Geodetic characterization of slow slip in Cascadia and New Zealand

Rob McCaffrey
Dept. of Geology
Portland State University

Topics

- Spatial and temporal relationship between slow-slip and tremor.
- How much of slip budget is taken up by slow-slip.
- Temperature controls on slow-slip.

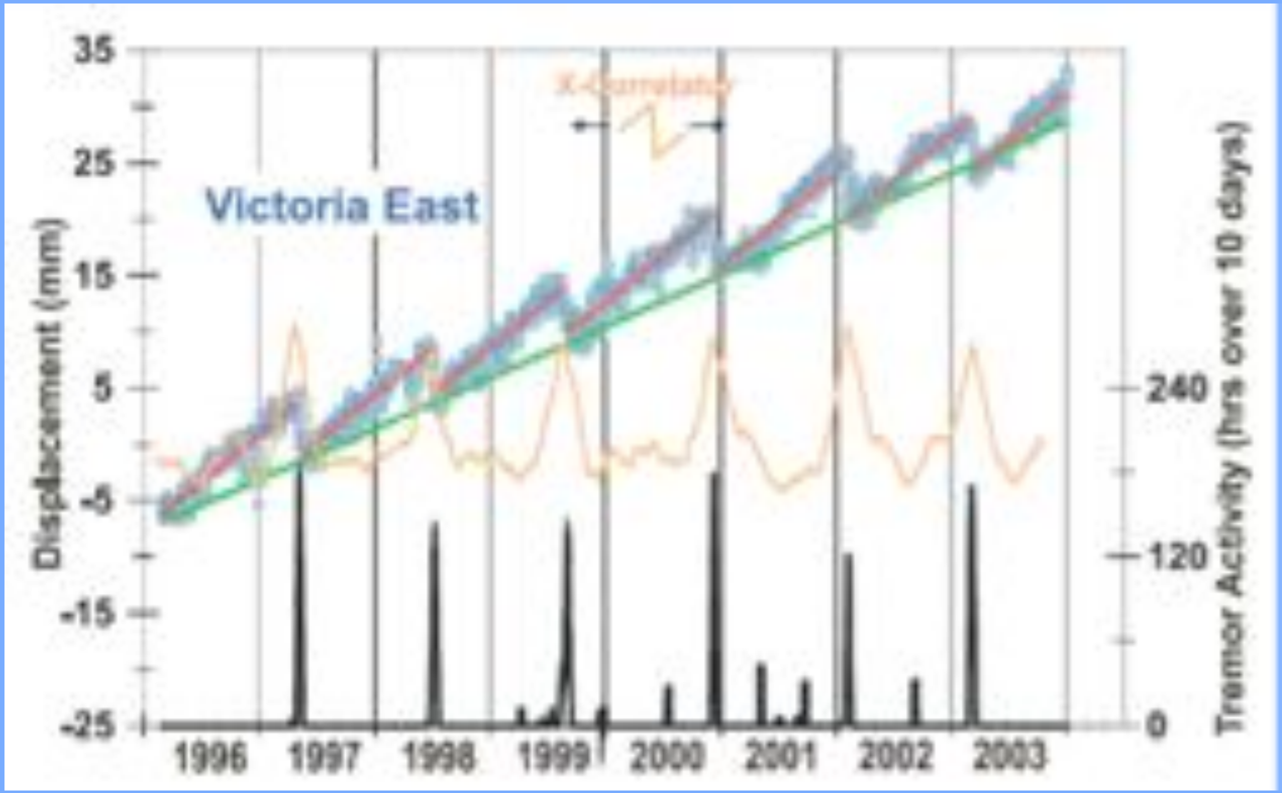
Slow-slip and tremor

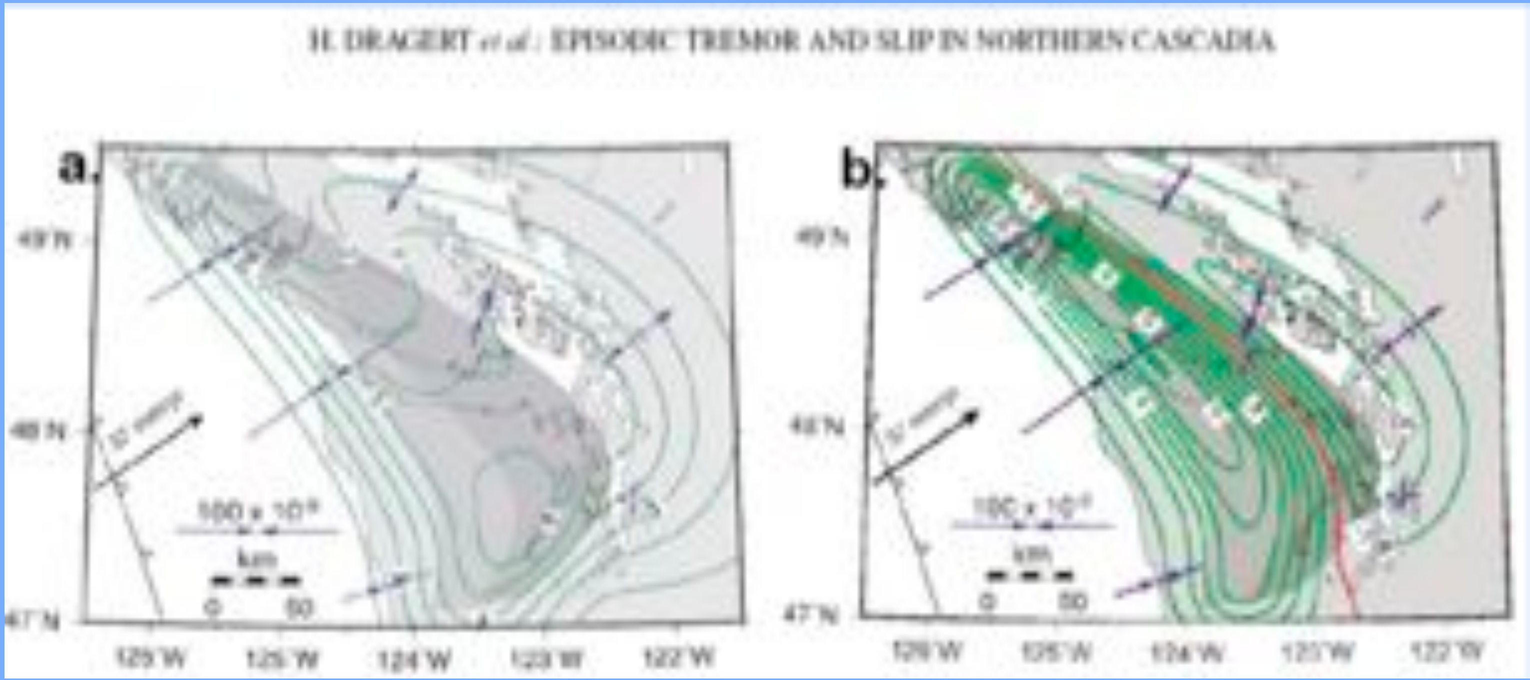
- Slow-slip events (SSE) and non-volcanic tremor (NVT) occur together or separately at many subduction zones
- How well are they spatially and temporally correlated?
- How well can we find the source regions of SSE with surface geodetic measurements?

Geodetic and seismic signatures of episodic tremor and slip in the northern Cascadia subduction zone

H. Dragert, K. Wang, and G. Rogers

Earth Planets Space, **56**, 1143–1150, 2004





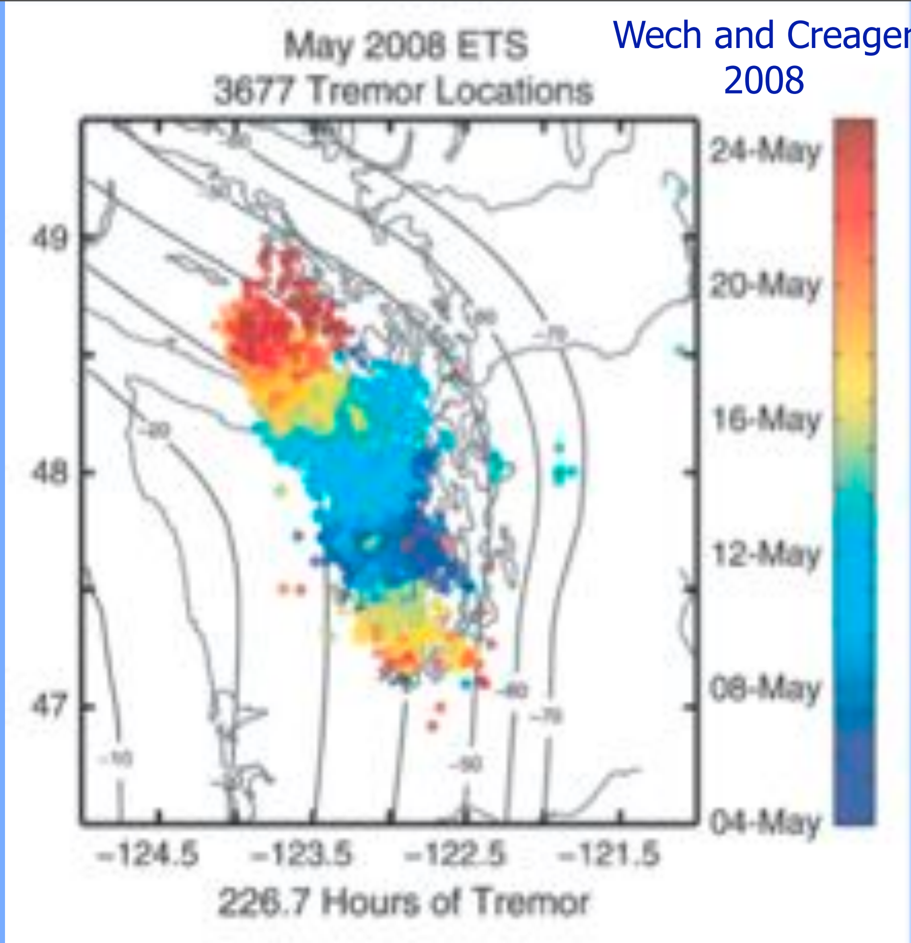
Horizontal magnitude, mm

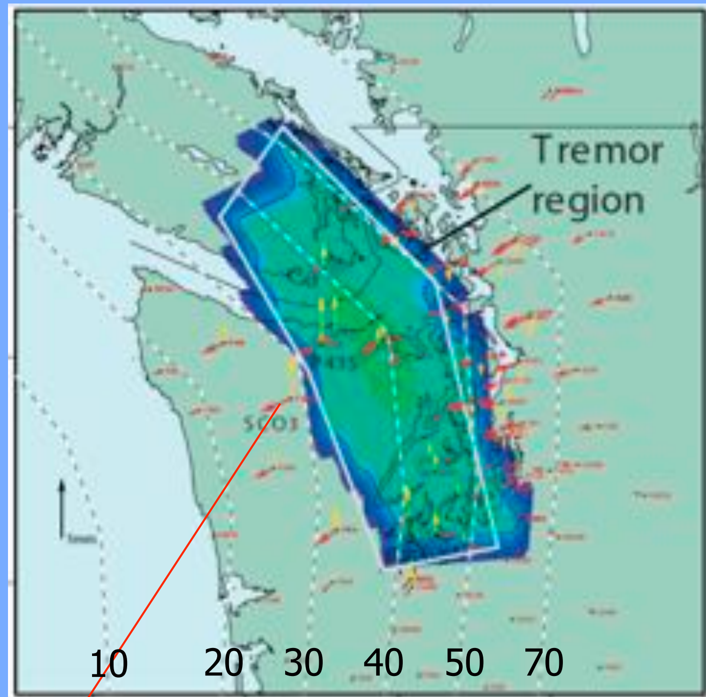
Vertical, mm

1999 SSE

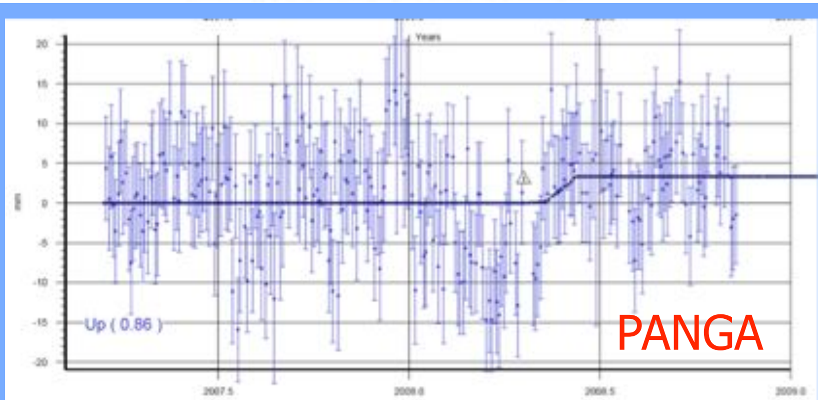
Models of abrupt up-dip termination of slip predict large vertical displacements over the up-dip edge.

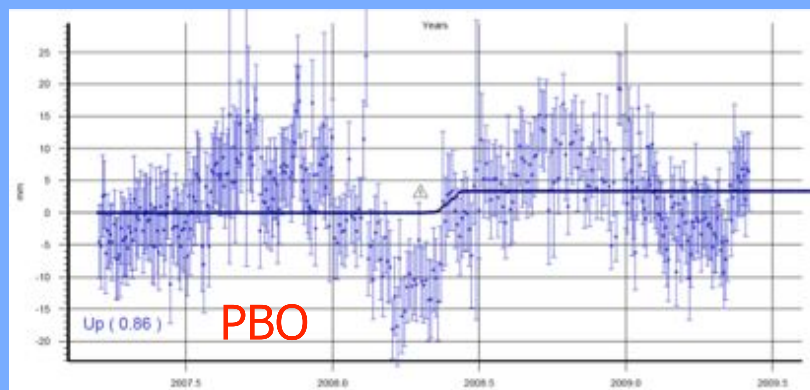
Wech and Creager 2008



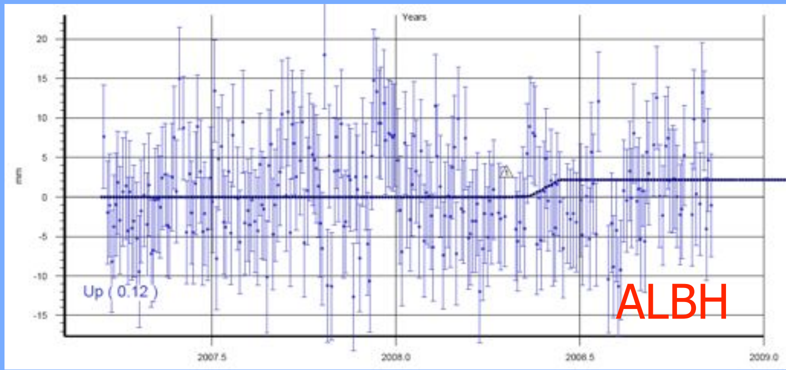


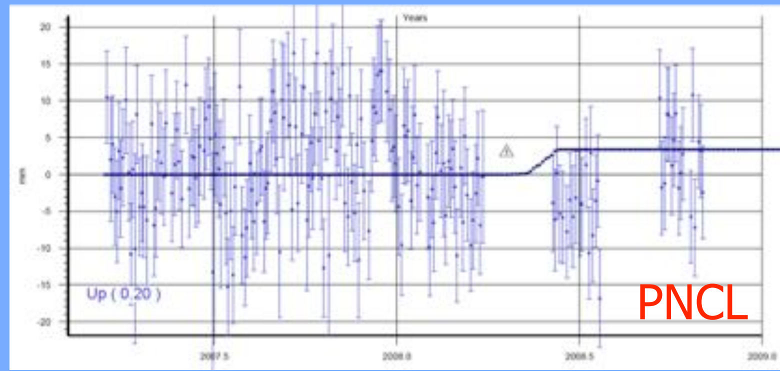
SC03 vertical

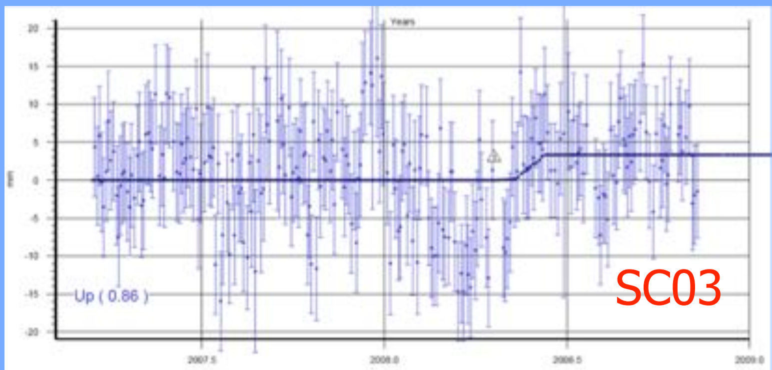


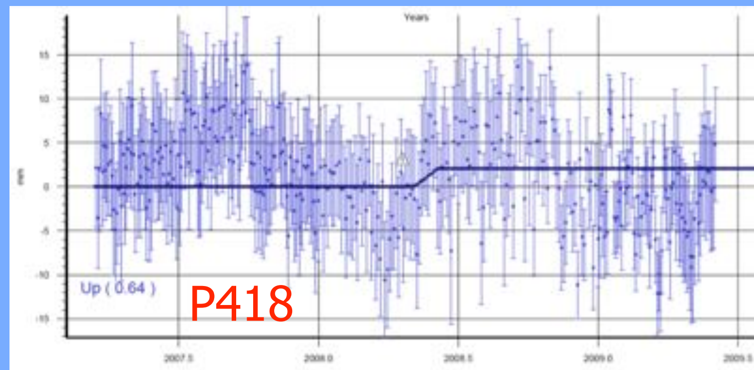


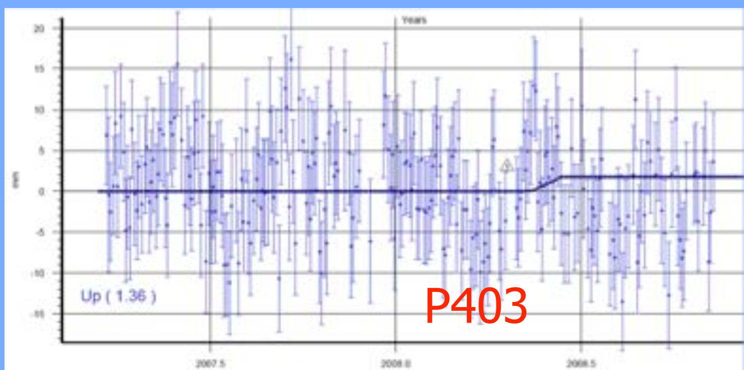
Vertical time series for sites predicted to have large vertical offsets – such offsets are not obvious in the time series.

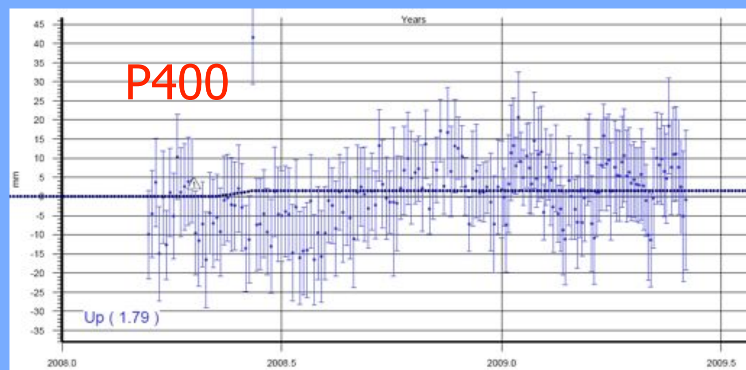


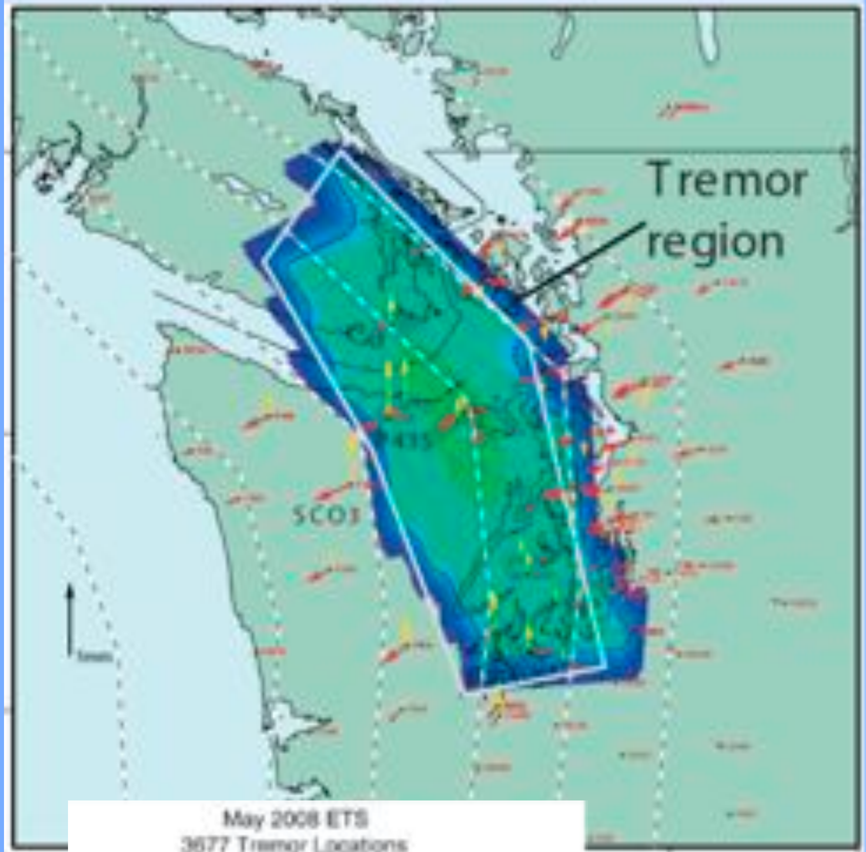


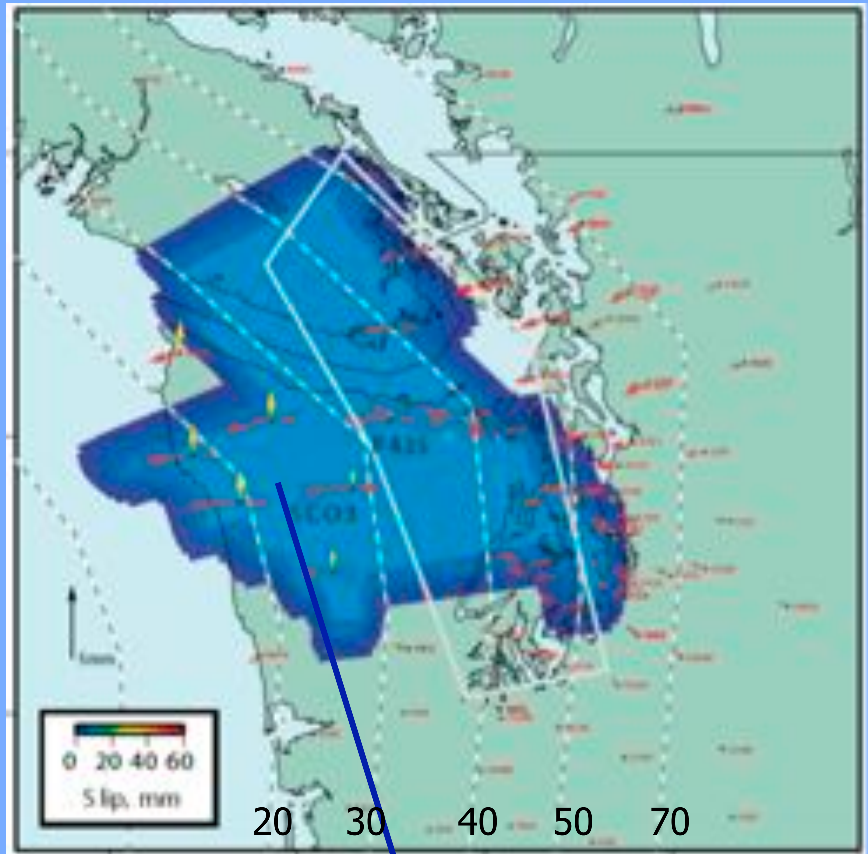


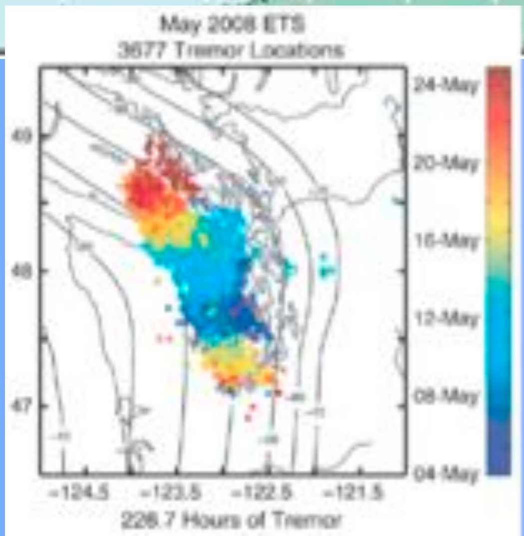






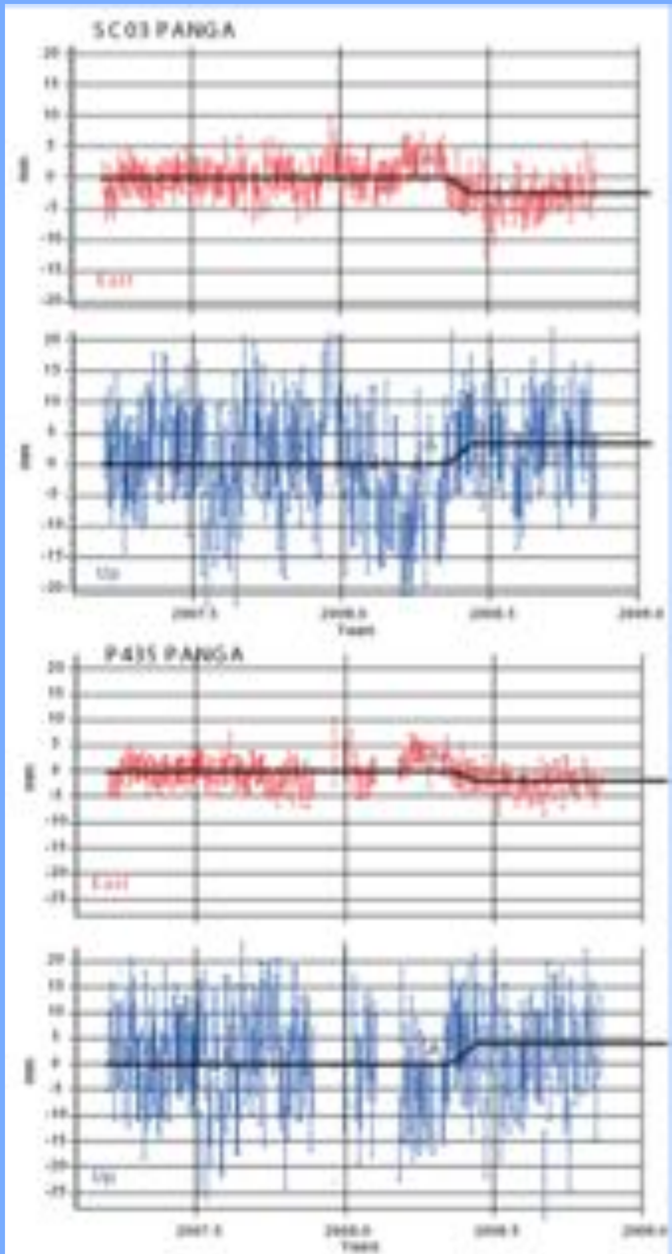




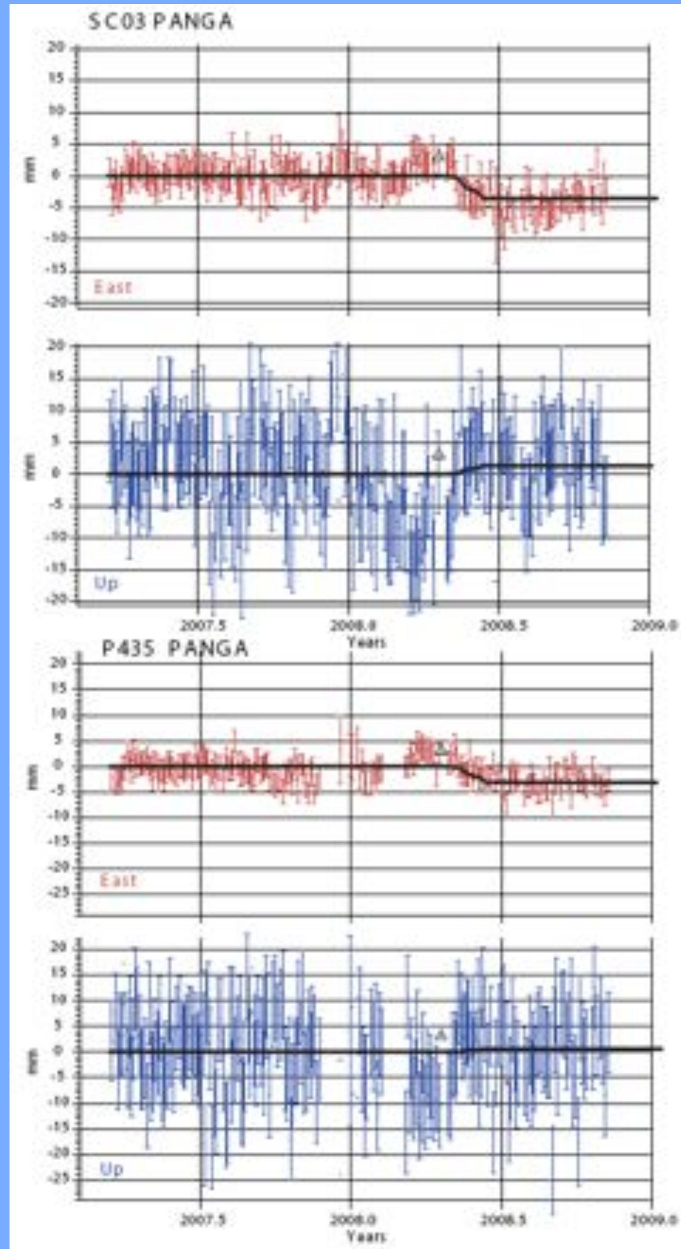


Relax constraints on slip region – slip moves updip and decreases vertical offsets.

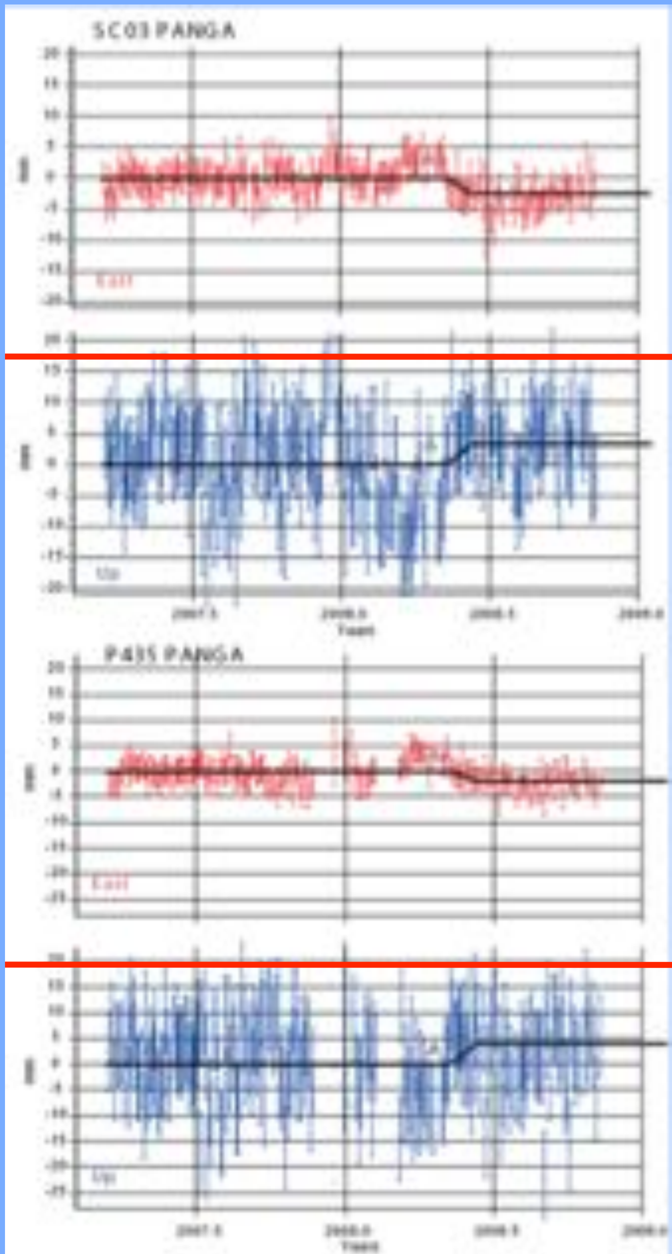
SSE = NVT region



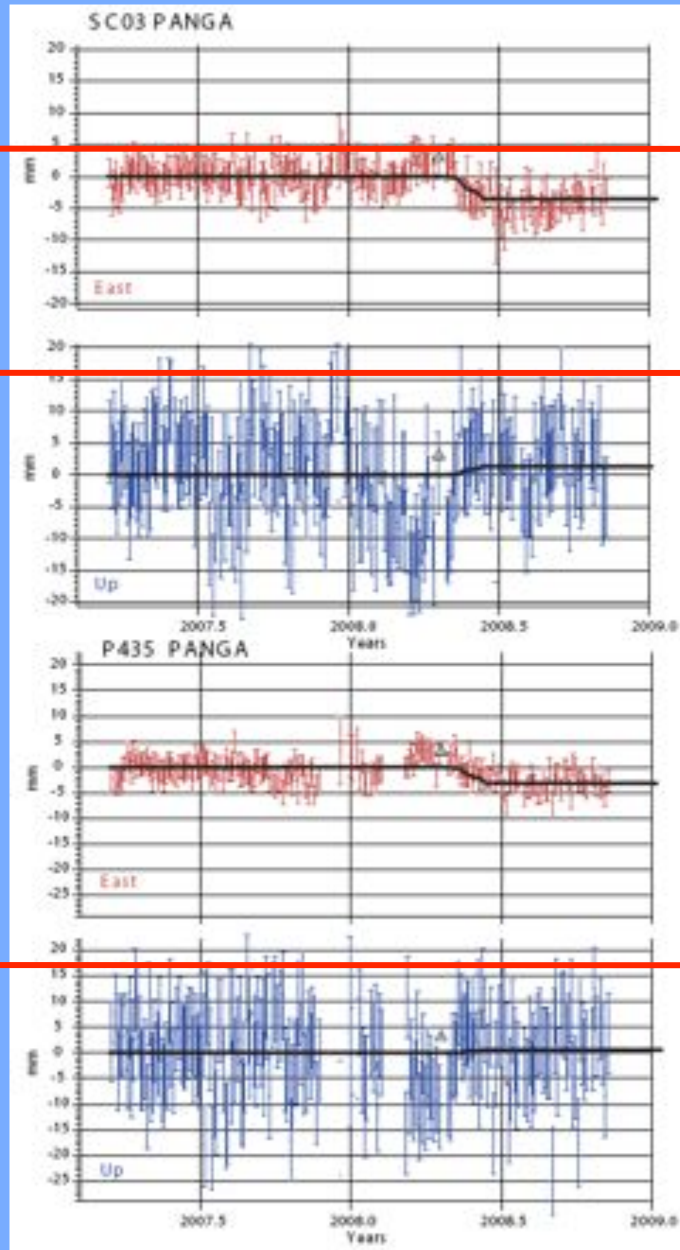
Expanded slip region



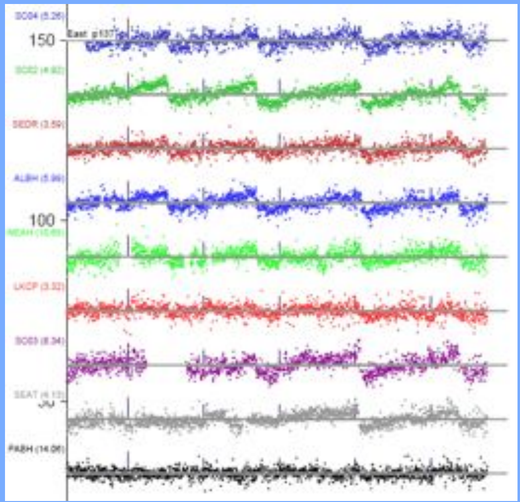
SSE = NVT region



Expanded slip region

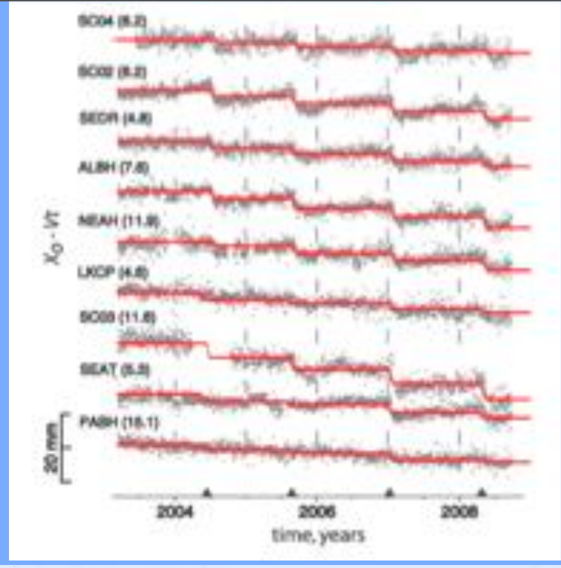


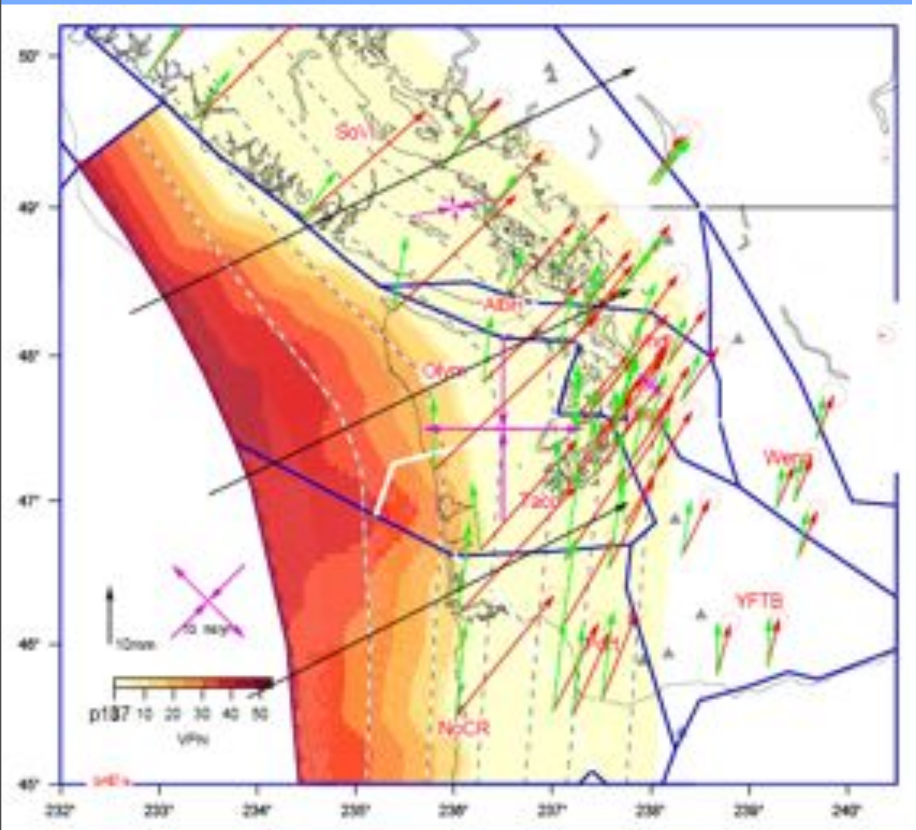
Slow slip released 7-10% of moment beneath OP in 5 years

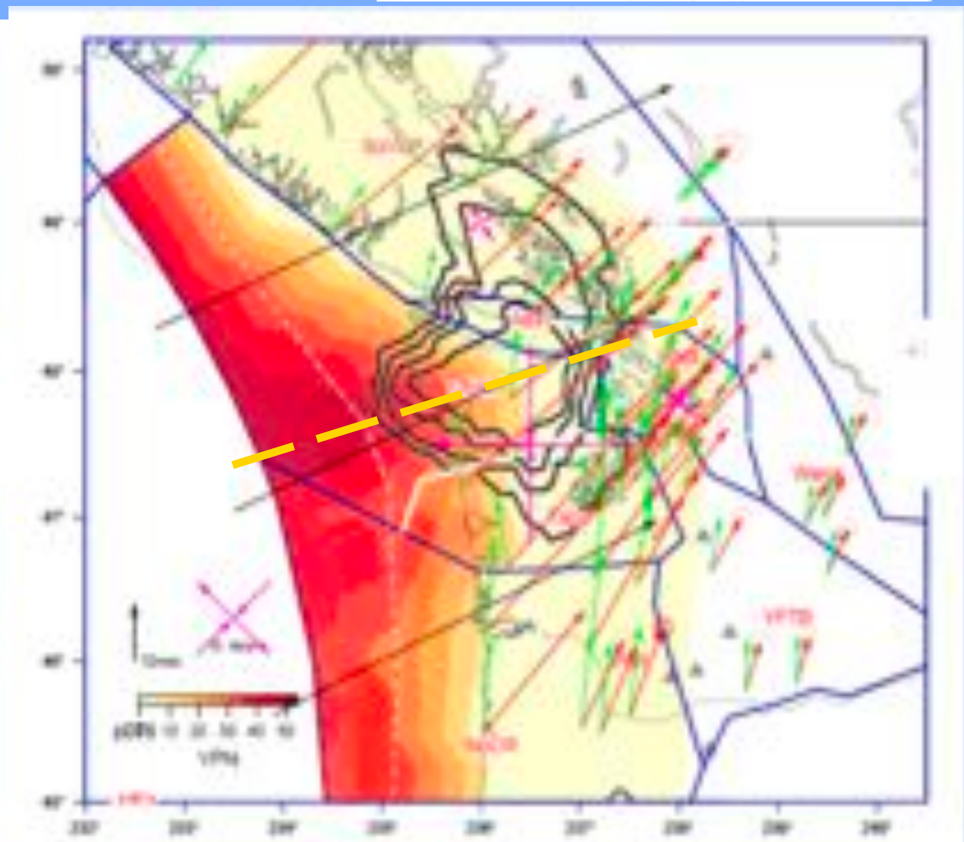


Solution without SSEs

Solution with SSEs

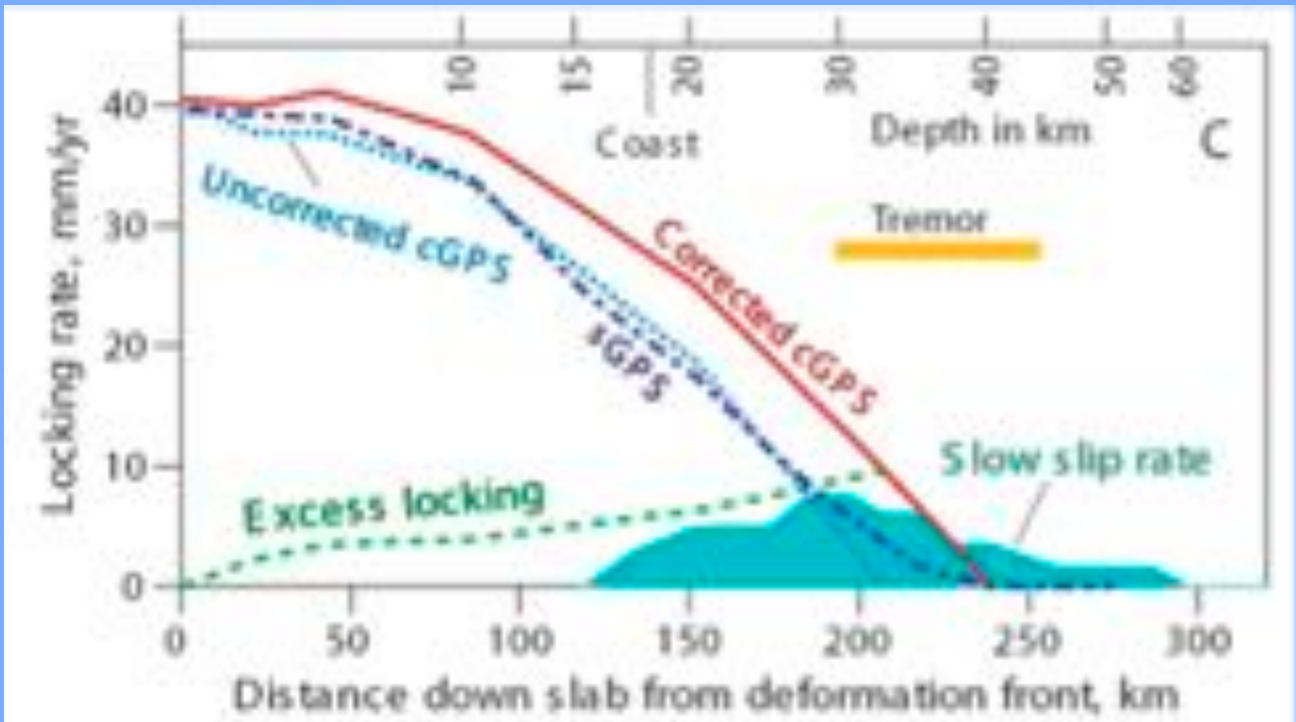




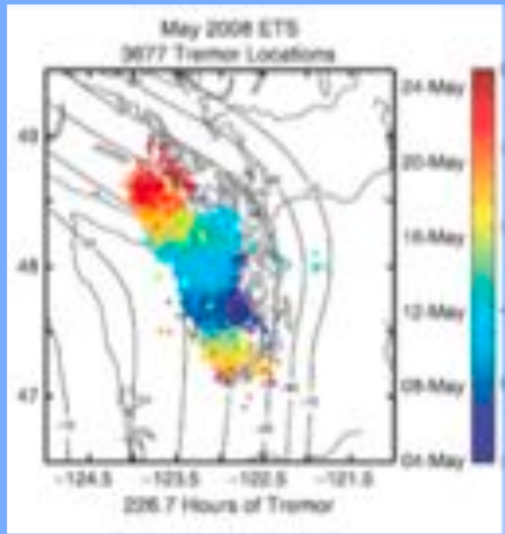


Between slow-slip events, fault locking extends farther downdip.

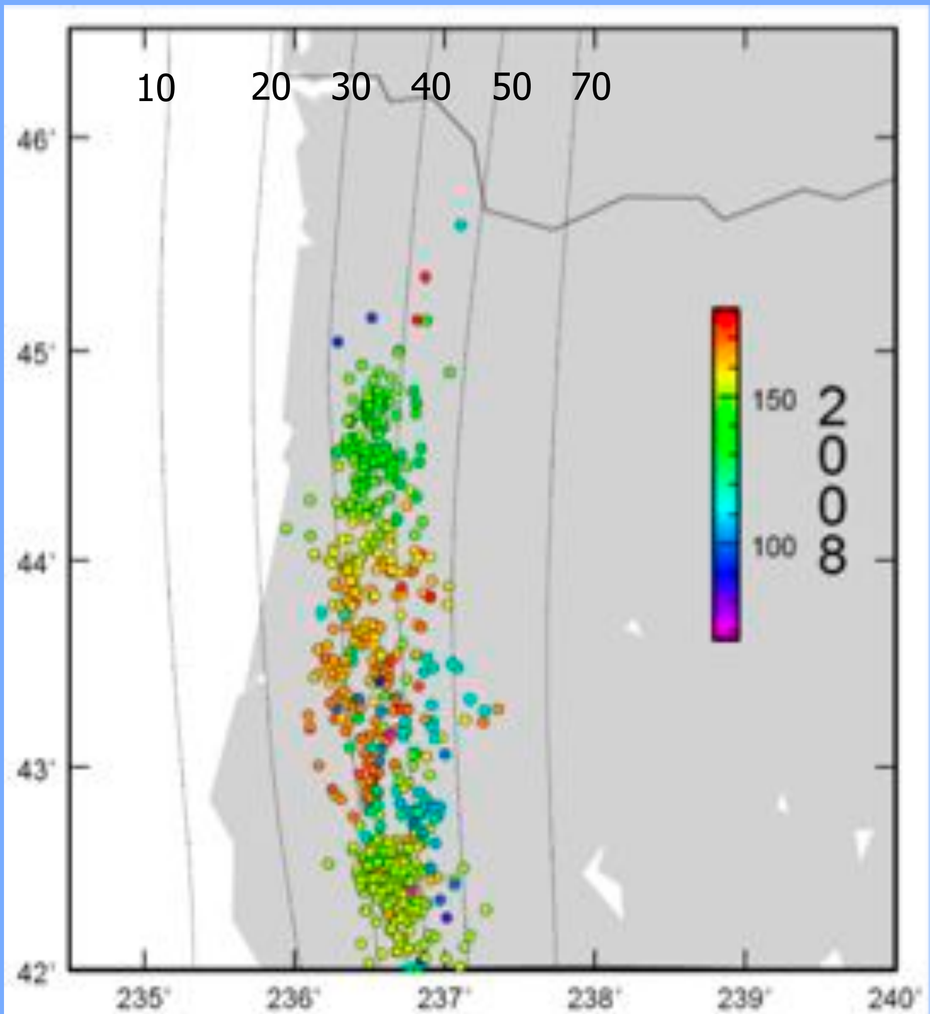
Slow slip ‘erodes’ the bottom of the ‘geodetic locked’ zone - it may explain in part why we see decreased locking at depth.



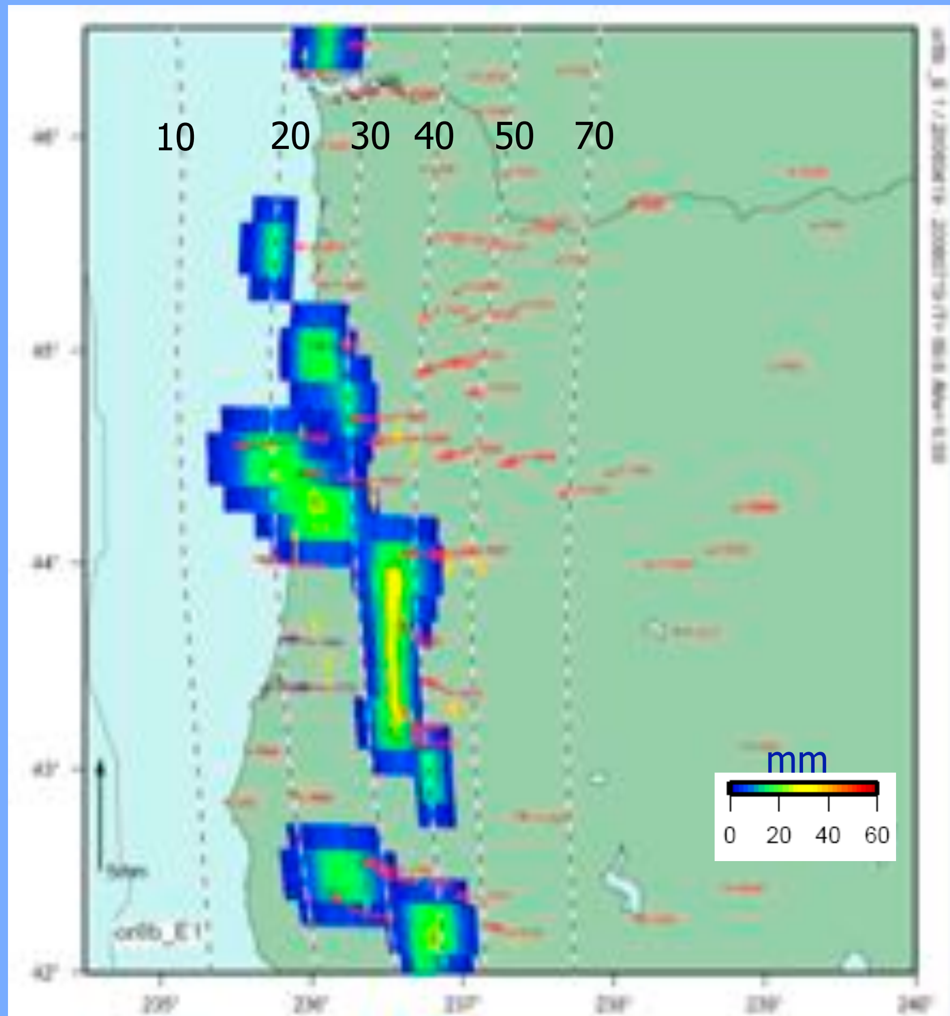
McCaffrey, 2009



Wech and Creager, GRL 2008



NVT – Boyarko and Brudzinski

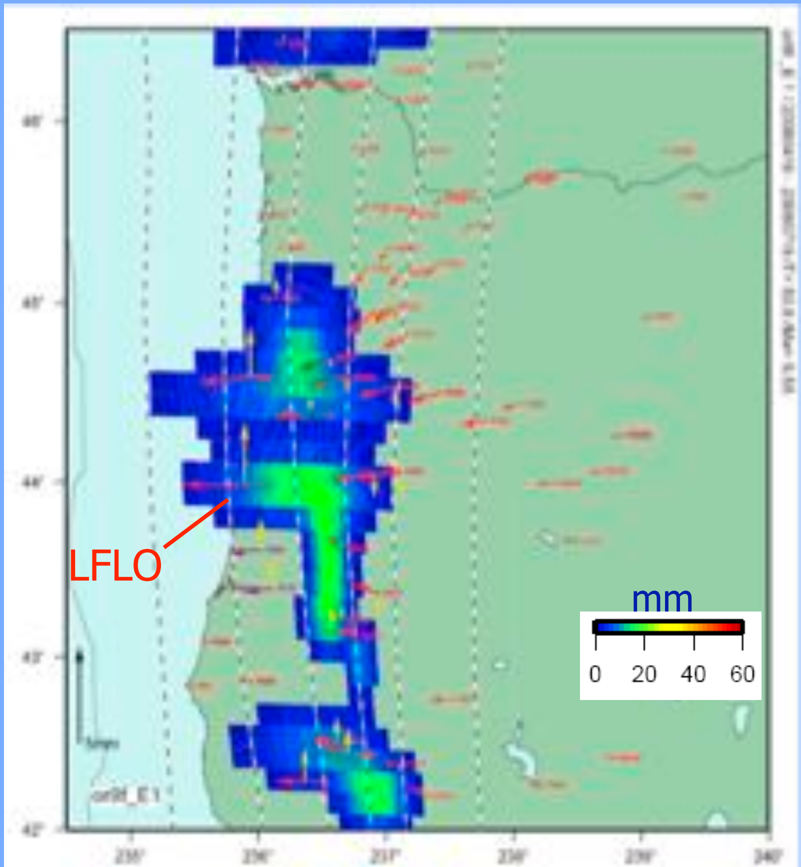


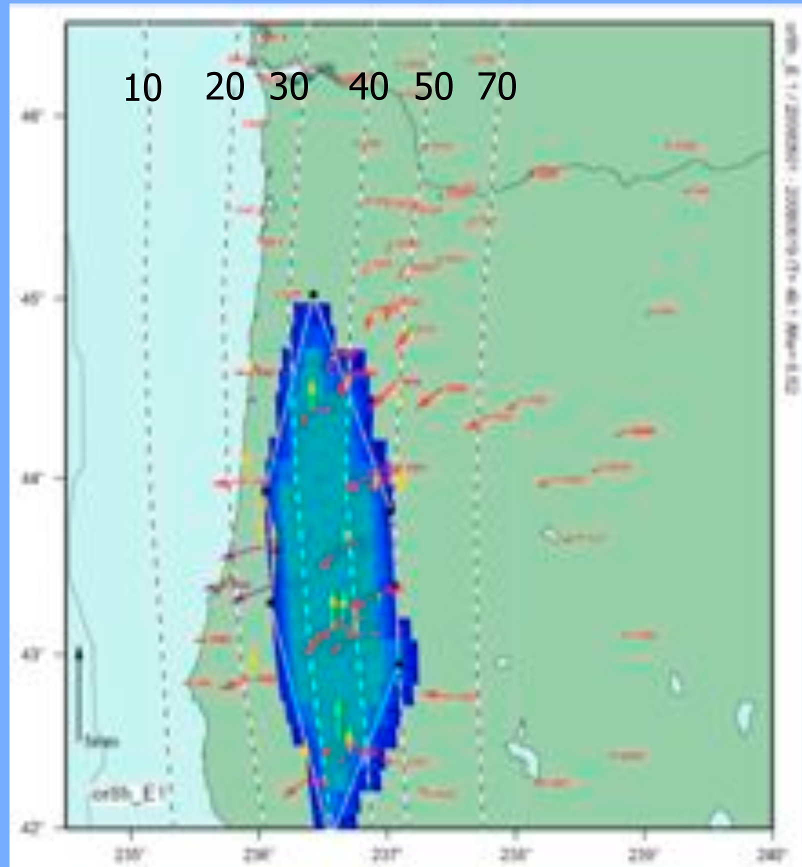
SSE – inversion of GPS time series

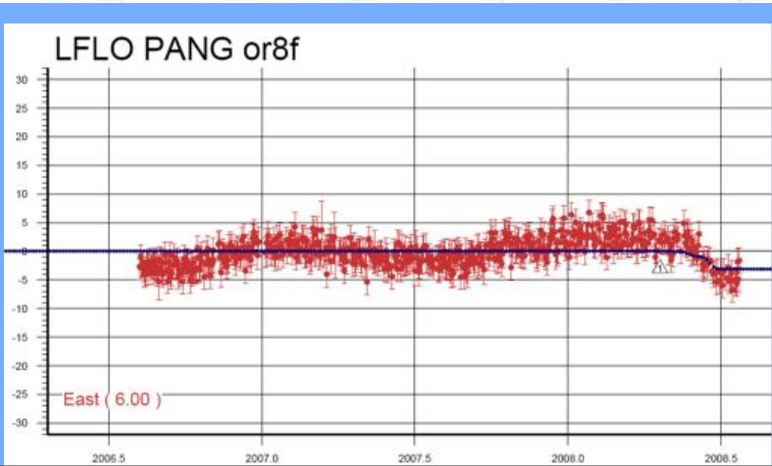
Central Cascadia – Oregon section

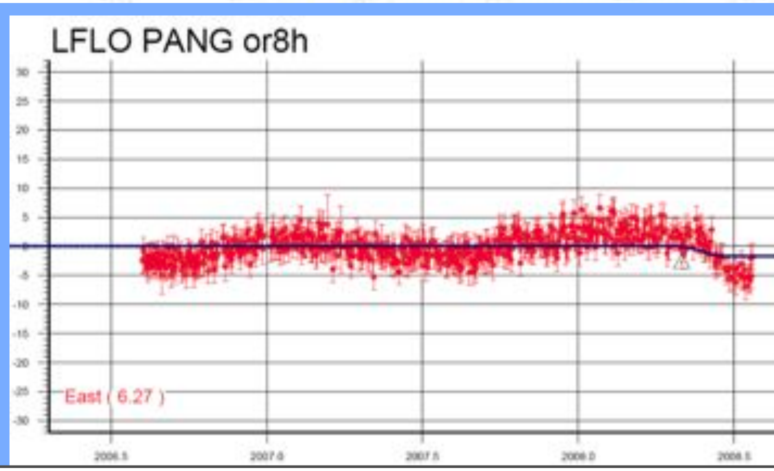
Slip constrained to 32 - 42 km depth

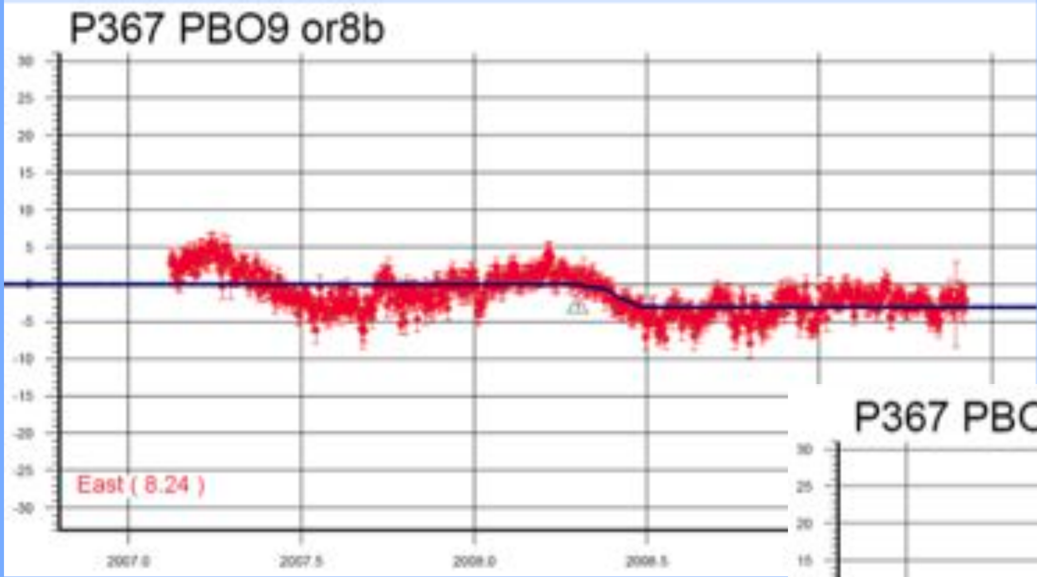
Slip constrained to region of NVT

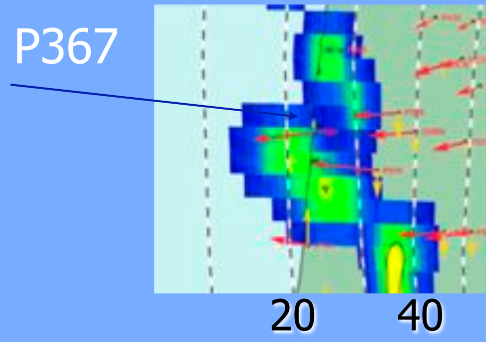




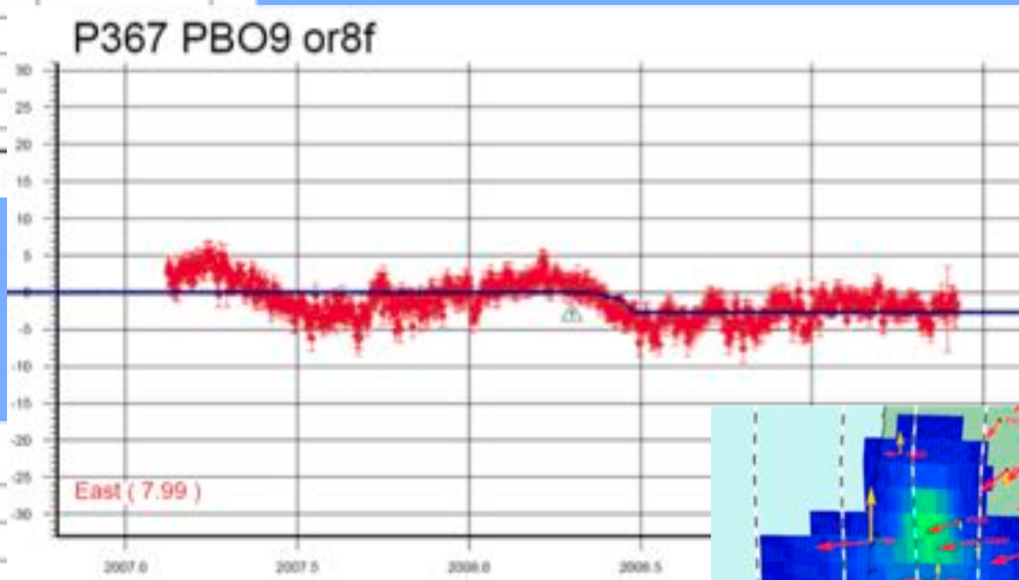


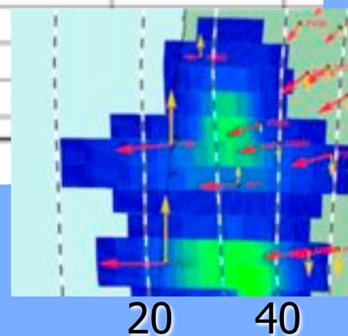


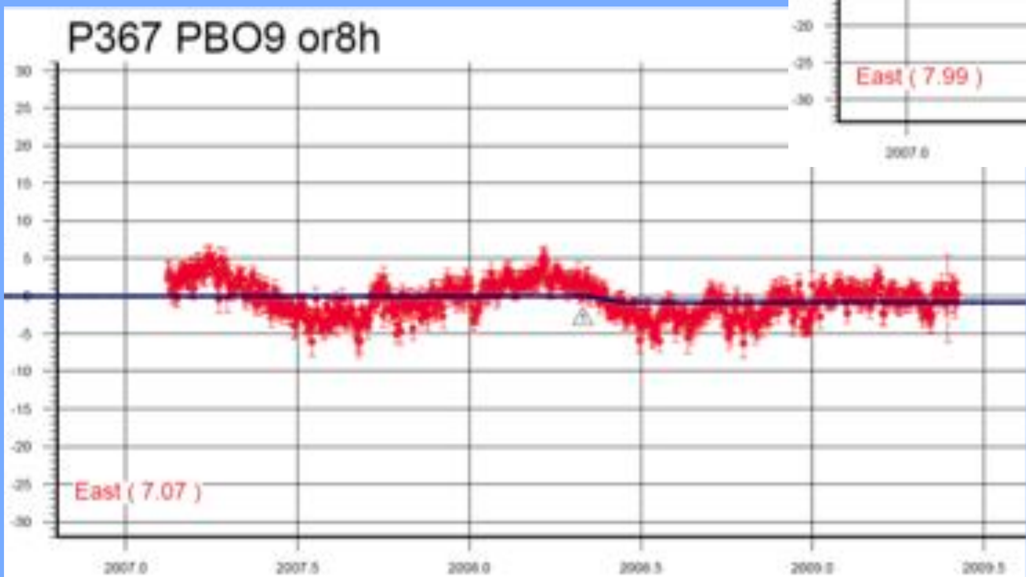


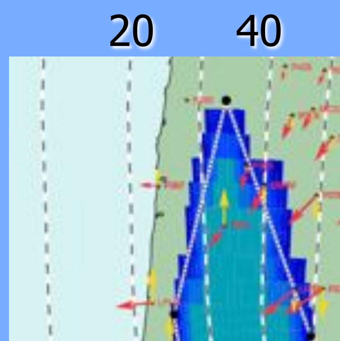


East component of PBO site P367

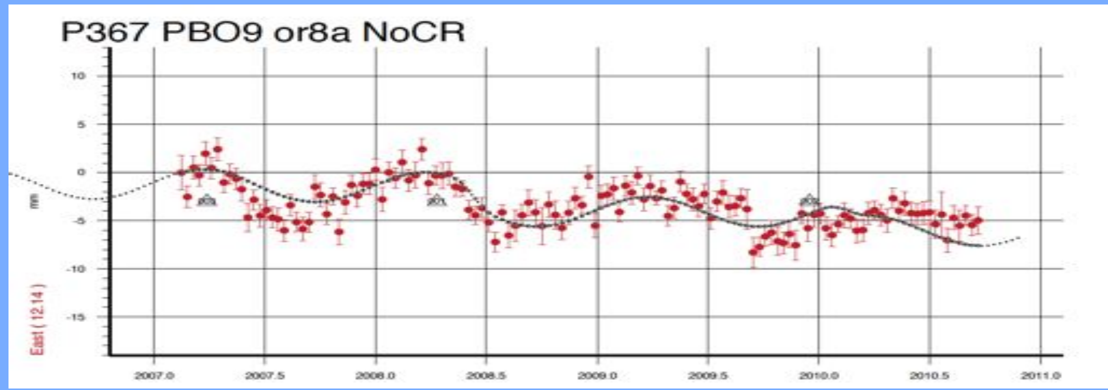


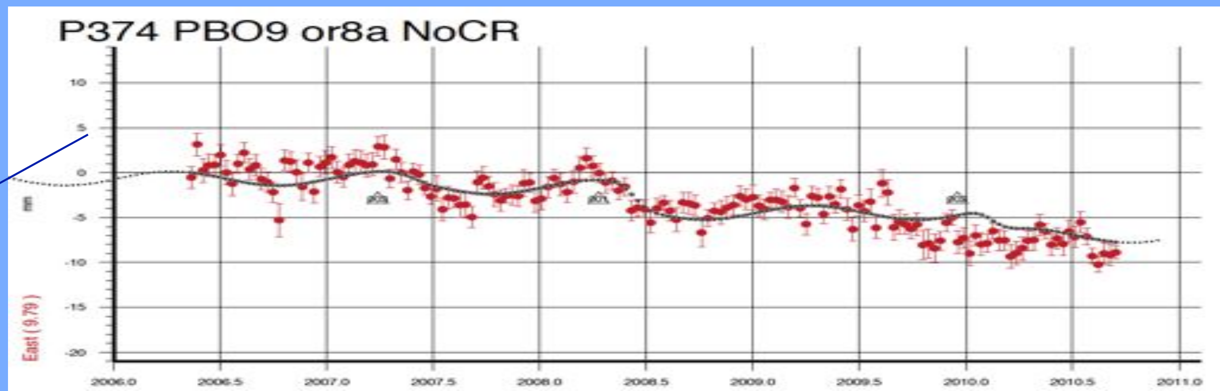


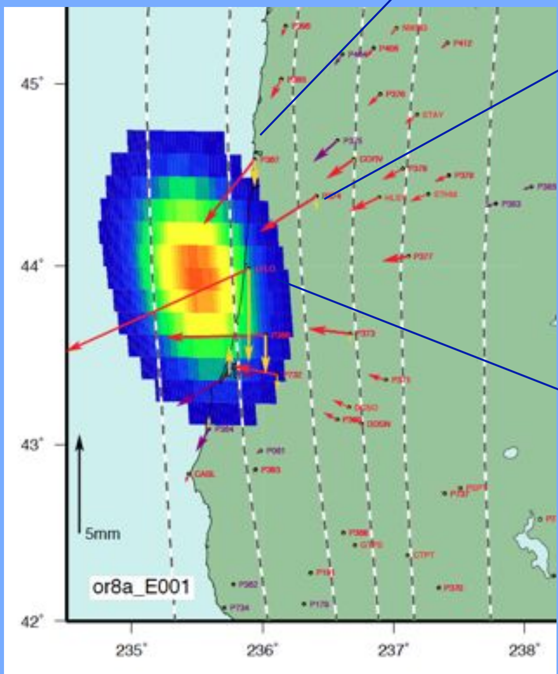


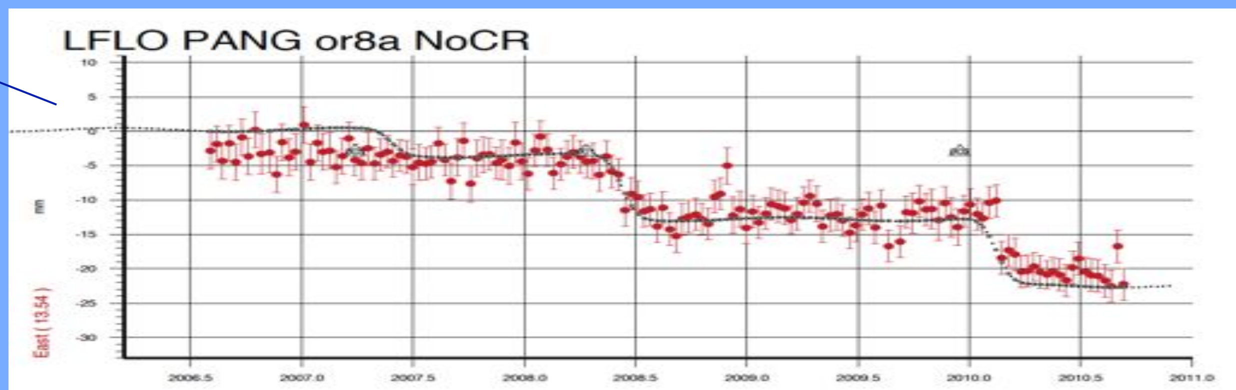


Amplitude large near coast



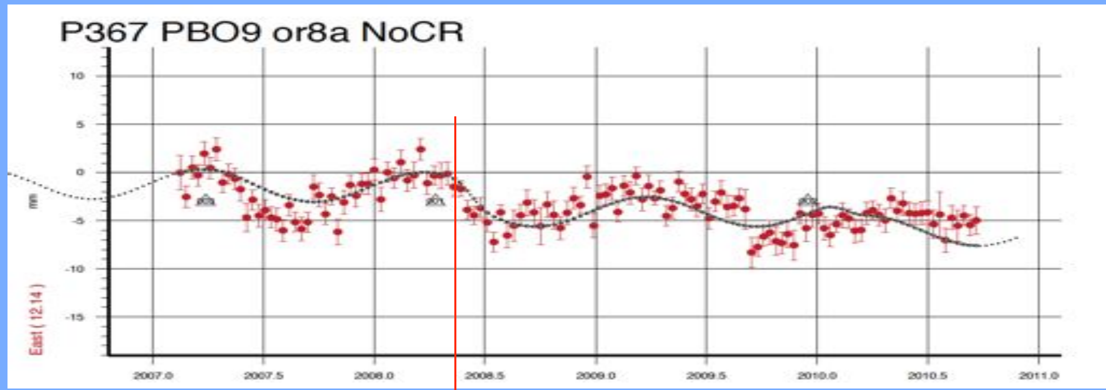


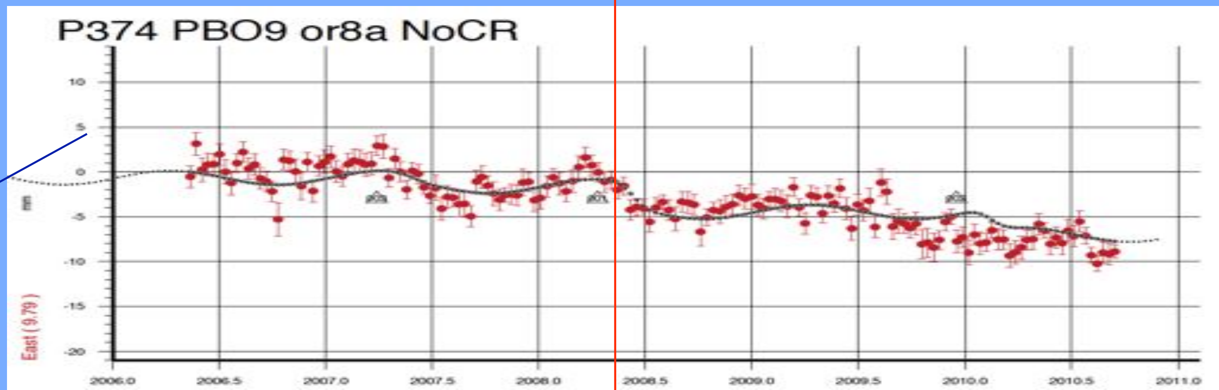


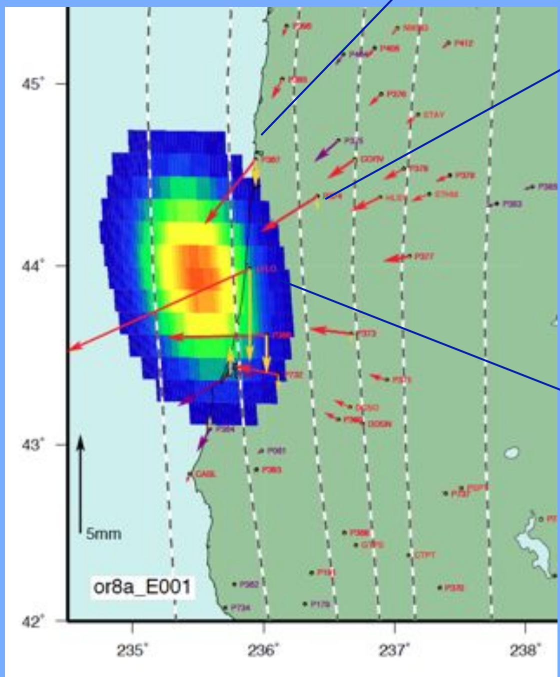


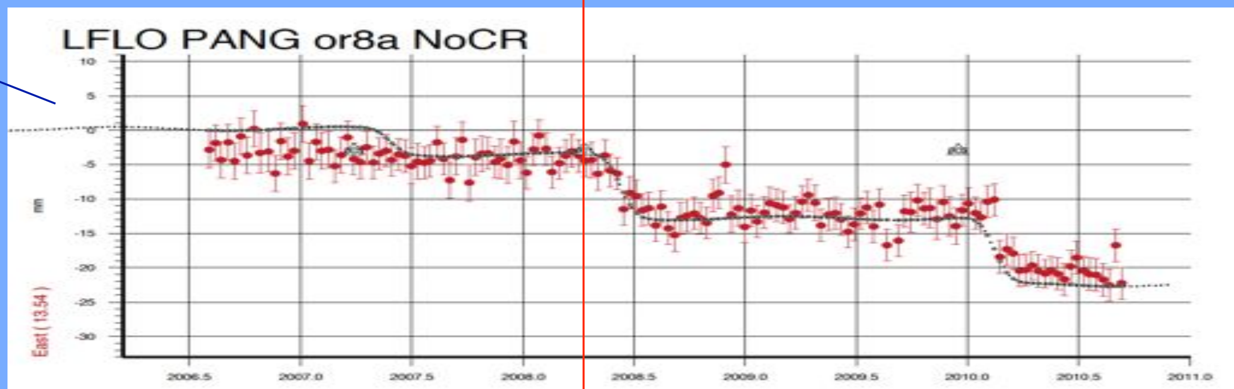
Solve for seasonal signal at same time

Amplitude large near coast









Solve for seasonal signal at same time

HIROSE AND OBARA: RECURRENCE BEHAVIOR OF SLOW SLIP EVENTS

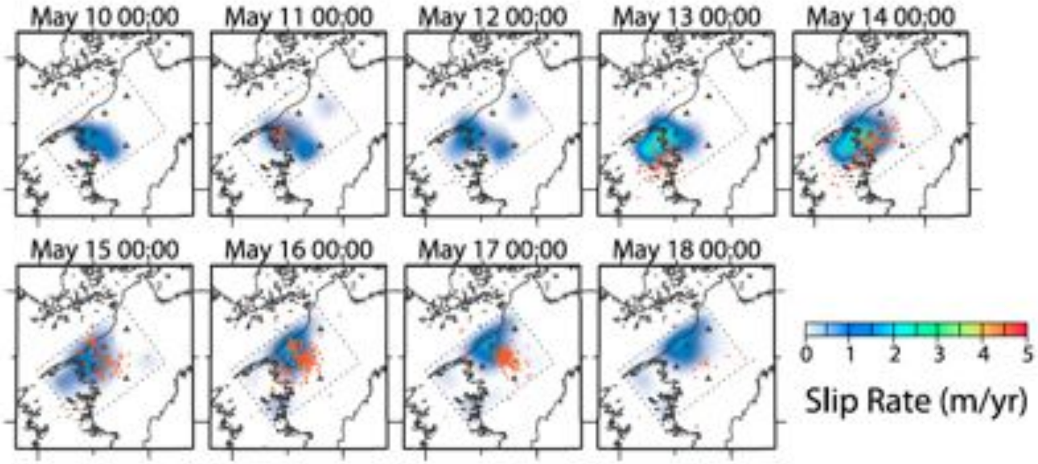


Figure 6. Estimated daily slip rate distributions of the May 2005 SSE. The time for each frame is 0000 LT. Orange dots show the tremor epicenters that occurred within a 1 day long time window from 1200 LT on the previous day to 1200 LT on the day of each frame. The rectangle indicated by dashed lines in each frame denotes the modeled region.

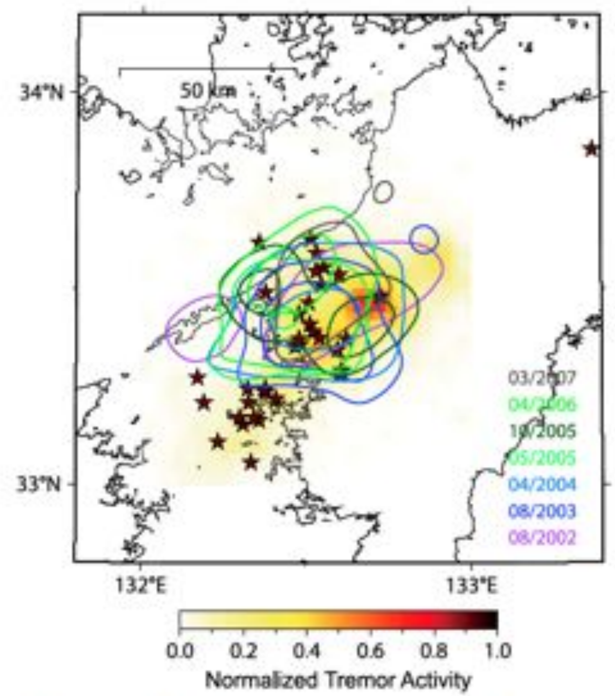


Figure 9. Slip distributions of seven SSEs. The contours show the cumulative slip distributions of each episode. Each episode has one or two contour lines. The outer contours indicate 1 cm slip, whereas the inner contours indicate 3 cm slip. The color of the contour lines indicates the month and year of a particular episode, as indicated in the lower right corner. The color scale indicates the normalized histogram of cumulative tremor activity during the seven episodes shown. The stars indicate the epicenters of VLFEs that also occurs during the specified episodes.

Recurrence behavior of short-term slow slip and correlated nonvolcanic tremor episodes in western Shikoku, southwest Japan

Hitoshi Hirose[1] and Kazushige Obara[1,2]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, B00A21, doi:10.1029/2008JB006050, 2010

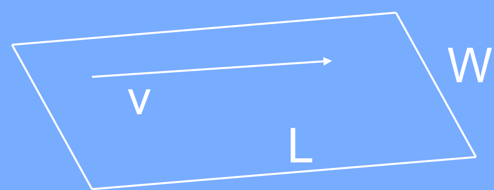
How much does slow-slip contribute to accommodation of total slip budget?

We've known for a long time that observed seismic moment rates lag expected rates (e.g. low 'coupling' coefficients)

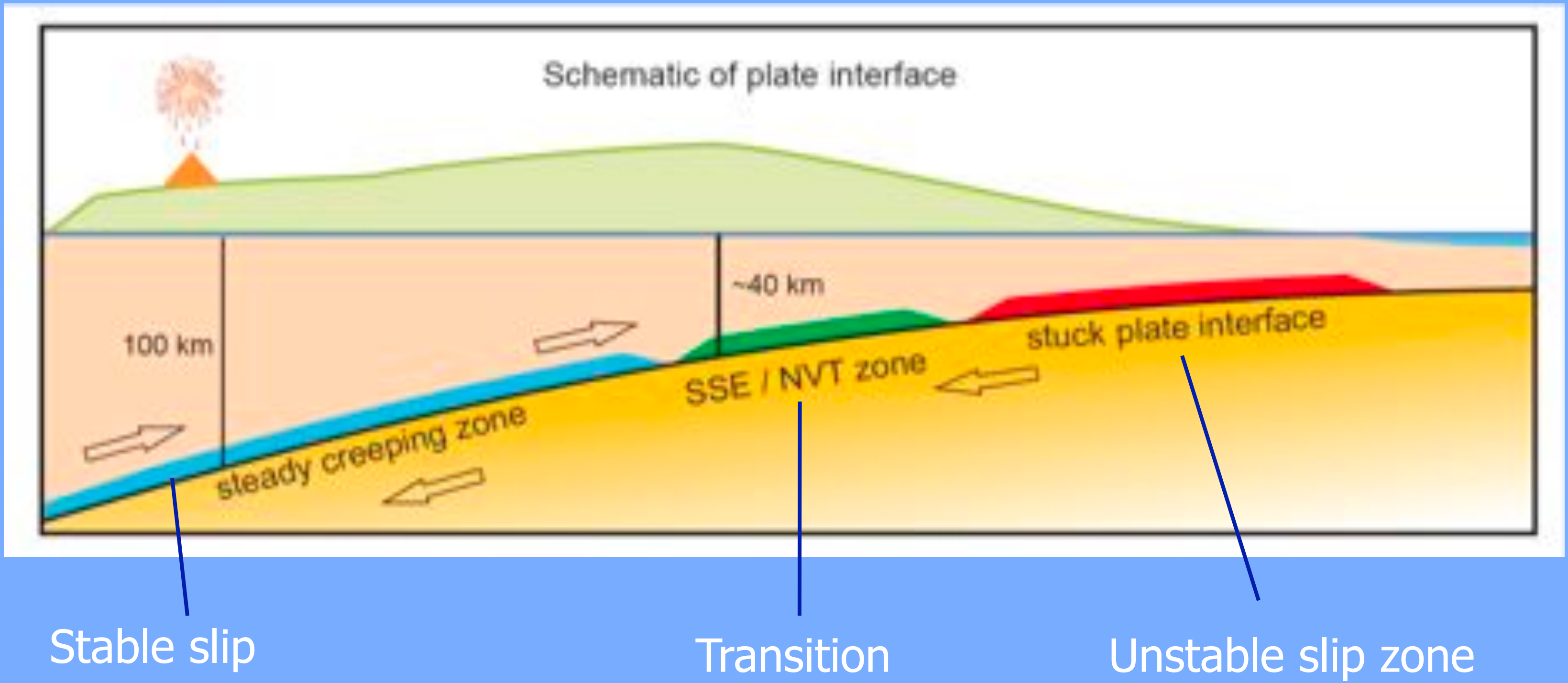
$$\Sigma M_o = \Sigma_{time}\, \mu\, L\, W\, v$$

Globally, $\Sigma M_o^{observed} \approx 1/3\ \Sigma M_o^{expected}$ - but why?

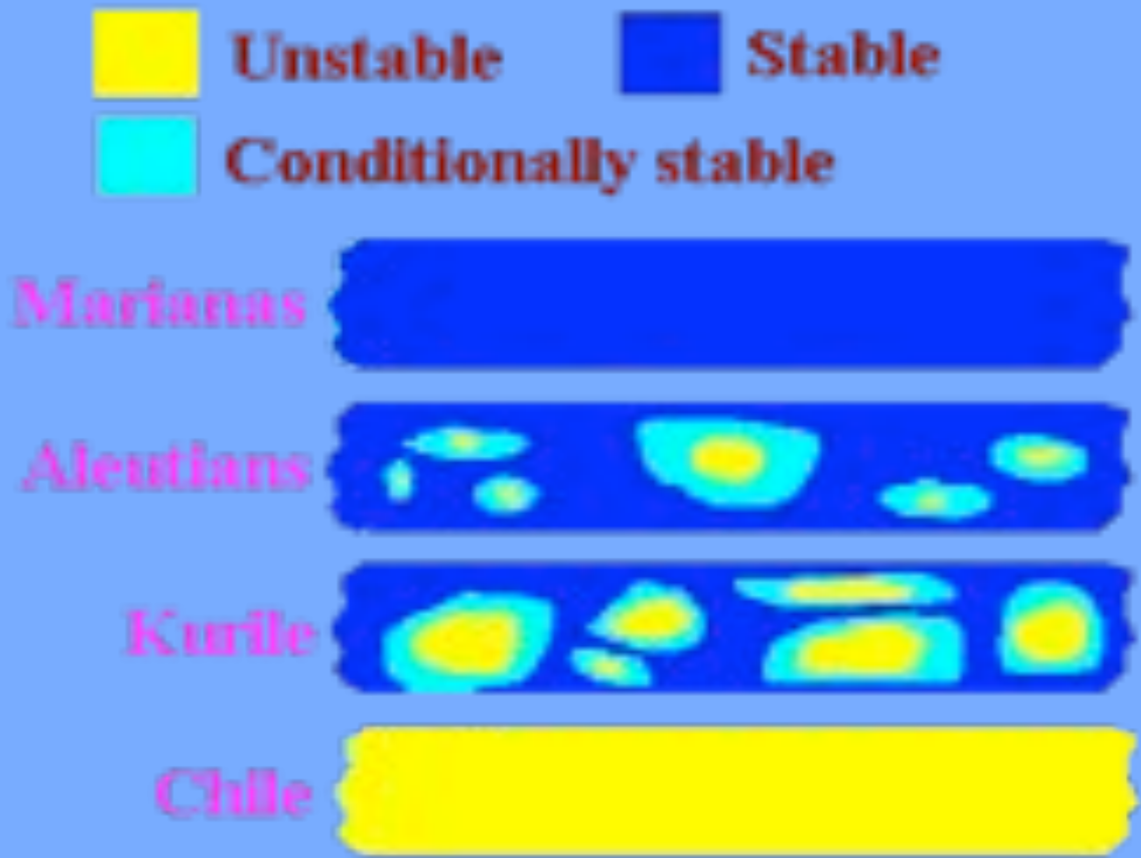
- Over-estimate of fault depths W (can be measured)
- Insufficient earthquake history (this is a problem)
- Steady aseismic slip within 'seismogenic' zone
- Slow-slip (new)



Depth-dependent view of friction

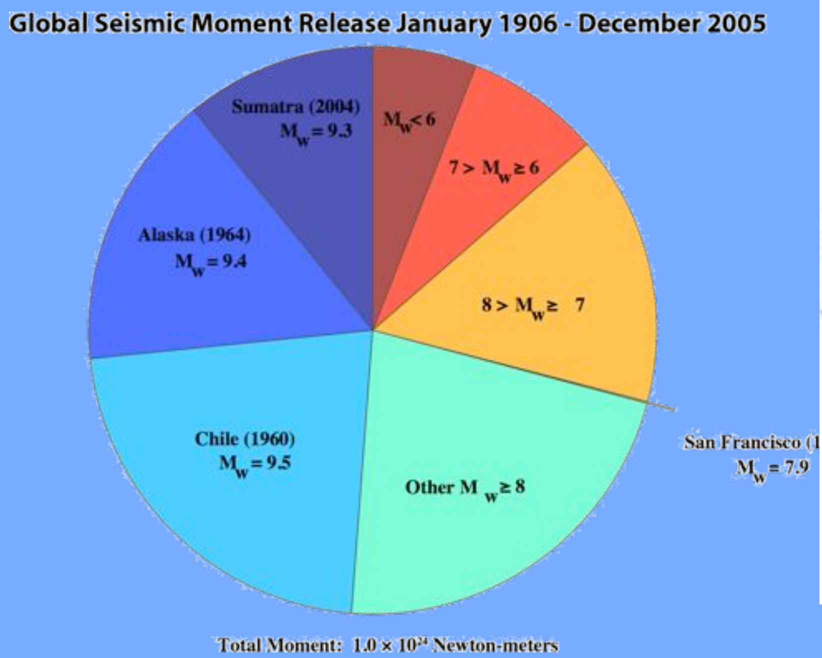


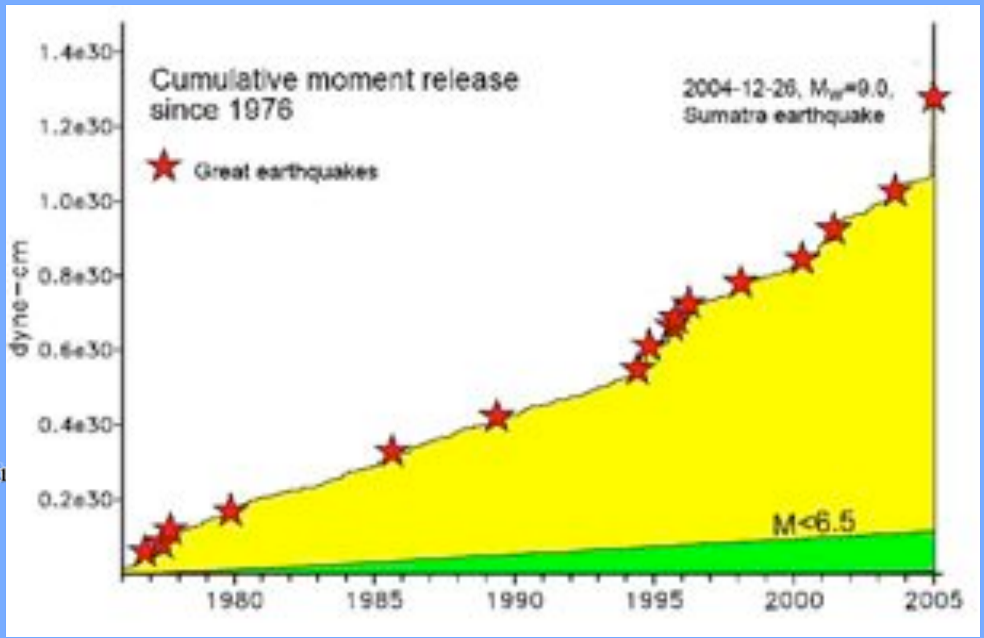
Heterogeneous view



Kanamori, Scholz

Earthquake moment v. time





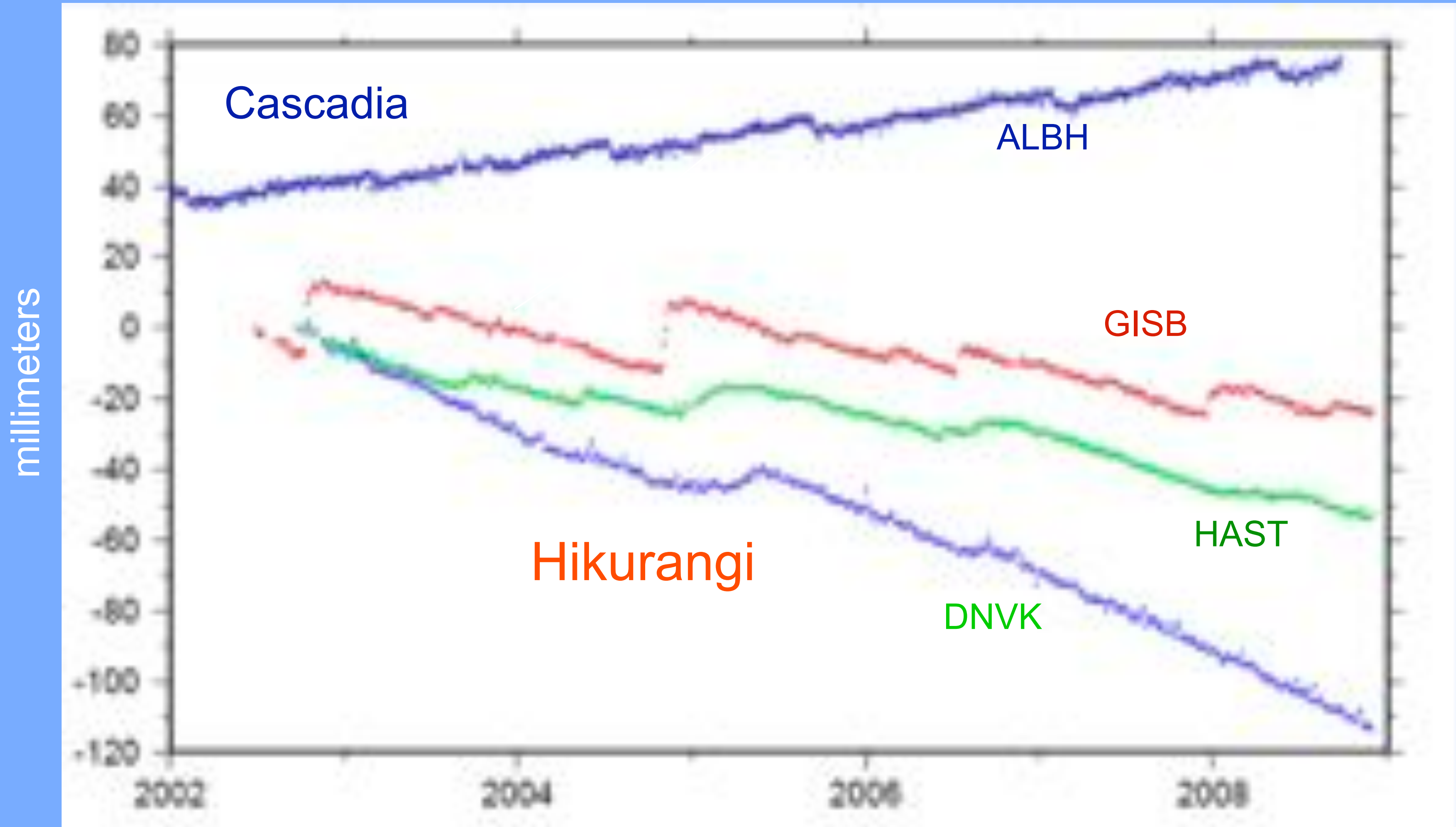
http://www.seismology.harvard.edu/projects/CMT/

Since the total moment depends on the very few, largest events, maybe we have not waited long enough.

Slow-slip

- ✓Slow-slip events are shear slip on fault but much slower than an earthquake - no seismic waves
- ✓Observed with geodetic instruments (GPS and strainmeters)
- ✓Prior to about 10 years ago, they were largely invisible (undetected)
- ✓Rate of slow-slip moment release at subduction zones is significant; Modifies earthquake recurrence rates
- ✓Modifies the stress cycle and stress transfer between earthquakes

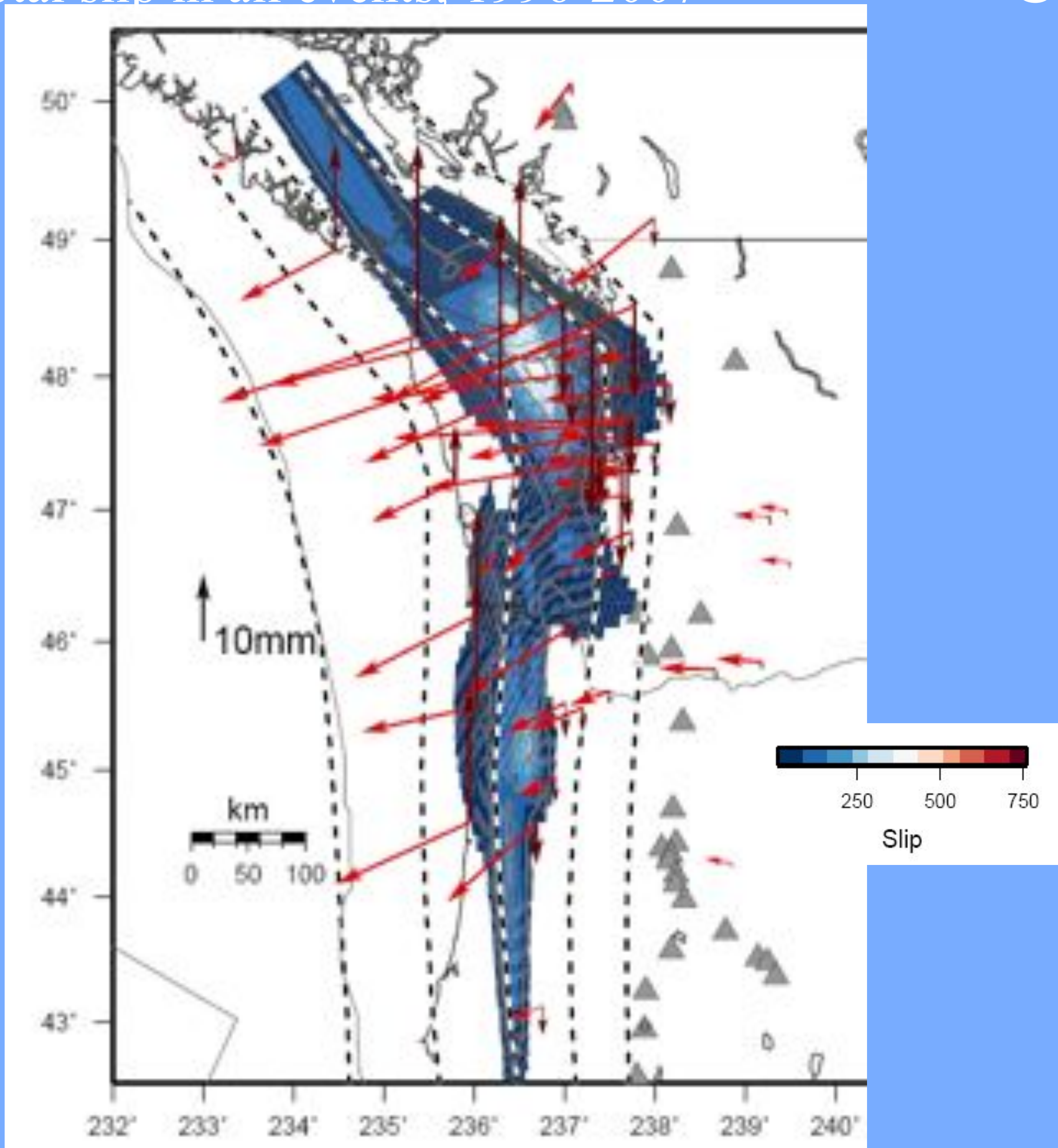
What they look like in a GPS time series

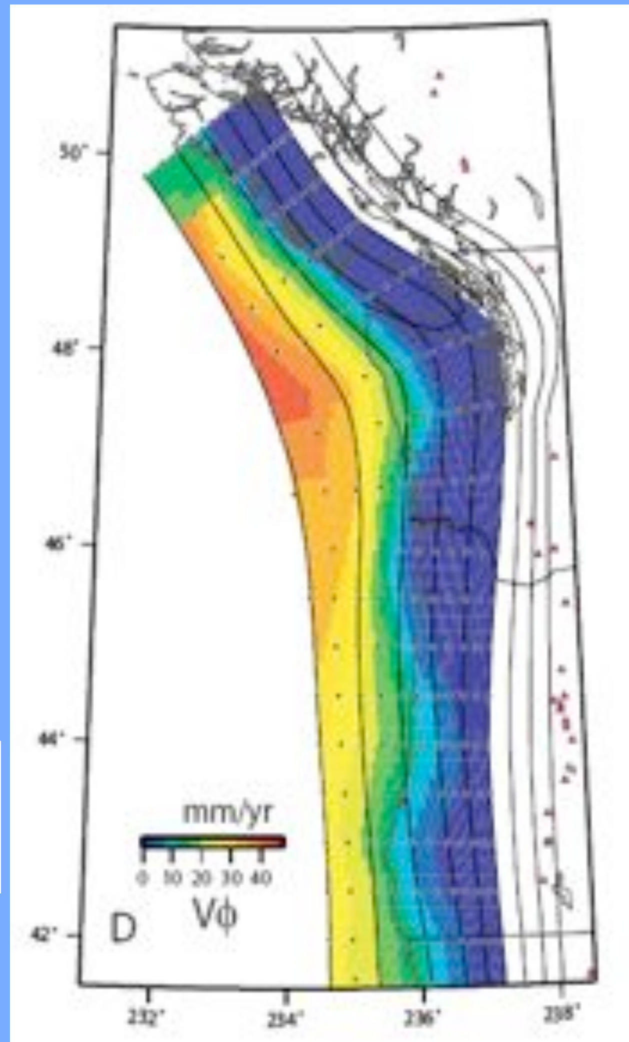


East components of continuous GPS

Total slip in all events: 1996-2007

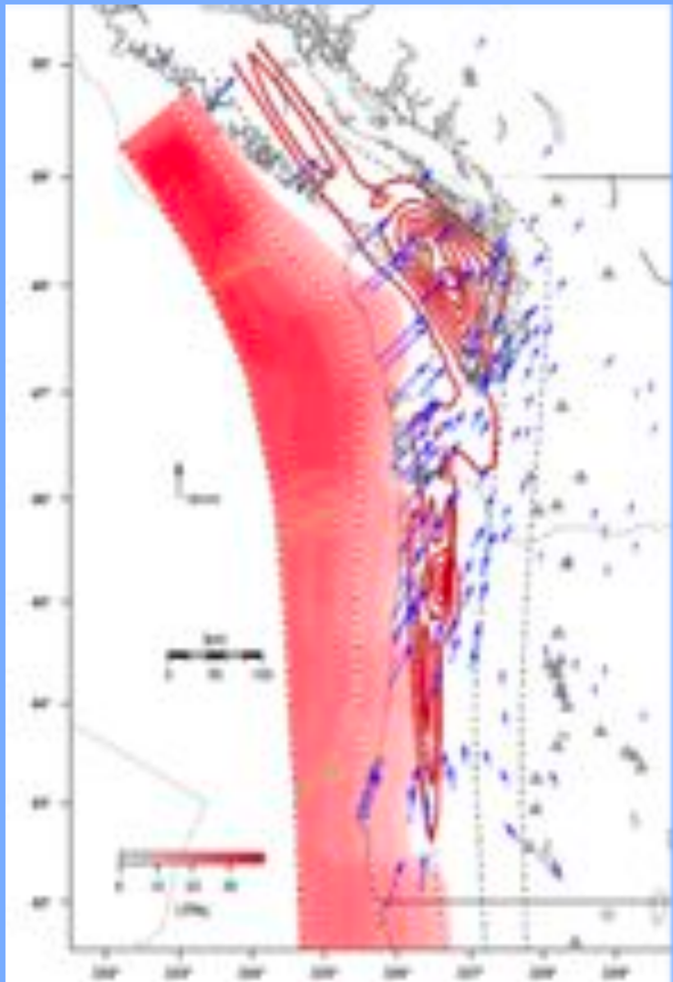
Cascadia



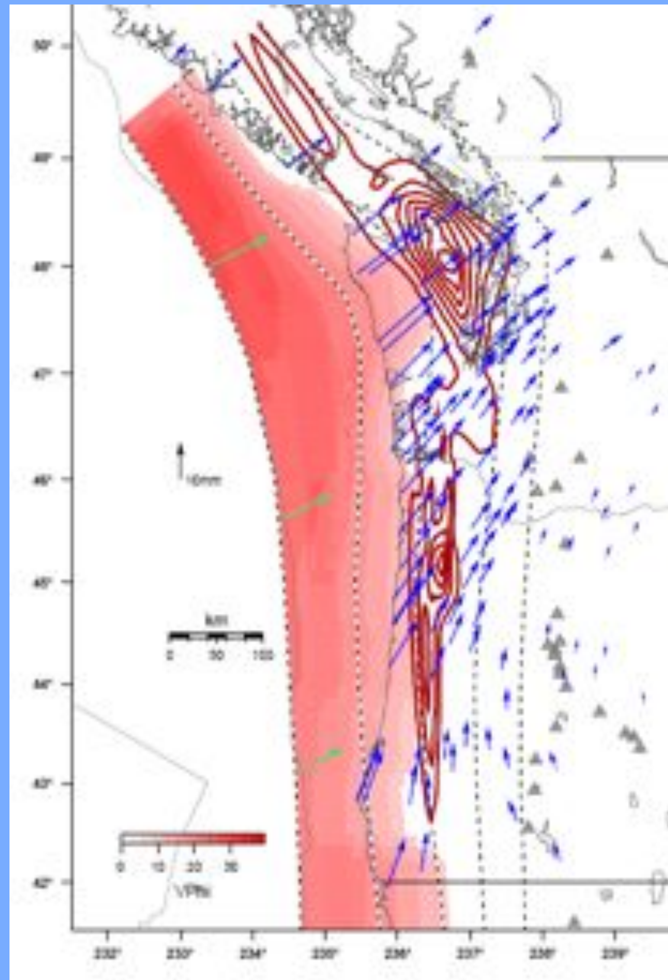


Campaign locking model

Average locking distribution

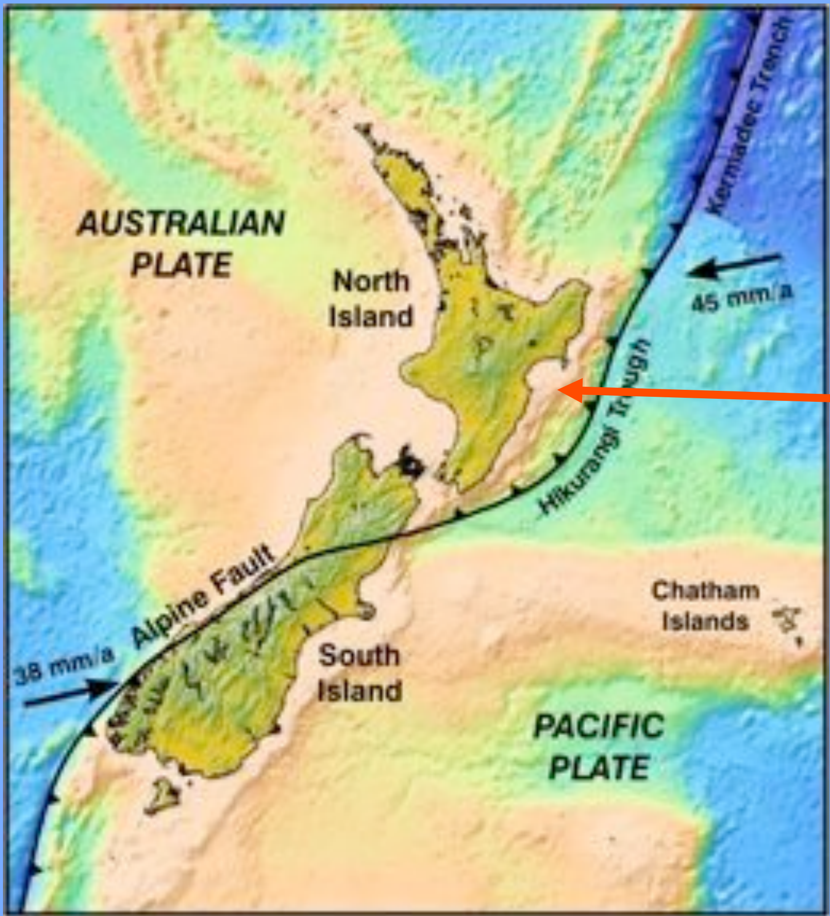


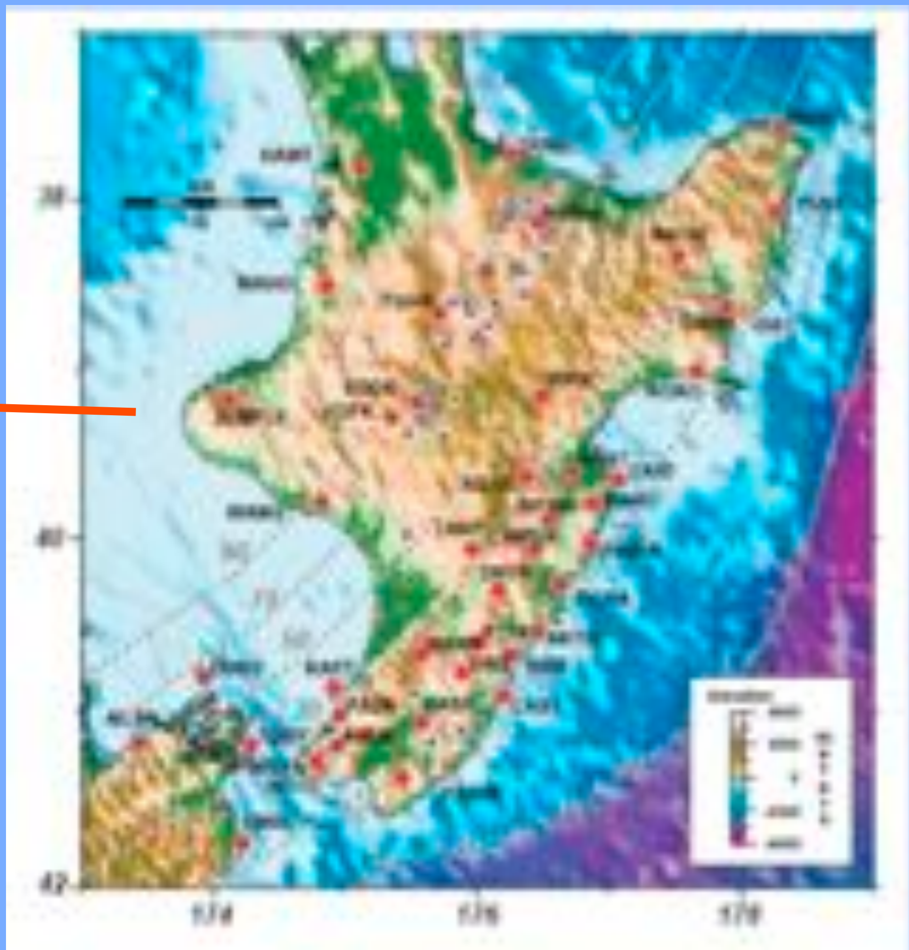
Locking between slip events



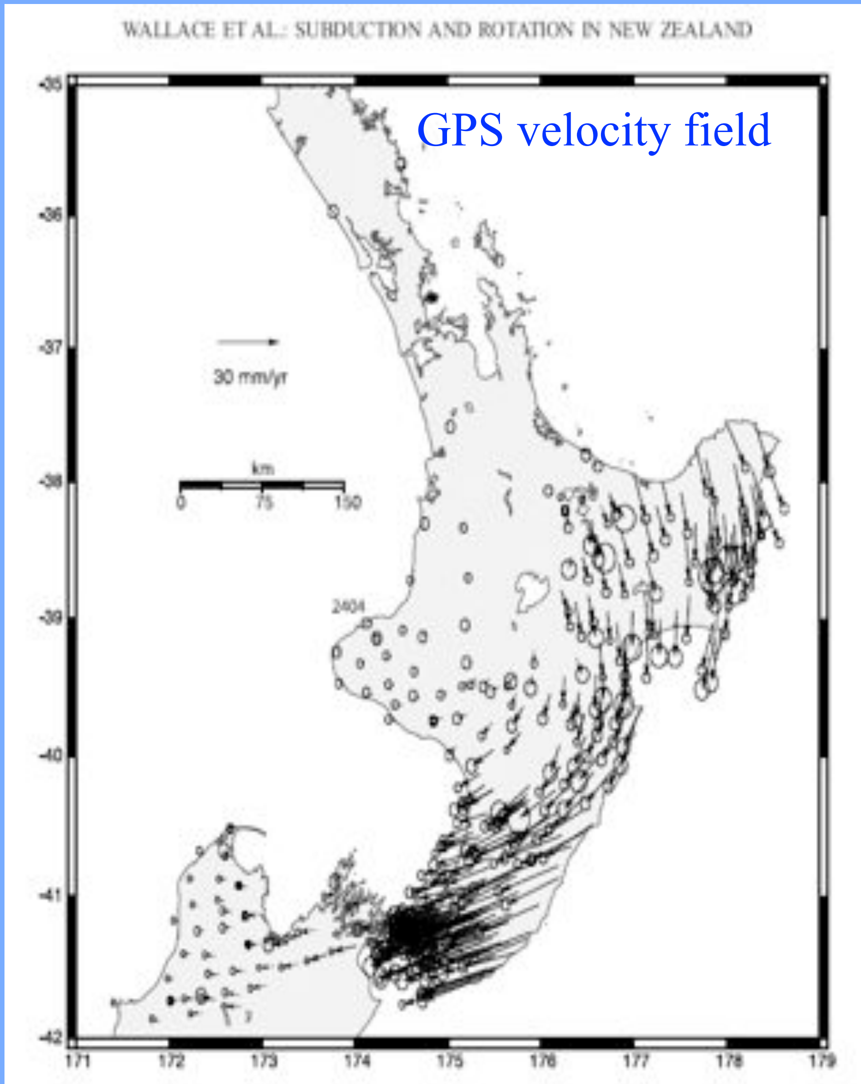
Contours are slow slip in 50 mm intervals.

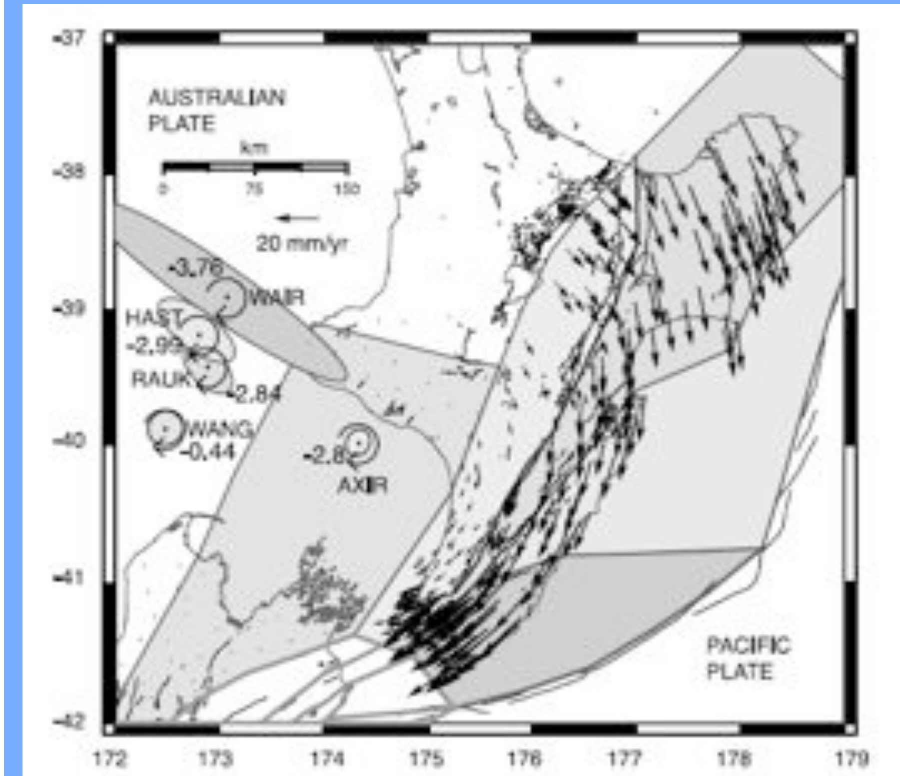
Hikurangi subduction zone, New Zealand





GeoNet - geonet.cri.nz

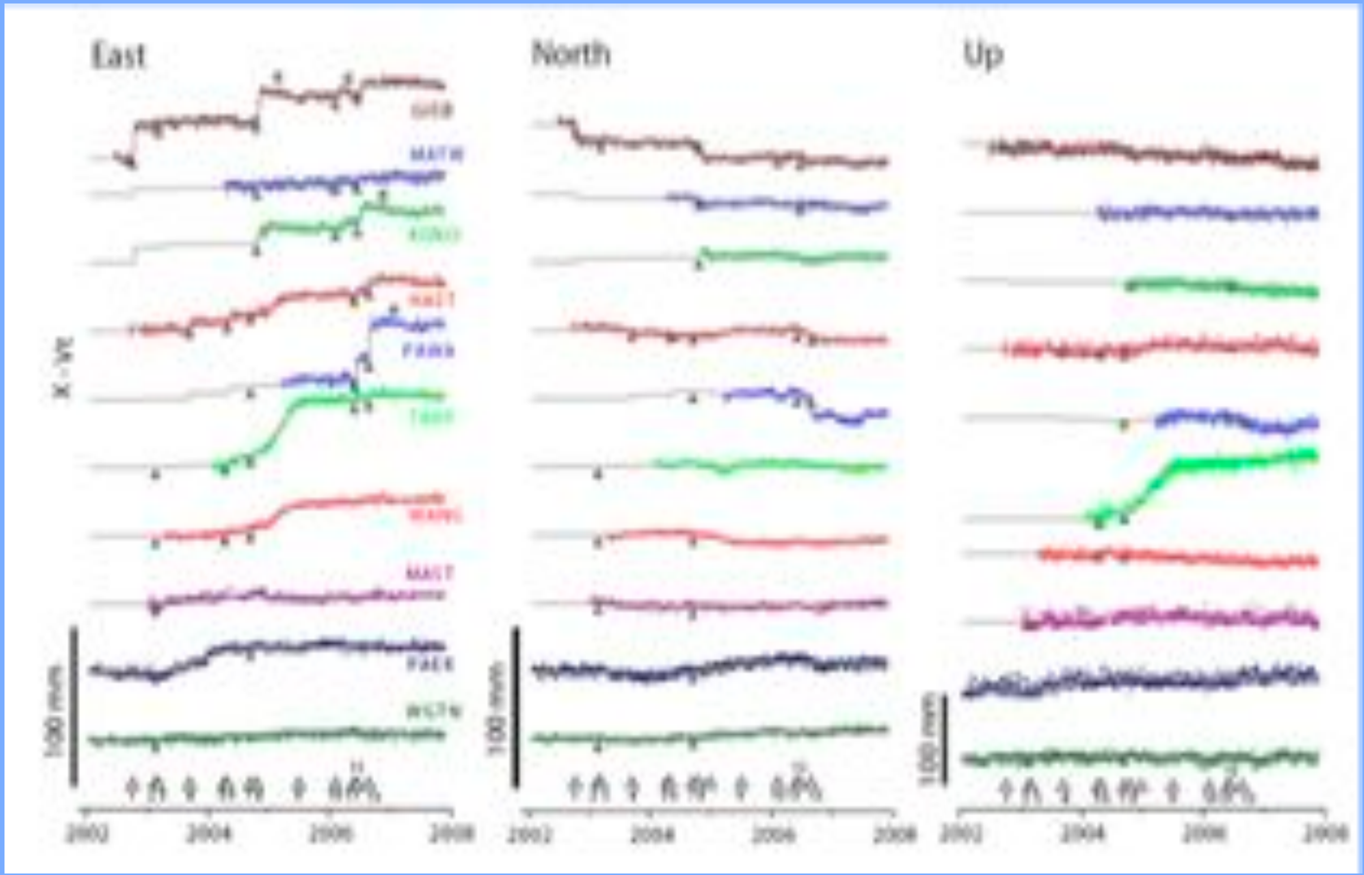




Rotational velocity field

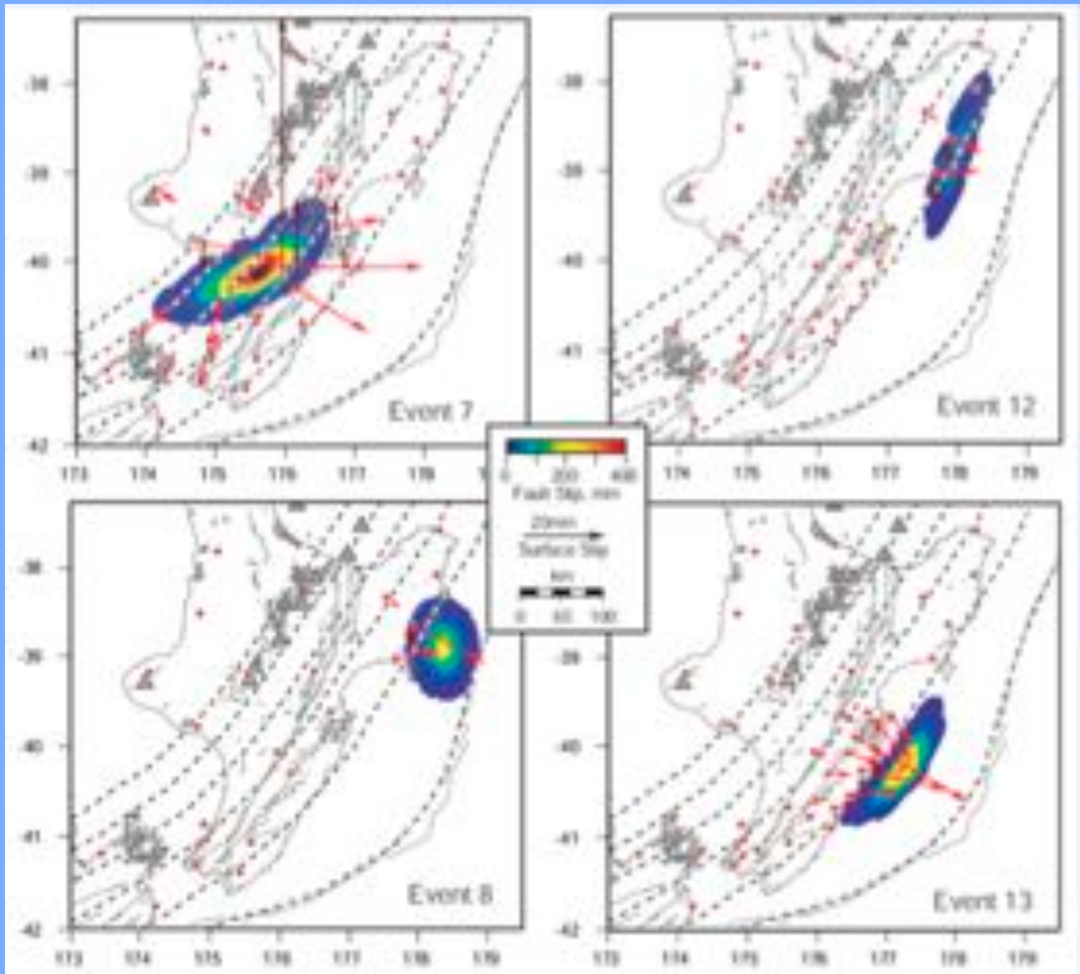
(Wallace et al 2004)

GeoNet continuous GPS show mixture of short- and long-duration events, superimposed in time and space.

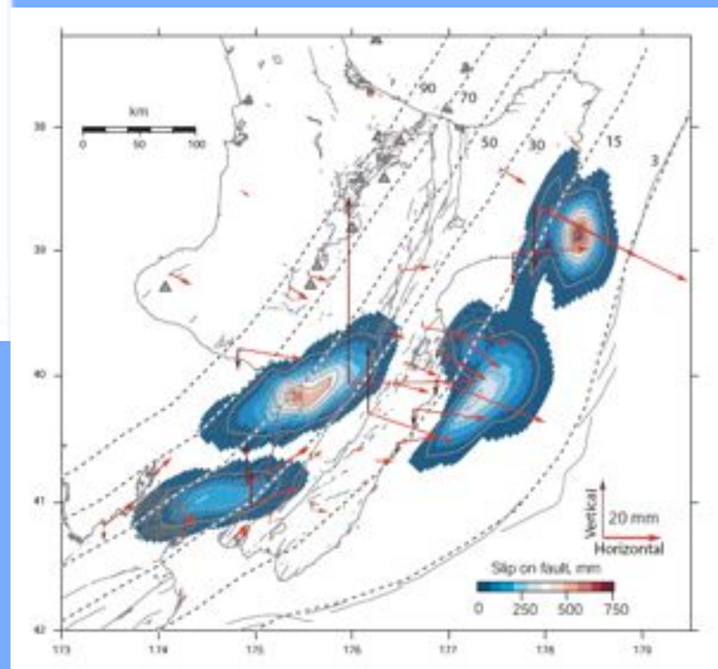


Model slow-slip events with Gaussian slip rate time histories and slip distributions.

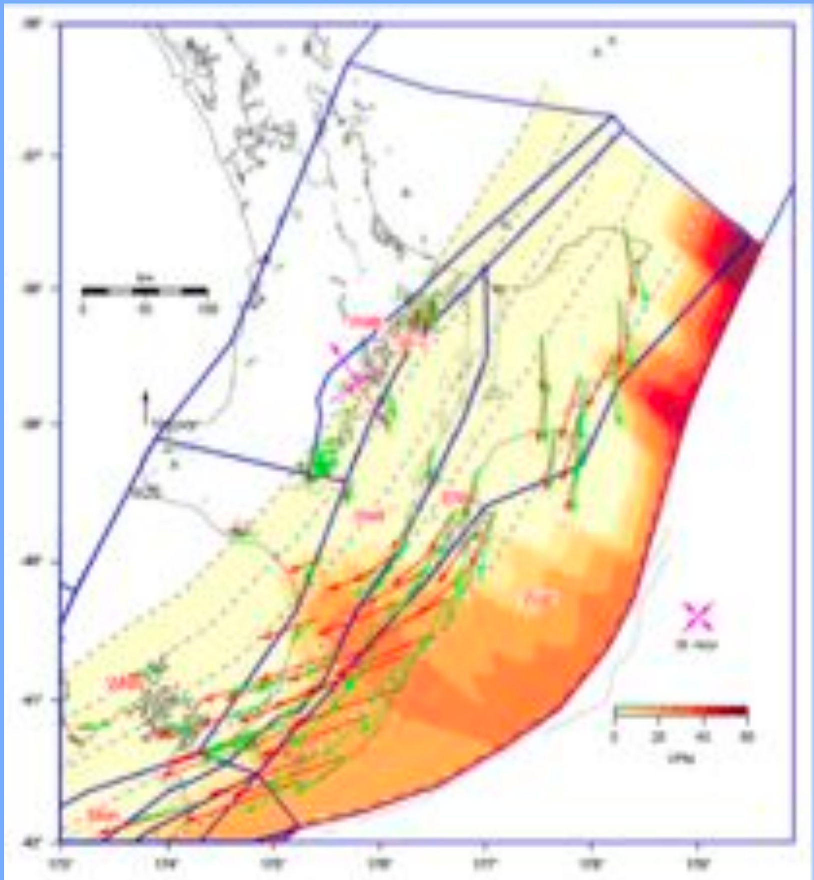
Simultaneously solve for block rotations and inter-seismic (and inter-SSE) locking.



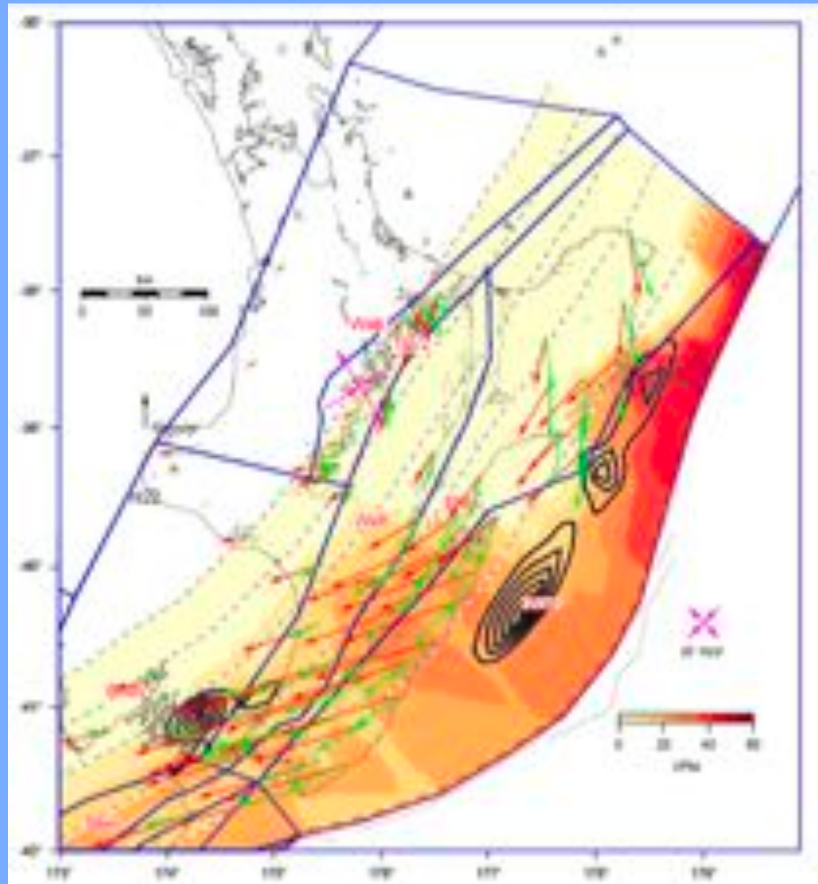
Total slip in all events



Examples of slip distributions in slow slip events.



Solution without transients (long-term)

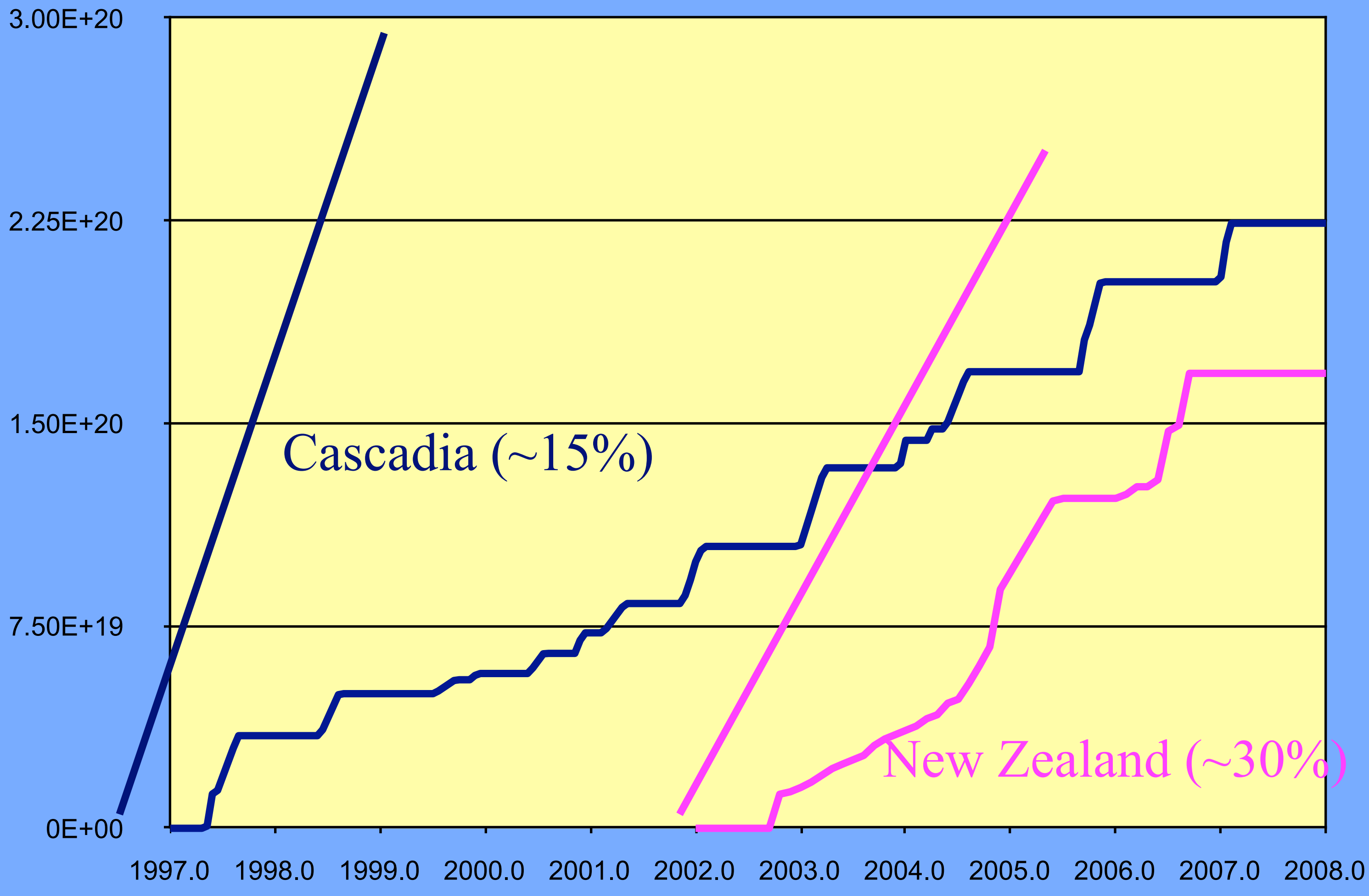


Solution with transients (inter-SSE)

Potency rates = *LWv;* x 10^9 m^3/yr
Long-term geodetic: 1.6
Inter-SSE: 2.3
SSE: 0.7
Tectonic: 4.8 (L=880 km, W=140 km, v=40 mm/yr)

Slow-slip accounts for about 15% of ‘theoretical’ moment release; 30% of moment accumulation rate

Cumulative moment buildup by locking and release in slow slip



Monday, November 1, 2010

Along-strike variations in short-term slow slip events in the southwest Japan subduction zone

Shutaro Sekine,[1,2] Hitoshi Hirose,[1] and Kazushige Obara[1,3]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, B00A27, doi:10.1029/2008JB006059, 2010

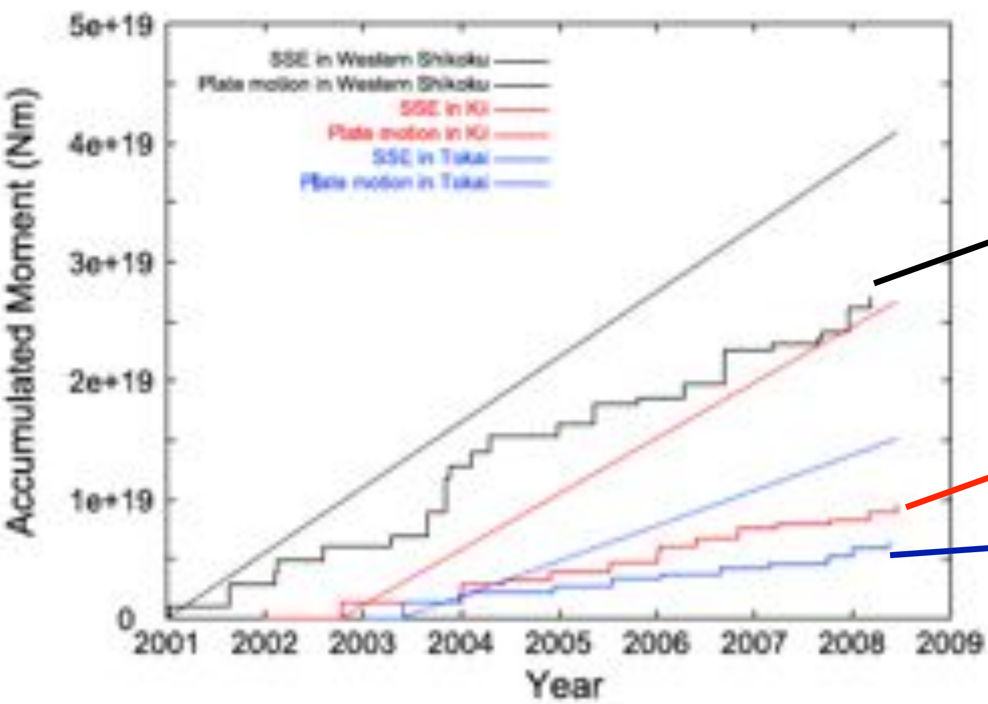
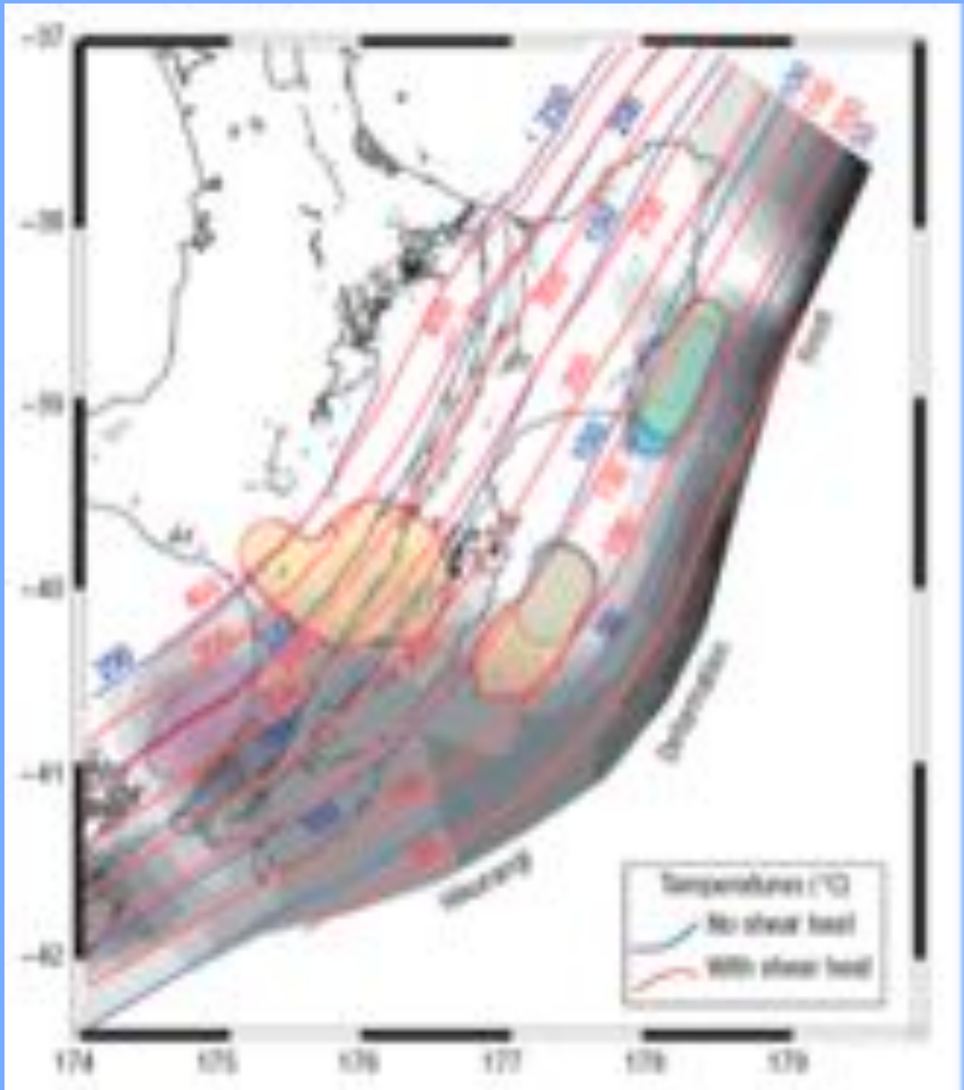


Figure 8. Estimated cumulative moment release of SSEs in three regions: western Shikoku, northeastern Kii, and Tokai. The three bold lines are cumulative moments of estimated SSEs for each region. The dashed lines denote the moments accumulated from the plate motion of the subducting PHS against the Amurian Plate with a convergence rate of 6.2 cm/yr [*Heki and Miyazaki*, 2001].

68% W Shikoku

30% Kii

40% Tokai

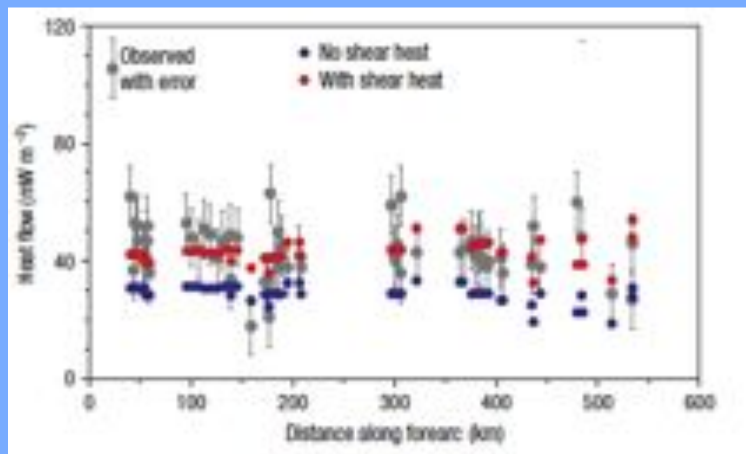


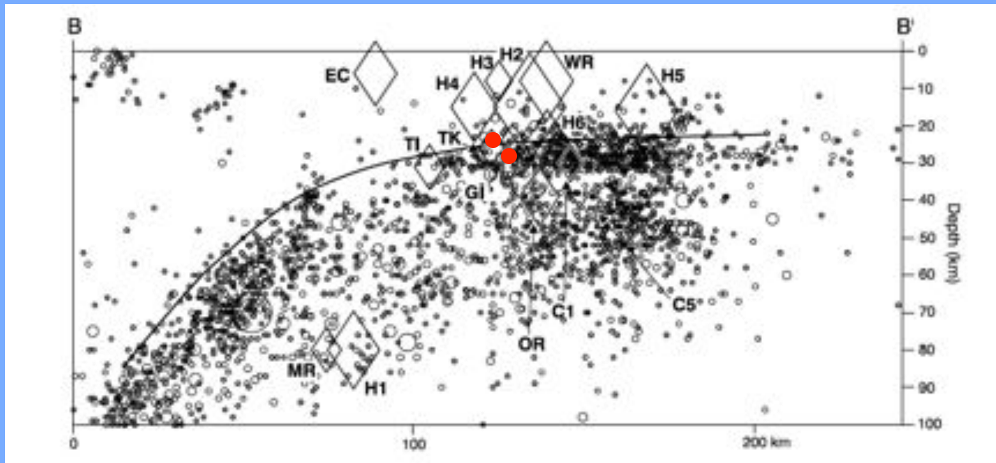
McCaffrey, Wallace and Beavan, Nature Geocsci, 2008.

A word about temperature control on the stability transition

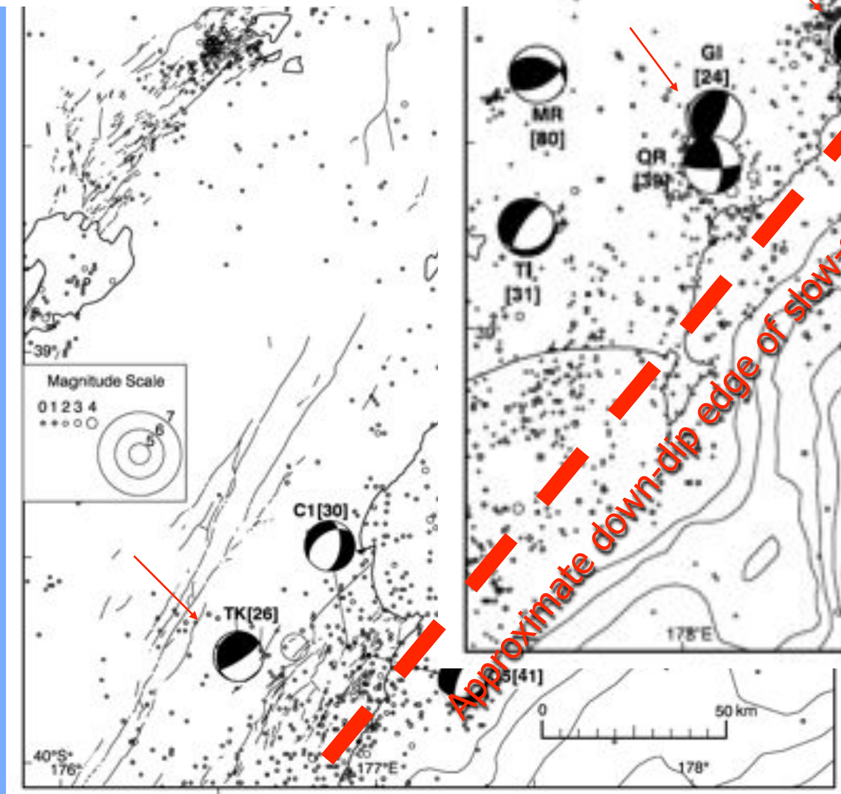
Estimated temperatures along plate interface from incoming plate age, convergence rate, etc.

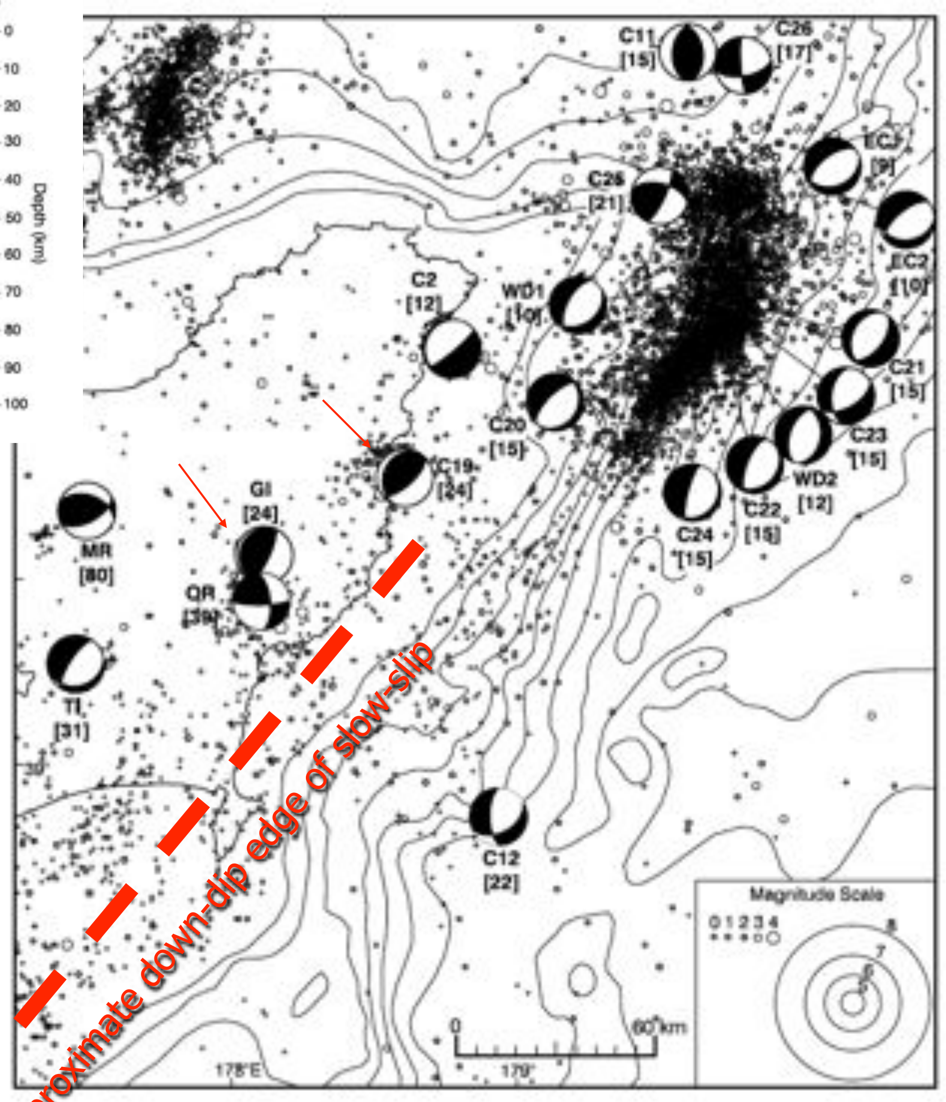
Even with shear heating, temperatures where slow-slip occurs are much less than predicted for the stability transition by lab experiments and inferred at other subduction zones.





Interplate (?) thrust earthquakes down-dip of slow-slip zone





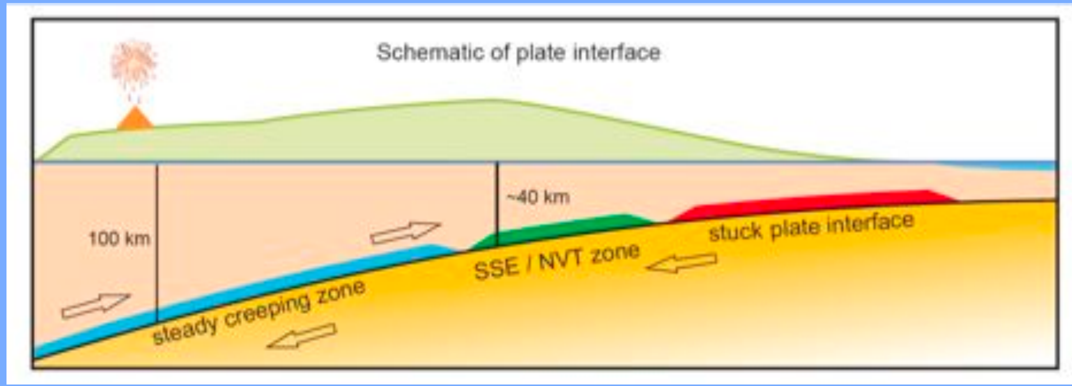
Focal mechanisms of large earthquakes in the North Island of New Zealand: slip partitioning at an oblique active margin

Terry H. Webb[1] and Helen Anderson[2]

Source parameters of large historical (1917–1961) earthquakes, North Island, New Zealand

Diane I. Doser[1] and Terry H. Webb[2]

Conclusions



- Slip in SSEs appears to extend up-dip of NVT
- SSE and NVT are related but not exactly the same process (they can occur together or separately)
- NVT not revealing the entire stability transition zone