Episodic Tremor and Slip

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UW ESS Seminar Series
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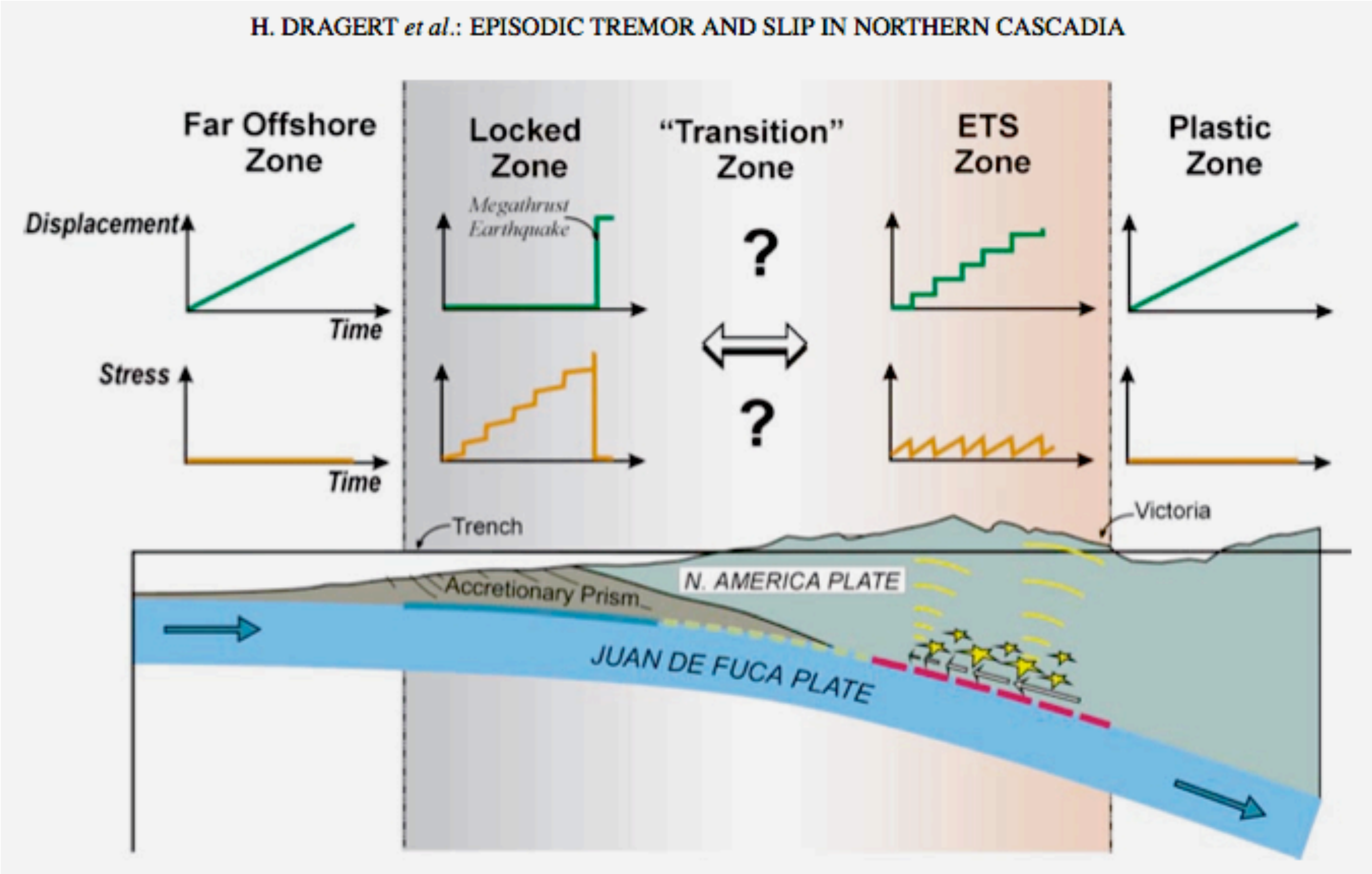
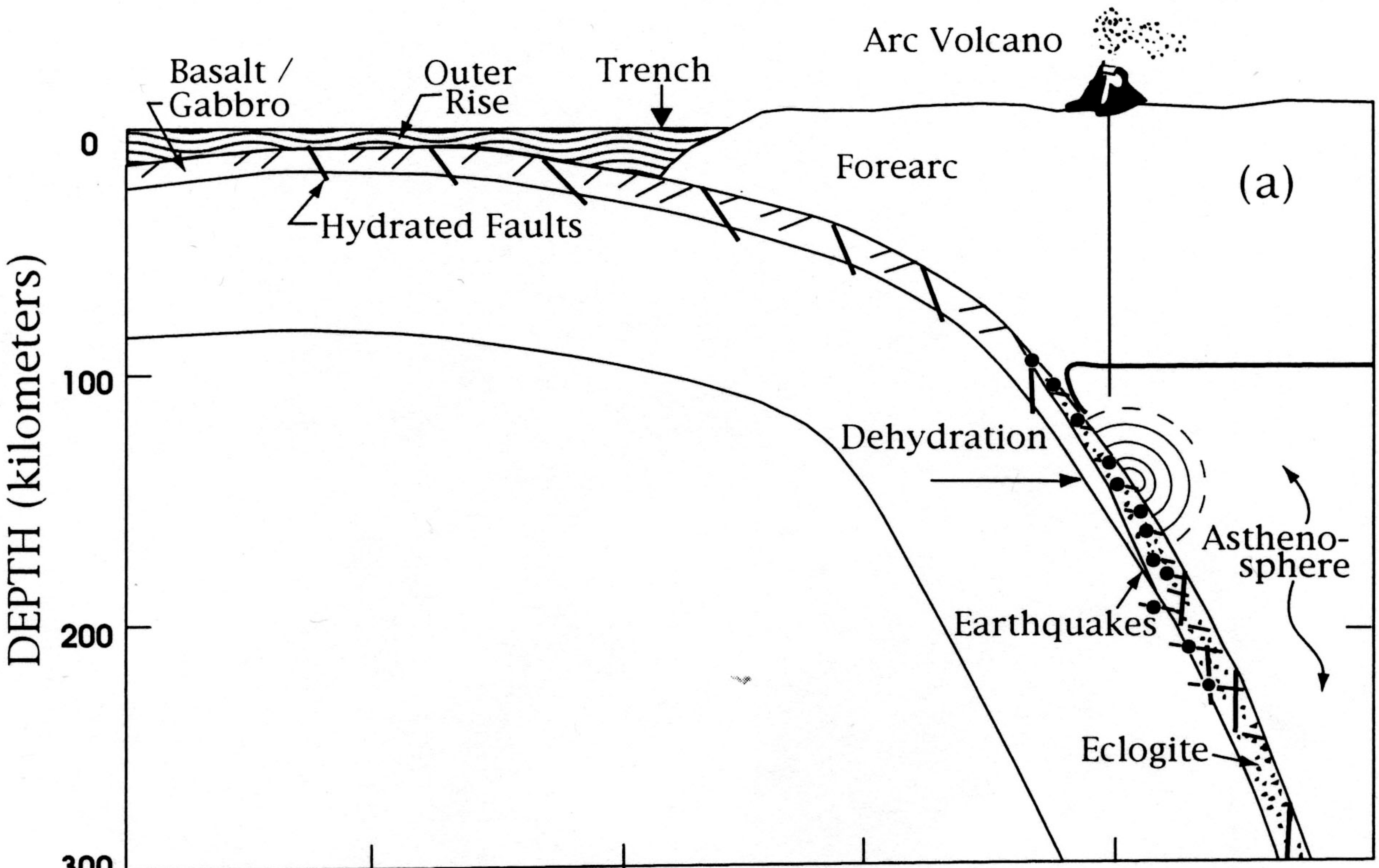
Outline

- How do plates slide past each other?
- Role of fluids
- Review of Tremor and Slip
- Comparison of Cascadia and Nankai ETS
- Two fundamentally different kinds or earthquakes?
- Hazard Implications
- Tremor detection and location
- ETS repeatability and periodicity
- Fault slip on plate interface
- Strong influence of small stresses from tides and surface waves of distant earthquakes

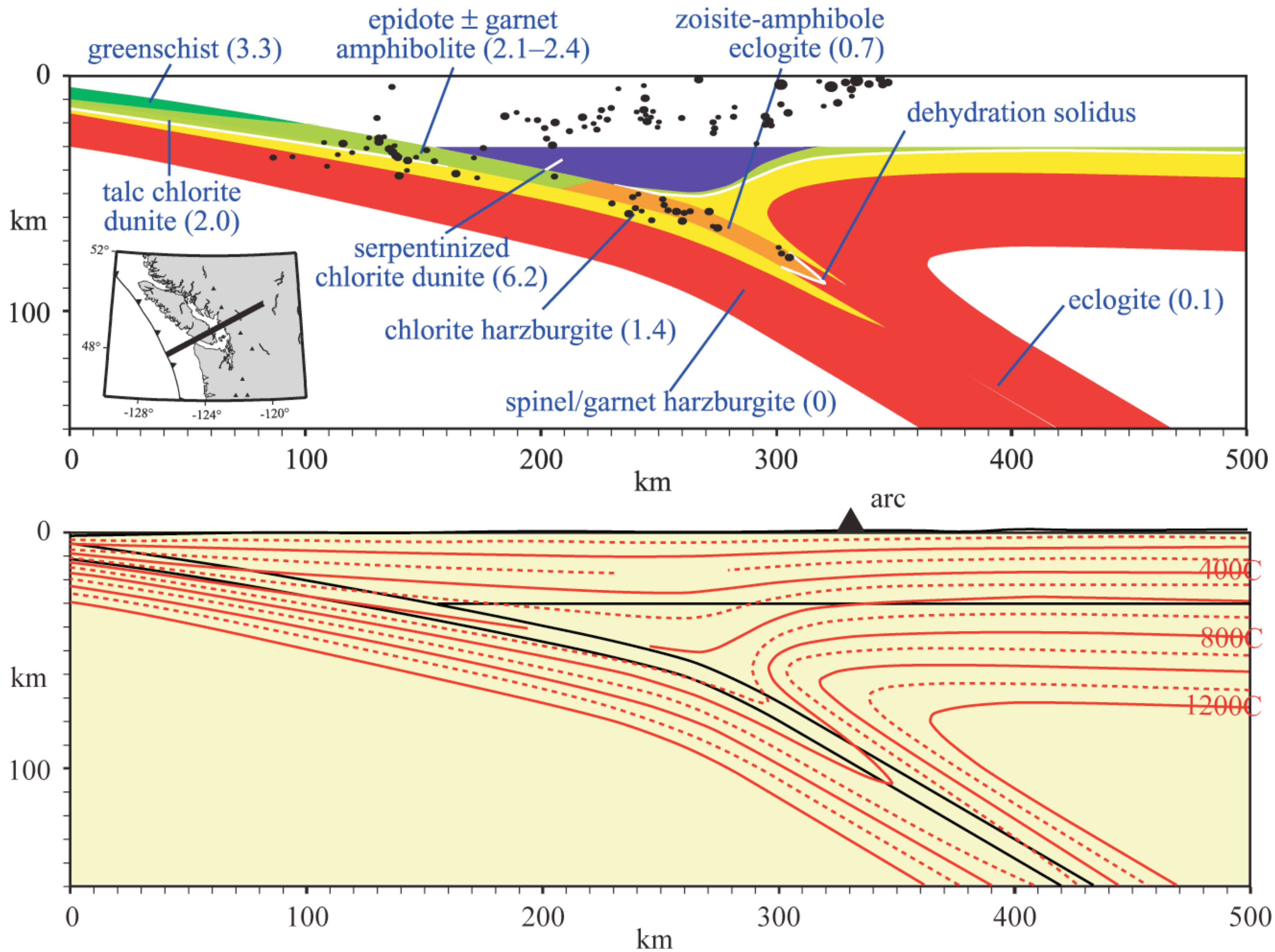
ETS schematic



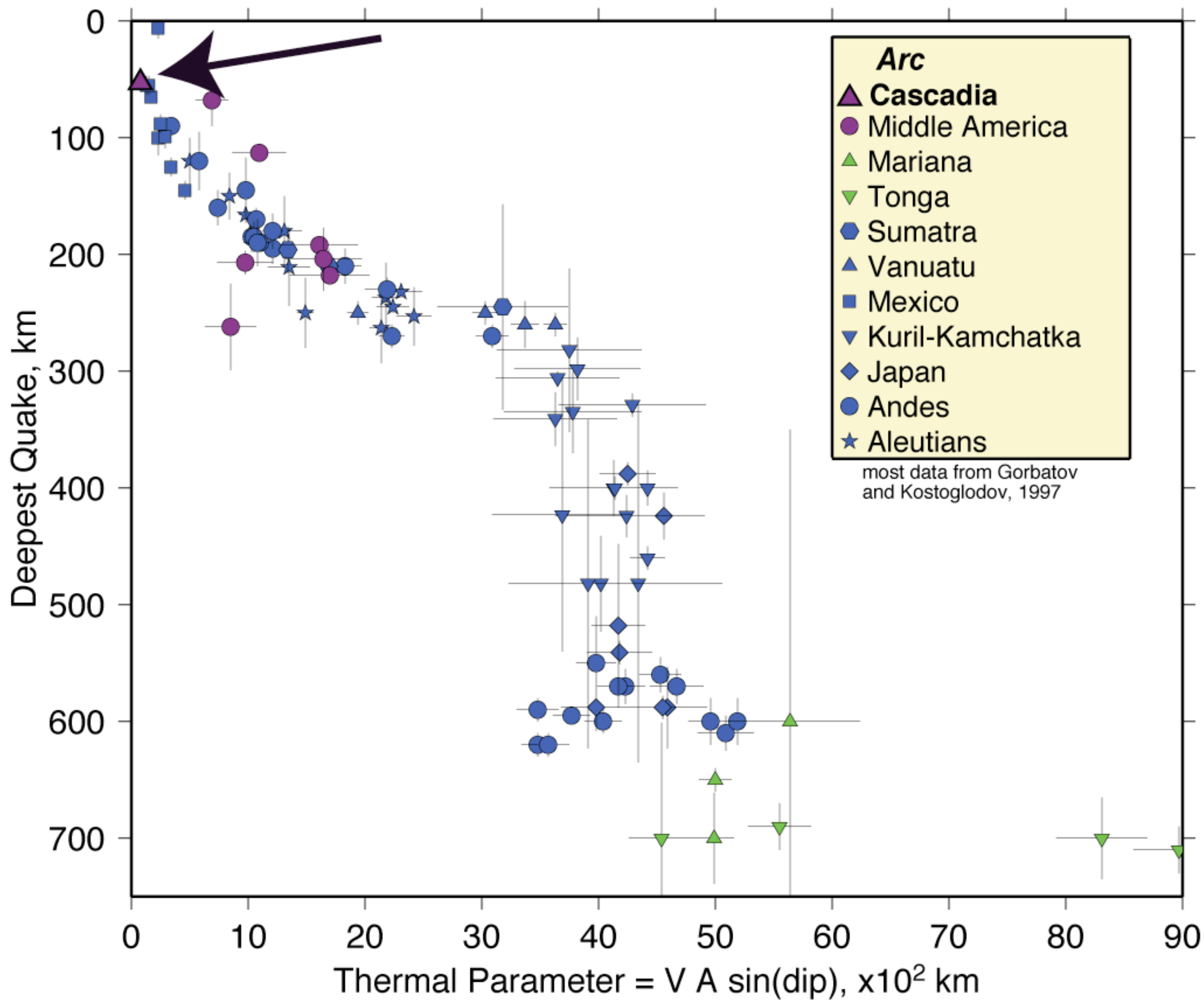
Faults Never Die: They Just Get Reactivated!



Metamorphic facies and mineralogically bound H2O, predicted from thermal models [Hacker et al., 2003]

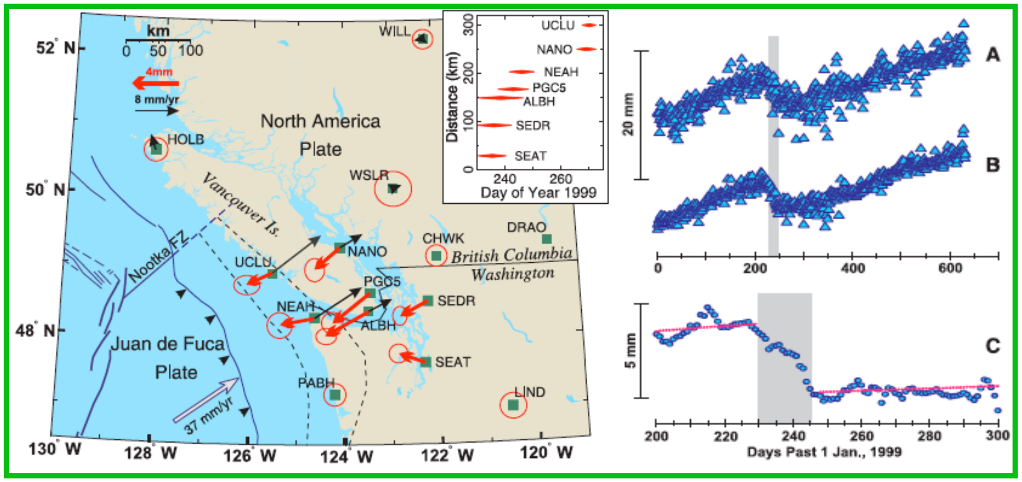


Cascadia is a global hot endmember in terms of slab thermal structure

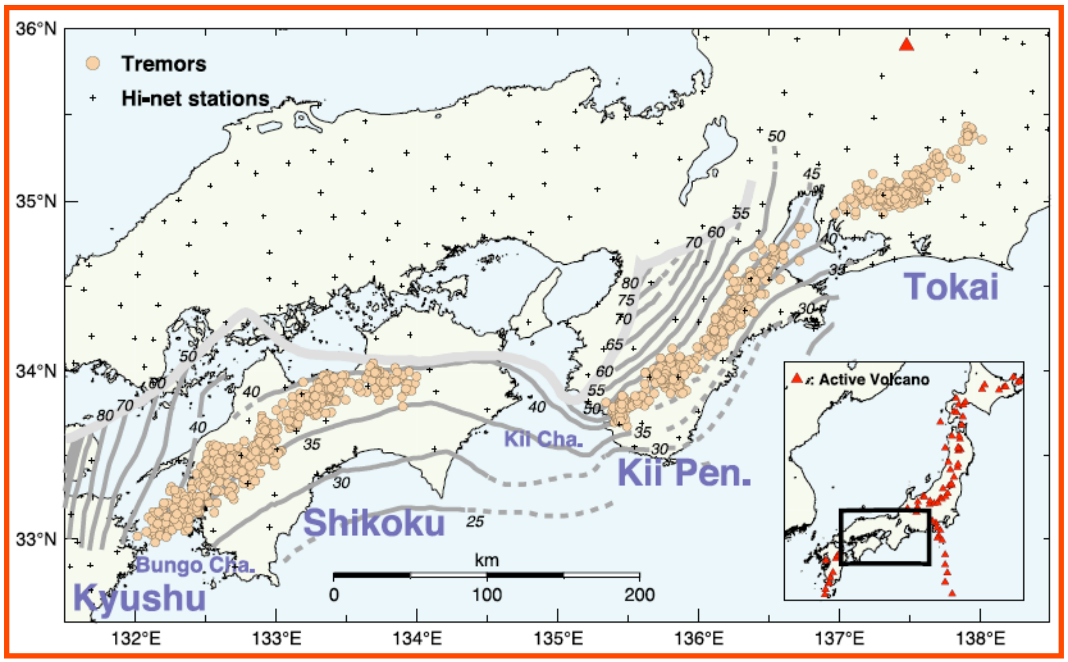


In the beginning…

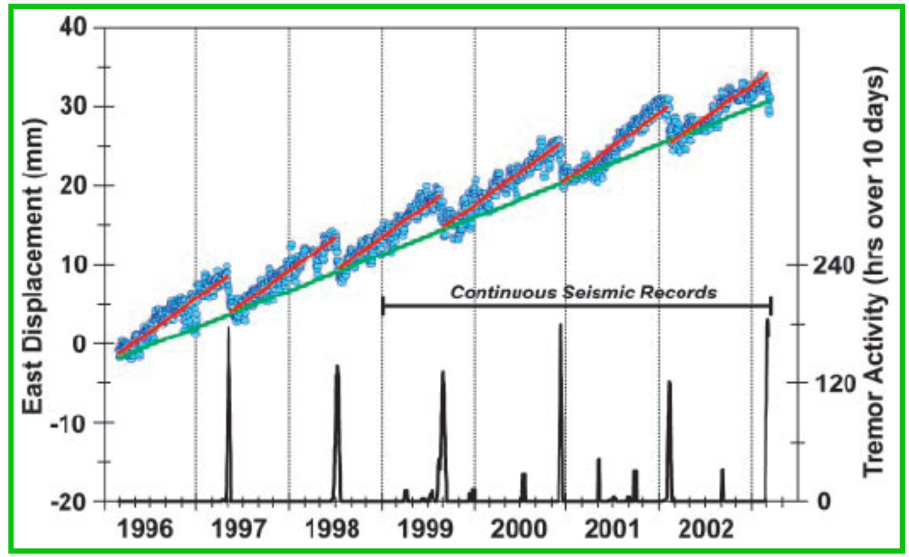
Dragert et al., 2001: Aseismic slip detected in northern Cascadia.



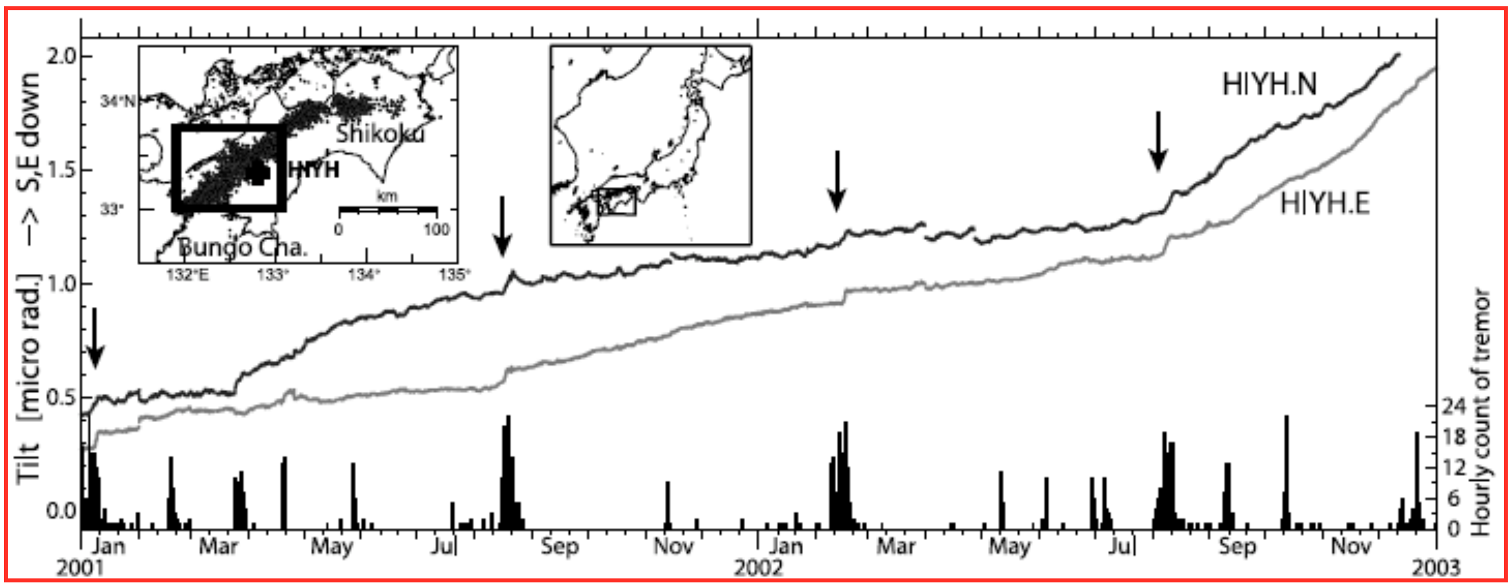
Obara, 2002: Nonvolcanic tremor detected in SW Japan.



Rogers & Dragert, 2003: Tremor correlated with slip in northern Cascadia.



Obara et al., 2004: Tremor correlated with slow slip in southwest Japan



Japan/Cascadia Comparison

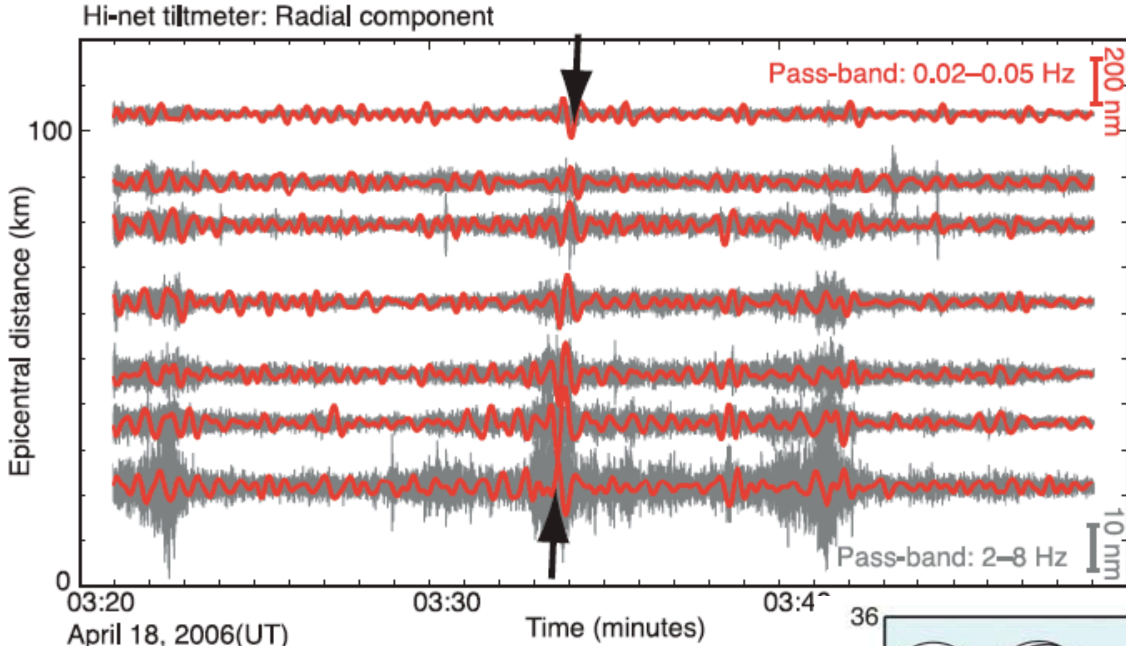
<u>Japan</u>

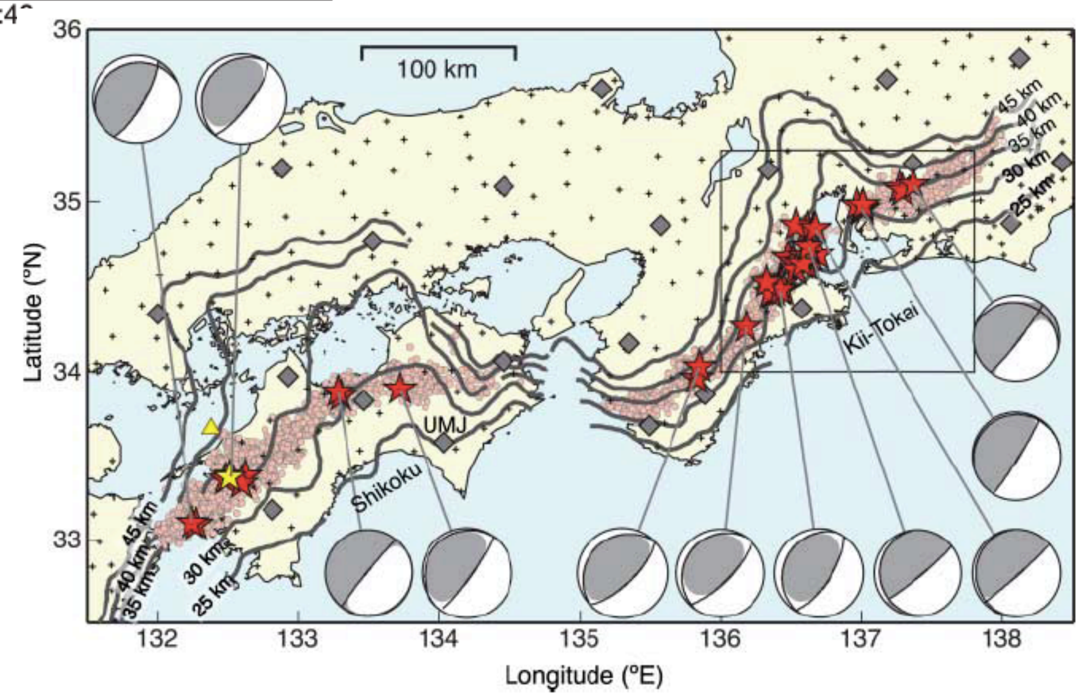
- ✓ Tremor w/ Slip
- ✓ Periodic
- ✓ Tremor epicenters above plate contours of 30-45 km

<u>Cascadia</u>

- ✓ Tremor w/ Slip
- ✓ Periodic
- ✓ Tremor epicenters above plate contours of 30-45 km

Japan very-low-frequency earthquake (VLF)

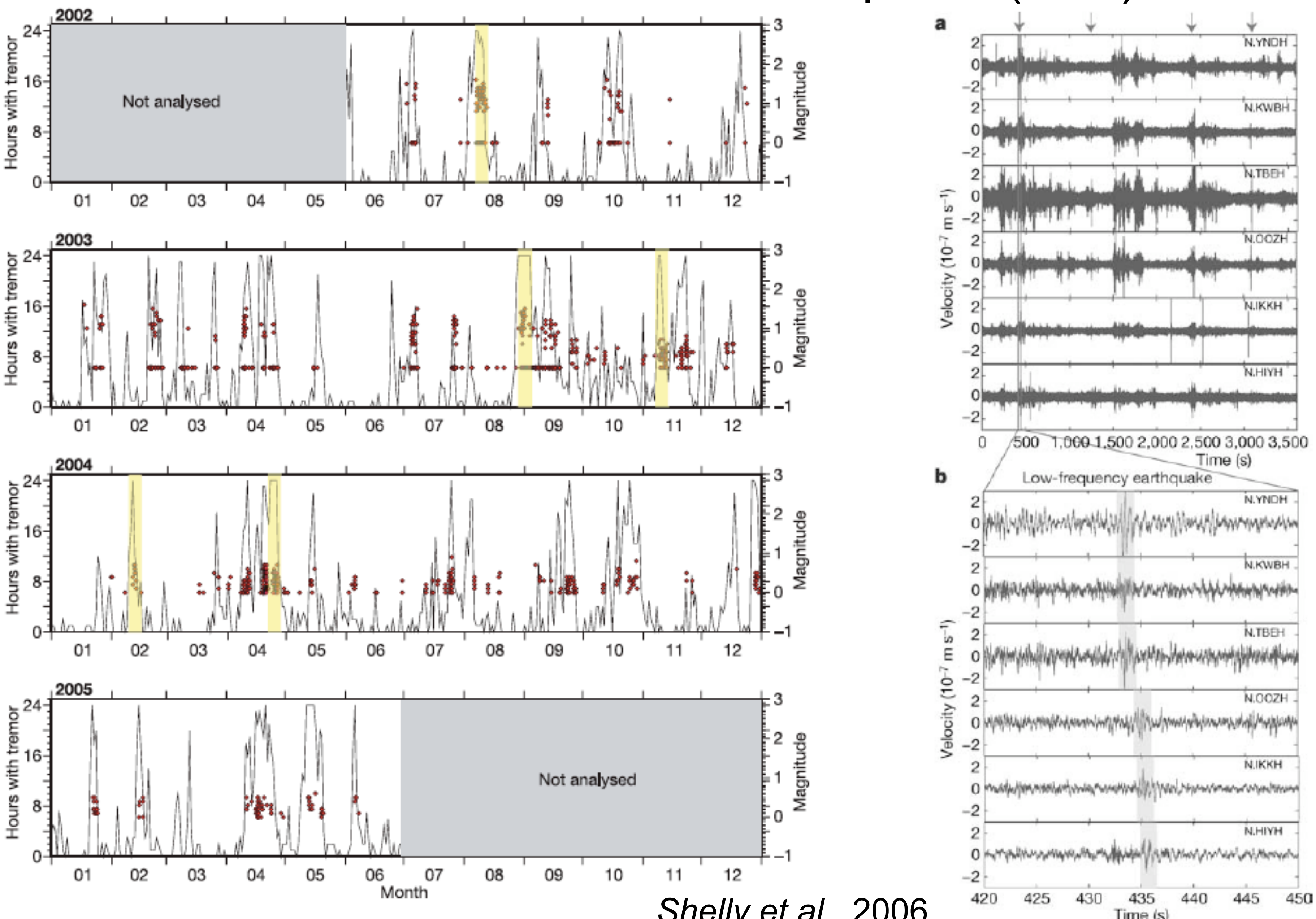




Ito et al., 2007

Cascadia very-low-frequency earthquake (VLF)

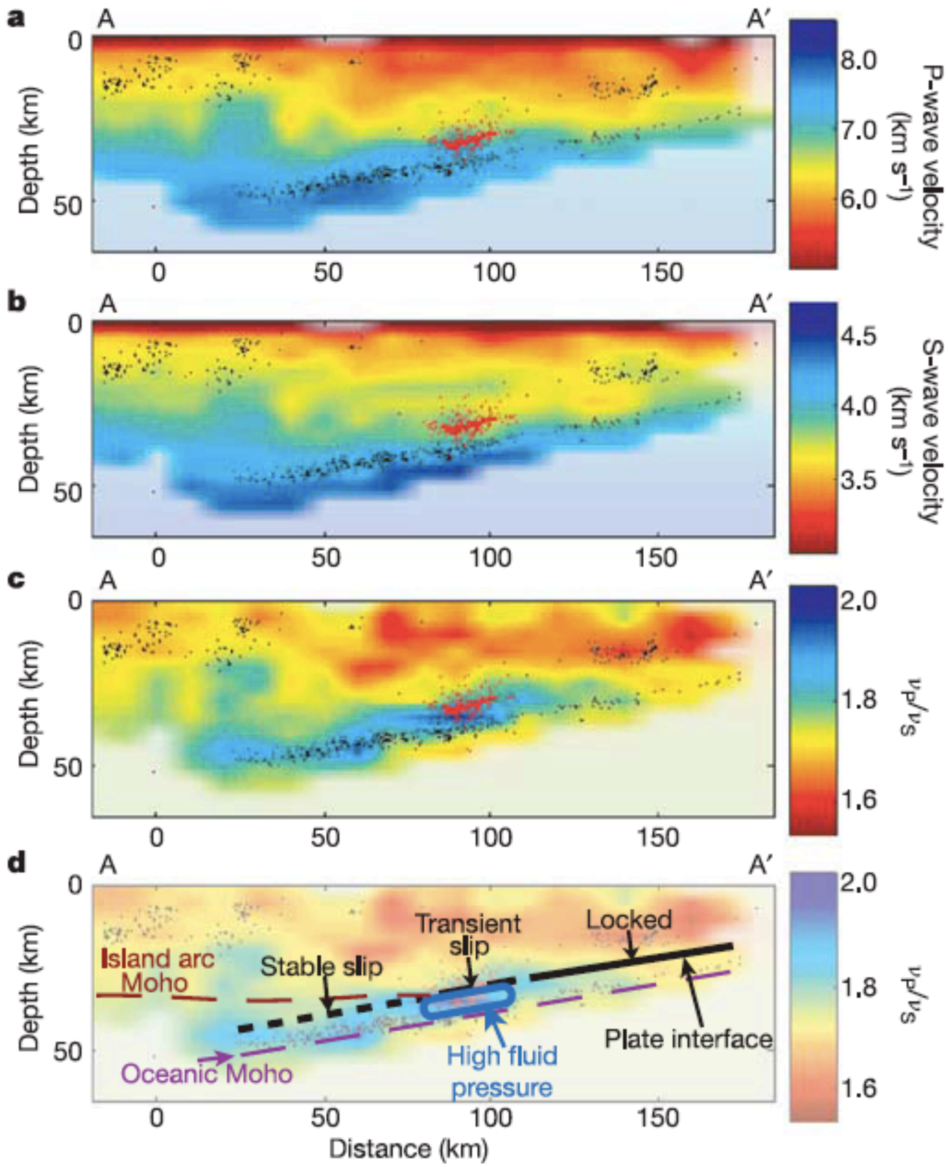
Japan low-frequency earthquake (LFE)



Shelly et al., 2006

Cascadia low-frequency earthquake (LFE)

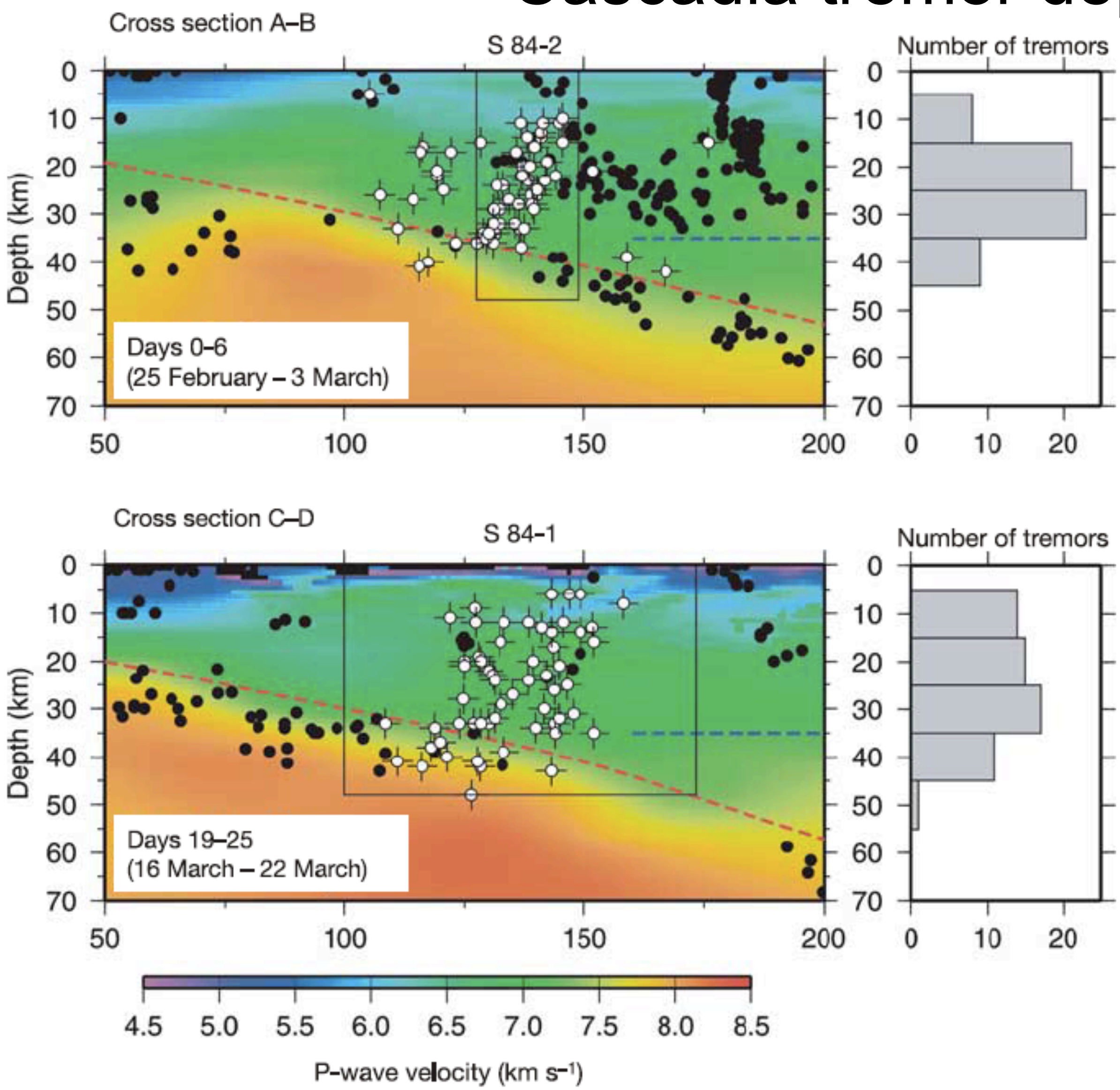
Japan tremor depths



Shelly et al., 2006

- Tremor comprised of LFE's (*Shelly et al.*, 2006)
- LFE's confined to plate interface (*Shelly et al.*, 2006)
- Tremor depths concetrated near Moho (*Obara*, 2002)
- VLF's consistent with plate interface (*Ito et al.*, 2007)

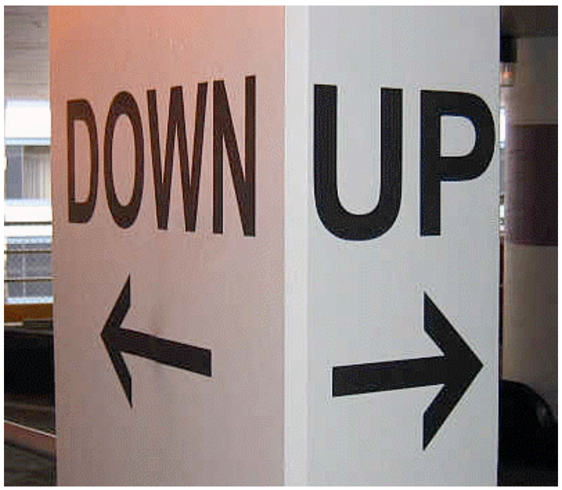
Cascadia tremor depths

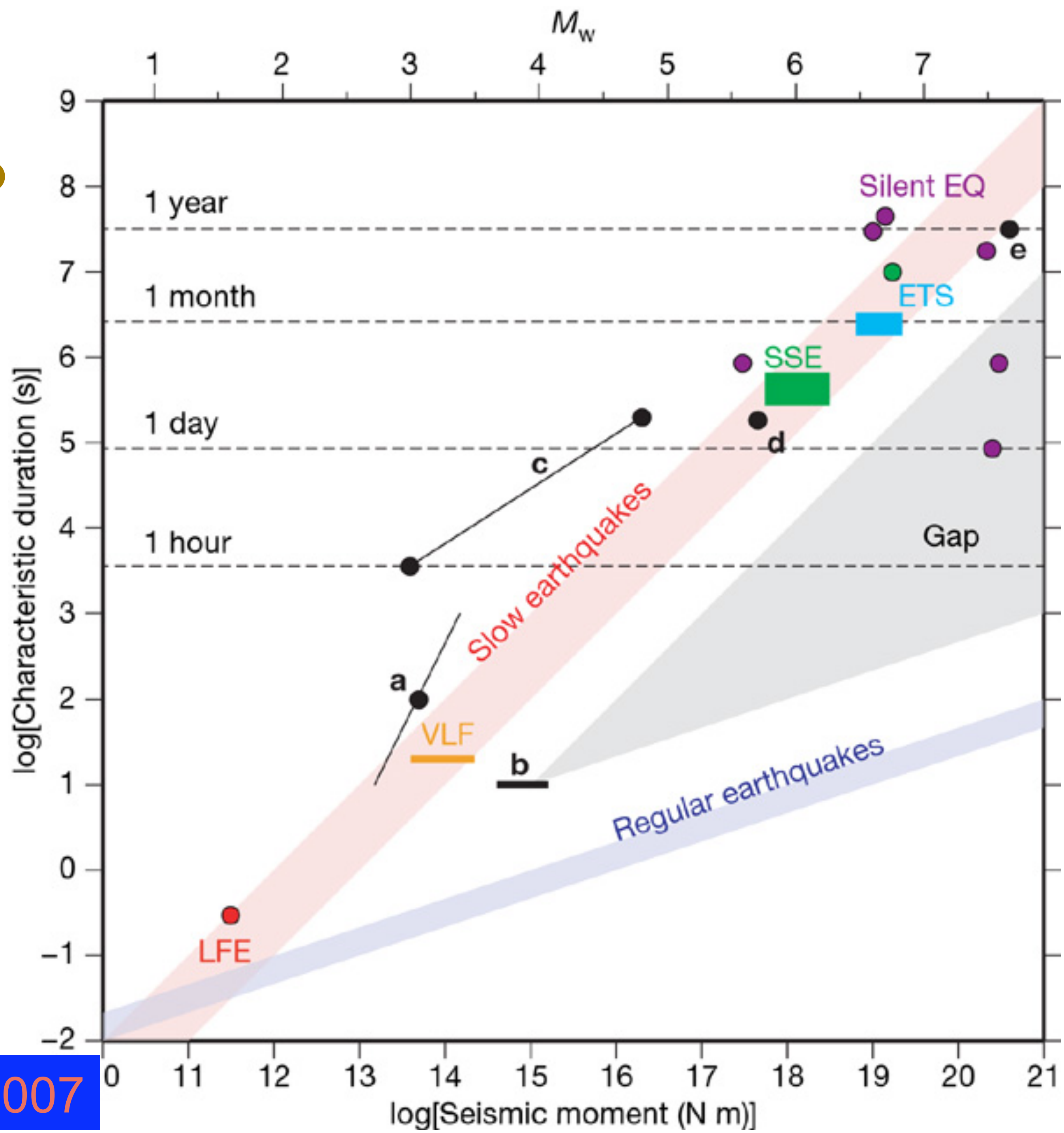


Kao et al., 2005

- Tremor distributed over 40 kms in depth in southern Vancouver Island (*Kao et al.*, 2005)
- Tremor distributed from 12 - 60 kms depth in Washington (*McCausland et al.*, 2005)
- Errors of ±5 km and ±10-20 km respectively

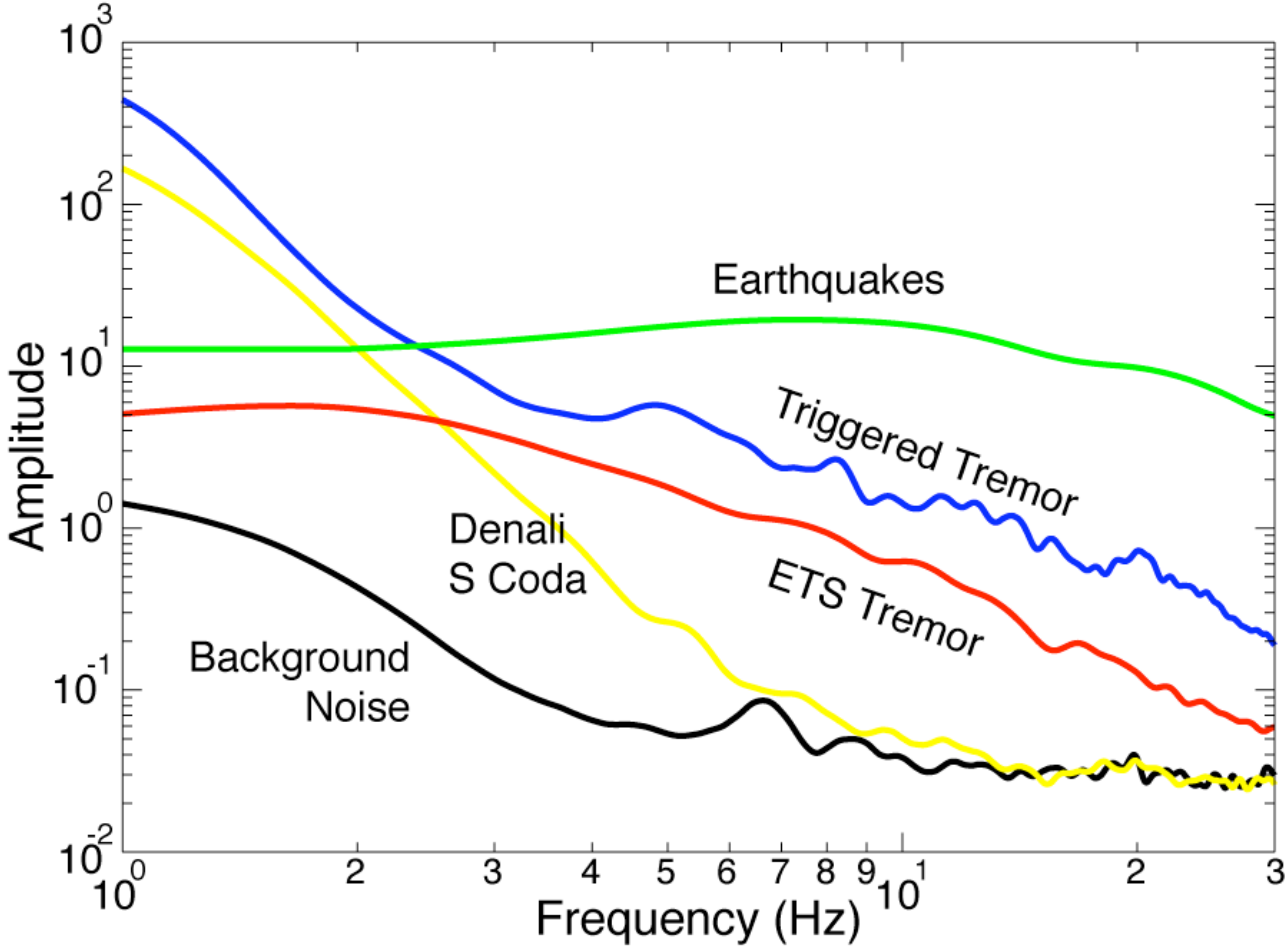
Two kinds of quakes?



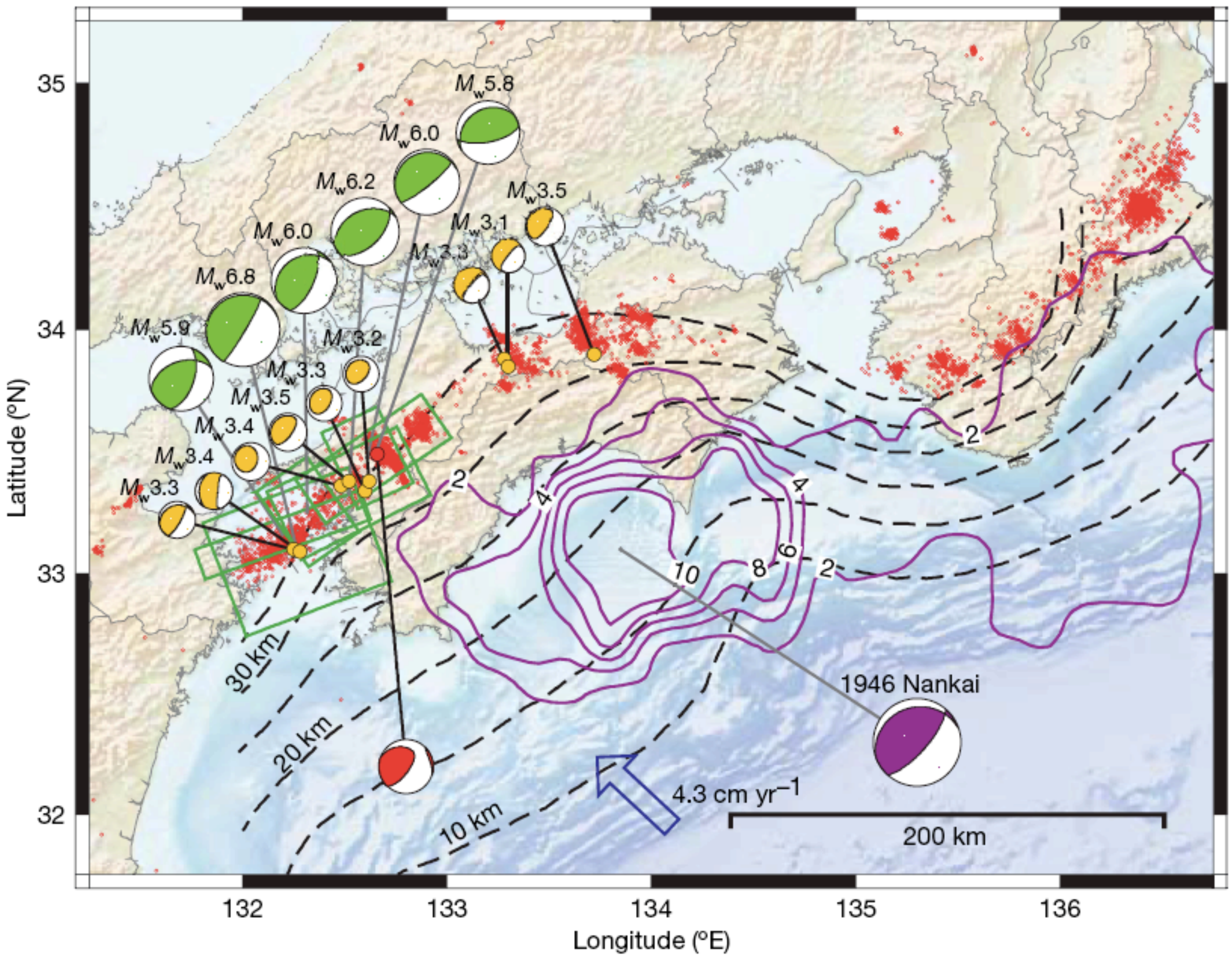


Ide *et al.*, *Nature*, 2007

Triggered resembles ETS Tremor



Tremors relative to Japan locked zone?

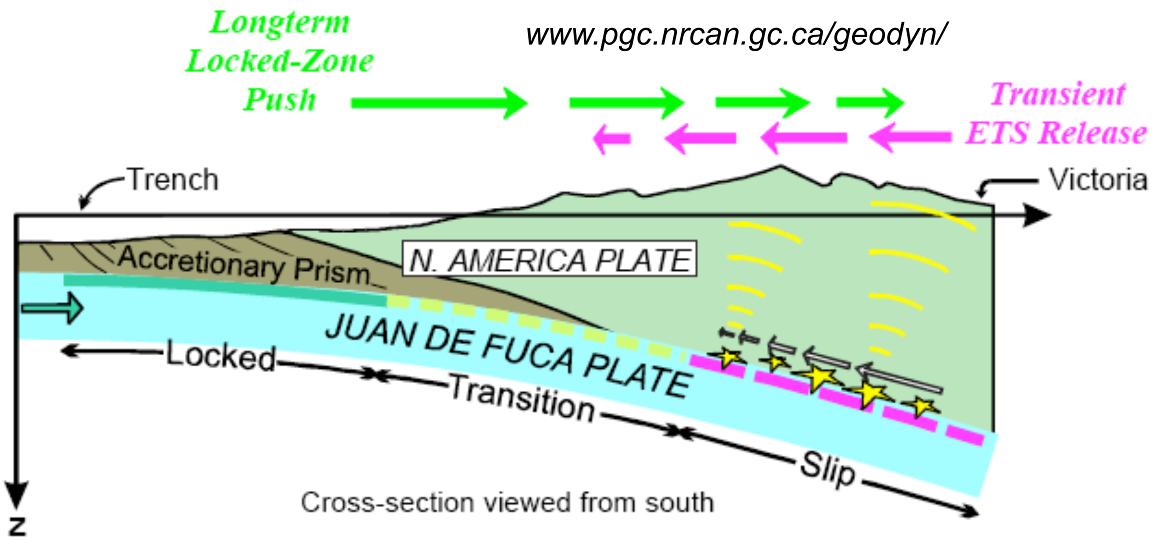


• Tremors

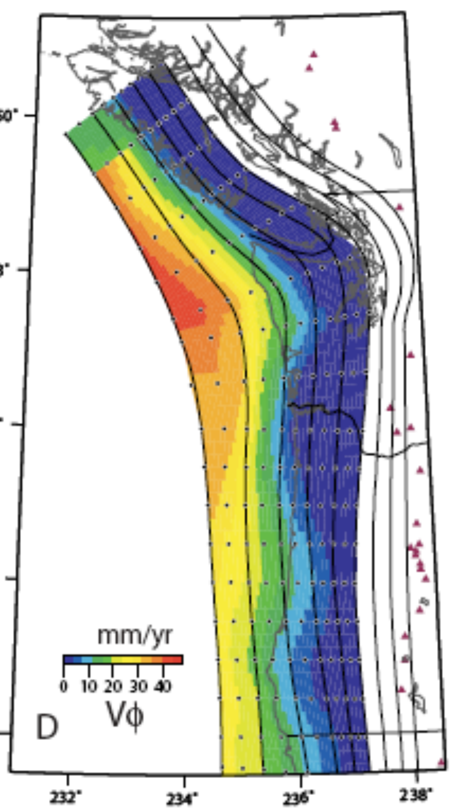
Megathrust
Slip Distribution

Ide et al., 2007

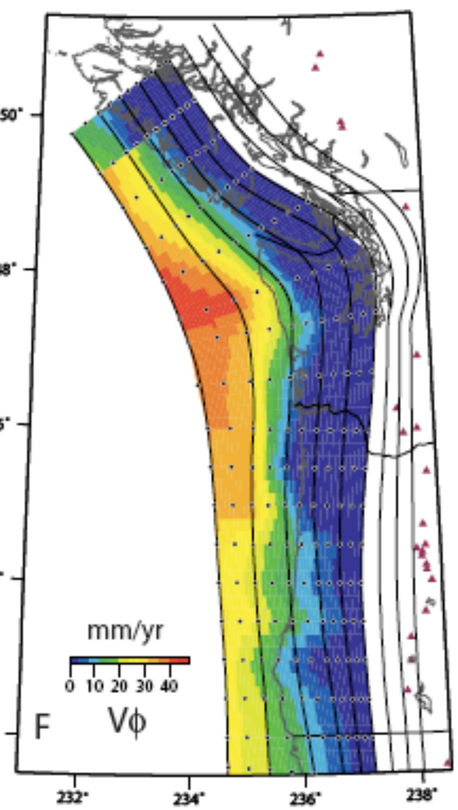
Cascadia locked zone ?



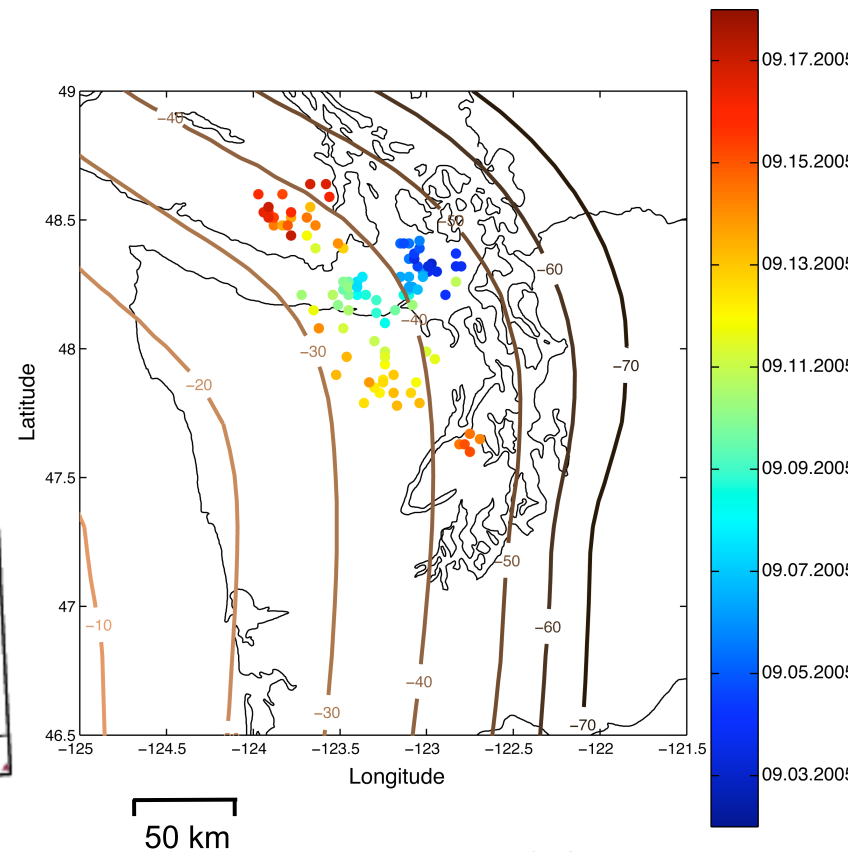
McCaffrey et al., 2007



Smooth factor = 0.2

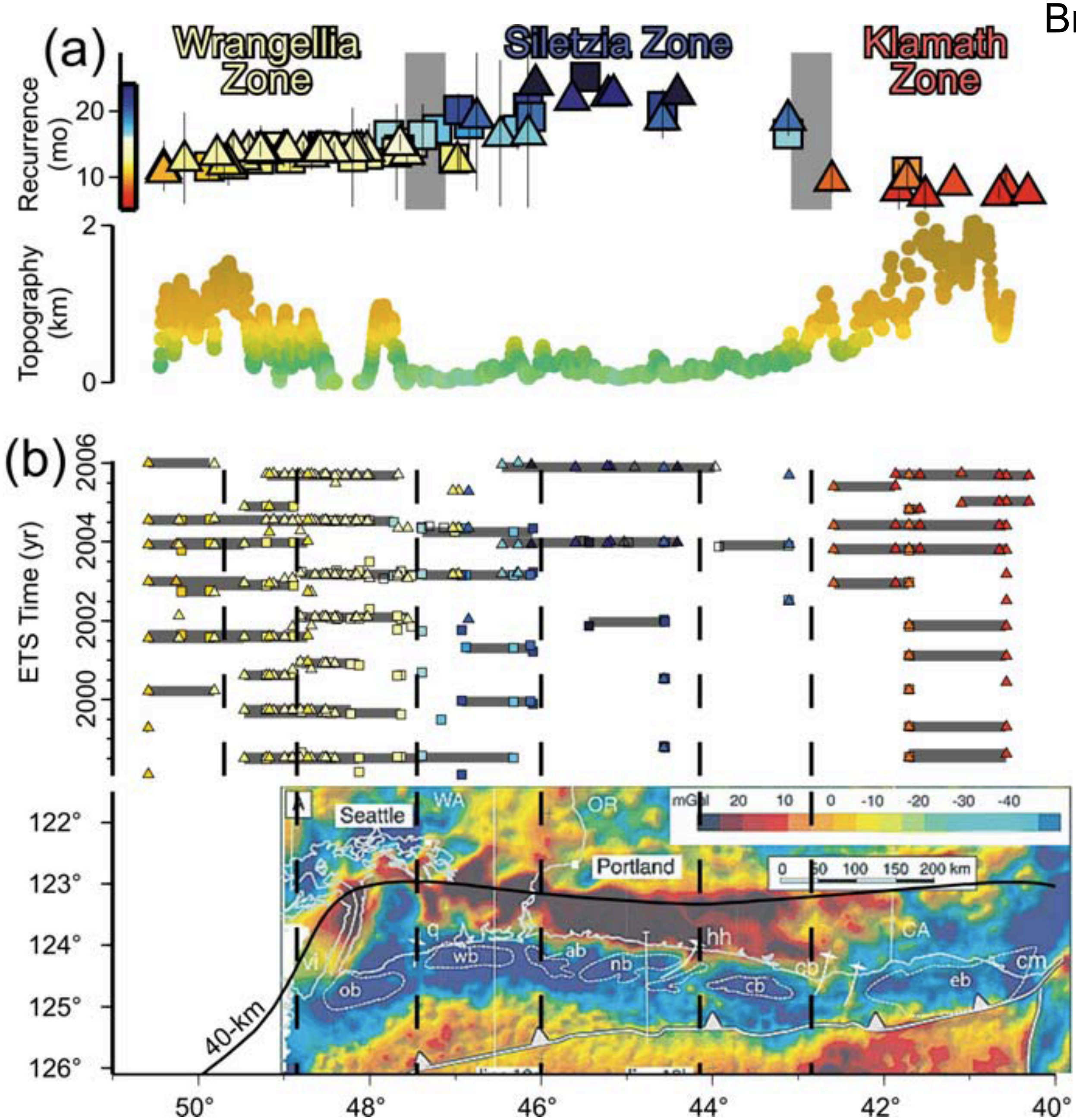


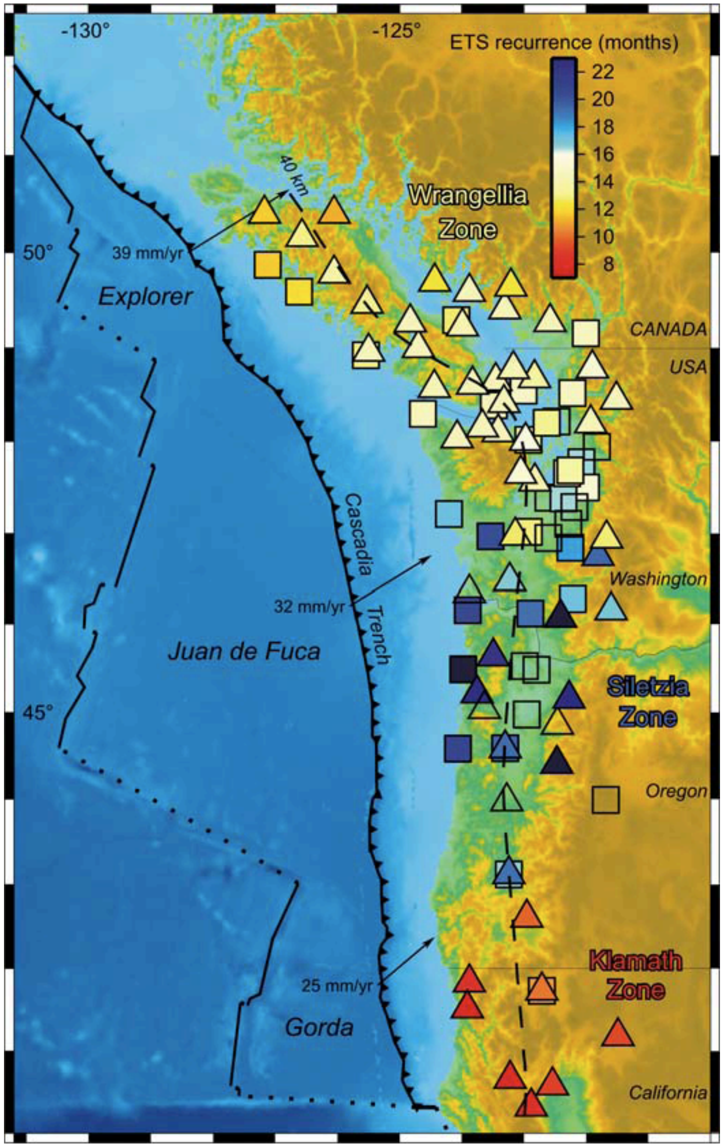
Smooth factor = 0.6

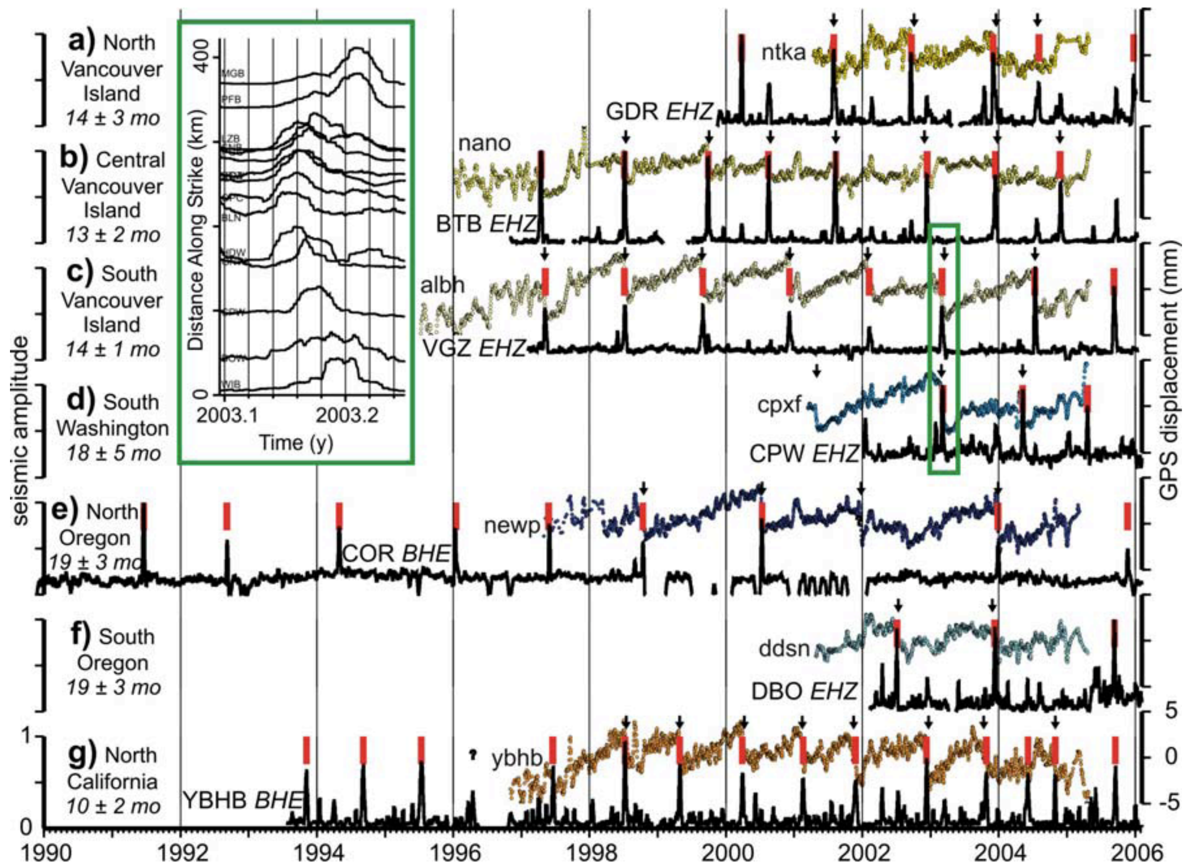


Wech & Creager, 2007

Brudzinski and Allen, 2007

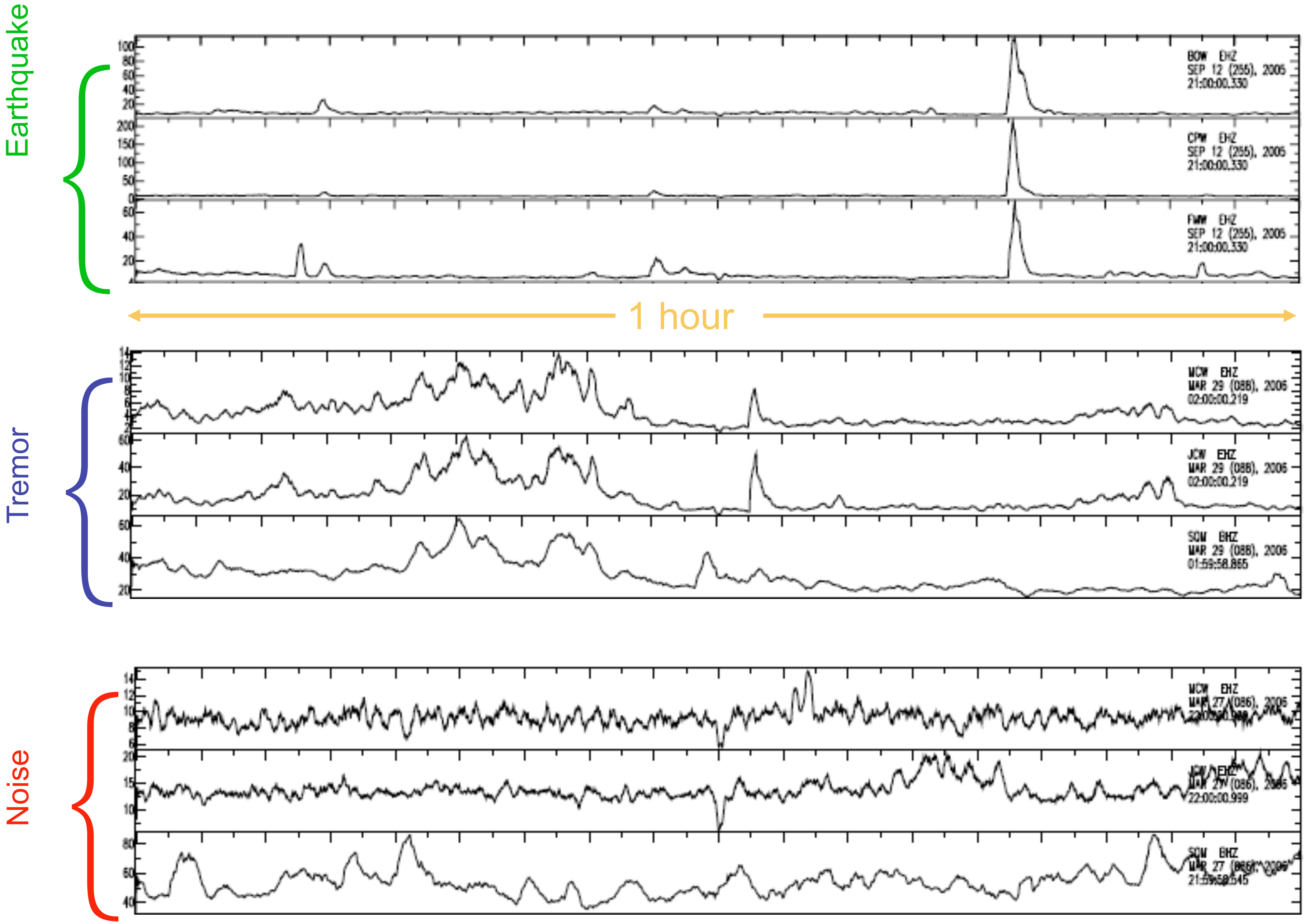



-130°
-125°
ETS recurrence (months)
22
20
18
16
14
12
10
8
40 km
Wrangellia Zone
39 mm/yr
50°
Explorer
CANADA
USA
Cascadia
Trench
Washington
32 mm/yr
Juan de Fuca
Siletzia Zone
45°
Oregon
25 mm/yr
Klamath Zone
Gorda
California

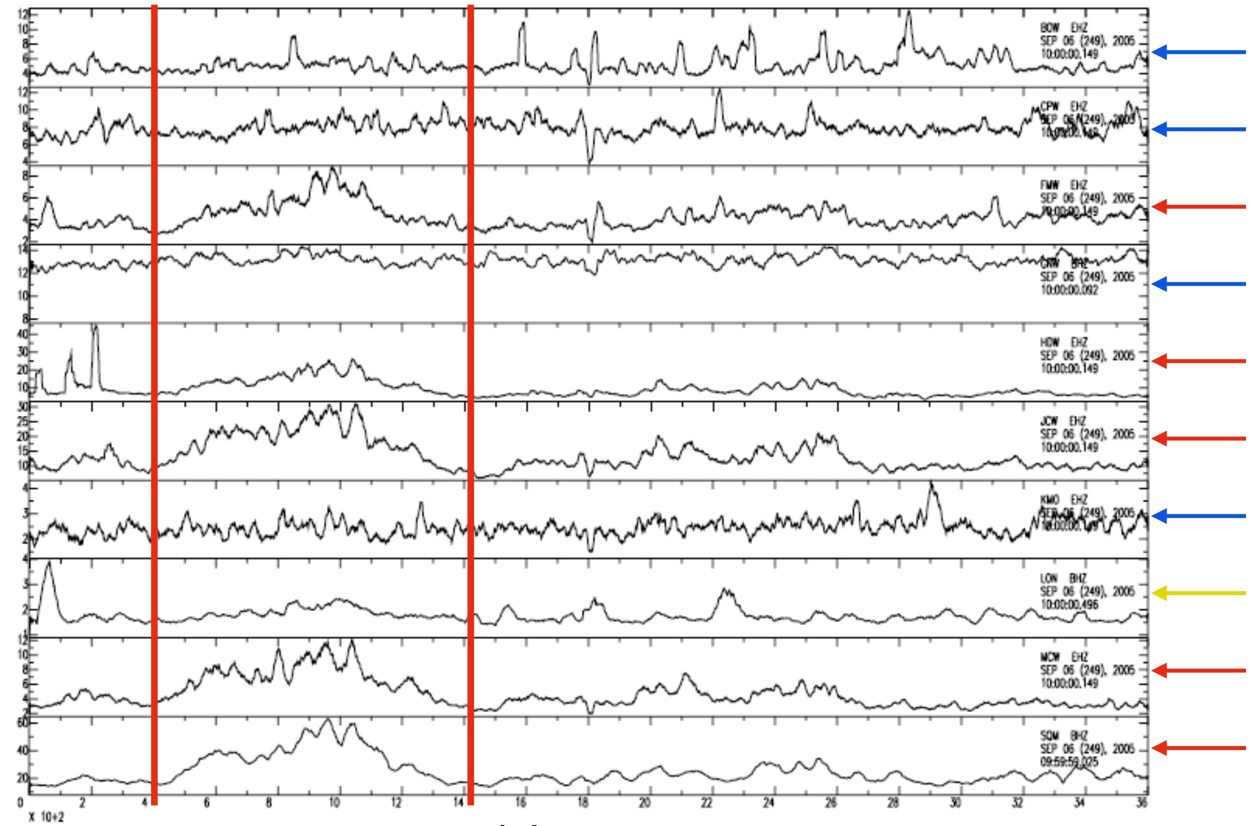

a) North Vancouver Island 14 ± 3 mo
ntka
GDR EHZ
b) Central Vancouver Island 13 ± 2 mo
nano
BTB EHZ
c) South Vancouver Island 14 ± 1 mo
albh
VGZ EHZ
d) South Washington 18 ± 5 mo
cpxf
CPW EHZ
e) North Oregon 19 ± 3 mo
newp
COR BHE
f) South Oregon 19 ± 3 mo
ddsn
DBO EHZ
g) North California 10 ± 2 mo
ybhb
YBHB BHE
seismic amplitude
GPS displacement (mm)
Distance Along Strike (km)
Time (y)
2003.1
2003.2
400
0
1
0
5
0
-5
1990
1992
1994
1996
1998
2000
2002
2004
2006

Tremor Detection:

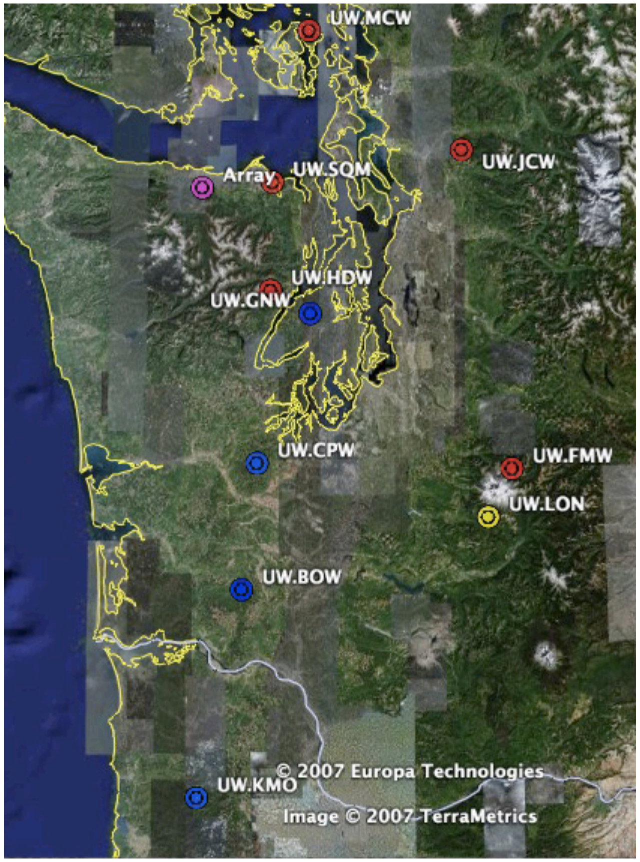
Envelopes


Earthquake
BOW EHZ SEP 12 (255), 2006 21:00:00.330
CPW EHZ SEP 12 (255), 2006 21:00:00.330
FMW EHZ SEP 12 (255), 2006 21:00:00.330
1 hour
Tremor
MCW EHZ MAR 29 (088), 2006 02:00:00.219
JCW EHZ MAR 29 (088), 2006 02:00:00.219
SQM EHZ MAR 29 (088), 2006 01:59:58.865
Noise
JCW EHZ MAR 27 (086), 2006 22:00:00.999

Identifying Tremor



1 hour

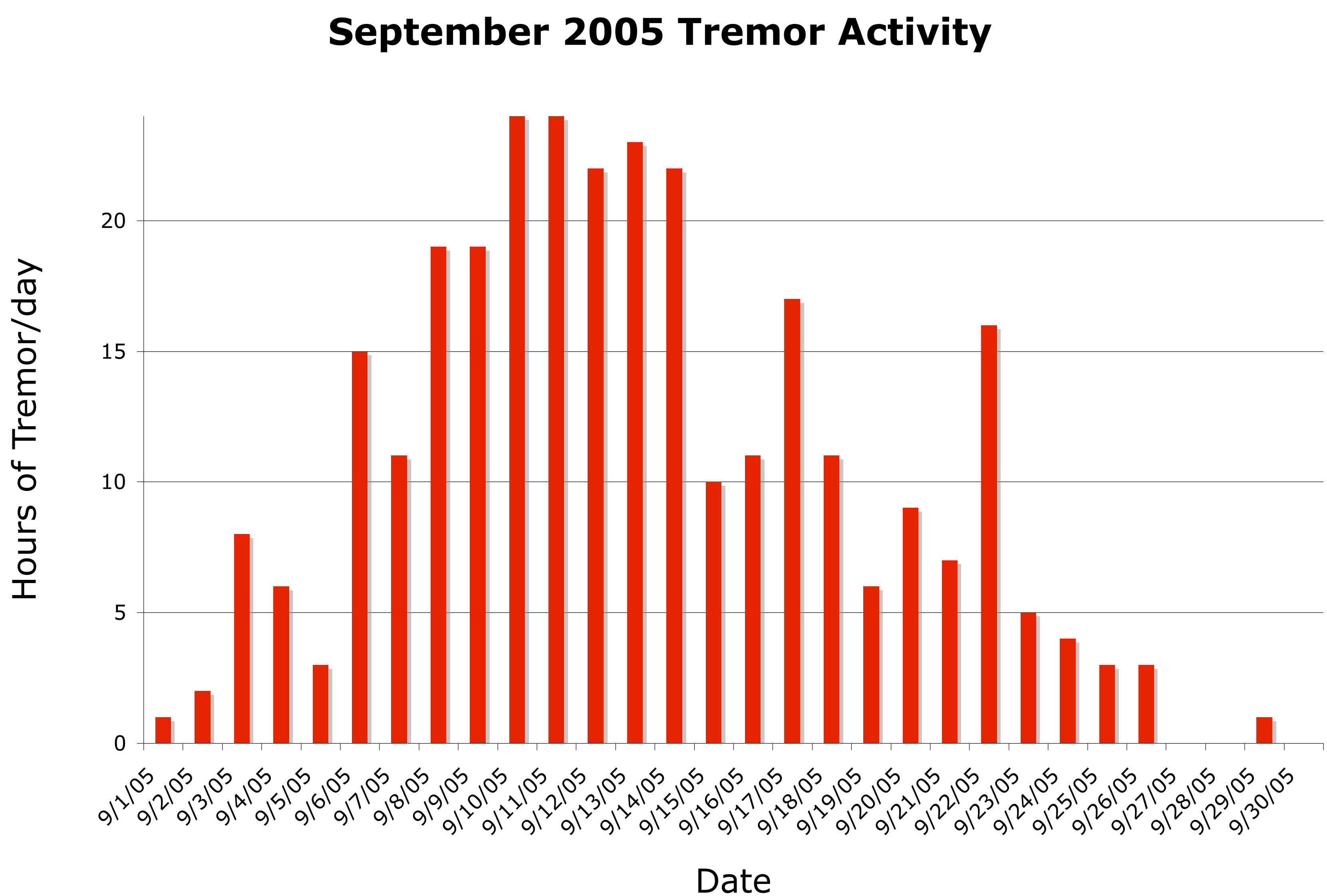


= Strong Tremor

= Weak Tremor

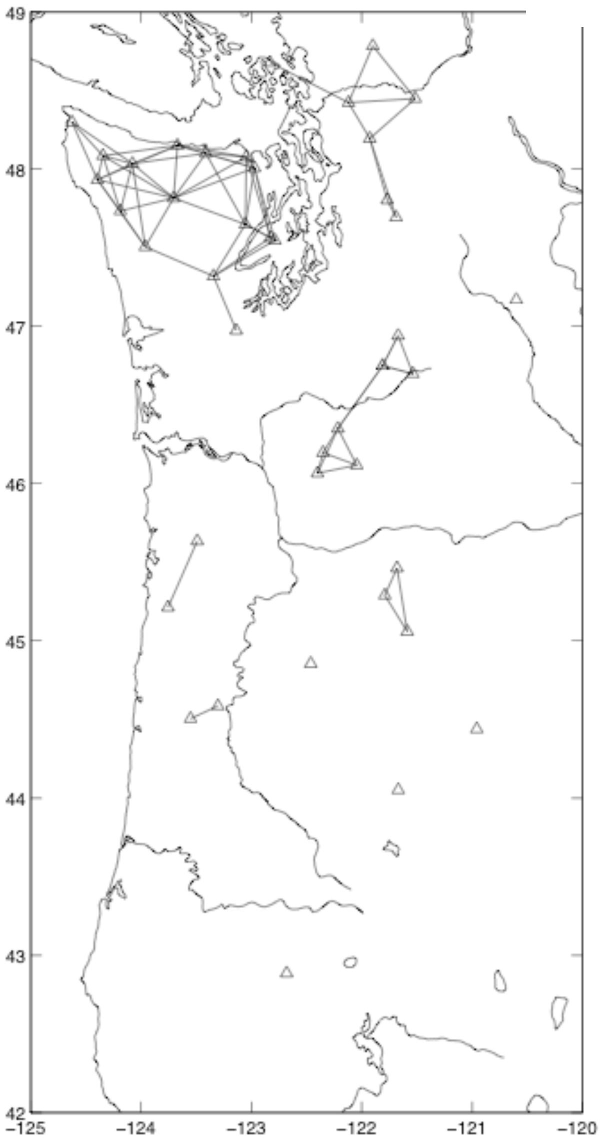
= No Tremor

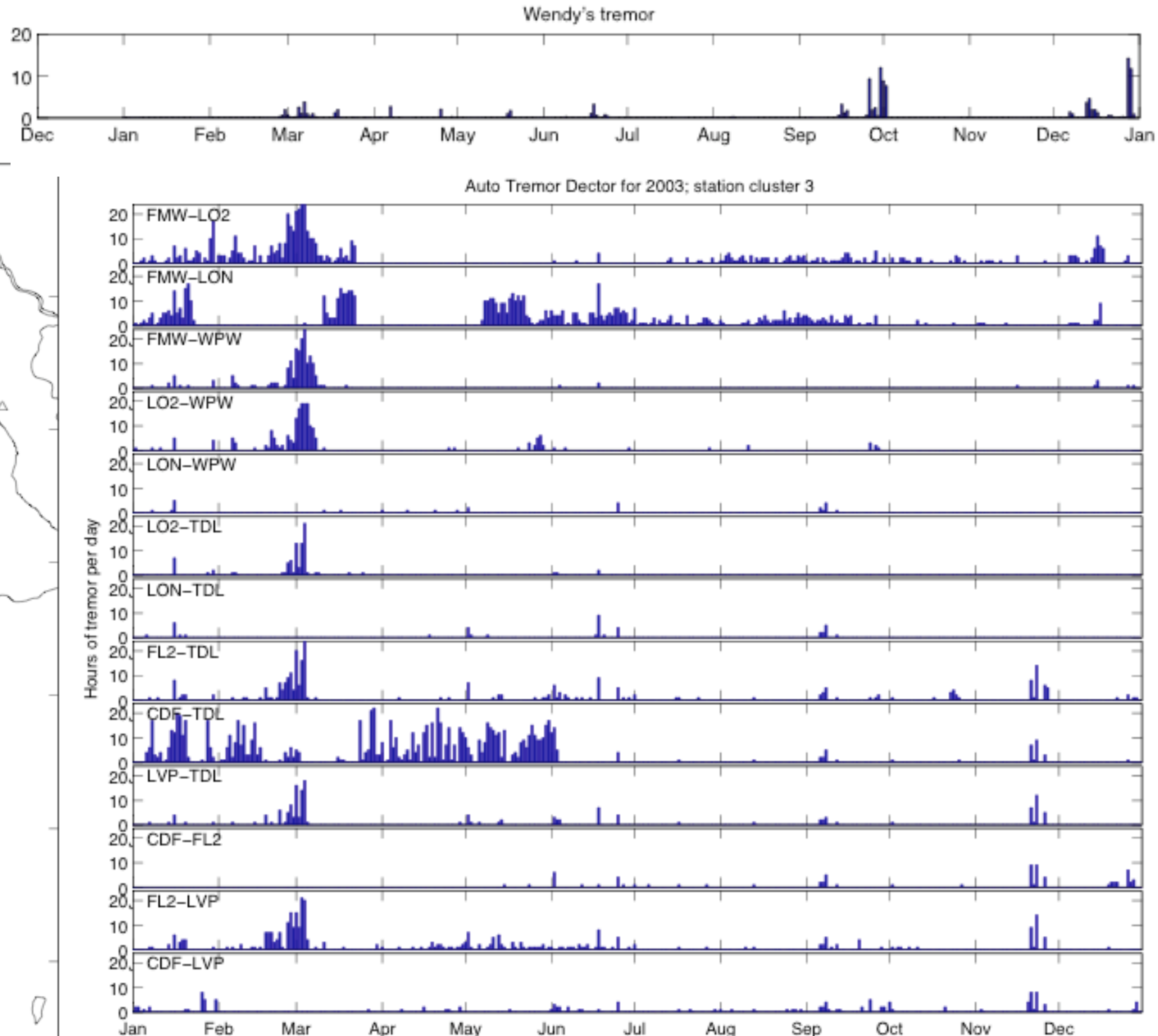
= Array



September 2005 Tremor Activity
Hours of Tremor/day
Date
0
5
10
15
20
9/1/05
9/2/05
9/3/05
9/4/05
9/5/05
9/6/05
9/7/05
9/8/05
9/9/05
9/10/05
9/11/05
9/12/05
9/13/05
9/14/05
9/15/05
9/16/05
9/17/05
9/18/05
9/19/05
9/20/05
9/21/05
9/22/05
9/23/05
9/24/05
9/25/05
9/26/05
9/27/05
9/28/05
9/29/05
9/30/05

2003 Tremor

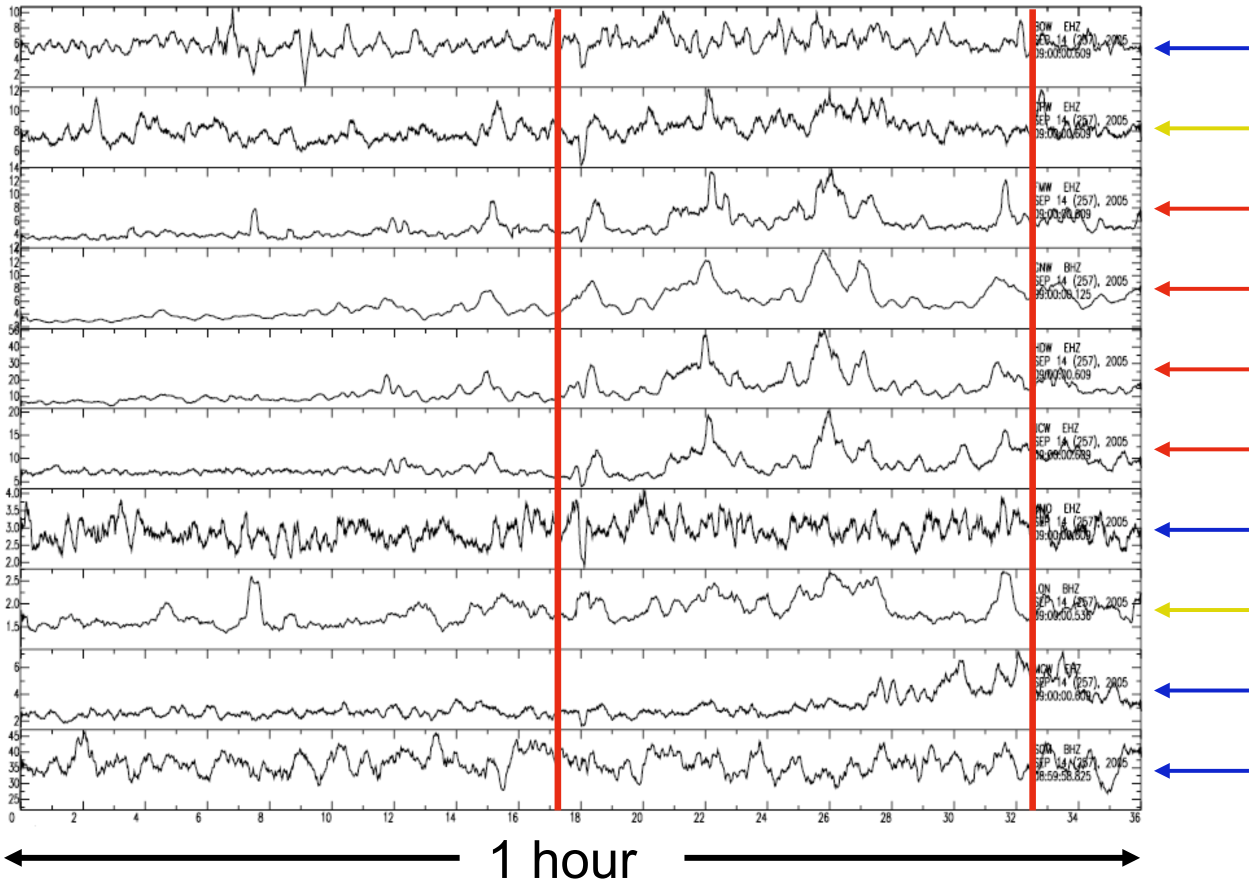


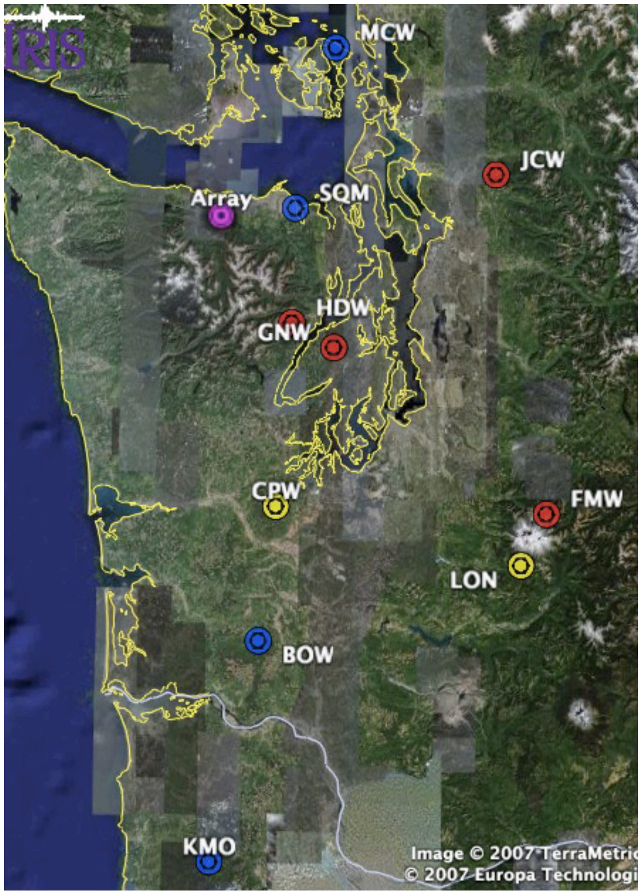


Automatic Tremor Detector

Tremor Location.

Locating Tremor





= Strong Tremor

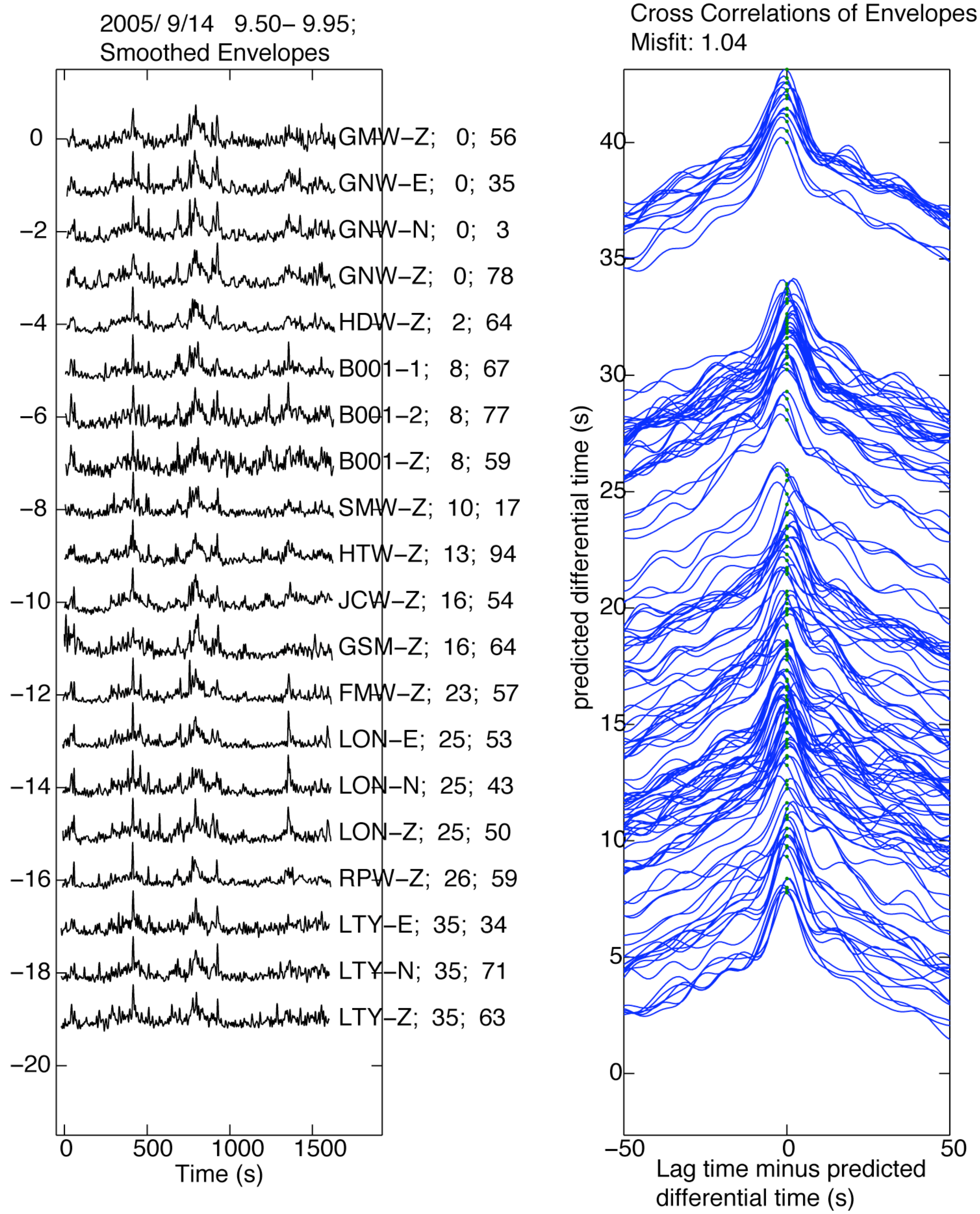
= Weak Tremor

= No Tremor

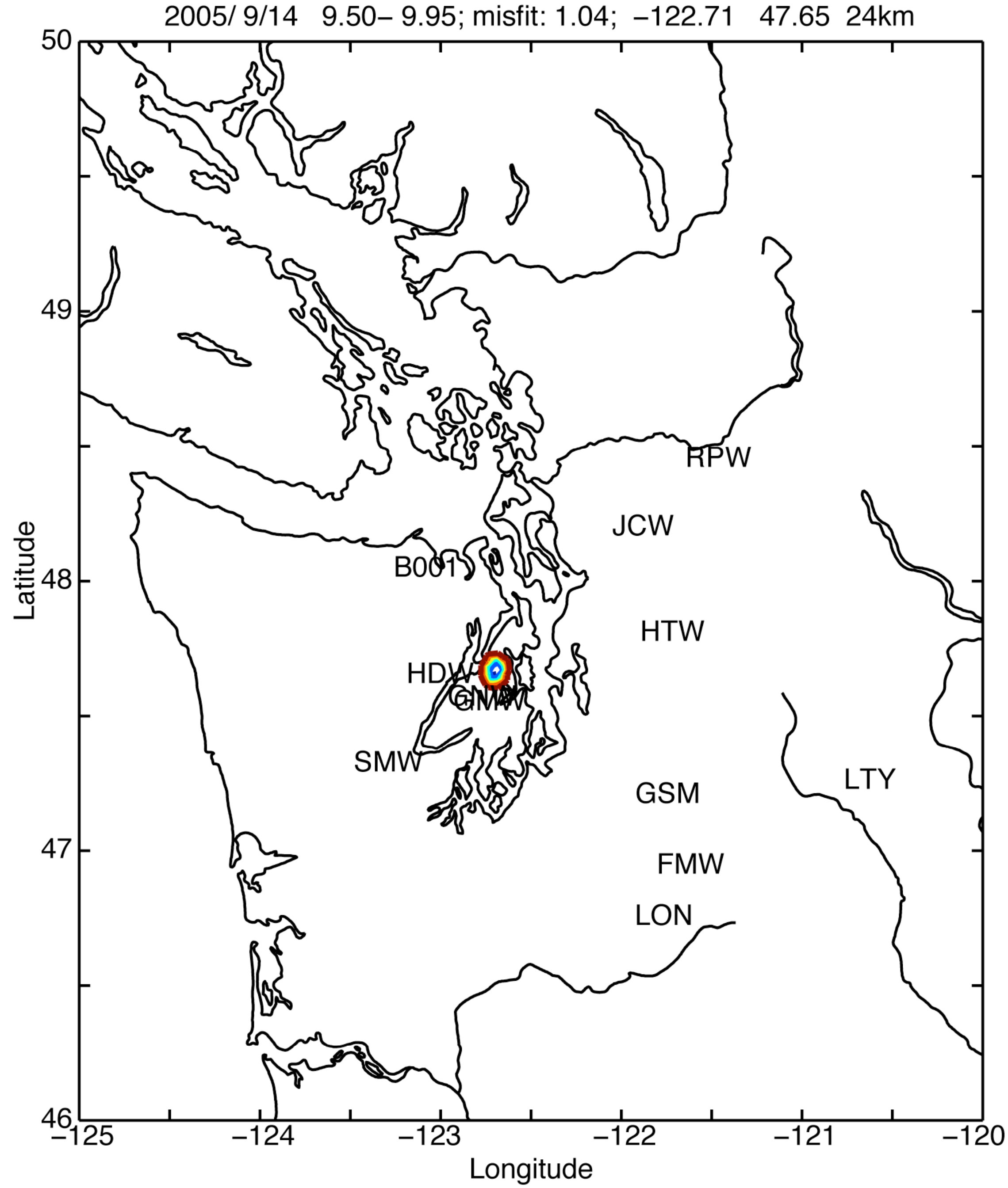
= Array

Location Method:

- Cross correlate pairs of smoothed envelope functions
- 3-D grid search that provides S-wave lag times
- Find set of lag times that maximizes cross correlation values



Example location from previous envelopes:

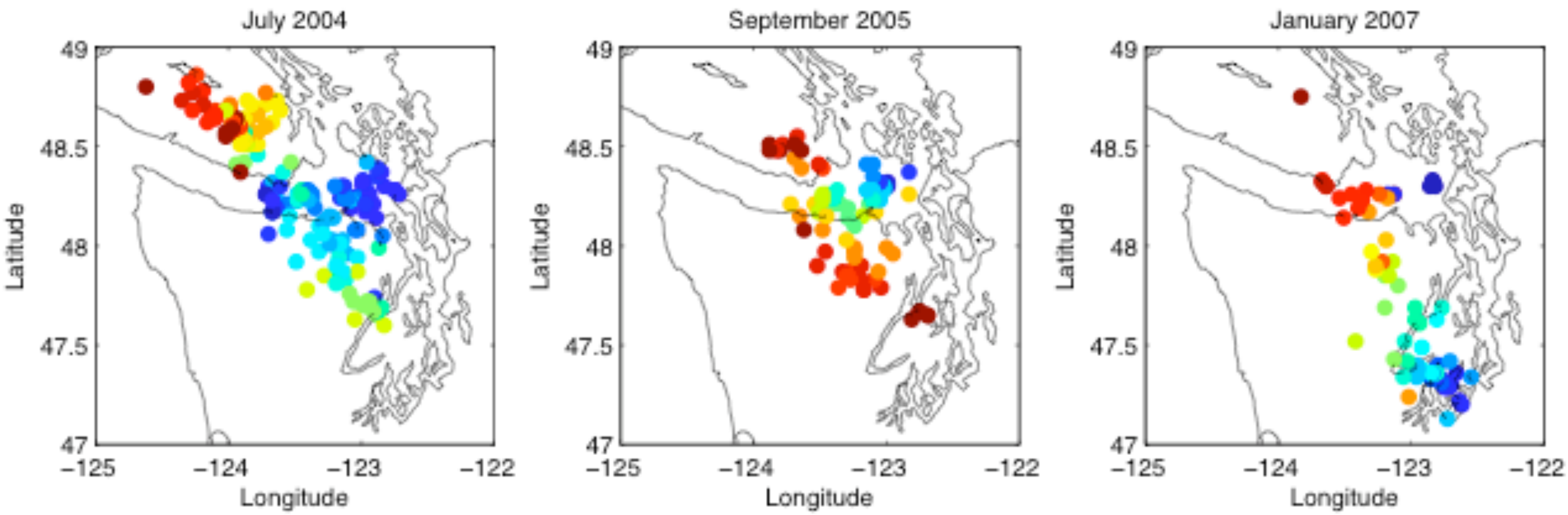


Testing Location Method

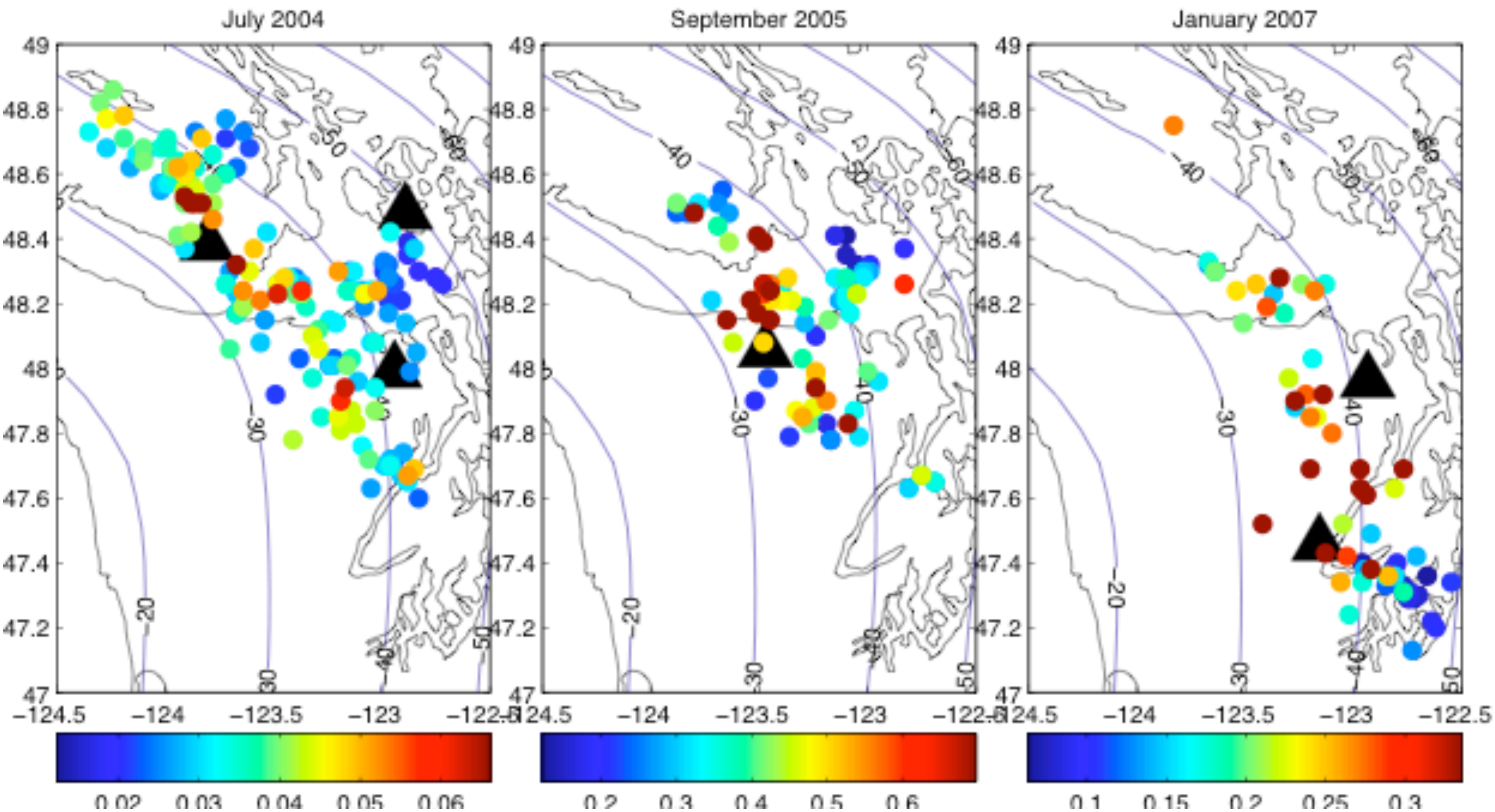
TEST:
- Used same processing to locate earthquakes
- Apply to 4 sample EQ's in vicinity of tremor

Date	Magnitude	Latitude	Longitude	Depth (km)	Epicenter Error (km)	Depth Error (km)
6/4/06	2.5	48.0027	-122.4065	57	1	-17
6/14/06	2.1	48.289	-122.6368	24	2	-14
6/30/06	2.3	48.605	-122.305	7	2	7
7/4/06	3.6	48.3547	-123.1953	46	3	-4

RESULT:
- Located within 3km of PNSN location
- Large depth error

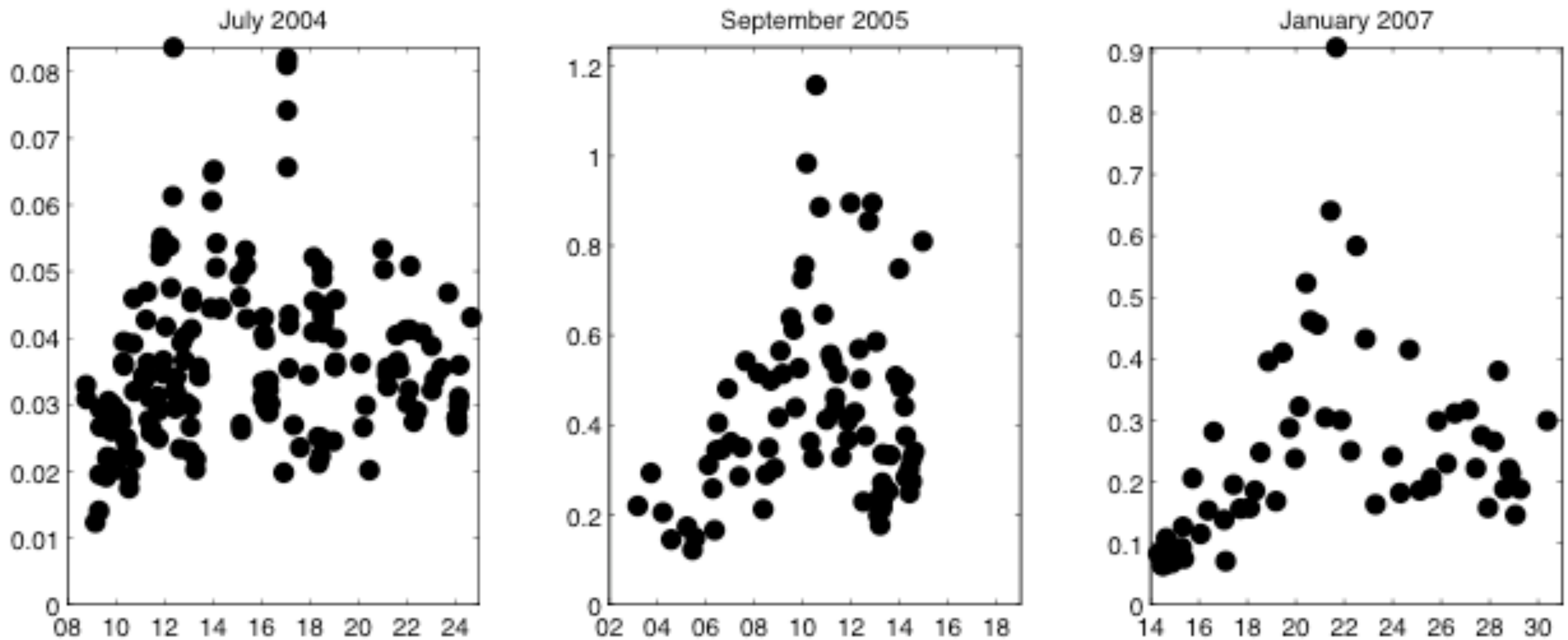

July 2004
September 2005
January 2007
Latitude
Longitude
49
48.5
48
47.5
47
–125
–124
–123
–122

Regions of large tremor amplitude (red) repeats
Caused by stress from tides or properties of the plate interface?

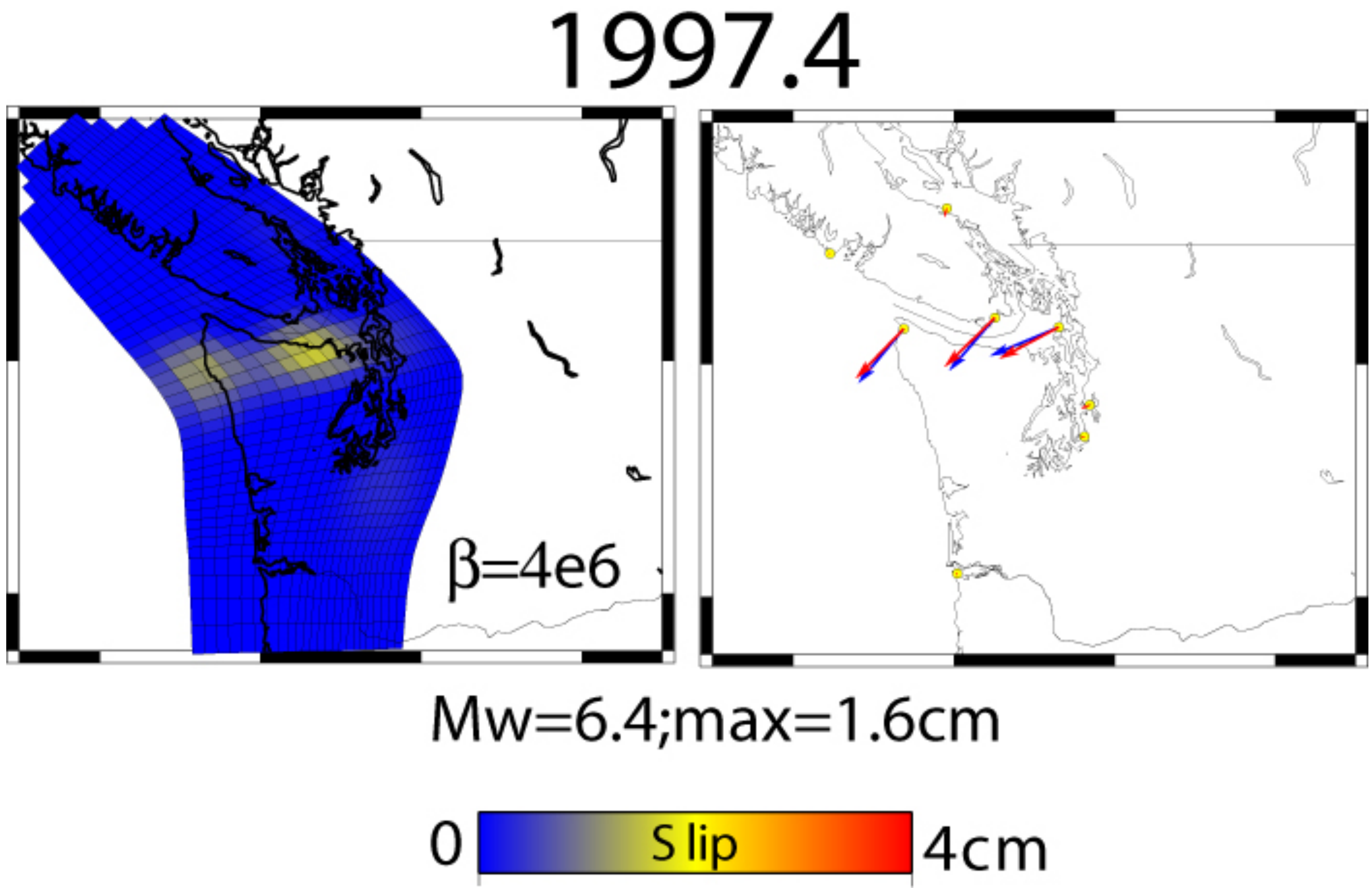


Amplitude of Tremor vs time

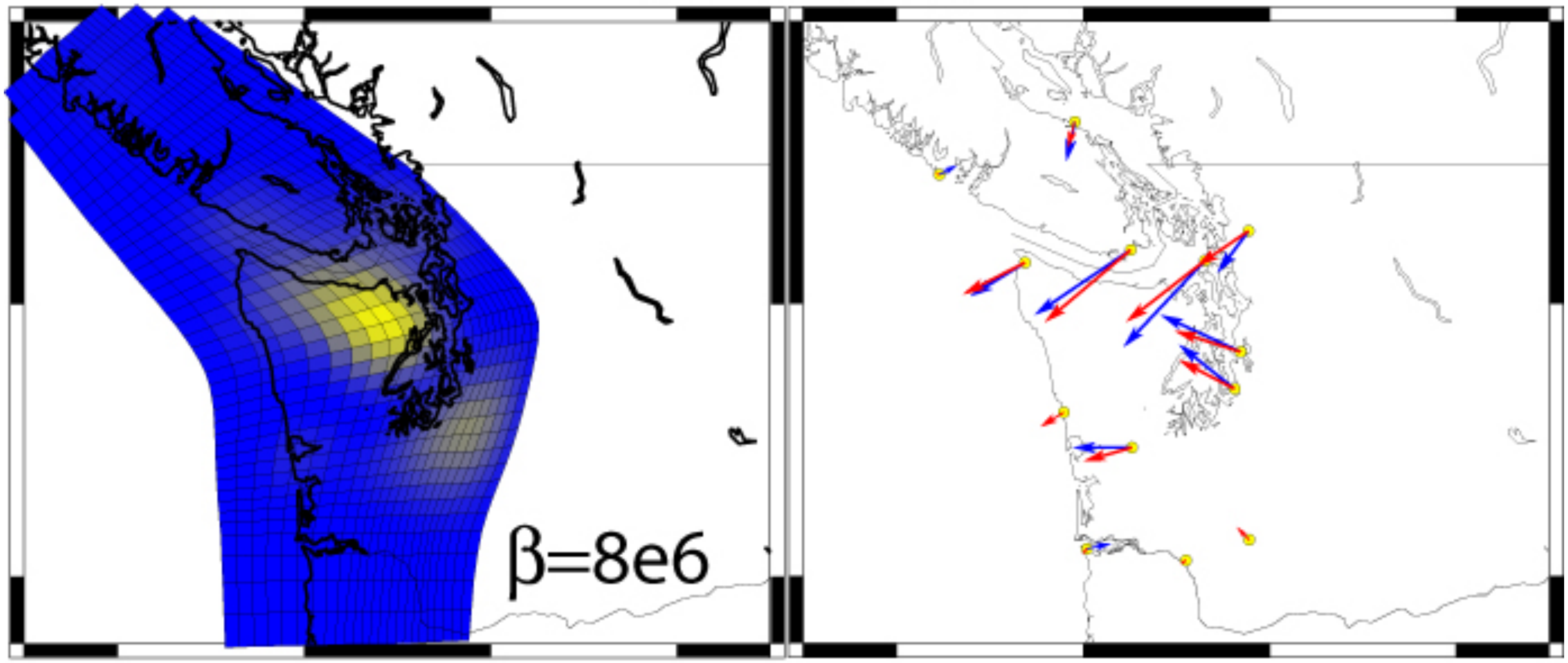
- Each ETS sequence starts small and ramps up over a period of one week
- Related to increasing area of slip or increasing elastic stress as more of the area slips?



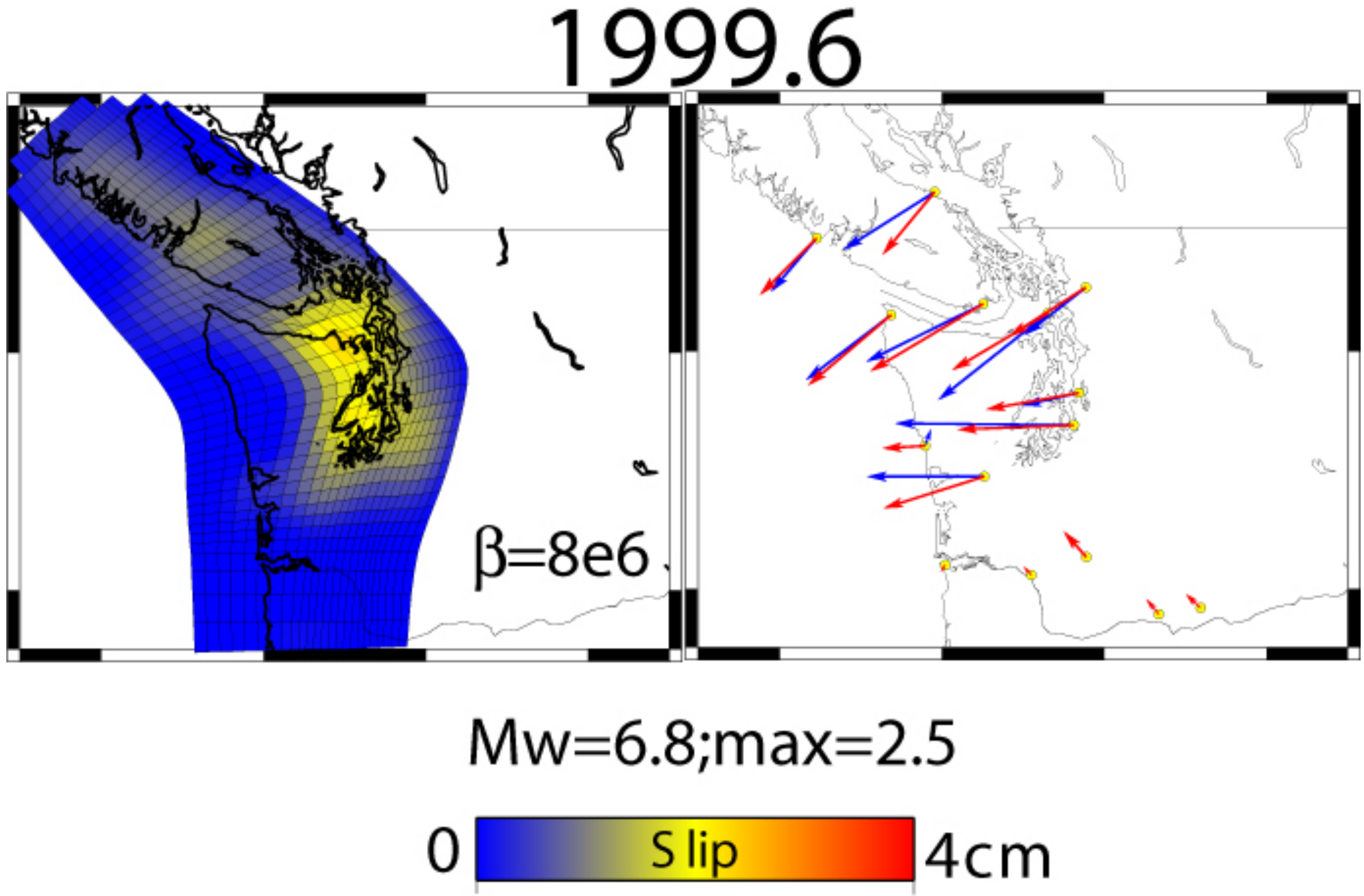
(Melbourne, 2006)



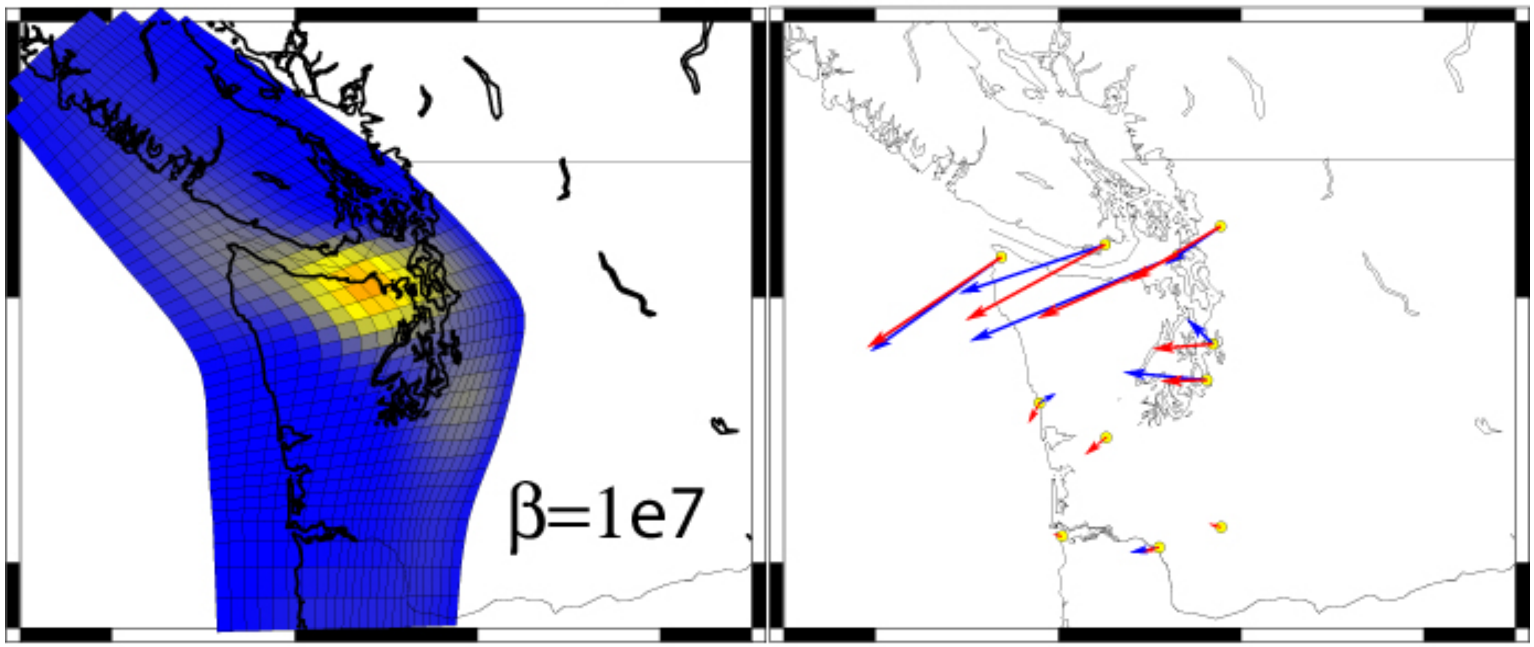
1998.5



Mw=6.6;max=2cm

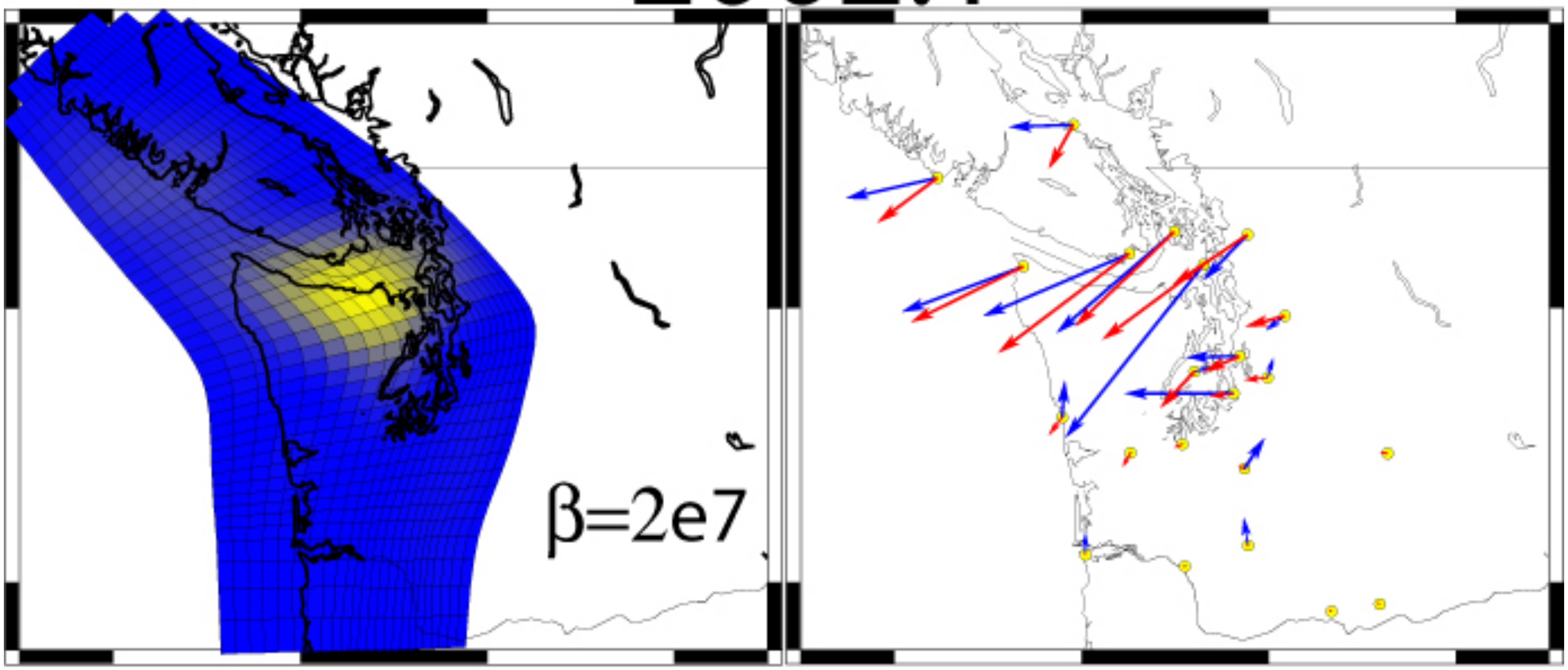

1999.6
β=8e6
Mw=6.8;max=2.5
0
Slip
4cm

2000.9



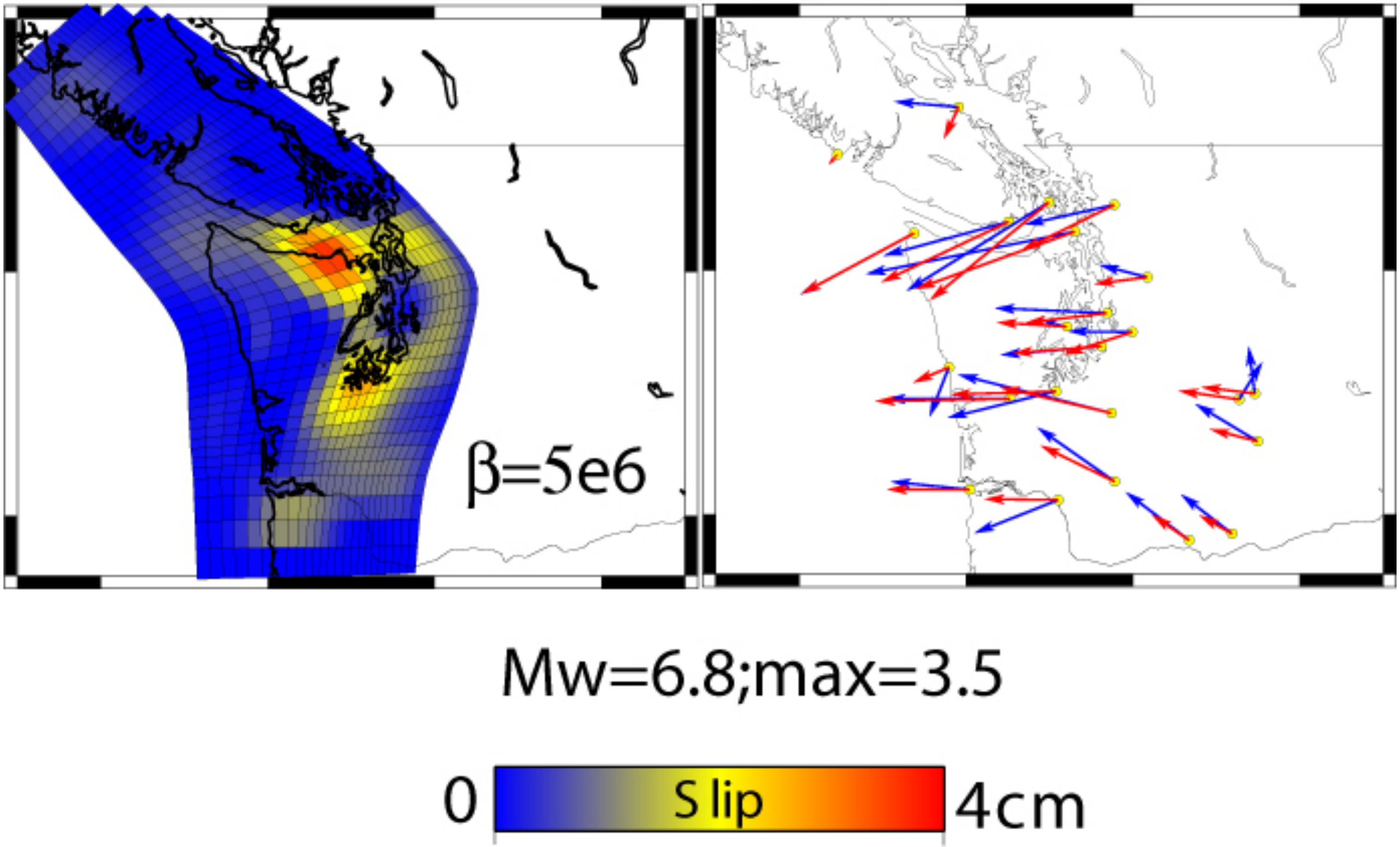
Mw=6.7;max=2.7 cm

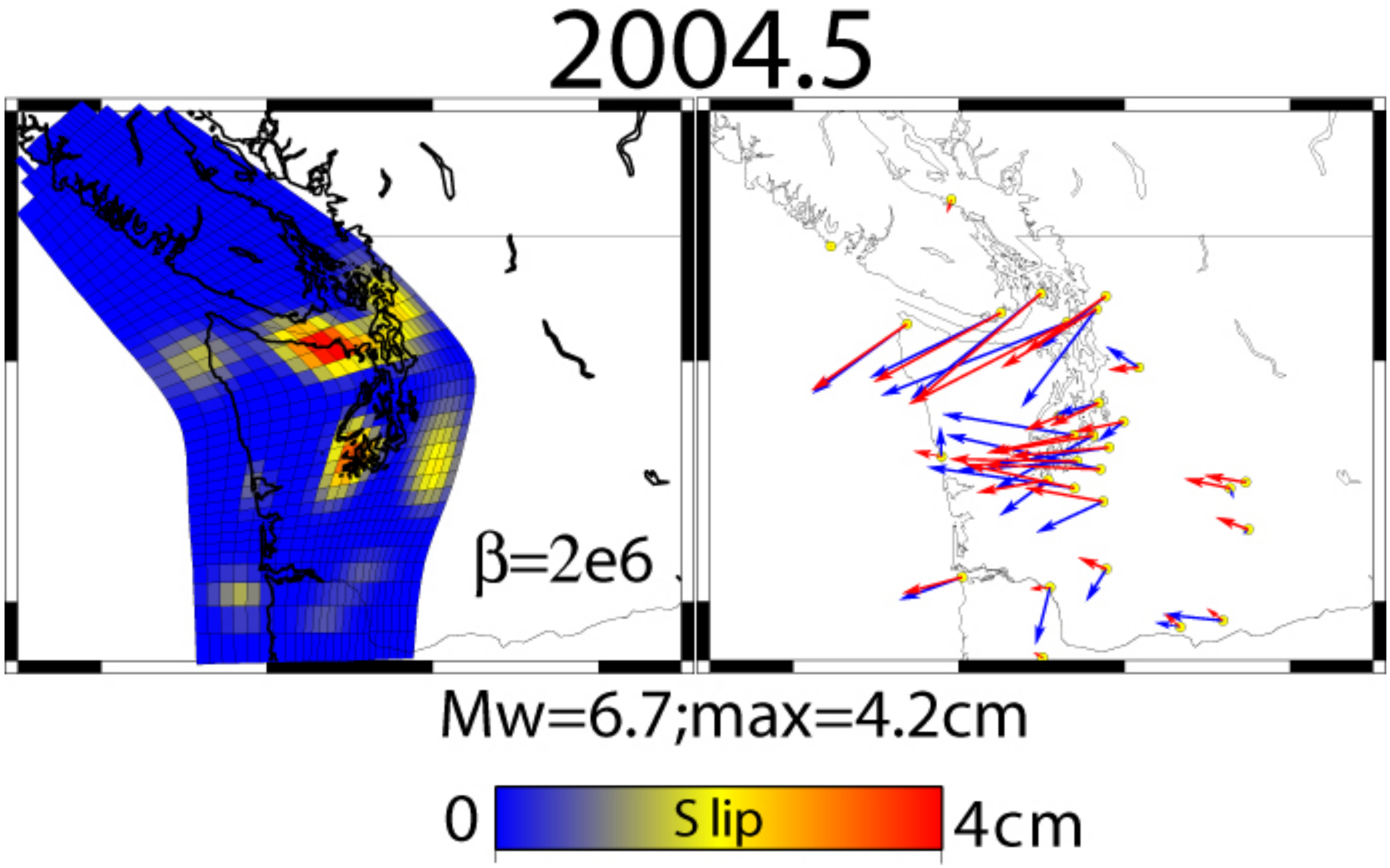
2002.1



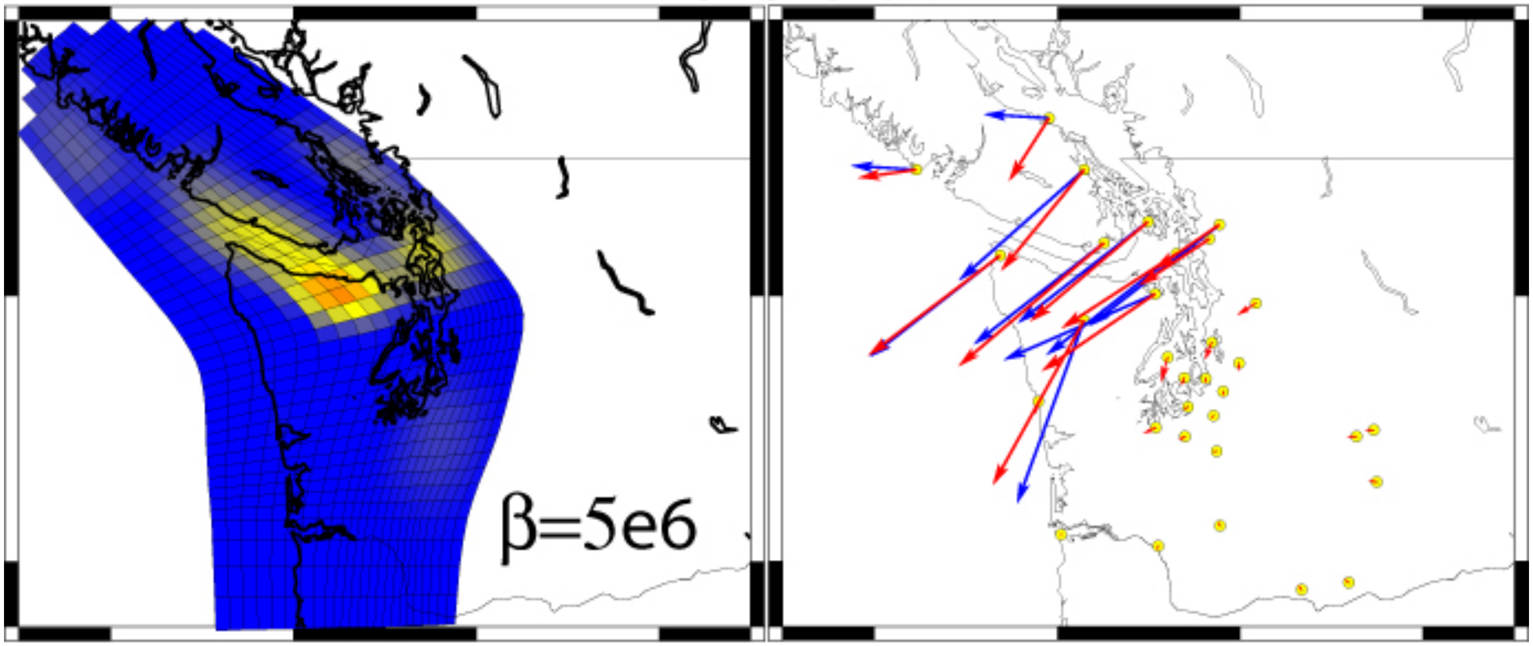
Mw=6.6;max=1.9cm

2003.2




2004.5
β=2e6
Mw=6.7;max=4.2cm
0
Slip
4cm

2005.7

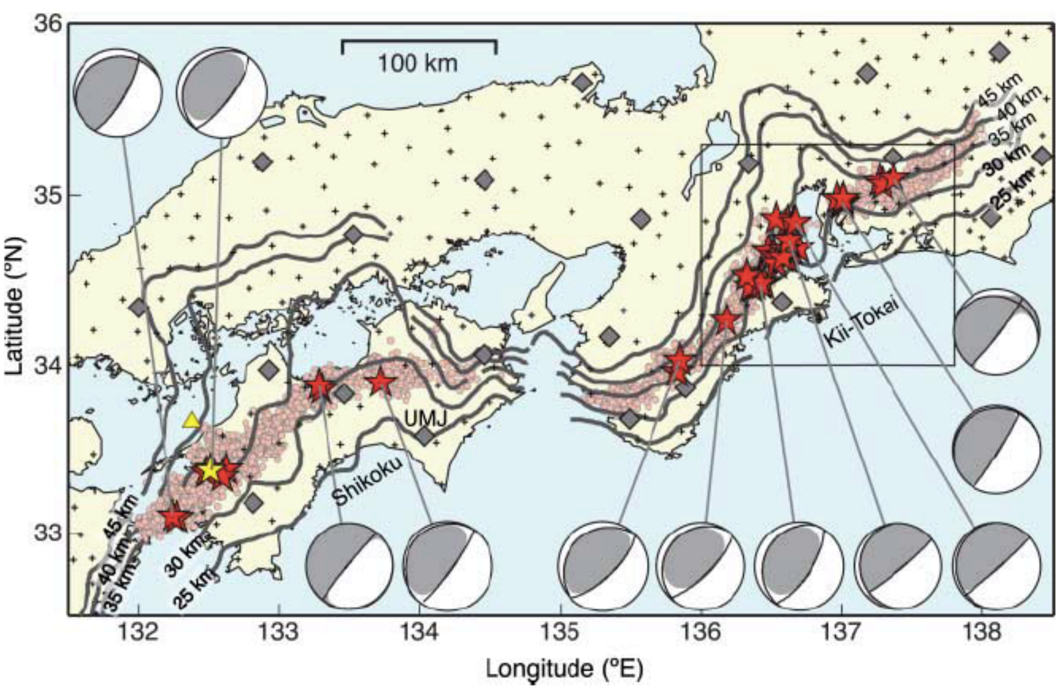


Mw=6.4;max=1.6cm

Japan low-frequency focal mechanisms

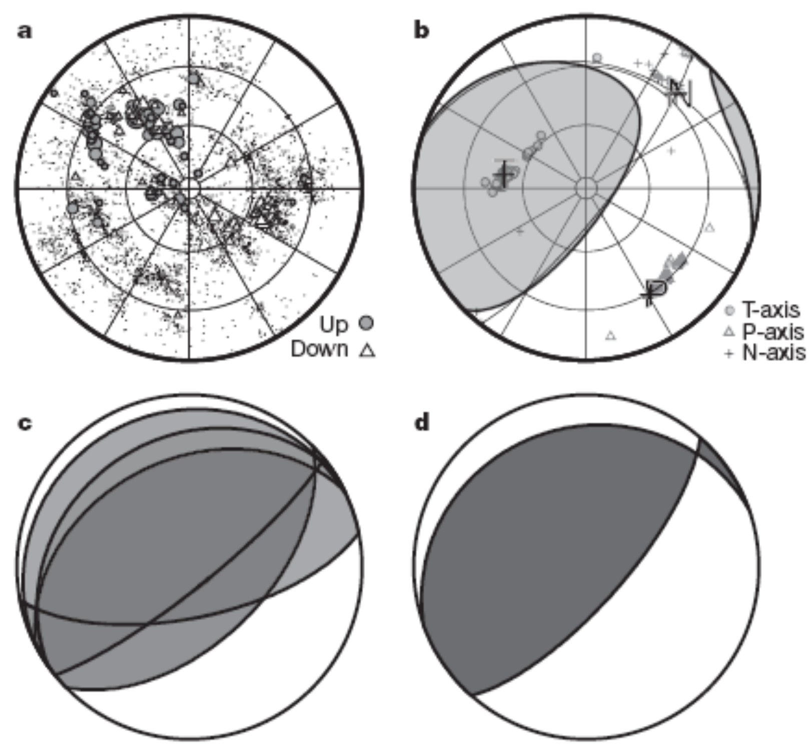
Fault slip on plate interface…

VLF's



Ito et al., 2007

LFE's



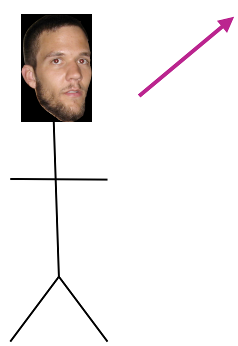
Shelly et al., 2007; *Ide et al.*, 2007

Cascadia low-frequency focal mechanisms

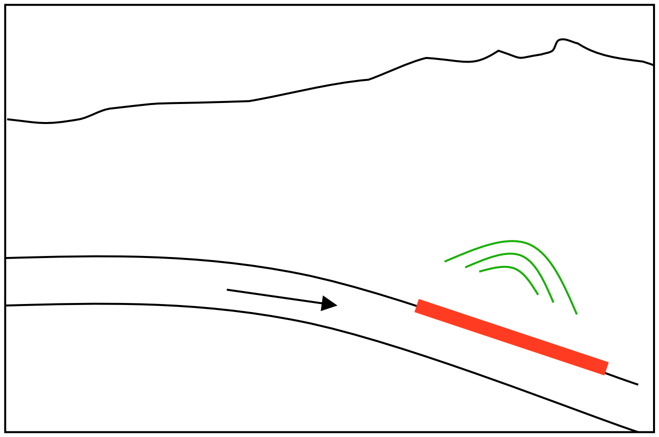
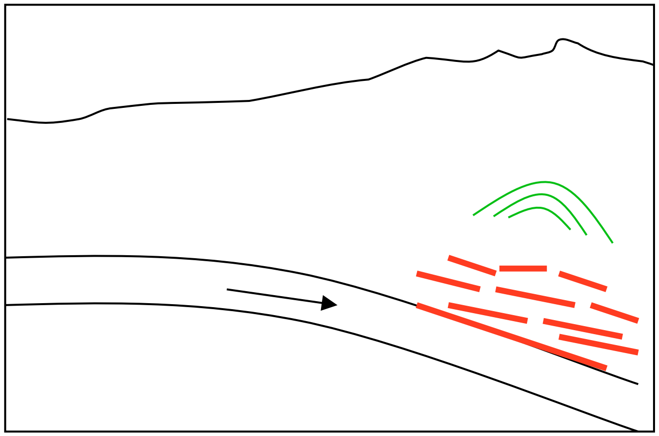
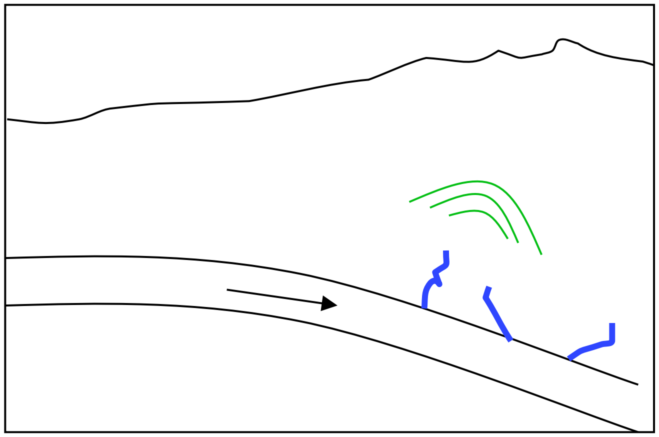
Japan/Cascadia Comparison

Japan	Cascadia
✓ Tremor w/ Slip	✓ Tremor w/ Slip
✓ Periodic	✓ Periodic
✓ Tremor epicenters above plate contours of 30-45 km	✓ Tremor epicenters above plate contours of 30-45 km
X Very low frequency (VLF) (20 sec) earthquakes w/ tremor	X No VLF's observed *yet*
X Low frequency earthquakes (LFE) (2--8 Hz) comprise tremor	X No LFE's observed *yet*
X LFE's imply tremor located on plate interface	X Tremor depths from 12--60 km
X Tremors edge at locked zone ?	X 100 km separation between tremors & locked zone ?
X VLF's & LFE's imply tremor is slip on plate interface	X No focal mechanism constraint.

Data ?



Proposed Models

Motivation:	Model:	
Tremor coincident with slow slip	Slip on plate interface	
Tremor coincident with slow slip & distributed in depth	Slip on faults	
Tremor distributed in depth & likeness to volcanic tremor	Fluids in cracks	

Hypothesis:

Tremor is the result of slip on the plate interface.

Test:

Slip on a fault generates a predictable particle motion polarization pattern at the Earth's surface.

Data:

1. Tremor epicenters
2. Small-aperture seismic array polarizations

Results:

Tremor particle motion polarizations consistent with with slip on plate interface.

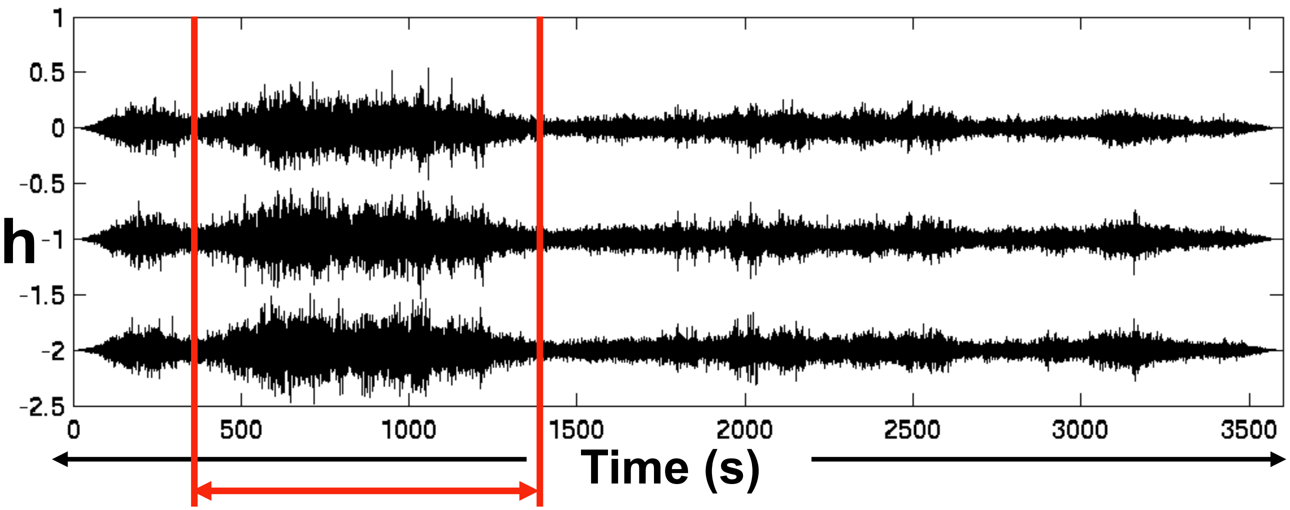
Measure Polarization.

Particle Motion Polarization

u_x: East-West

u_y: North-South

u_z: Vertical



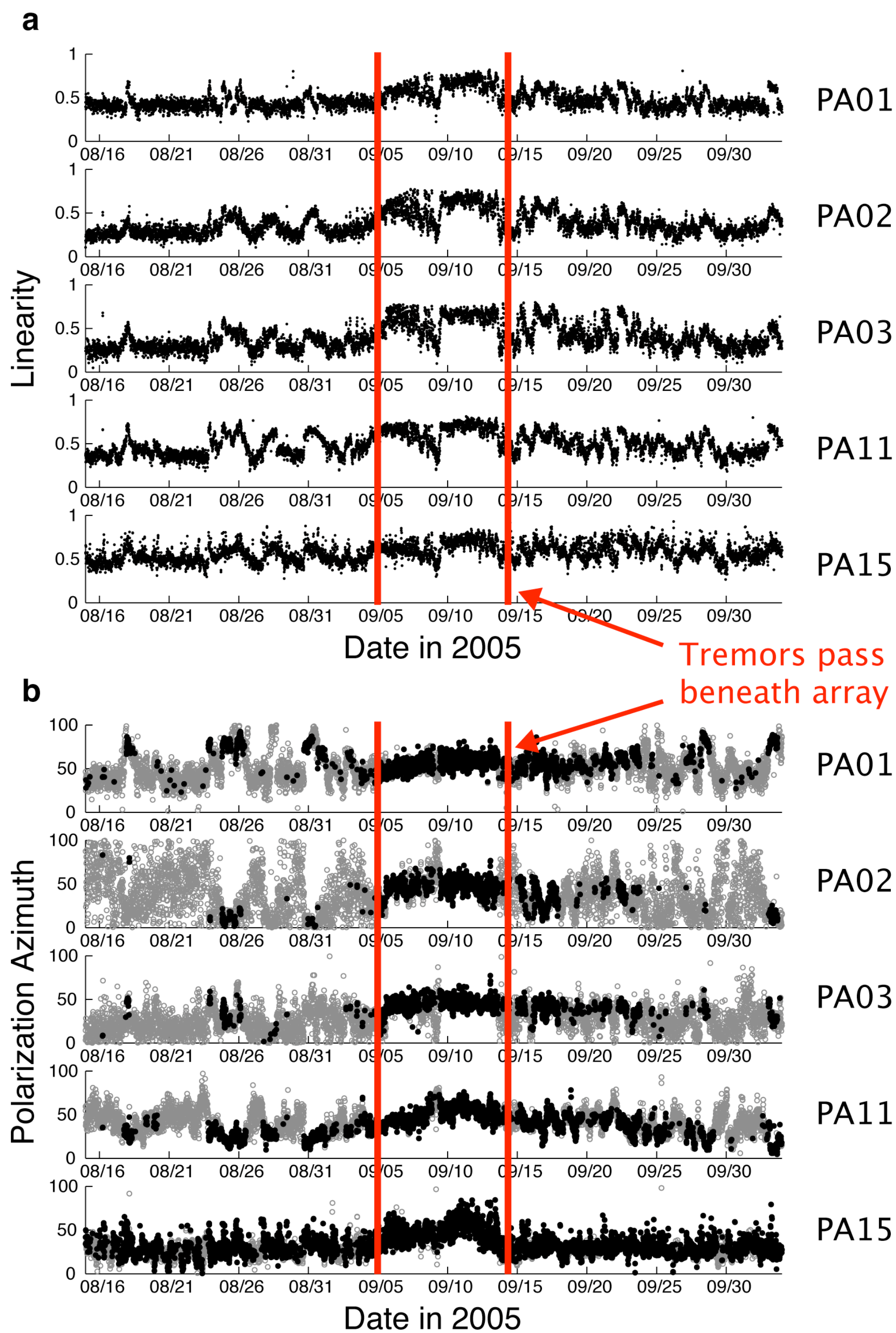
$$C = \begin{bmatrix} \mathbf{u}_x \cdot \mathbf{u}_x & \mathbf{u}_x \cdot \mathbf{u}_y & \mathbf{u}_x \cdot \mathbf{u}_z \\ \mathbf{u}_y \cdot \mathbf{u}_x & \mathbf{u}_y \cdot \mathbf{u}_y & \mathbf{u}_y \cdot \mathbf{u}_z \\ \mathbf{u}_z \cdot \mathbf{u}_x & \mathbf{u}_z \cdot \mathbf{u}_y & \mathbf{u}_z \cdot \mathbf{u}_z \end{bmatrix} \longrightarrow$$

Eigenvalues: $\lambda_1 \; , \; \lambda_2 \; , \; \lambda_3$

Eigenvectors: $\begin{bmatrix} v_{1x} \\ v_{1y} \\ v_{1z} \end{bmatrix}, \begin{bmatrix} v_{2x} \\ v_{2y} \\ v_{2z} \end{bmatrix}, \begin{bmatrix} v_{3x} \\ v_{3y} \\ v_{3z} \end{bmatrix}$

Polarization Direction

Jurkevics, 1988



Results of 2005 Array

1. Calculate linearity and polarization for overlapping 10-minute windows.

2. During days in red, tremor passes beneath array.

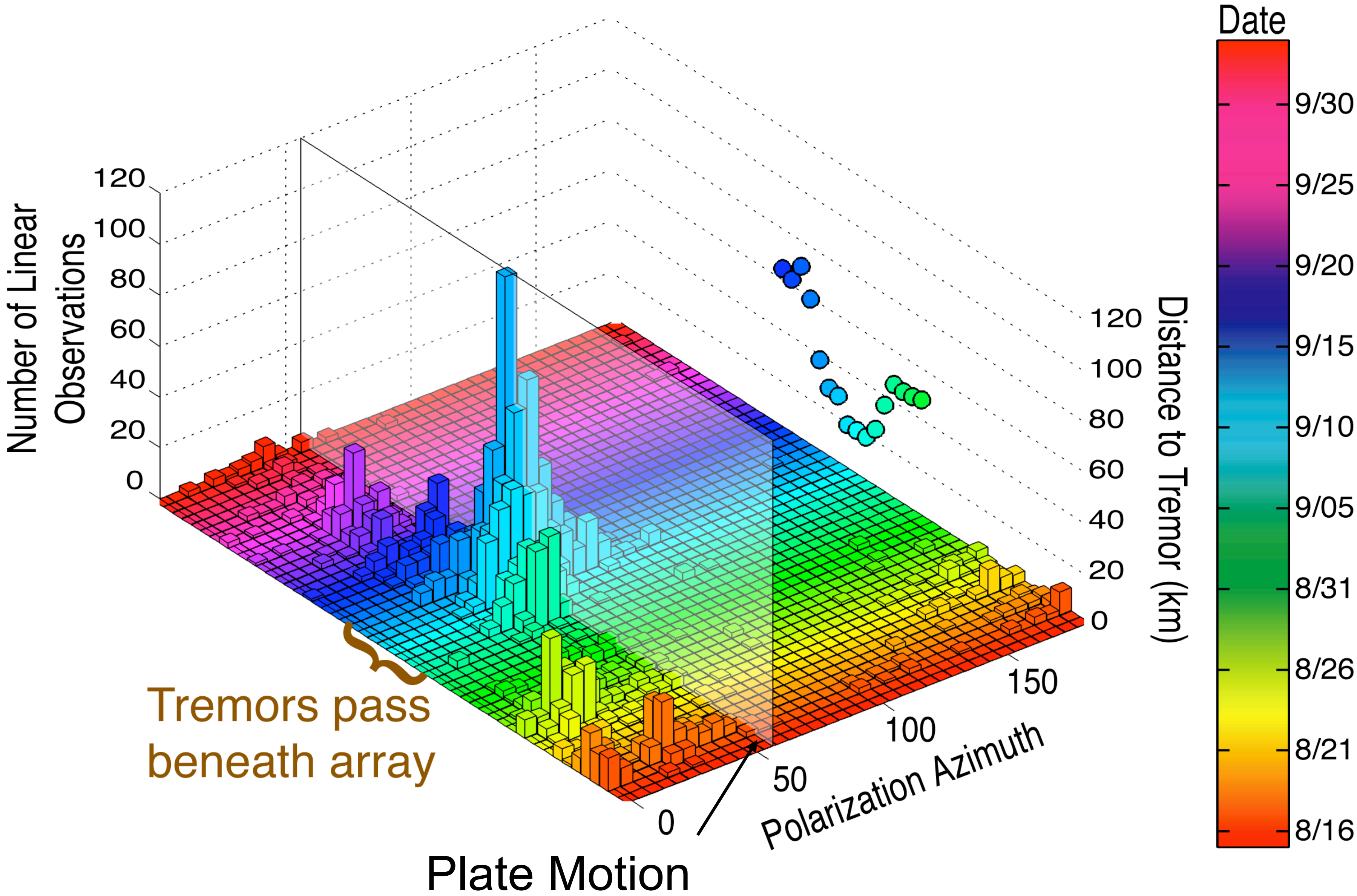
4. Polarization becomes more linear and azimuth more constant.

5. Azimuth averages 54 ± 8^o.

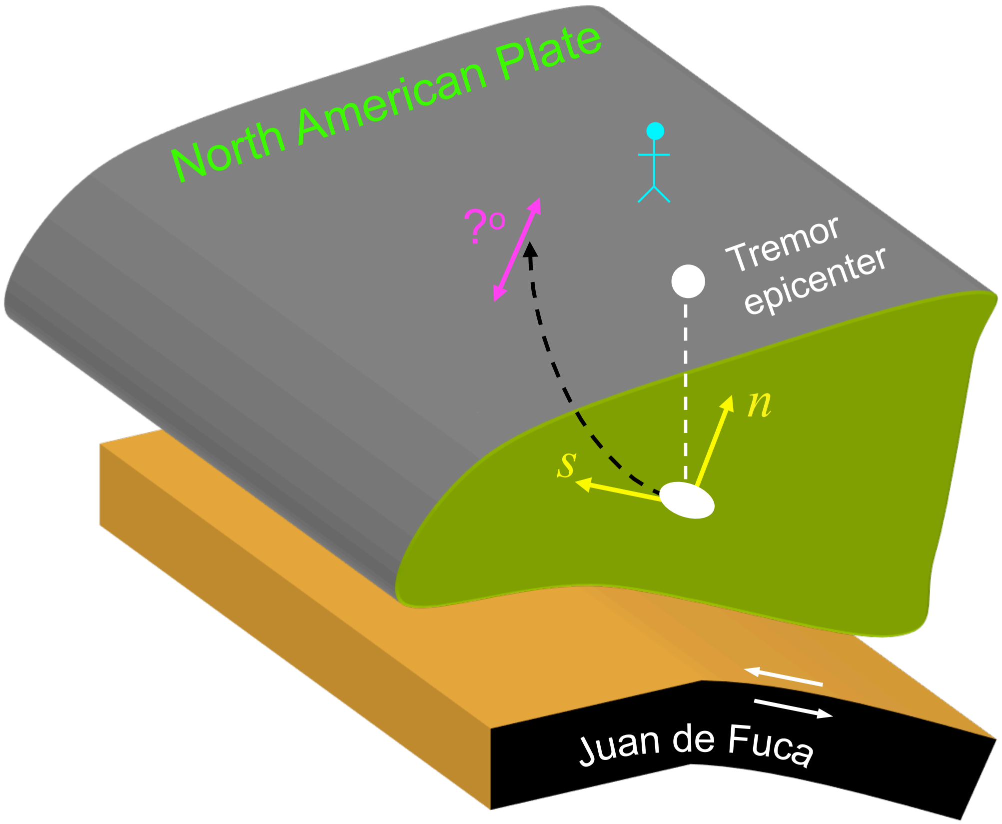
6. Subduction zone slip is at azimuth of 56^o.

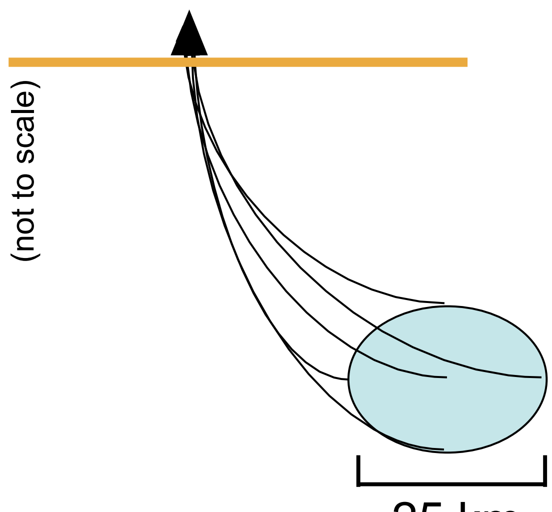
7. Measured polarization matches expected value from slip beneath array.

Polarization azimuths with linearities > 0.7



Test with model.





1. For each tremor epicenter, assume a depth at plate interface
2. Calculate moment tensor from from thrust fault using plate geometry:

$$M = M_o[\vec{s} \cdot \vec{n} + \vec{n} \cdot \vec{s}]$$

3. Predict take-off angle from plate interface
4. Calculate S-wave emitted in this direction:

$$u_i^S(\mathbf{x} - \mathbf{x}_0, t) = \frac{(\delta_{ij} - \gamma_i \gamma_j)\gamma_k}{4\pi\rho\beta^3}\frac{1}{r}\dot{M}_{jk}\left(t - \frac{r}{\beta}\right)$$

5. Sum up vectors from circular distribution around centroid location
6. Calculate resulting polarization azimuth

Test Polarization Method

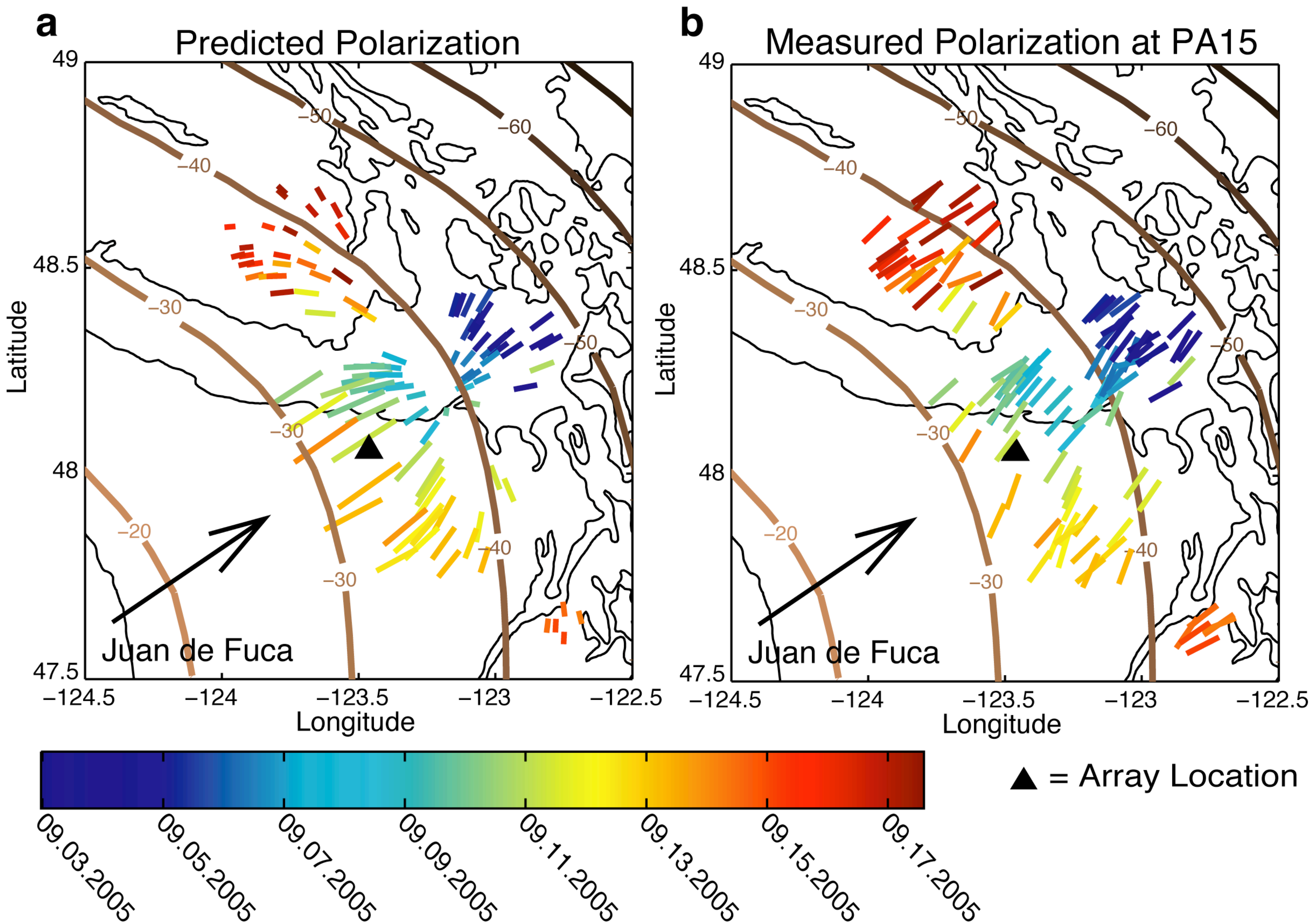
Test:

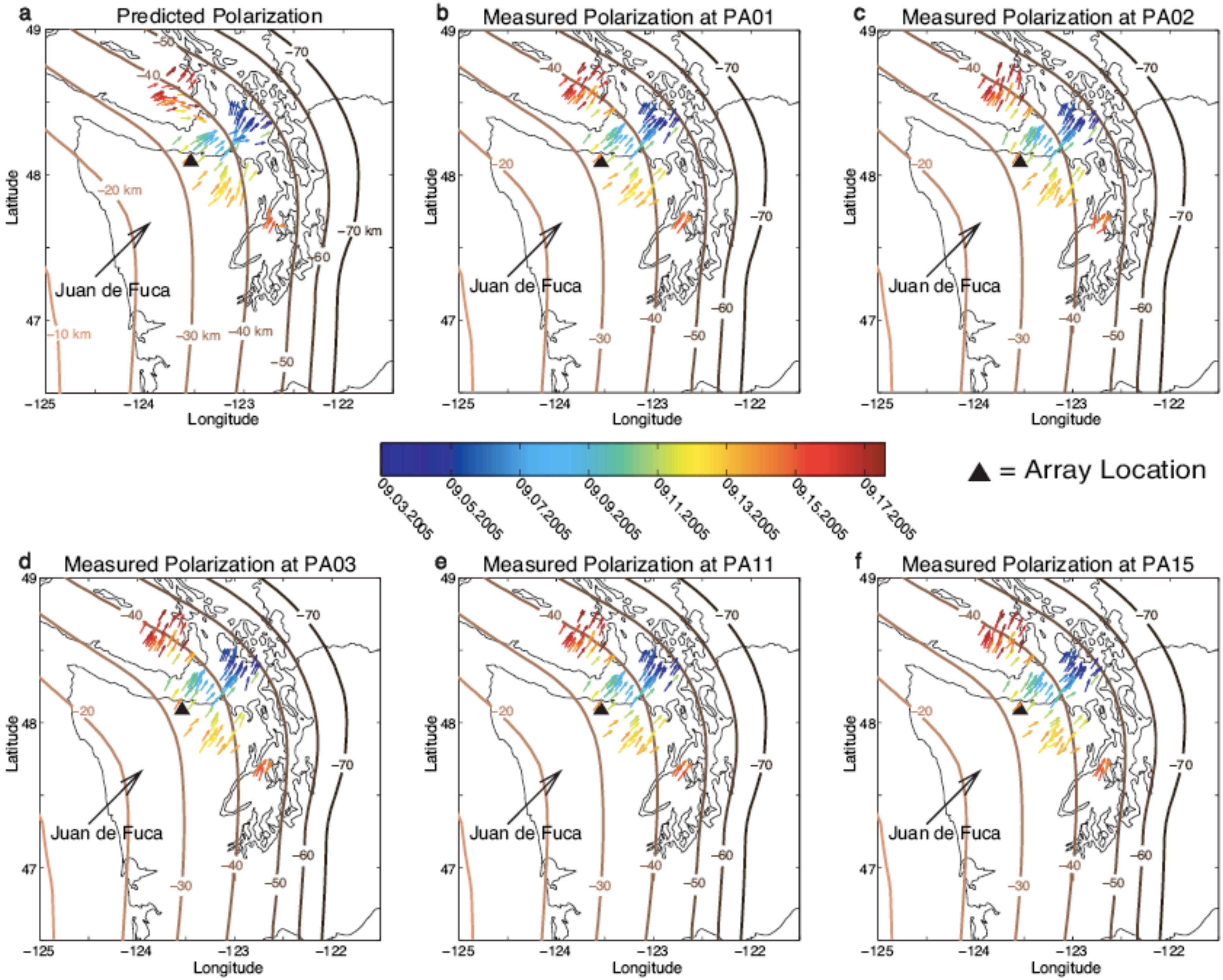
- Only local earthquake recorded at array
- Use PNSN focal mechanism to predict polarization azimuth
- Test possibility of coda dominating polarization azimuth

STATION	P,S-Waves		Coda		P,S-Waves + Coda	
	Linearity	Polarization	Linearity	Polarization	Linearity	Polarization
PA01	**0.716**	**185.3**	0.484	50.4	0.354	44.6
PA02	**0.801**	**162.7**	**0.740**	**88.4**	0.642	102.7
PA03	**0.803**	**145.9**	0.688	156.0	**0.769**	**149.4**
PA04	**0.900**	**166.6**	**0.800**	**173.3**	**0.870**	**165.4**
PA06	0.650	161.6	0.523	162.3	**0.723**	**155.9**
PA11	0.605	180.7	0.656	105.7	0.586	111.8
PA12	**0.885**	**121.7**	**0.789**	**94.6**	**0.813**	**110.3**
PA13	**0.802**	**135.2**	**0.714**	**120.3**	**0.733**	**132.3**
PA14	**0.882**	**168.6**	0.493	105.3	**0.834**	**166.3**
PA15	0.624	51.9	0.446	83.9	0.405	24.9
	mean=	**155.2**			mean =	**146.6**
	predicted=	147.5				

Result:

- Demonstrate ability to recover predicted polarization at array
- Coda is not dominating measured polarization
- Local geology is not affecting polarization


a
Predicted Polarization
b
Measured Polarization at PA15
49
48.5
48
47.5
Latitude
−124.5
−124
−123.5
−123
−122.5
Longitude
−20
−30
−40
−50
−60
Juan de Fuca
09.03.2005
09.05.2005
09.07.2005
09.09.2005
09.11.2005
09.13.2005
09.15.2005
09.17.2005
▲ = Array Location



a
Predicted Polarization
b
Measured Polarization at PA01
c
Measured Polarization at PA02
d
Measured Polarization at PA03
e
Measured Polarization at PA11
f
Measured Polarization at PA15
Latitude
Longitude
Juan de Fuca
–10 km
–20 km
–30 km
–40 km
–70 km
▲ = Array Location
09.03.2005
09.05.2005
09.07.2005
09.09.2005
09.11.2005
09.13.2005
09.15.2005
09.17.2005

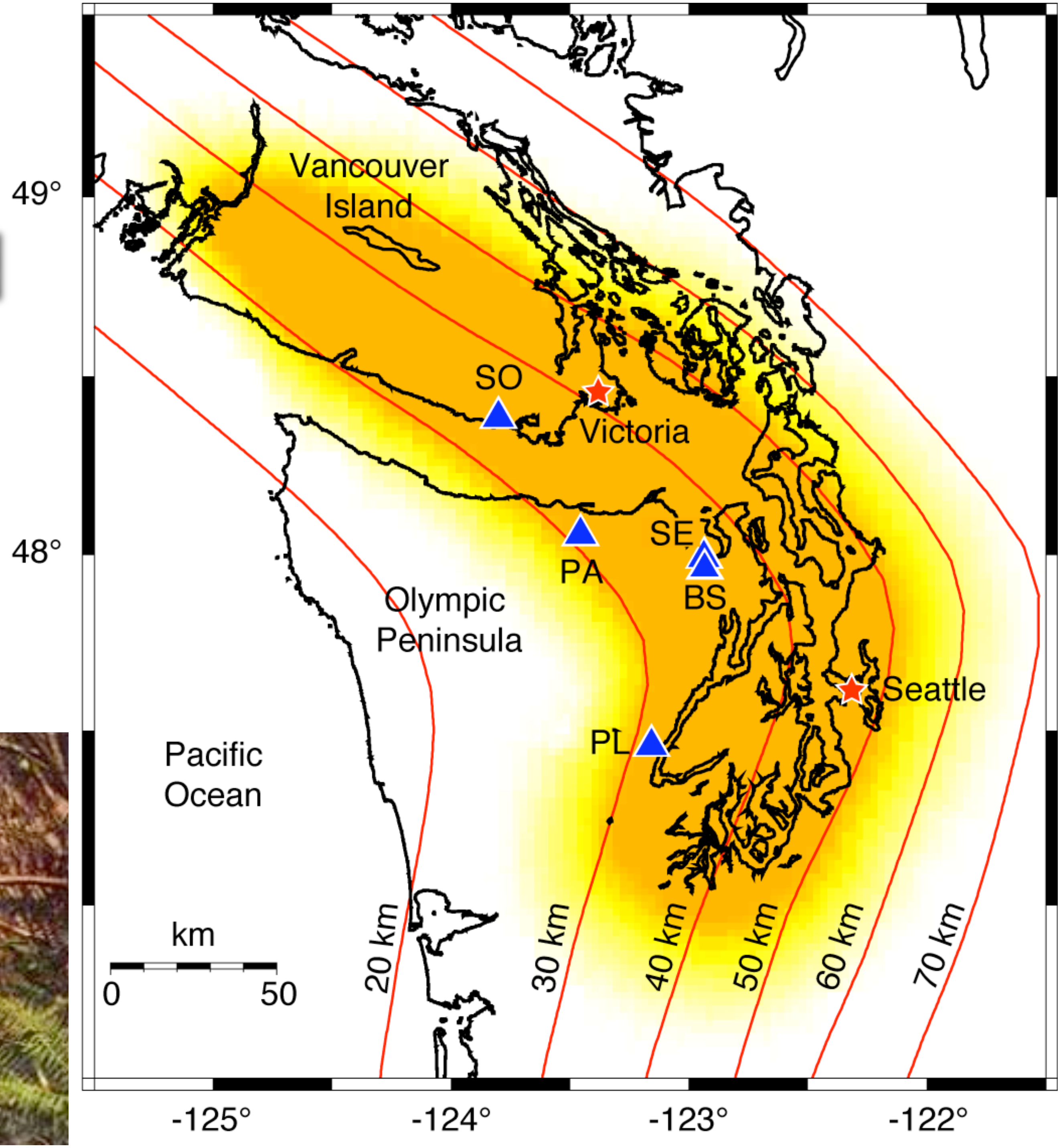
Model Compared with Data

- Tremor bursts located < 40 km from the array
- AND with linearity > 0.7

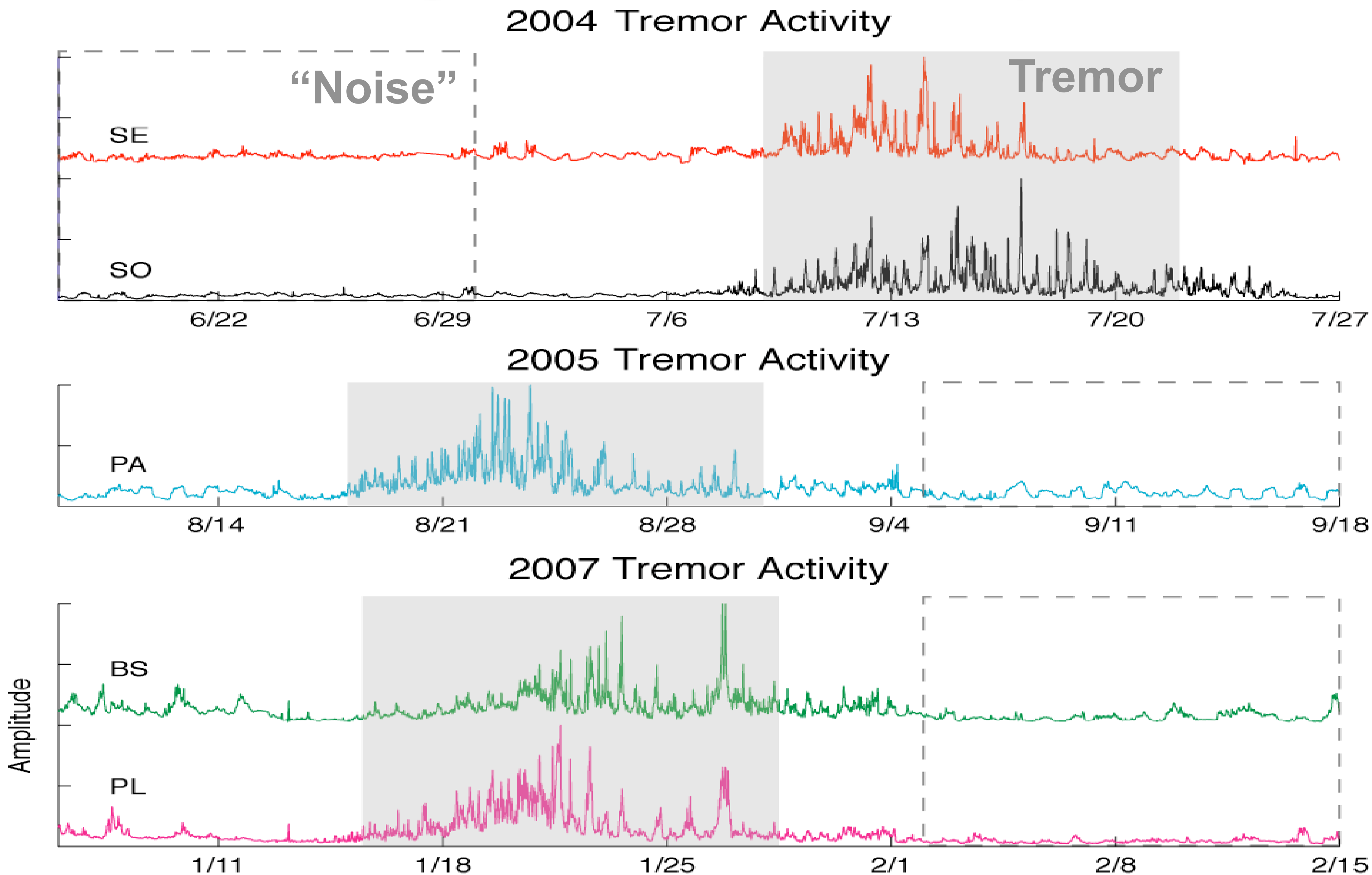
STATION	Mean Difference	Median Difference	Standard Deviation of Difference	Number of Observations
PA01	6.1	9.0	13.4	20
PA02	-7.8	-6.7	15.8	12
PA03	-9.8	-9.6	19.7	14
PA04	NaN	NaN	NaN	0
PA06	-2.9	-1.0	13.8	7
PA11	2.8	6.7	16.1	24
PA12	13.9	13.9	0.0	1
PA13	-6.3	-5.9	13.8	20
PA14	-6.9	-6.3	10.5	13
PA15	-0.6	1.3	15.7	25

Total difference = $-2^{o} \pm 15^{o}$

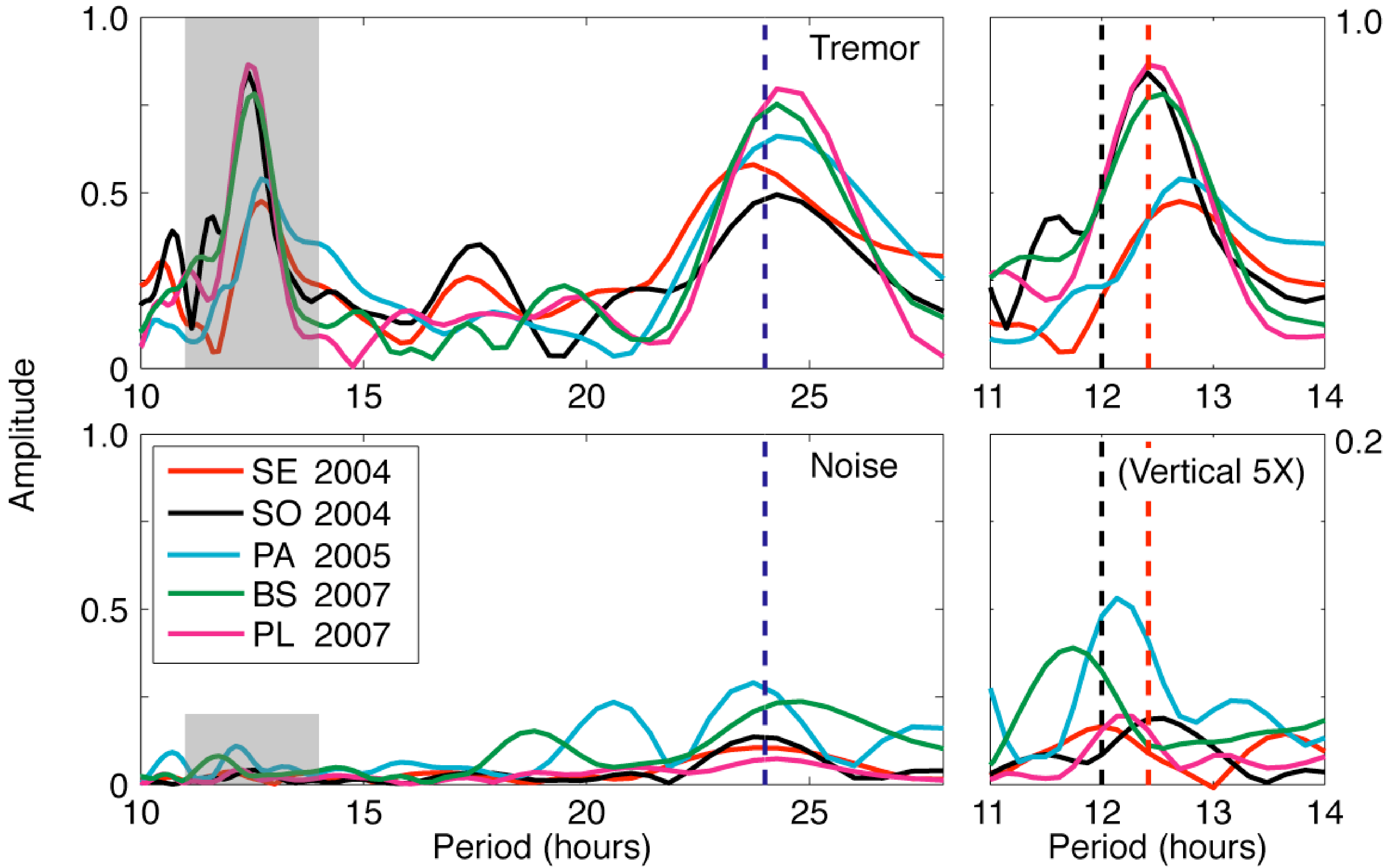
ETS region and 5 dense arrays



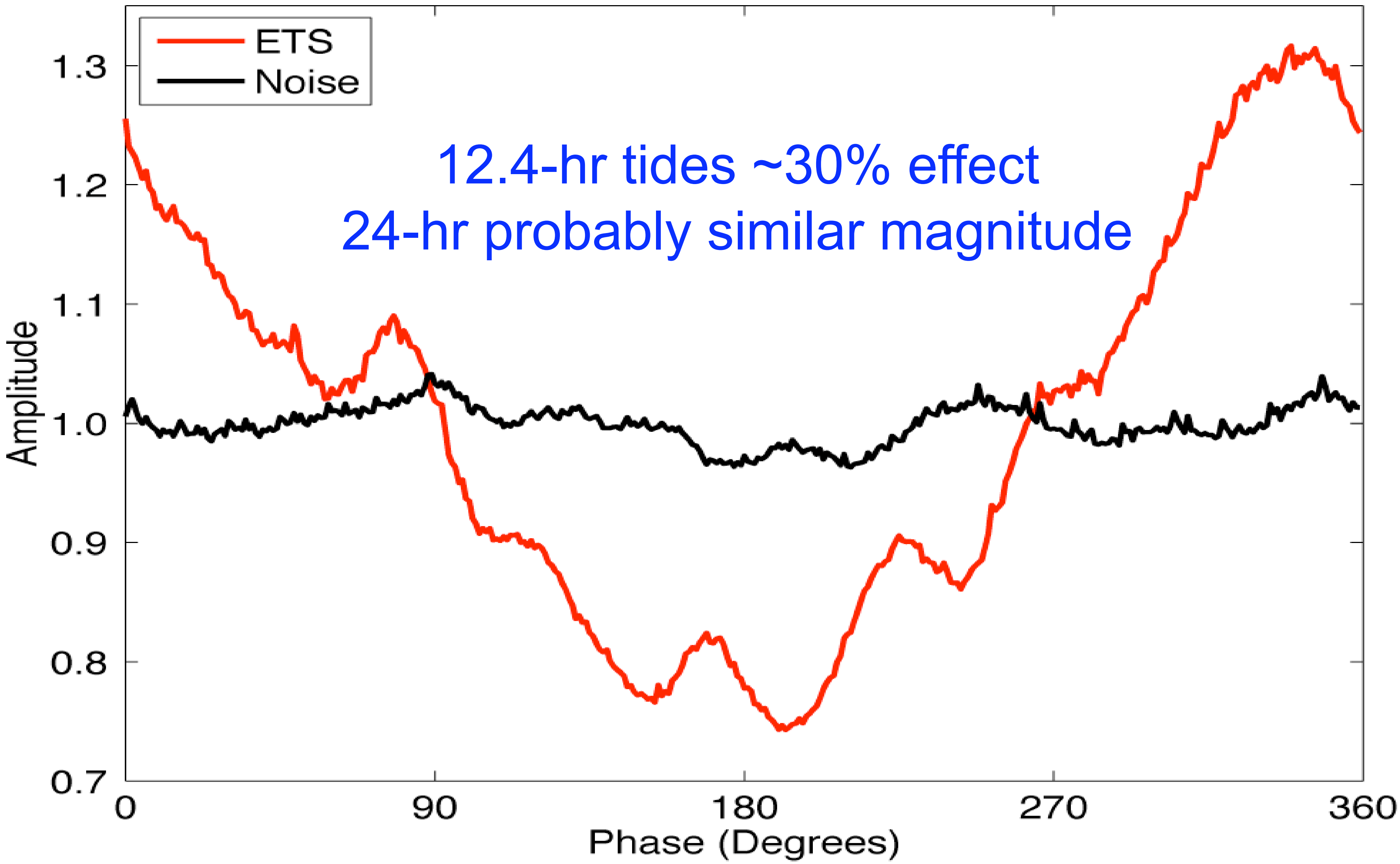
Recordings of last 3 ETS episodes



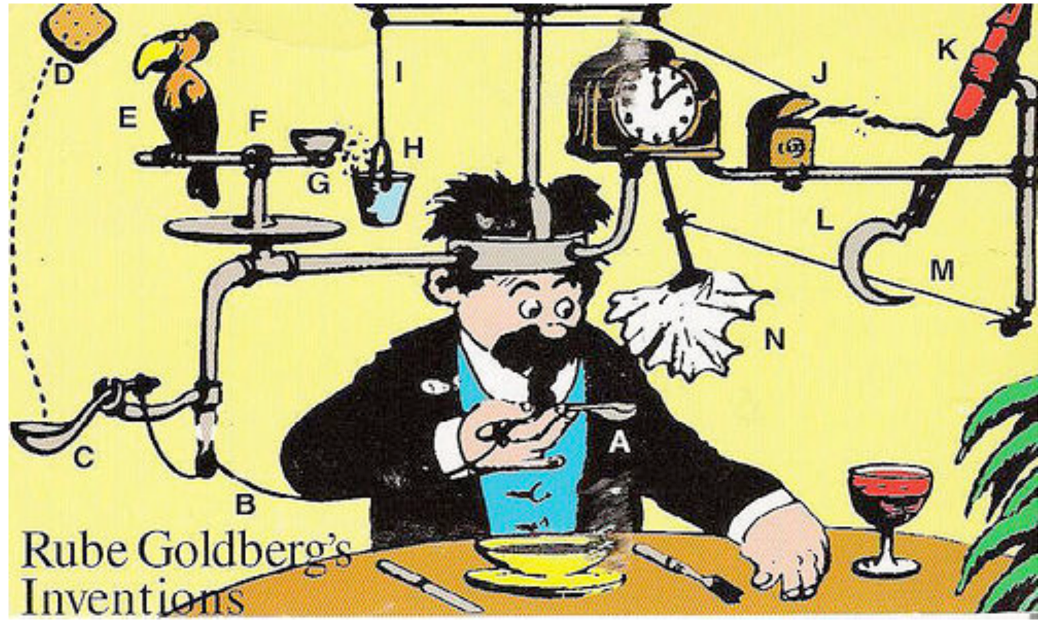
Tremor spectra for the 5 arrays



Amplitude variation with 12.4-hr period

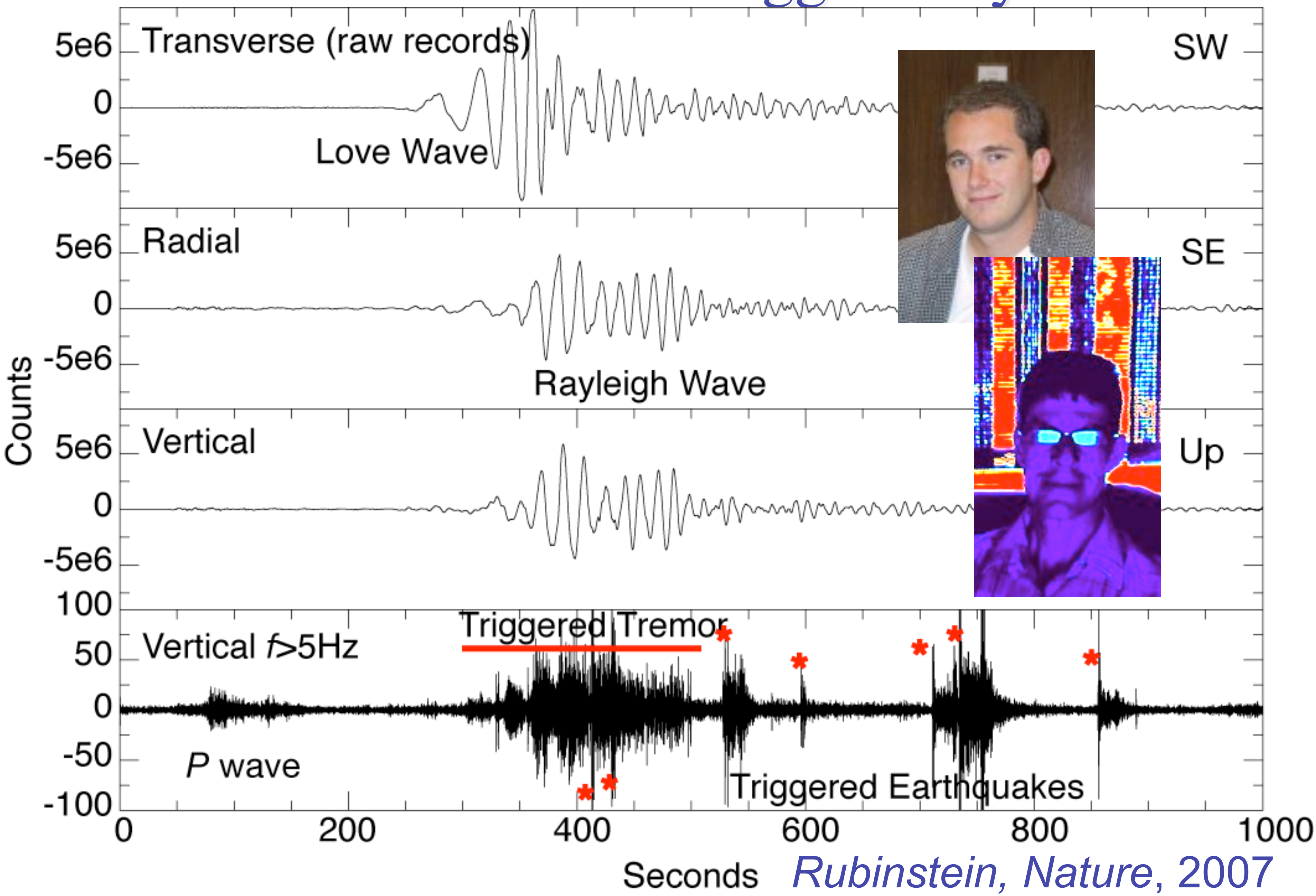


So what?



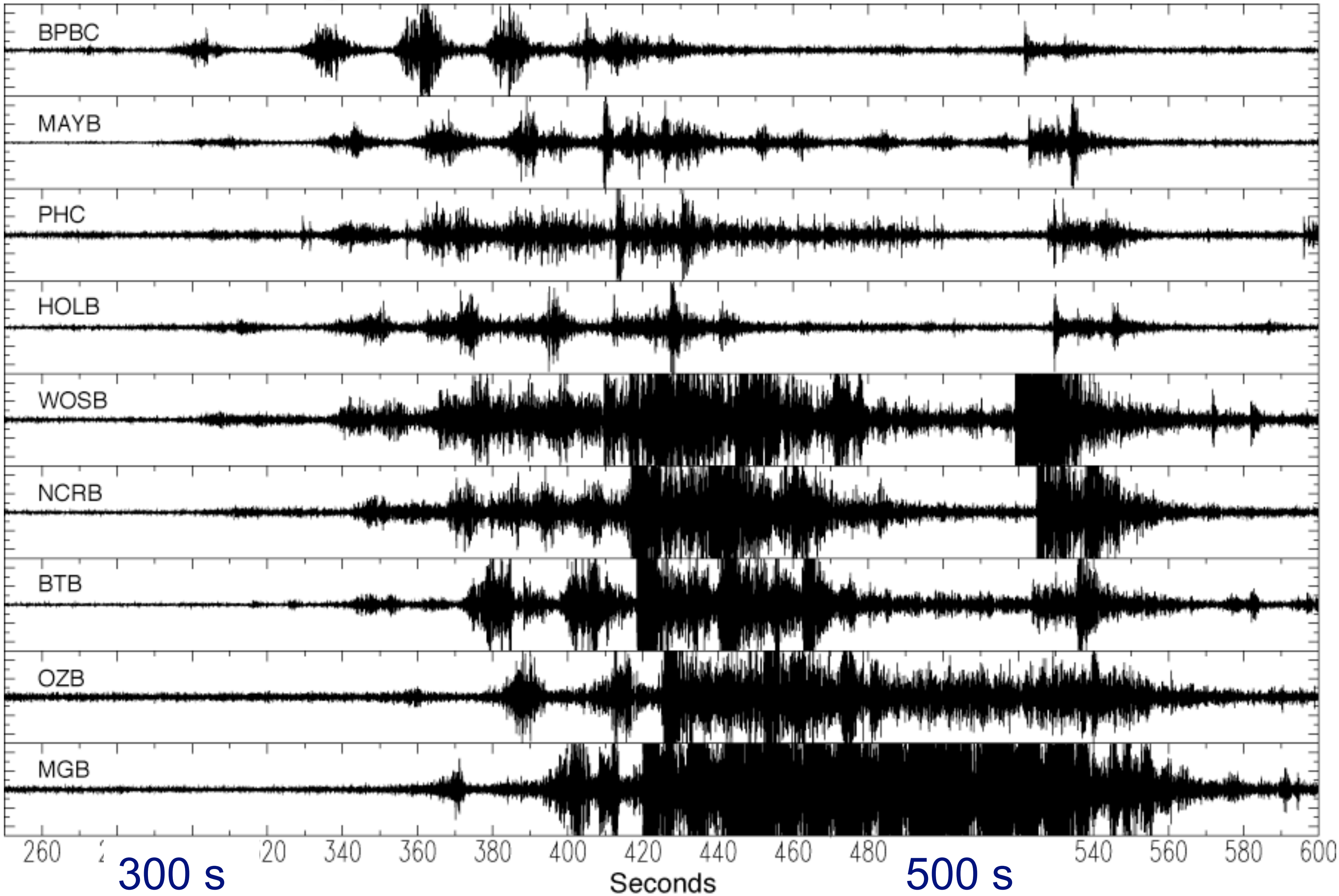
- Similar claims
  - Japan and Mexico
- Polarity is puzzling
  - High water -> more tremor
  - Stress due to surface water loading of inland waterways is complicated
- Tremor much more responsive to small stresses than earthquakes
  - Low stress, low friction, heavily fluid influenced, pervasive connected plumbing, *pick your favorite*

Vancouver tremor was triggered by Denali

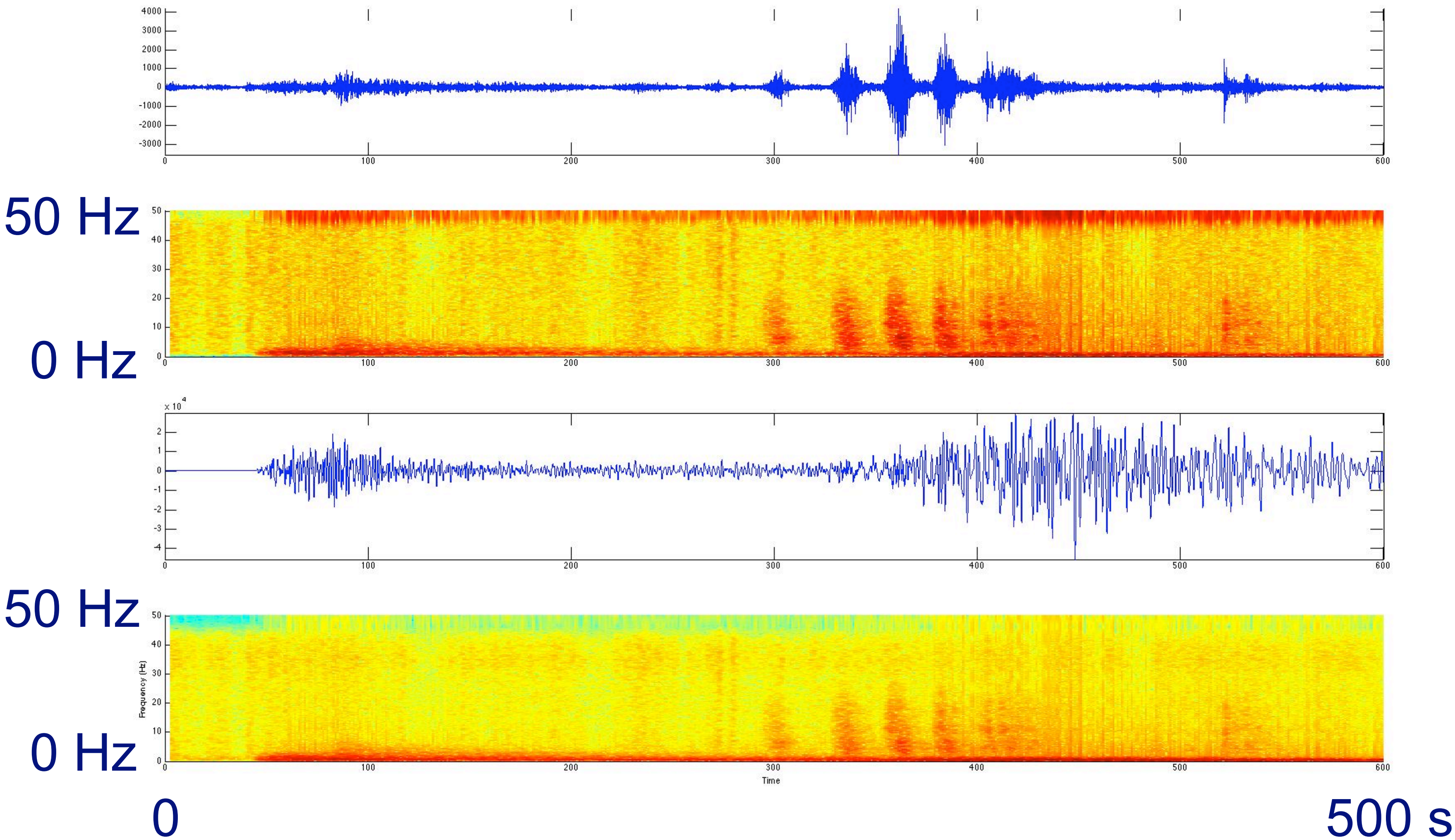


Rubinstein, Nature, 2007

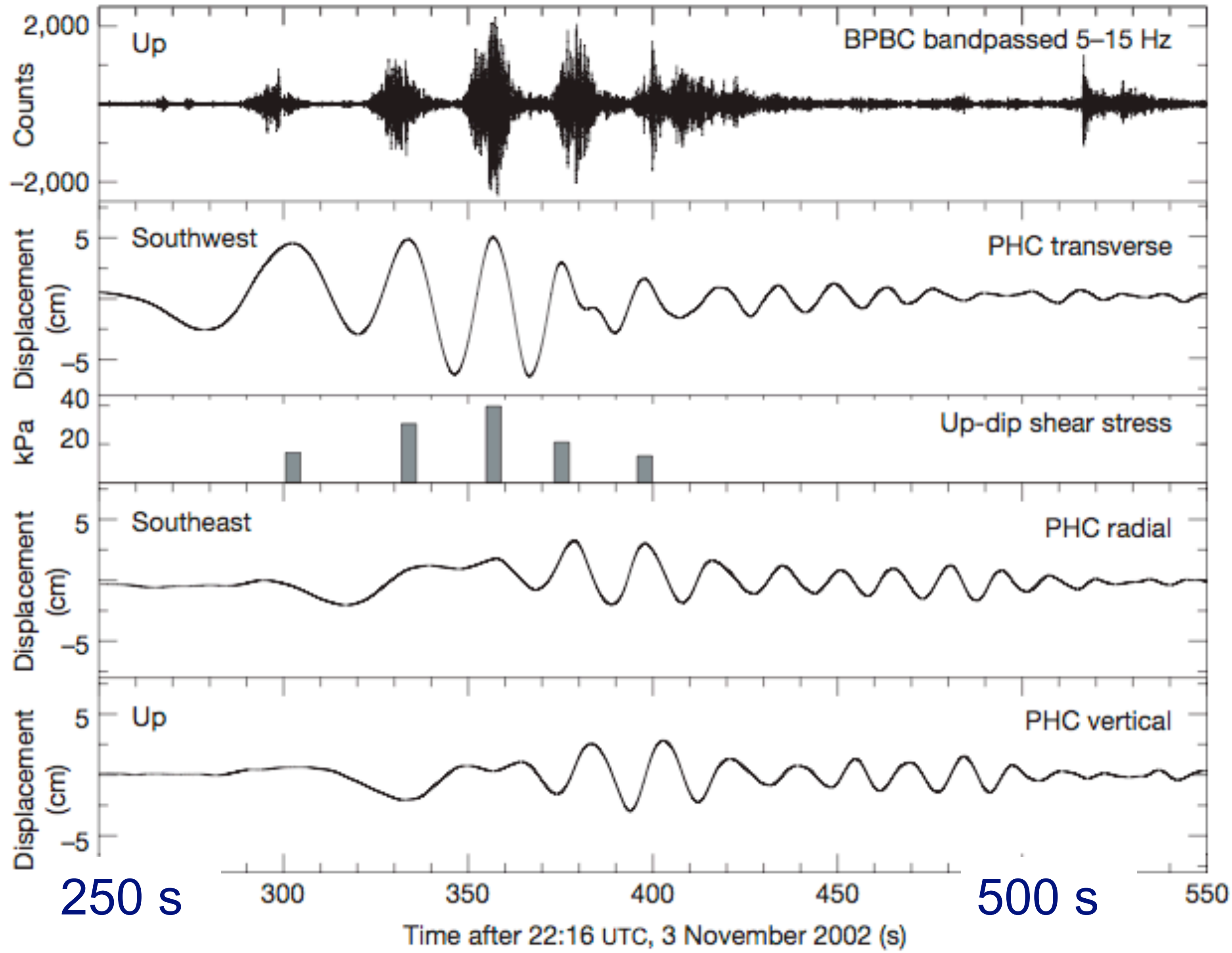
Tremor gather across Vancouver Island



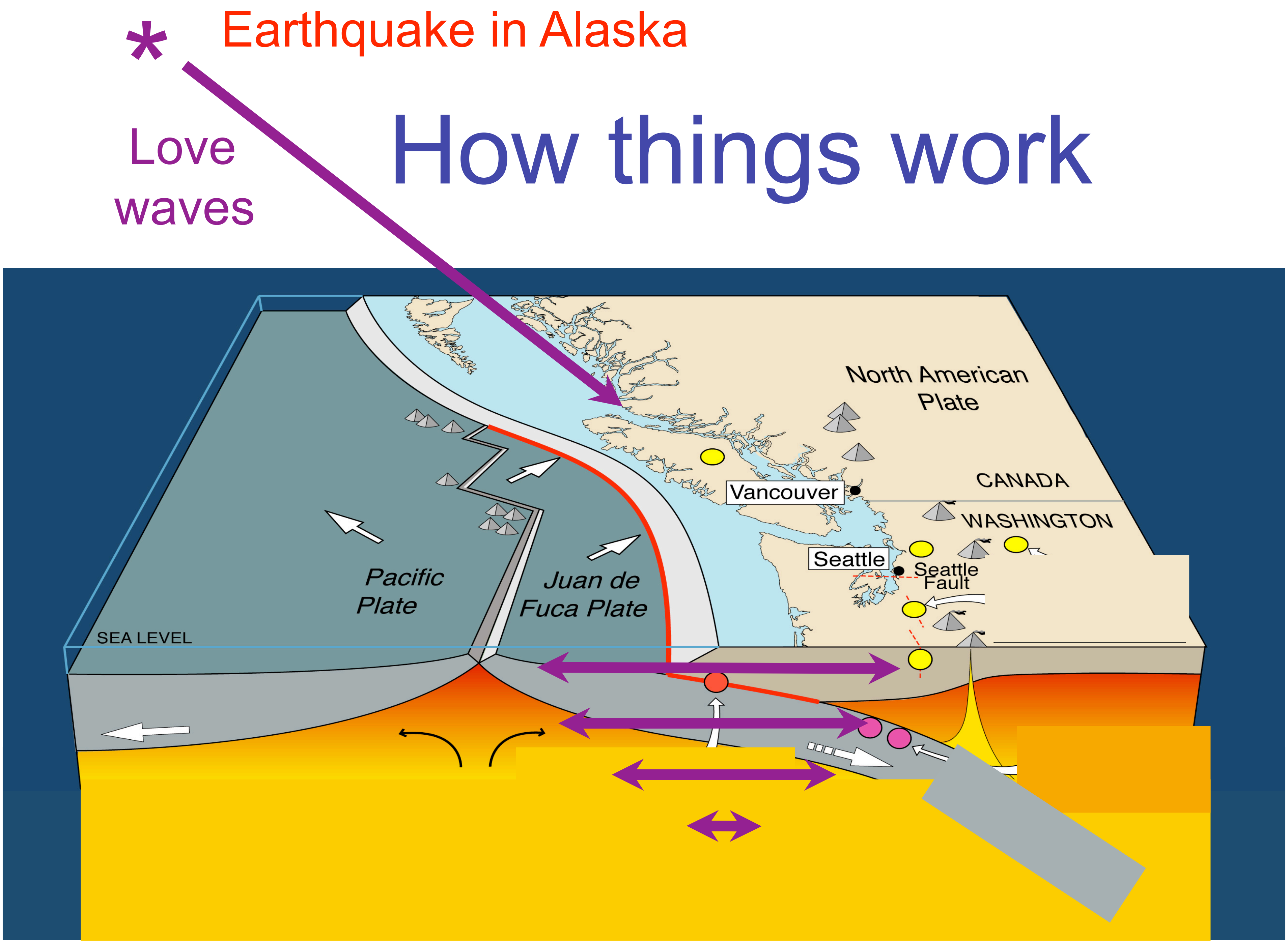
Spectrogram of Triggered Tremor



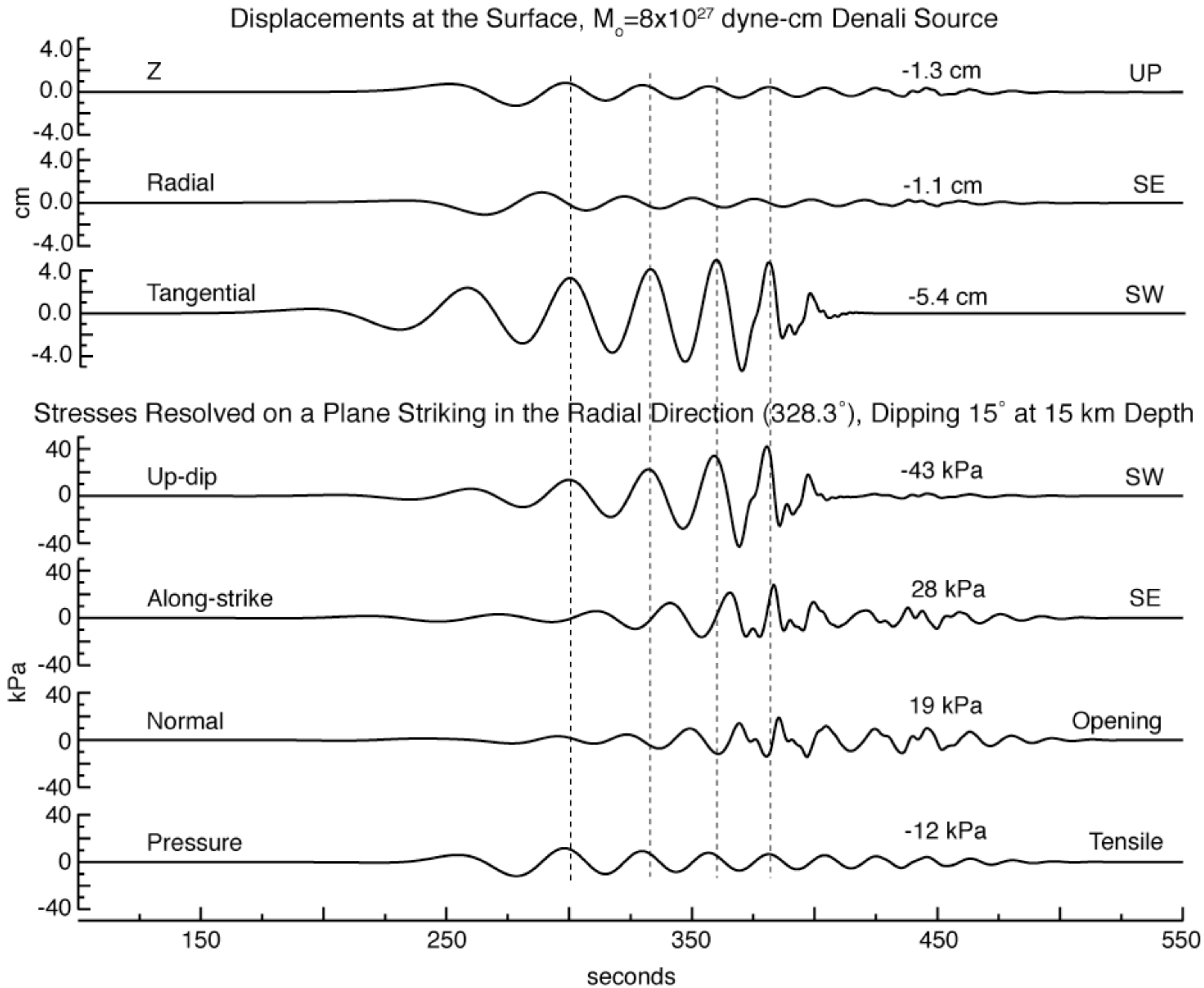
Tremor is Modulated by Love Waves



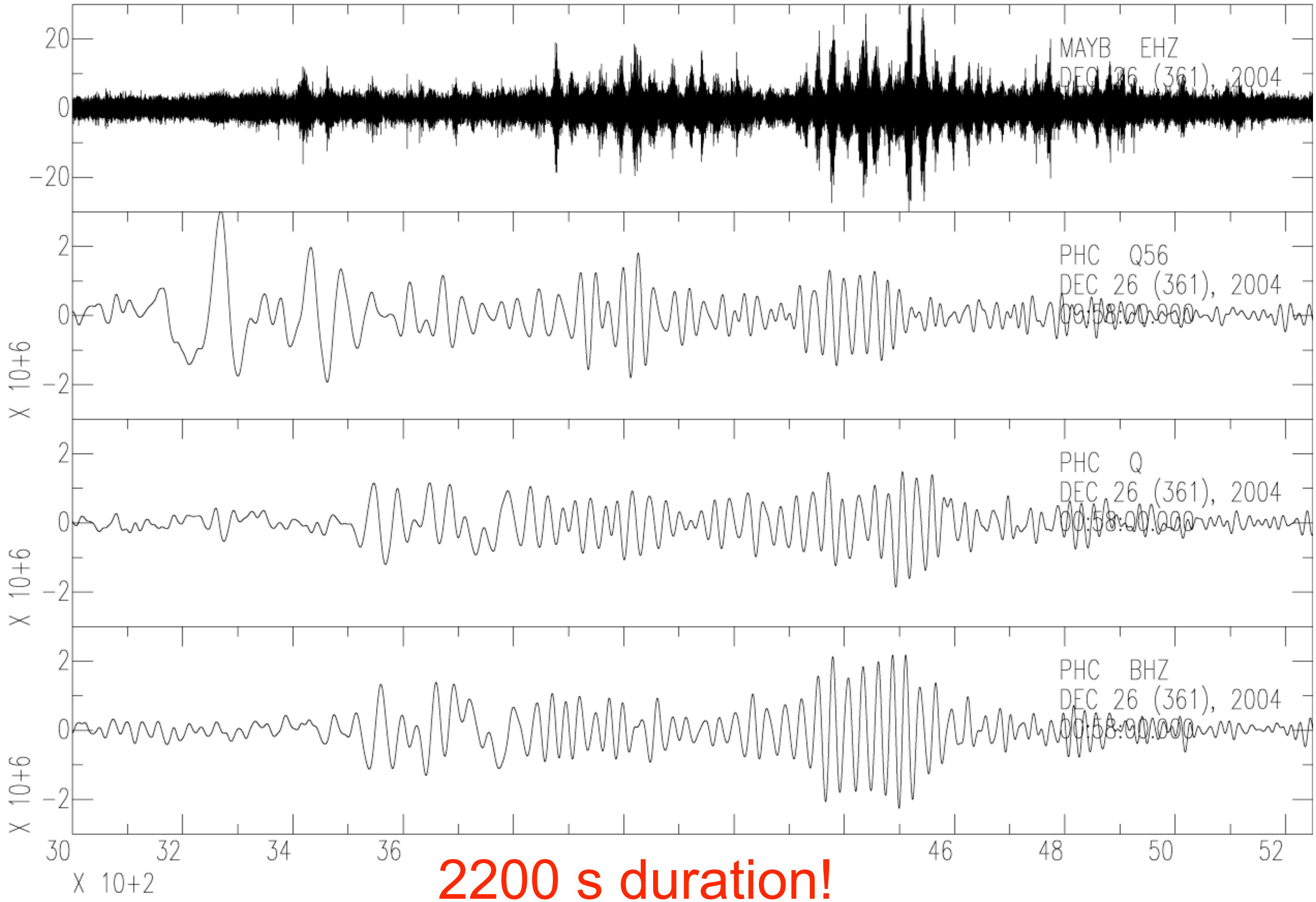
How things work



Stress/Displacement Modeling



Sumatra Modulation

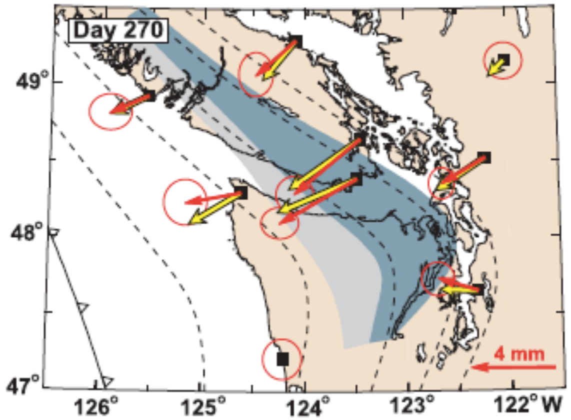


2200 s duration!

Discussion

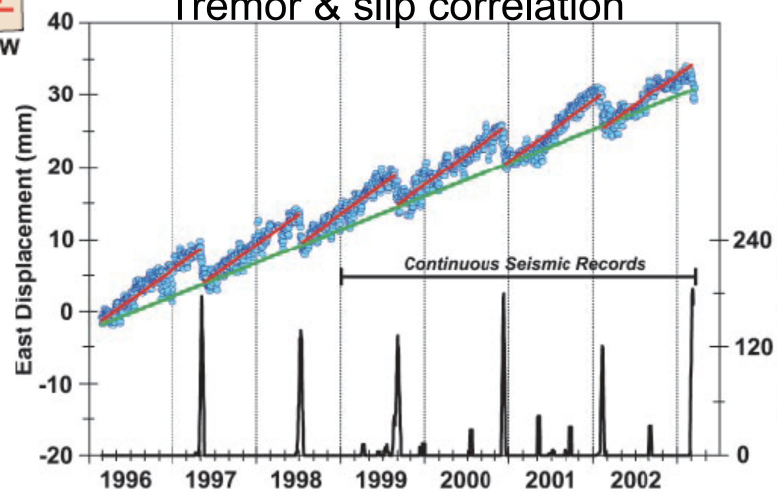
- Polarizations suggest fault slip in the direction of subduction
- No depth control
  - Polarization is consistent with current hypocenter estimations
  - Polarization is consistent with hypocenter on plate interface
- Stable polarization directions difficult to reconcile in fluid-flow paradigm
- Interpretation of source process?

Evidence Pile

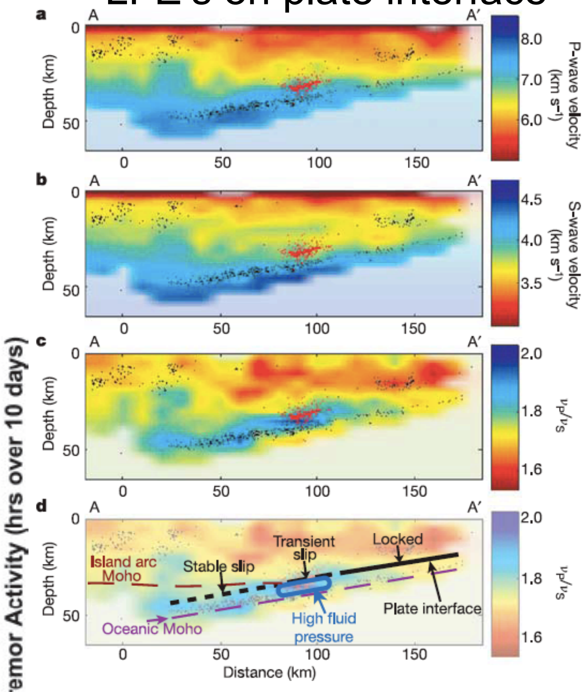


Slip on plate interface

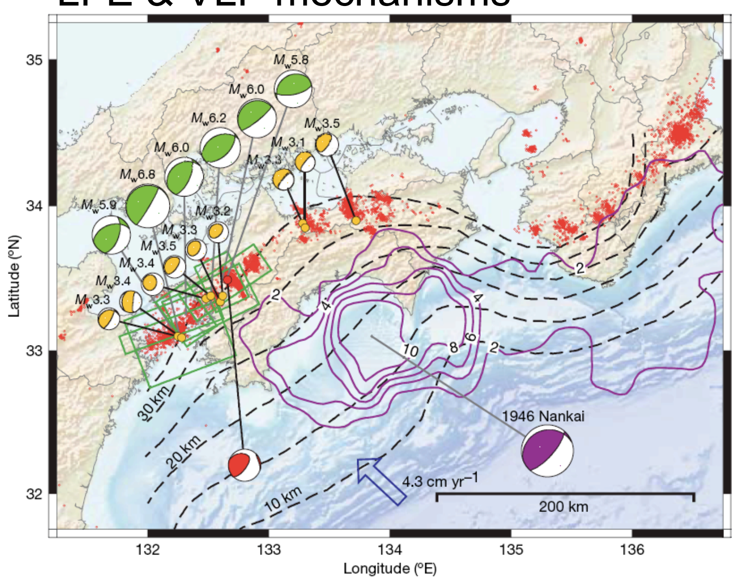
Tremor & slip correlation

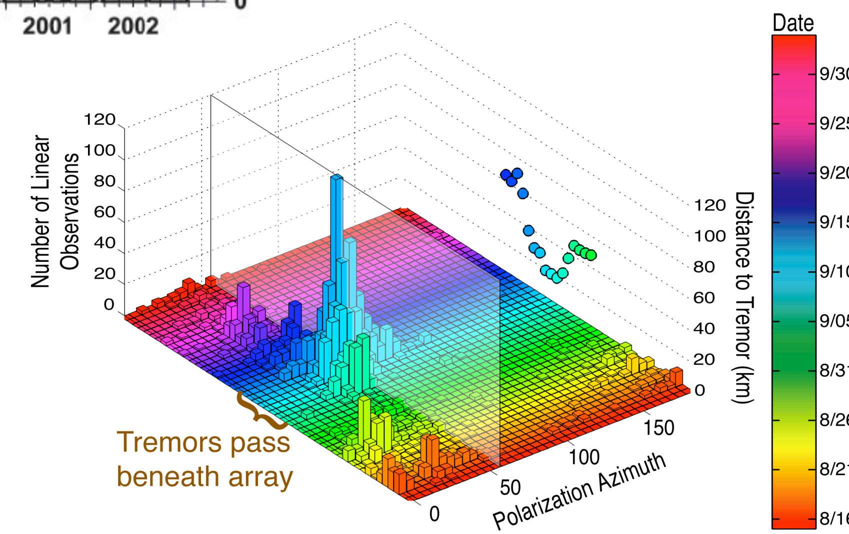


LFE's on plate interface



LFE & VLF mechanisms



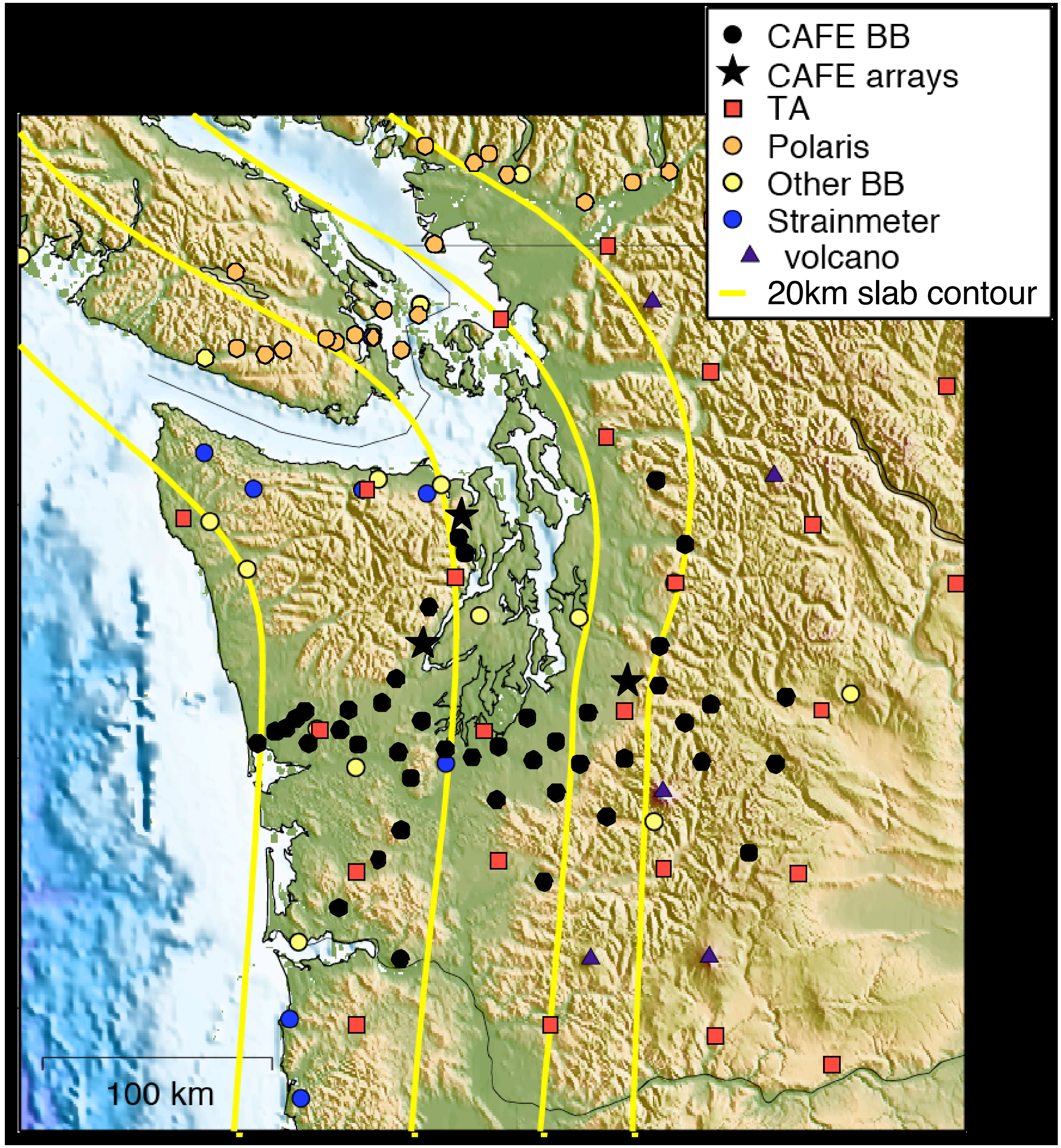


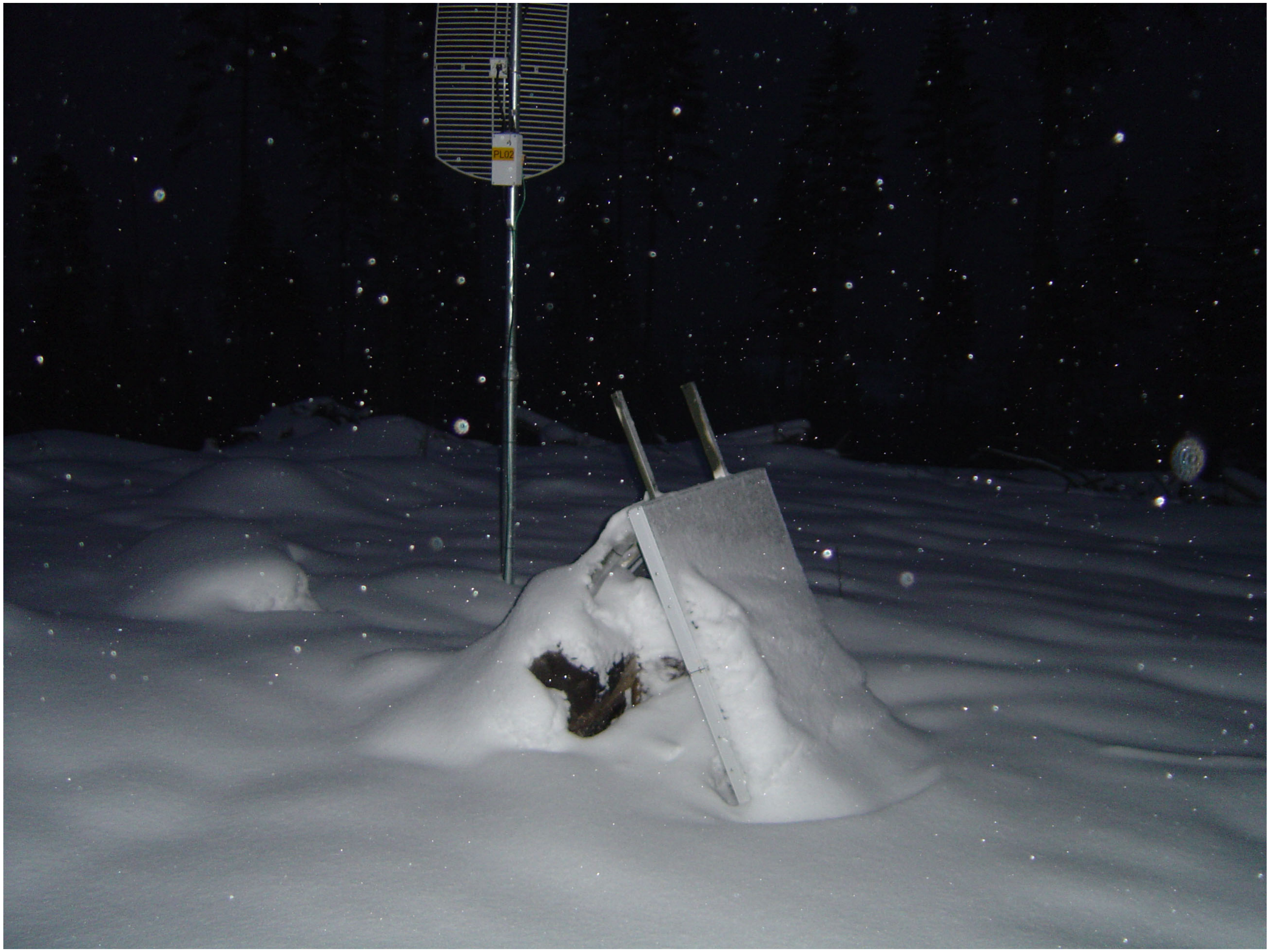
Polarization consistent will interface slip

Conclusions

- Cascadia tremor is slip on the plate interface
- Cascadia tremor and slip are manifestations of same process
- Tremor, LFE, VLF, ETS, SSE all scale with duration proportional to moment
- ETS Tremor is modulated by tidal stresses
- Tremor is triggered by surface wave stresses and responds instantly
- Coulomb friction can explain triggering, but not clear for tidal forcing
- Some ETS events repeat in propagation history and regions of strong tremor and slip
- Each region has its own repeat interval

The CAFE seismic arrays



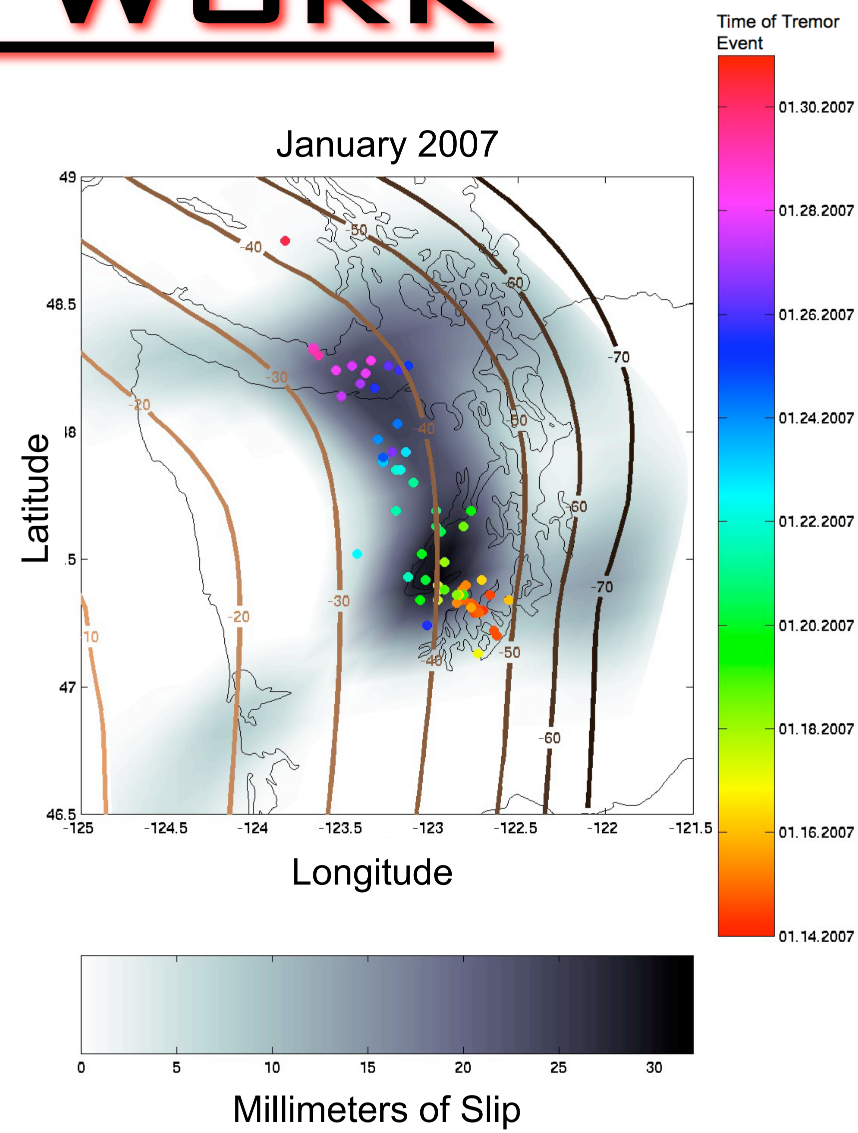

PL02

Implications

- ETS in Cascadia is same as ETS in Japan
  - This suggests a global process of subduction zone dymanics
- If LFE's do not exist or do not dominate tremor in Cascadia…
  - This suggests a new type of slow shear separate from LFE's, VLF's, and short- or long-term SSE's, possibly reinforcing the new scaling law for slow earthquakes [*Ide et al.*, 2007].
- Tremor = slip
  - We can use tremor locations to track stress loading on the locked zone
- Can possibly use polarization in detection and/or location methods

Future Work

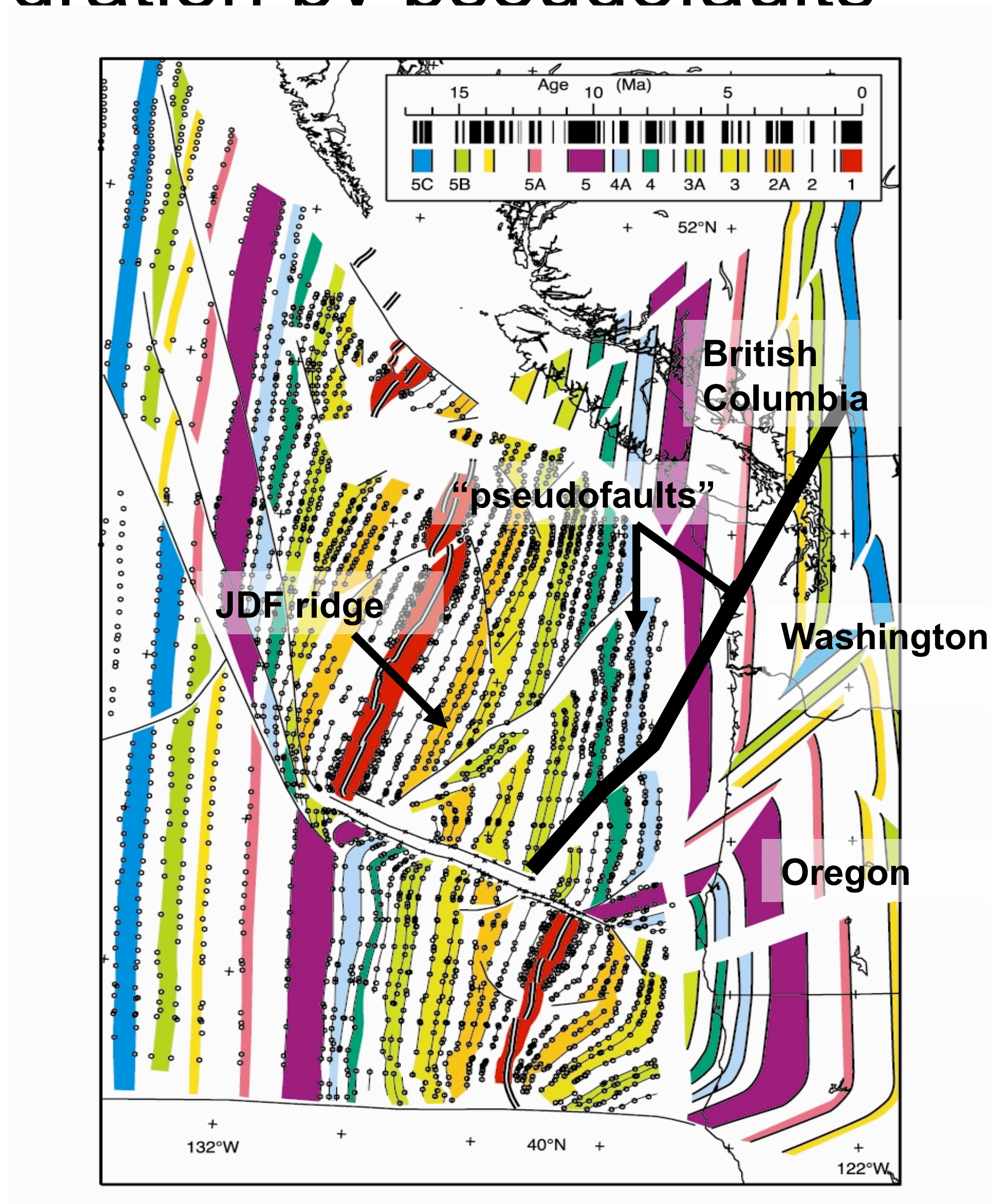
- Perform polarization analysis in southwest Japan
- Begin analysis of January 2007 Cascadia ETS event
- Find LFE's in Cascadia
- Do some good science



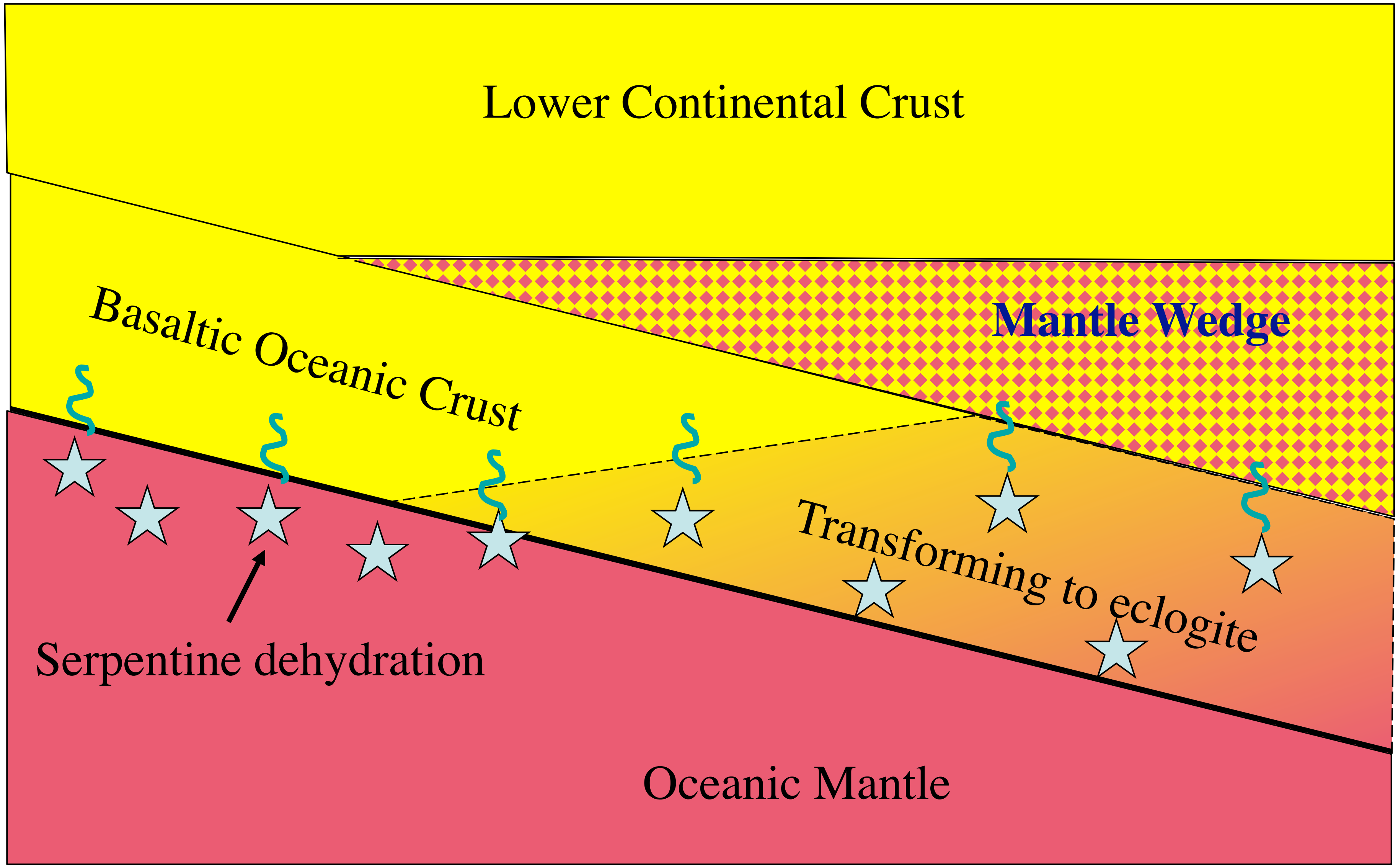
Locations: *Wech & Creager*
Slip Inversion: *Melbourne*

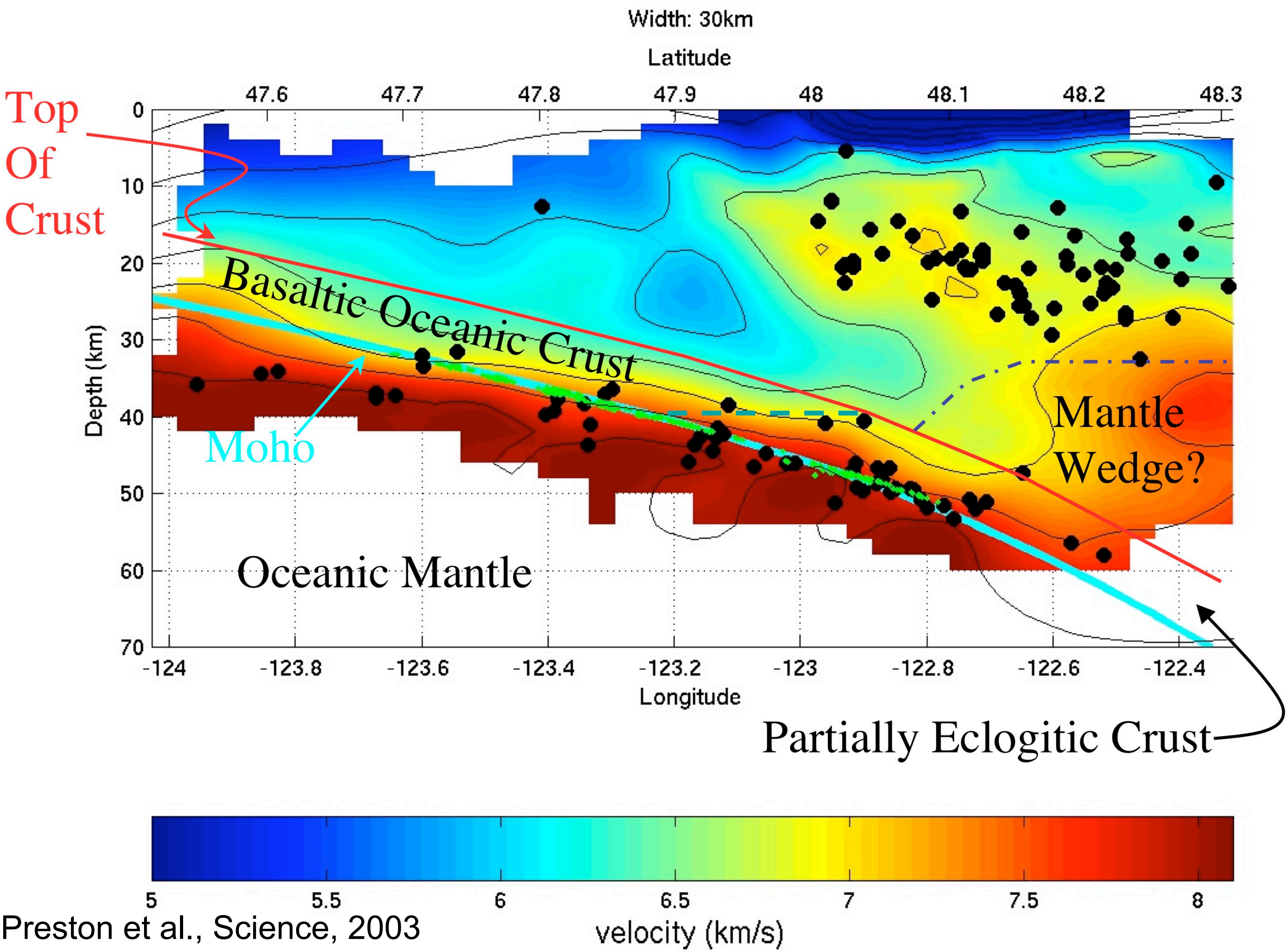
Local mantle hydration by pseudofaults

- Propagating Juan de Fuca ridge creates offsets in isochrones called pseudofaults
- Pseudofaults may hydrate the uppermost mantle producing 25% serpentine (McClymont and Clowes, 2005)
- Subsequent dehydration of this serpentine as it heats up during subduction appears to cause intraslab earthquakes in the mantle lithopshere



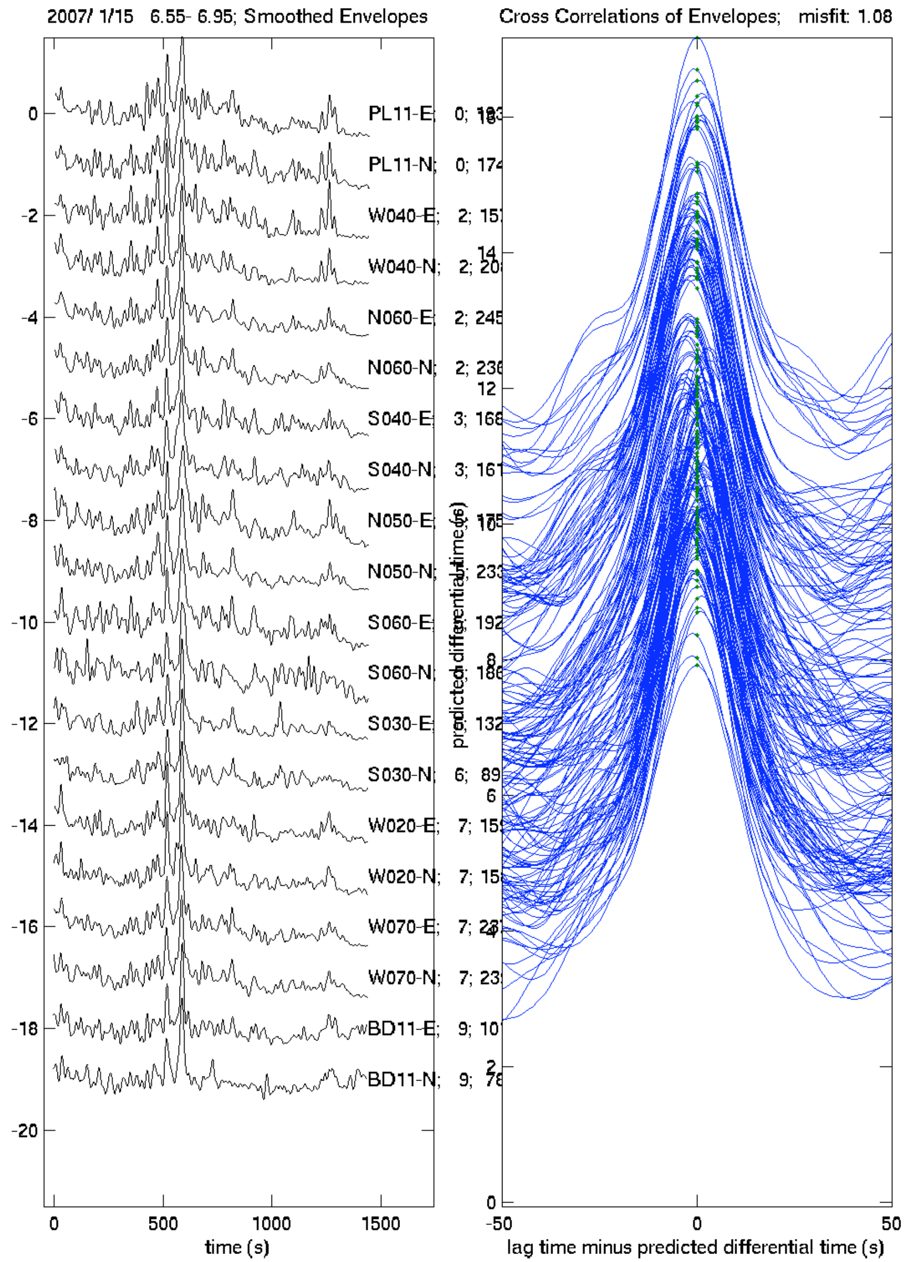
Wilson, 2002


Lower Continental Crust
Mantle Wedge
Basaltic Oceanic Crust
Transforming to eclogite
Serpentine dehydration
Oceanic Mantle

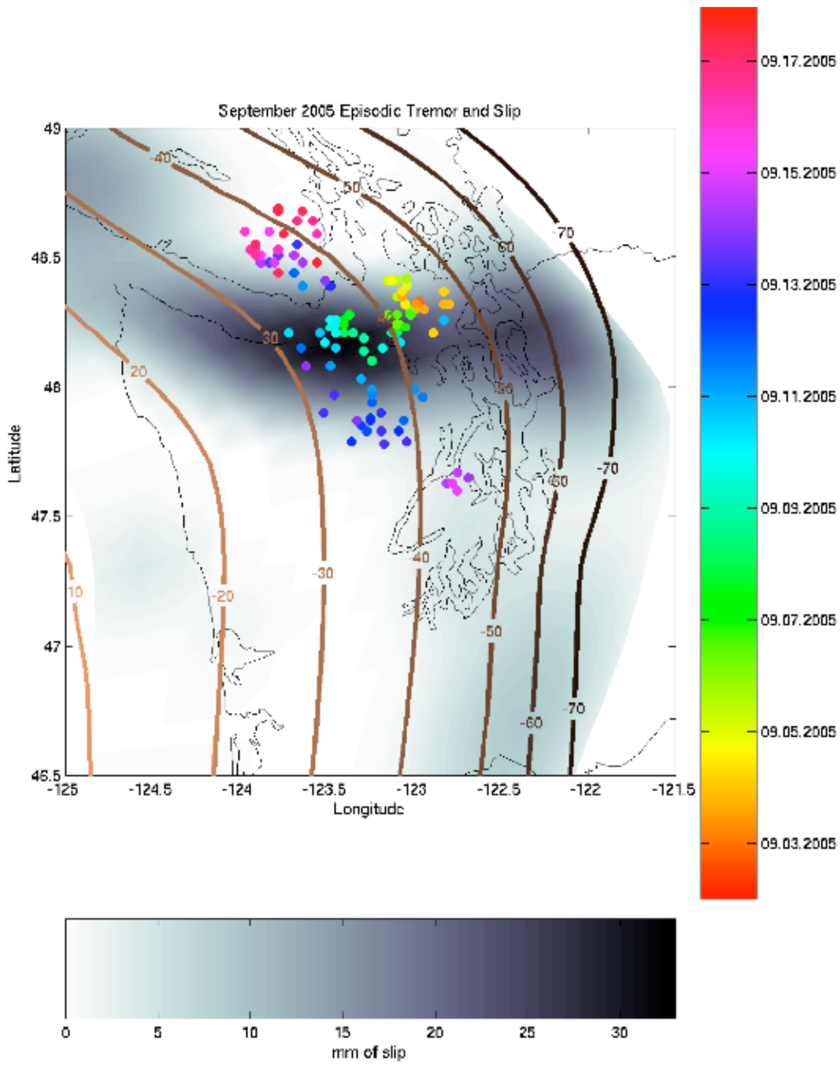


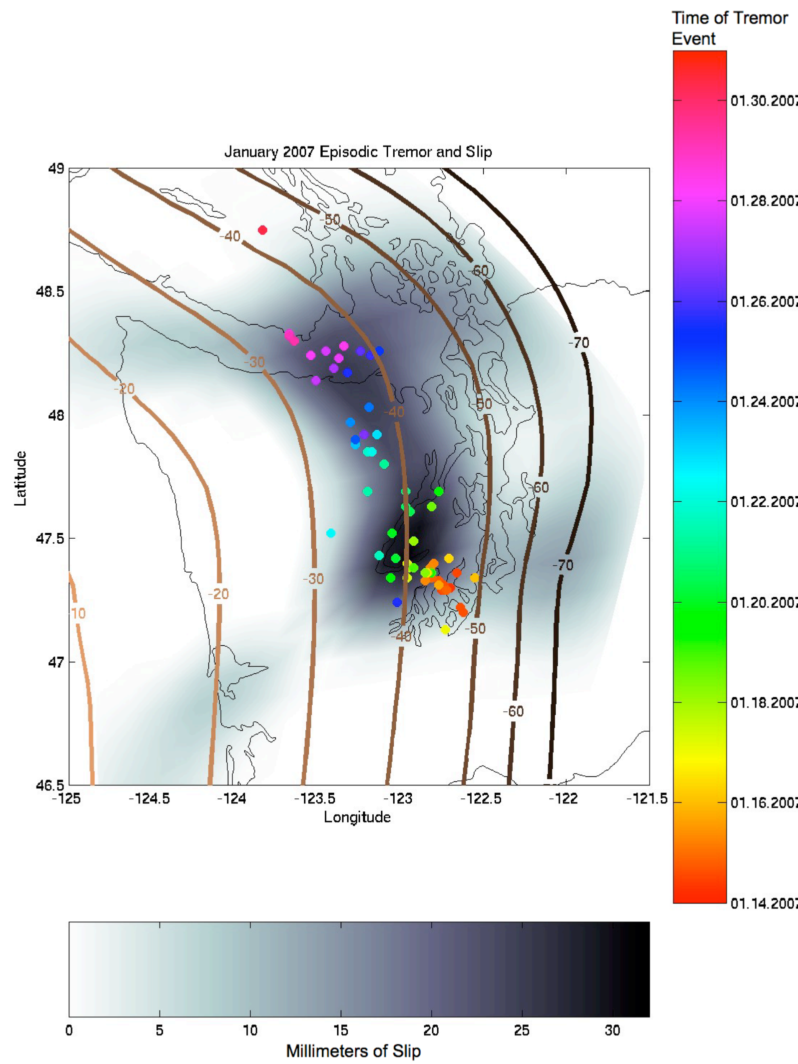
Preston et al., Science, 2003

January 2007 ETS observed at CAFE stations



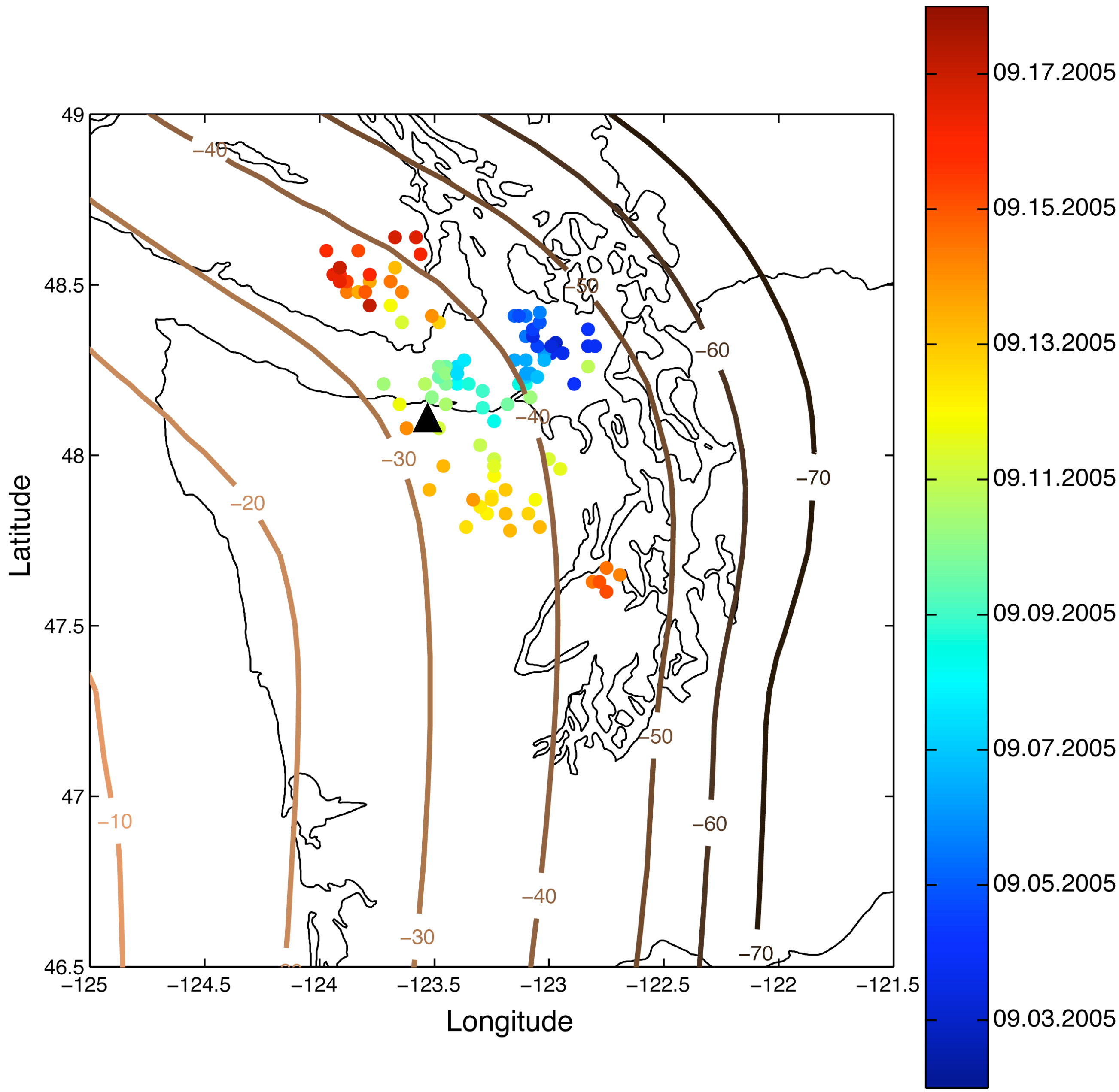
Sept. 2005 and Jan. 2007 Episodic Tremor and Slip: Tremor migration and Fault Slip





September 2005

- Locate bursts every 3 to 4 hours
- Obtain 111 tremor locations
- After September 17 tremor is beyond network & polarization is much noisier
- Our array (▲) is close to tremor



Definitions

Linearity

- Defined by eigenvalues:

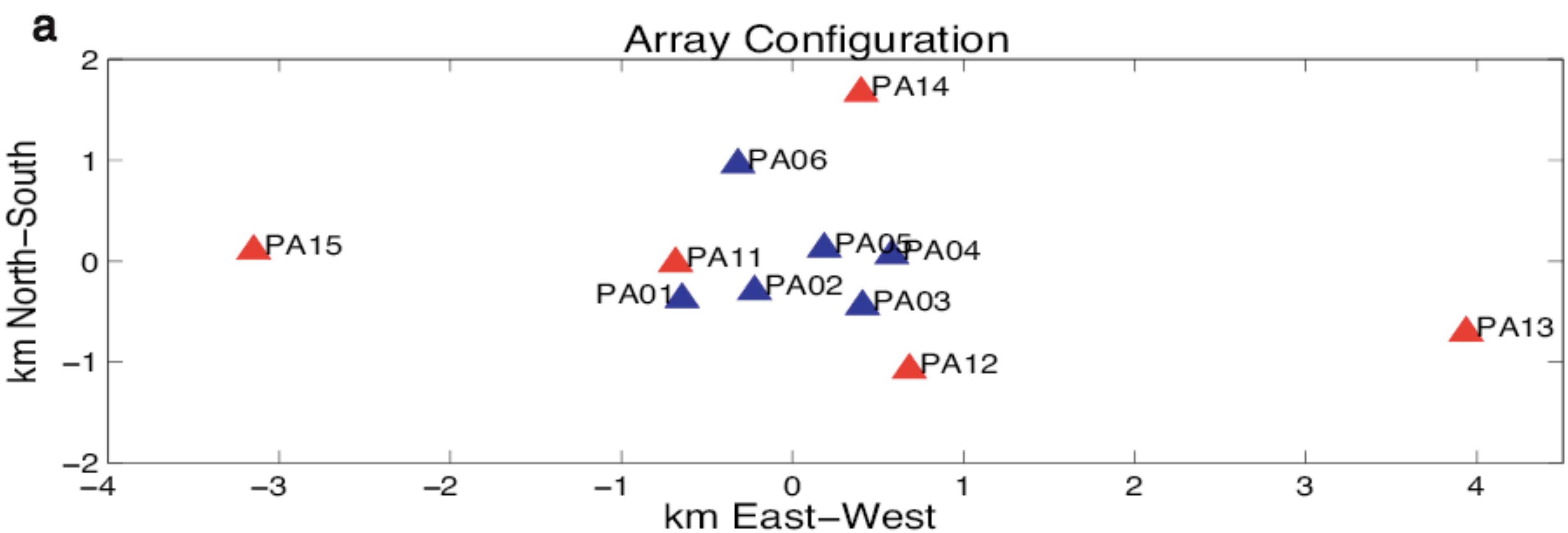
$$L = 1 - \frac{\lambda_2 + \lambda_3}{2\lambda_1}$$

- λ_i are ordered from greatest to smallest
- 1 = perfect linearity
  0 = not linear
- Provides measure of confidence

Polarization

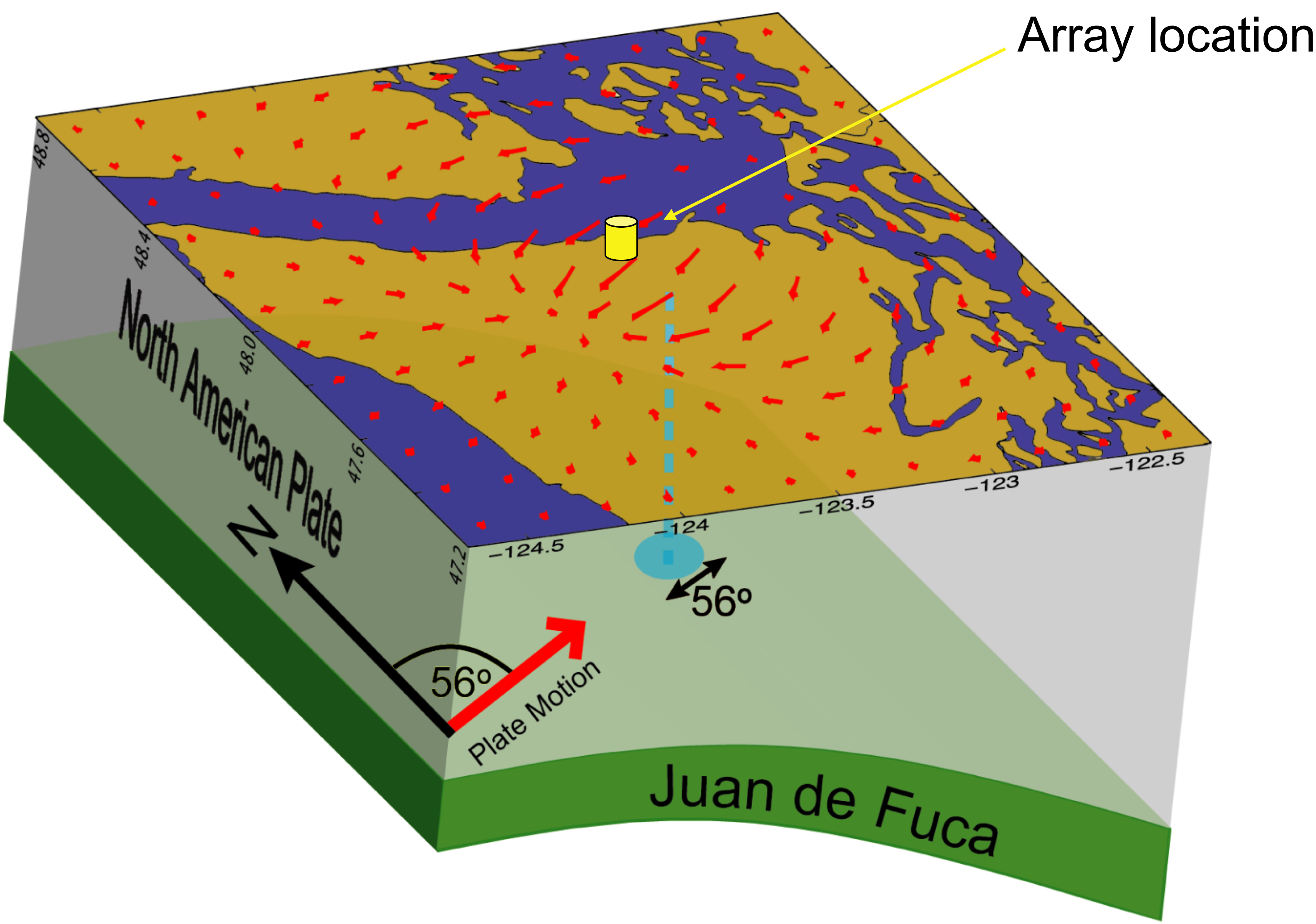
- Measuring azimuth of horizontal ground motion
- There is a 180° ambiguity
- We force everything to have positive east component

Array

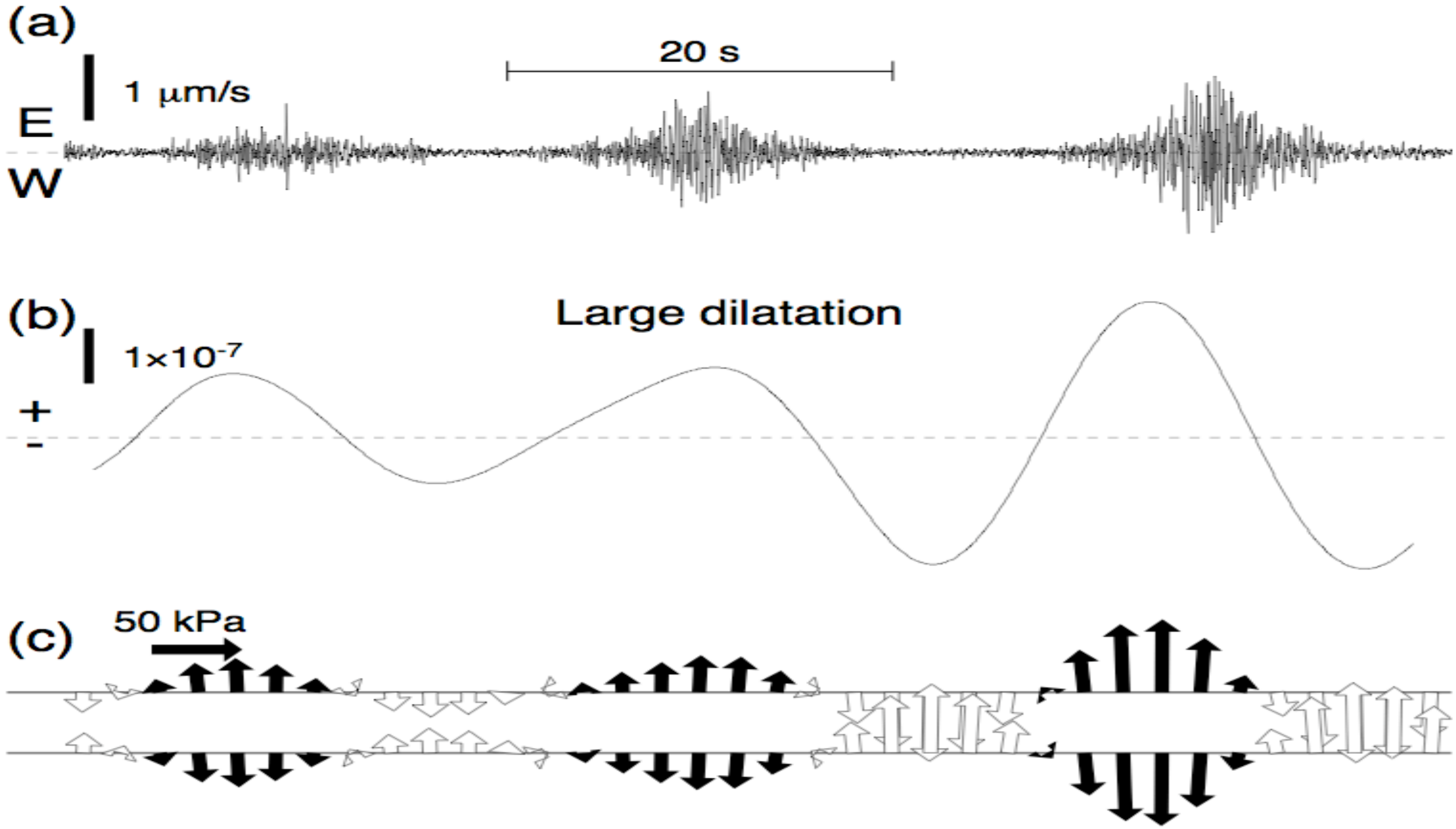


All 3 component stations…

Polarization Test



Triggered tremor



Inspiration from 2006 observations from Japan: Miyazawa, Mori, Brodsky papers & preprints