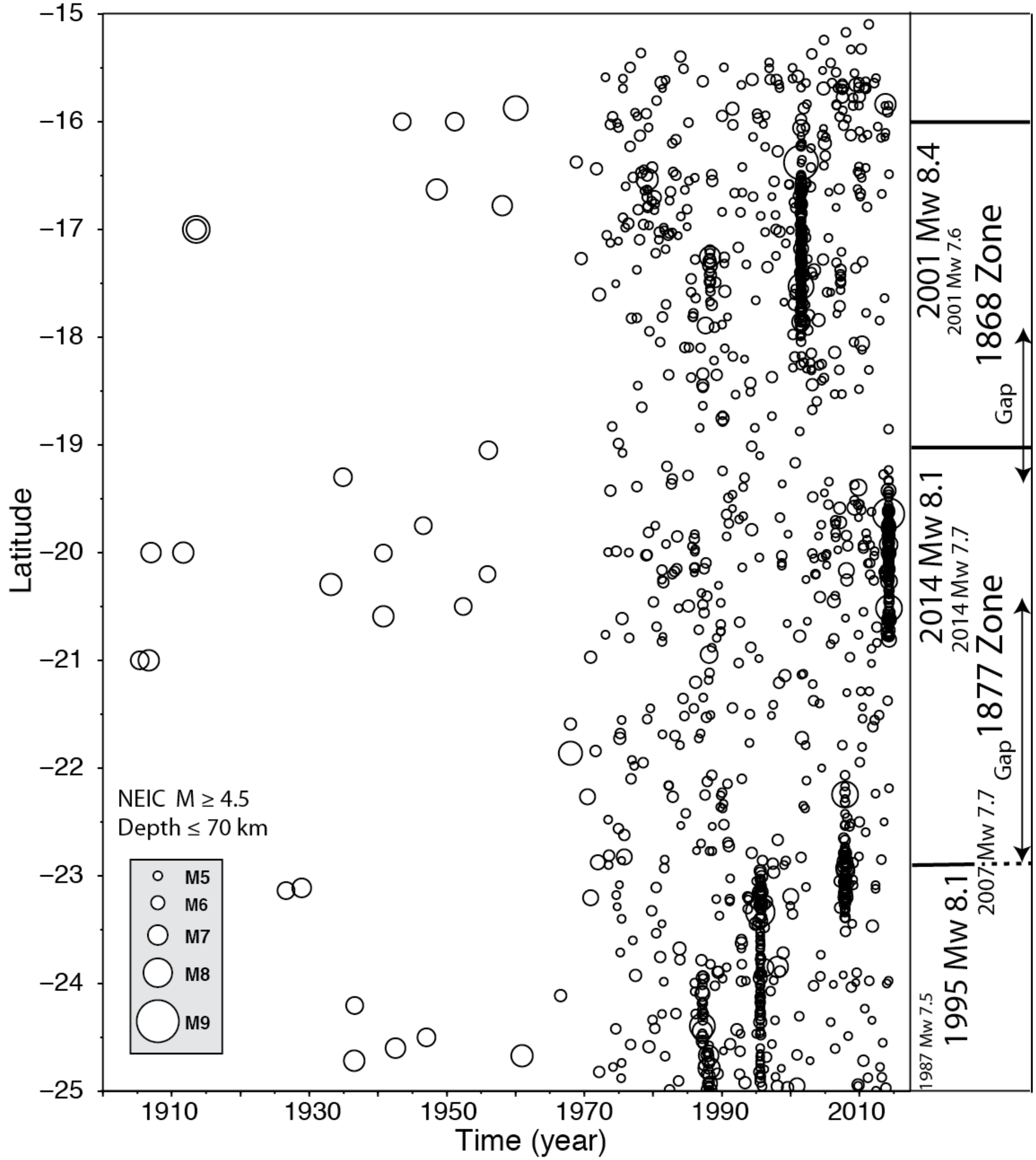


Number of large earthquakes in 10–year intervals

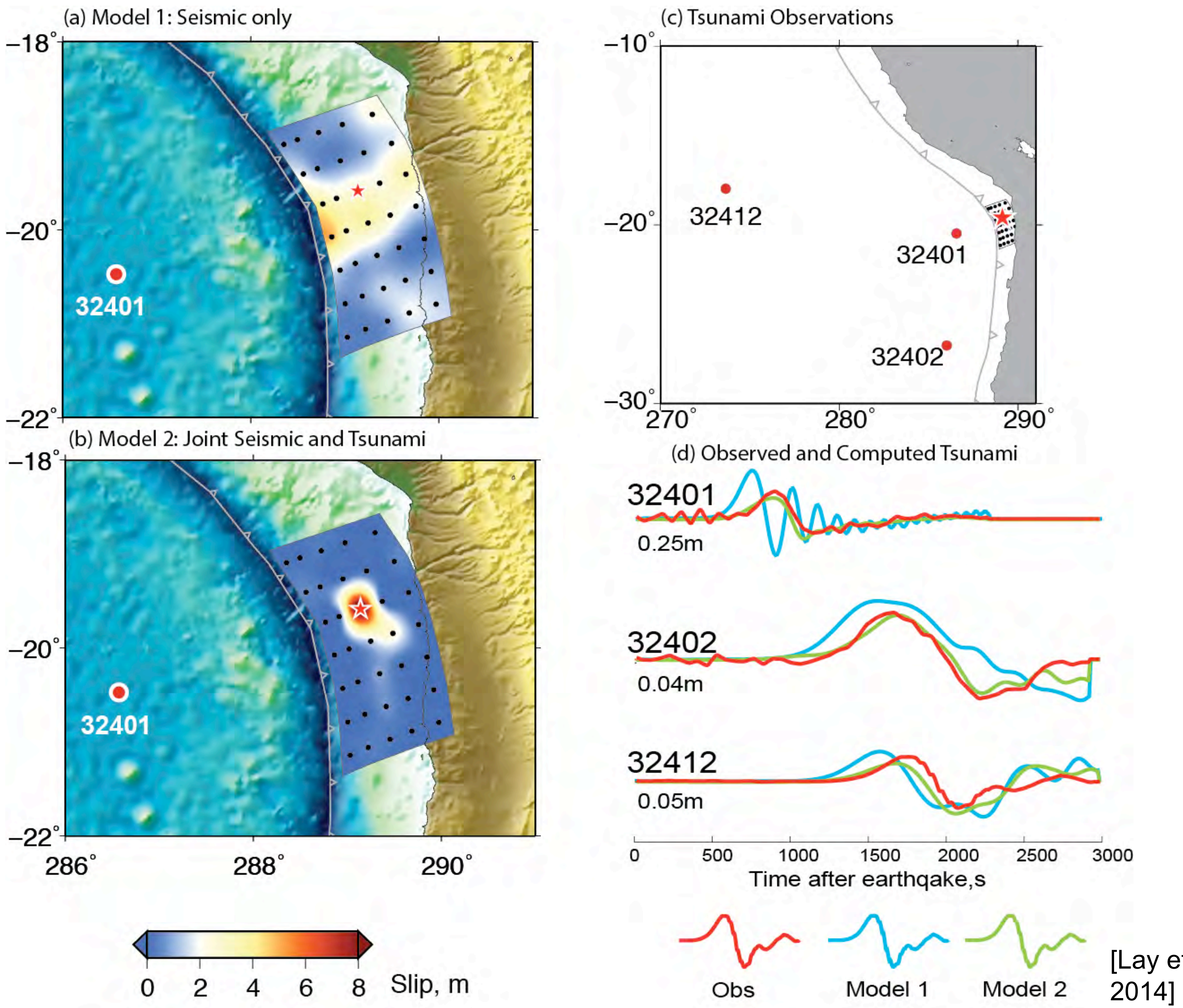




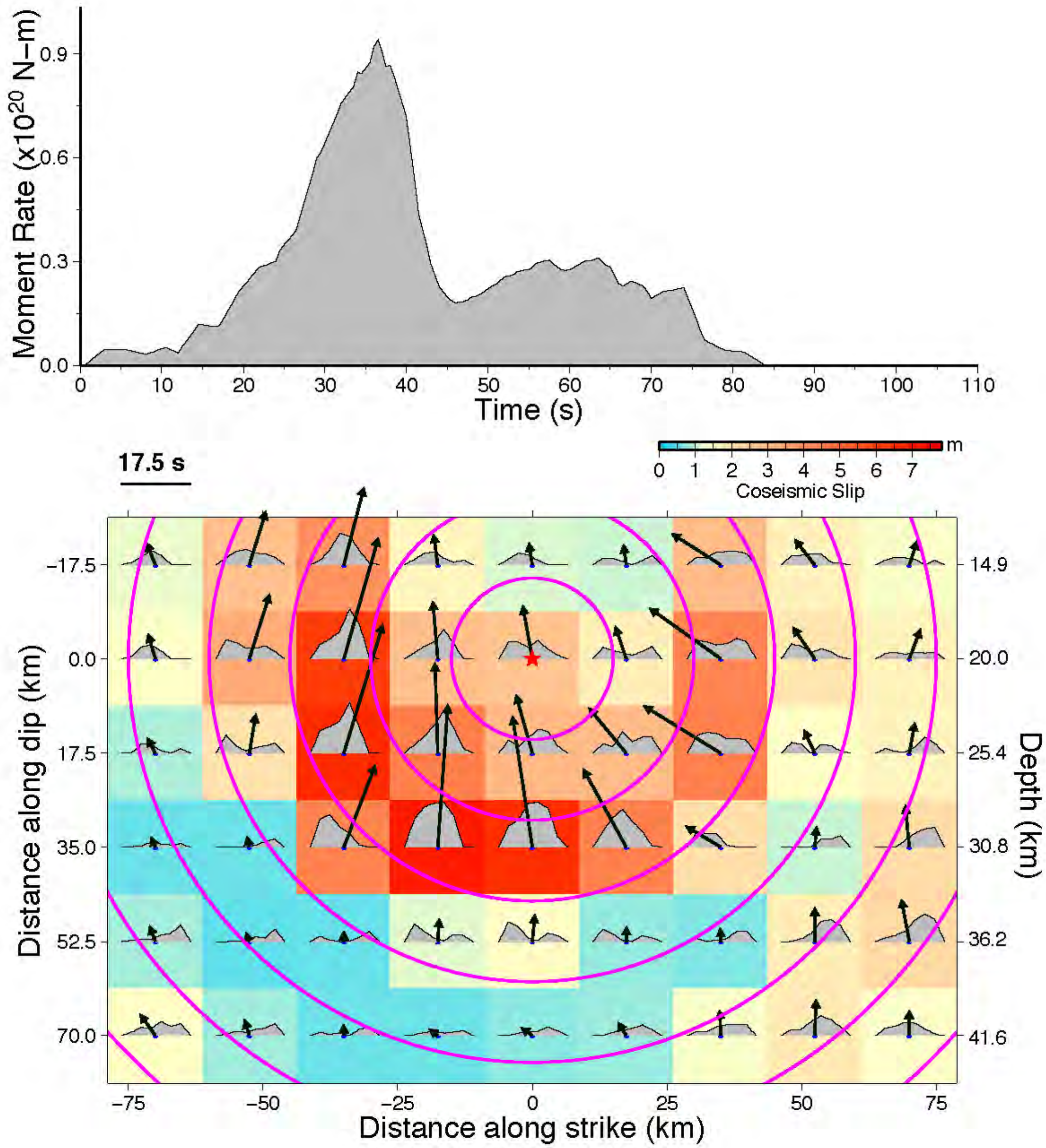
From: Ammon, Lay, Simpson, 2010



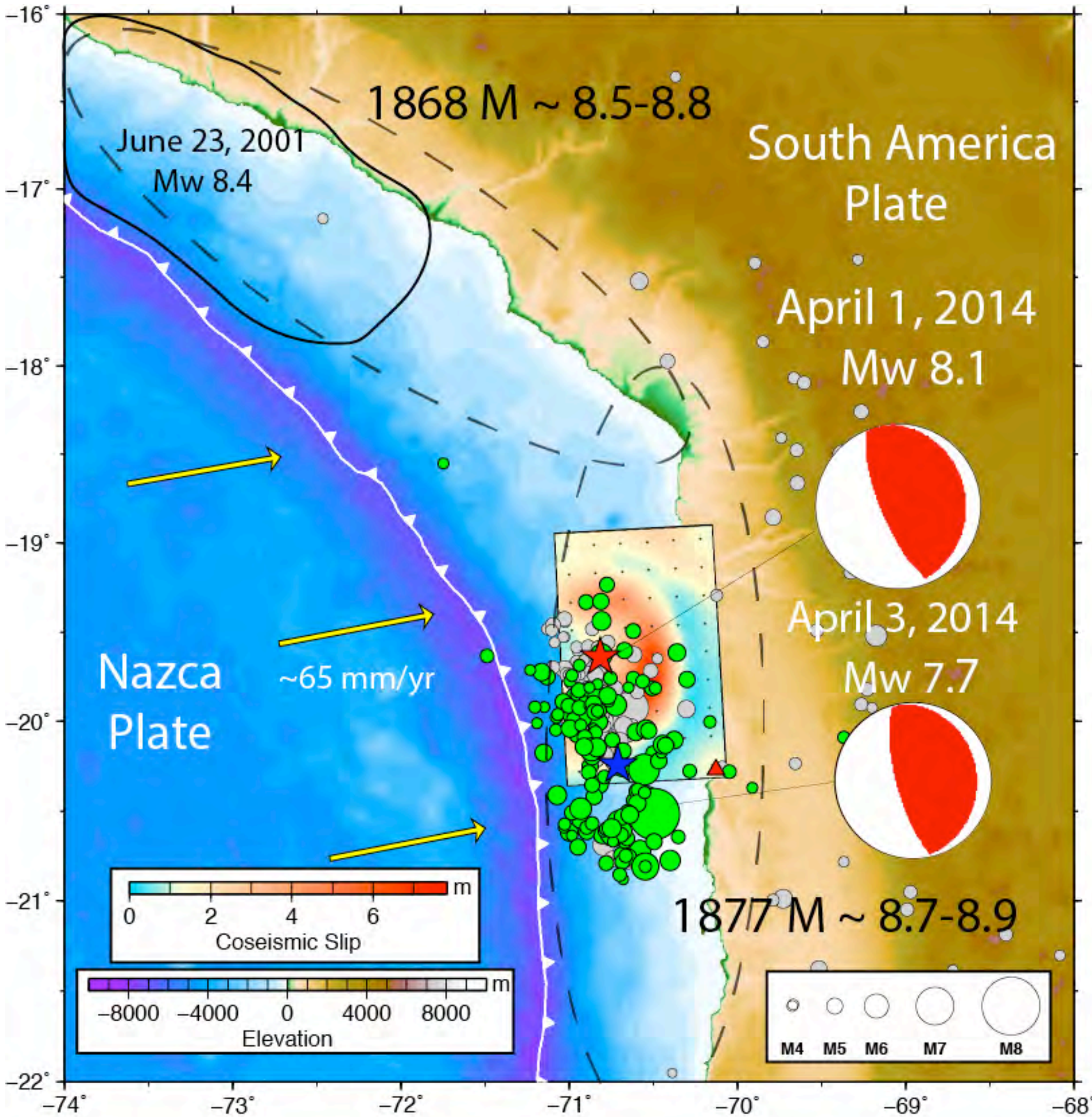
[Lay et al., 2014]



[Lay et al., 2014]

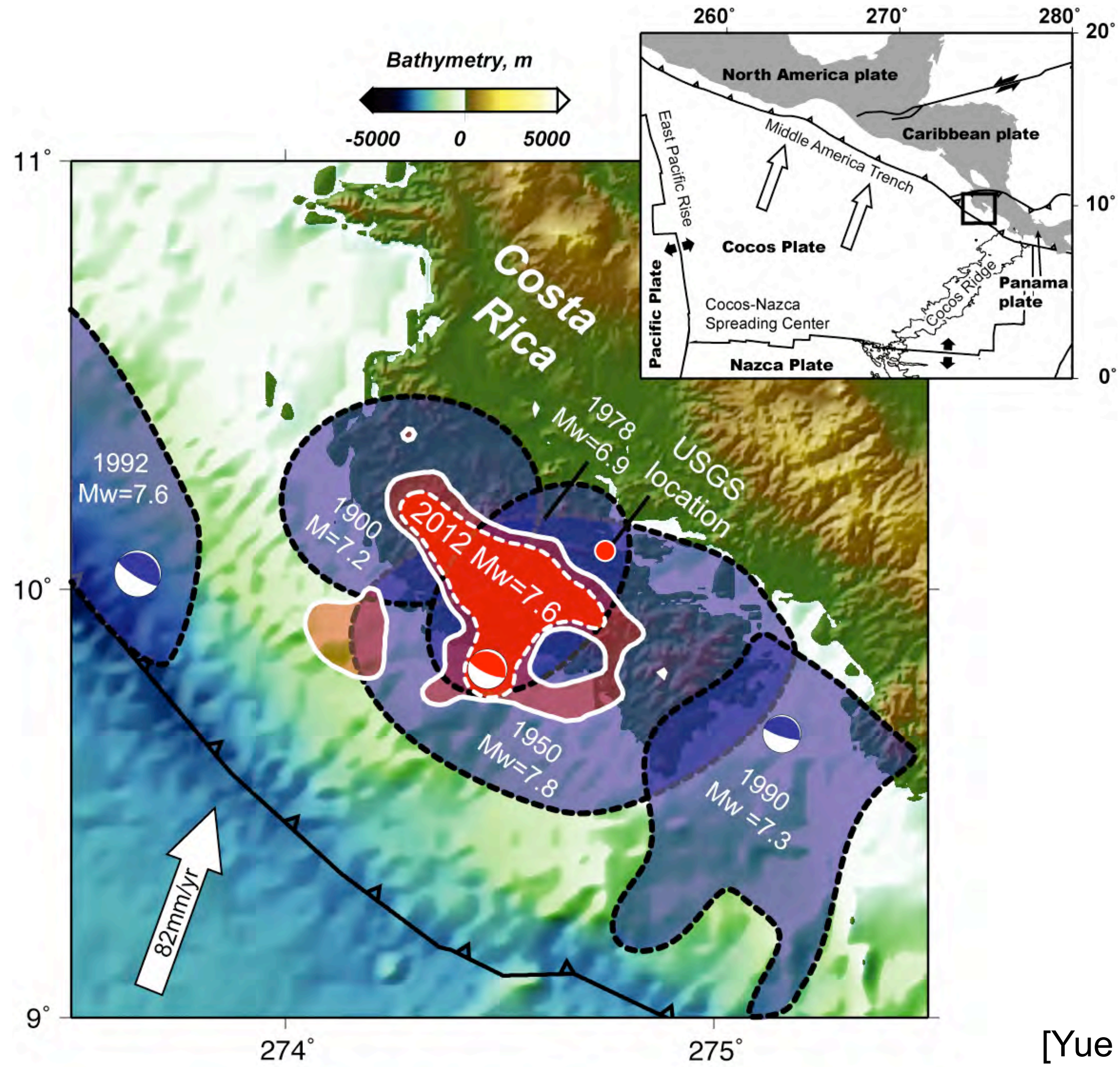


[Lay et al., 2014]



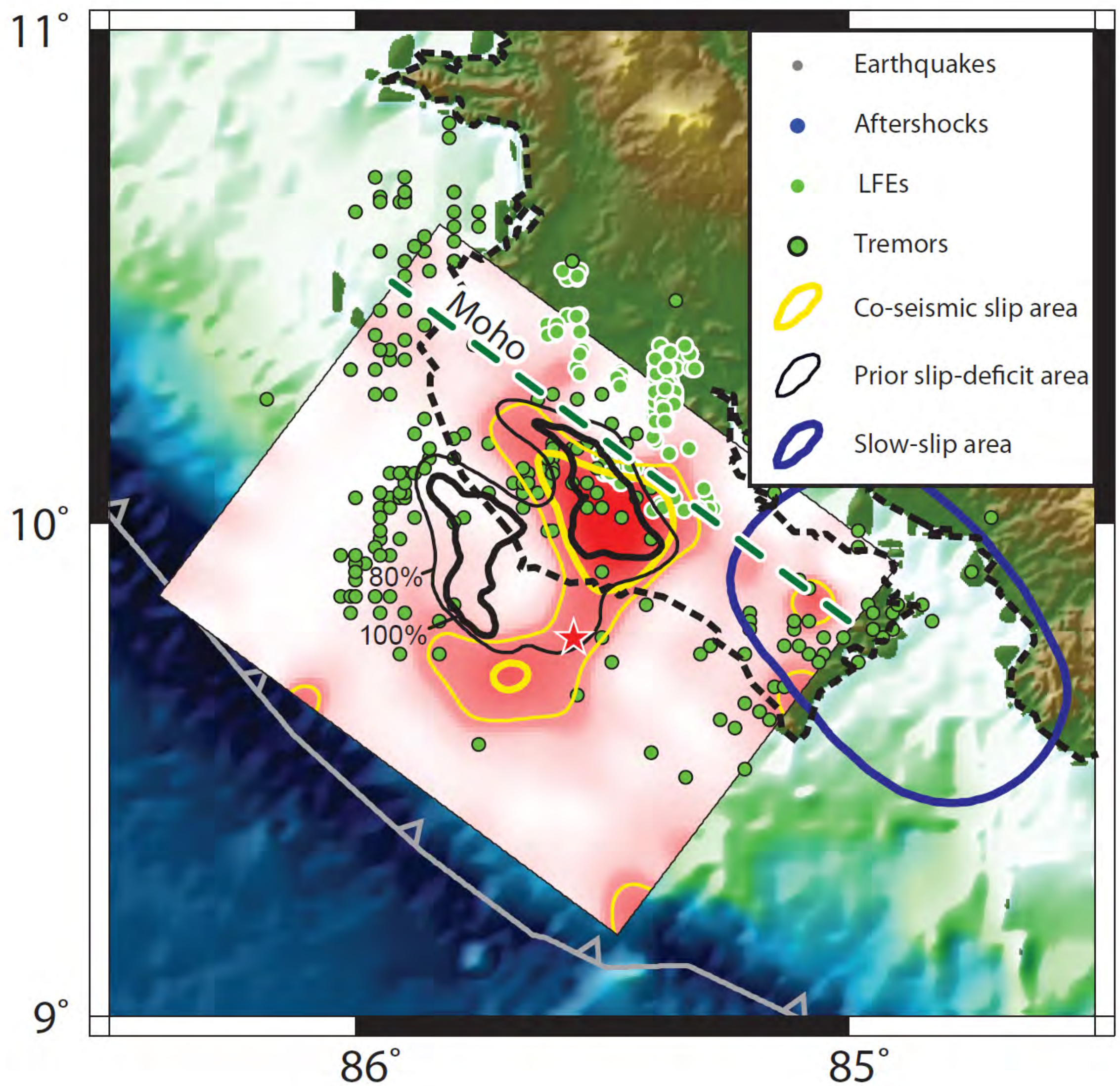
[Lay et al., 2014]

Sept. 5, 2012 Nicoya, Costa Rica M_w 7.6 Earthquake



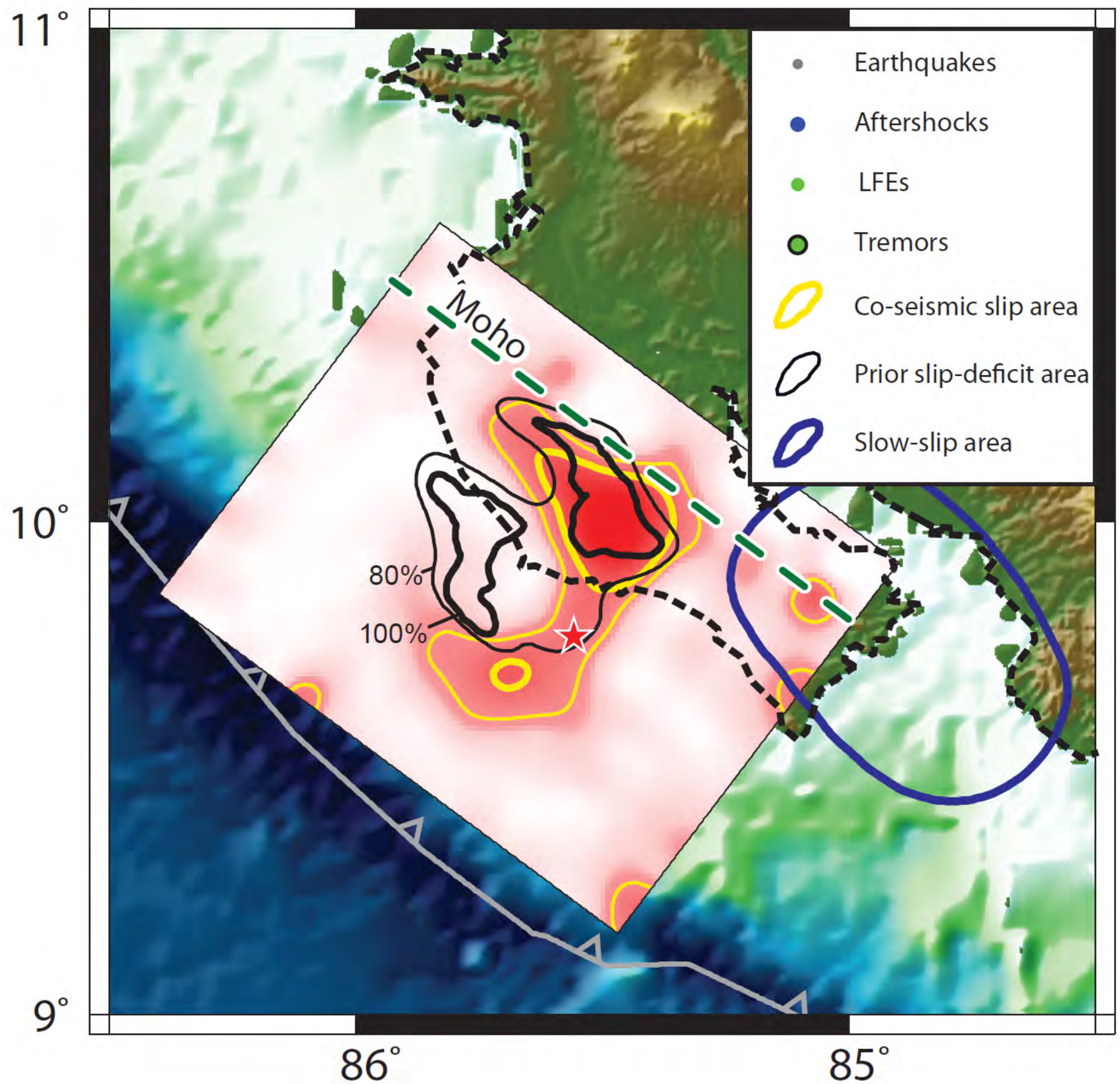
[Yue et al., 2013]

Comparison with tremor and LFE locations



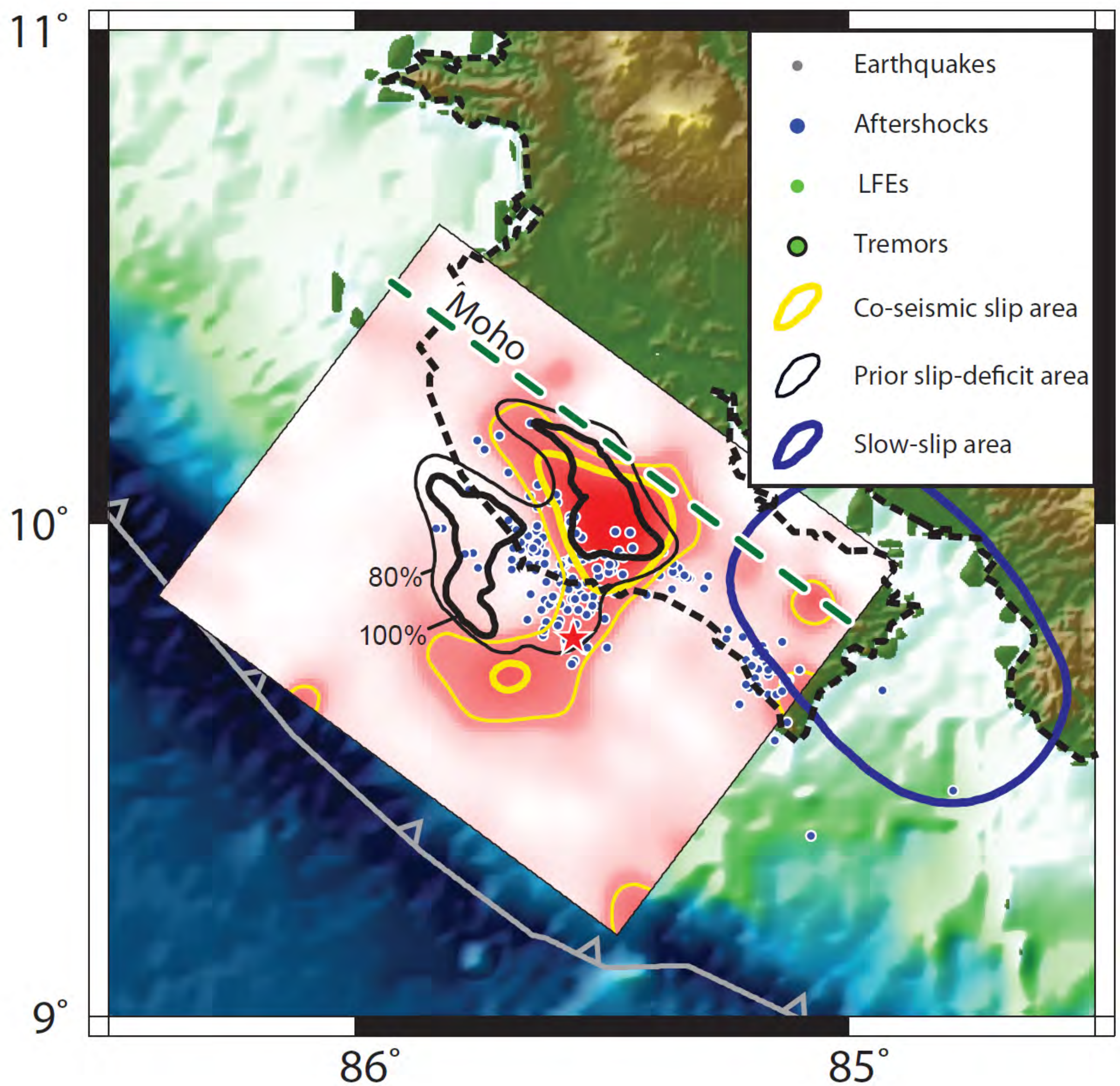
[Yue et al., 2013]

Comparison with inter-seismic locking pattern

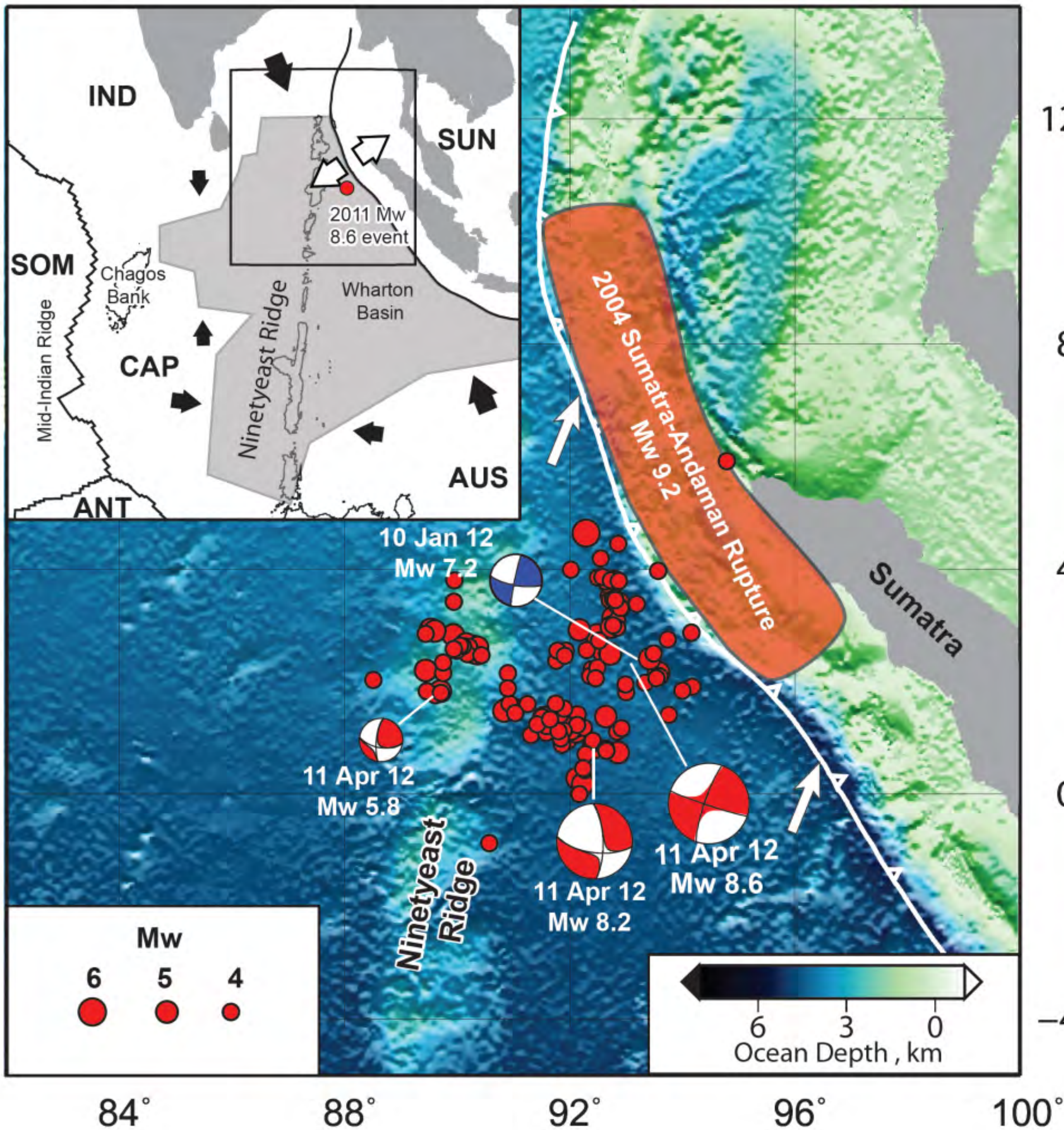


[Yue et al., 2013]

Comparison with aftershock locations



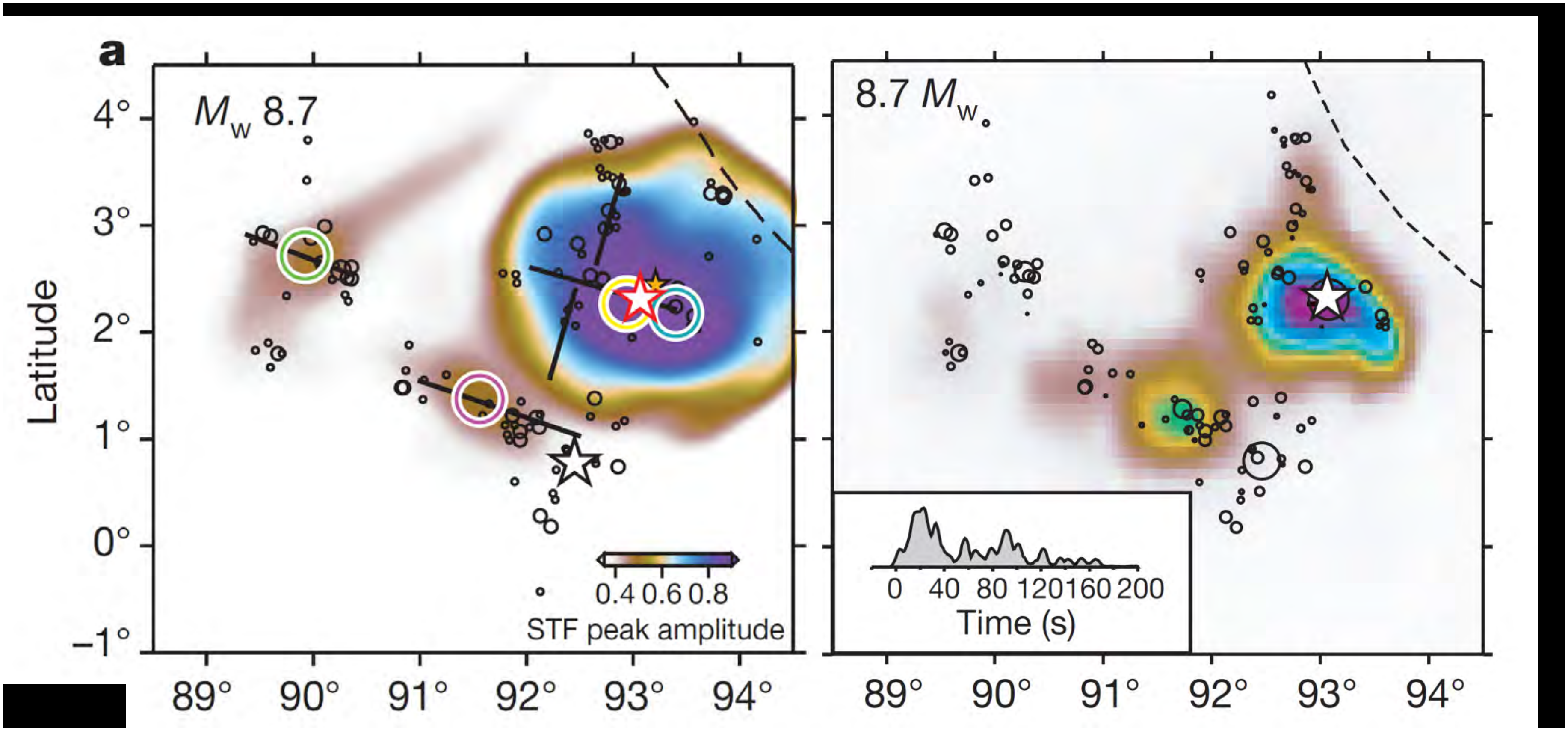
[Yue et al., 2013]



- 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.

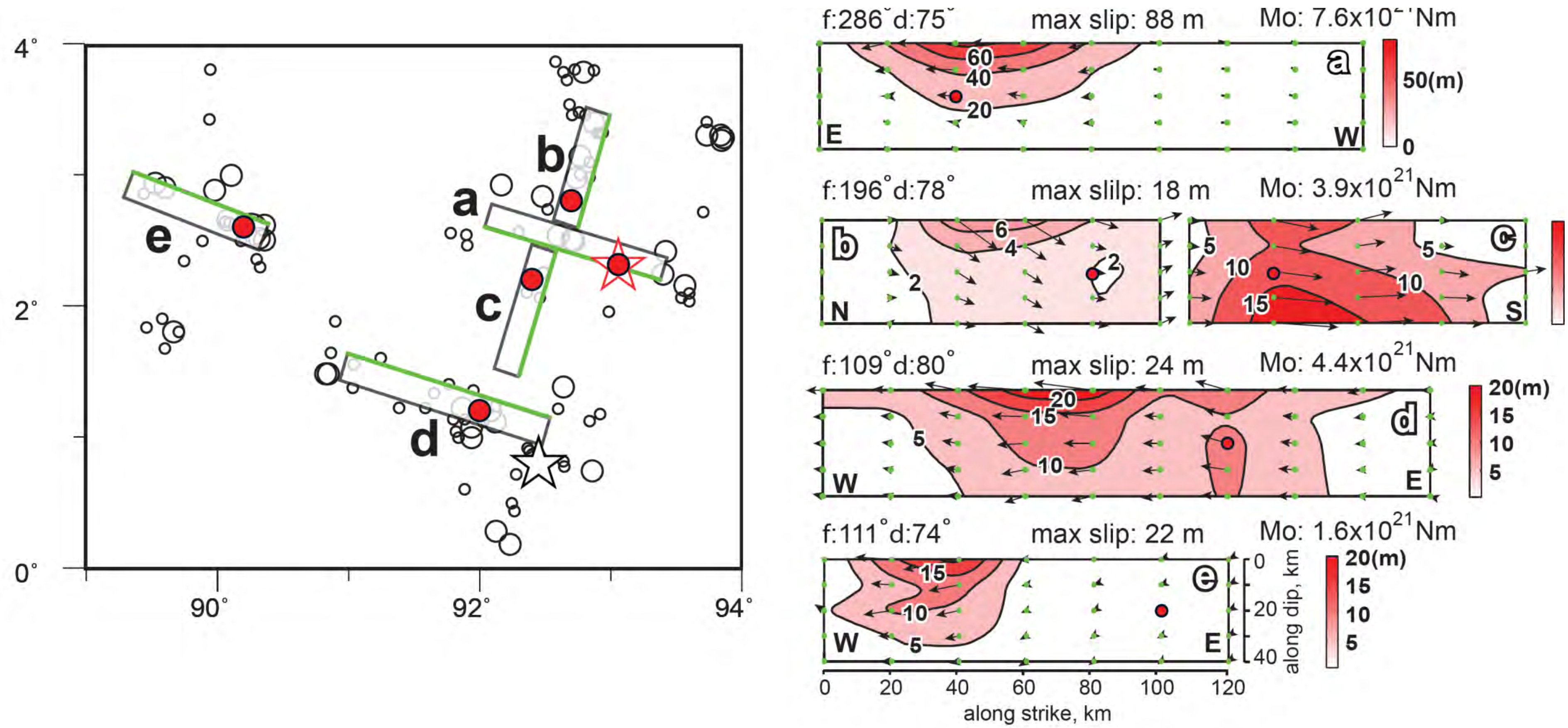
[Yue et al., 2012]

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

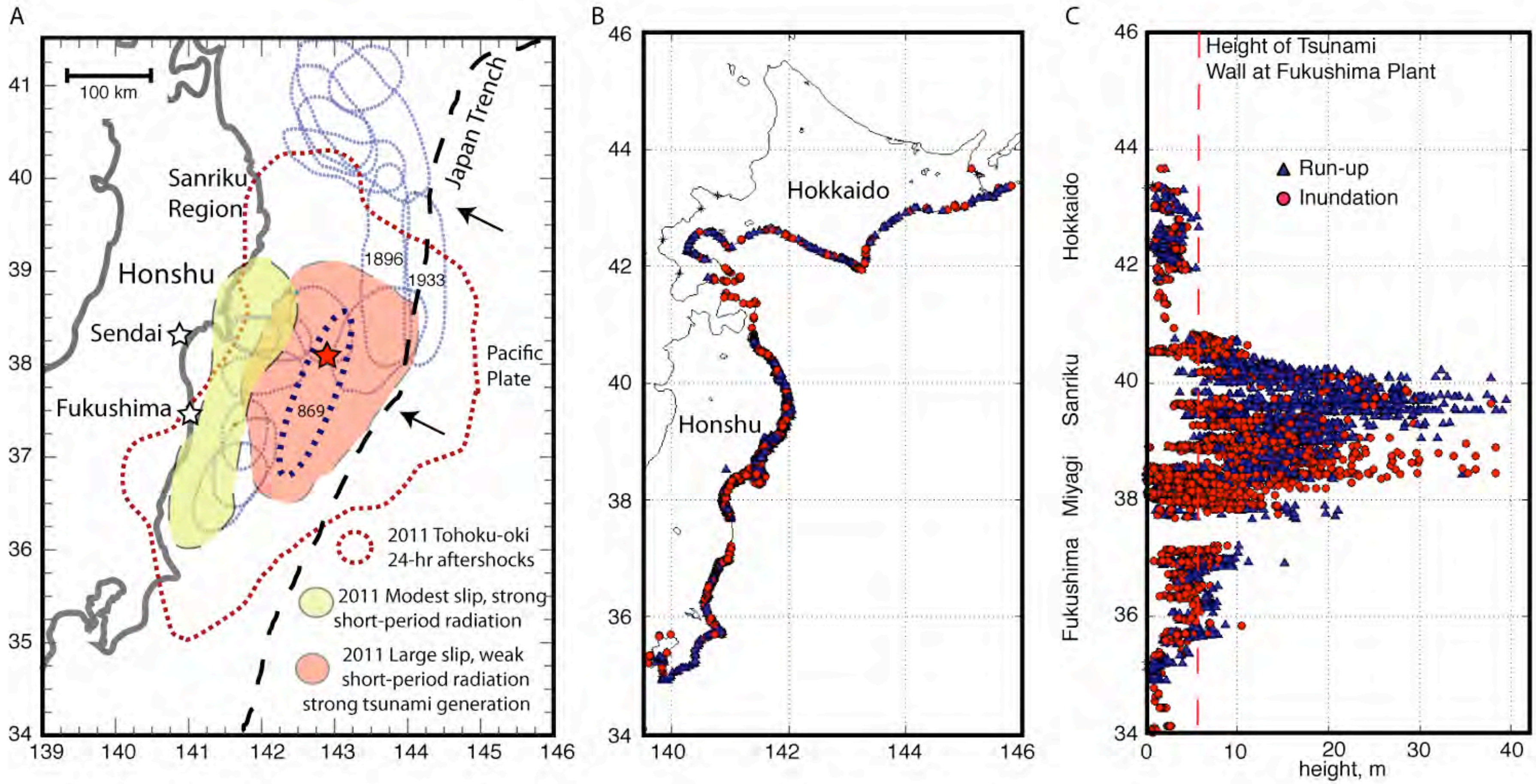


(Yue et al. 2012)

Finite fault model on multiple fault segments



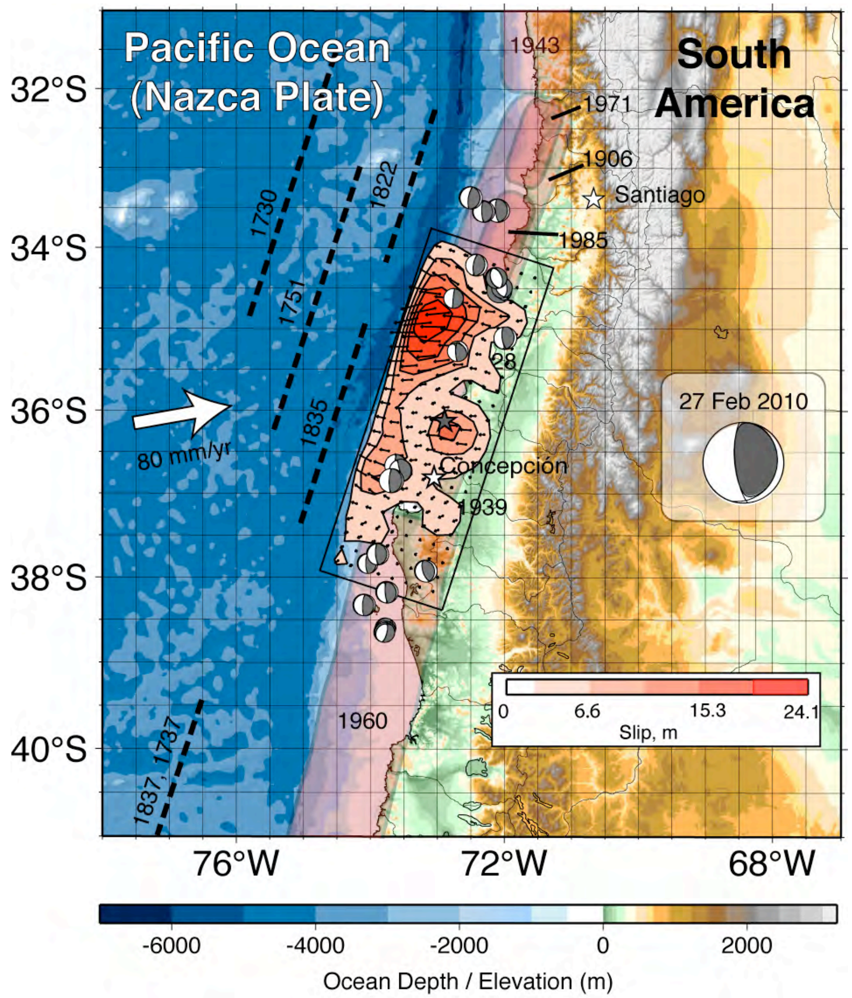
[Yue et al., 2012]



[Lay and Kanamori, 2012]

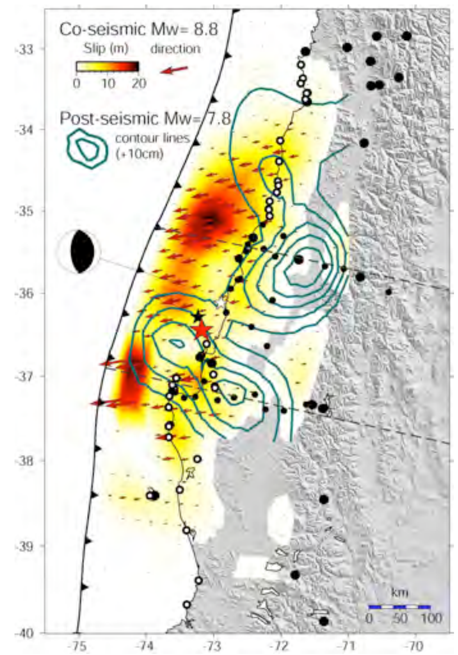
2010 Chile M_w 8.8 – Rupture expands bilaterally with most slip in the north (near 1928 event), not conforming to 1835 seismic gap

Teleseismic

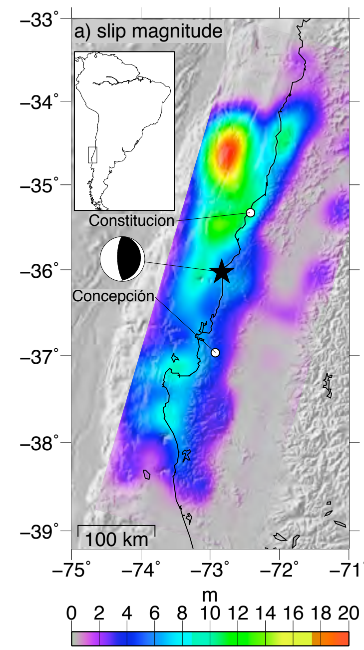


Lay et al., GRL, 2010;
Koper et al., JGR 2012

Geodetic



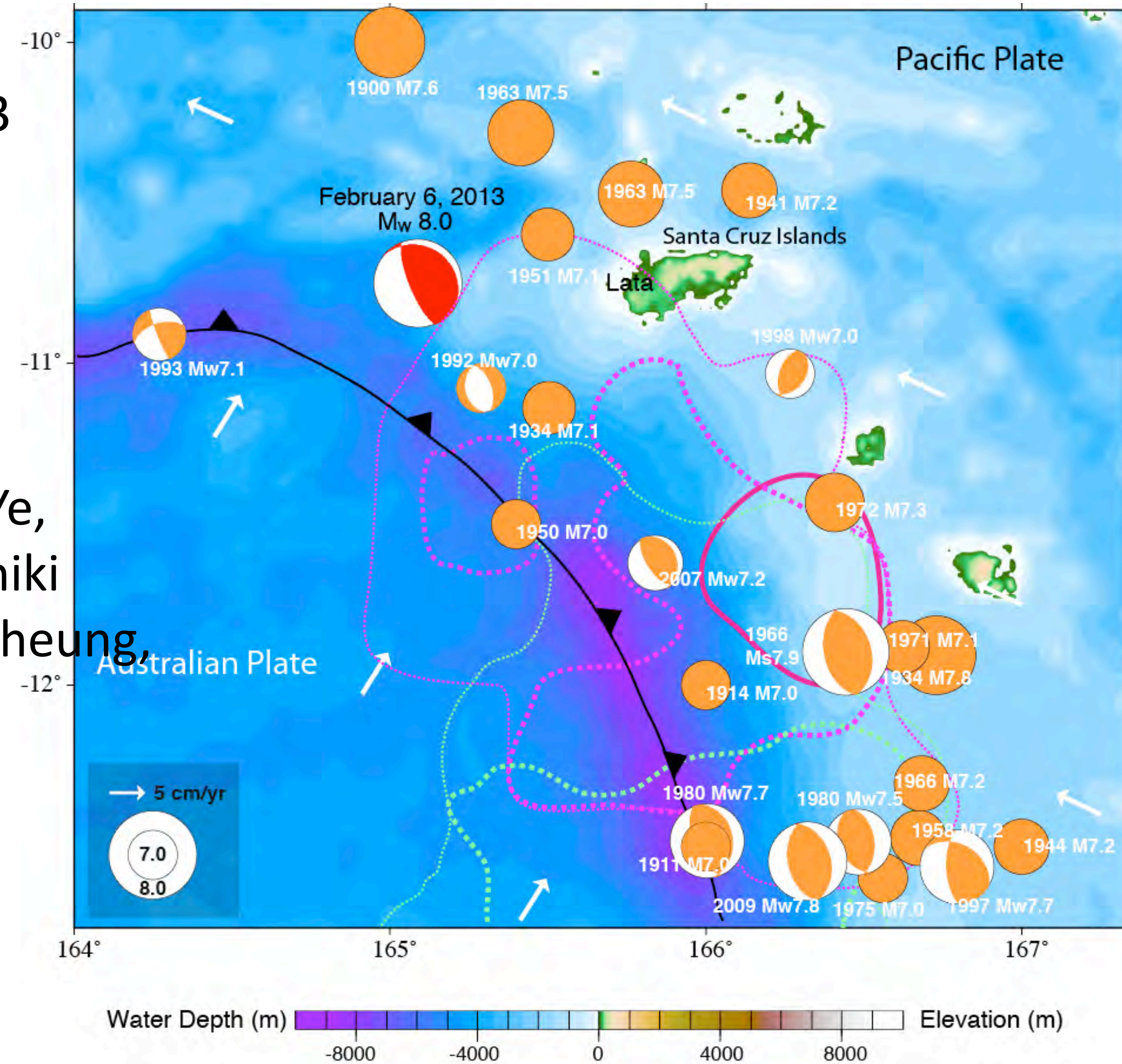
Vigny et al. 2011



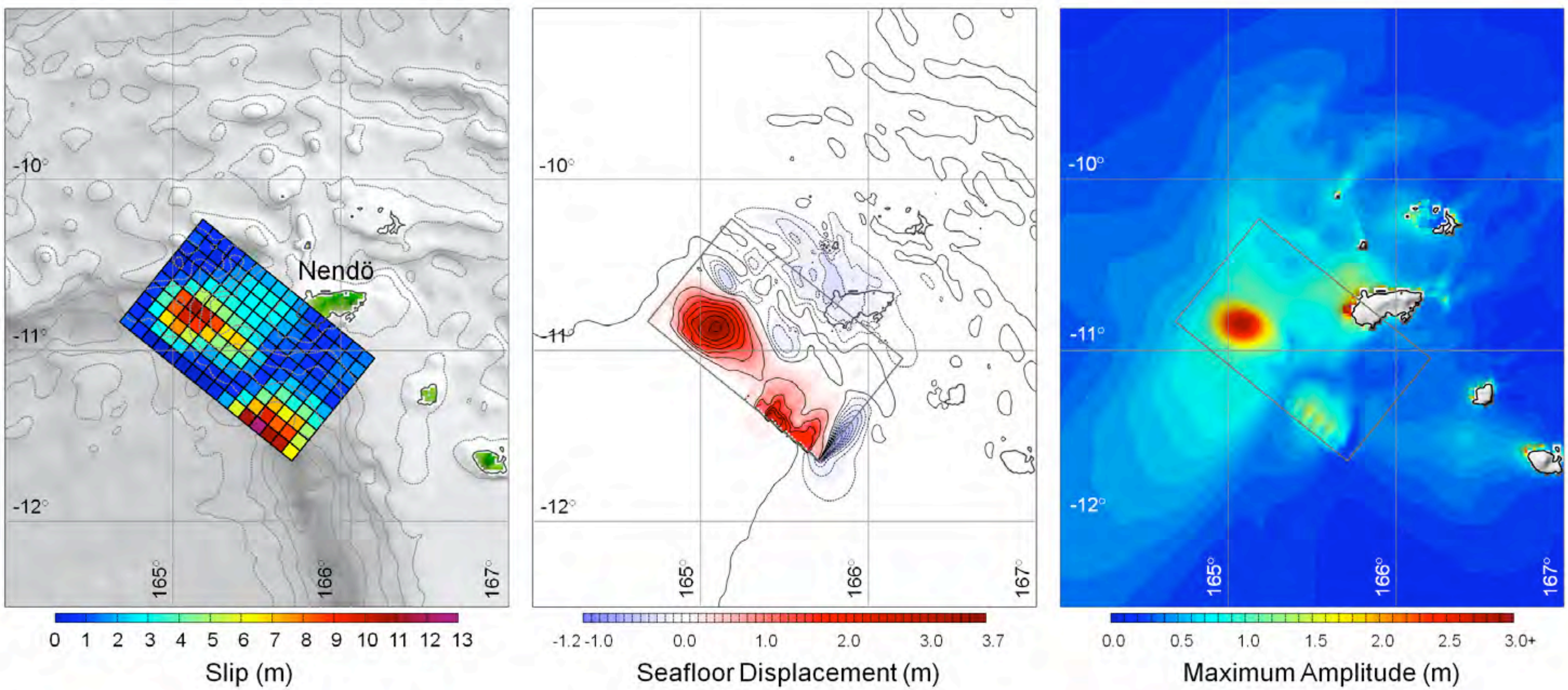
UCSD, 2011

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

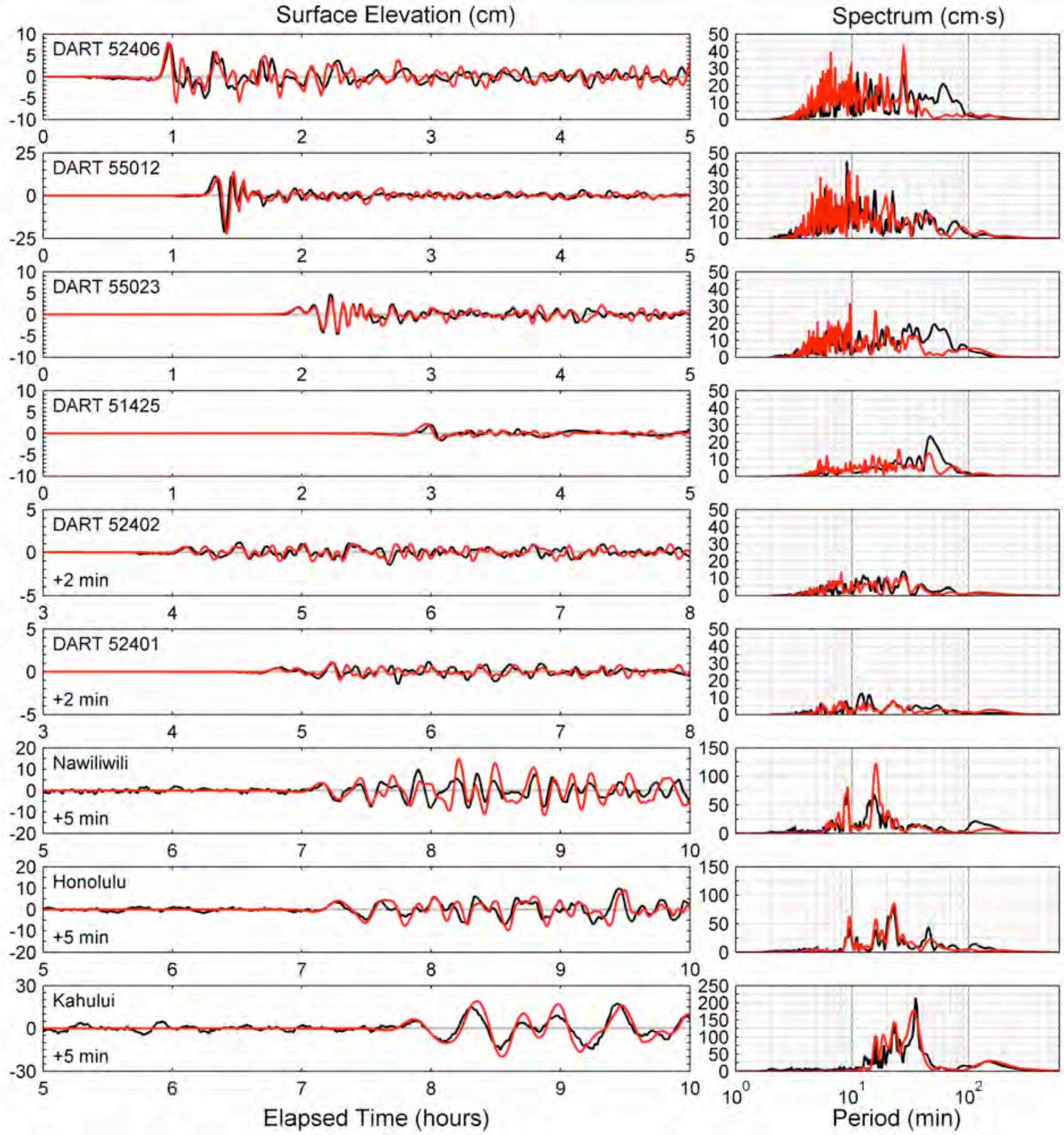
Thorne Lay, Lingling Ye, Hiroo Kanamori, Yoshiki Yamazaki, Kwok Fai Cheung, Charles J. Ammon



Lay et al., Tectonophysics, 2013

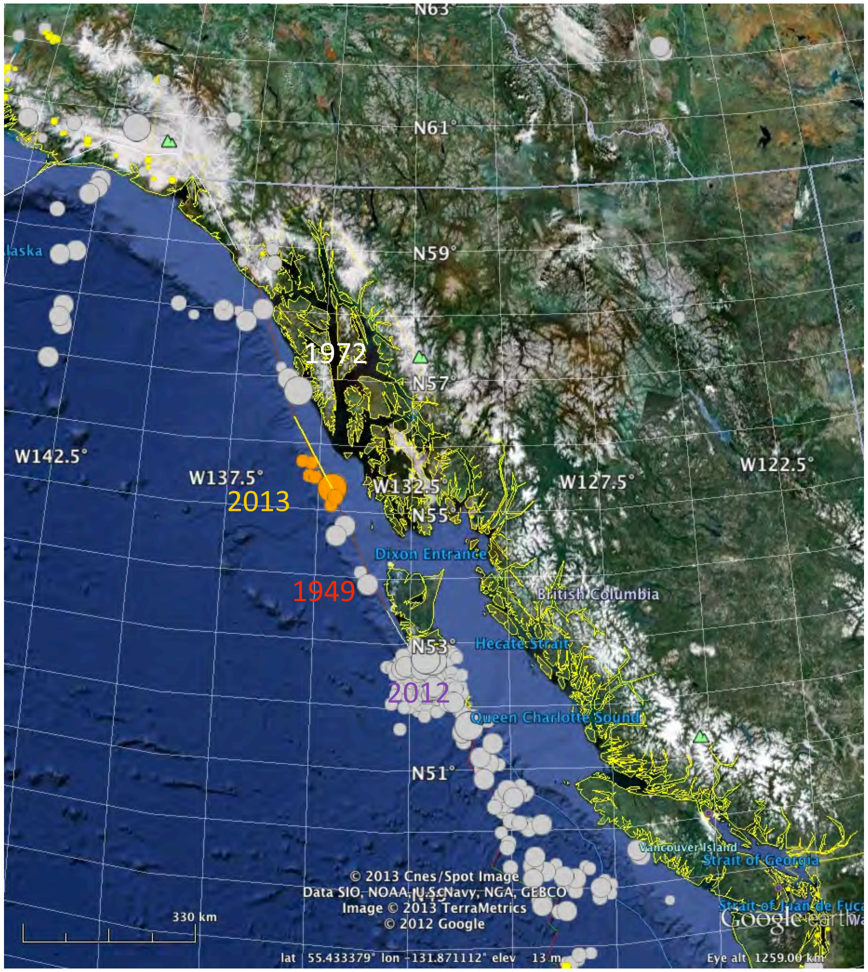


Lay et al., Tectonophysics, 2013



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



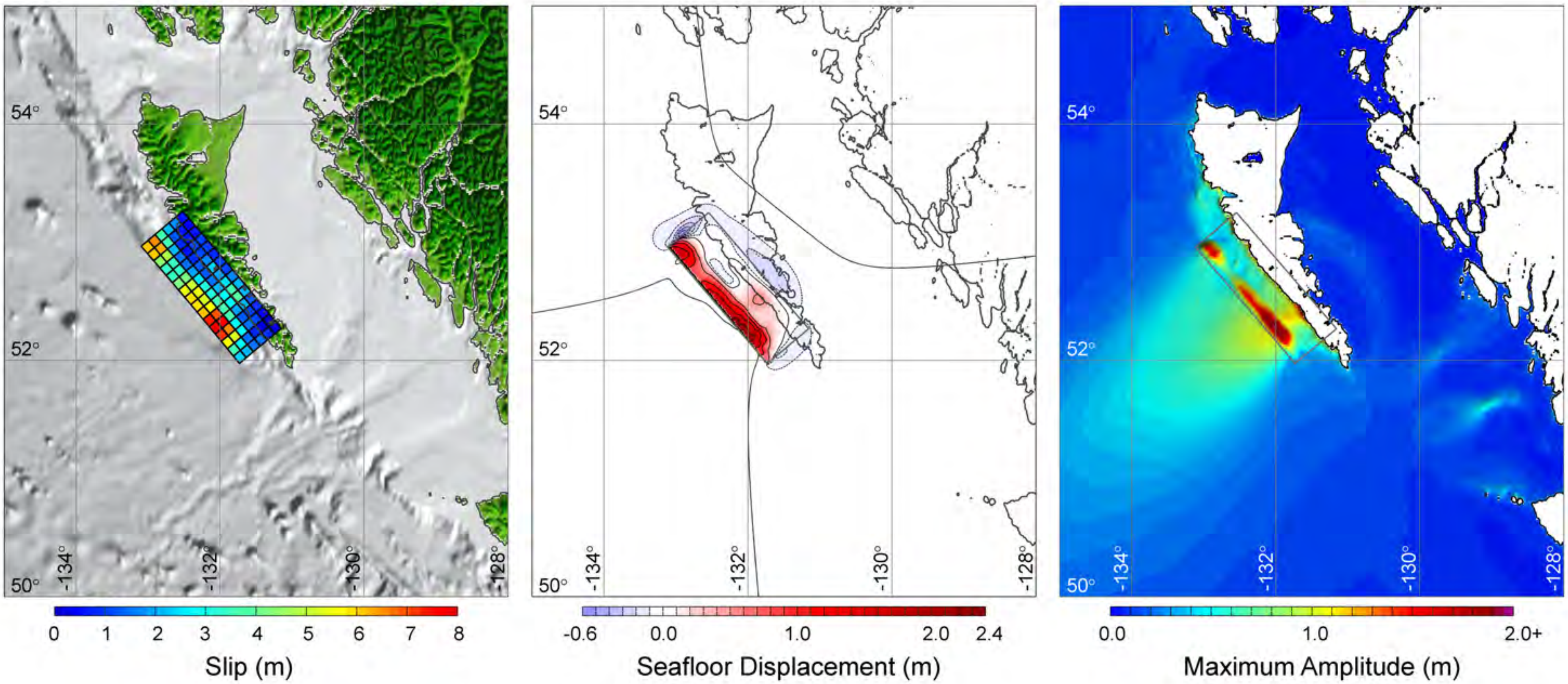
T. Lay, UCSC

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

Hadia Gwaii Final Slip Model

Surface Vertical Displacement

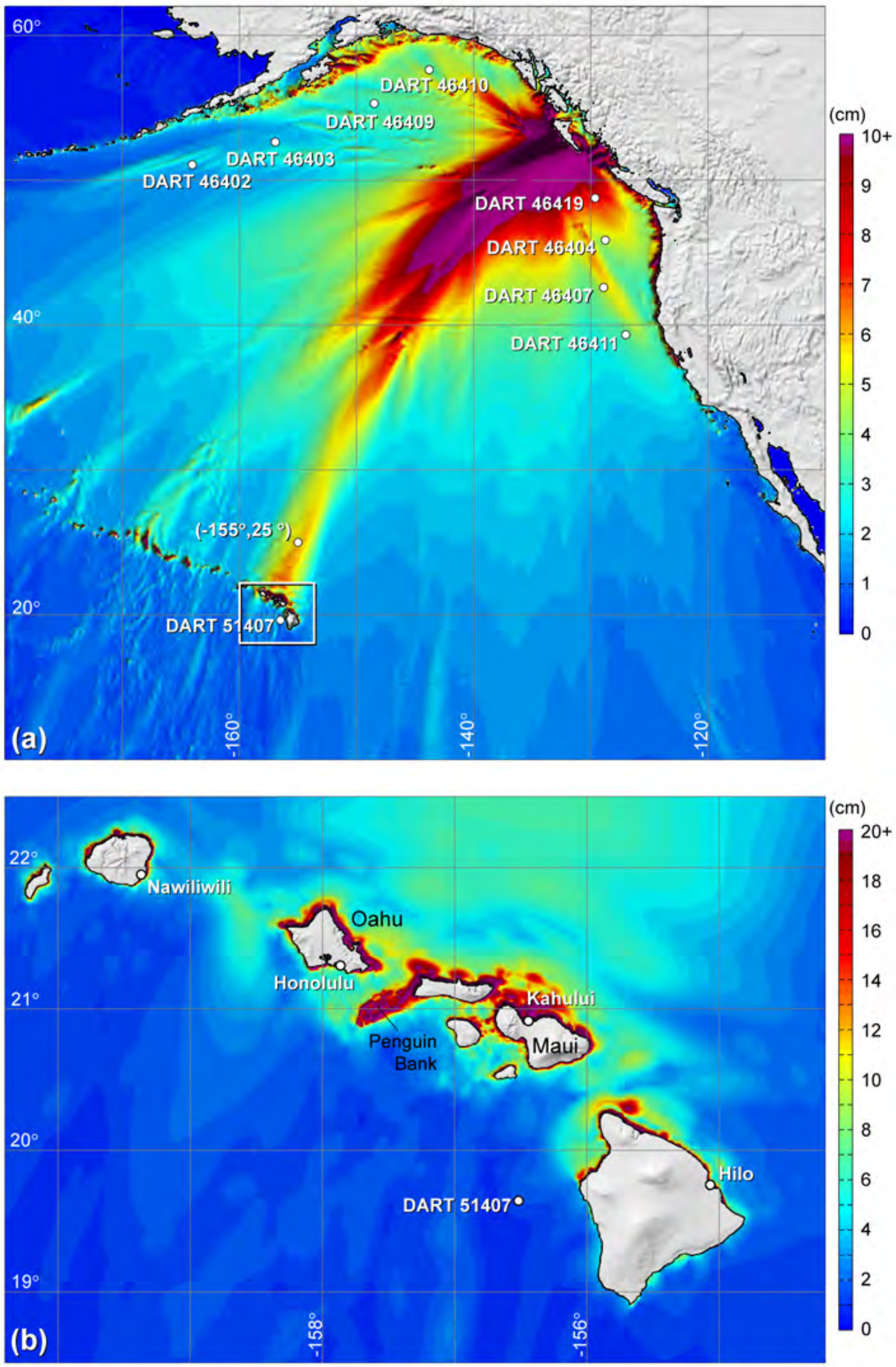
Local Peak Tsunami



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

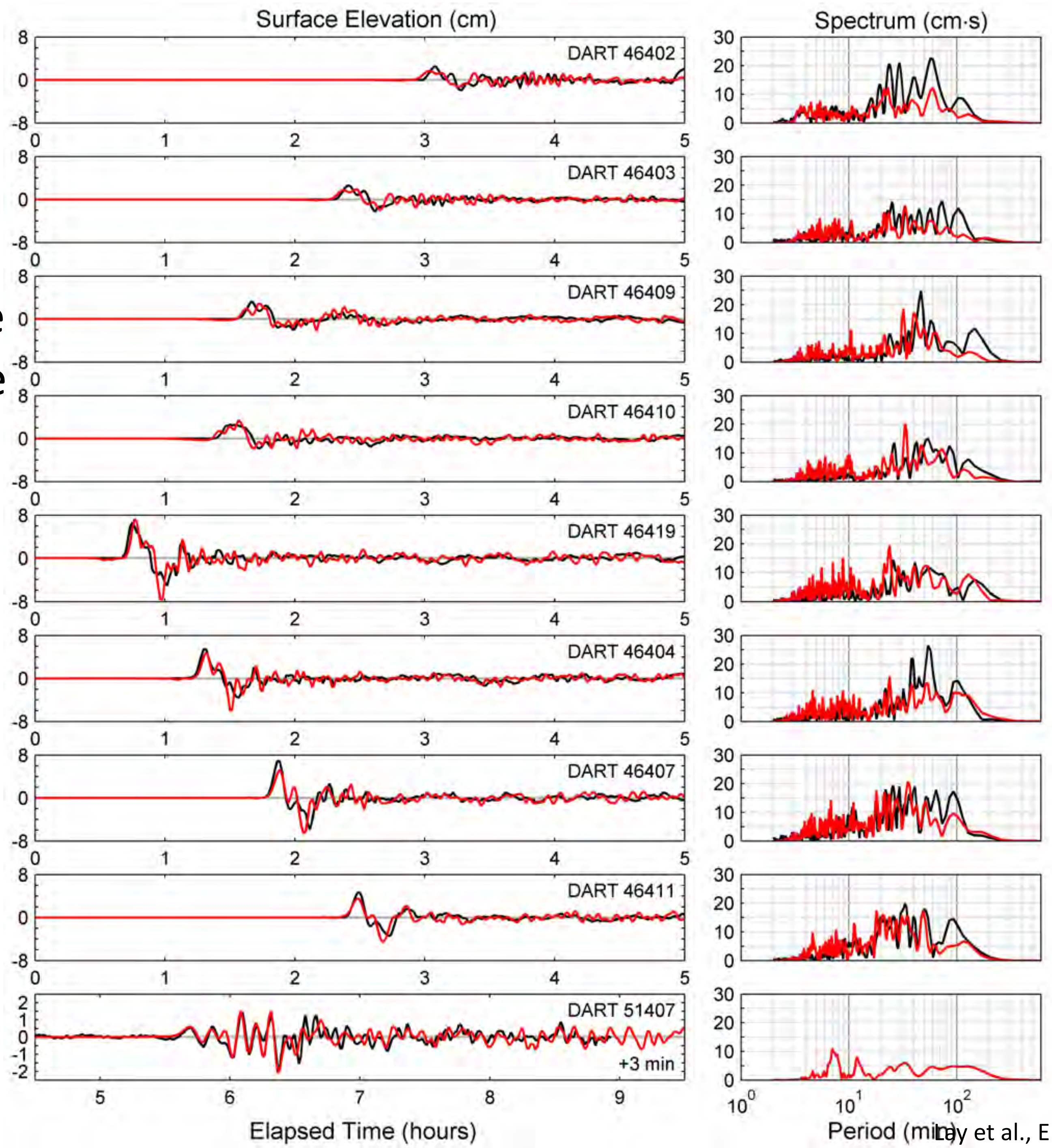
(Lay et al., EPSL, 2013)

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.

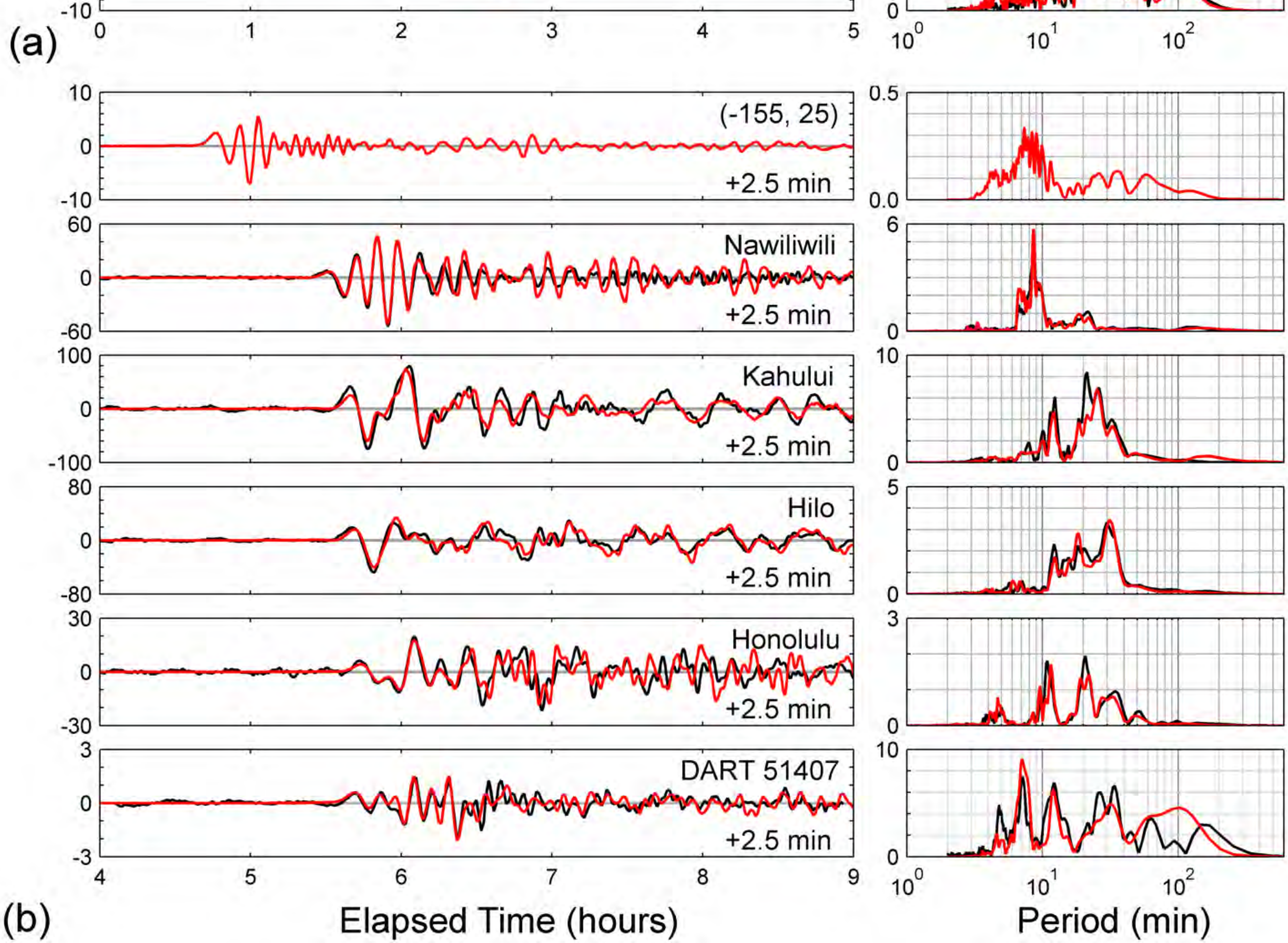


(Lay et al., EPSL, 2013)

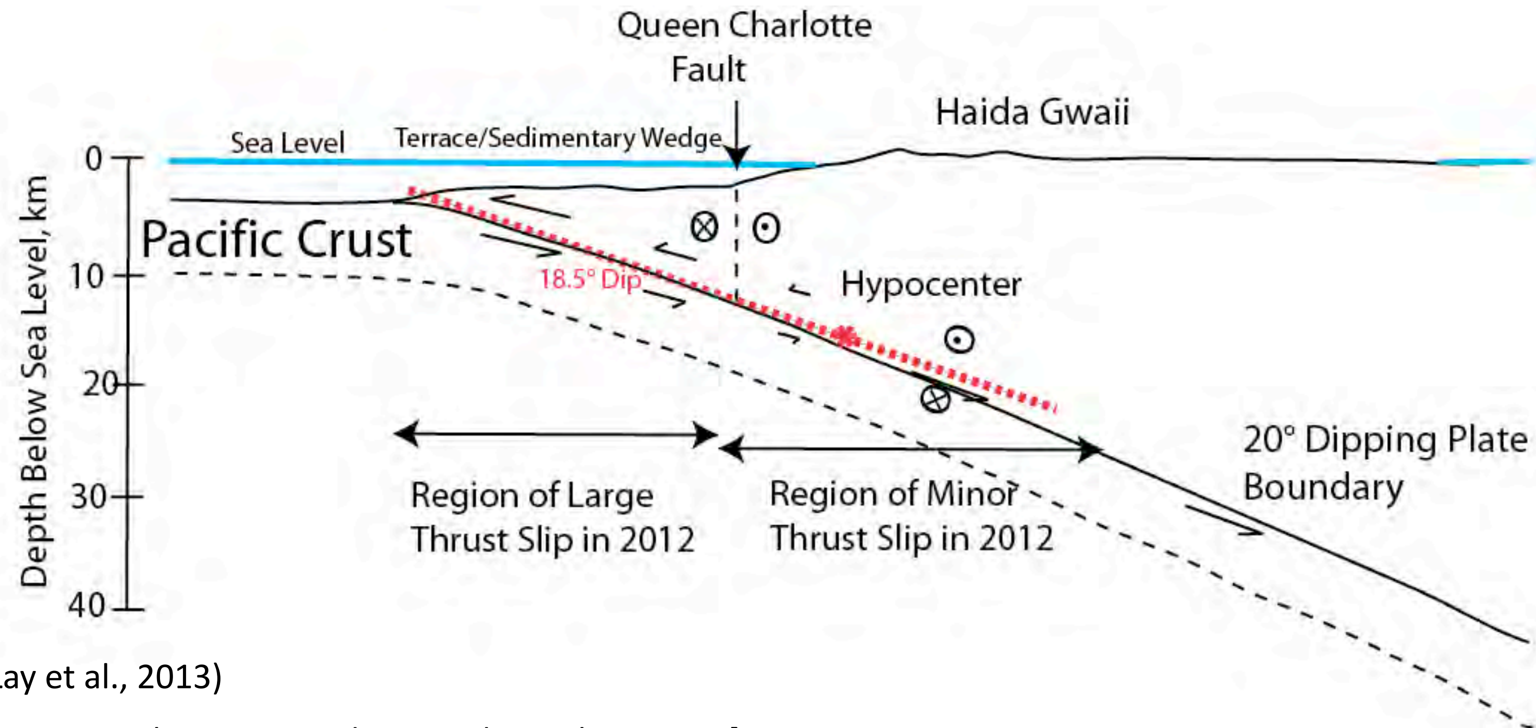
DART data and model predictions in red for the final iterative model.



Lay et al., EPSL, 2013

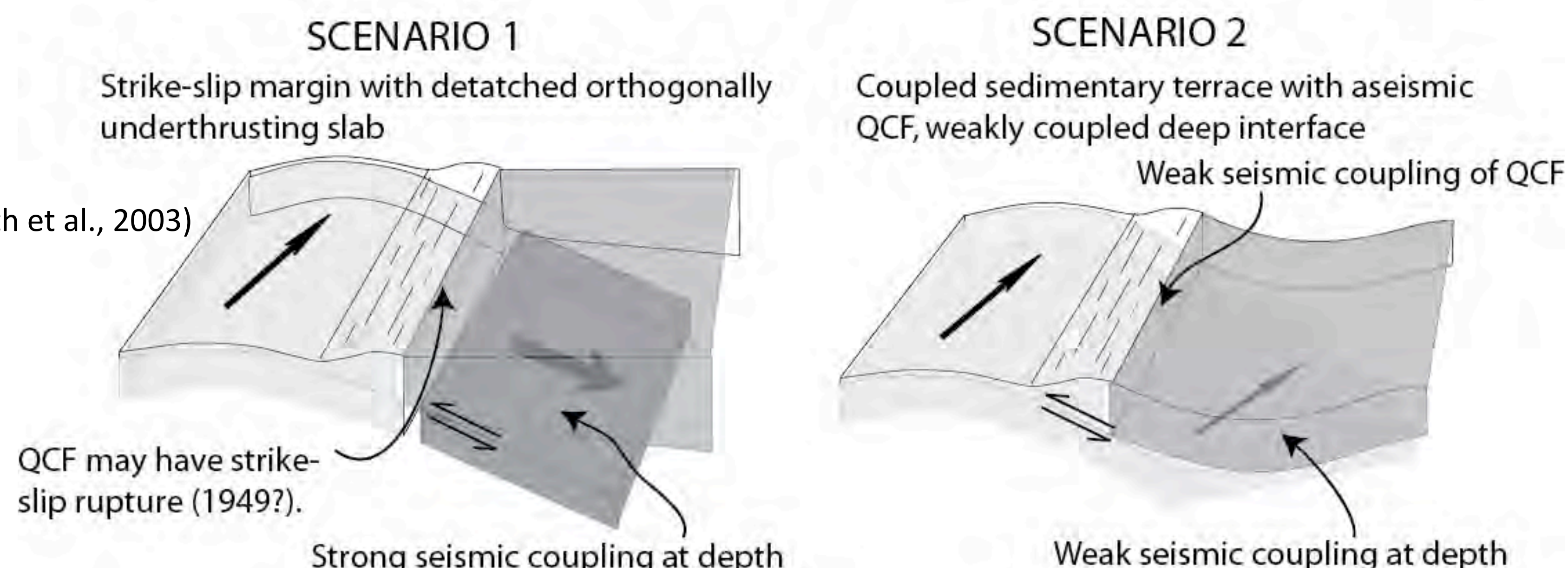


(Lay et al., EPSL, 2013)



(Lay et al., 2013)

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



(Smith et al., 2003)

(Lay et al., EPSL, 2013)