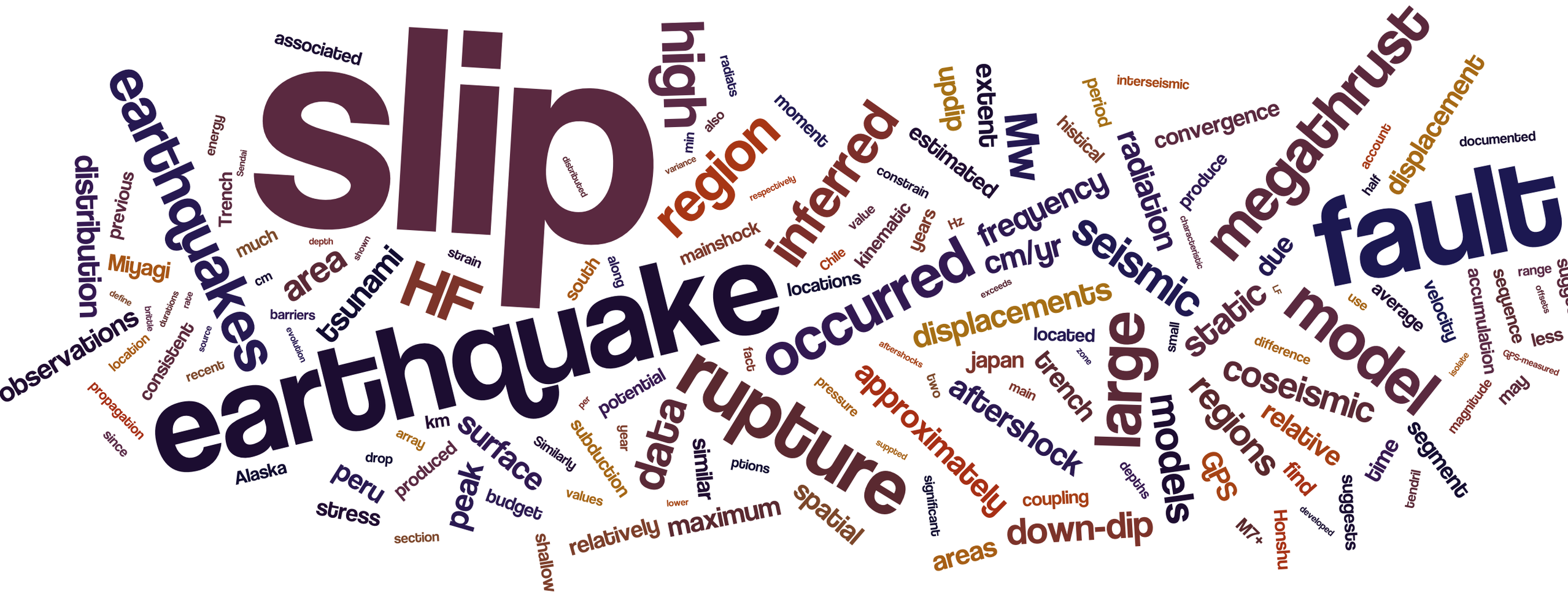
# Faulting and Deformation Processes




Our task - Seed discussion about future directions in understanding earthquakes, seismic cycle, fault rheology, induced seismicity & volcanoes

Tag team: **Mark** Simons & **Eric** Dunham

# Discussion via tantalizing examples

Where are we now?

# Motivate Using Subduction Megathrusts

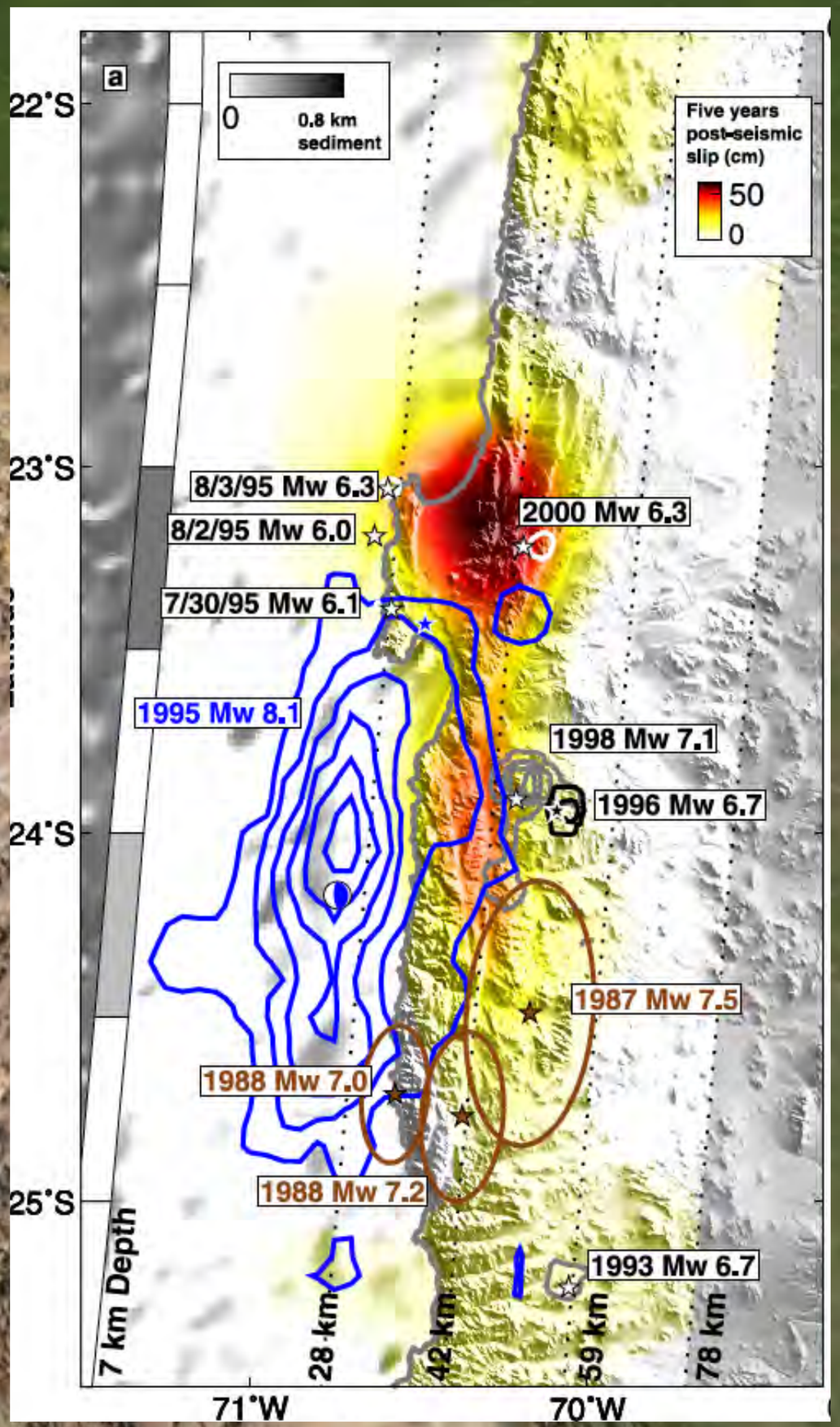
## A sampling of important intertwined questions

Time Scale

- Do major seismogenic “asperities” only slip seismically?
- Role of conditional stability (e.g., near trench)?
- Do creeping segments only creep?
- Is pre-seismic creep (EQ swarms?) ubiquitous?
- What are the relationships between post-seismic creep, transients, tremor and seismicity (rate, repeat intervals, location…)?
- What happens immediately after a large earthquake - aseismic slip pulses?
- What is the role of off-fault damage?
- Can we constrain the role of fluids as a function of space and time?
- Is there a relationship between short term behavior and geologic evolution?

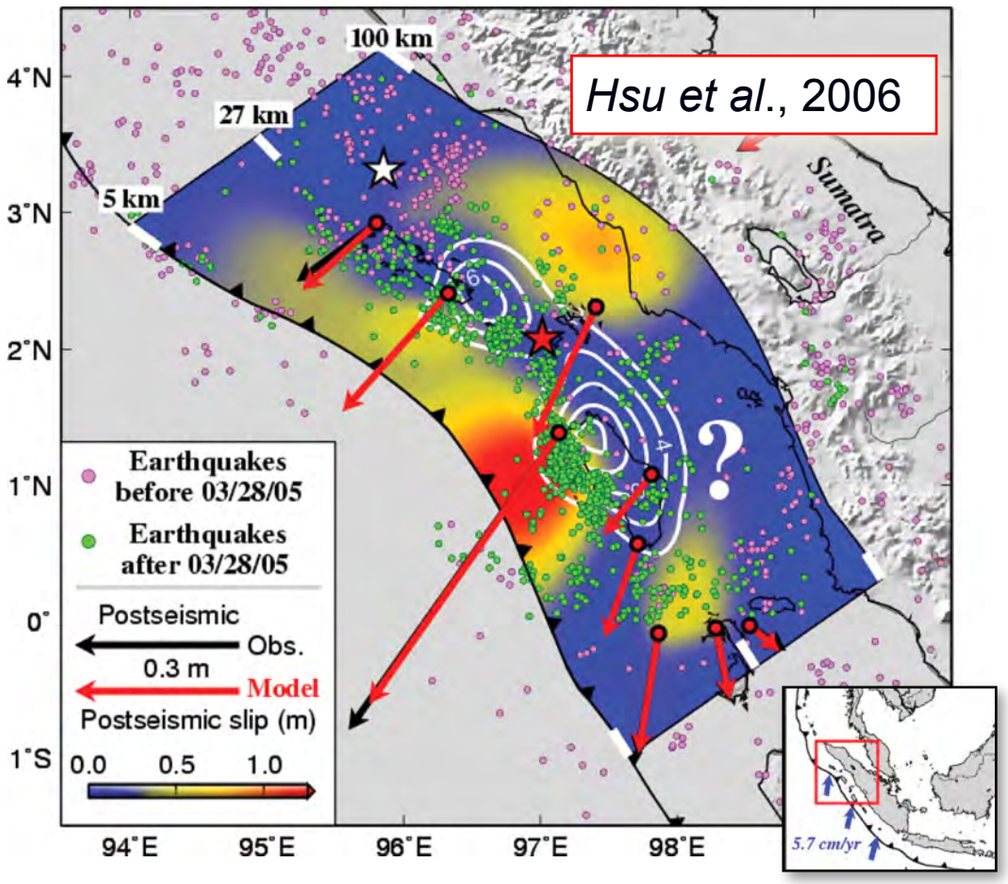
# Complexity of slip behavior on a single fault

- ➡ Along strike variability in behavior
- ➡ Little overlap between co-seismic / post-seismic / aseismic
- ➡ Aftershocks surround the aseismic patch
- ➡ Aseismic transient event downdip of main rupture superimposed on post-seismic after slip
- ➡ Megathrust below the peninsula appears “aseismic” - coincidental?

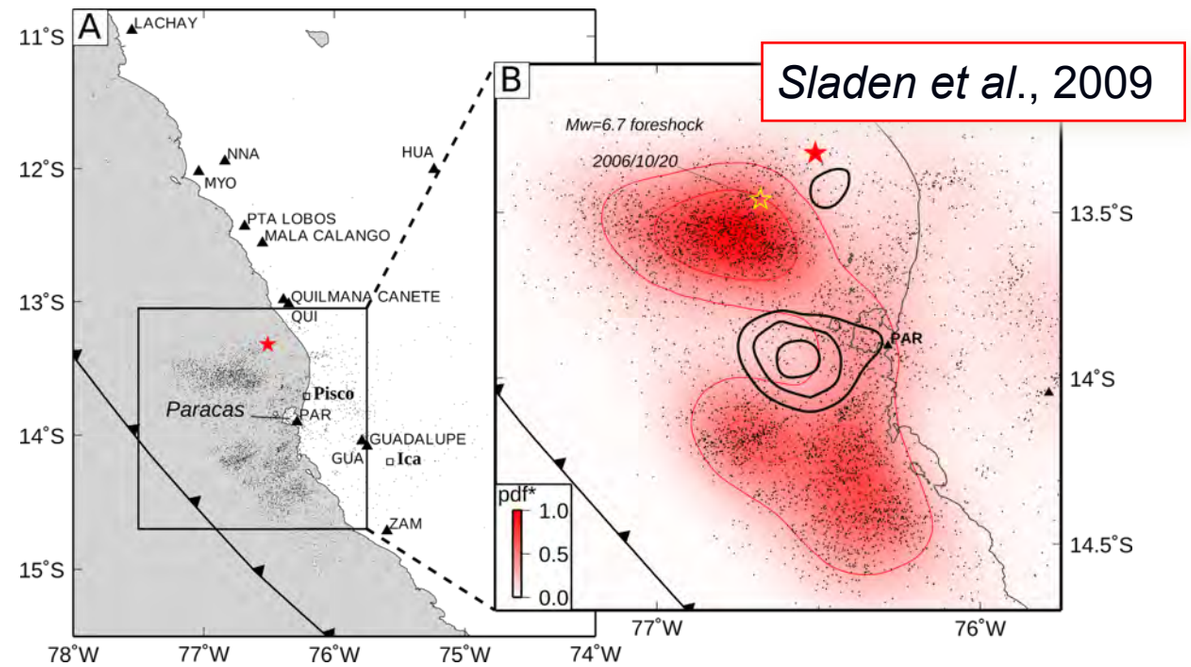



*Pritchard & Simons*, 2006

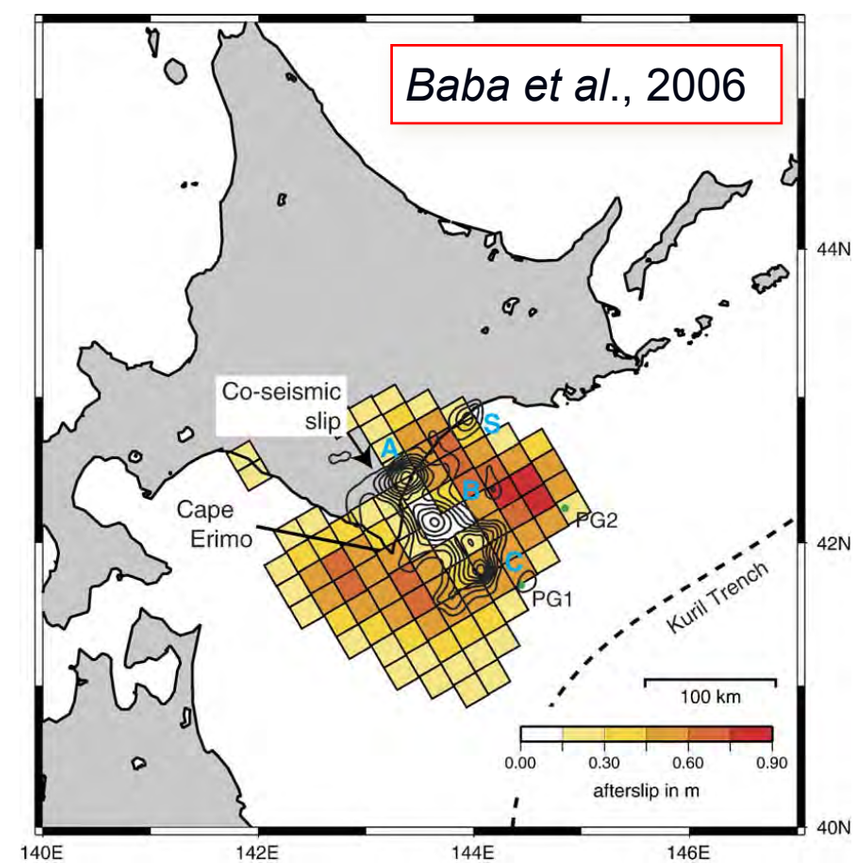
## 2005 $M_w$ 8.7 Nias, Sumatra




## 2007 Mw 8.0 Pisco, Peru




## 2003 $M_w$ 8.3 Tokachi-Oki, Japan

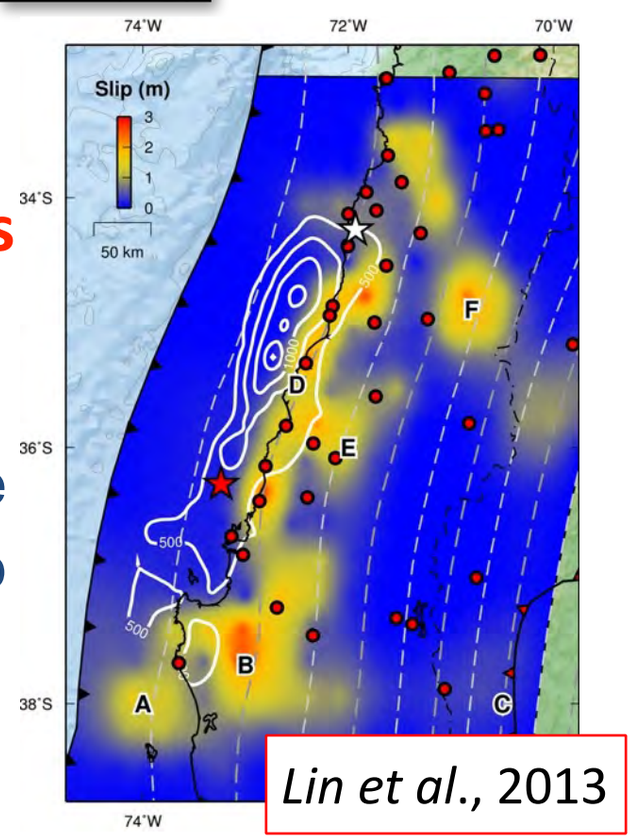



**Note importance of joint geodetic/seismic inversions**

Co-seismic/post-seismic

- Slip heterogeneous in space
- Negligible (?) spatial overlap

## 2010 $M_w$ 8.8 Maule, Chile



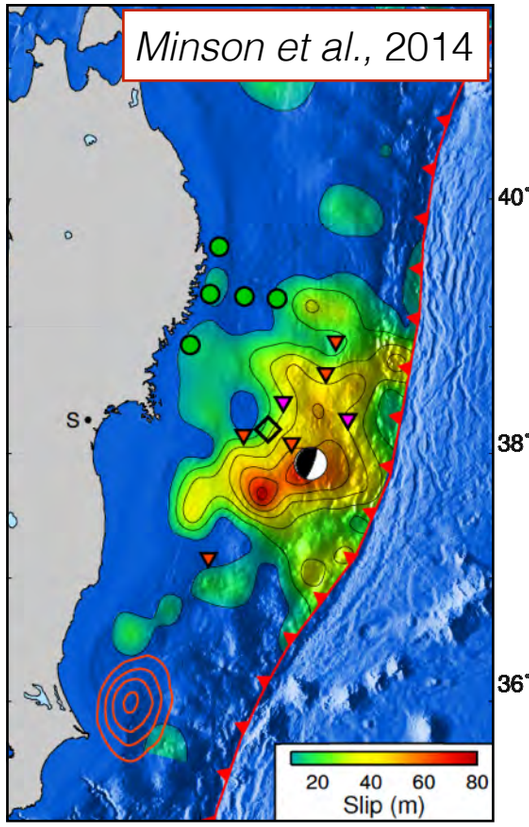
# 2011 Tohoku-Oki, Japan

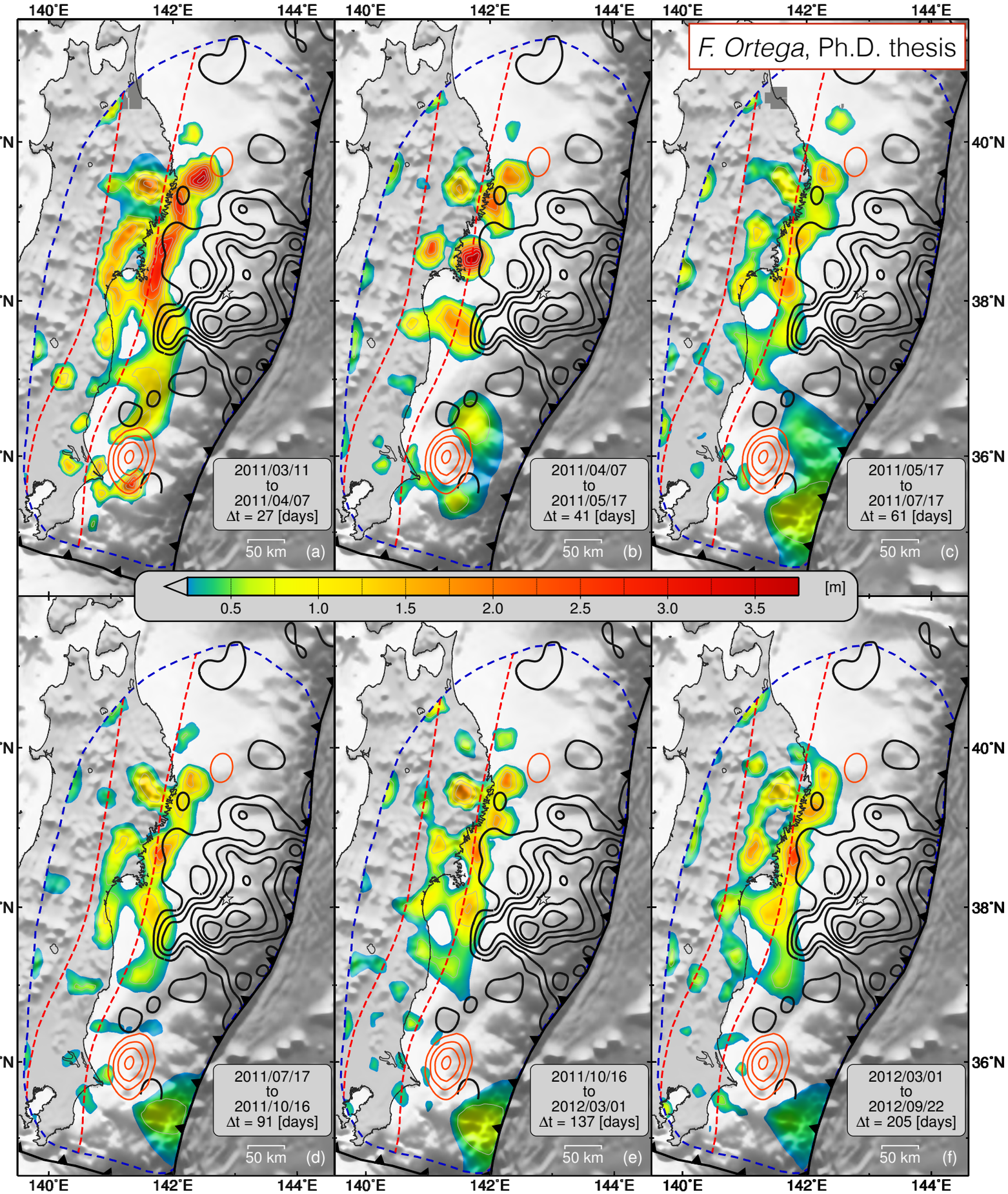
Co-seismic slip:

- Amplitude and location of peak slip, frequency dependence?
- Relationship to post-/inter-seismic?

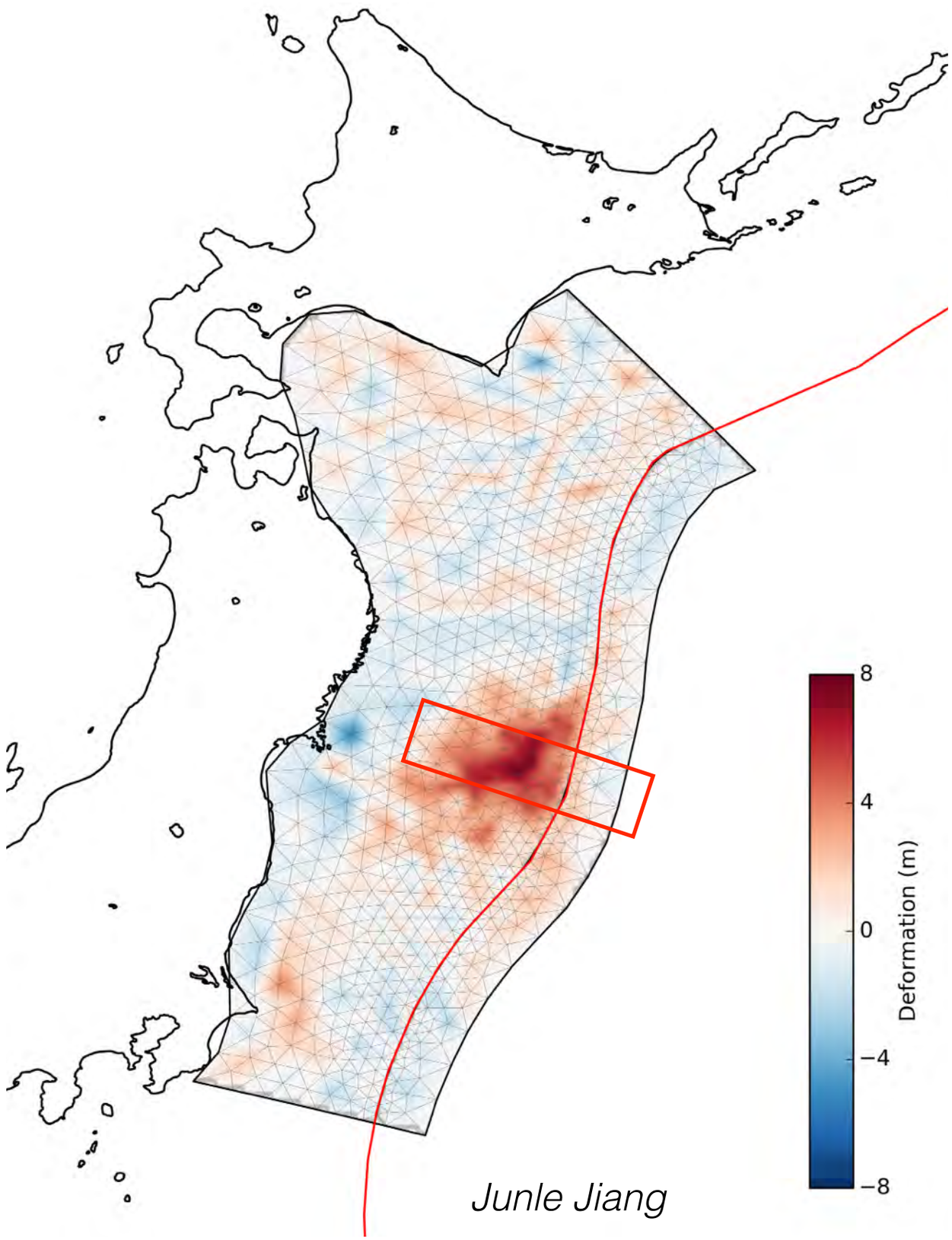
Post-seismic afterslip:

- Total time = 1.5 years
- Mutually exclusive time windows of increasing duration using a fixed color scale

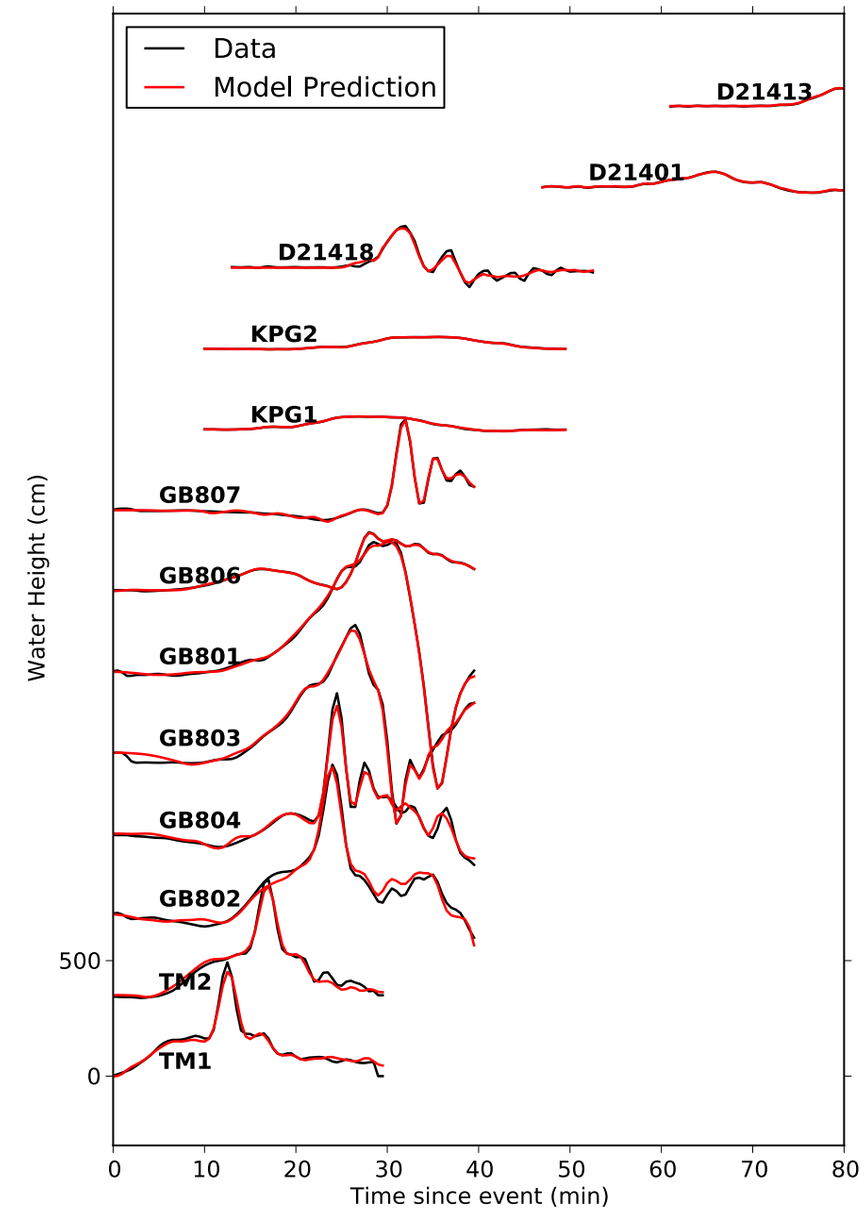


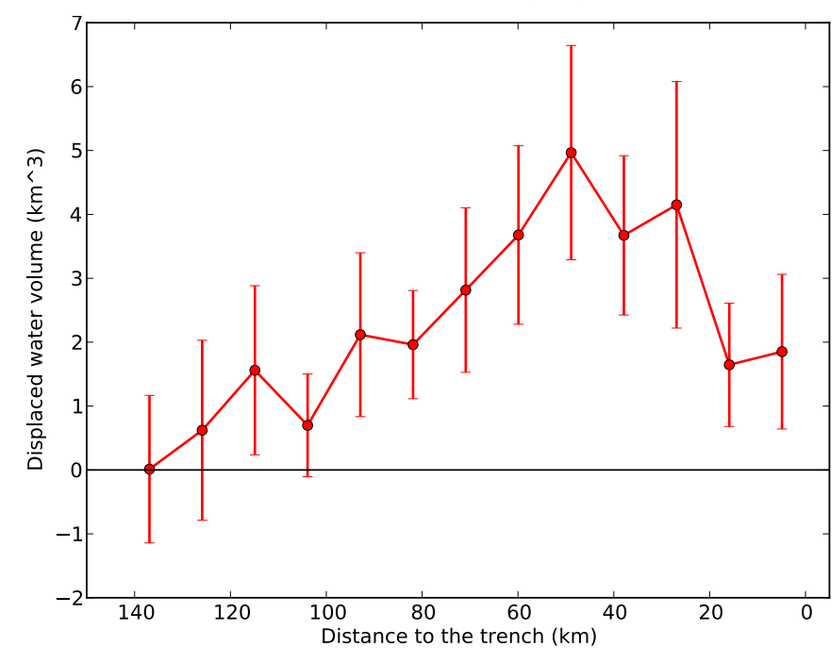



# Mapping *effective* seafloor displacement using just tsunami observations



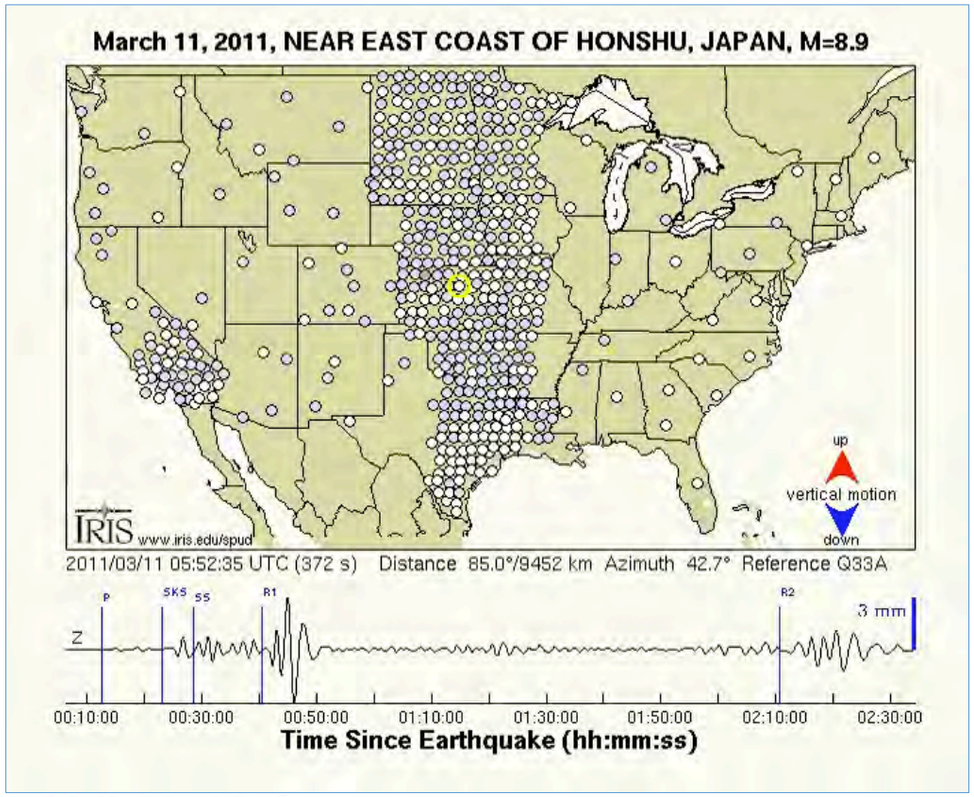

*Junle Jiang*

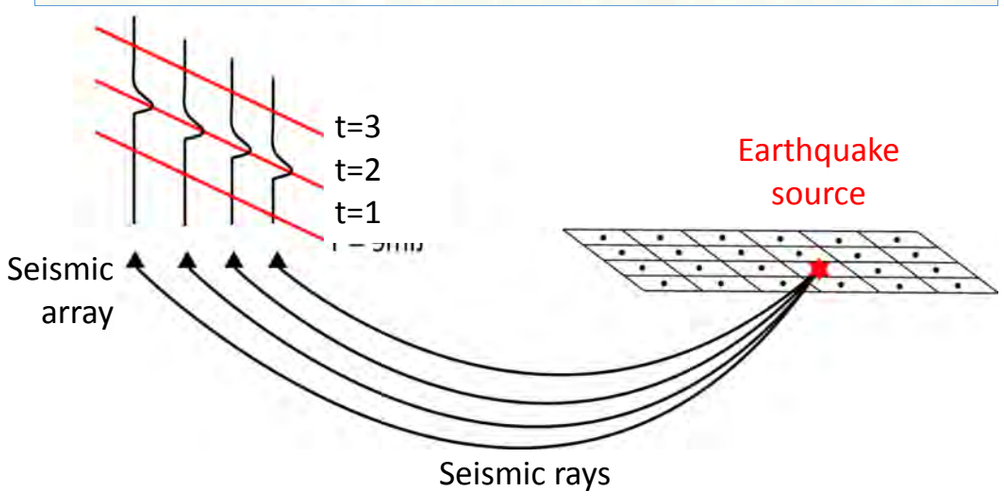


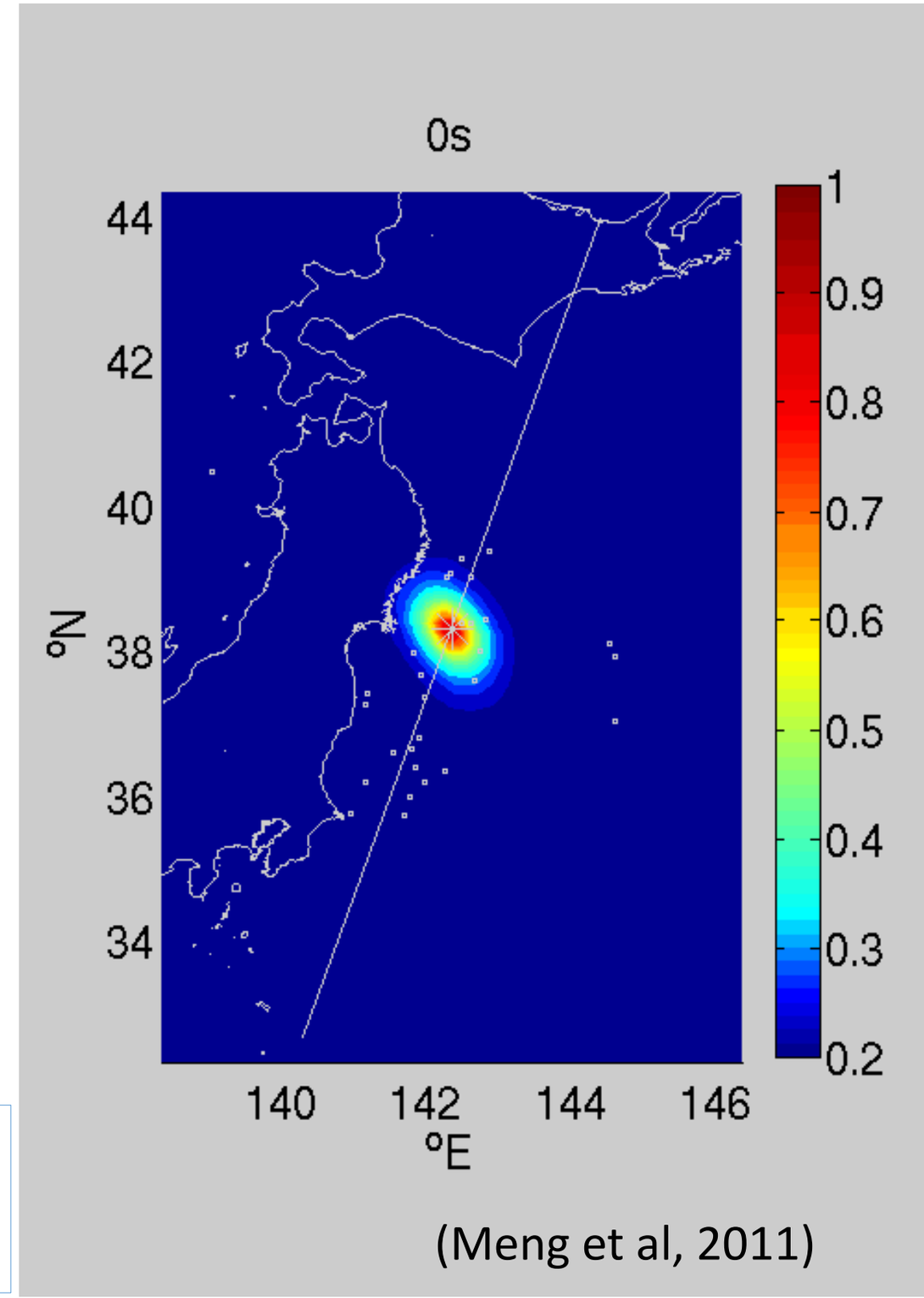



# High resolution imaging of distant high frequency seismic radiation with large and dense seismic arrays

## 2011 Tohoku-Oki earthquake as seen by USArray data



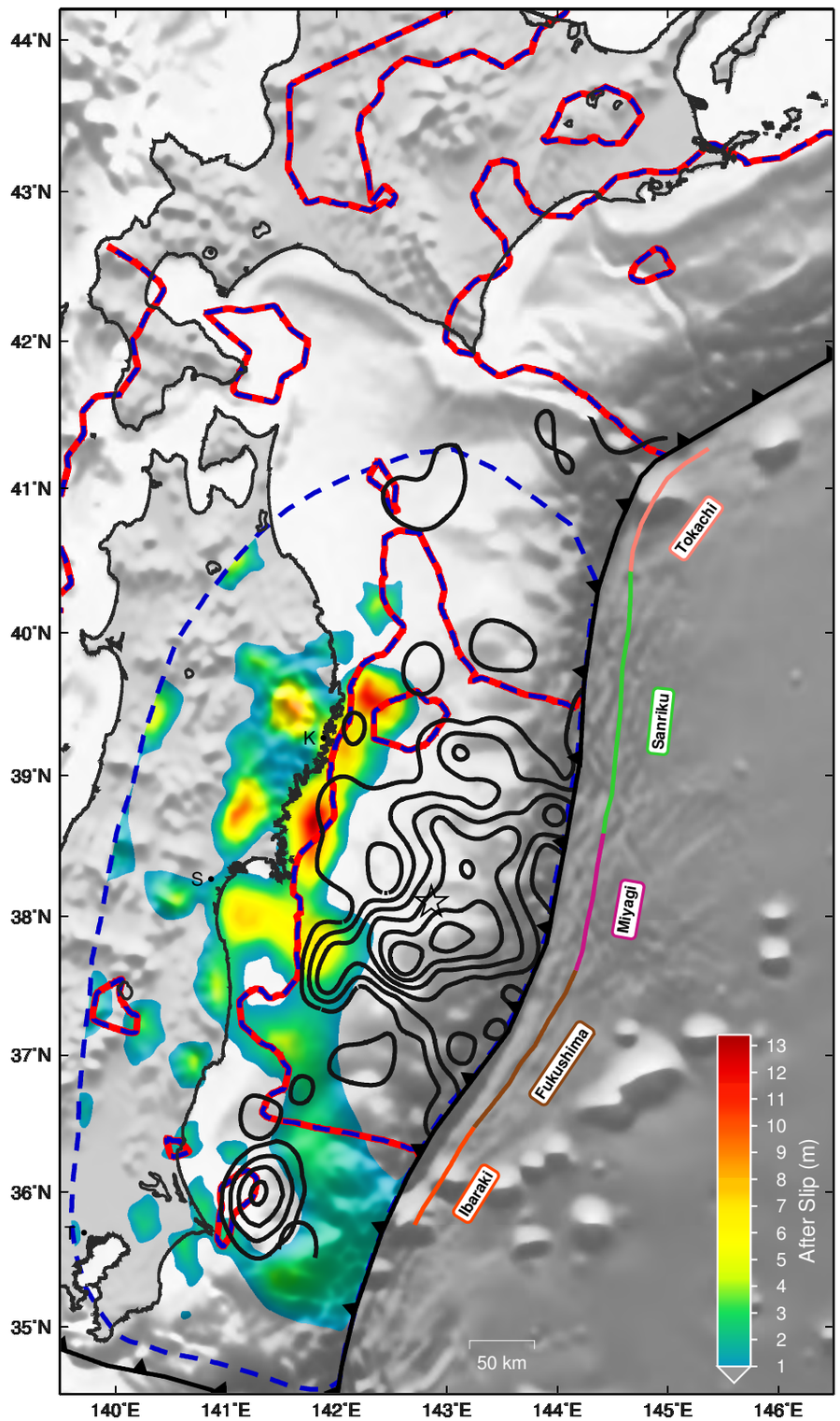




(Meng et al, 2011)

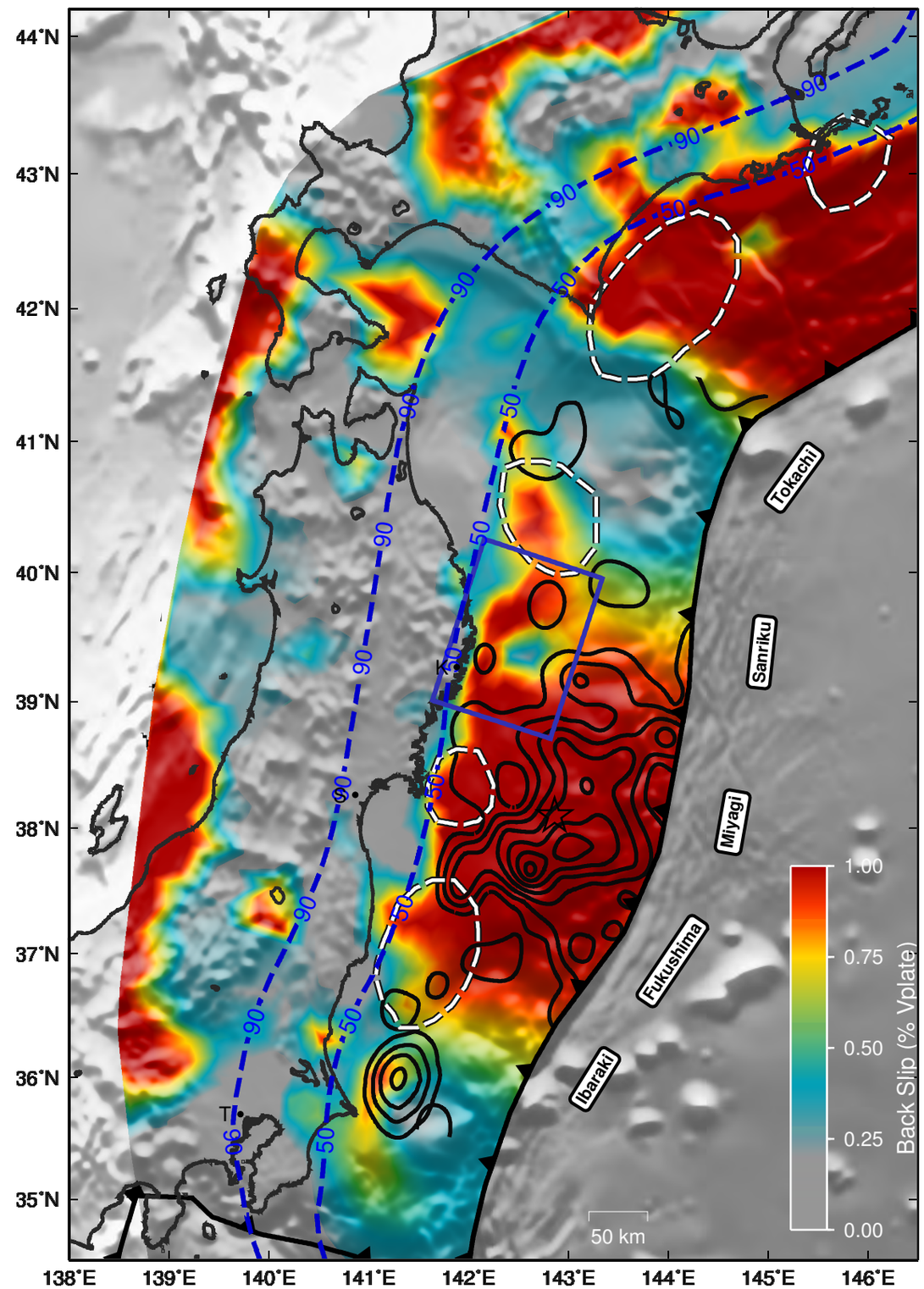
Array processing and back-projection to track migration of the high frequency component of the rupture:

Fault zone rheology / prestress / strong ground motions

# Post-seismic (1.5 yrs)




# Inter-seismic



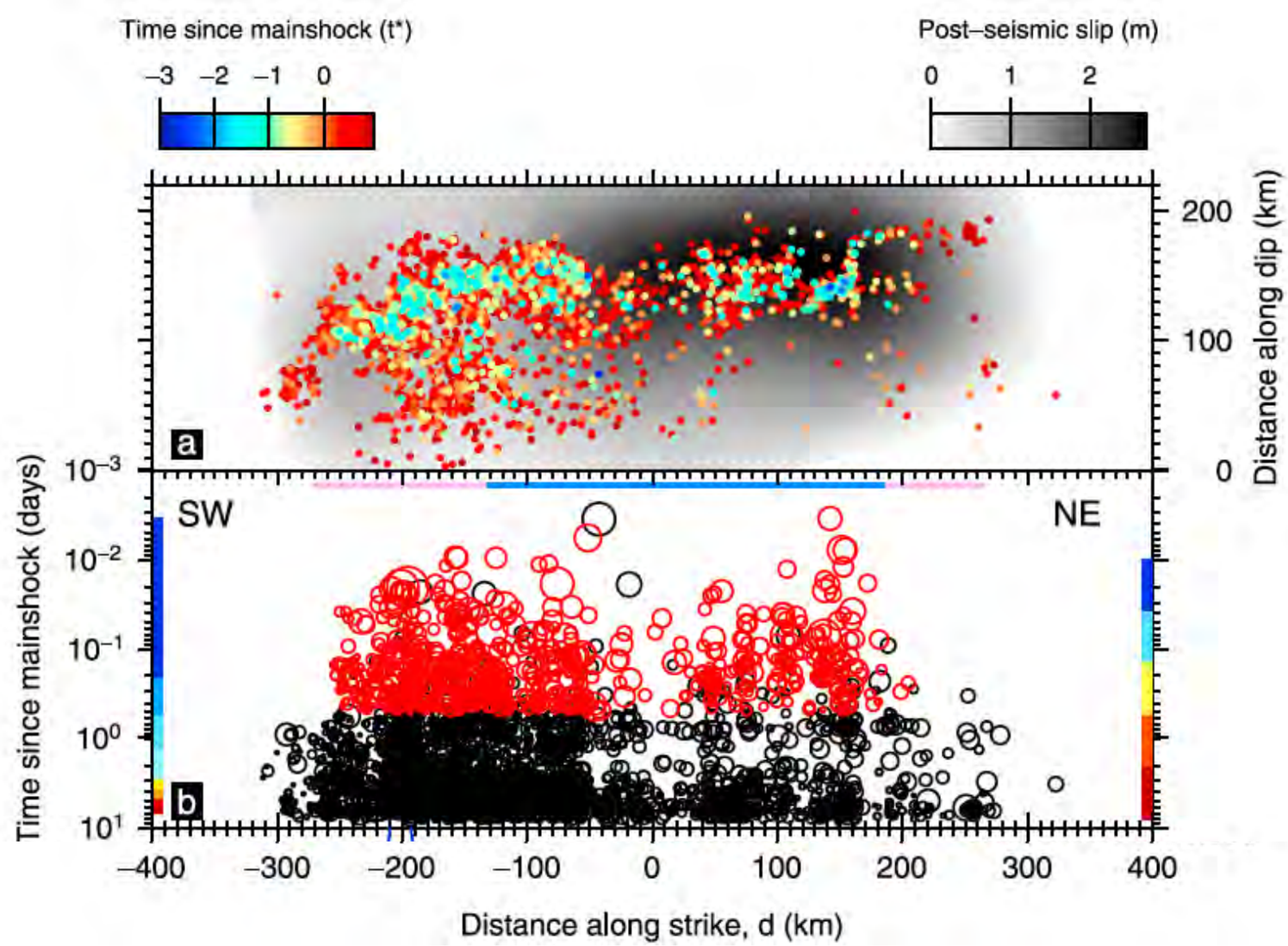

*F. Ortega*, Ph.D. thesis

# What about shorter time scales?

Decay and expansion of the early aftershock activity following the 2011, Mw 9.0 Tohoku earthquake

**Geodesy**: Pattern of after-slip is more or less constant (?) but time scales are really days to years.

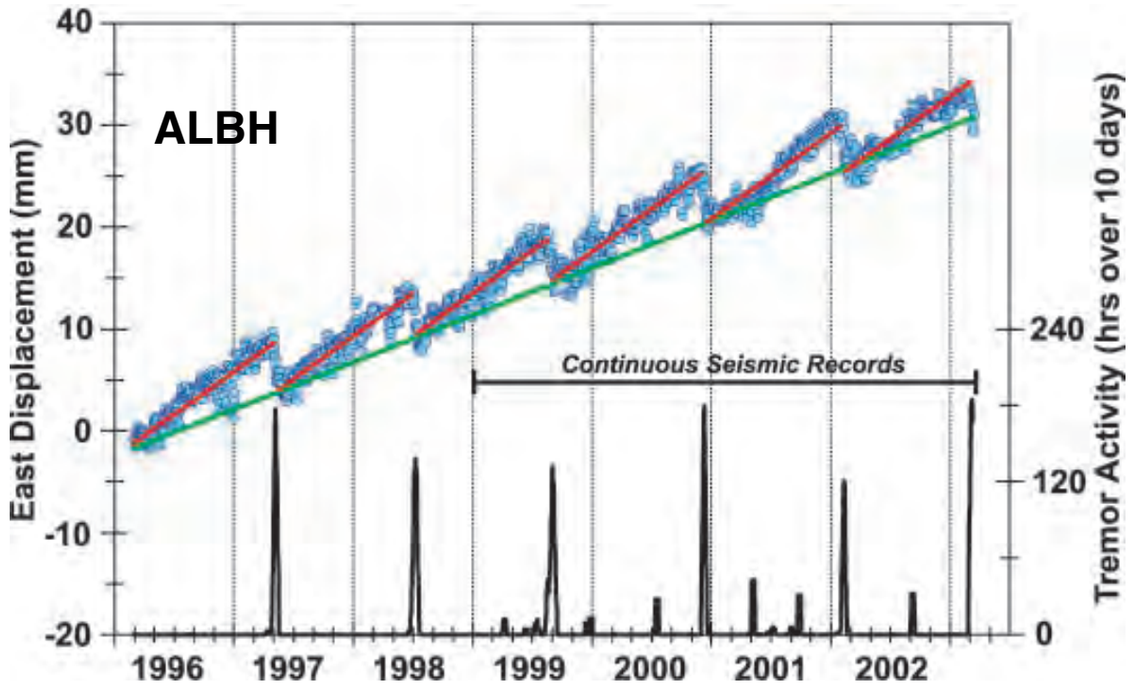
**Seismology**: Rapid spatial expansion of after-slip over short time scales?



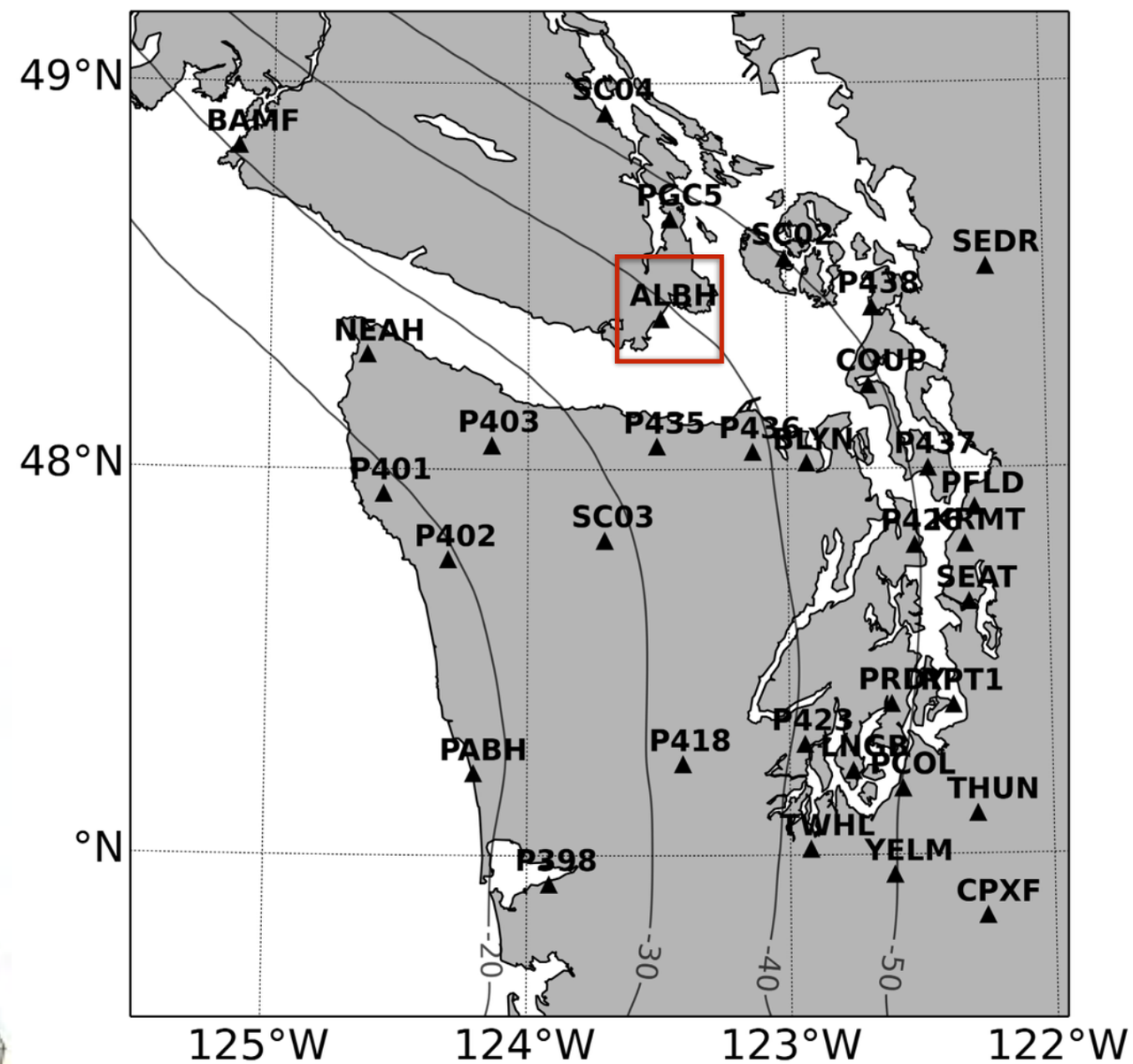

*Lengliné et al.*, 2012.

For application to Parkfield, see: *Peng and Zhao*, 2009

# Slip transients and Tremor: Cascadia




Rogers and Dragert (2003)



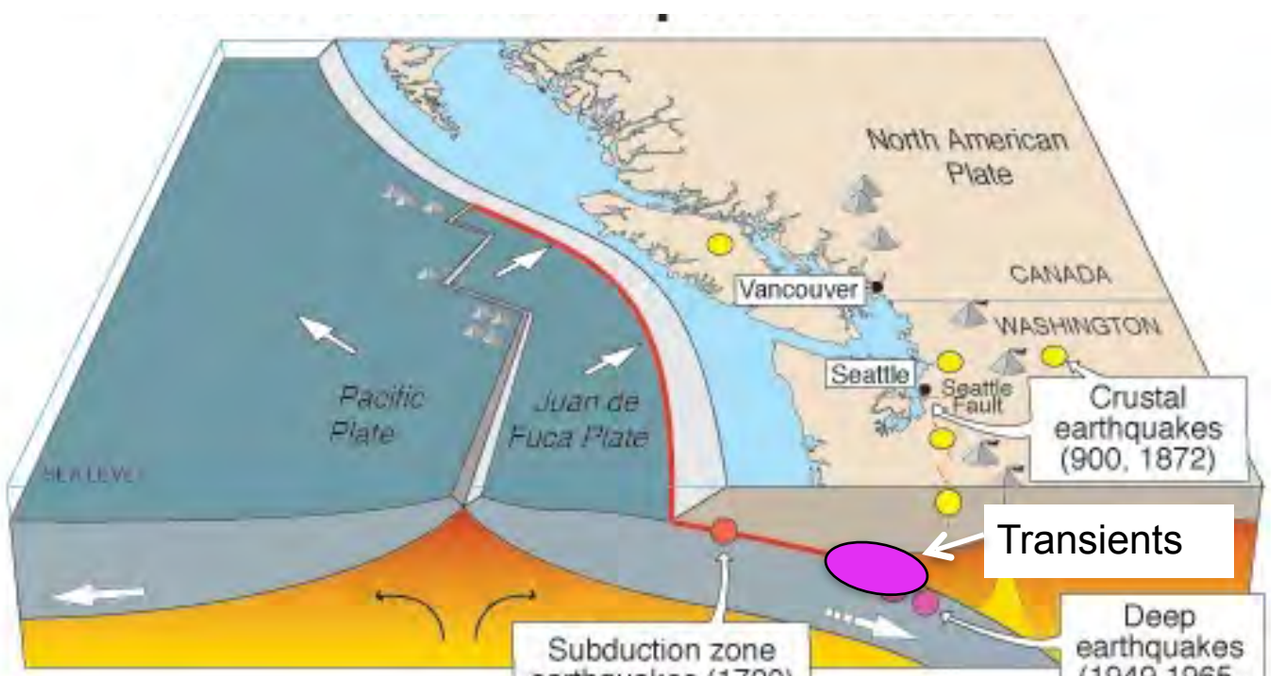
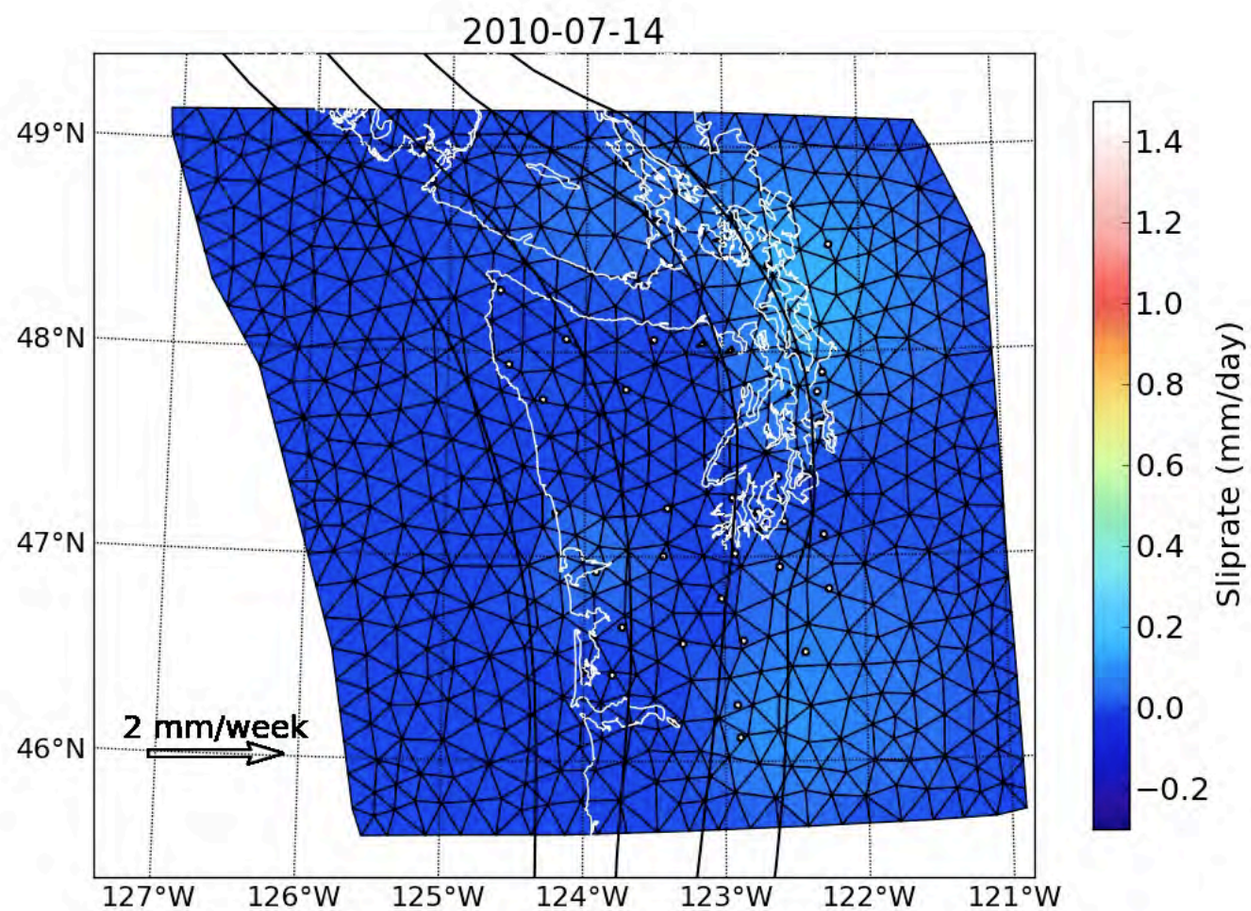




Image from IRIS

# Cascadia 2010 SSE: Slip rate + tremor




Analysis and models: *Bryan Riel*

**Issues**

- 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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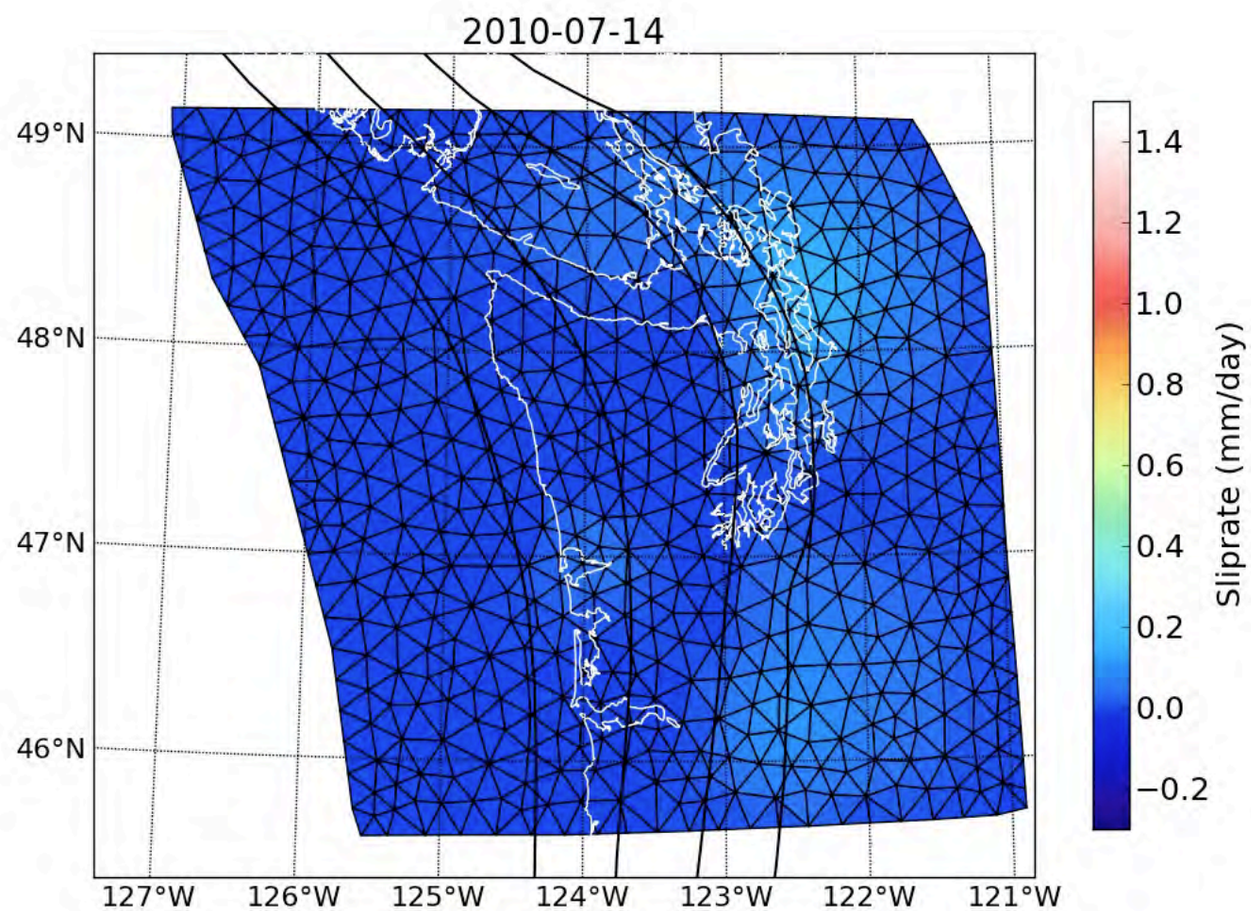


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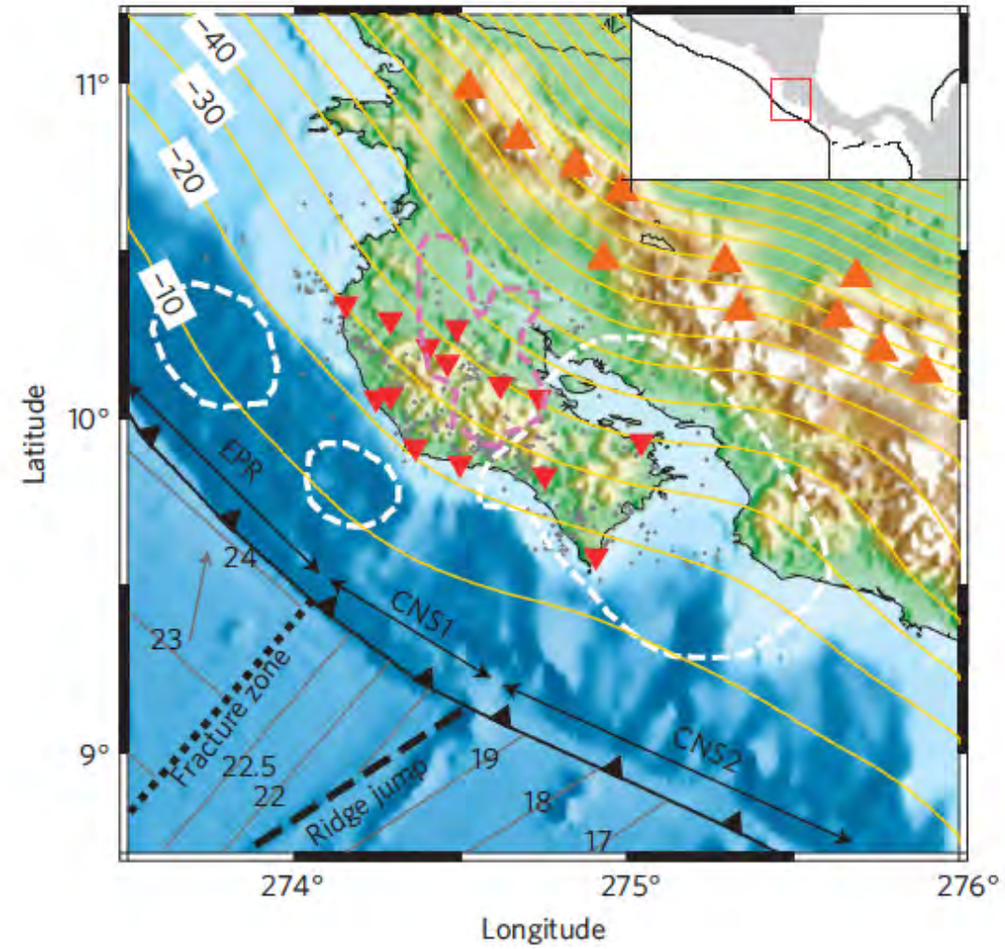
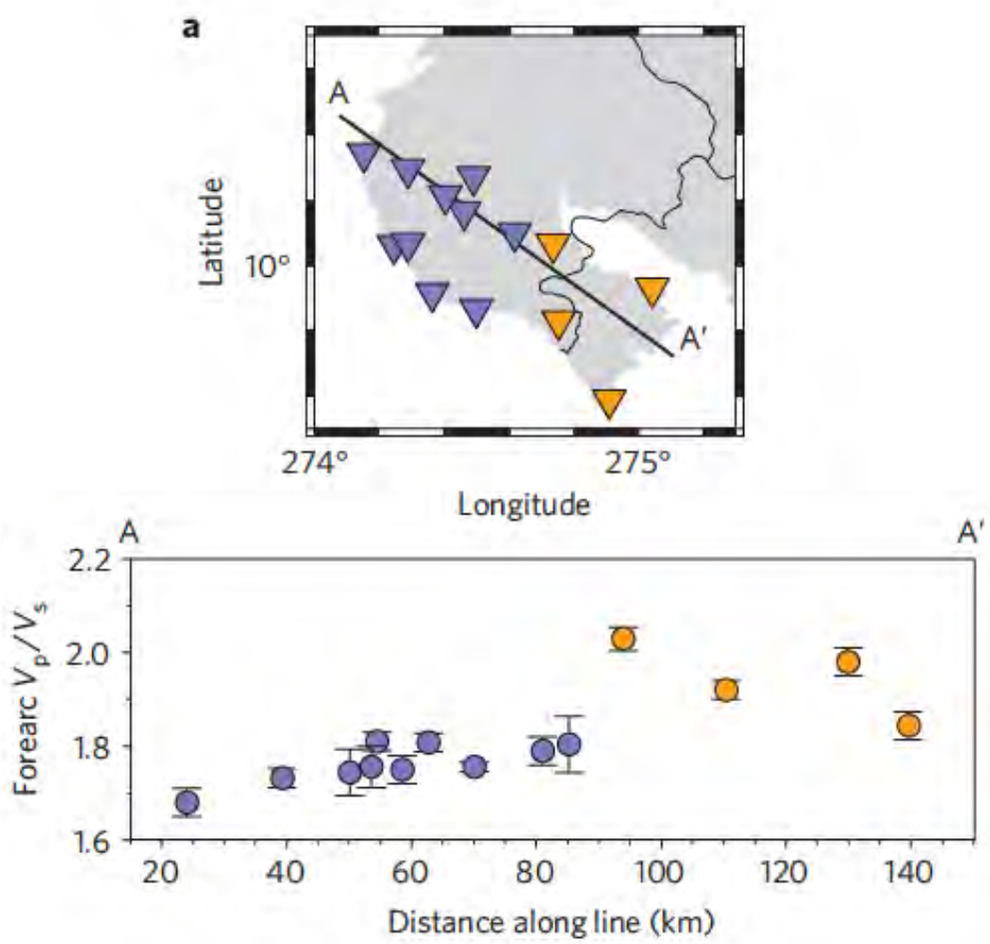
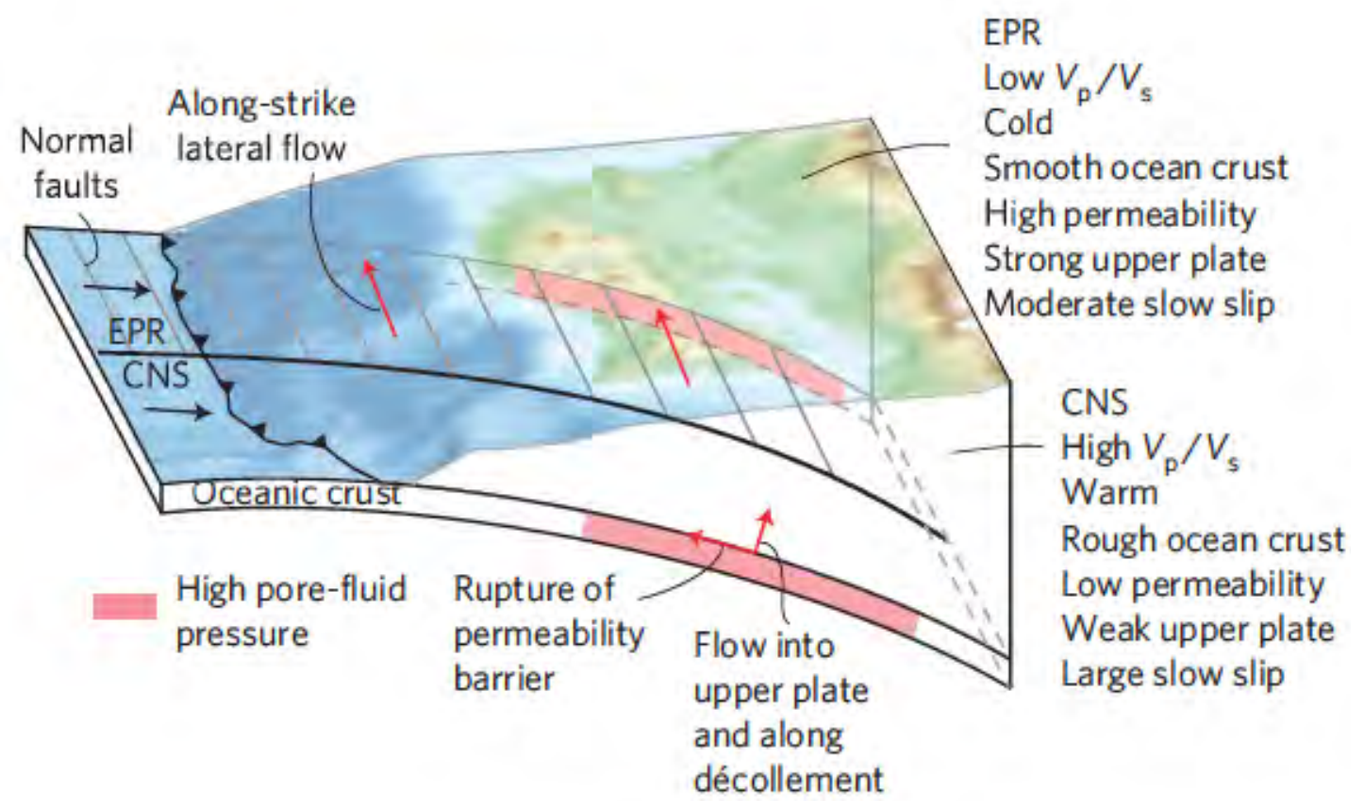
# Hydrologic control of forearc strength and seismicity in the Costa Rican subduction zone

*Audet and Schwartz*, 2013

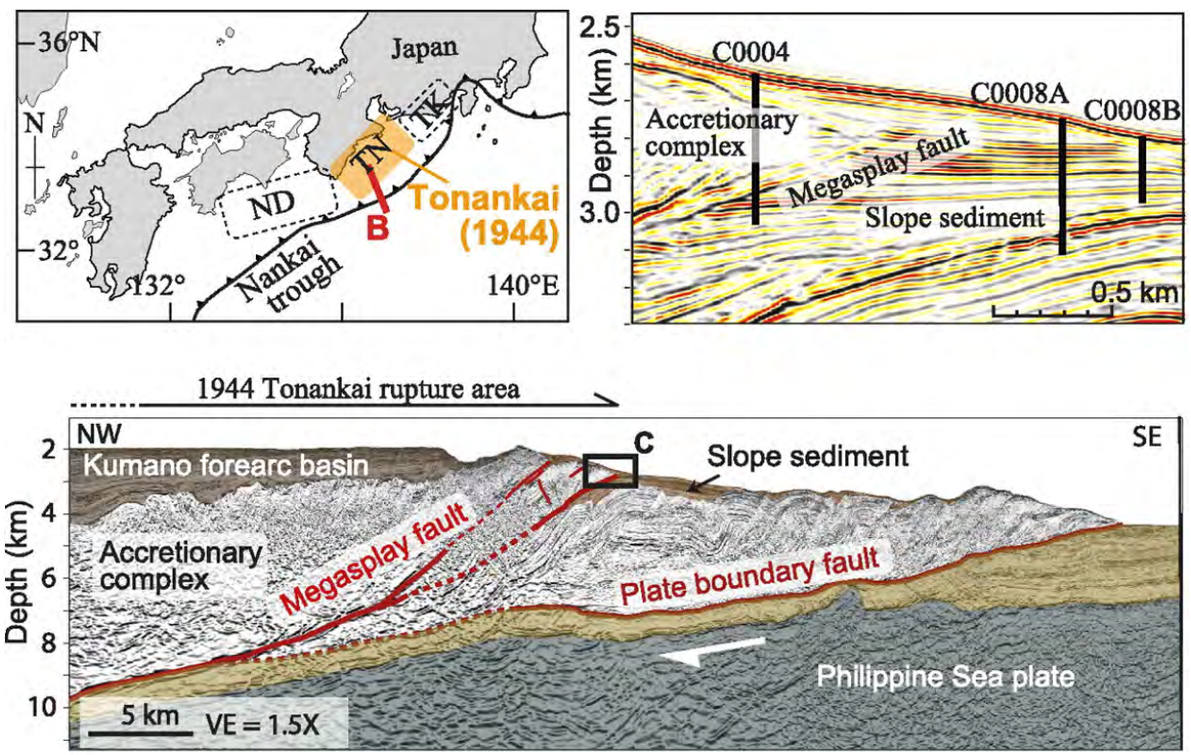


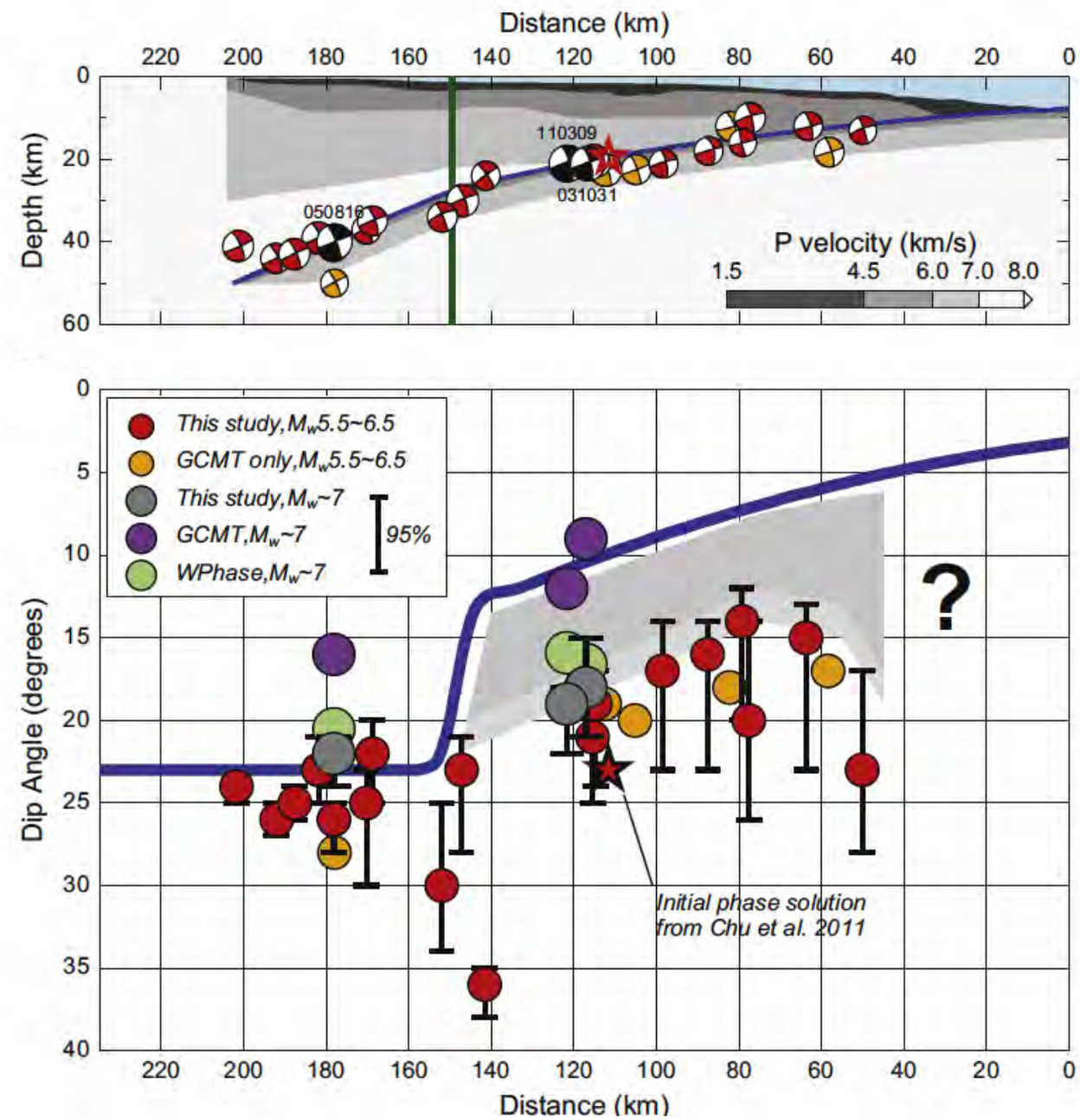
# Caveat Emptor

## Structure of the Nankai SZ




*Sakaguchi et al.*, 2011

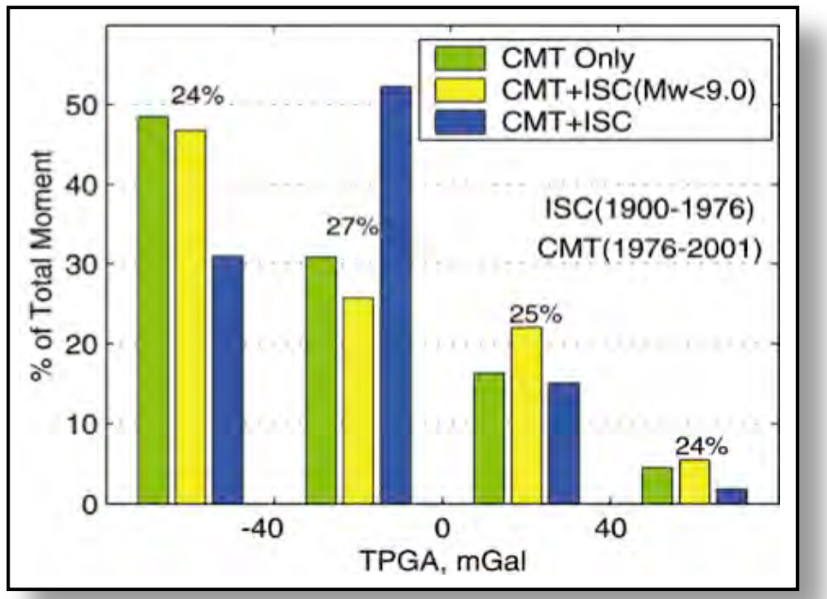
## Complex Faulting on the N. Japan Megathurst




*Zhan et al.*, 2012

# Trench Parallel Gravity Anomaly (TPGA)

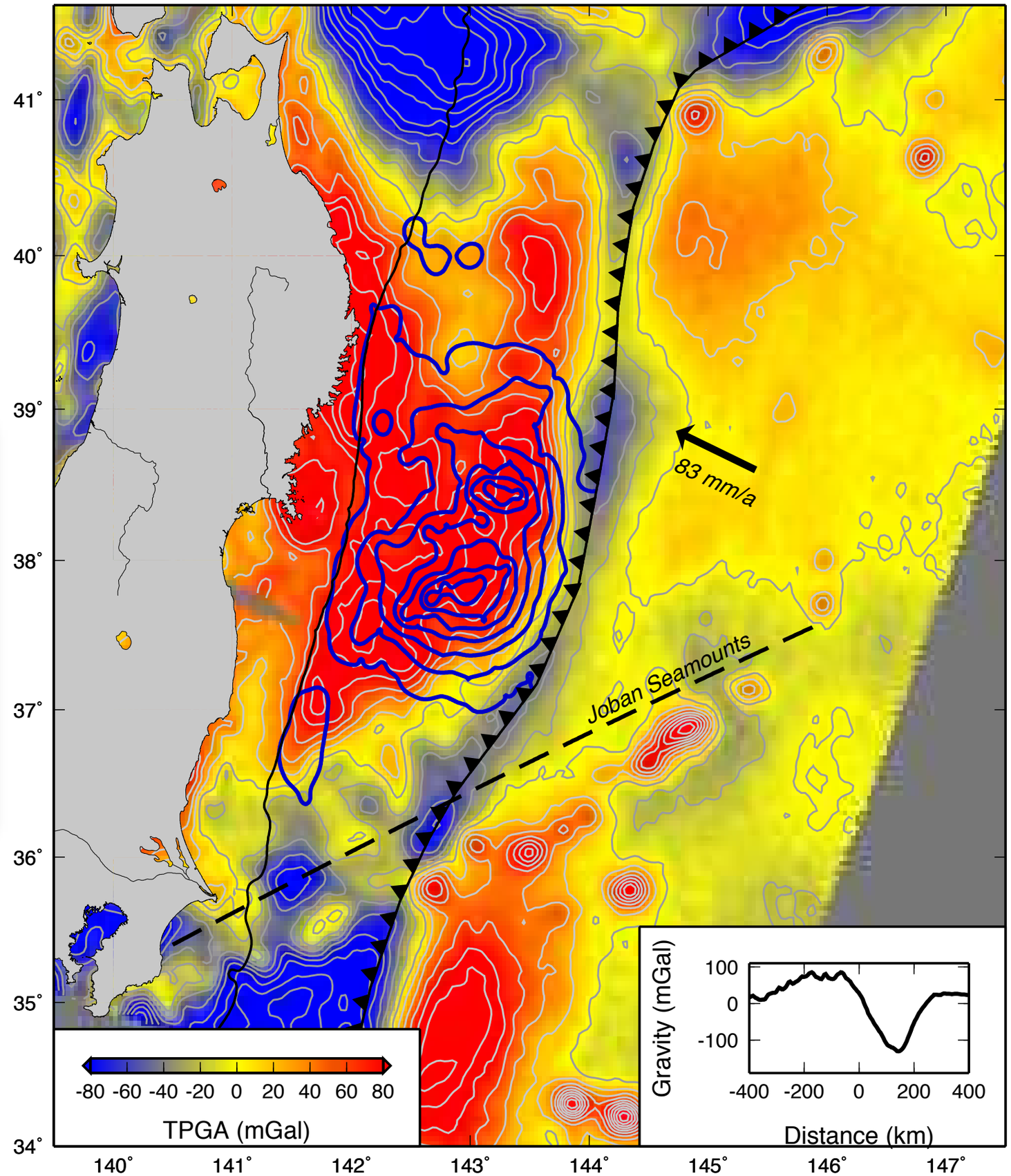
TPGA < 0 in region of large earthquakes




*Song & Simons*, 2003

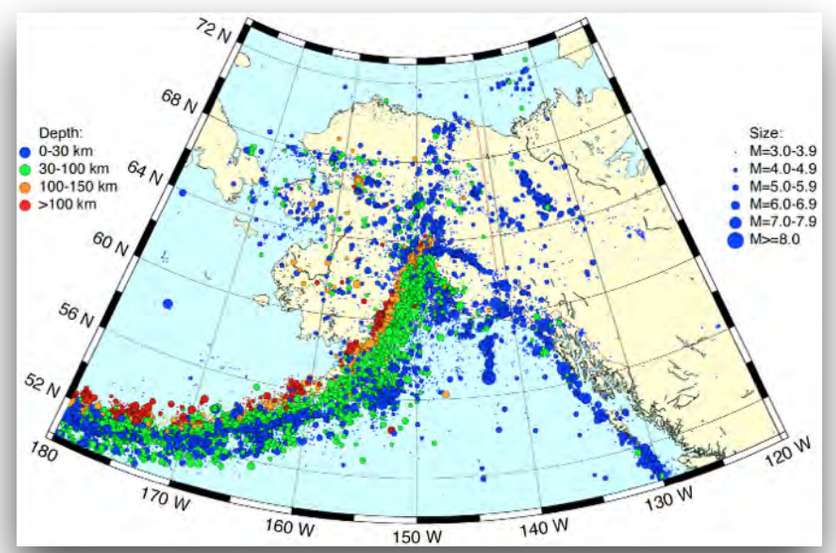
Also *Wells et al.*, 2003

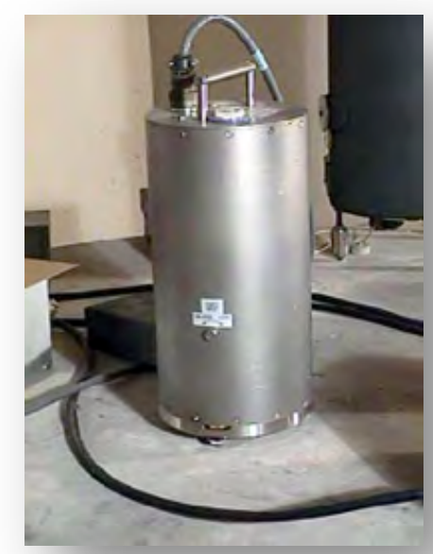
- Prediction failed
- Low/high stress drop events different?



# Going Forwards: Assumptions (will need some effort)

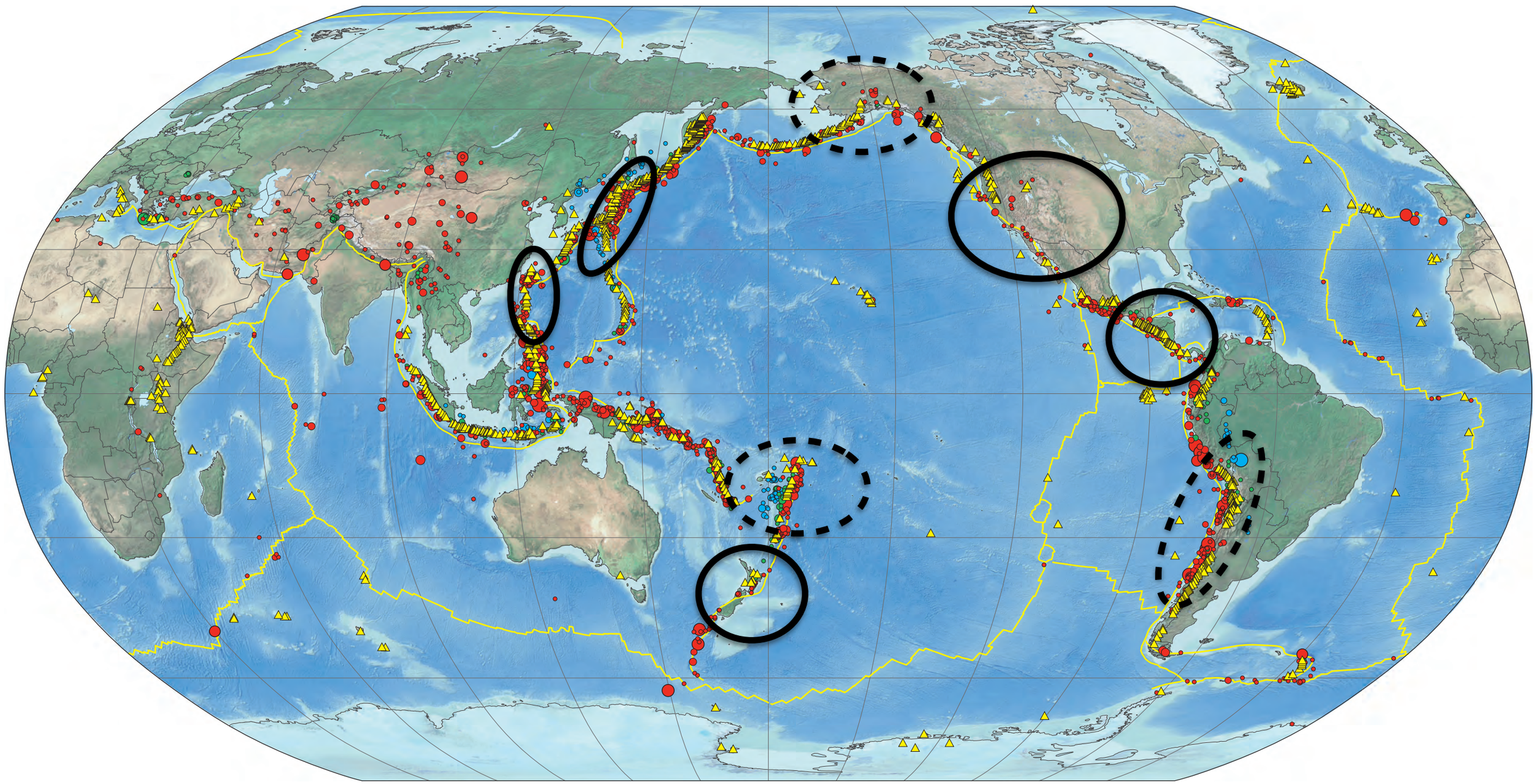
- Existing GPS/seismic networks (particularly those we are responsible for) **must** continue to exist and be maintained
- USArray in Alaska (most active region in the U.S.) exists and a subset is permanent
- Sub-weekly InSAR data easily available to all



# A Global Perspective

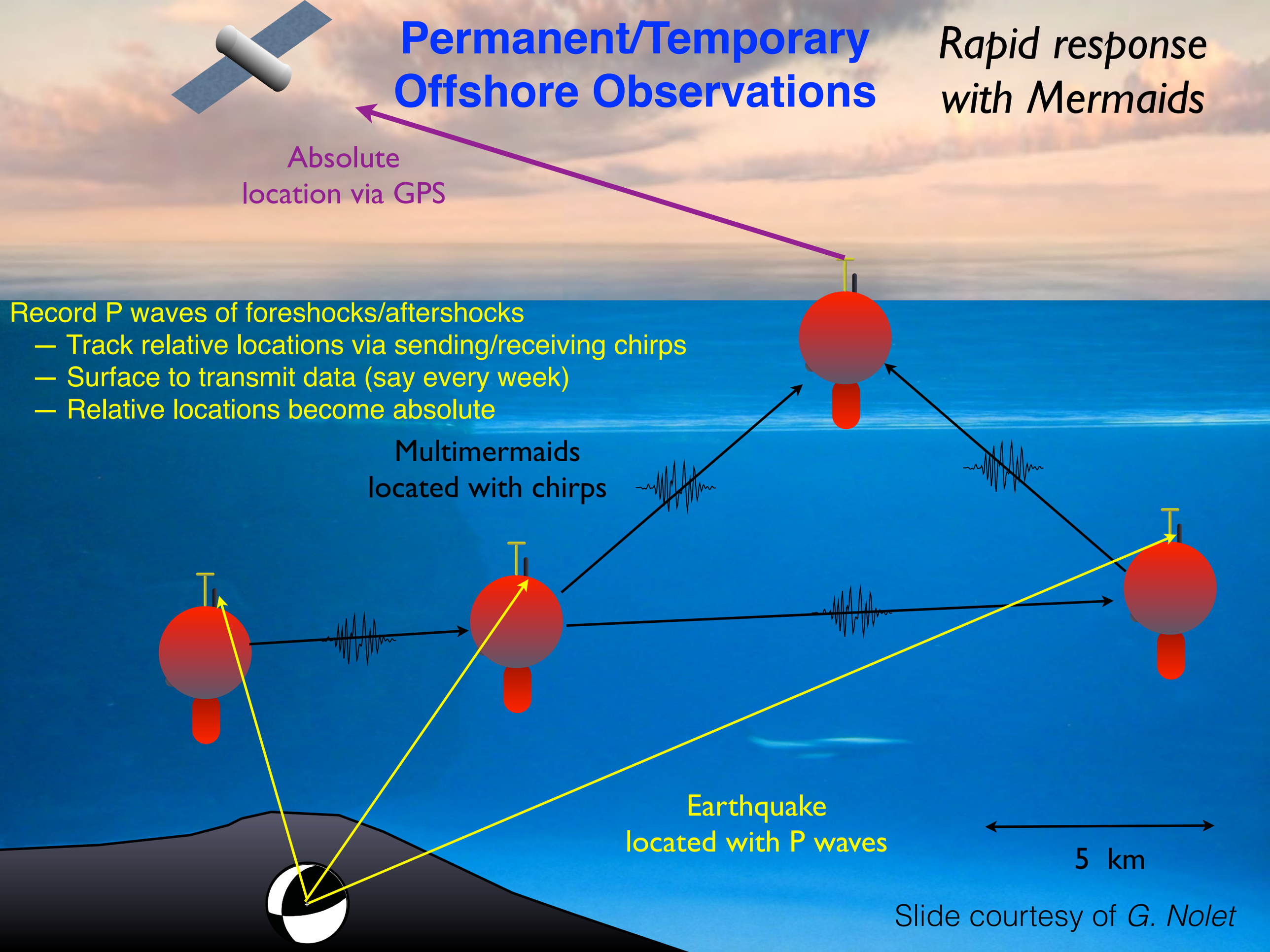
Increasing the number of natural laboratories/examples



http://earthquake.usgs.gov/earthquakes/world/seismicity_maps/world.pdf

# Permanent/Temporary Offshore Observations

*Rapid response with Mermaids*




Slide courtesy of *G. Nolet*

# Formally or informally, we are engaged in the inverse problem of improving our image of fault slip:

- Refine spatial and temporal resolution
- Describe both what we know & don't know
- Go beyond 1st order estimates

$$P(\theta \mid D) \propto P(D \mid \theta) P(\theta)$$

What we learned

$$\exp\left[-\frac{1}{2}(\mathbf{d}_{obs} - \mathbf{Gm})^T \mathbf{C}_{\chi}^{-1} (\mathbf{d}_{obs} - \mathbf{Gm})\right]$$

What we thought we knew

- $\exp\left[-\frac{1}{2}(\mathbf{m} - \mathbf{m}_{prior})^T \mathbf{C}_M^{-1} (\mathbf{m} - \mathbf{m}_{prior})\right]$
- Laplacian ….
- Rake
- Magnitude

IRIS
UNAVCO
USGS
NASA
…

$$\mathbf{C}_{\chi} = \mathbf{C}_d + \mathbf{C}_p$$

Misfit Covariance:
Observational and modeling components

Improve:
- Fault geometry
- Elastic structure

IRIS
USGS
…

- Theory & Computation
- "Physical Regularization"

# Motivate Using Subduction Megathrusts

## A sampling of important intertwined questions

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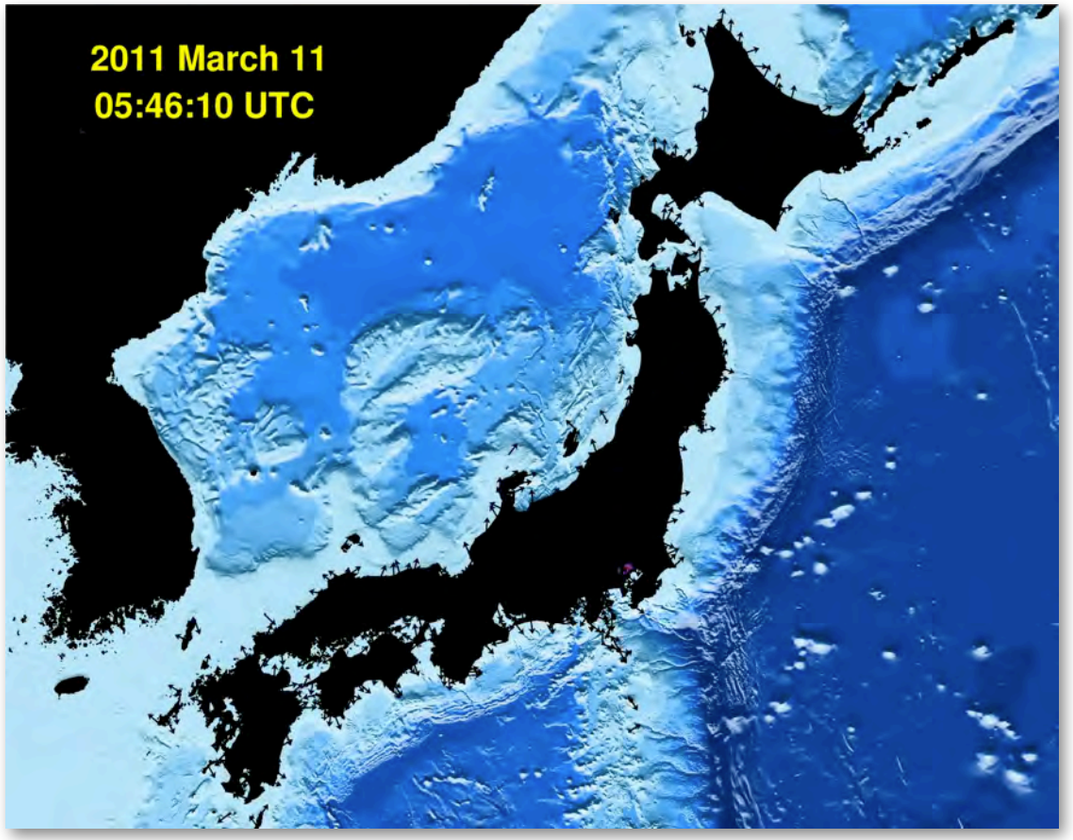


1 sample/sec GPS

# Assumptions

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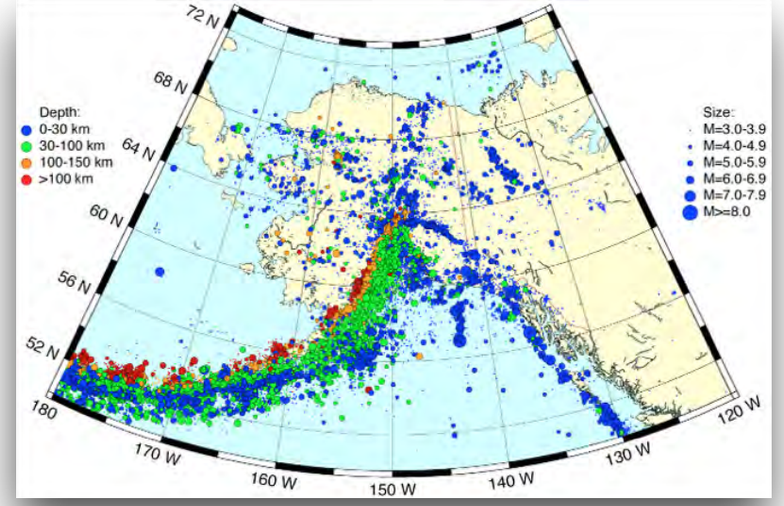


# Recommendations

- Ensure previous assumptions hold - if not, jettison what follows!
- Large-N arrays to capture spatial and temporal variations in fault zone and broad scale structure (faults, damage zones, bulk…)
- Suites of offshore observatories for megathrust related questions
- Rapid response capabilities to chase suspicious foreshock & big aftershocks sequences, volcanic crises
  - Precise locations & mechanisms
  - Lower magnitude thresholds
  - Increased resolution of big events
- Improved analysis tools
  - Data processing
  - Forward/inverse modeling
  - Common workbench environment
  - Access to sufficient compute power at different scales using different strategies
- Consider decoupling observatories and mechanism for funding analysis in order to ensure vibrant research support that is not overly concerned with consensus vision