Temporal and spatial variations in earthquake source characteristics

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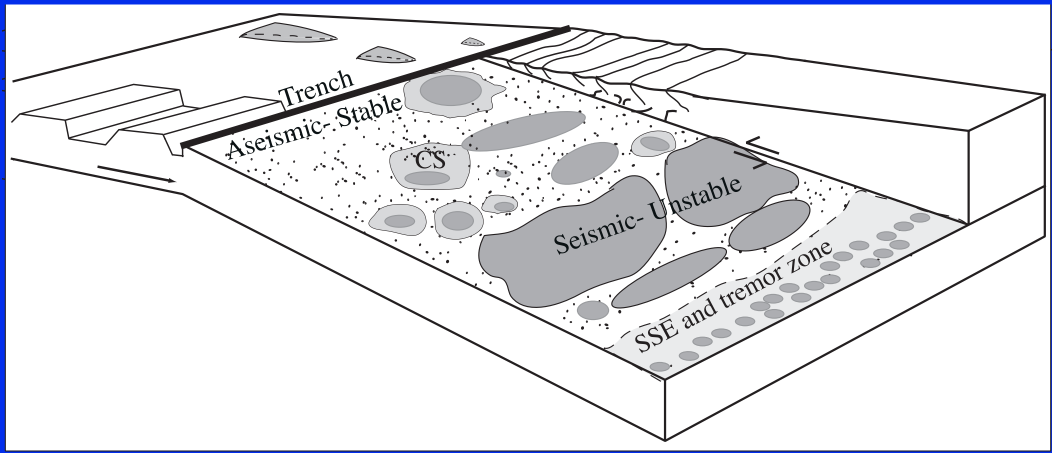
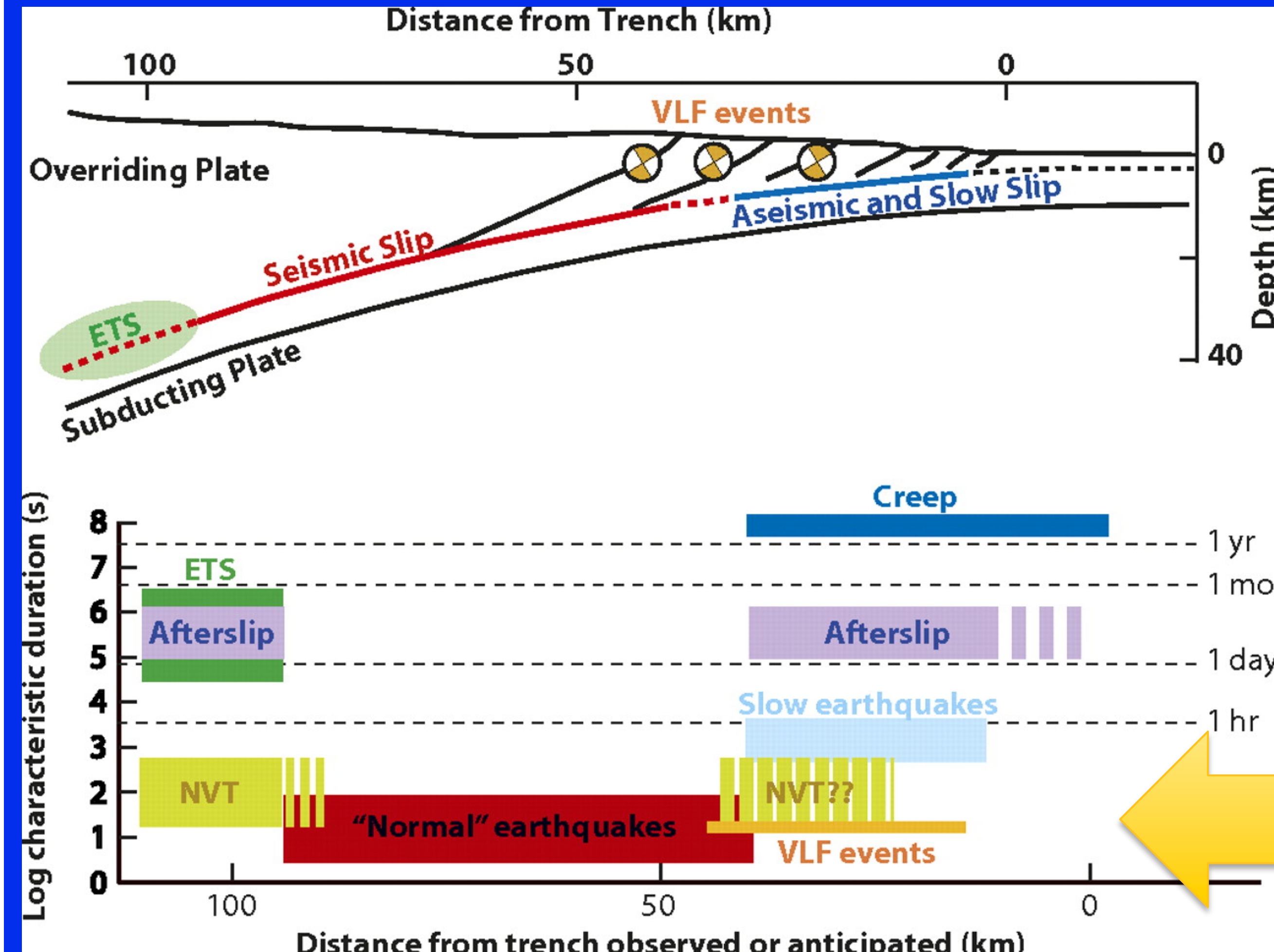
w/ Heather DeShon, Bob Engdahl, Scott Phillips, Susan Schwartz, Andy Newman, Zhigang Peng, Jake Walter, and many others

Outline

- Observations of earthquake source parameter variations
- Earthquake source parameter review
- Examples in subduction zones
  - Global overview
  - Japan & Sumatra
  - Costa Rica & Nicaragua
- Connections with fault heterogeneity – can we define areas of fault that have earthquakes of similar properties?



Spectrum of Fault Slip



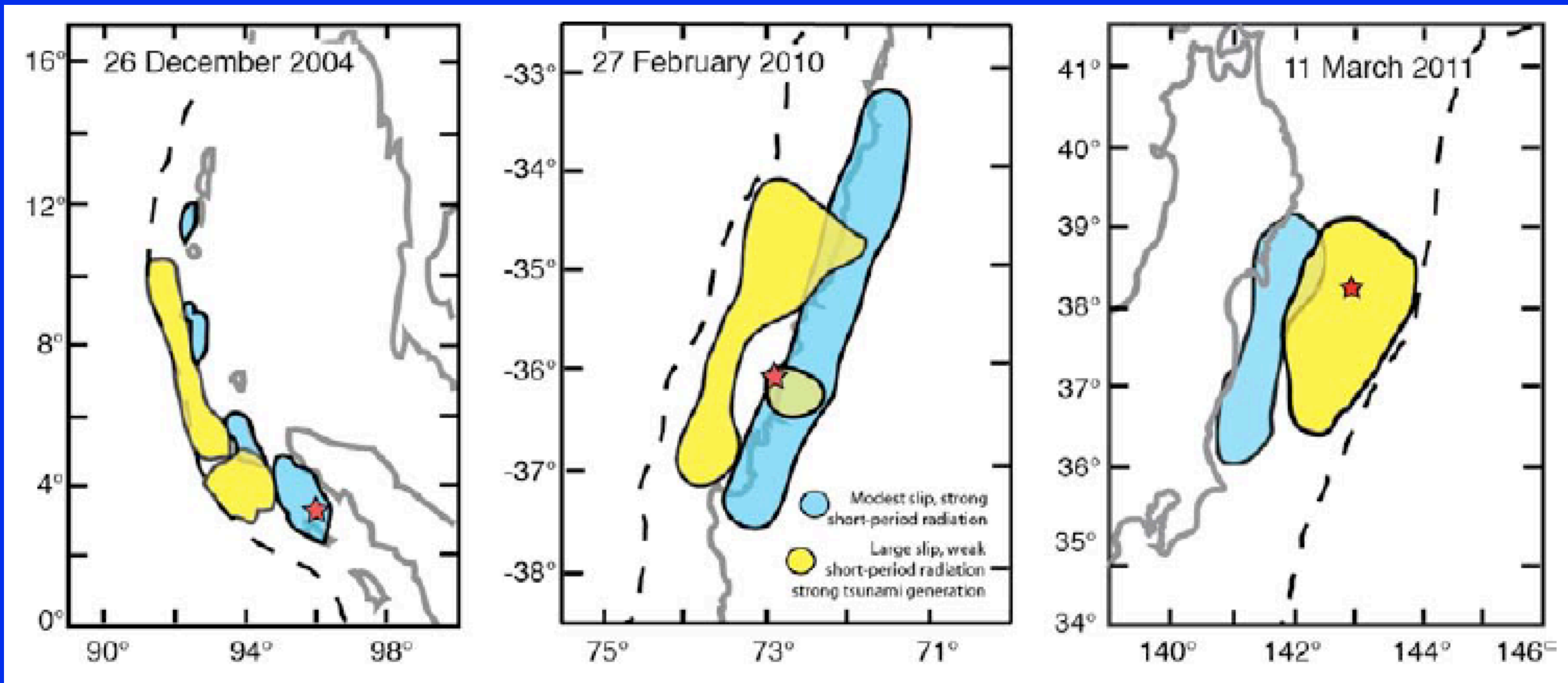
New observations and analysis in recent ~15 years have taken us far beyond considering "normal" earthquakes

Many scientific targets in Earth Science today relate to understanding behavior and controls on this slip spectrum

Focus mostly here today, but also touch on transitions between groups

Saffer et al., 2009

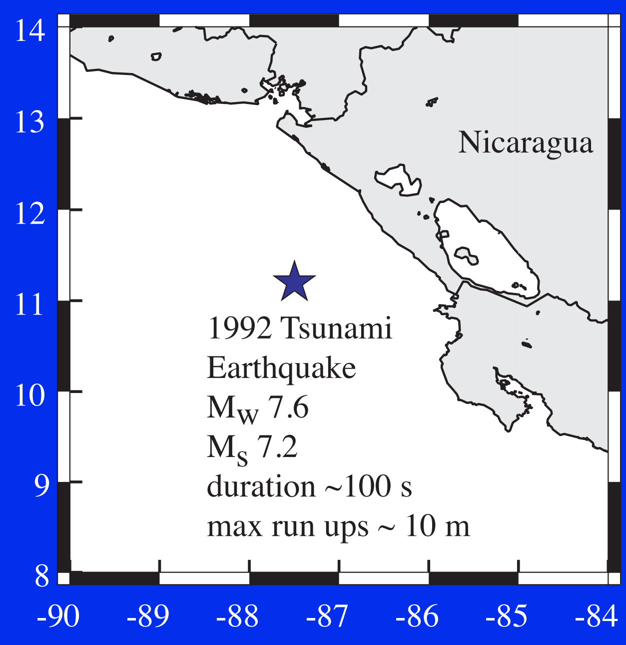
Depth dependence of high frequency seismic radiation

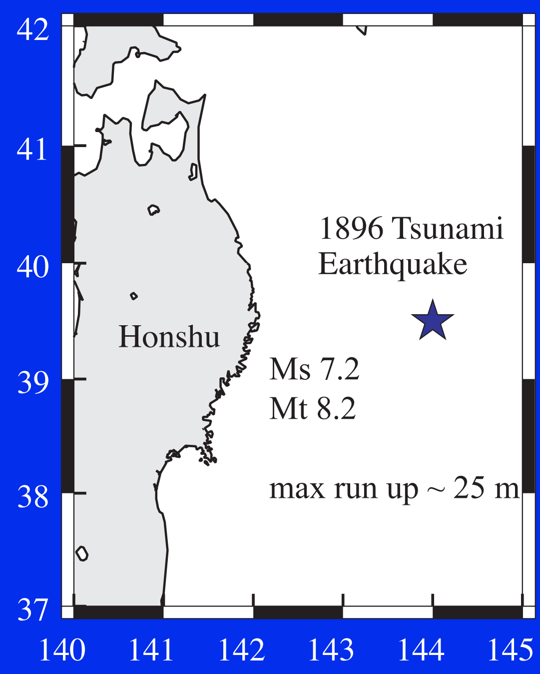


Lay et al, 2012, *Koper et al*., 2011, *Ishii*, 2011, and others

Evidence in large subduction zone ruptures – downdip part of fault has largely short-period radiation, updip part of fault has larger slip, but relatively weak short-period radiation

Tsunami Earthquakes





Subset of documented earthquakes are puzzles….

- Large tsunami generated, but not from "giant" earthquakes (M 9 2011 Tokohu event)

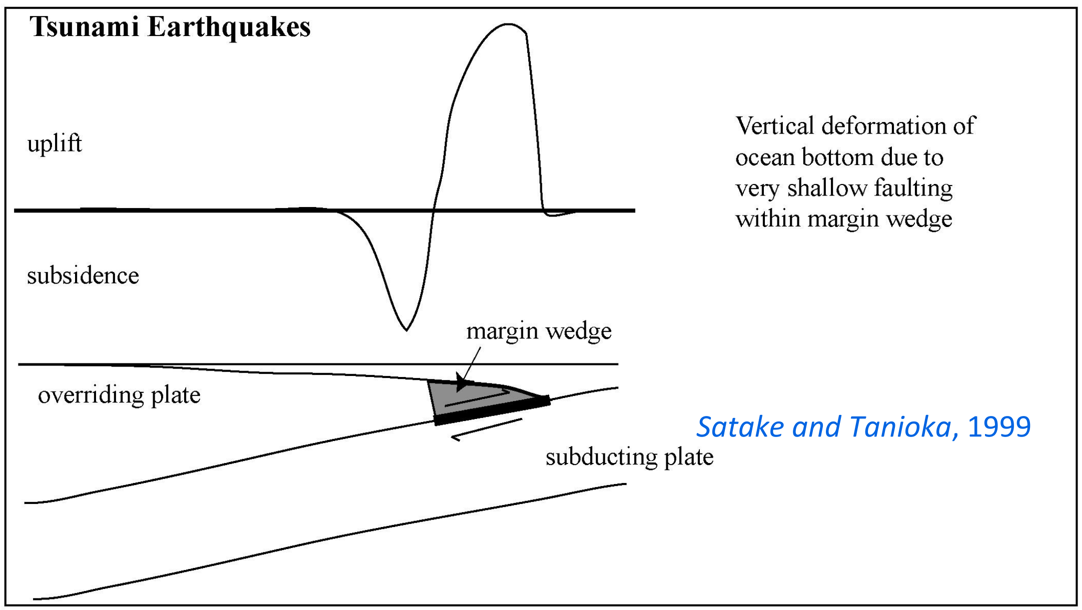
- Events have very long rupture durations, long-period magnitudes larger than short period magnitudes, deficient in high frequency seismic radiation

- Also tend to be very shallow slip… an important clue

Tsunami Earthquake Slip

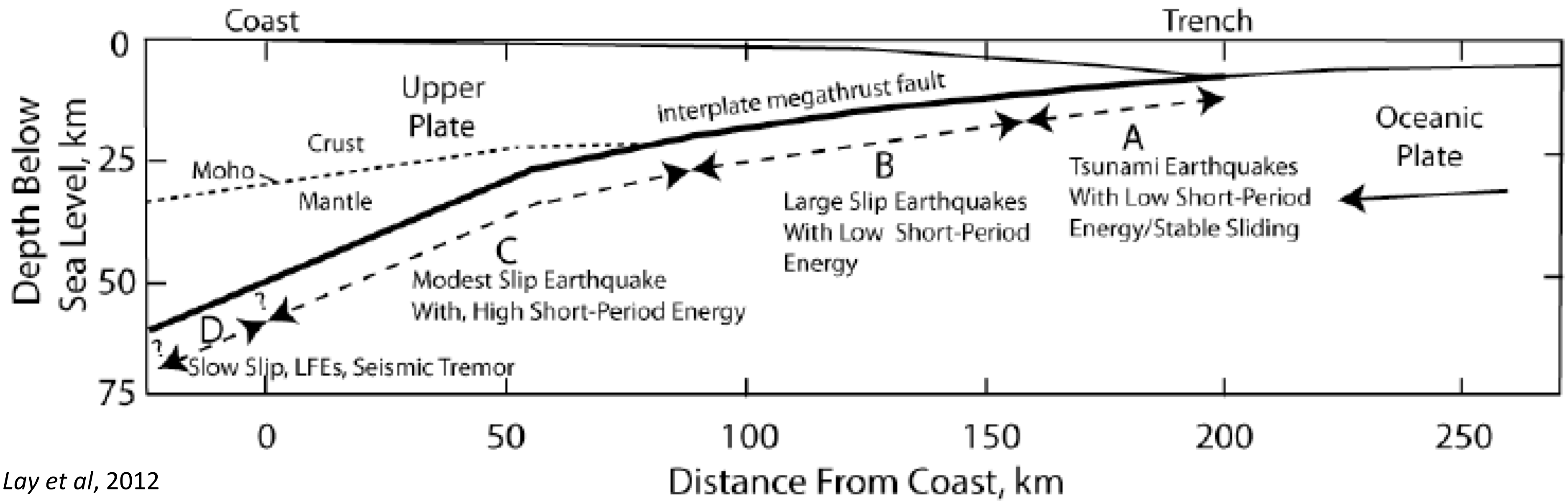
Likely model for tsunami earthquakes:

- Large slip in *shallow* portion of subduction zone
-
- Long durations due to low rupture velocity
    - in shallow subduction zone – can easily have weaker (and heterogeneous) lithologies, heterogeneous (and low) friction, fluids to reduce Vr



Satake and Tanioka, 1999

Depth variation of rupture characteristics

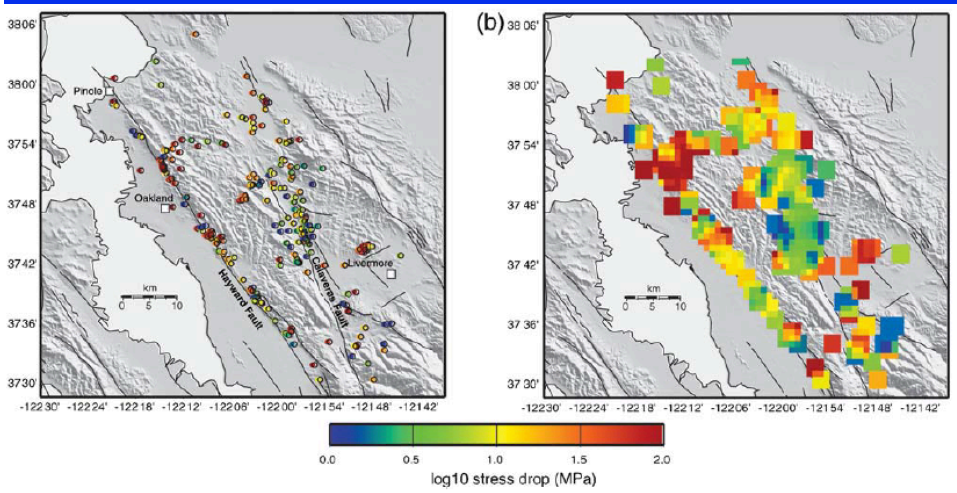


Lay et al, 2012

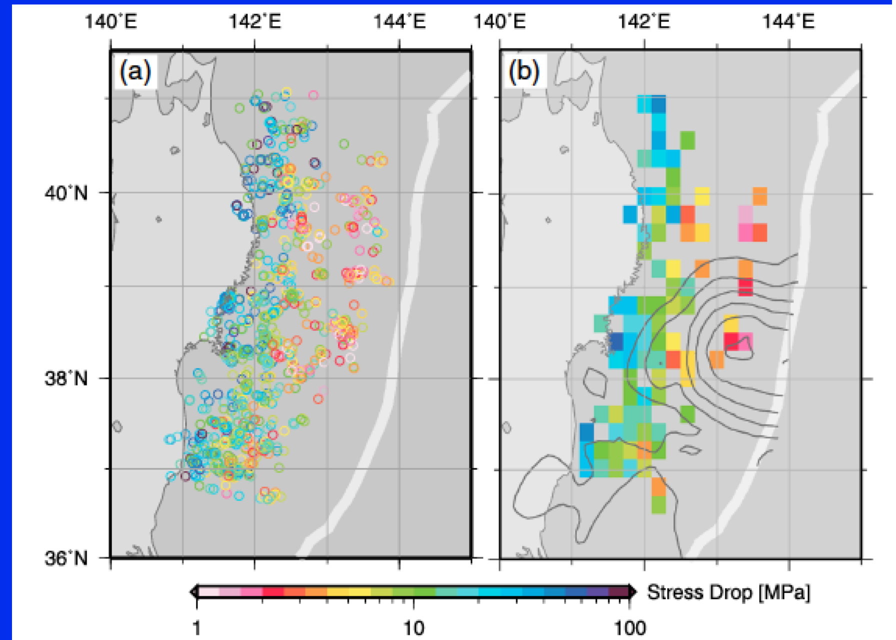
Model of shallow subduction zone used to characterize several observations for earthquakes in subduction zones -- needed because of the wide variety of slip behaviors now observed

But….

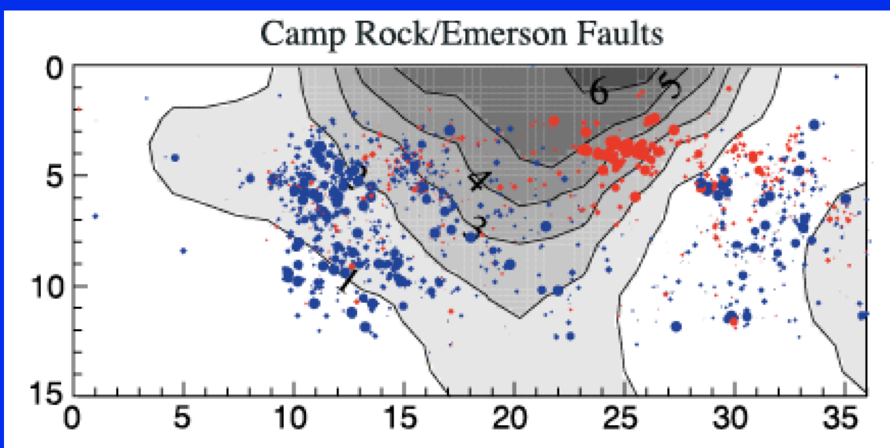
Fault Zone Heterogeneity – Extends along strike



Variations in stress drop along Hayward fault, linked to strength variations (*Hardebeck and Aron*, 2009)

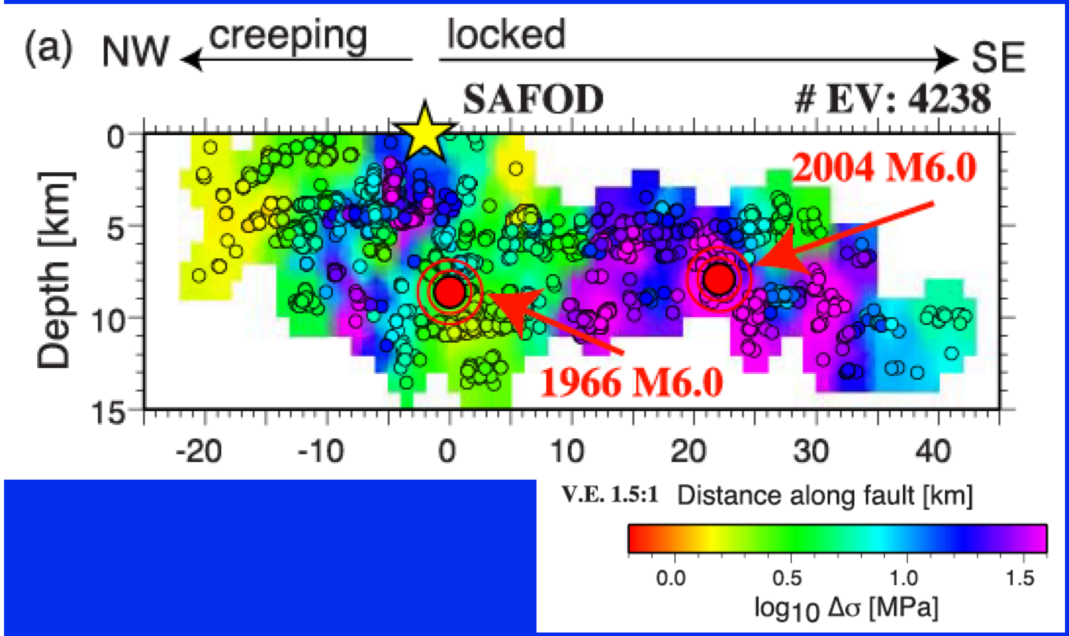


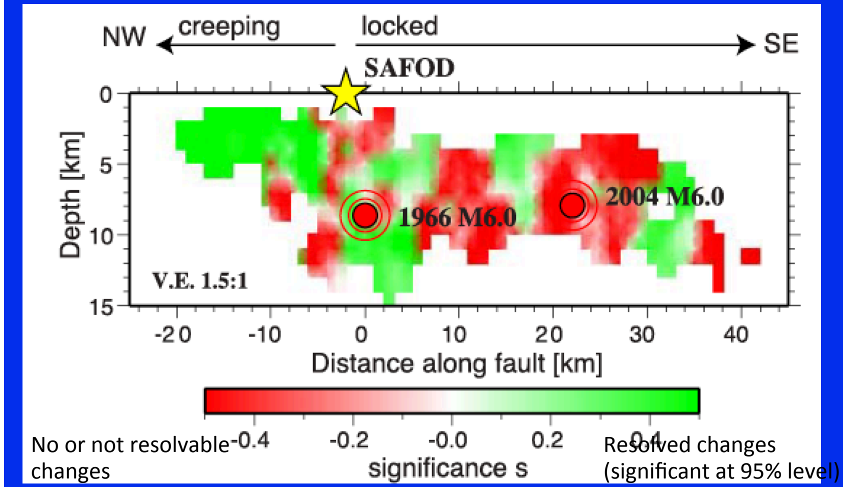
Stress drop for Japan trench earthquakes before 2011 Tohoku (*Uchide et al*, 2014)



Stress drop (blue high, red low) along one fault segment from 1992 Landers – variable along fault – inversely correlated with high slip (*Shearer et al.*, 2006)

Fault Zone Heterogeneity – Extends along strike and in time





Spatial variations in stress drop along portion of San Andreas, with higher values in area of eventual 2004 M6 event

Low values of $\Delta\sigma$ in creeping section of fault

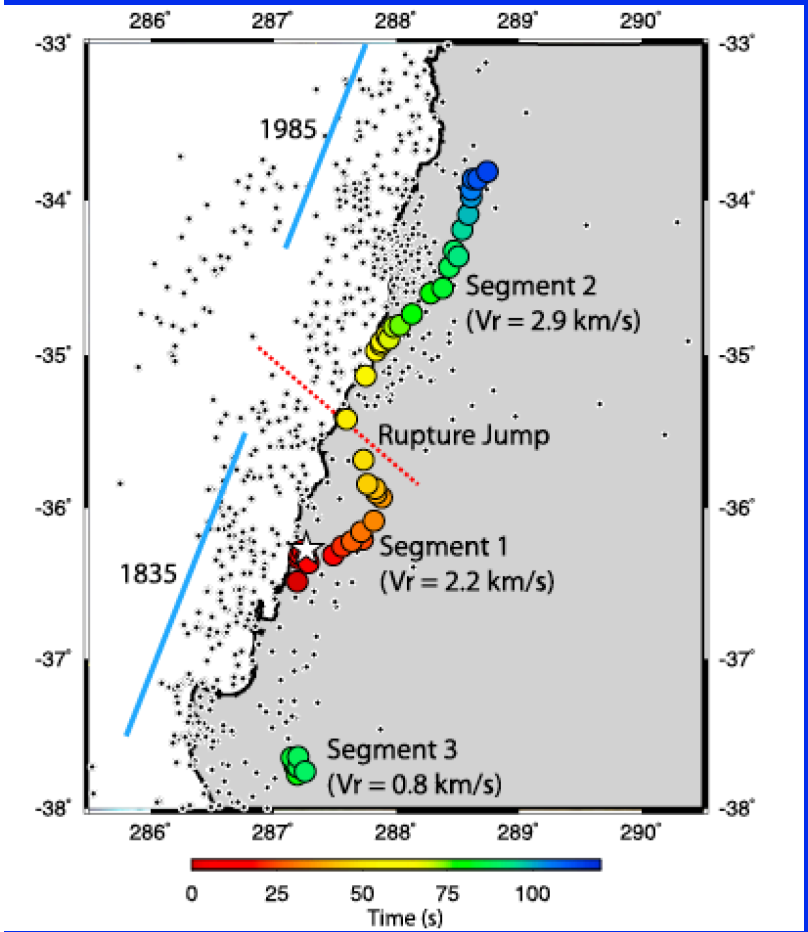
Indicative of fault variations?

Temporal variations – resolvable stress drop changes from before and after 2004 event

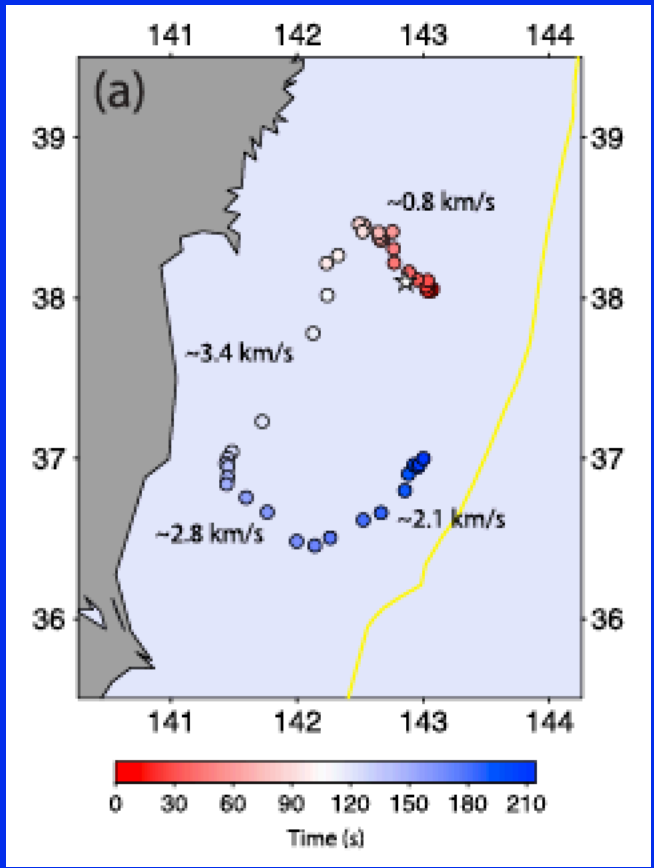
Allmann and Shearer, 2007

Variable V_r within fault zone

Kiser and Ishii, 2011

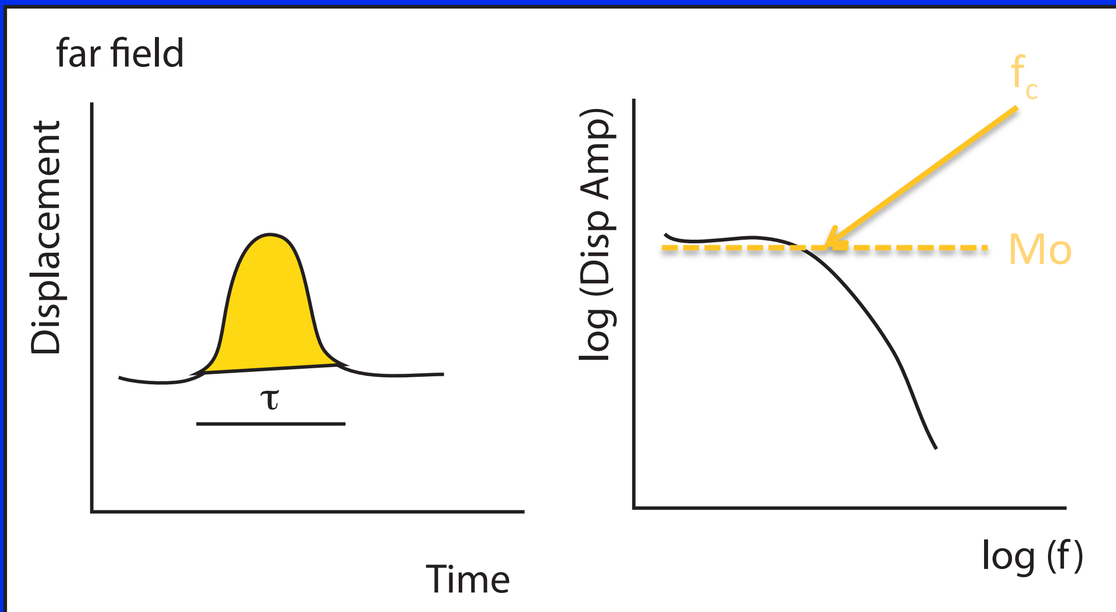


Kiser and Ishii, 2012



Proposed segmentation and rupture velocity variations along 2010 Chile M 8.8 and 2011 Tohoku M 9 rupture zone

Tools for exploring source variations – using the seismic data



Use seismic data, in time or frequency domain, to understand size and timescale of rupture, use to estimate stress drops and/or rupture velocities

Thanks Joan!

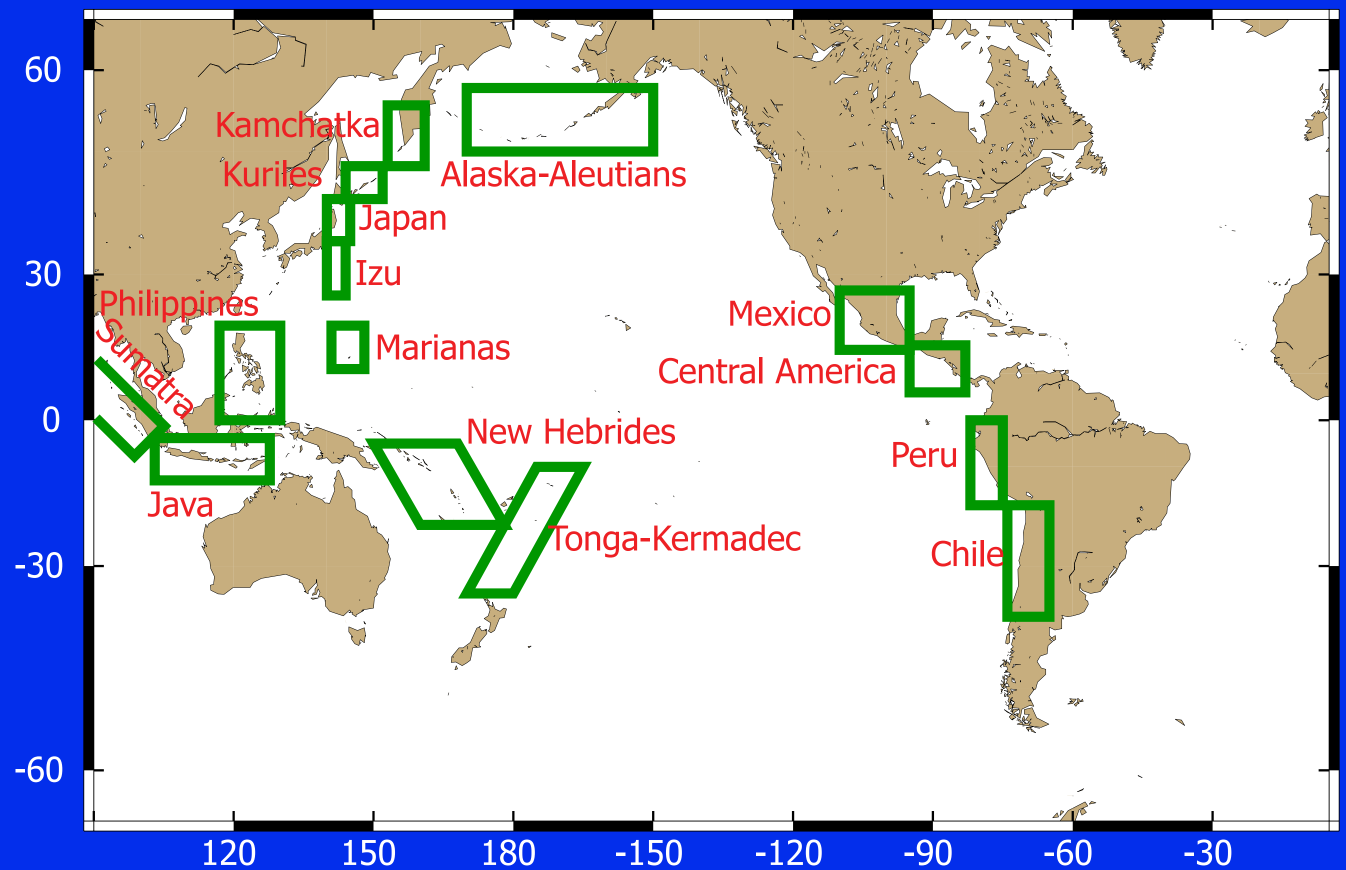
Far-field displacements related to time derivative of the moment tensor

In time domain, pulse width of displacement pulse related to rupture time of the earthquake, area under curve proportional to seismic moment (M_o)

Using displacement spectra, f_c inversely proportional to τ, often used to compute stress drop

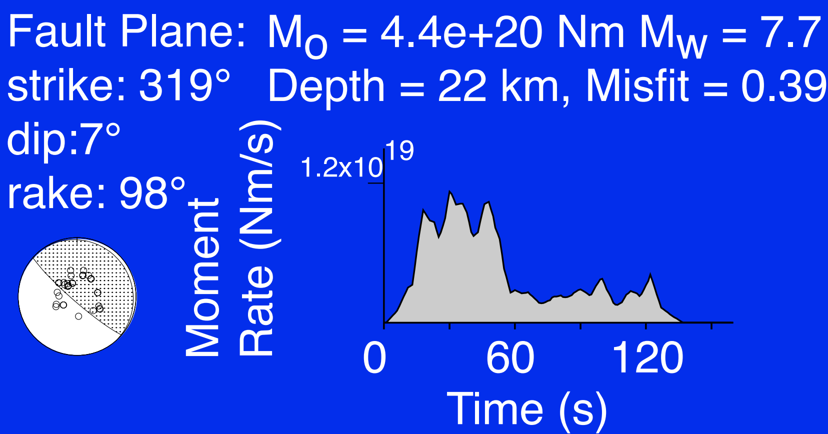
Global Survey of Earthquake Source Parameters

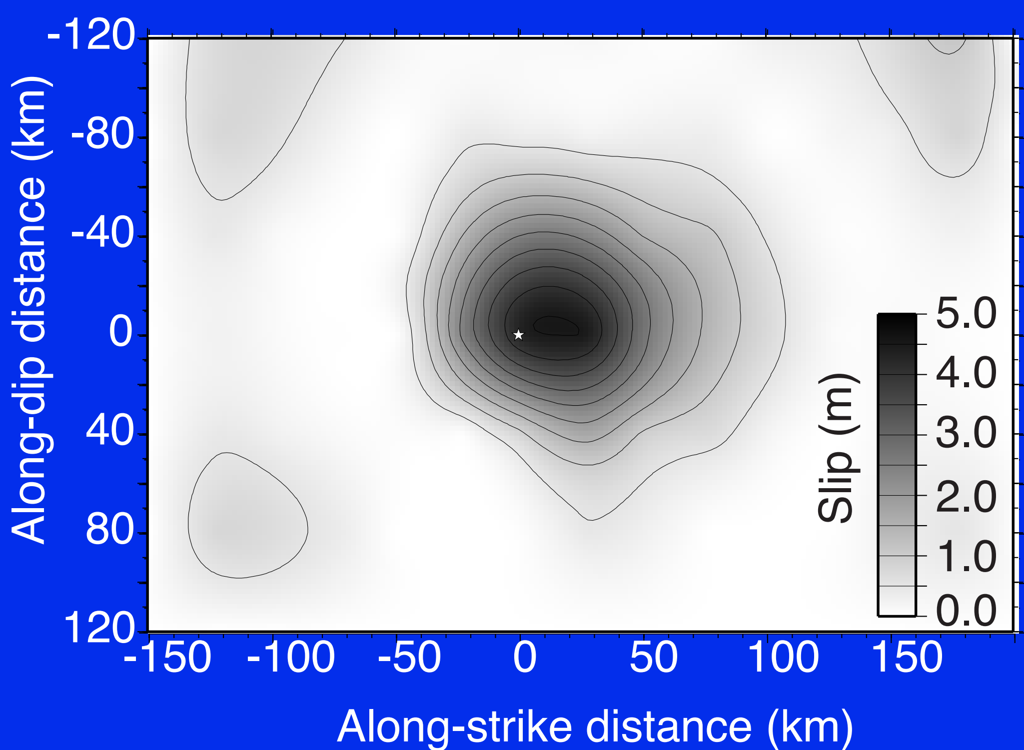
Focus on:
Pulse width
(Duration)



- Why?
  - Can be linked to rupture velocity or fault area
  - Using link to rupture velocity:
    - Long durations -- slower rupture velocity
    - Can link to fault properties that could lead to lower Vr

Source Parameter Determination





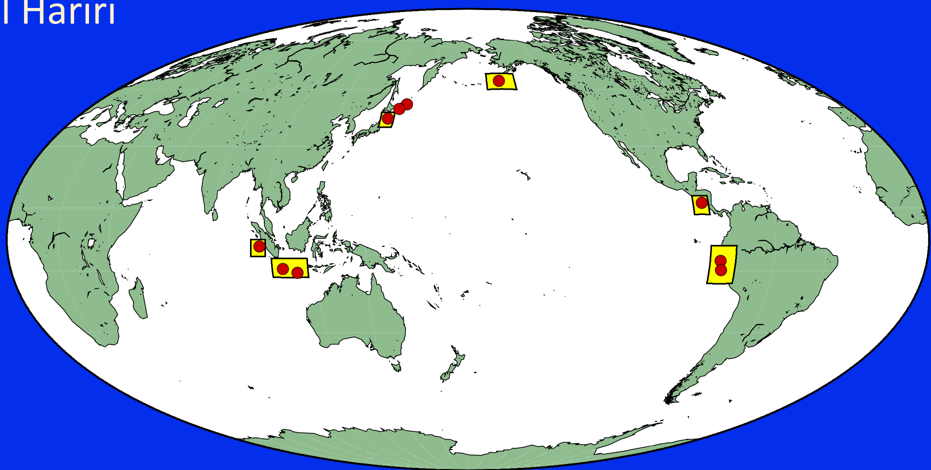
Use variety of techniques, including body wave and surface wave deconvolution; finite fault inversion results to determine source time function for all, plus slip distribution for larger events

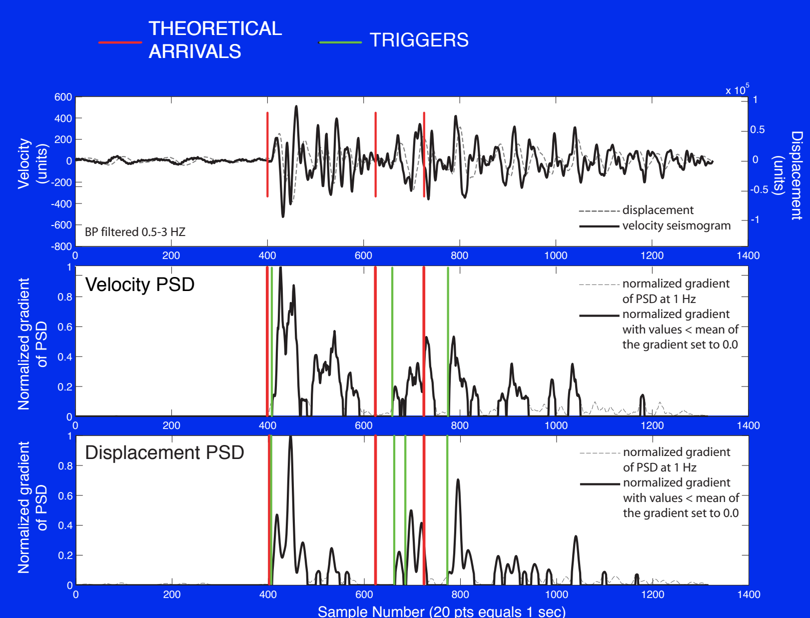
Example Event: 2010 Sumatra
- 20 P waves, 12 SH waves
- fault plane grid of 25 km along strike, 40 km along dip
- subevent moment pulses of 5 overlapping triangles, 10 s duration

Results: concentrated slip patch near and updip of hypocenter, ~130 s long rupture (~16 s moment-normalized duration)

Earthquake Relocations

Work with Heather DeShon,
Bob Engdahl, Maya
El Hariri





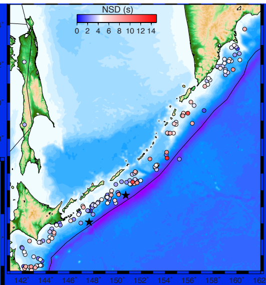
From DeShon et al., 2007 (AGU)

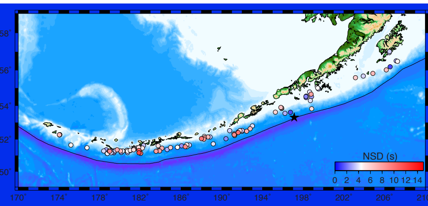
improved locations by using Engdahl et al. (1998) relocation techniques, including use of ak135 velocity model, first arriving P, S, PKP phases, depth phases

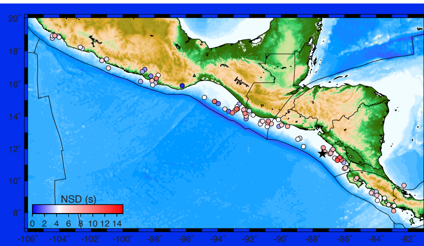
- improved depth estimates using additional/revised depth phase arrivals determined using time picks based on power spectral density functions (*DeShon et al.*, 2007)

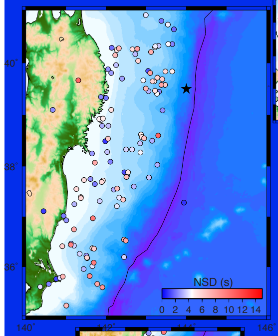
Example of improvements:
Japan:

- 27% reduction in depth uncertainties for events
- 2x of events with depth phase arrival picks









Large Earthquake Results

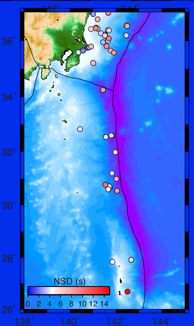
698 events in 10 subduction zones

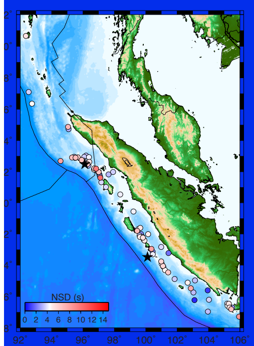
1989-2012

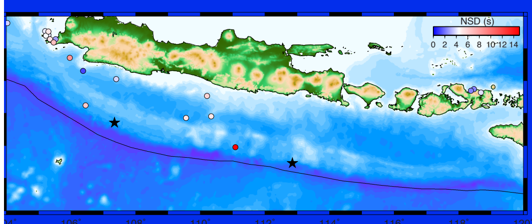
Mw 5.4-8

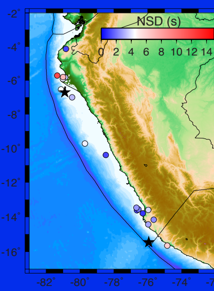
Normalized Duration: 0.3-16 s (median 4.25 s)

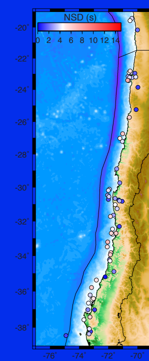
Depth: 5-61 km (median 25 km)

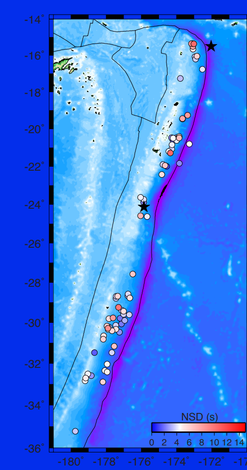


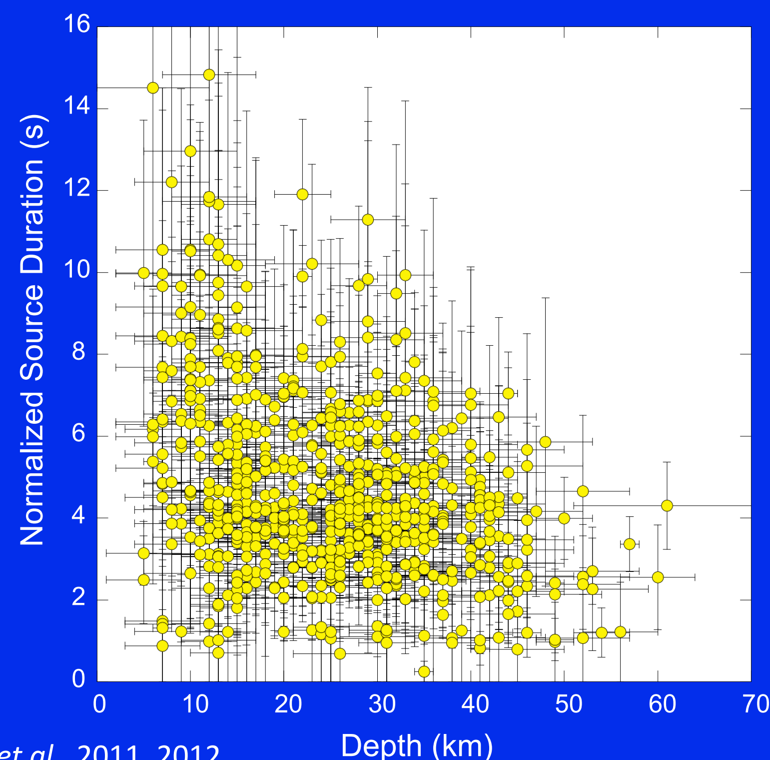








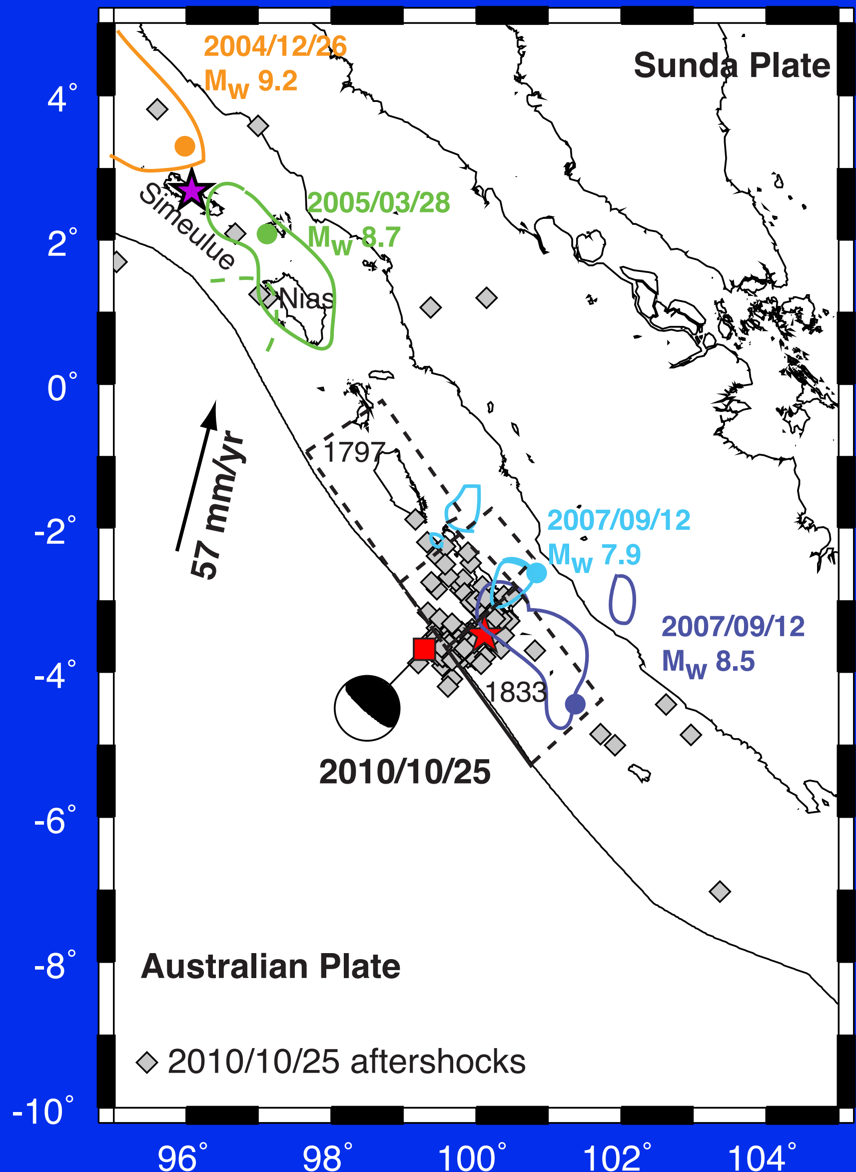




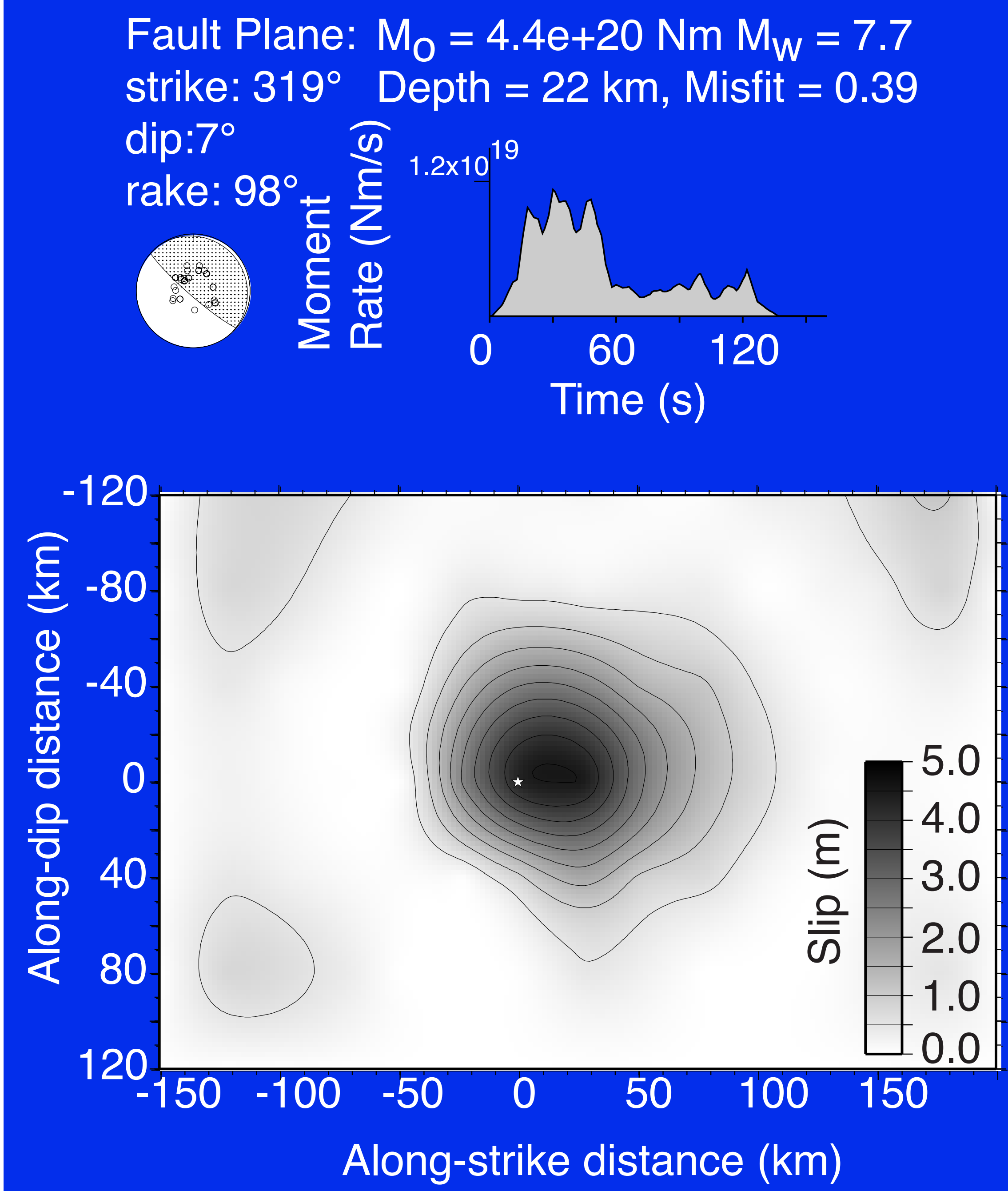
El Hariri et al, 2013, *Bilek et al.*, 2011, 2012

Are there patches of the fault that consistently produce long-duration events?

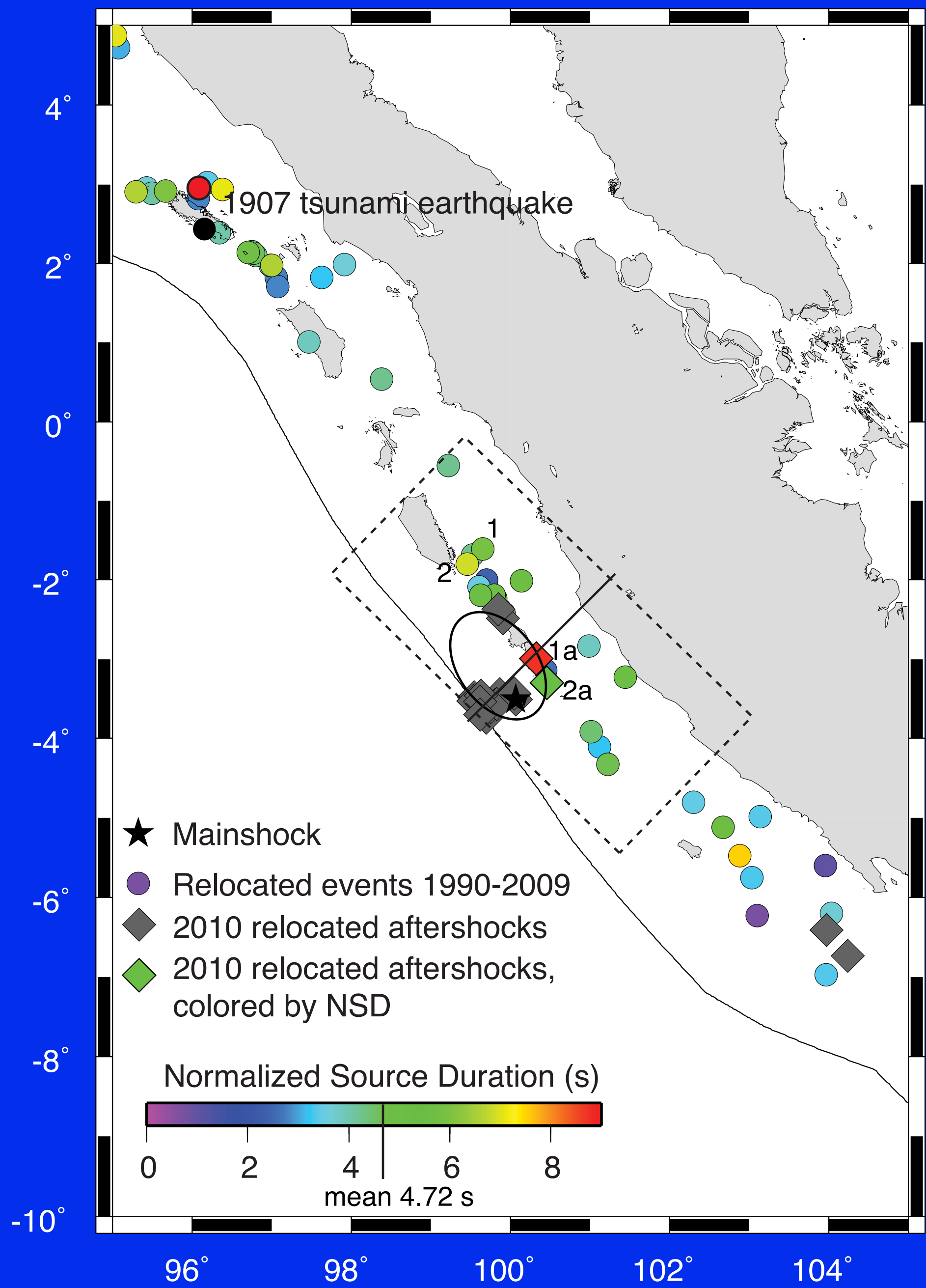
2010 Sumatra tsunami earthquake

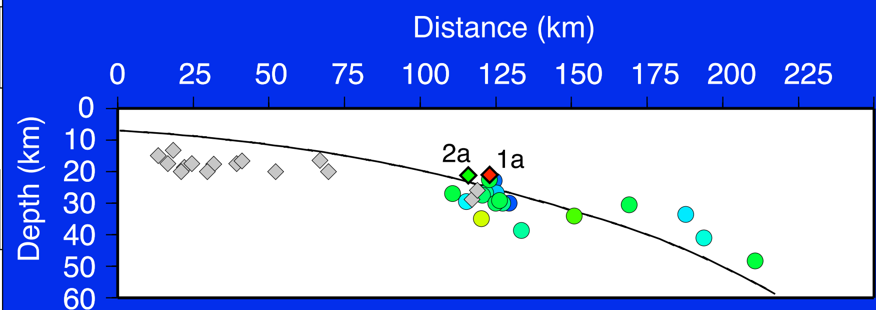


- Most recent tsunami earthquake (25 October 2010, mb=6.5, Ms=7.3, Mw=7.7)
- Tsunami caused peak run-ups of 2.5-9 m
- Over 400 fatalities
- Occurred in region south of 2004/2005 events, in region of past large earthquakes (1797, 1833, 2007)



Use waveform modeling techniques to solve for moment-rate function (duration) and define high slip area for the tsunami event





Aftershocks of 2010 event

- Majority are updip
- 2 have long normalized durations

Previous seismicity

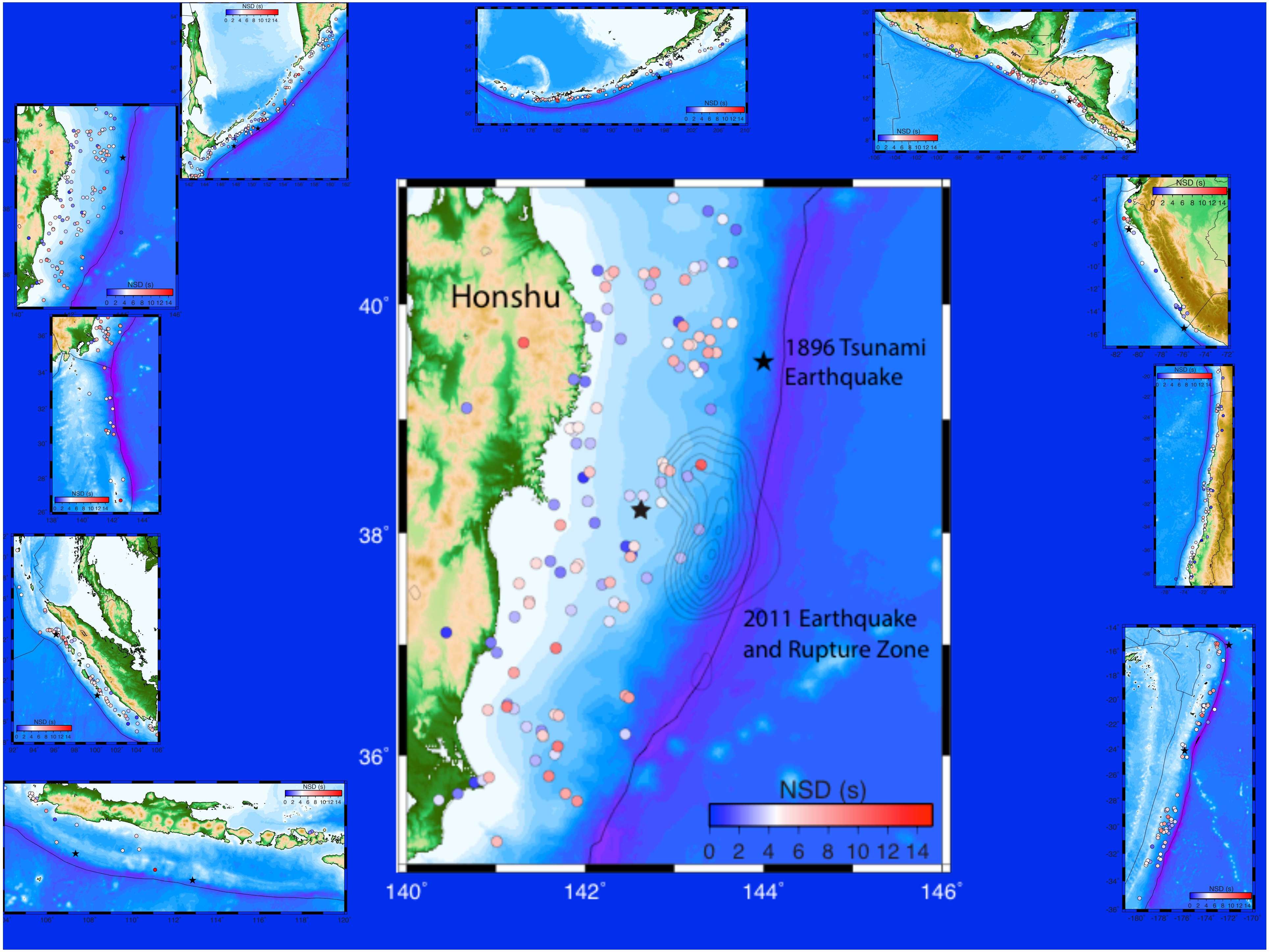
- 2 events (2005, 2007) have long durations, occur at northern edge of 2010 rupture zone

Region of 1907 tsunami earthquake

- 2 events with long durations
- Boundary between 2004 and 2005 great earthquakes where *Dean et al* (2010) suggest change in decollement and lowermost sediment properties

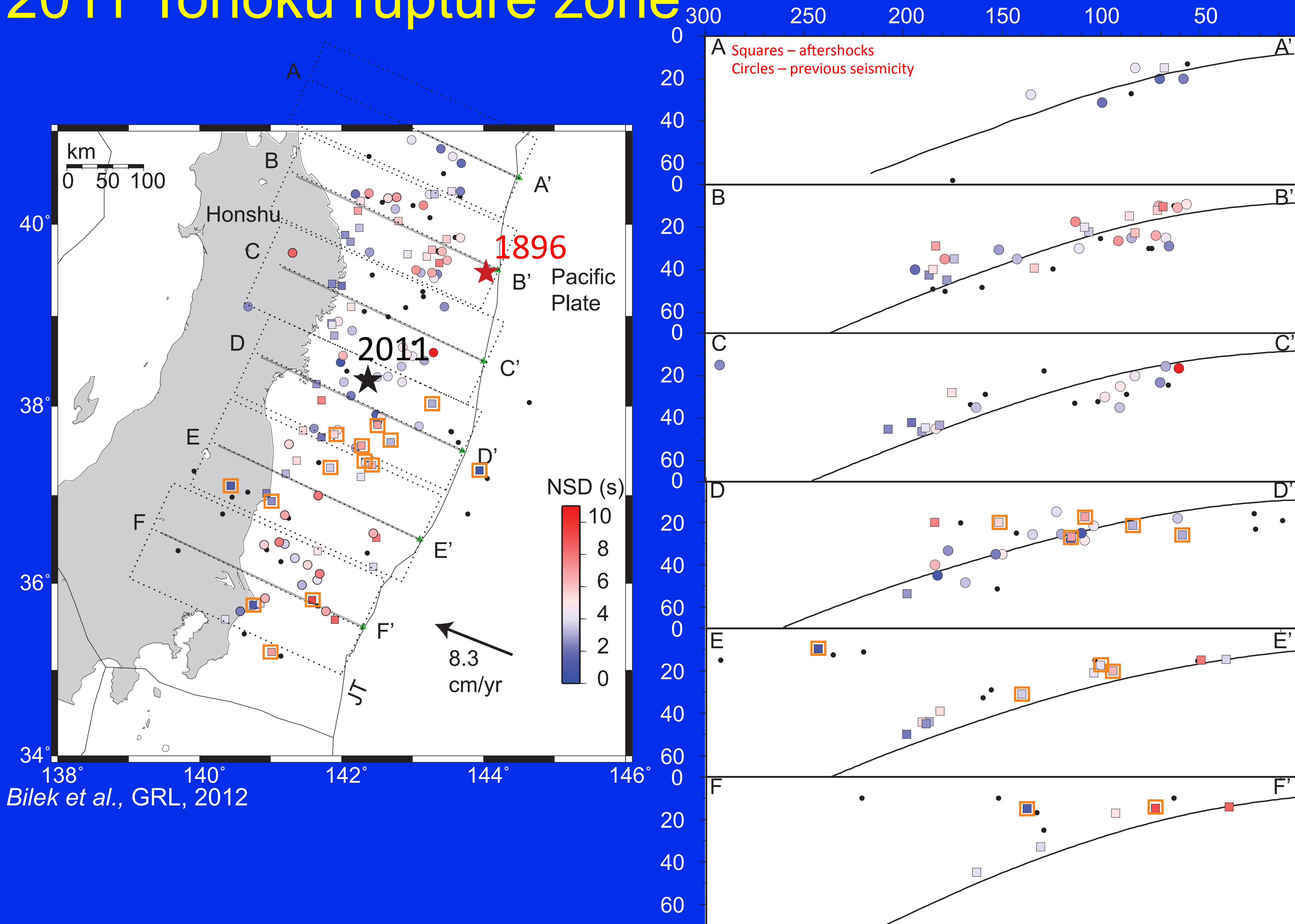
Results have implications for possible spatial distribution of slow slip, temporal stability of fault zone conditions

Bilek et al., 2011



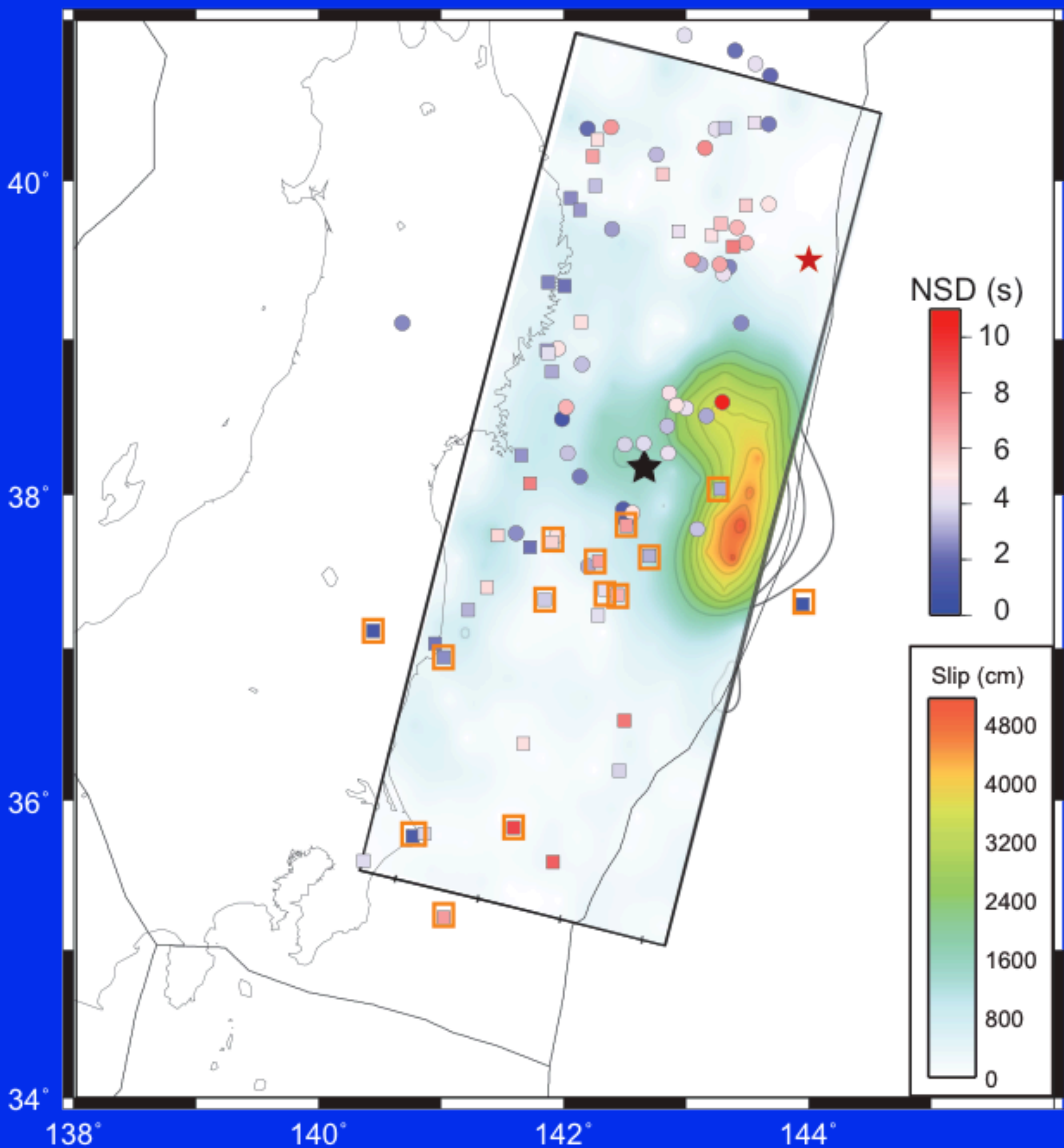
Honshu
1896 Tsunami Earthquake
2011 Earthquake and Rupture Zone
NSD (s)
0 2 4 6 8 10 12 14
40°
38°
36°
140°
142°
144°
146°

2011 Tohoku rupture zone



Bilek et al., GRL, 2012

- Concentration of long duration events in 1896 tsunami earthquake zone

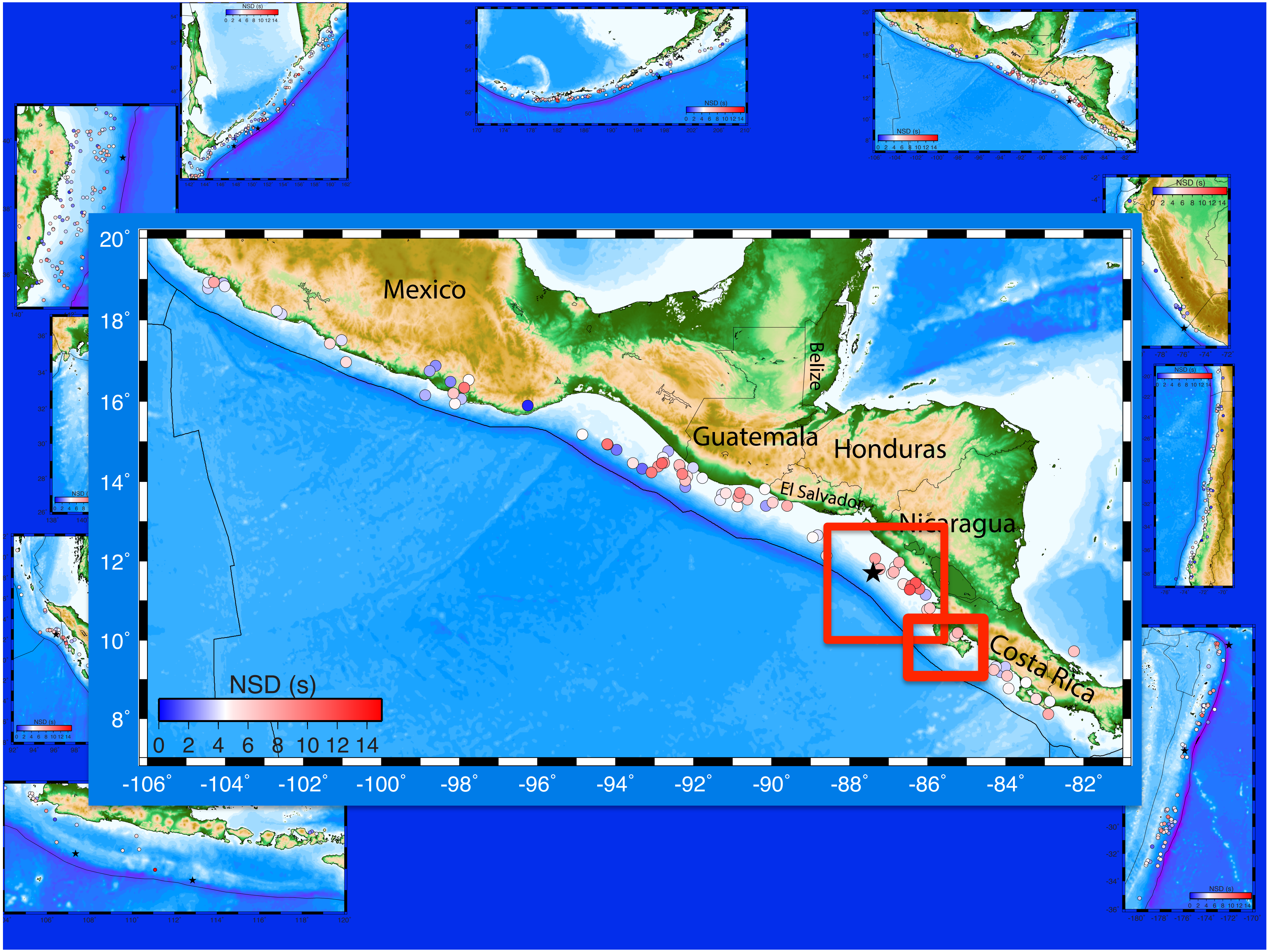


Comparison with 2011 Tohoku slip distribution:

-Longest duration event occurred 1 day prior to mainshock in area of moderately high slip

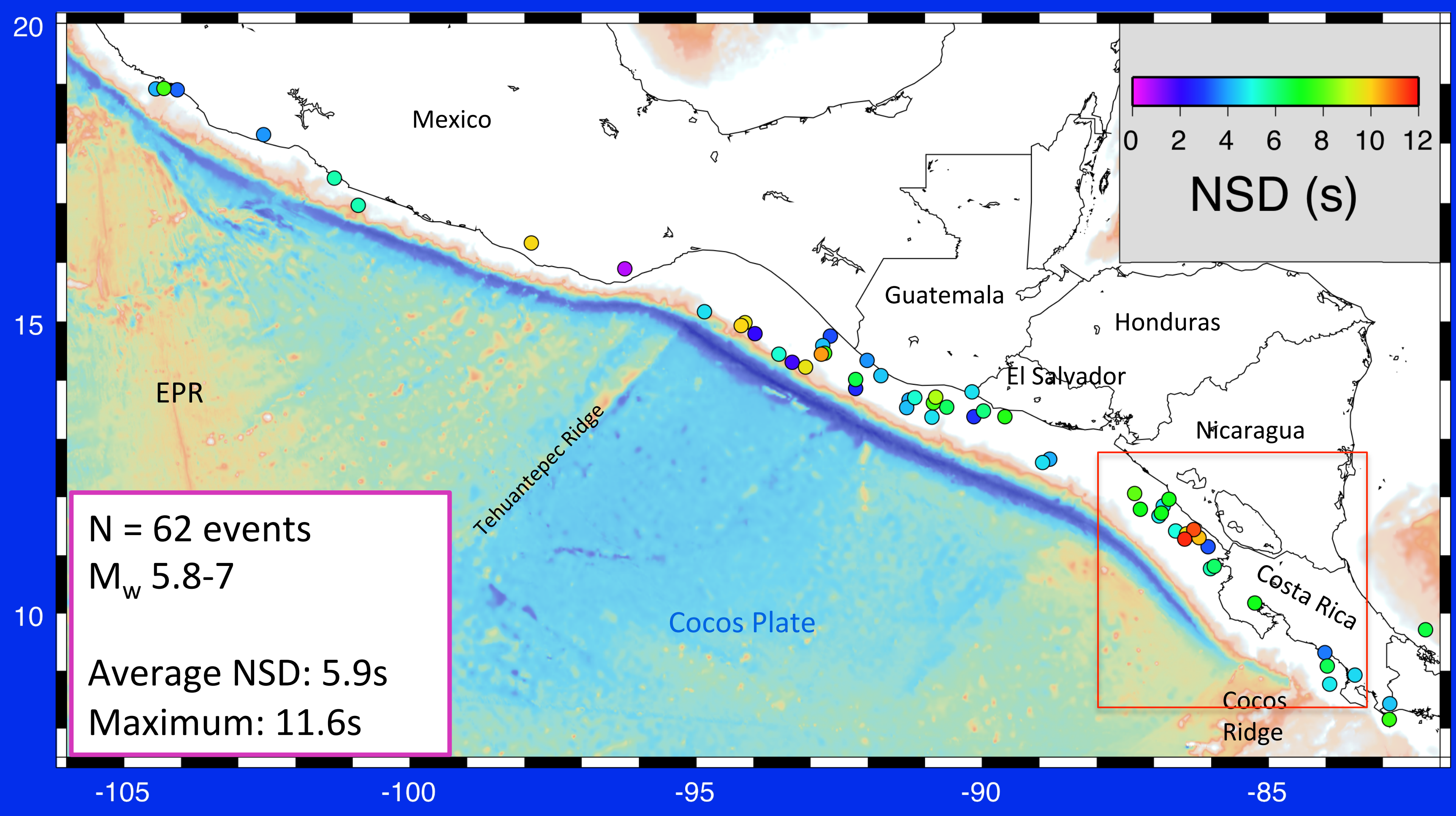
-Aftershocks scattered throughout without much overlap in high slip zone

- No clear trend of short duration events only at downdip end of slip zone (as might be expected in downdip source of high-frequency radiation)



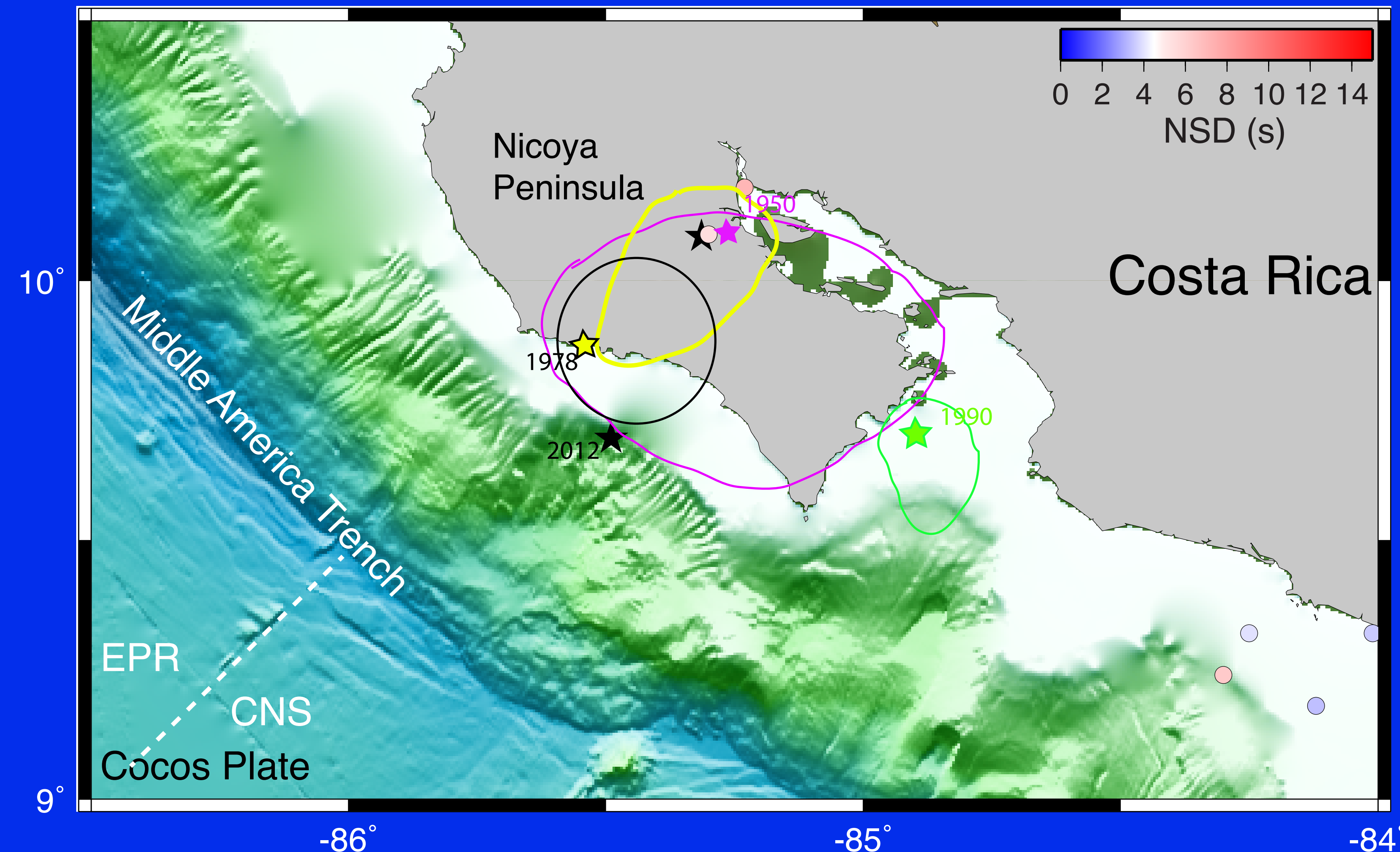
Mexico
Belize
Guatemala
Honduras
El Salvador
Nicaragua
Costa Rica
NSD (s)
0 2 4 6 8 10 12 14
20°
18°
16°
14°
12°
10°
8°
-106°
-104°
-102°
-100°
-98°
-96°
-94°
-92°
-90°
-88°
-86°
-84°
-82°

Central America Margin



Source duration is highly variable along the Central America margin, with several regions of significantly long duration events.

Costa Rica – Nicoya Peninsula

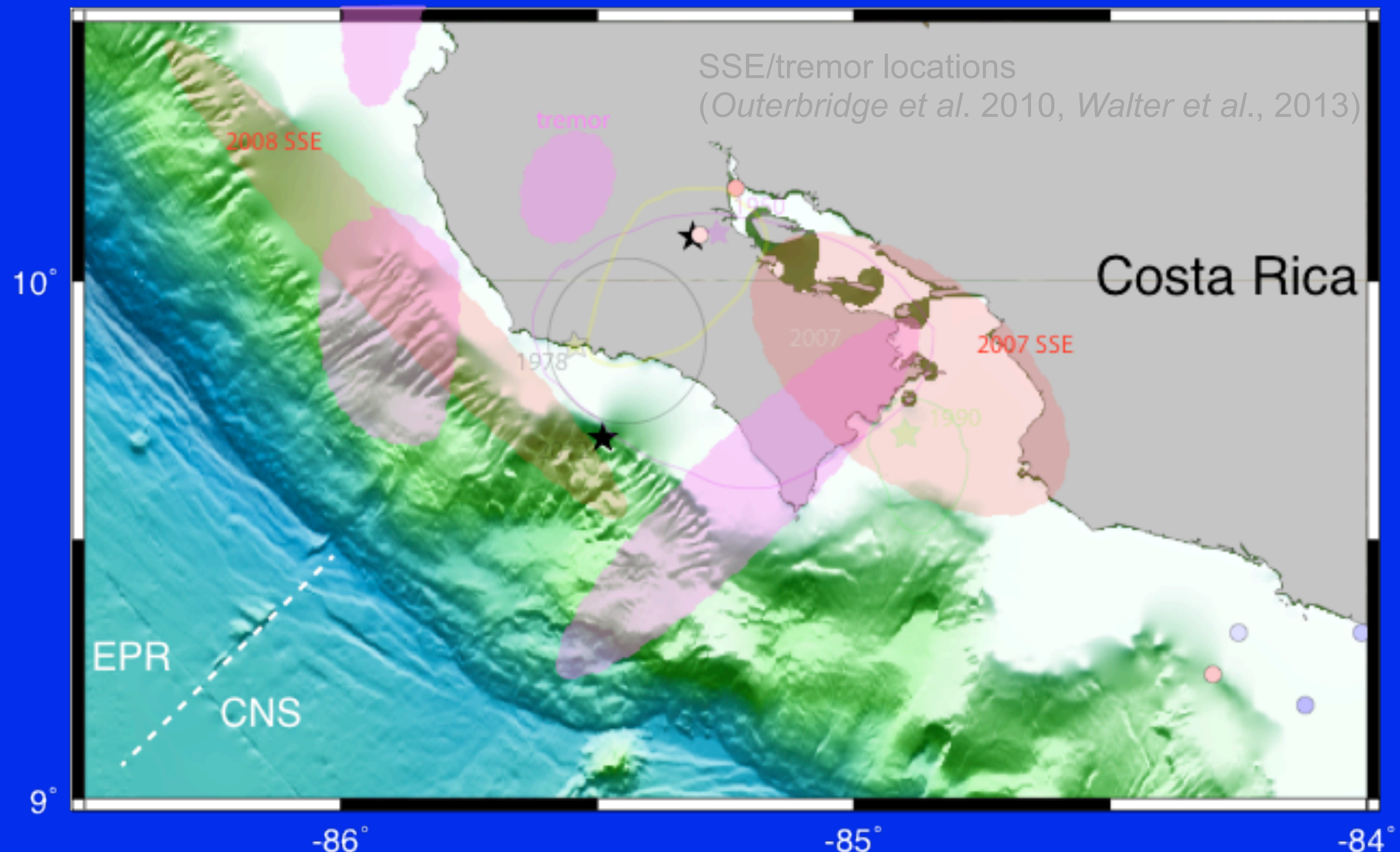


M > 7 earthquakes along southern Nicoya Peninsula in 1950, 1978, 1990, 2012

Geologic conditions – complex

How does this heterogeneity affect earthquakes/slip?

Costa Rica – Nicoya Peninsula

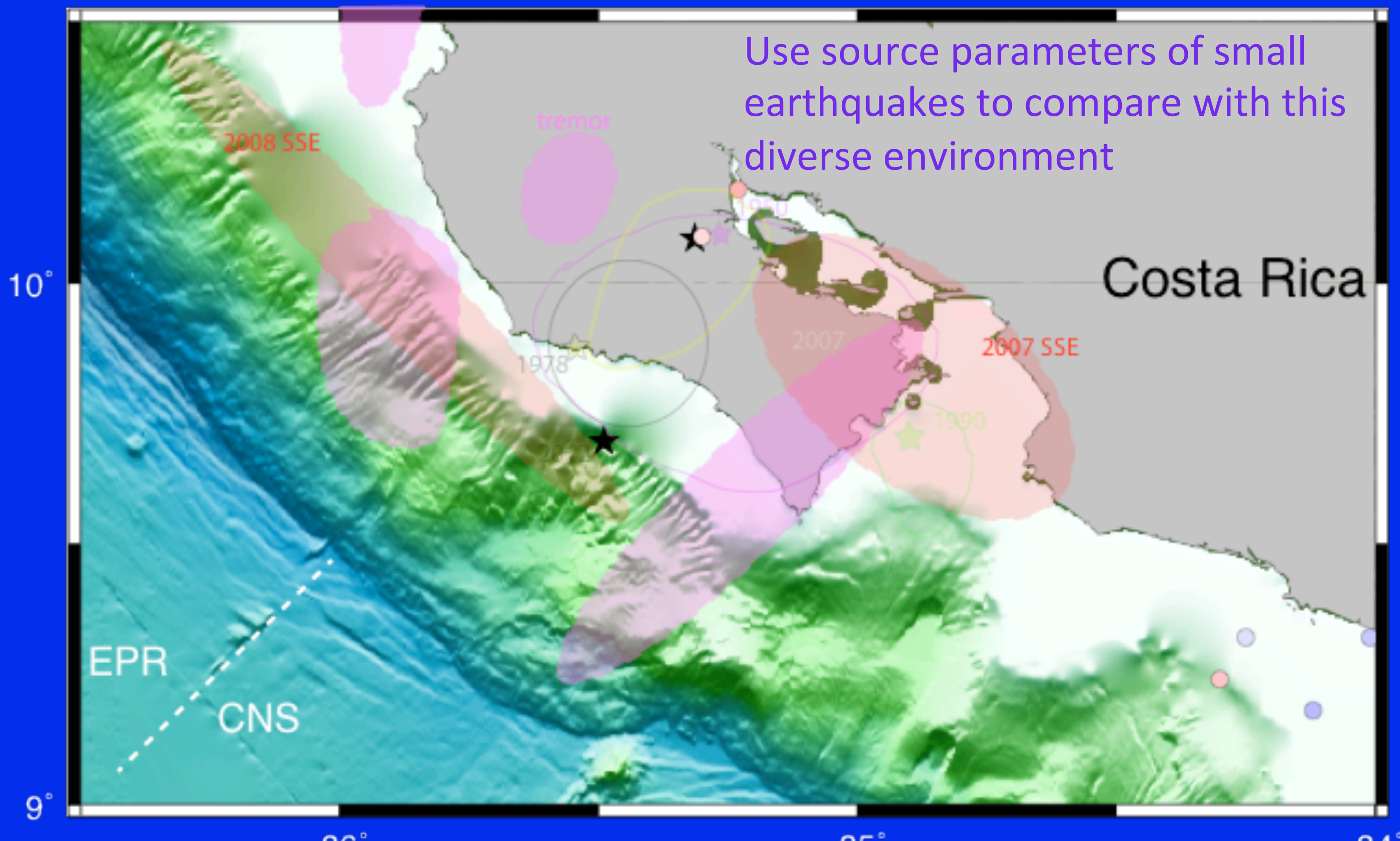


Complex tremor and slow slip patterns – both updip and downdip tremor and SSE

Ide (2012) suggests tremor patches linked to subducted structures – spatial heterogeneity of incoming plate important for tremor processes

Zhang et al. (2011) suggests tremor have very low stress drops (few kPa)

Costa Rica – Nicoya Peninsula



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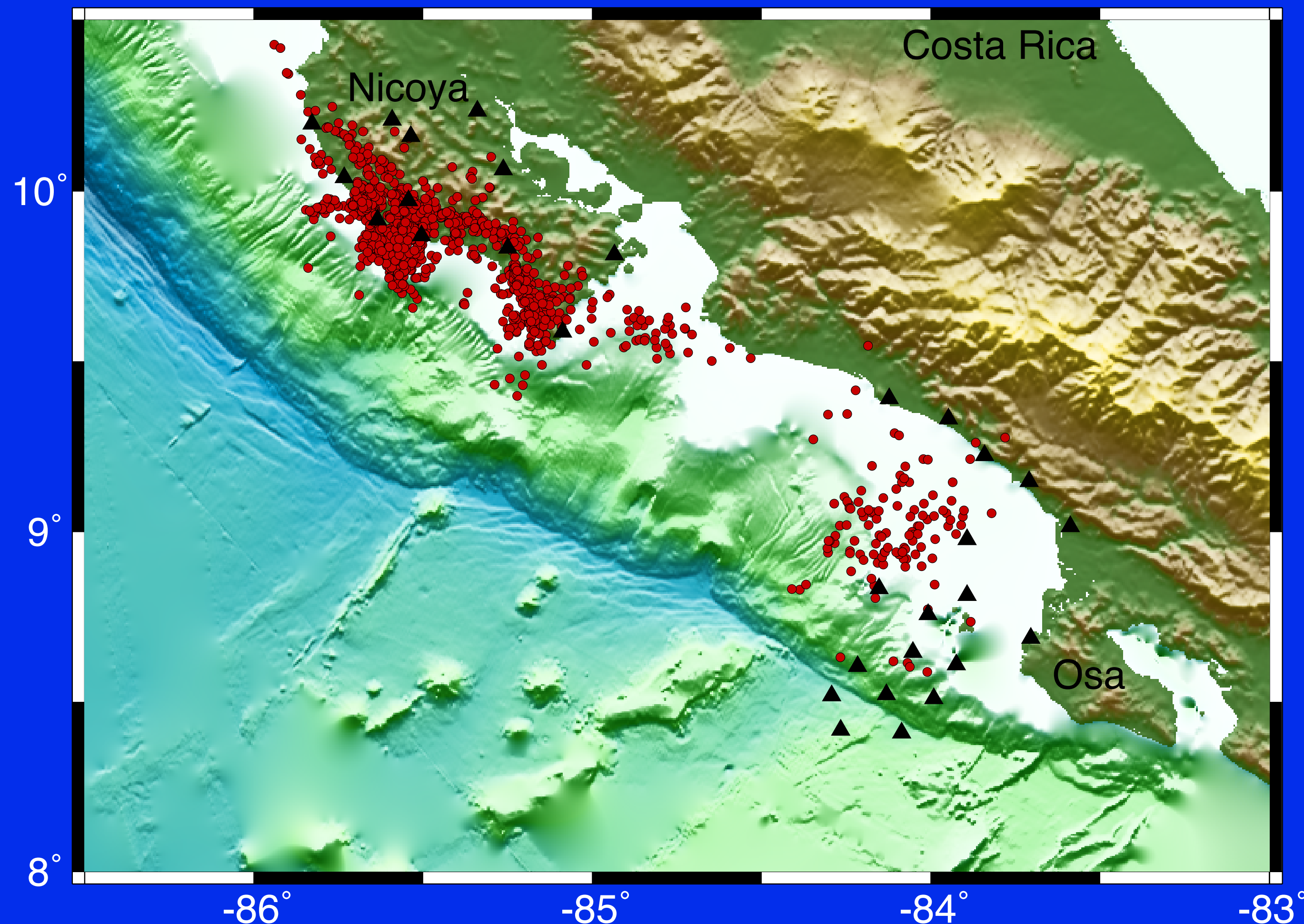
Costa Rica Dataset



Time periods:
Osa: 1999 (3 months, 114 events)

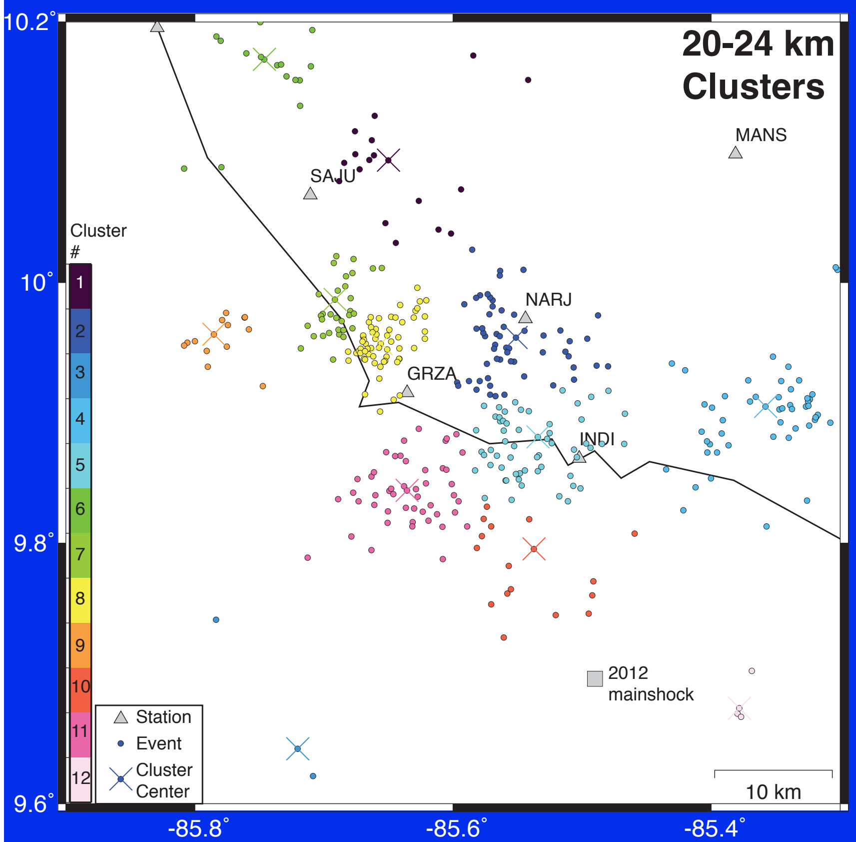
Nicoya: 2012 (Sept 5-Oct 2, 1054 events)
1999-2001 (73 events)

Total Events: 1241

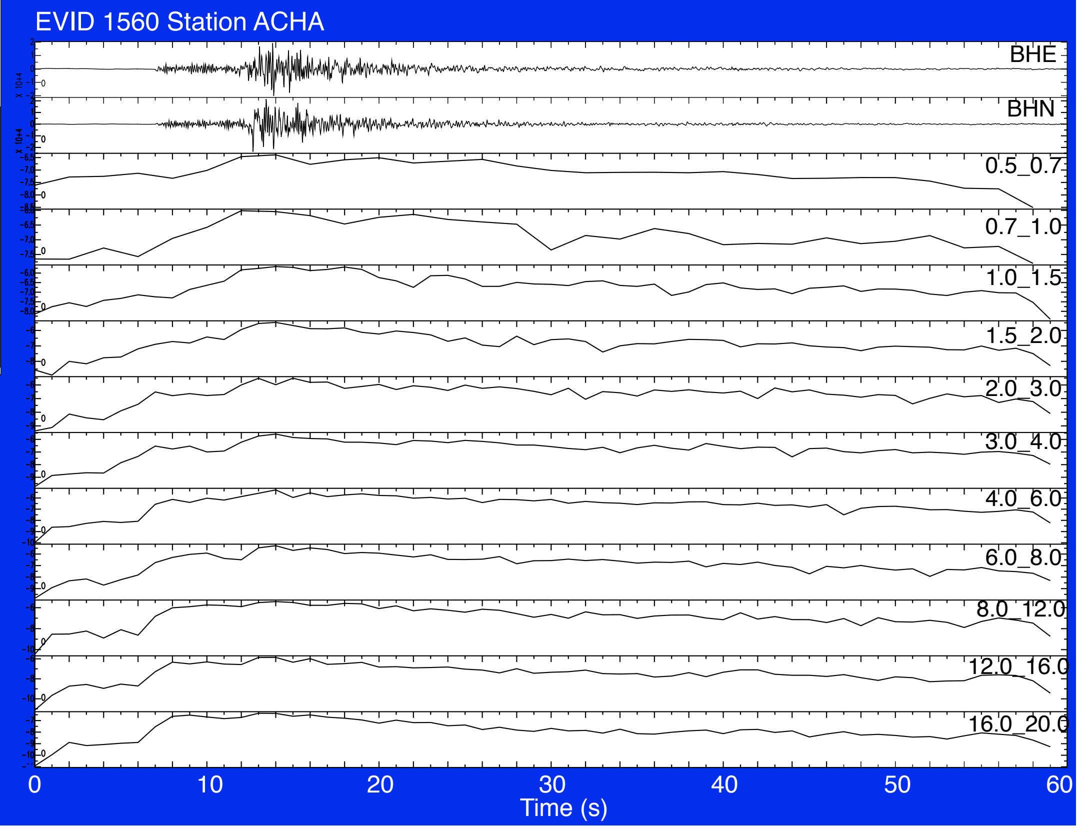
Magnitude range: 1.5-5

Stations: Mix of 3 component BB and SP land, OBS

Source Parameter Methods – Event Clustering and Envelopes

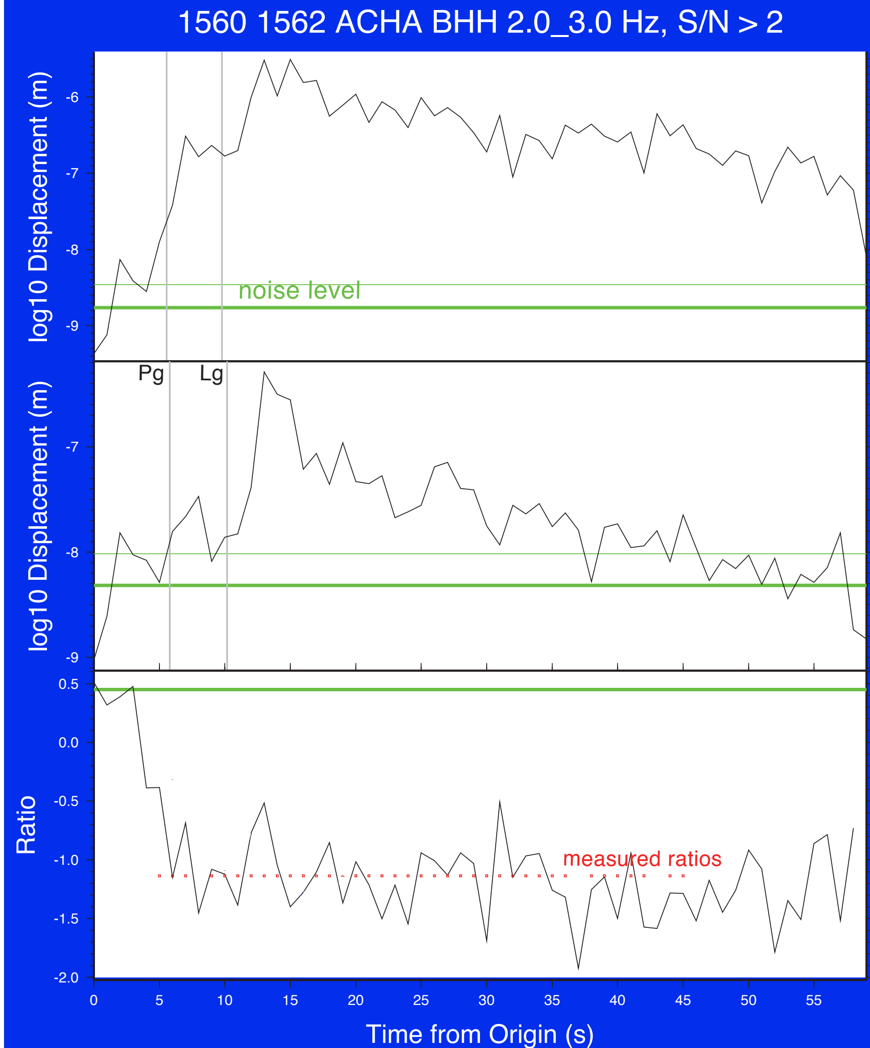


For each event within a cluster, combine horizontal components and compute envelopes at specific narrow frequency bands



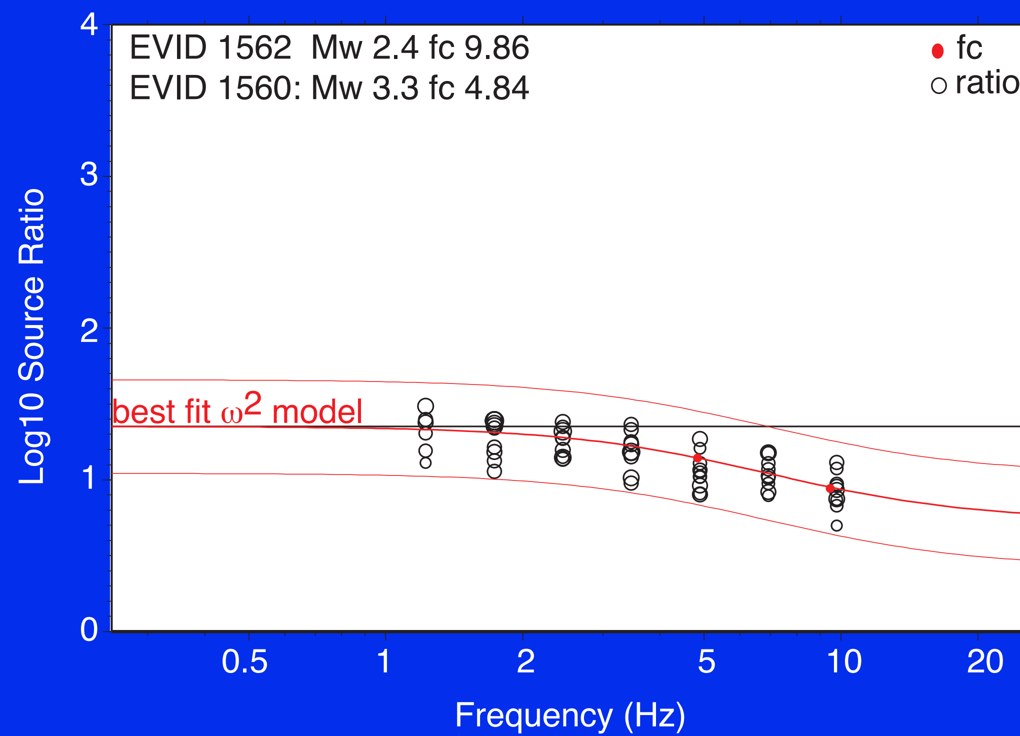
Determine event clusters within narrow depth bins with at least 3 events per cluster

Methods – Envelope Measurements and Spectral Ratios



For event pairs, difference log of envelope amplitudes where amplitudes are greater than noise level

Fit an ω^2 Brune source model to the ratios, finding M_o and f_c for each event pair



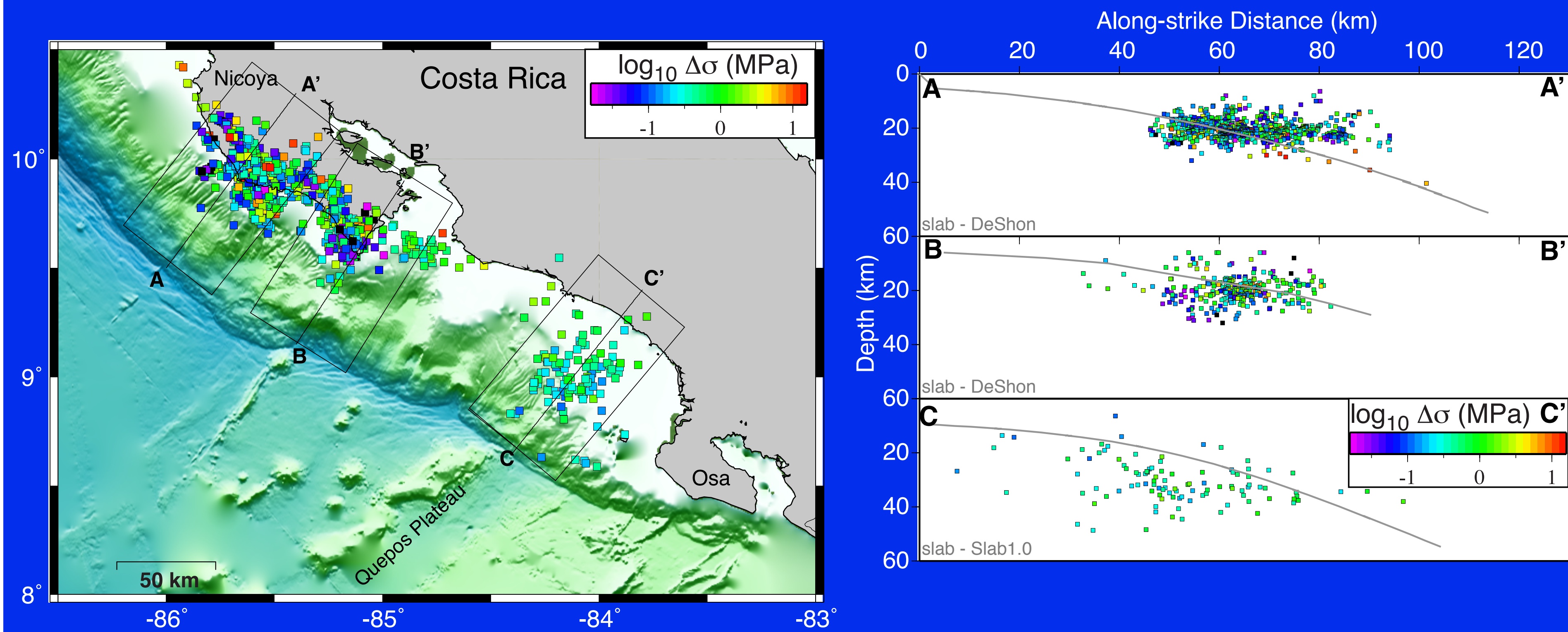
Compute stress drop ($\Delta\sigma$) using M_o and f_c, and

$$f_c = cv\left(\frac{\Delta\sigma}{M_0}\right)^{\frac{1}{3}}$$

c constant related to phase type, geometry
v source medium velocity

Method modified from *Fisk and Phillips*, BSSA, 2013

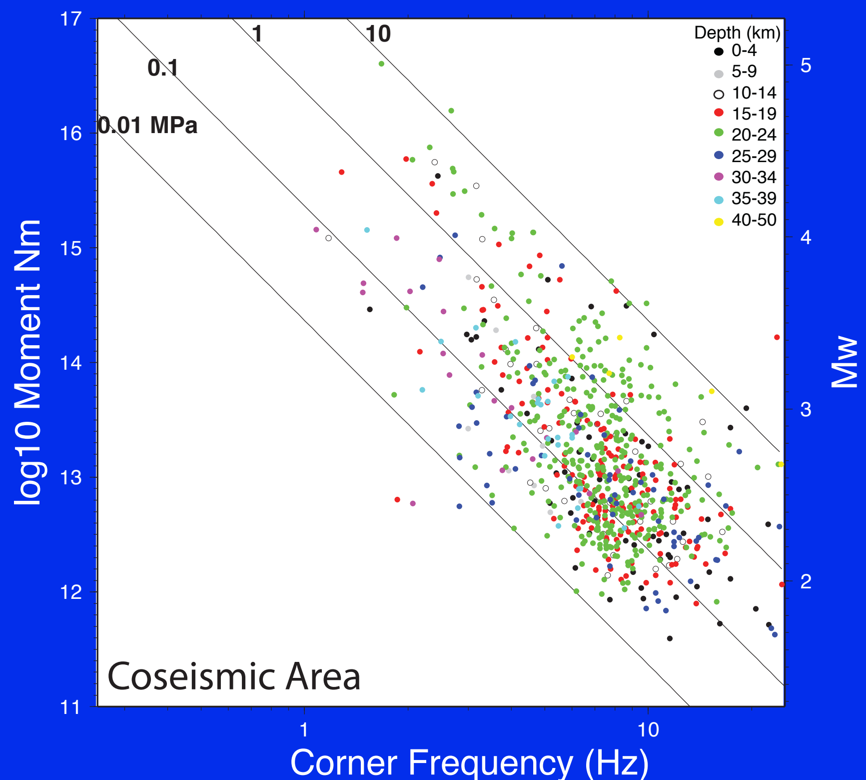
Costa Rica Source Parameter Results

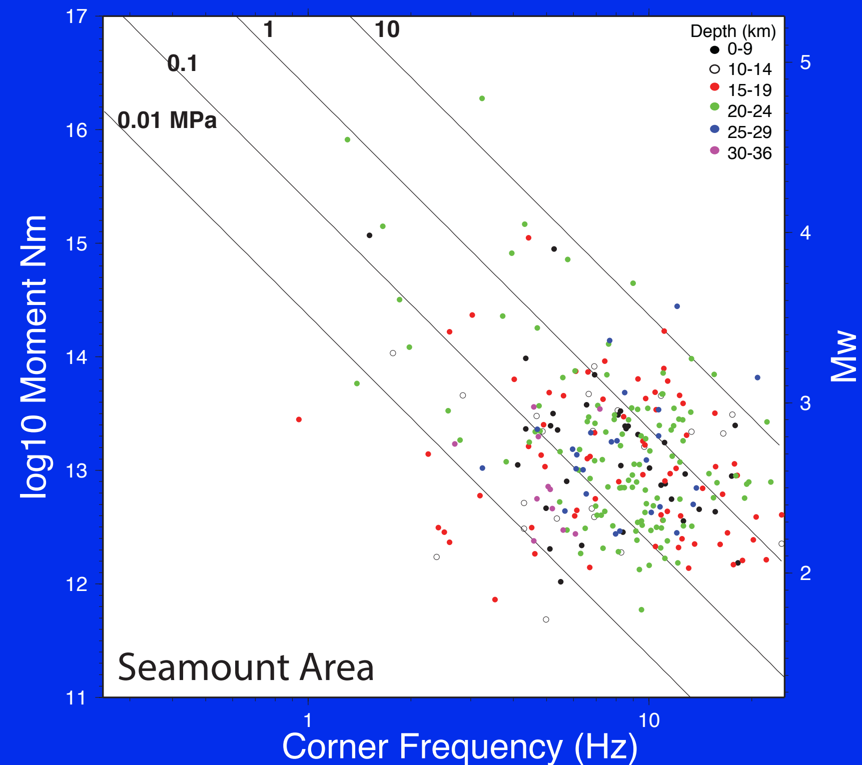


- Variations along-strike, with generally higher (and more heterogeneous values) along the Nicoya Peninsula relative to Quepos Plateau region

- No obvious depth trends

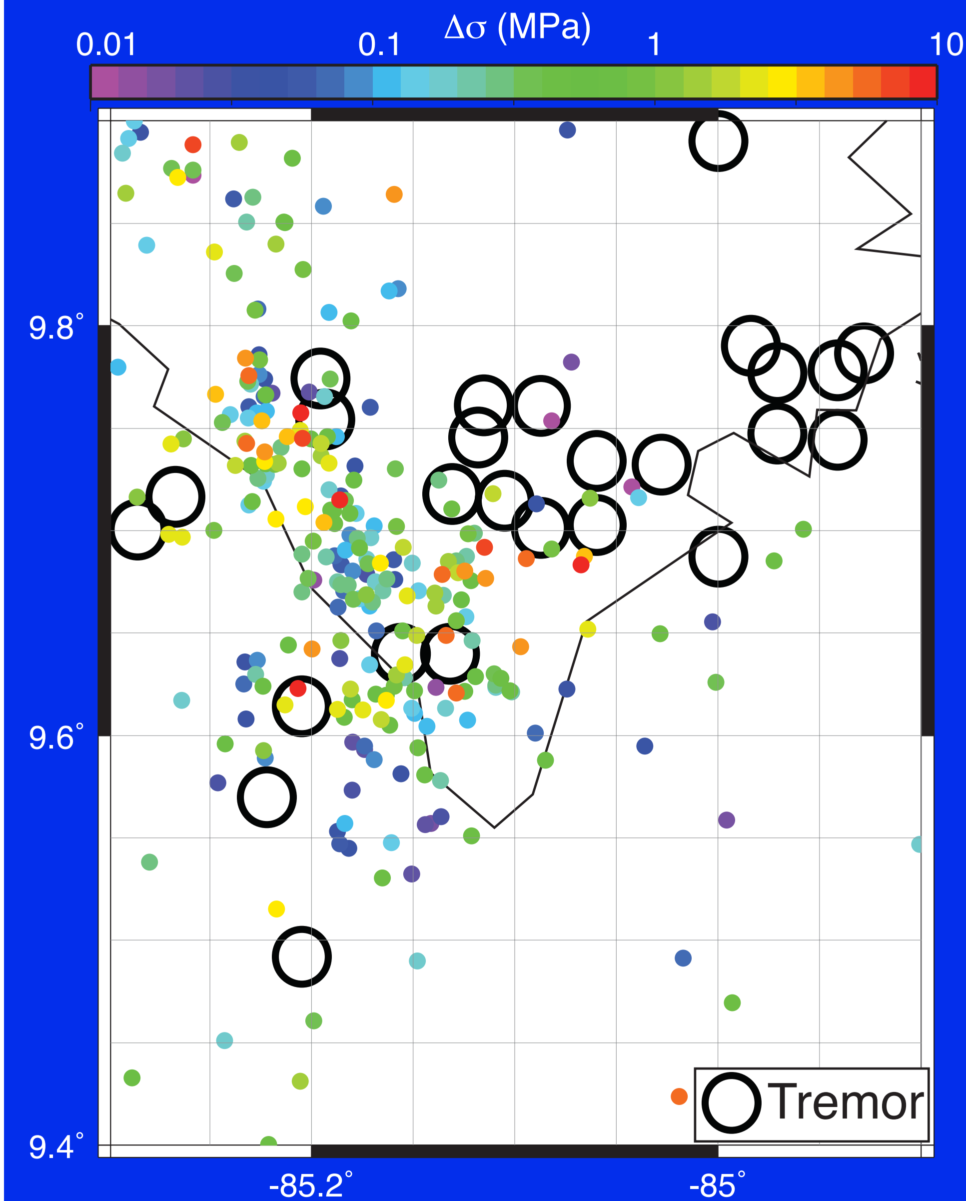
Results: Costa Rica Aftershocks





- Majority of events in coseismic area fall within expected range of $\Delta\sigma$ (0.1-1 MPa)
  - median 0.32 MPa, mean 0.97 MPa
- Overall mean and median $\Delta\sigma$ in seamount region (rough plate) similar to those in 2012 coseismic region (smoother plate)
  - median 0.35 MPa, mean 1.06 MPa
- $\Delta\sigma$ higher for older events than 2012 aftershocks
  - median 0.66 MPa, mean 1.4 MPa
  - Possible temporal variations? (caveat – small numbers of previous events 73 vs 1000+)

“Regular” earthquake stress drops - co-located with tremor



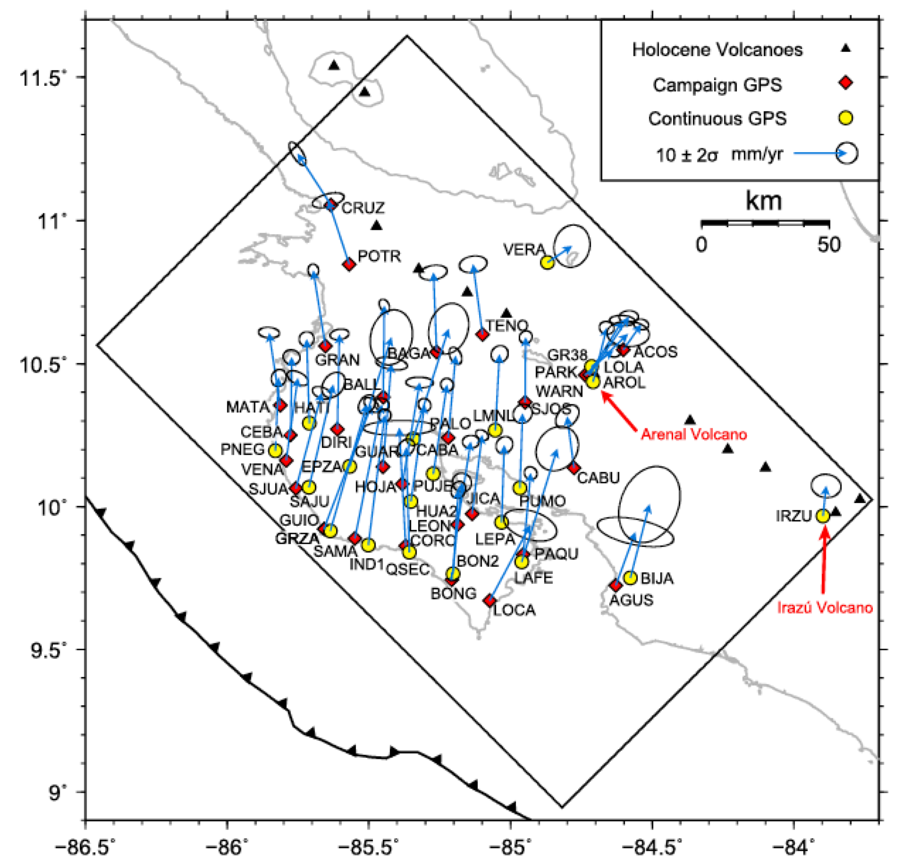
Costa Rica (*preliminary*):
Tremor not occurring in area solely marked by very low stress drop “regular” earthquakes (Zhang et al. (2011) suggested Cascadia comprised of v. low stress drop events)

- but need to explore the other tremor areas in Costa Rica

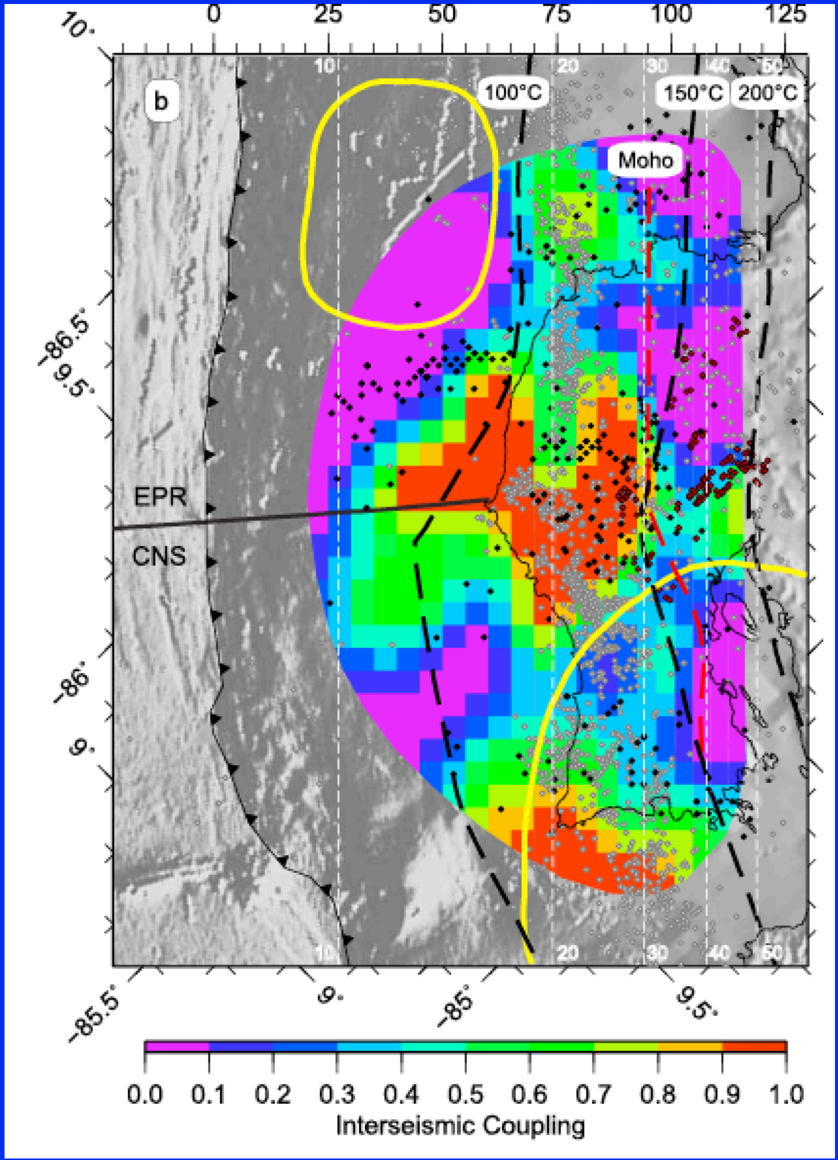
Comparisons with Plate Coupling and Coseismic Slip

Are there any differences linked to plate coupling or seismic slip?

Dense GPS network led to maps of seismic coupling prior to 2012 earthquake

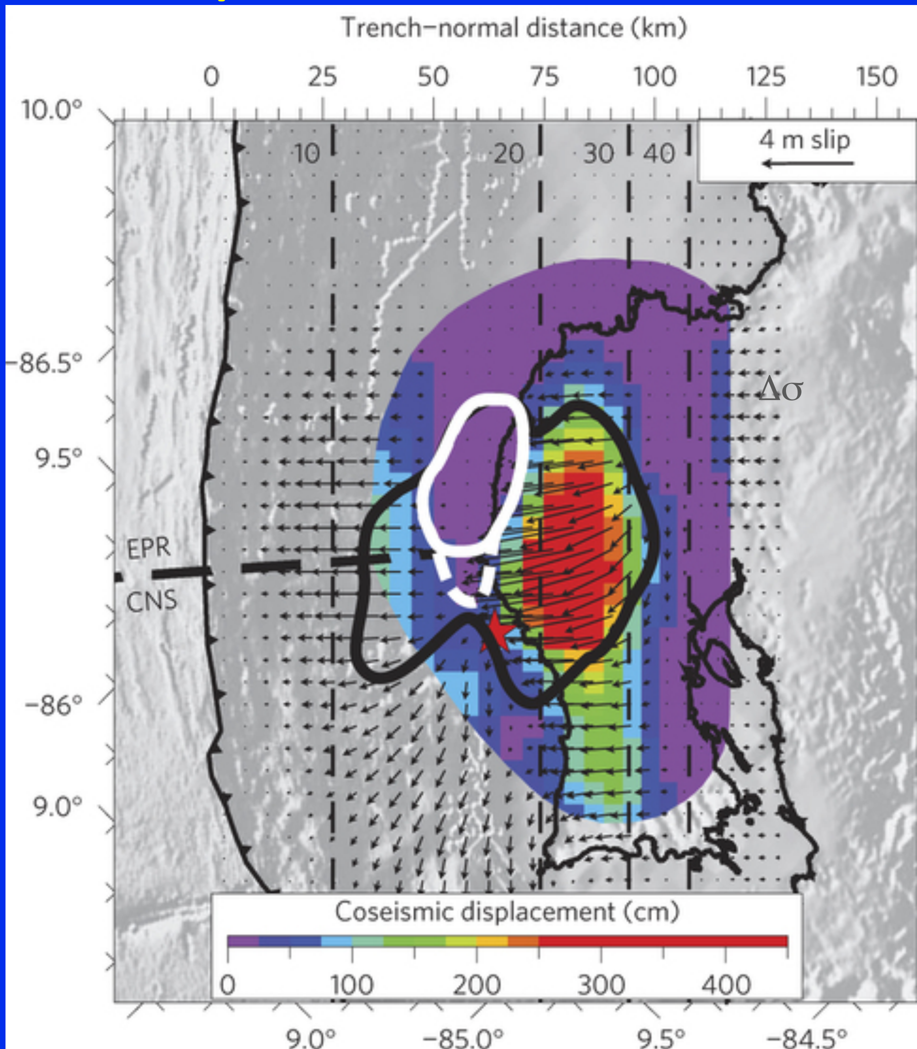


Feng et al., 2012

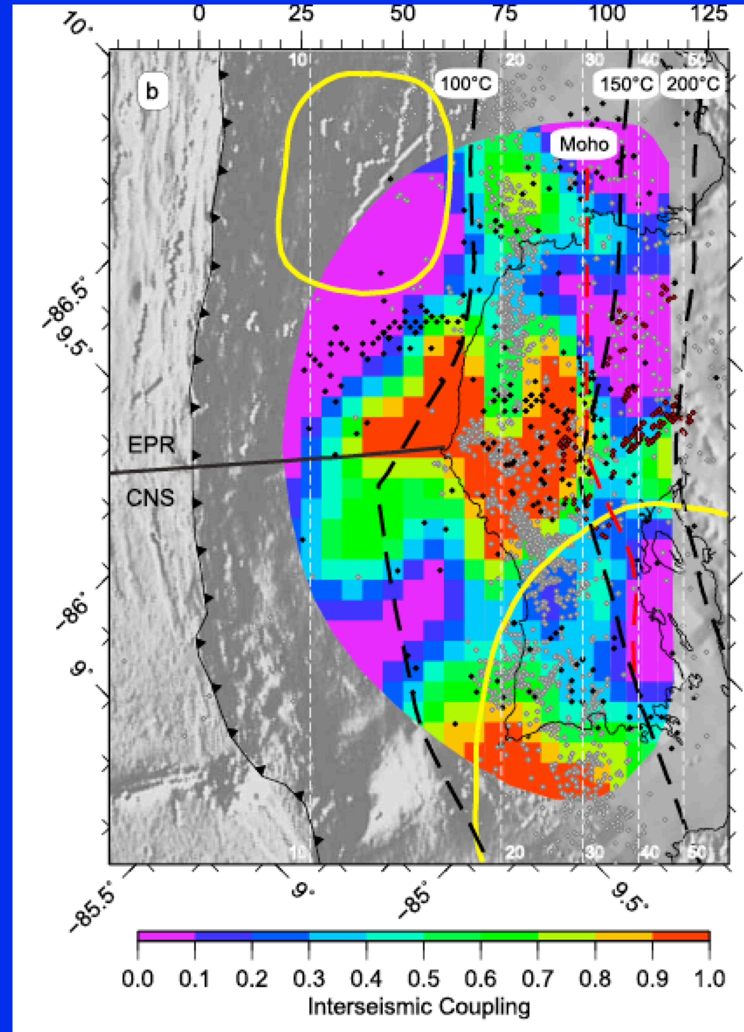


Feng et al., 2012

Comparisons with Plate Coupling and Coseismic Slip



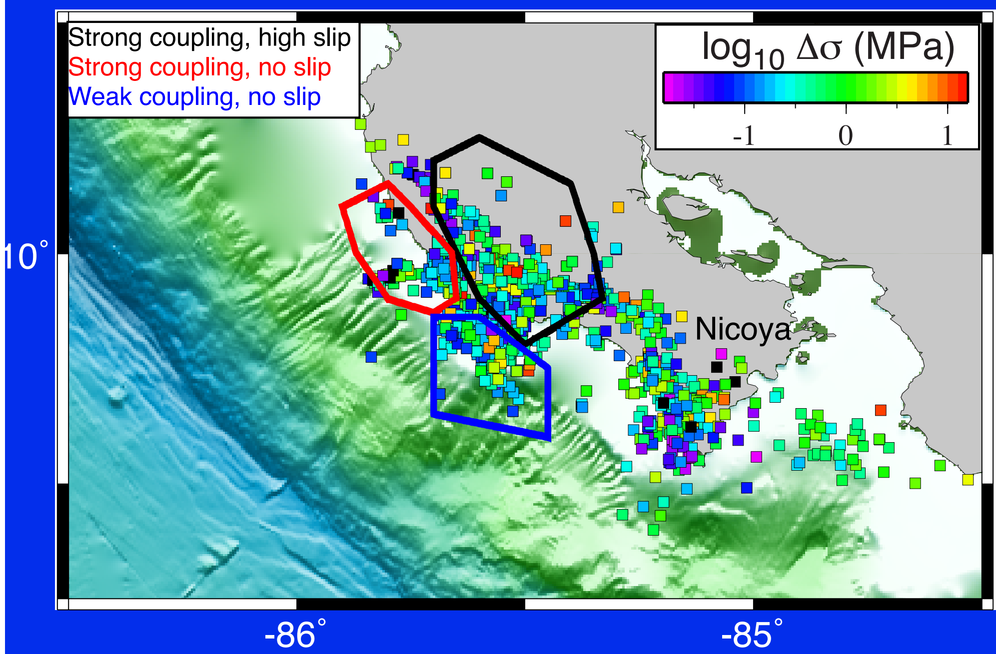
From *Protti et al.*, 2014



Within 2012 M_w 7.6 event region, detailed geodetic models suggest significant variation in geodetic coupling that links partially to area of coseismic slip during the 2012 event, prompts questions/concerns about updip locked patch that did not slip in 2012

Comparisons with Plate Coupling and Coseismic Slip

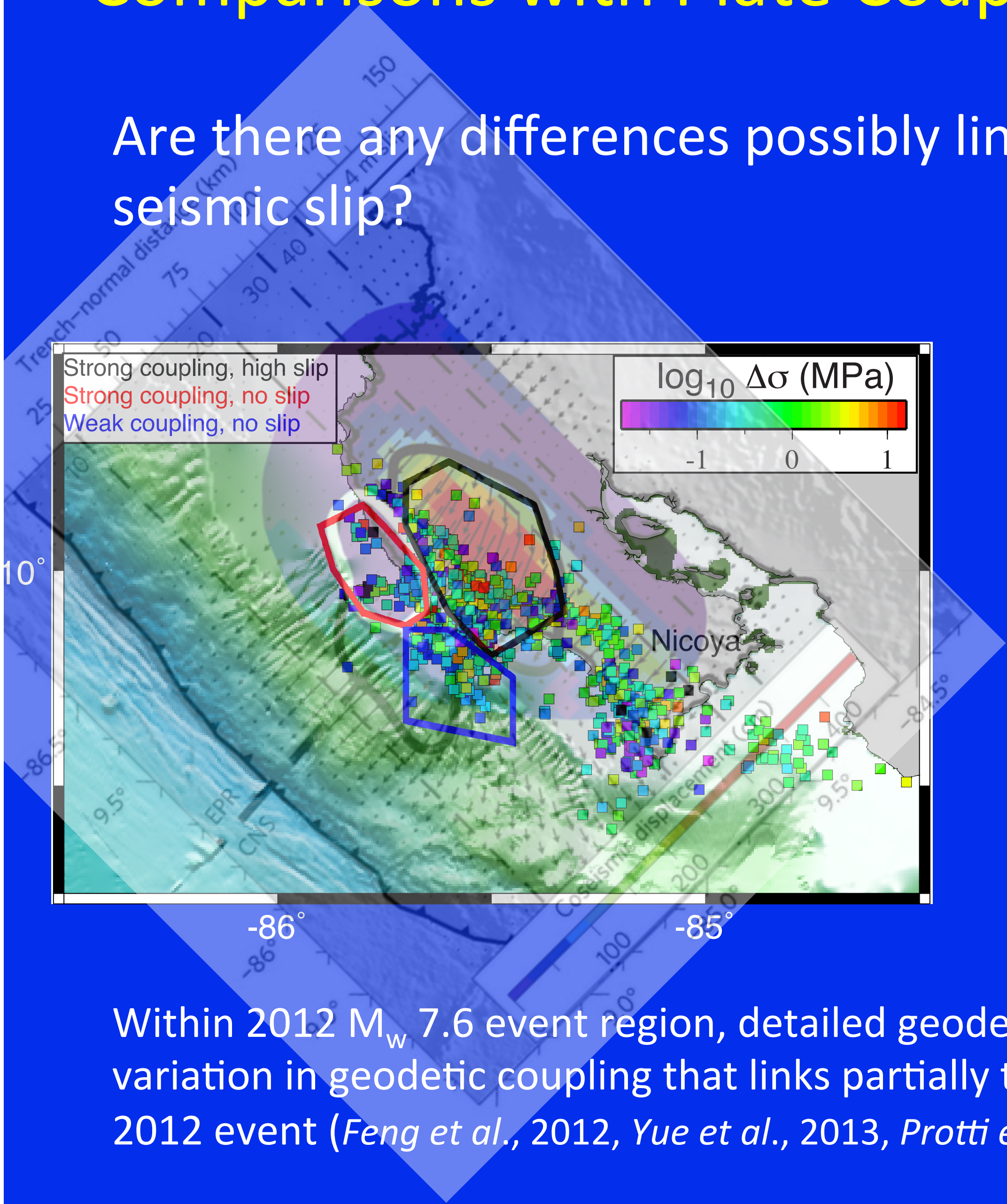
Are there any differences possibly linked to plate coupling or seismic slip?



Focus on observations within 3 key subsets in/near the 2012 rupture zone along Nicoya Peninsula

Comparisons with Plate Coupling and Coseismic Slip

Are there any differences possibly linked to plate coupling or seismic slip?



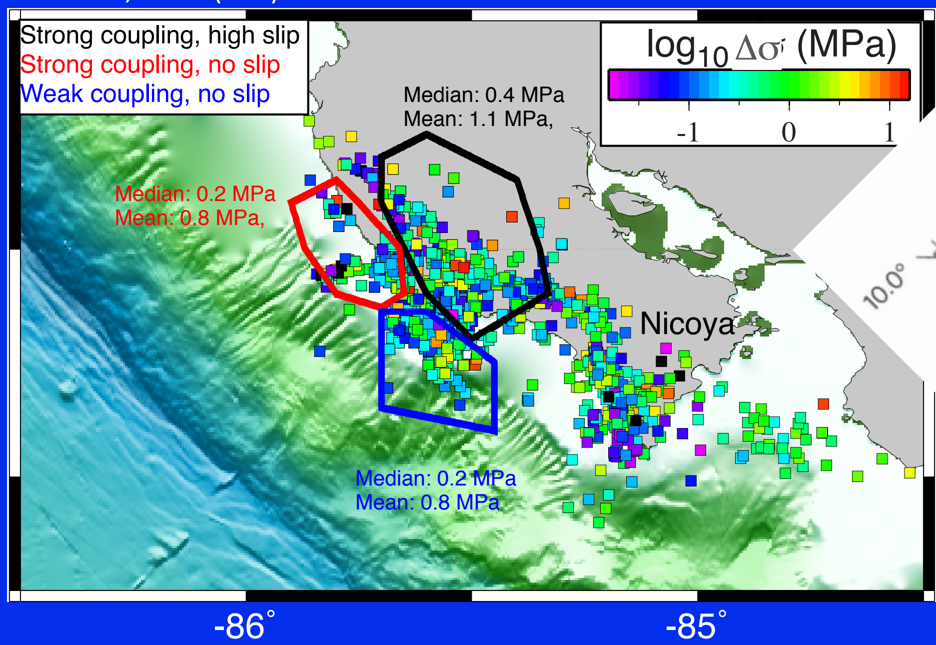
Focus on observations within 3 key subsets in/near the 2012 rupture zone along Nicoya Peninsula

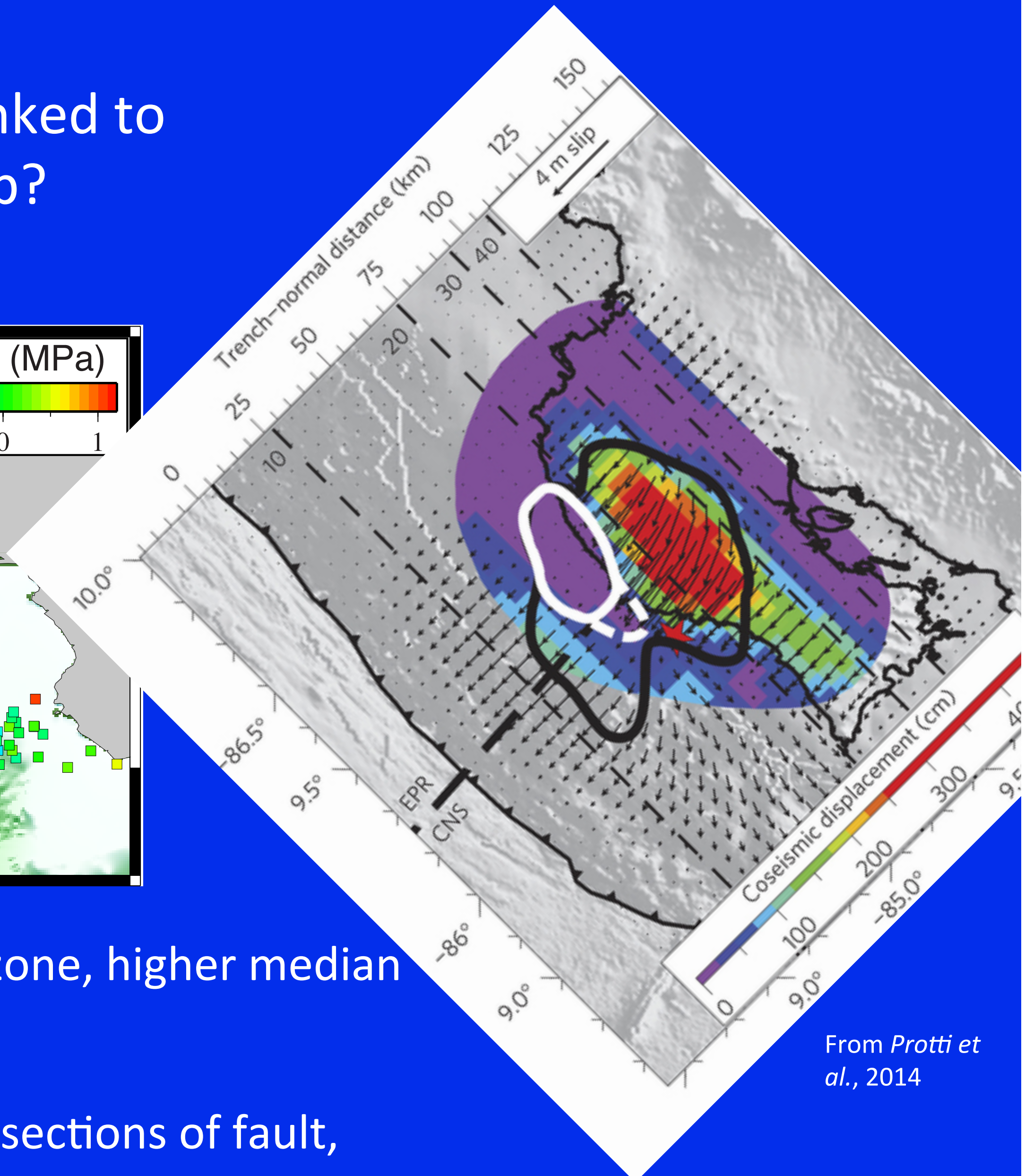
Within 2012 M_w 7.6 event region, detailed geodetic models suggest significant variation in geodetic coupling that links partially to area of coseismic slip during the 2012 event (*Feng et al*., 2012, *Yue et al*., 2013, *Protti et al*., 2014)

Comparisons with Plate Coupling and Coseismic Slip

Are there any differences linked to plate coupling or seismic slip?

Bilek et al, 2014 (SSA)





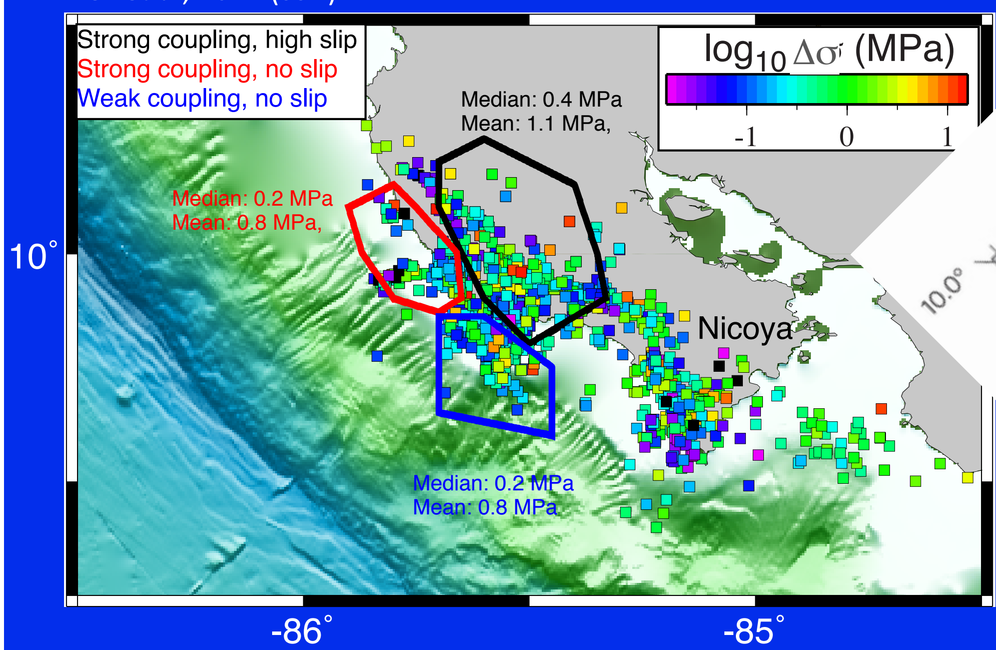
From *Protti et al.*, 2014

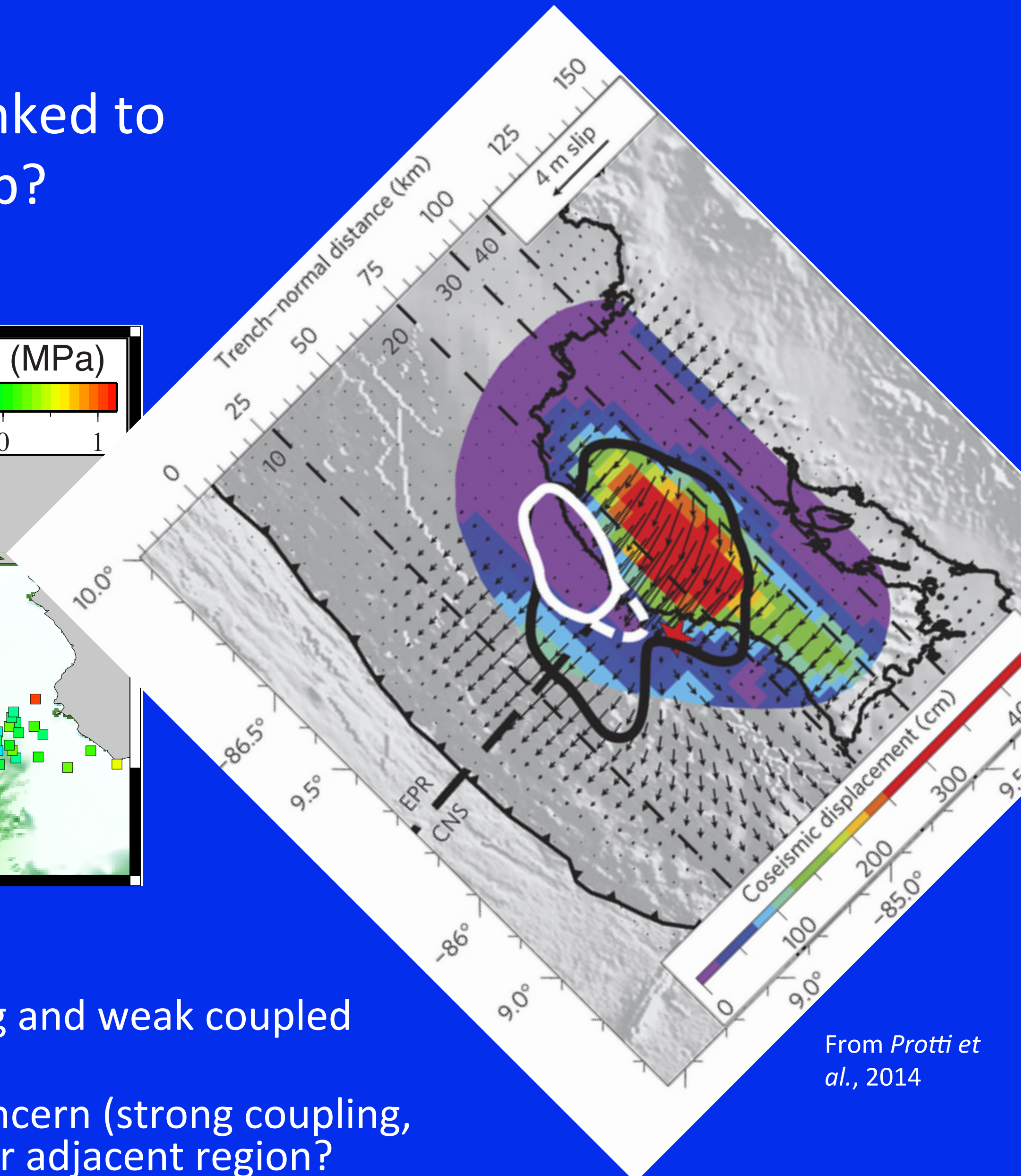
- Within high slip, strongly coupled zone, higher median $\Delta\sigma$ relative to adjacent areas
- Stress drop is similar in the no-slip sections of fault, regardless of geodetic coupling

Comparisons with Plate Coupling and Coseismic Slip

Are there any differences linked to plate coupling or seismic slip?

Bilek et al, 2014 (SSA)

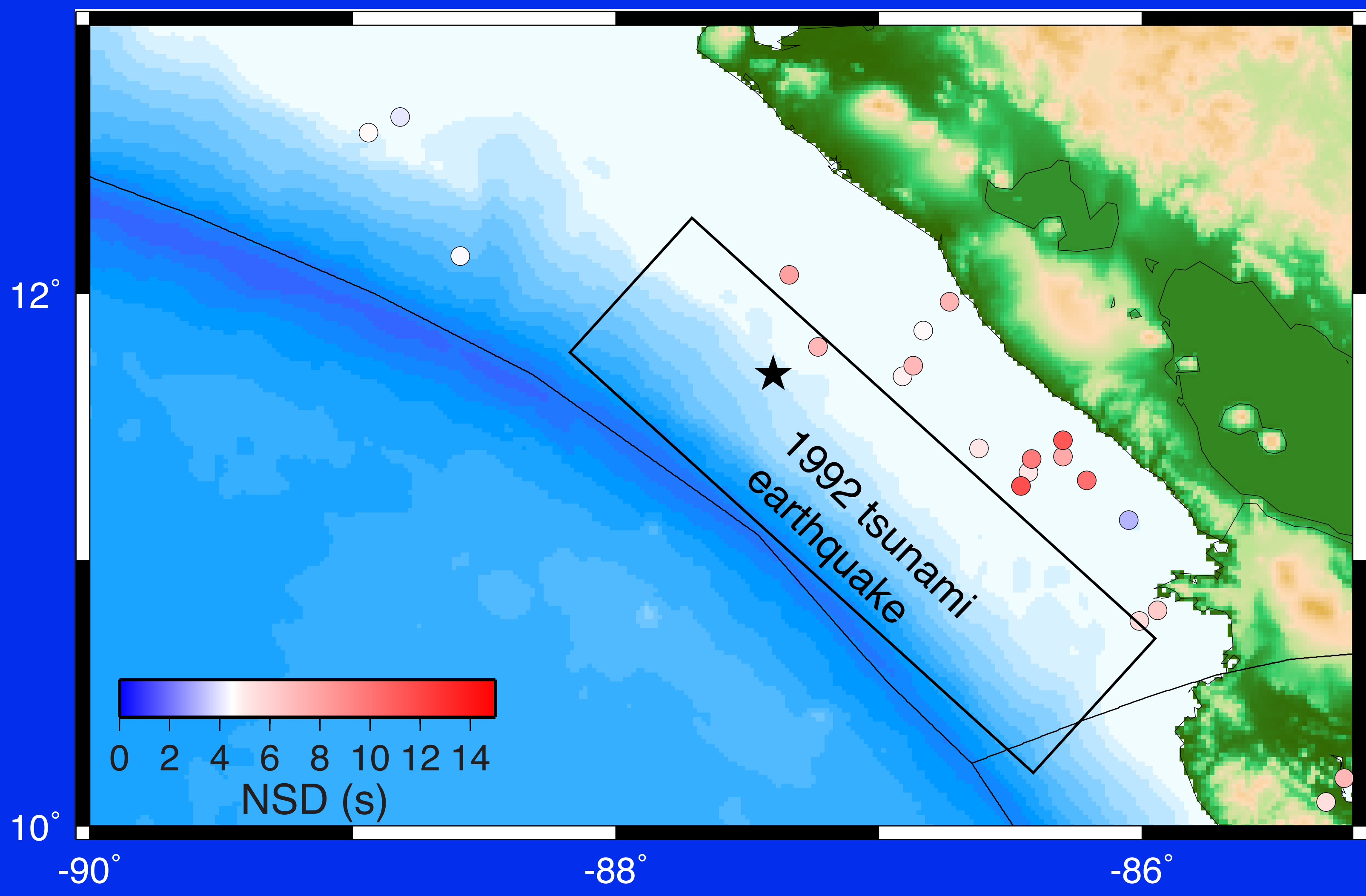




From *Protti et al.*, 2014

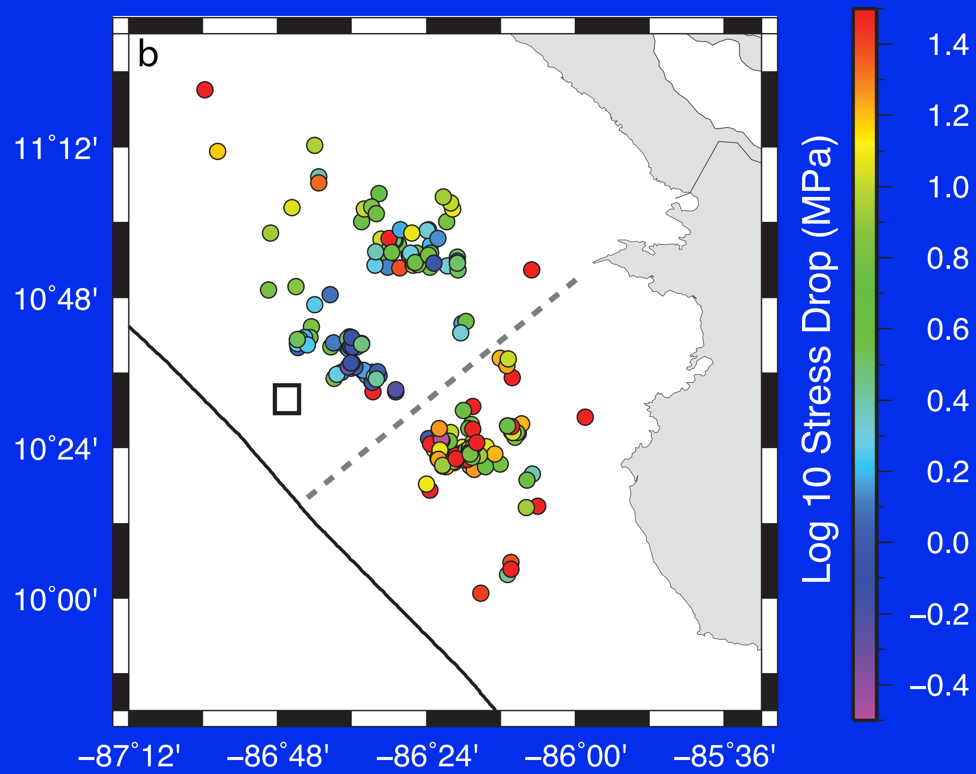
- Implications/Questions:
  - What is difference between strong and weak coupled areas?
  - Is area highlighted as region of concern (strong coupling, no slip) more similar to downdip or adjacent region?

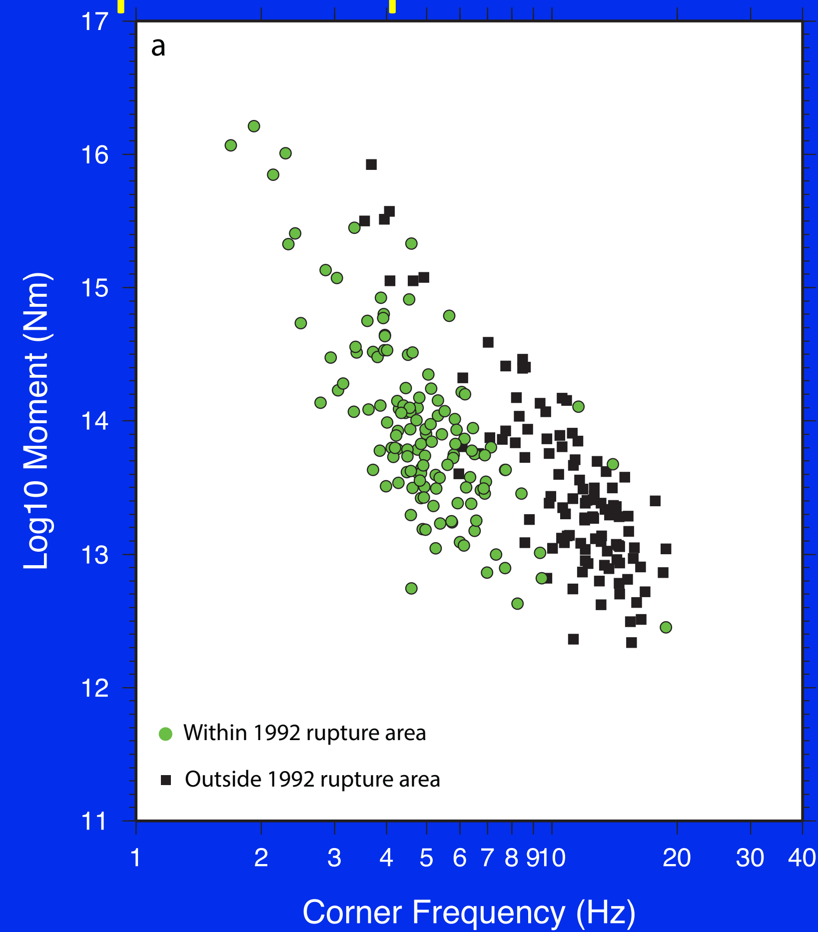
Nicaragua



Concentration of long duration events (M 5.5-7) in area of 1992 tsunami earthquake, although at the downdip end of the 1992 rupture zone

1992 Nicaragua tsunami earthquake rupture zone

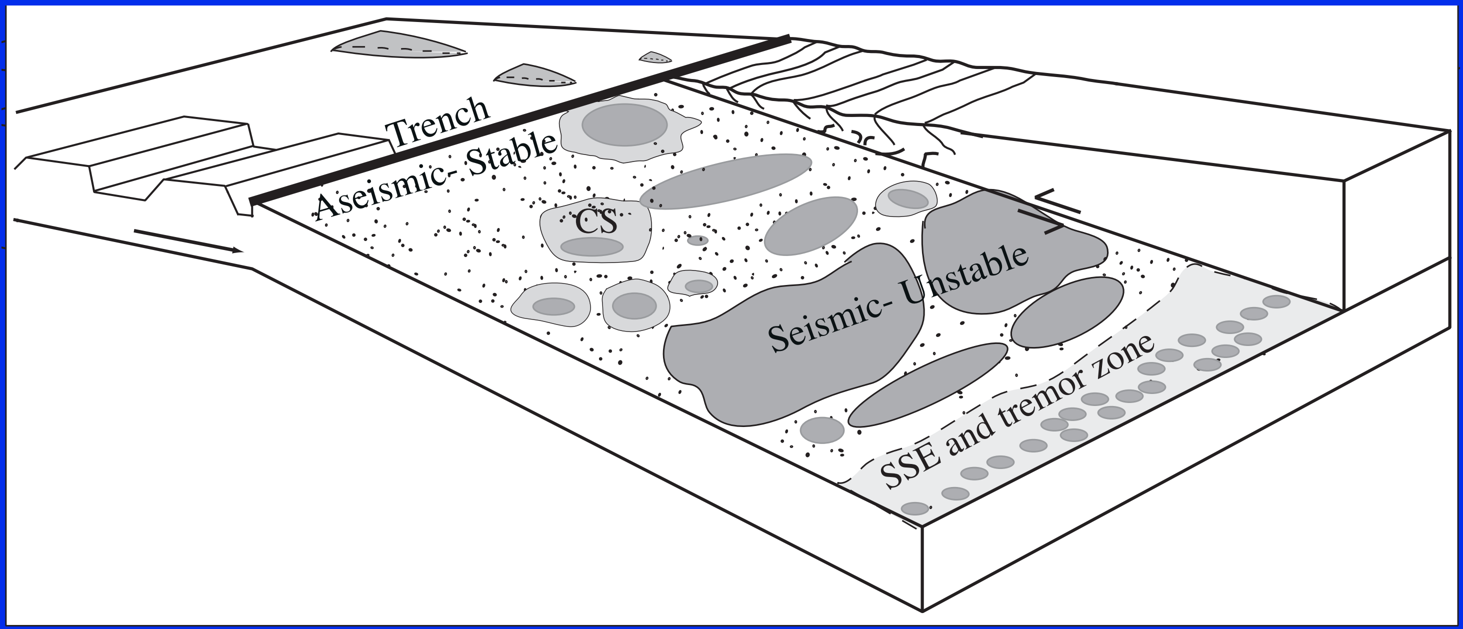




Rotman, Bilek, Phillips, in prep

- $\Delta\sigma$ significantly lower to north, within rupture area of the 1992 tsunami earthquake
- Implications/Questions:
  - Is tsunami earthquake zone distinctly different from other parts of the megathrust?
  - Can these small earthquakes map out these anomalous regions?

Some Complexity Required!



- Earthquake source parameter variations can be used as probes for the fault heterogeneity

- Source parameters can map out areas of variable fault conditions
  - important for tsunami and shaking hazards

- Variety of earthquake magnitudes useful for probing at different scales
  - Important for understanding transitions between different slip behaviors

Thank You!