From the earthquake cycle to mantle structure – current and future uses of dense GPS

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PY09: GNSS-derived Troposphere Delays & Applications of IGS Products for Geodesy and Geophysics Research

From the earthquake cycle to mantle structure – current and future uses of dense GPS

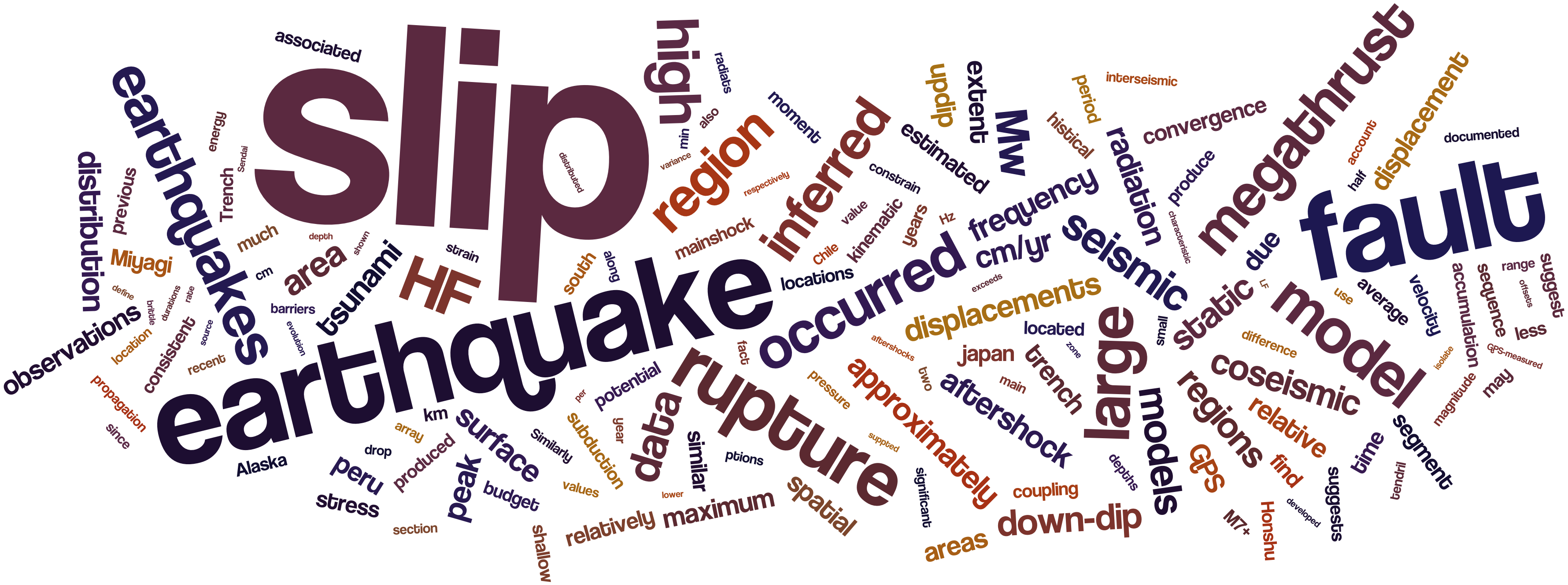
- Using data from O(10^3) sites in Japan for inter-/co-/post-seismic deformation associated with the 2011 Mw 9 Tohoku-oki, Japan earthquake
- Using Earthscope/PBO to image aseismic transients and their relationship to tremor
- Using dense networks to measure the response to ocean tidal loads and thus constrain depth variations in elastic and density parameters in the upper mantle.

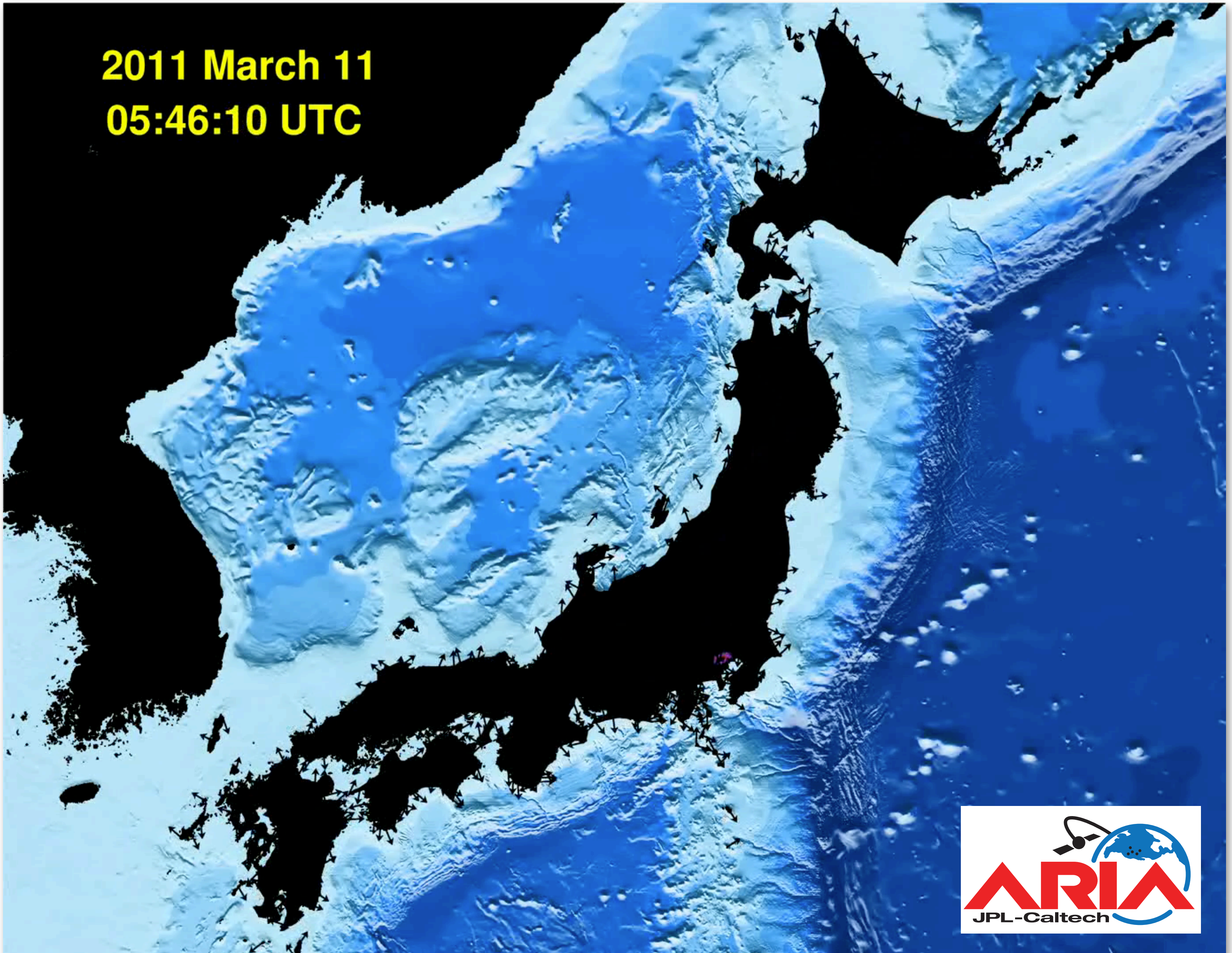
Seismogenic Behavior of Subduction Megathrusts

A sampling of important intertwined questions

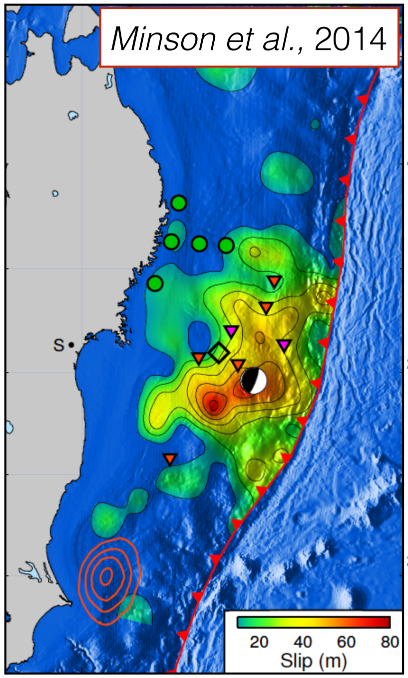
Time Scale

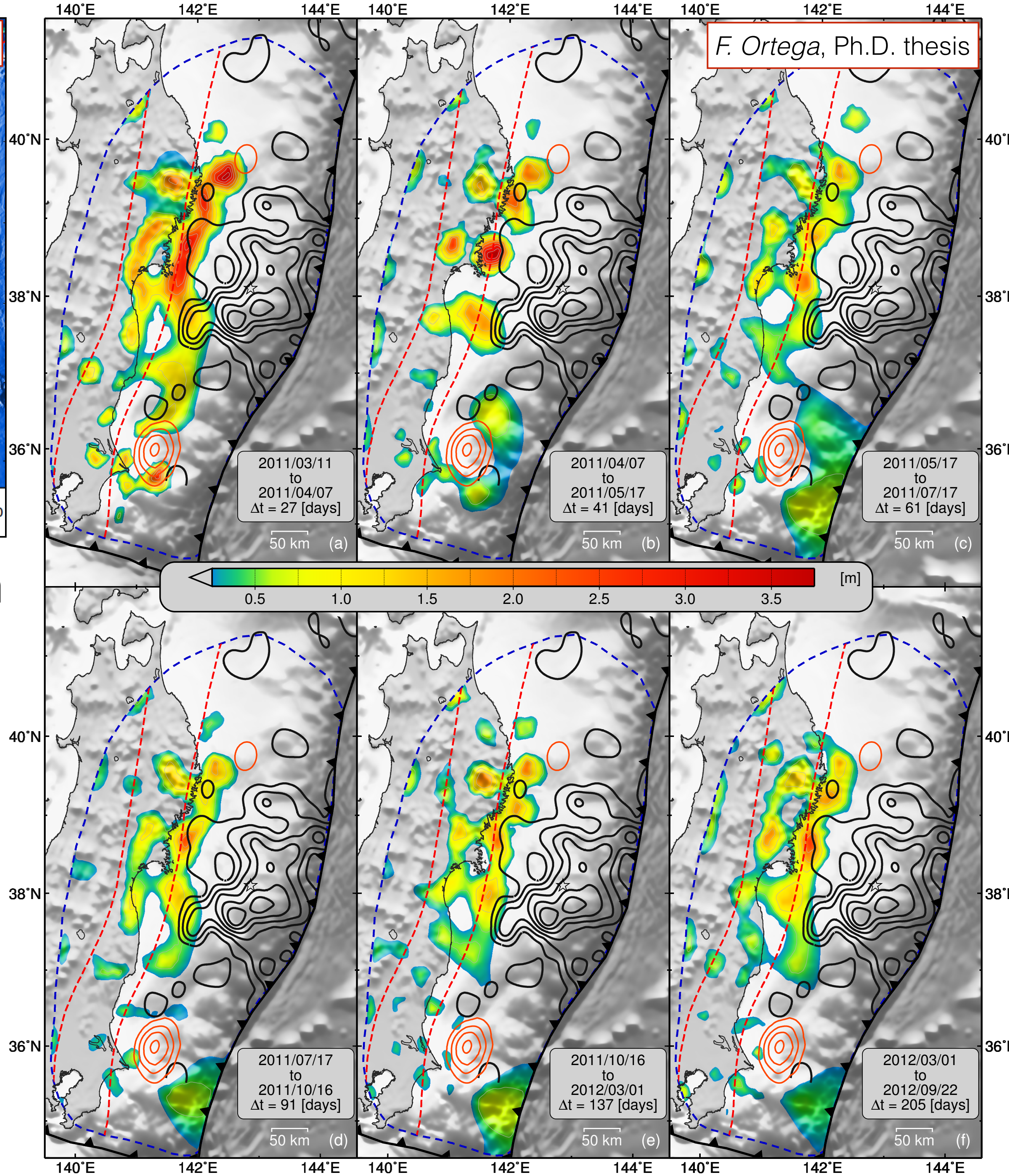
- Do major seismogenic "asperities" only slip seismically?
- Do creeping segments only creep?
- Role of conditional stability (e.g., near trench)?
- What are the relationships between post-seismic creep, transients, tremor and seismicity (rate, repeat intervals, location…)?





1 sample/sec GPS observations - sidereally filtered





2011 Tohoku-Oki, Japan

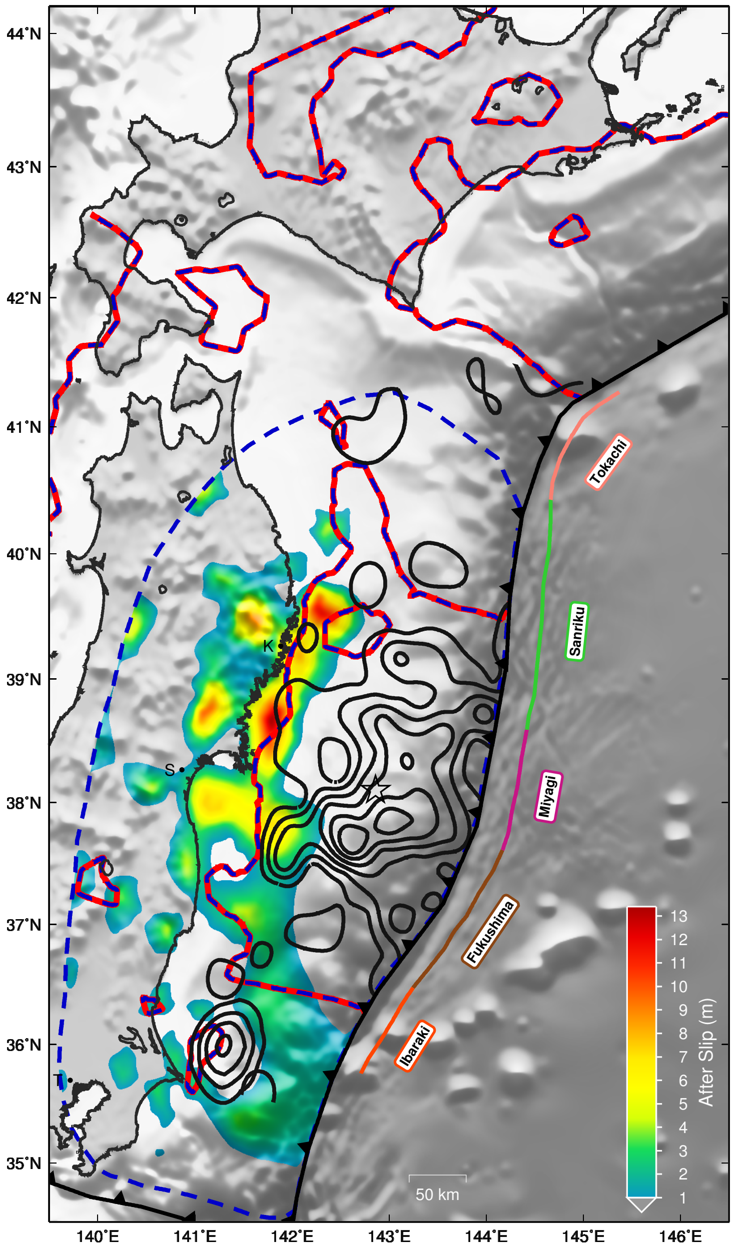
Co-seismic slip:

- 1sec GPS, DART, seafloor geodesy
- 80 m peak slip over a small region
- M7.8 aftershock

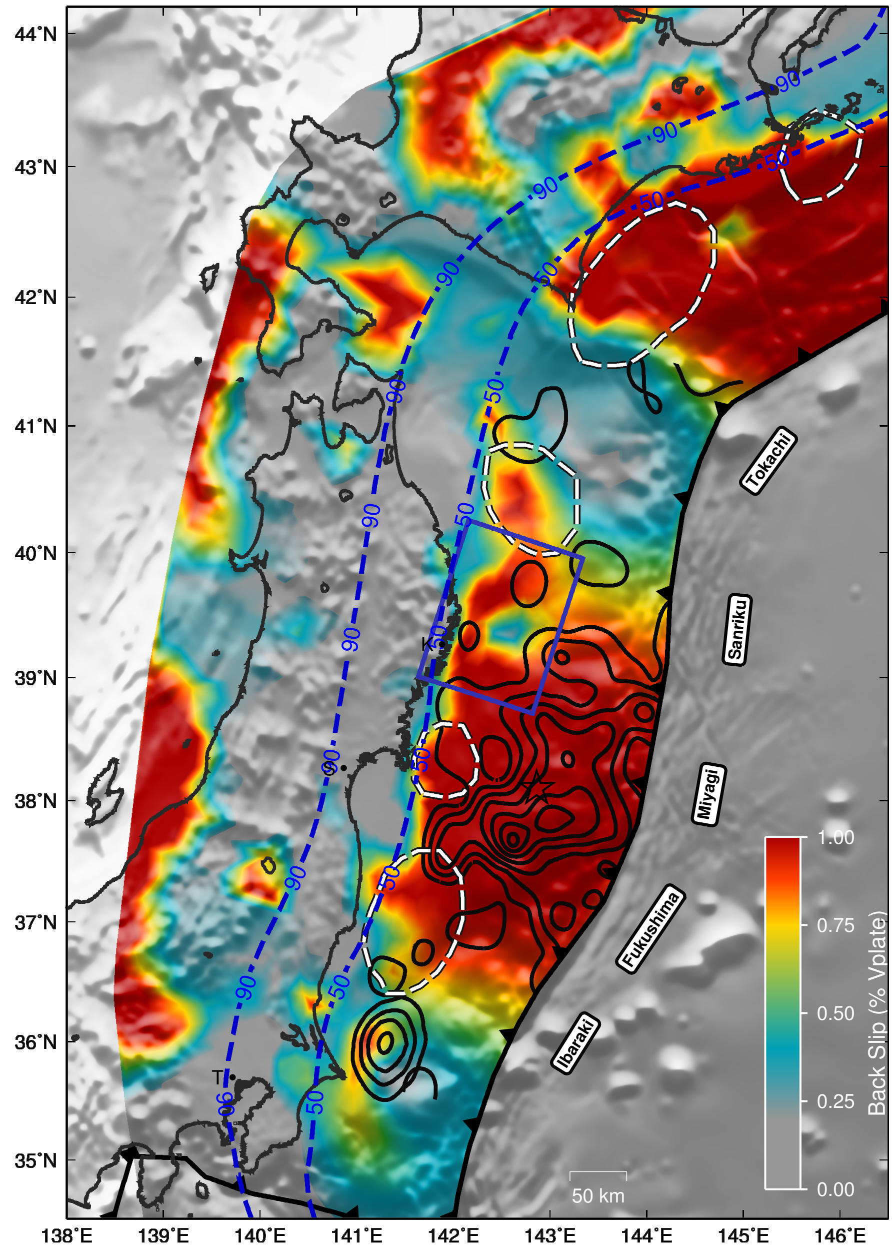
Post-seismic afterslip:

- Total time = 1.5 years
- Negligible overlap of co-/post-seismic
- Post-seismic pattern ~constant

Post-seismic (1.5 yrs)

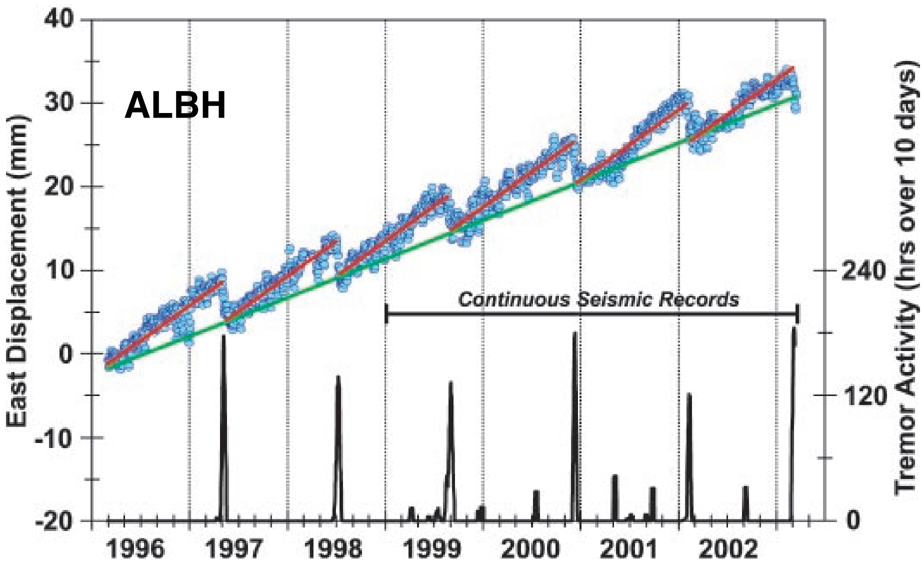


Inter-seismic



F. Ortega, Ph.D. thesis

Slip transients and Tremor: Cascadia



Rogers and Dragert (2003)

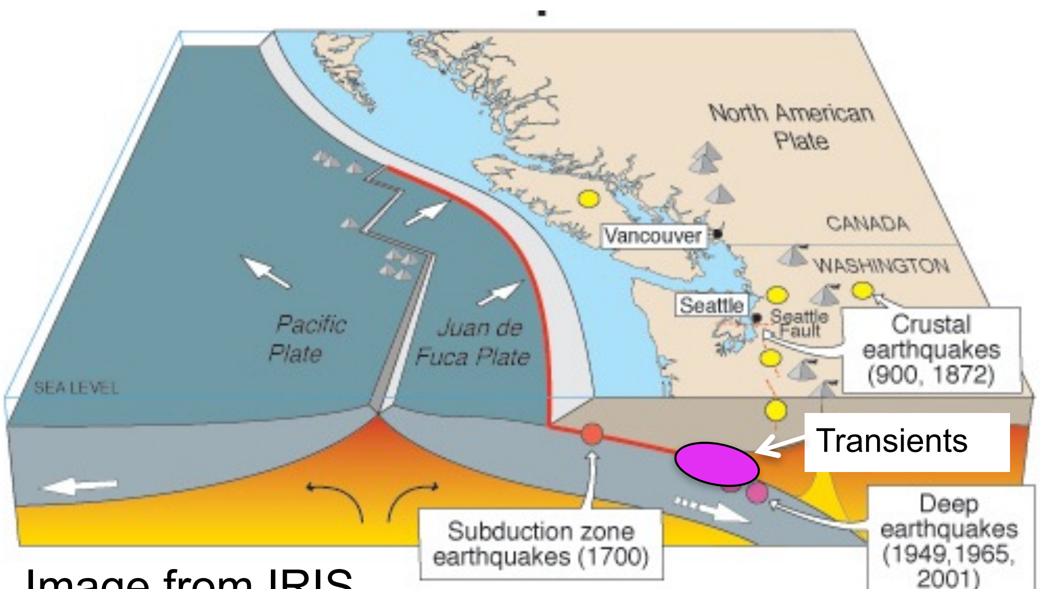
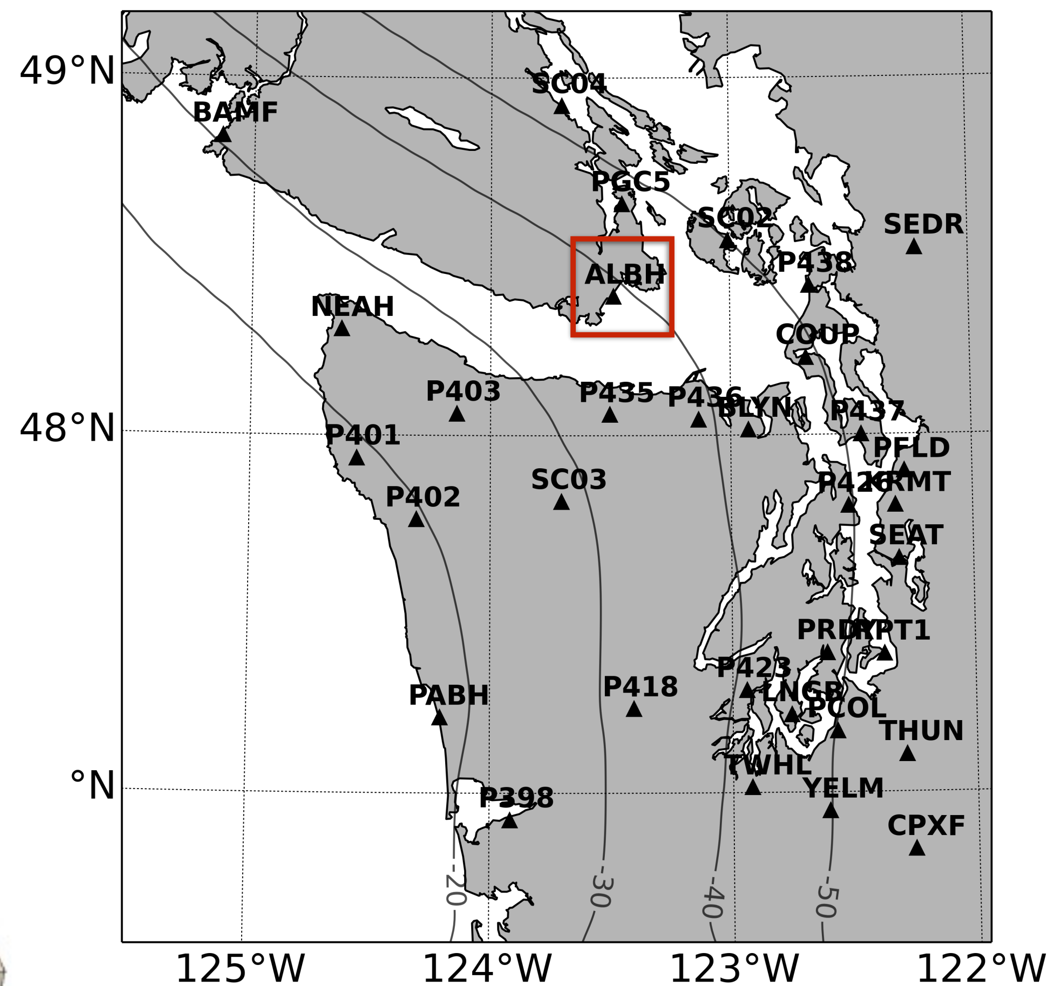


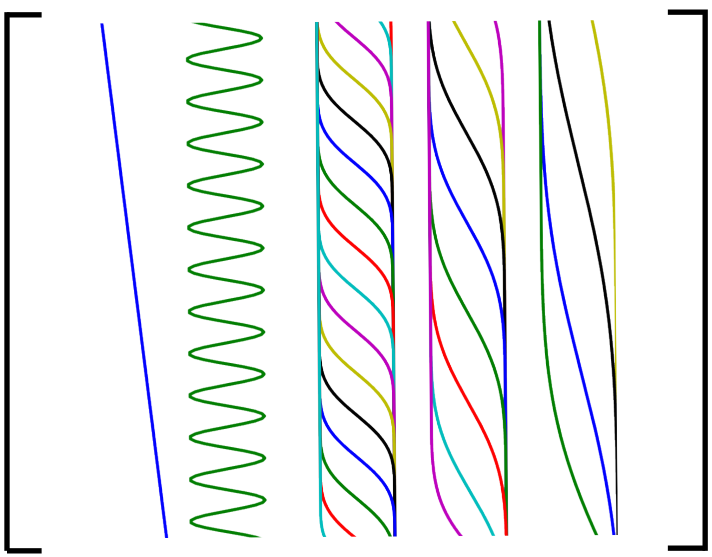
Image from IRIS



Finding Transients

- With no *a priori* information on the physical mechanisms responsible for transients, we cannot only assume time functions corresponding to specific physical descriptions, i.e. exponential or logarithmic decay
- Use a flexible time parameterization using functions that resemble our expectation of transients (*over-complete dictionary* of “behaviors”)
- Secular and periodic components + integrated 3rd-order B-splines of different scales and center times (not orthogonal)

$\mathbf{G}_{NxP}$ $\mathbf{m}_{Px1}$ $\mathbf{d}_{Nx1}$



$$\begin{bmatrix} m_0 \\ m_1 \\ \vdots \\ m_{P-1} \end{bmatrix} = \begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_{N-1} \end{bmatrix}$$

Penalize the # of non-zero coefficients in **m**: $\mathbf{m} = \underset{\mathbf{m}}{\text{argmin}} \, \|\mathbf{d} - \mathbf{G}\mathbf{m}\|_2^2 + \lambda \|\mathbf{m}\|_0$

Sparsity-Promoting Regularization

- Penalize the *number* of non-zero coefficients in **m**:

$$\mathbf{m} = \underset{\mathbf{m}}{\operatorname{argmin}} \|\mathbf{d} - \mathbf{G}\mathbf{m}\|_2^2 + \lambda \|\mathbf{m}\|_0$$

  where $\| \cdot \|_0$ = L_0-pseudo-norm, or the "counting norm"

- **Sparse-compression**: represent time series by a small set of B^i-splines

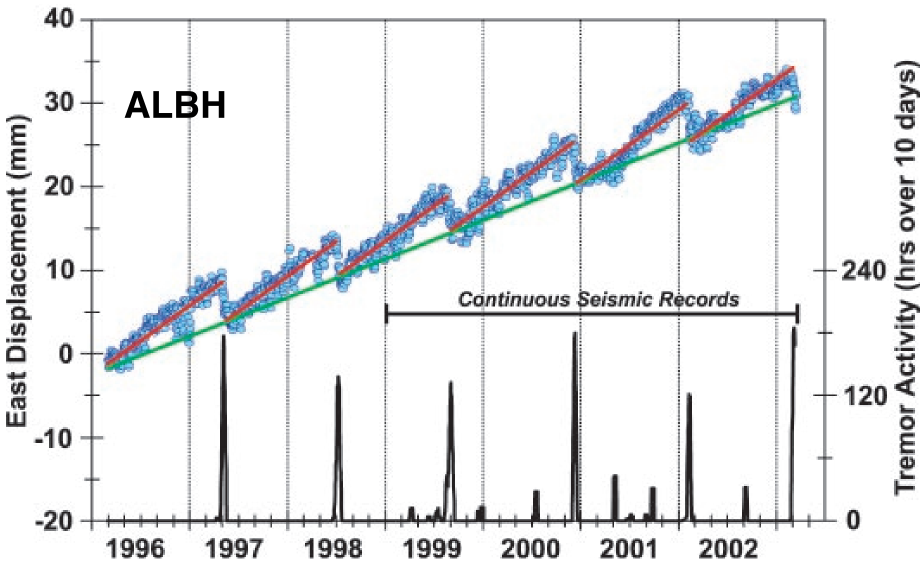
- But using the L_0-pseudo-norm is a hard combinatorial problem

- Use L_1-norm relaxation (iterative reweighting) to make problem convex (Candes et al., 2007):

$$\mathbf{m} = \underset{\mathbf{m}}{\operatorname{argmin}} \|\mathbf{d} - \mathbf{G}\mathbf{m}\|_2^2 + \lambda \|\mathbf{m}\|_1$$

$$\|\mathbf{m}\|_1 = \sum_i |m_i|$$

Slip transients and Tremor: Cascadia



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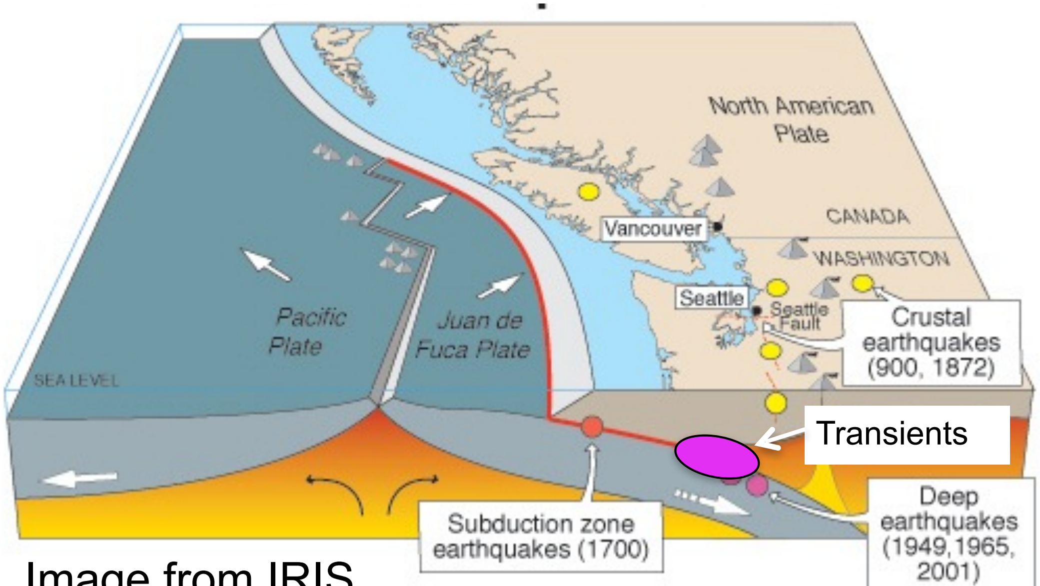

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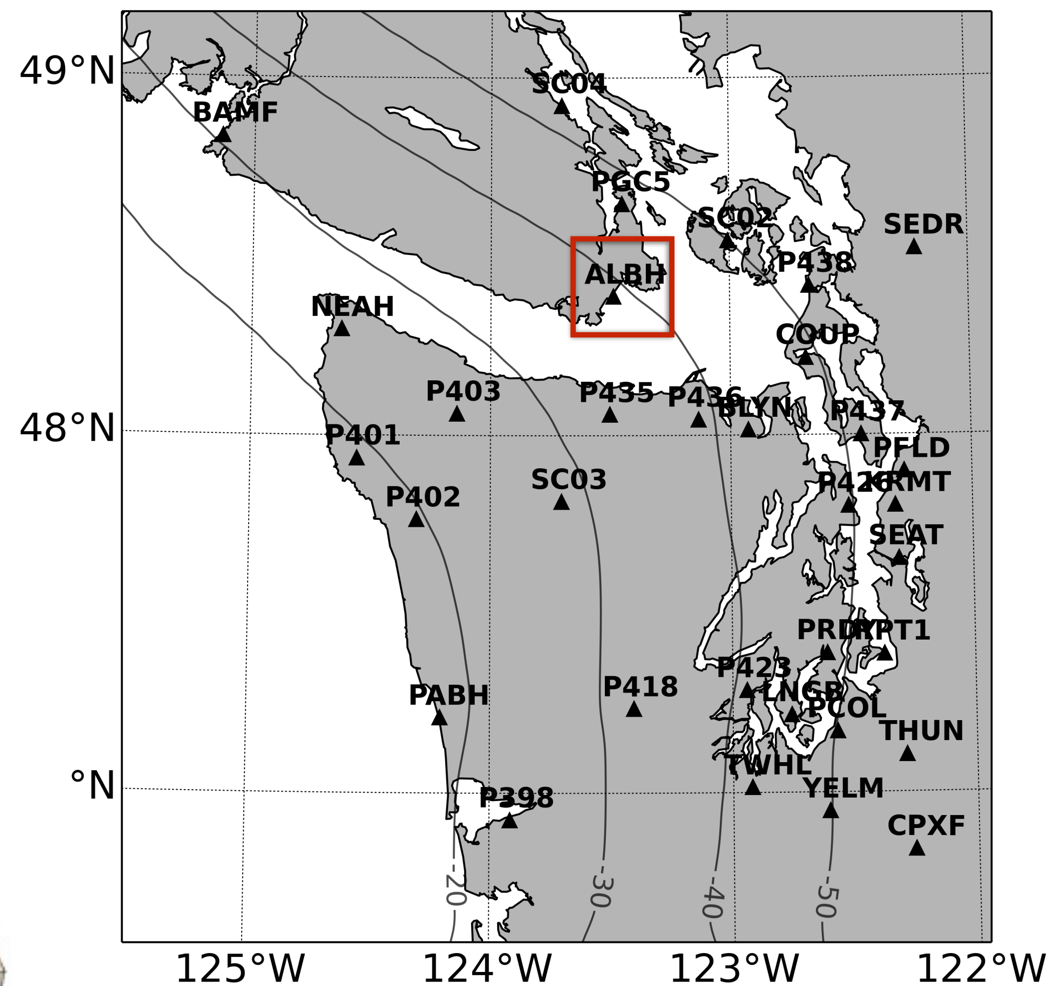
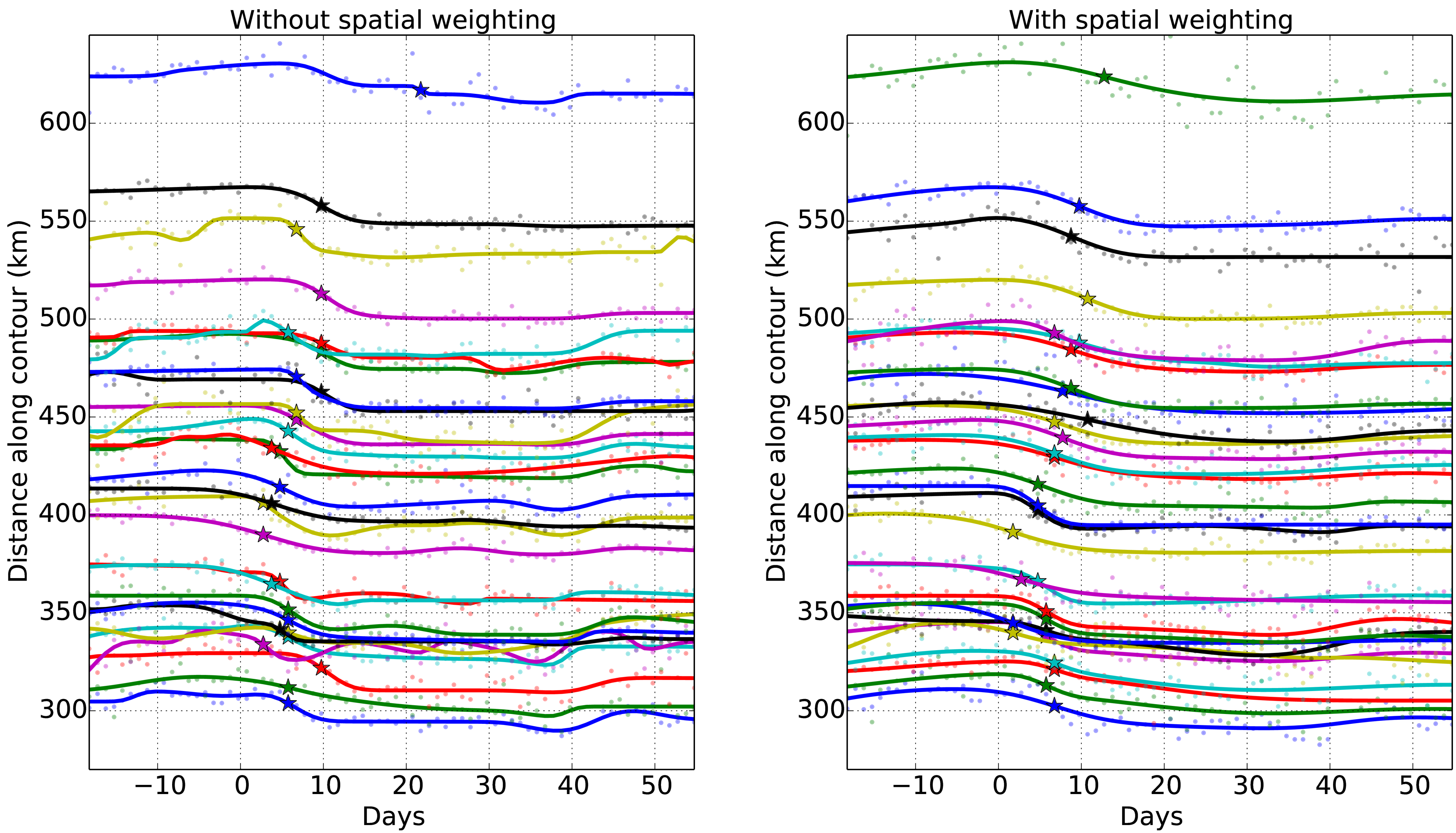


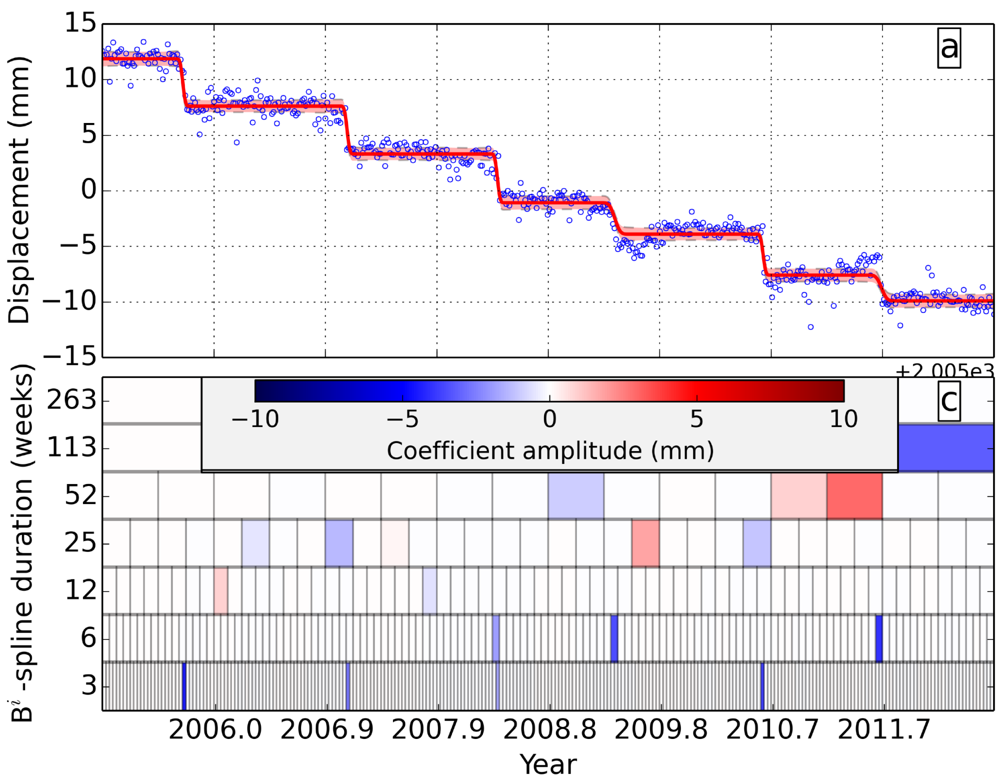
Spatial Sparsity Weighting for Cascadia



ALBH GPS Time Series

- Use sparsity-promoting regularization to fit time series and determine elements of **m** with the largest amplitudes (effectively we are compressing the data)
- Form reduced **G** and estimate reduced **m** using standard least squares:

$$\tilde{\mathbf{m}} = \left(\tilde{\mathbf{G}}^T \mathbf{C}_d^{-1} \tilde{\mathbf{G}}\right)^{-1} \tilde{\mathbf{G}}^T \mathbf{C}_d^{-1} \mathbf{d}$$



← Episodic SSE reconstruction with only 6 B^i-splines

← B^i-spline scalogram: Localized, high amplitudes for short duration B^i-splines

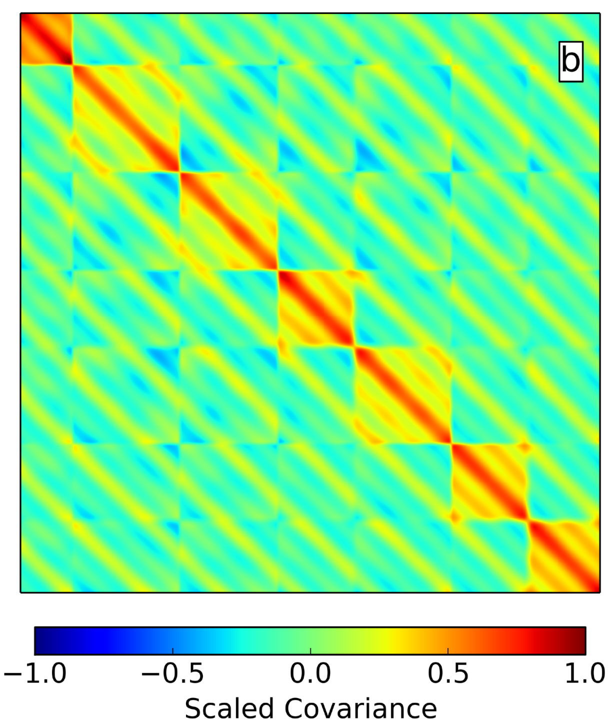
Posterior Uncertainties

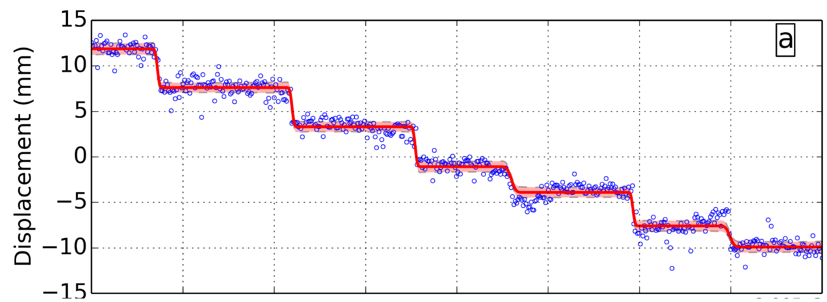
- Standard least squares formulation allows for estimation of posterior covariances for B^i-spline coefficients:

$$\tilde{\mathbf{C}}_m = \left(\tilde{\mathbf{G}}^T \mathbf{C}_d^{-1} \tilde{\mathbf{G}}\right)^{-1}$$

- Extend to posterior covariances for data fit:

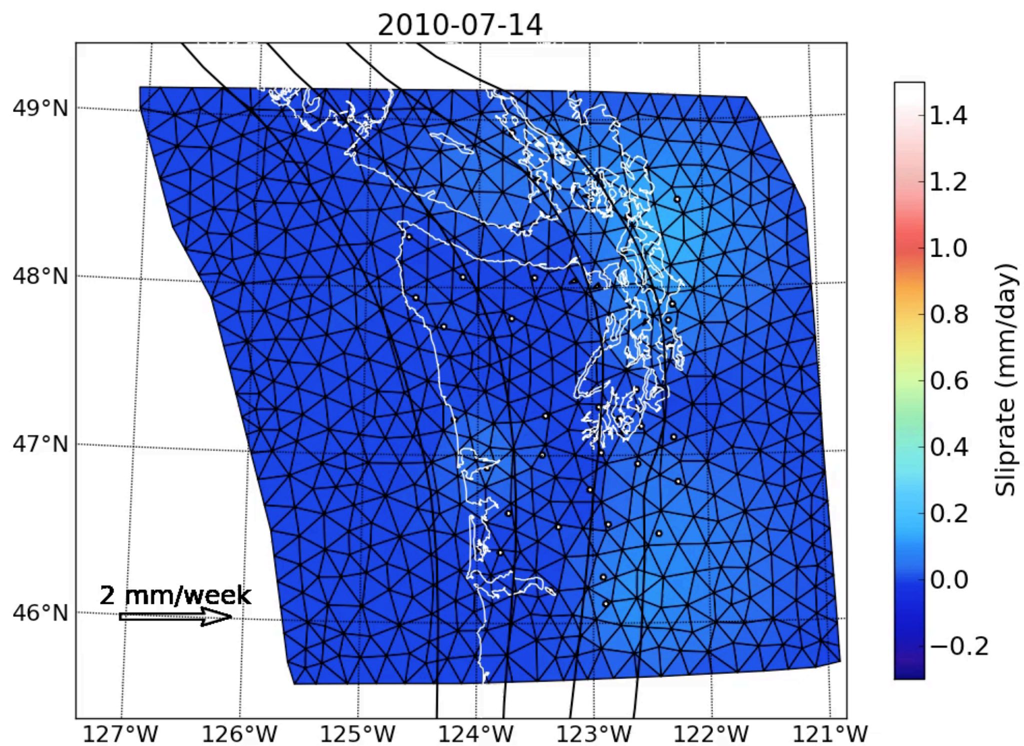
$$\tilde{\mathbf{C}}_d = \tilde{\mathbf{G}}\tilde{\mathbf{C}}_m\tilde{\mathbf{G}}^T$$





← Posterior data covariance matrix for modeled transient displacement

Cascadia 2010 SSE: Slip rate + tremor



Analysis and models: *Bryan Riel*

Issues (not addressed today)

- Controls on location and temporal evolution? Role of fluids? Ubiquitous, yes/no/why?
- Relationship to regions of big EQ and eventual post-seismic deformation?
- Relationship to forearc/slab structure?

Approach

- Detect/reconstruct/model transient ground deformation in GPS time series due to SSE using sparsity-based approaches
- Time-dependent slip using Network Inversion Filter: *Segall and Matthews* (1997)
- Slab interface: *McCrory et al*. (2004)
- Tremor epicenter locations: Pacific Northwest Seismic Network (http://www.pnsn.org/tremor)

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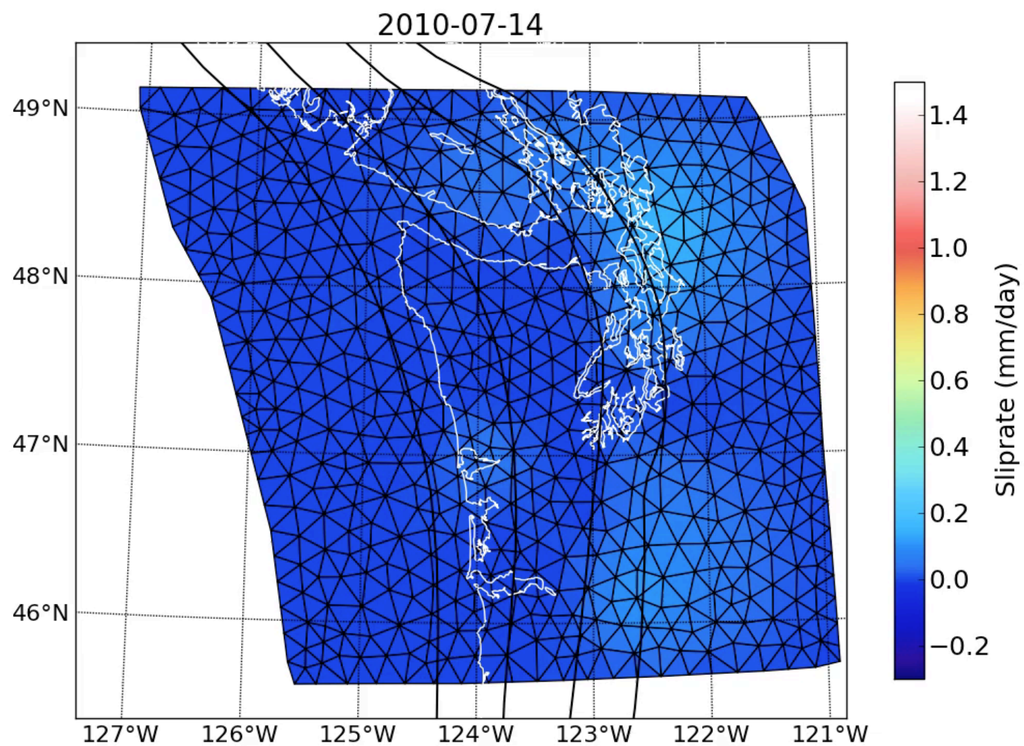

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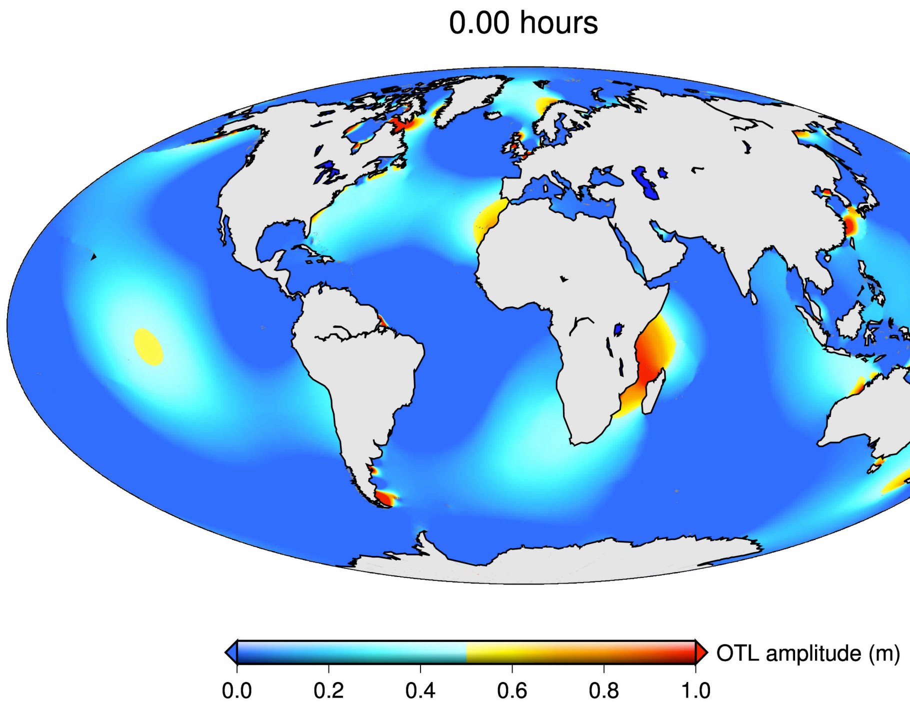
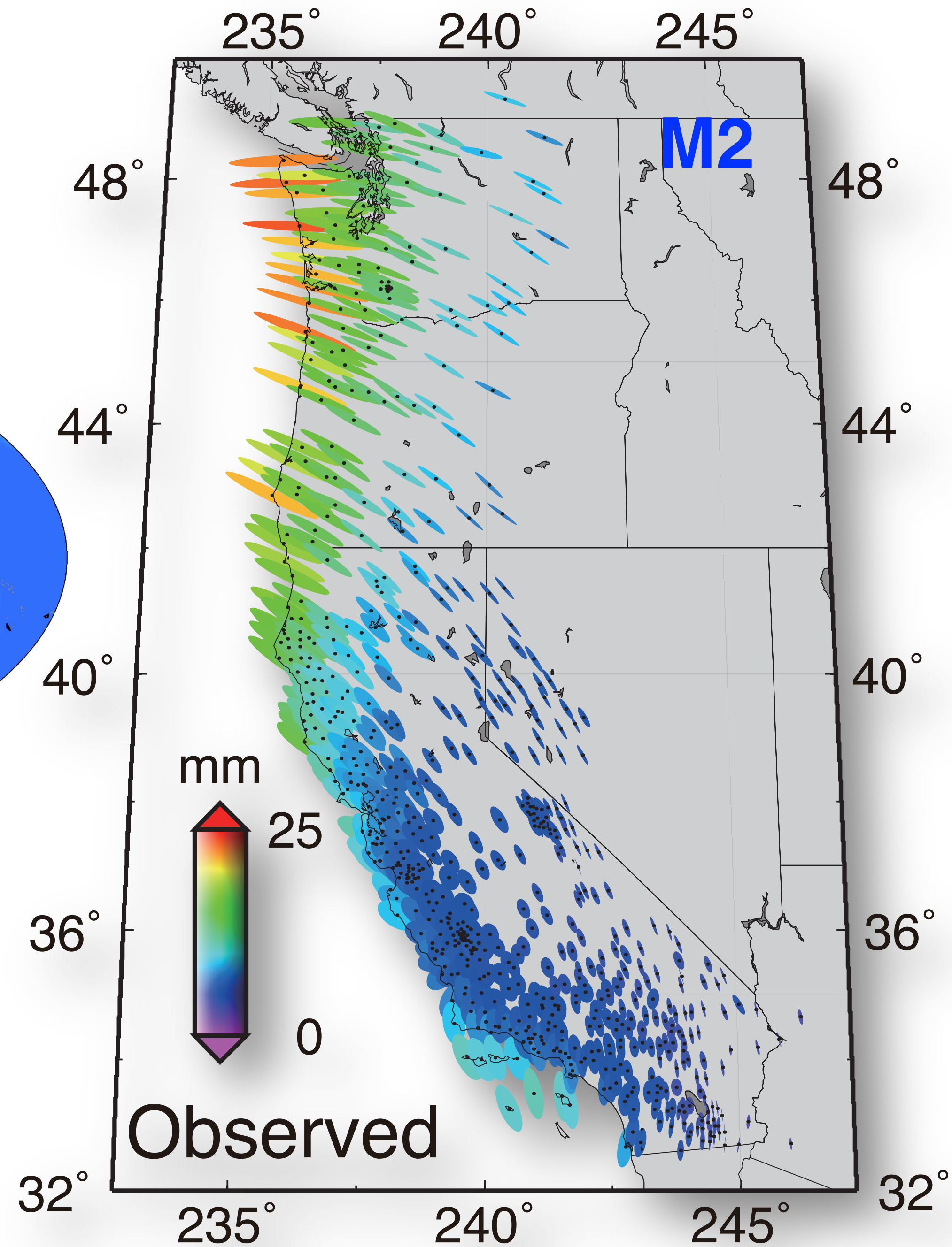
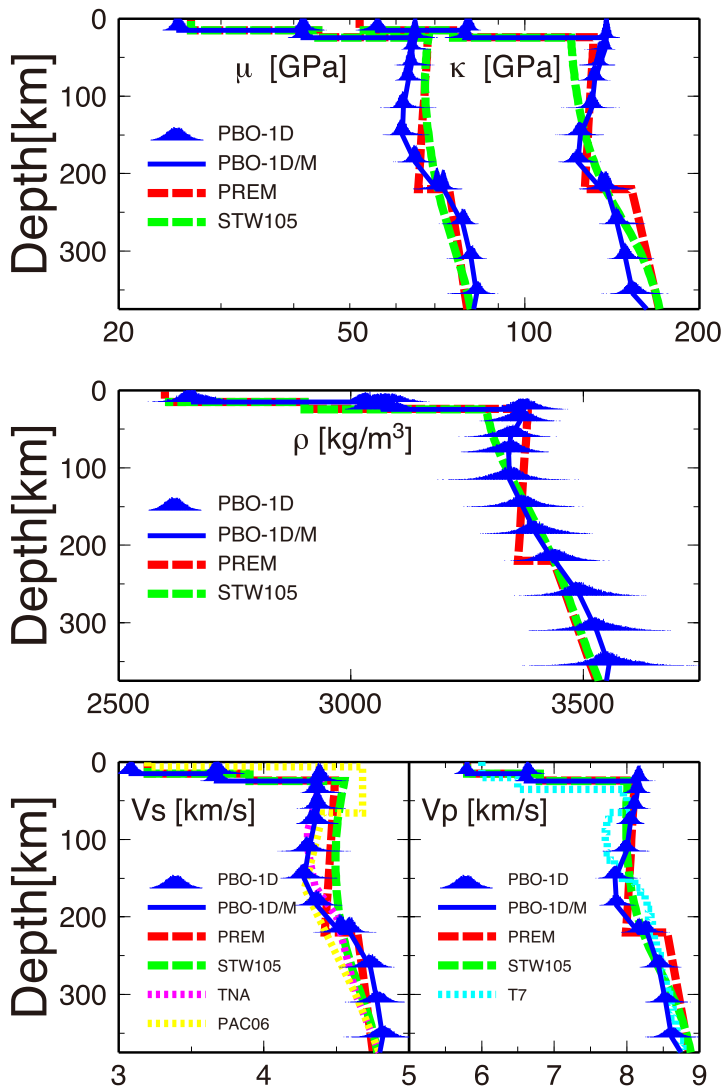
Measuring OTL response with dense GPS networks





Particle motion ellipses (PMEs)

OTL response as an opportunity: Constraining properties of the upper mantle

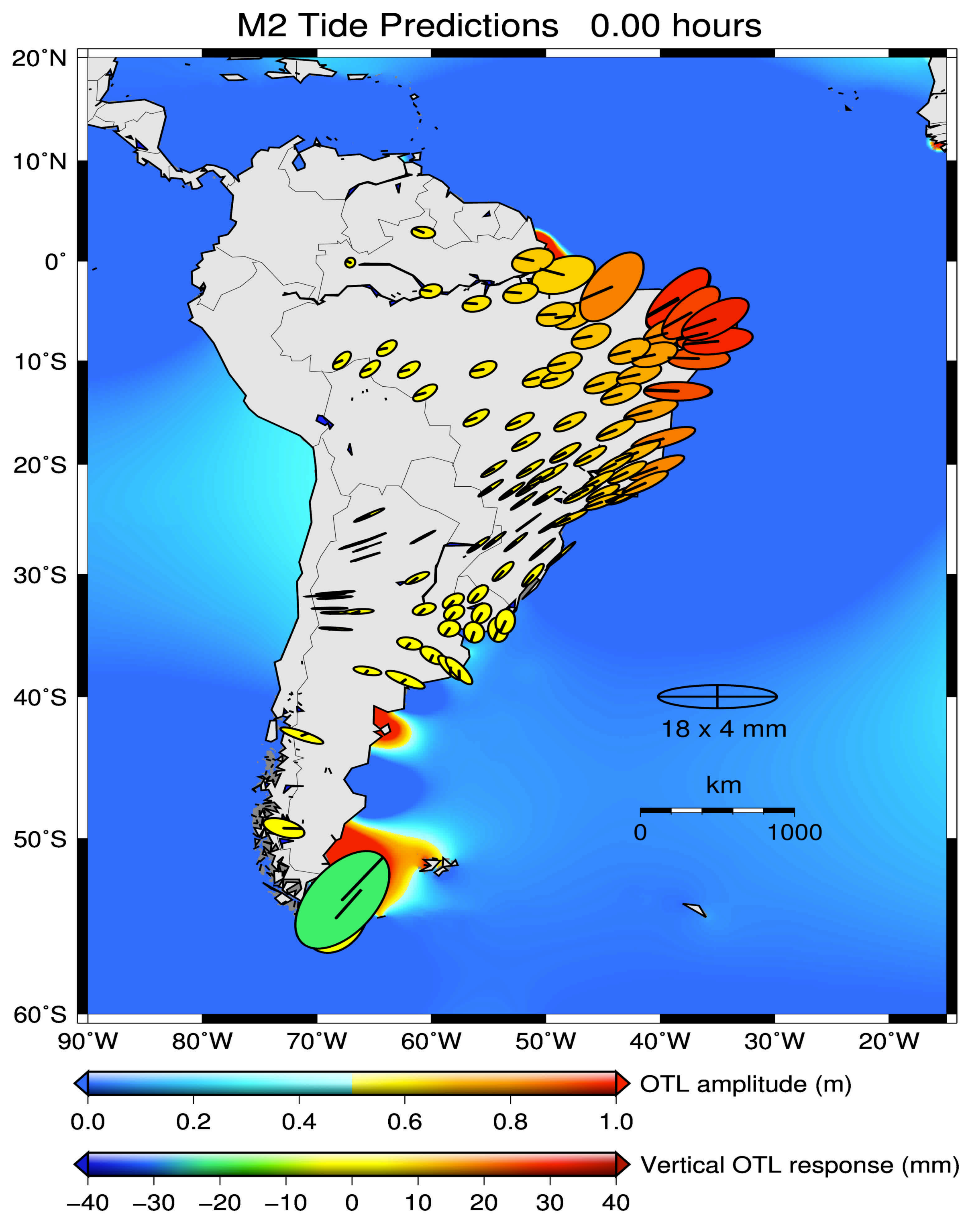


Ito & Simons, 2011

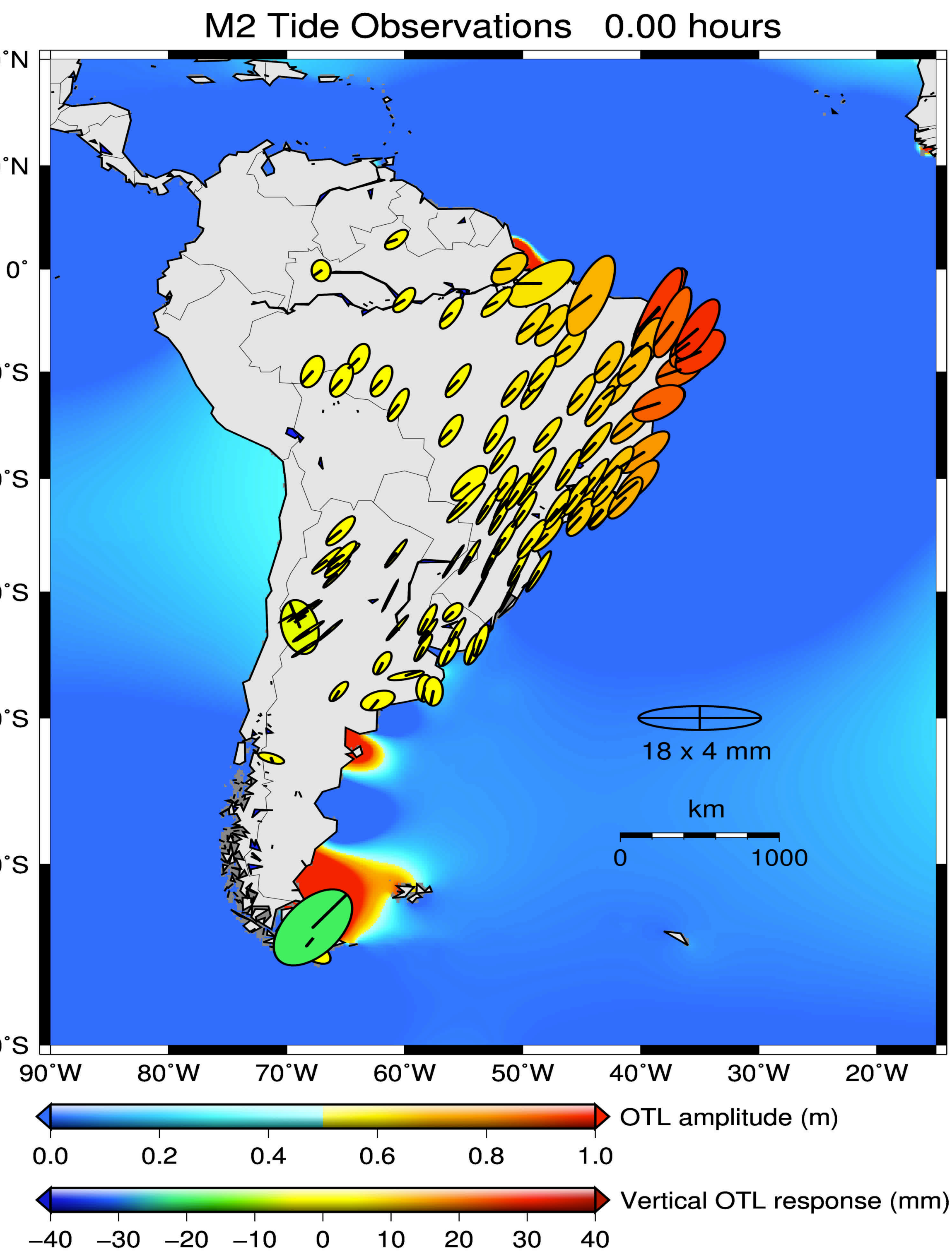
Next

- Confirm with much longer time series
- Improve estimates of positions
- Explore sensitivity to:
  - Newer OTL models
  - Approach to removing solid earth tides
- Improve geodynamical interpretation
- Explore other regions (1D)
- Go to 3D

For each cGPS site, we should establish empirical tidal corrections and use to improve transient detection



M2 Tide Predictions 0.00 hours
20˚N
10˚N
0˚
10˚S
20˚S
30˚S
40˚S
50˚S
60˚S
90˚W
80˚W
70˚W
60˚W
50˚W
40˚W
30˚W
20˚W
18 x 4 mm
km
0
1000
OTL amplitude (m)
0.0
0.2
0.4
0.6
0.8
1.0
Vertical OTL response (mm)
−40
−30
−20
−10
0
10
20
30
40



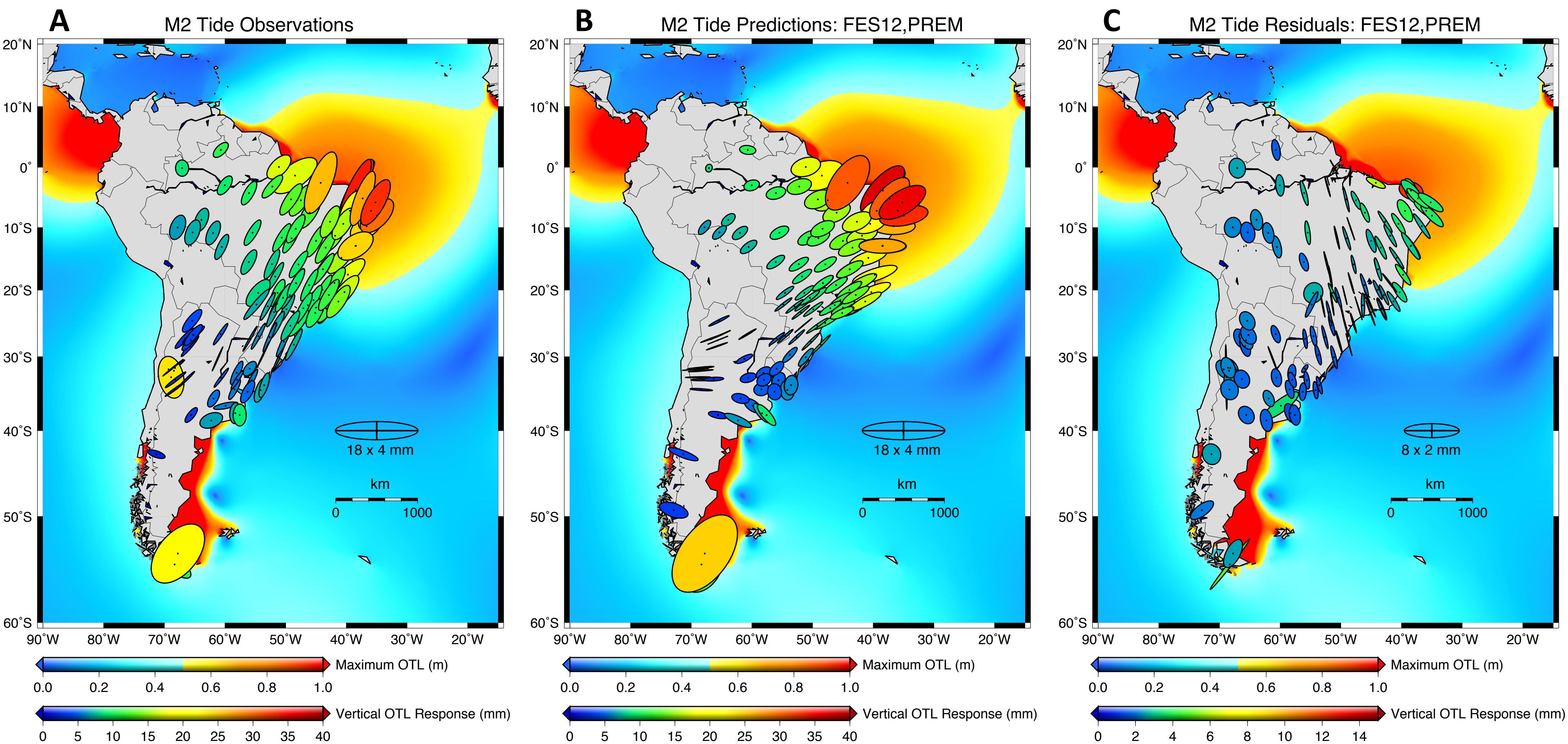
M2 Tide Observations 0.00 hours
20˚N
10˚N
0˚
10˚S
20˚S
30˚S
40˚S
50˚S
60˚S
90˚W
80˚W
70˚W
60˚W
50˚W
40˚W
30˚W
20˚W
18 x 4 mm
km
0
1000
OTL amplitude (m)
0.0
0.2
0.4
0.6
0.8
1.0
Vertical OTL response (mm)
−40
−30
−20
−10
0
10
20
30
40

Observations

Forward Model

PREM & FES2012

Residuals



Goal: Elastic and density structure of a craton

From the earthquake cycle to mantle structure – current and future uses of dense GPS

- Tohoku-oki
  - Relatively constant pattern of post-seismic after slip (with notable exceptions)
  - Lack of overlap between co-seismic/post-seismic distribution of fault slip
  - Consistency of co-seismic and inter-seismic
  - Consistency of co-seismic and post-seismic
  - Importance of high-rate GPS (and in near real time)
- Cascadia aseismic transients
  - New rigorous methods for automatic transient detection based on sparsity and overcomplete dictionaries.
  - Slip transients and tremor co-located in space and time
- OTL load response to probe upper mantle structure
  - Ability to separate depth variation of density and elastic moduli.
  - Needs careful analysis of sensitivity to processing approach