The search for time-dependent physical changes on the megathrust and a framework for quantification of their earthquake predictive power

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TE PŪTEA RANGAHAU A MARSDEN

GNS SCIENCE

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- HOBITSS project team
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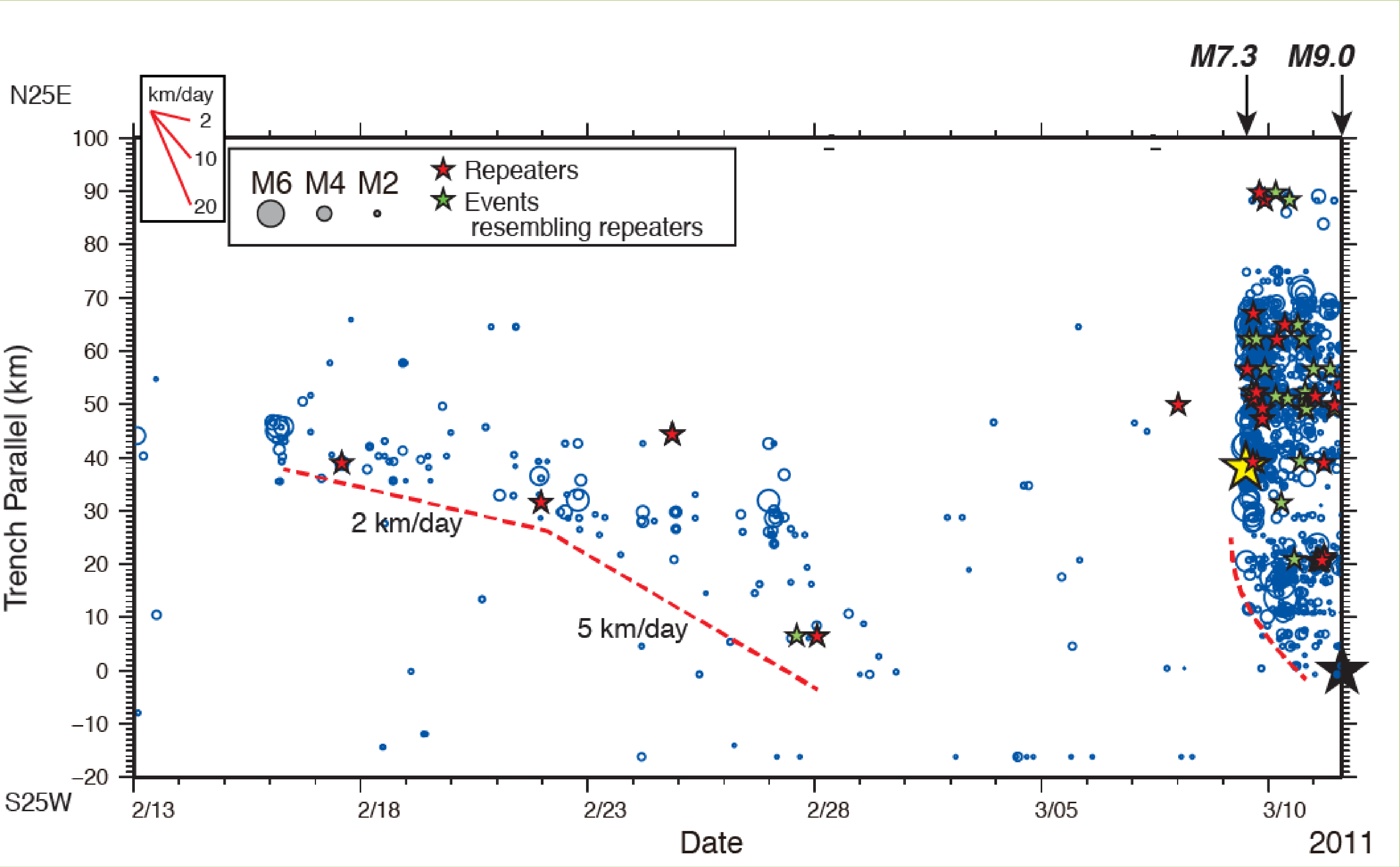
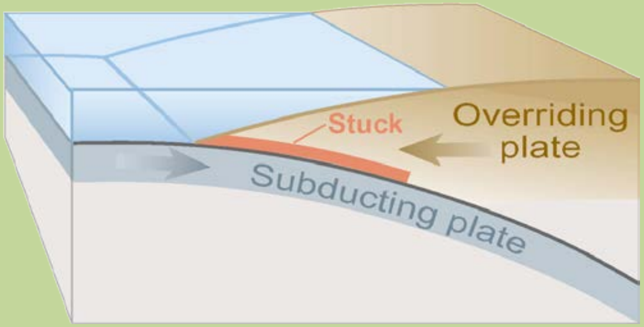
  - K. Mochizuki
  - S. Henrys
  - S. Schwartz
  - A. Sheehan)

Could transient deformation precede mega earthquakes?

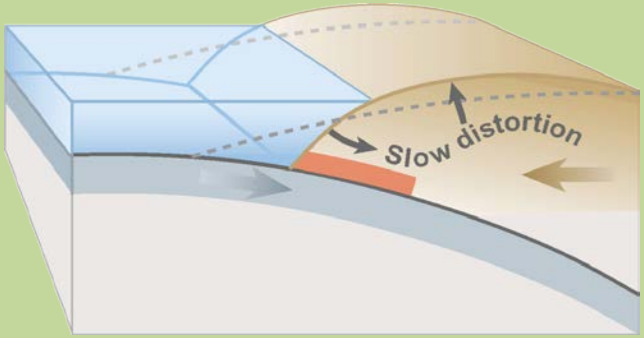


Kato et al., 2012

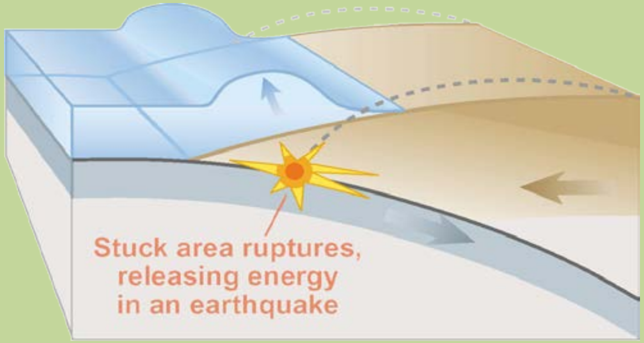
The subduction megathrust

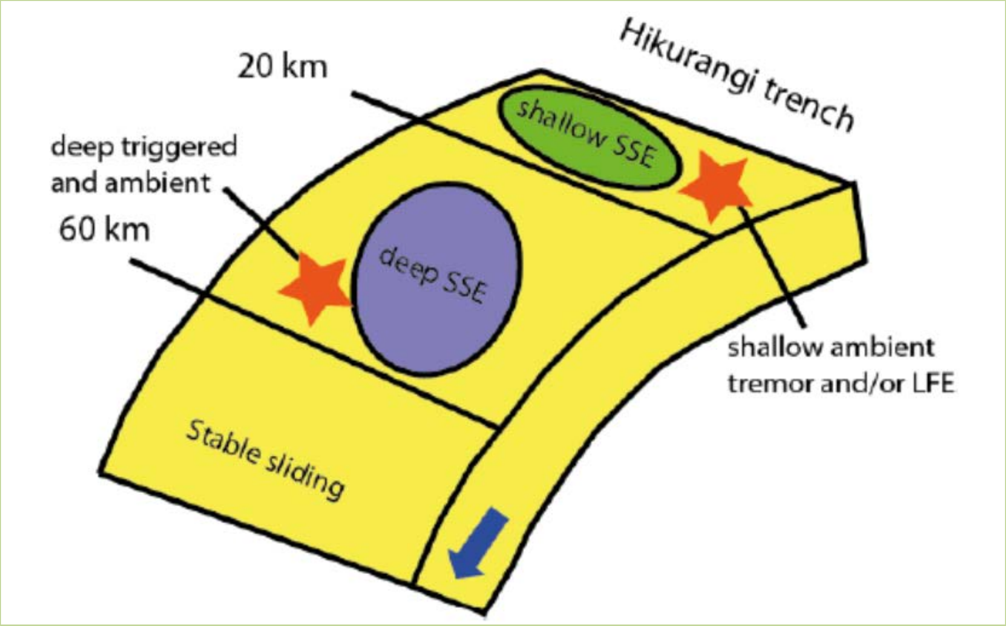


Interseismic period of deformation

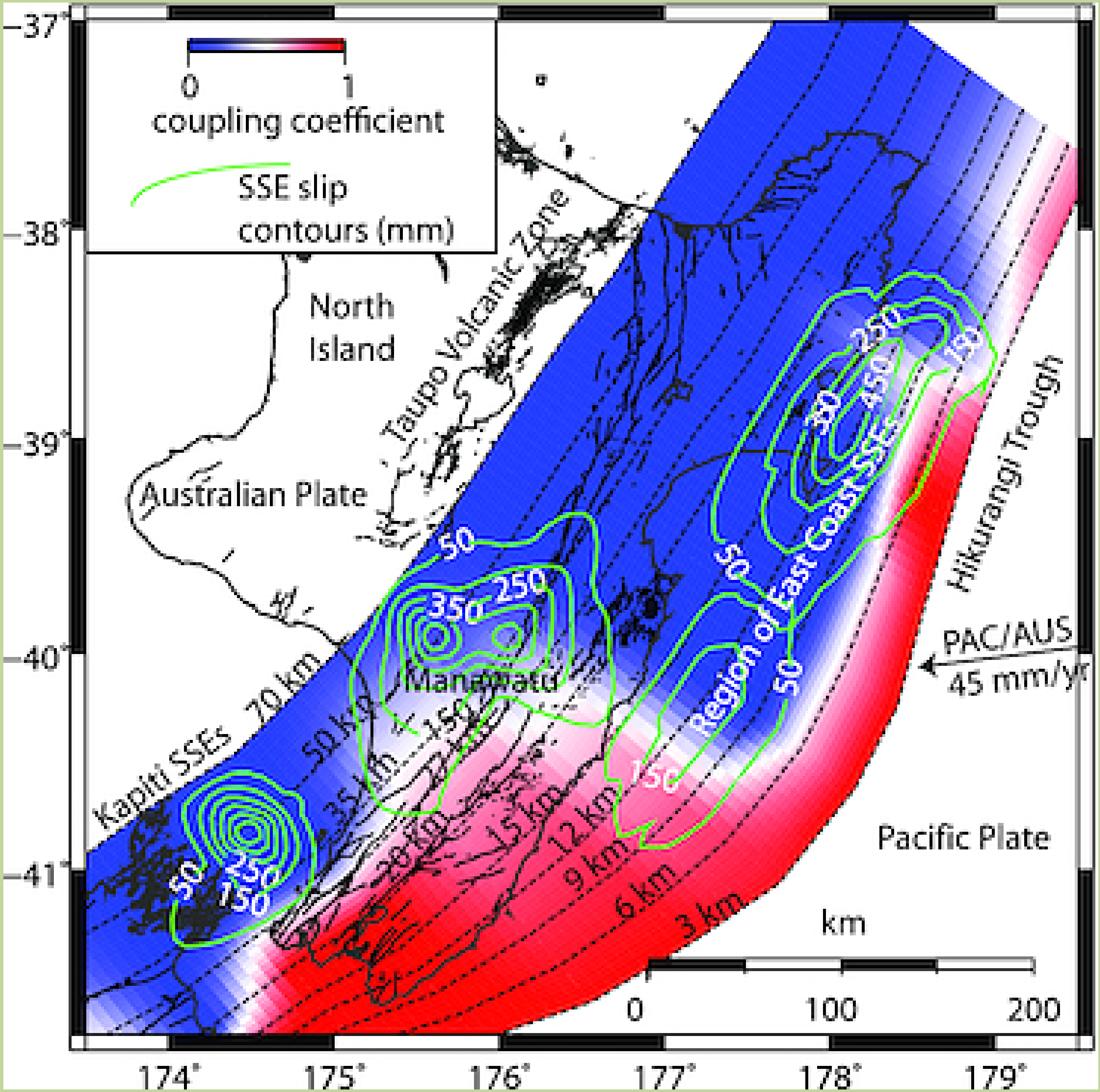


Sudden deformation; possible tsunami





NI, New Zealand: Can it host great subduction earthquakes? Are aseismic events precursors to them?



Wallace et al., 2014

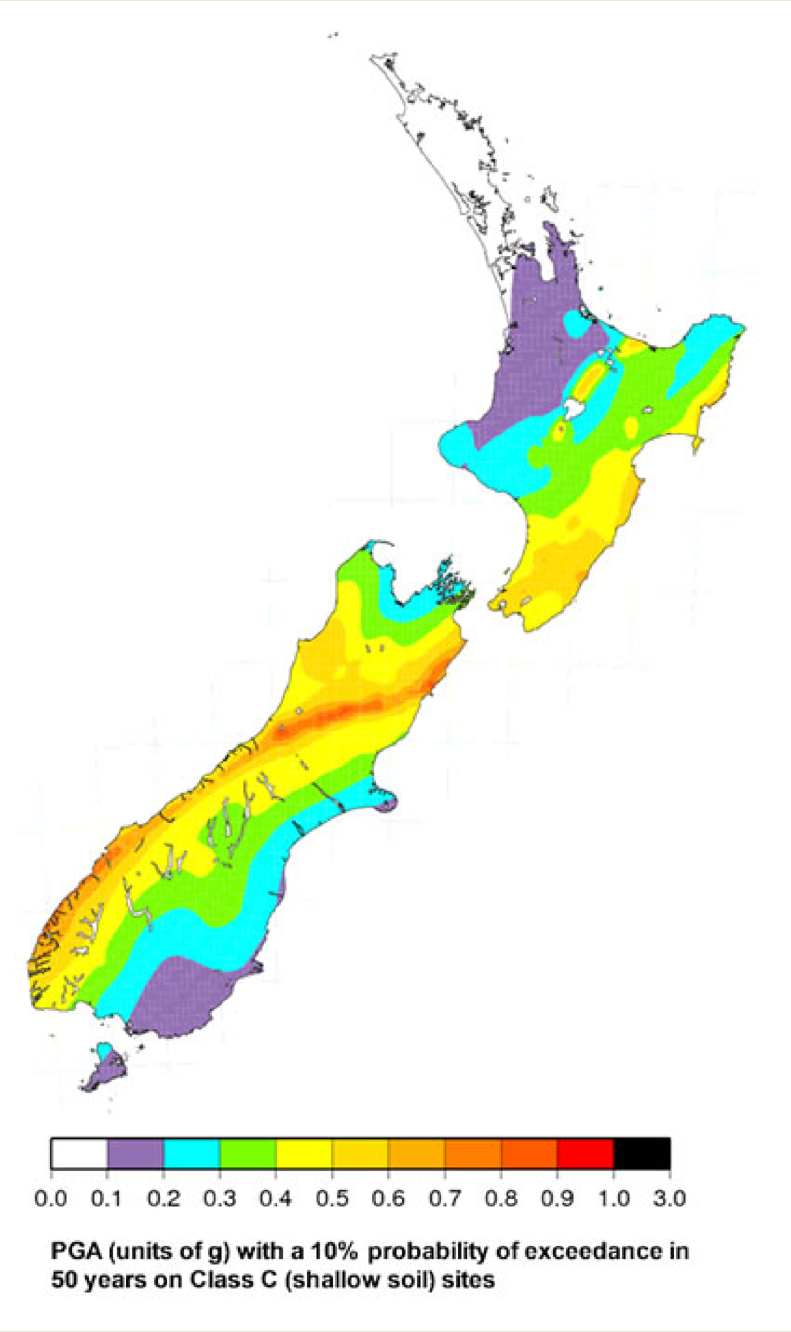
Two parts to talk. Hypotheses:

SSE are associated with changing stress conditions that sometimes increase rates of seismicity (Part 1). The ambient noise wavefield responds to changes on or around megathrust faults during the SSE and this change *is measureable over short time scales* (Part 2).

Background on how seismic hazard mapping actually works (or doesn't, depending on who you ask!)

Probabilistic Seismic Hazard Models

- Spatially variable model of occurrence of ground shaking
- Components
  - Source model
    - Characteristic ruptures
    - Background sources
  - Ground motion prediction



Sterling et al., 2012

Hybrid models: The way of the future in hazard 'source modelling'

Forming hybrids is one way to increase the information gain of forecasts. Sometimes the physics will demand complex hybrids (for example, tidal forcing, delayed triggering, dynamic stressing, etc.).

Types of hybrid models

- **Additive hybrids**
  - **Protect against "blind-spots" of individual models**
- **Maximum hybrids**
  - **Compensate for diminishing time-varying information with** increasing time horizon
- **Multiplicative hybrids**
  - **Exploit independent information on earthquake occurrence held by different models or data sets to ramp up probabilities in some cells. This is especially useful when datasets contain both complementary AND overlapping sensitivities.**

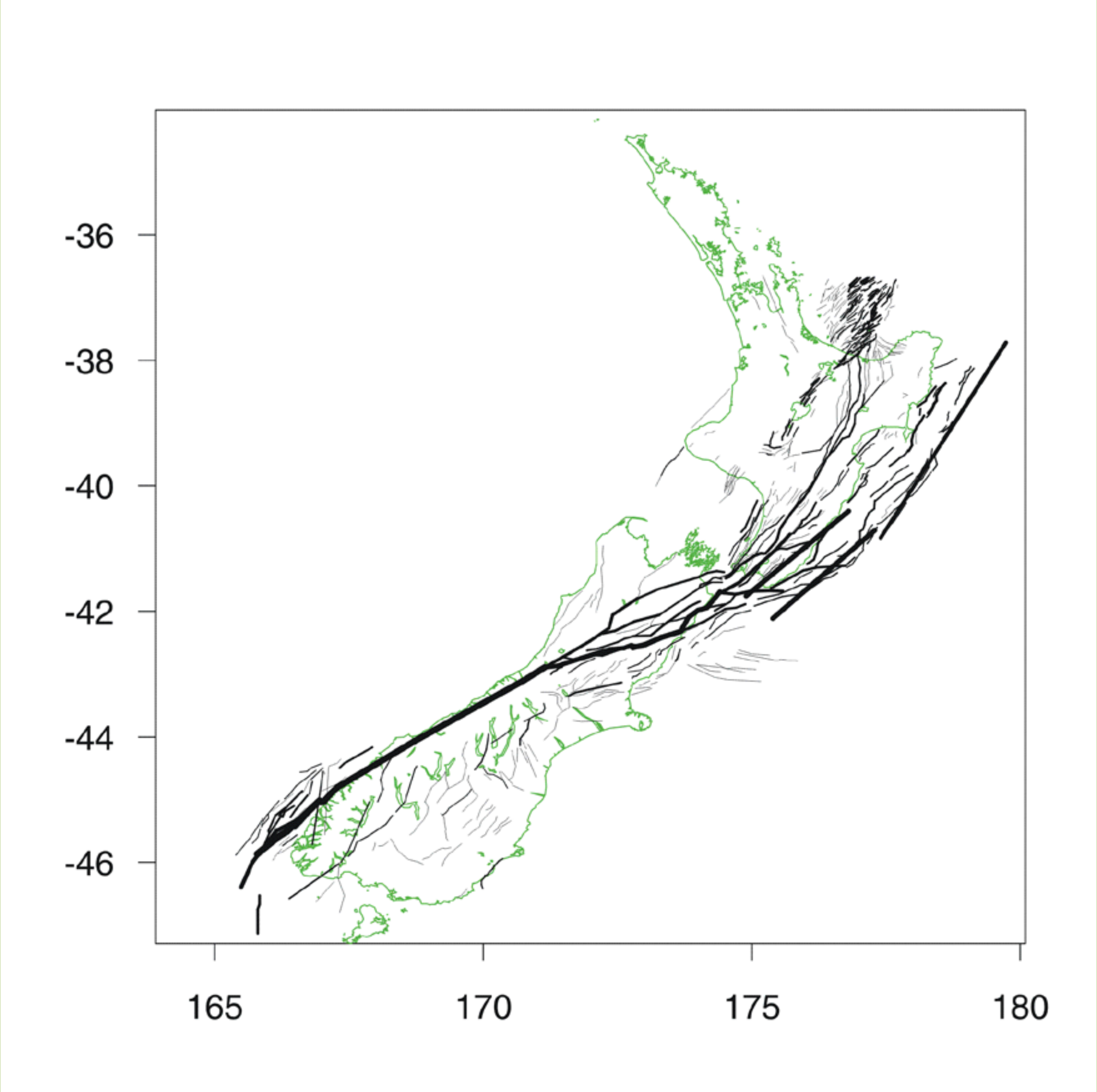
Our approach Multiplicative Hybrid (Rhoades et al., 2014 & 2015) but time variable

- Utilizes machine learning and artificial intelligence
- New and improved data streams and modeling methods relevant to earthquake occurrence are increasingly becoming available, e.g.
  - GPS network data
  - Stress change modelling
  - Plate coupling models
  - Models of delayed triggering
- Some may lead to new individual models for earthquake occurrence.
- In any case, the key practical question is: do they contain predictive information?

Mhybrid - optimize on 'training period' and validate on 'testing period'

- Fit coefficients of multiplicative models on first period of data (training) and use those same coefficients to test predictive value during the testing period
- IGPE = $(\ln L_{\mathrm{model}} - \ln L_{\mathrm{SUP}}) / N_{eq}$
- Dependent on number of earthquakes and optimization windows

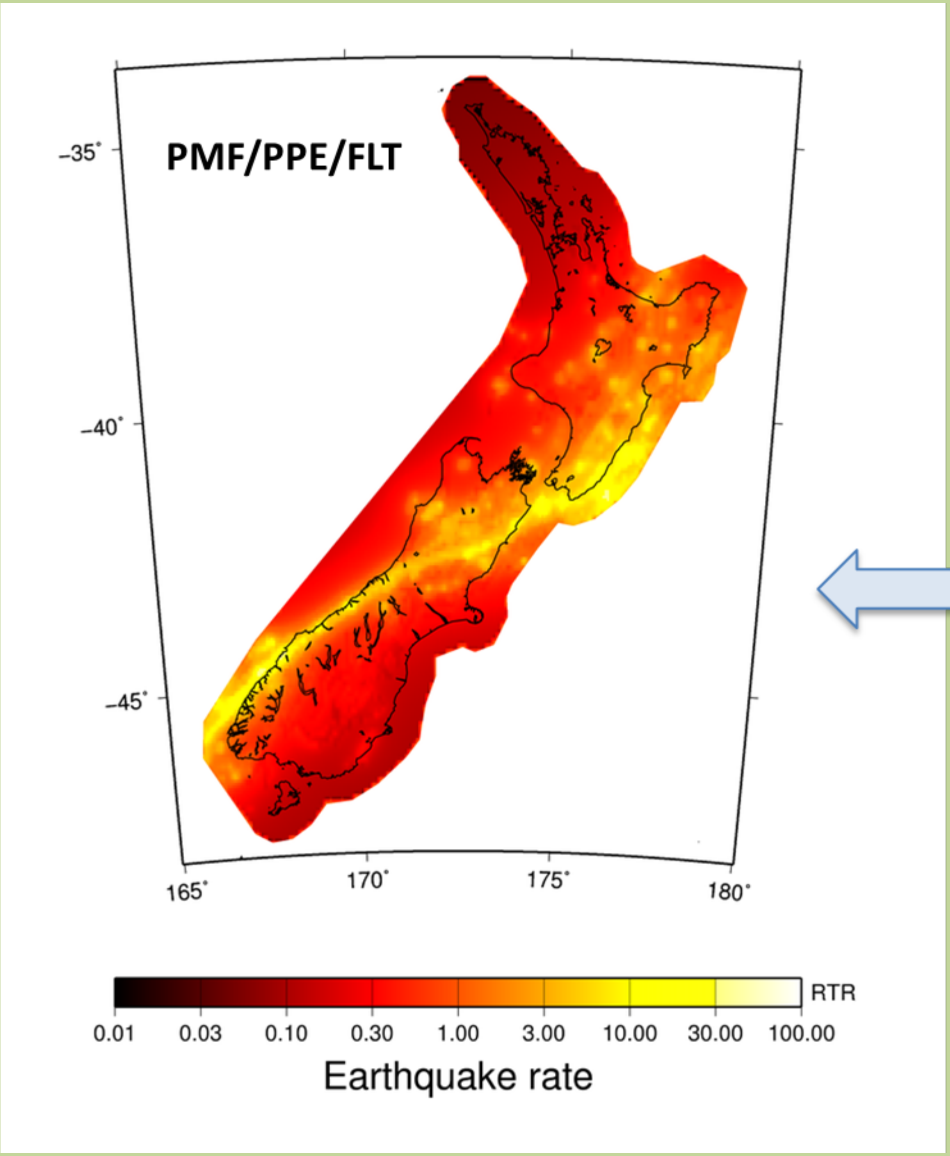
Example input layer: Proximity to Mapped Faults (PMF)



The earthquake occurrence rate density is high near to mapped faults, and low far away from mapped faults.

The faster the slip-rate of nearby mapped faults, the greater the rate density.

Example of time independent source model from MHybrid



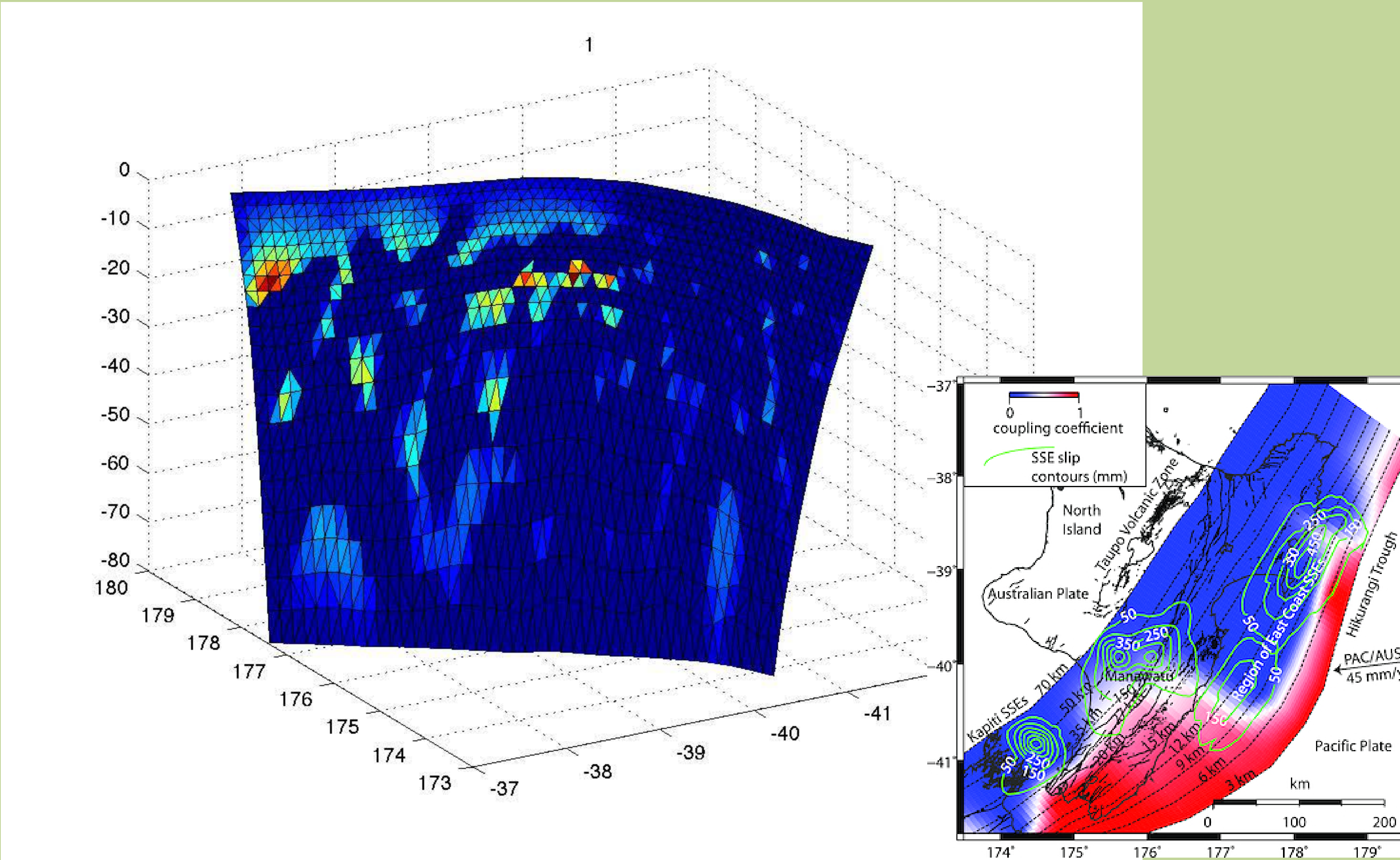
Rhoades et al., 2015 RTR –relative to reference in which one earthquake per year is expected to exceed any magnitude M in an area of 10^M km^2.

This model is base on a time and space invariant background model (SUP), proximity to mapped faults (PMF), proximity to past earthquakes (PPE) and a binary descriptor of cell (FLT)

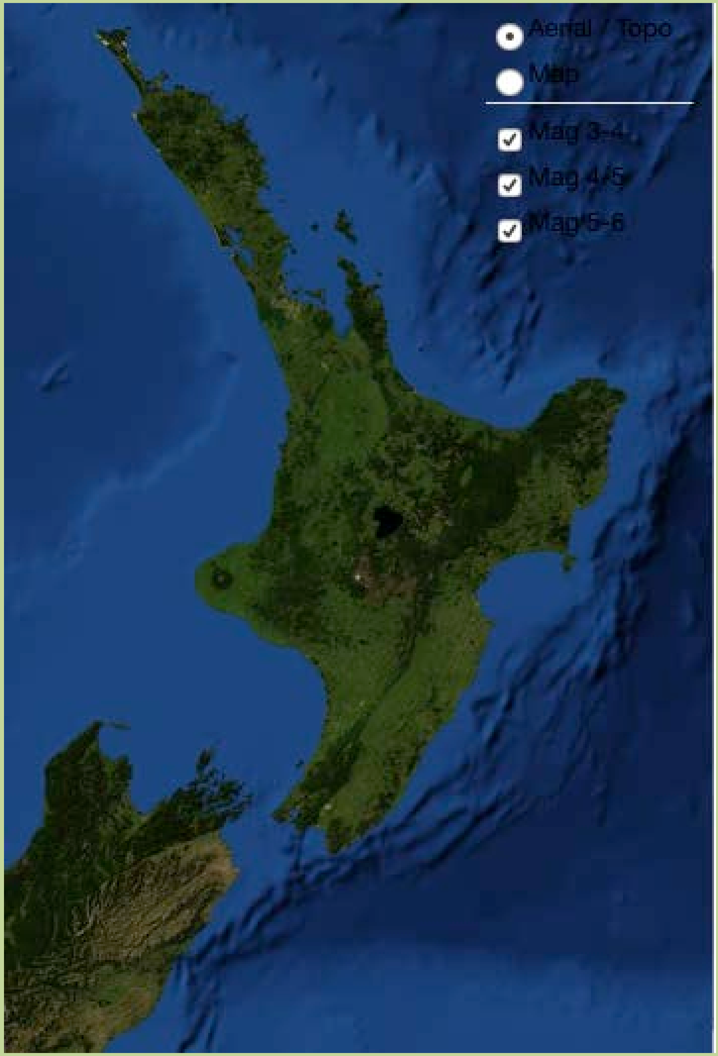
Hypotheses:

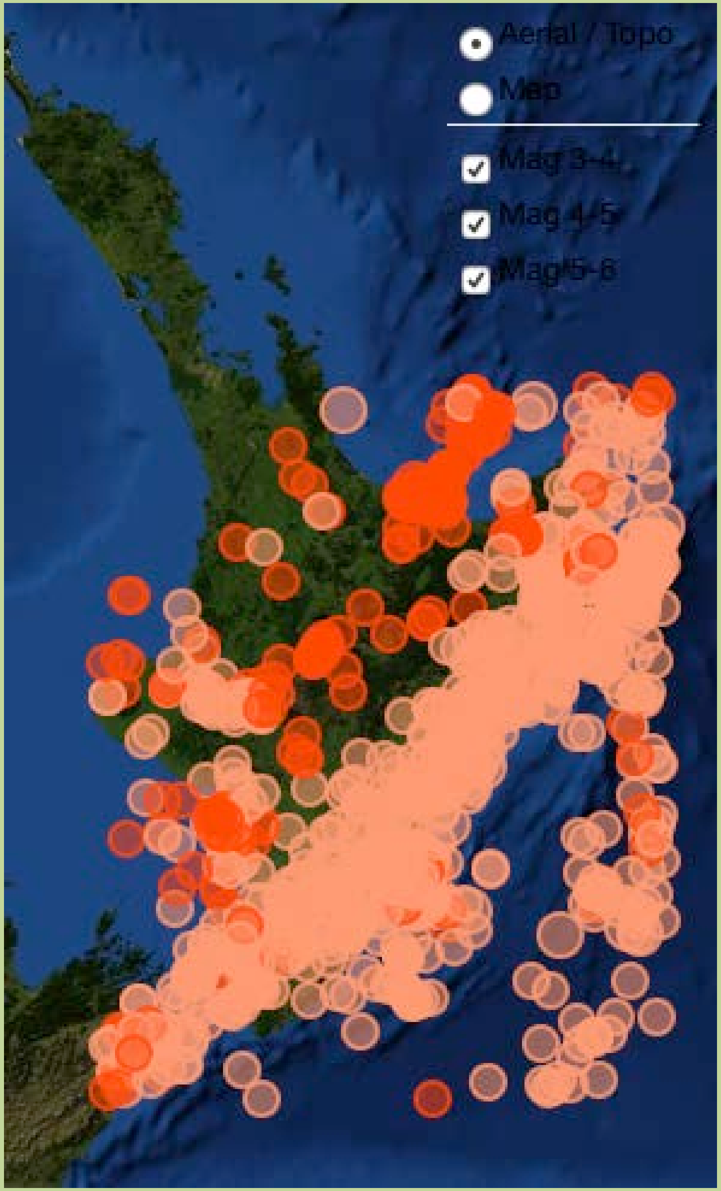
SSE are associated with changing stress conditions that sometimes increase rates of seismicity. The ambient noise wavefield responds to changes on or around megathrust faults during the SSE and this change *is measureable over short time scales.*

Network Inversion Filter (NIF) results showing SSE on the Hikurangi Margin (Bartlow et al., 2014)

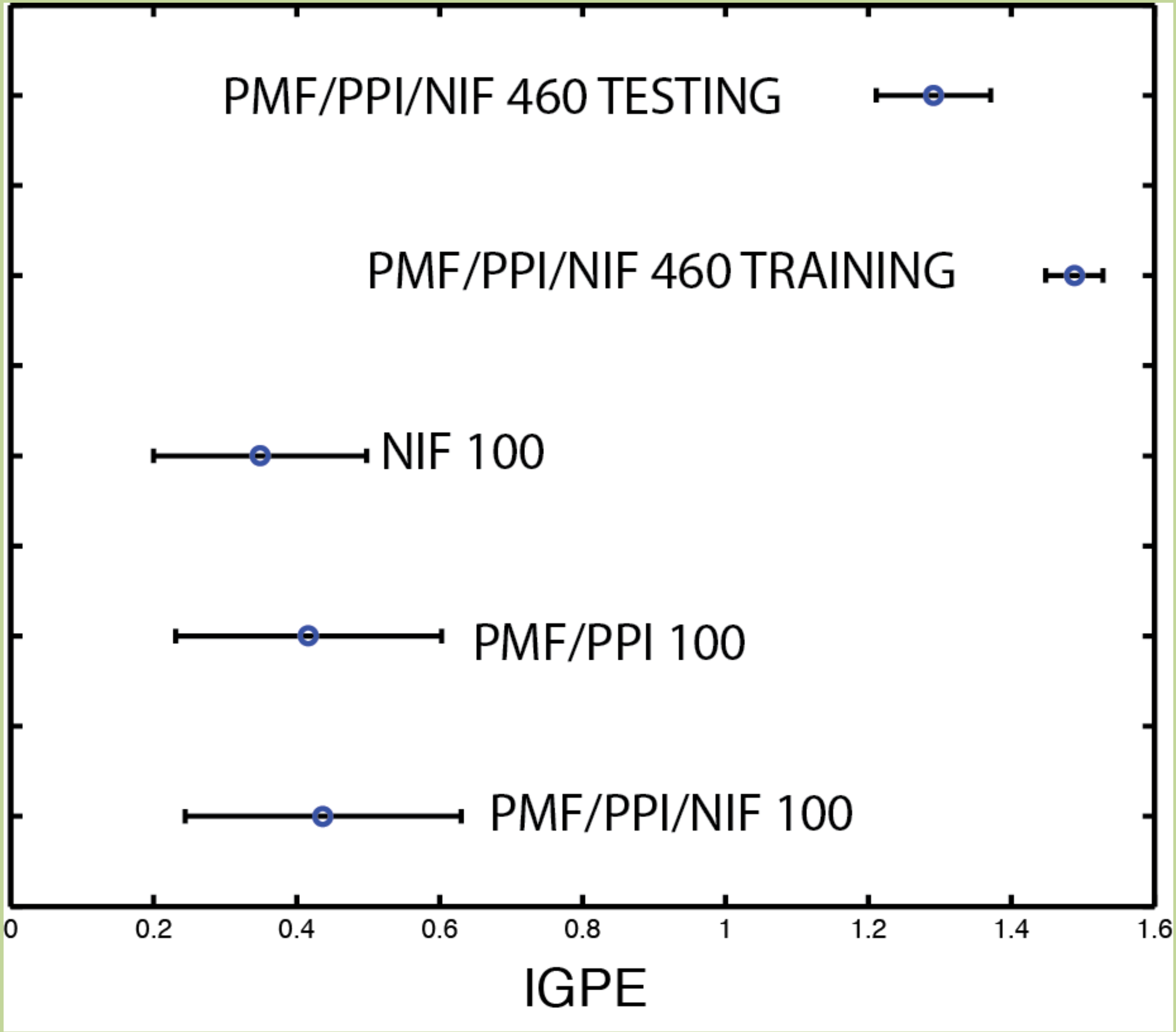


M3+ November 2009 – October 2013 test for Mhybrid

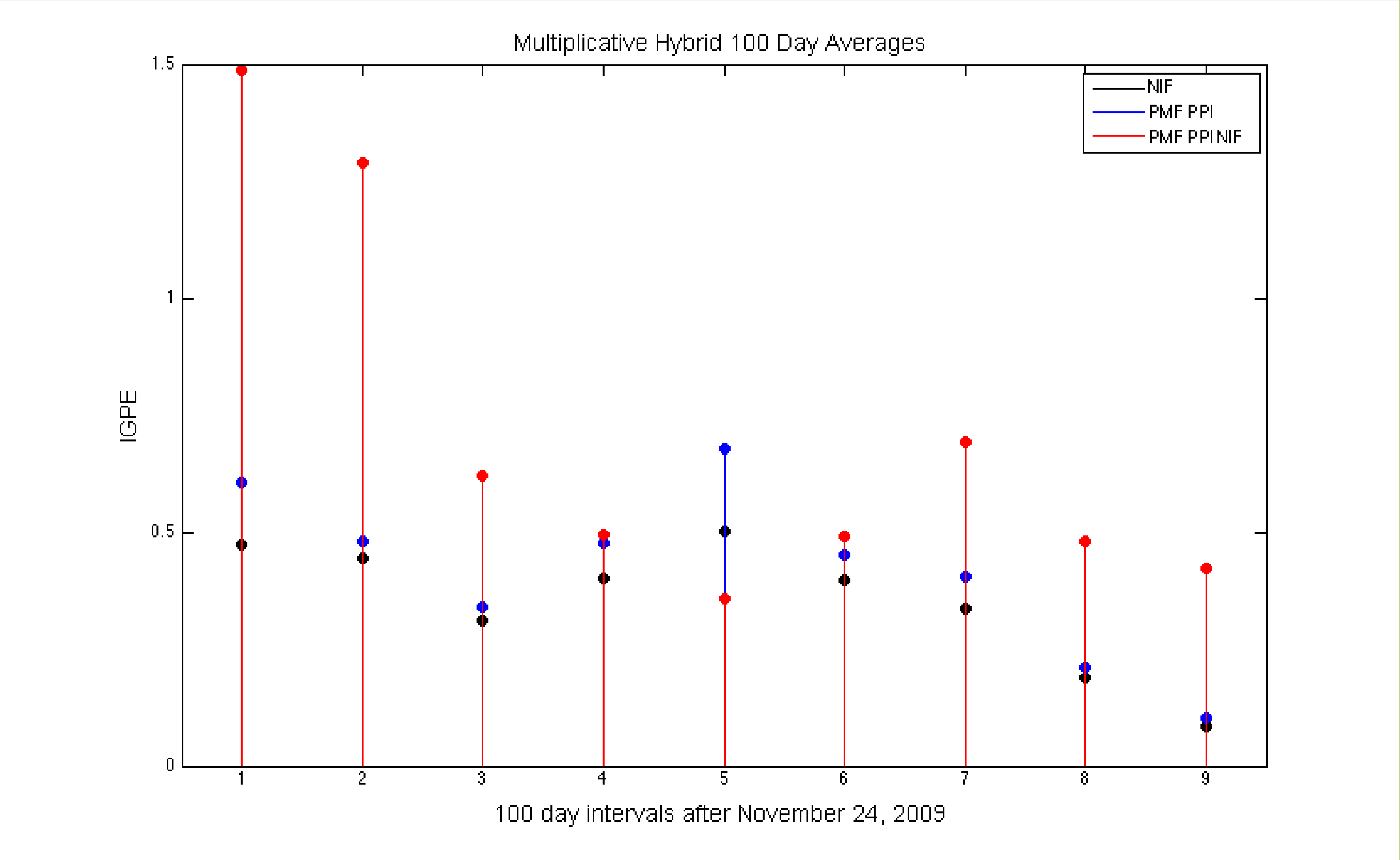


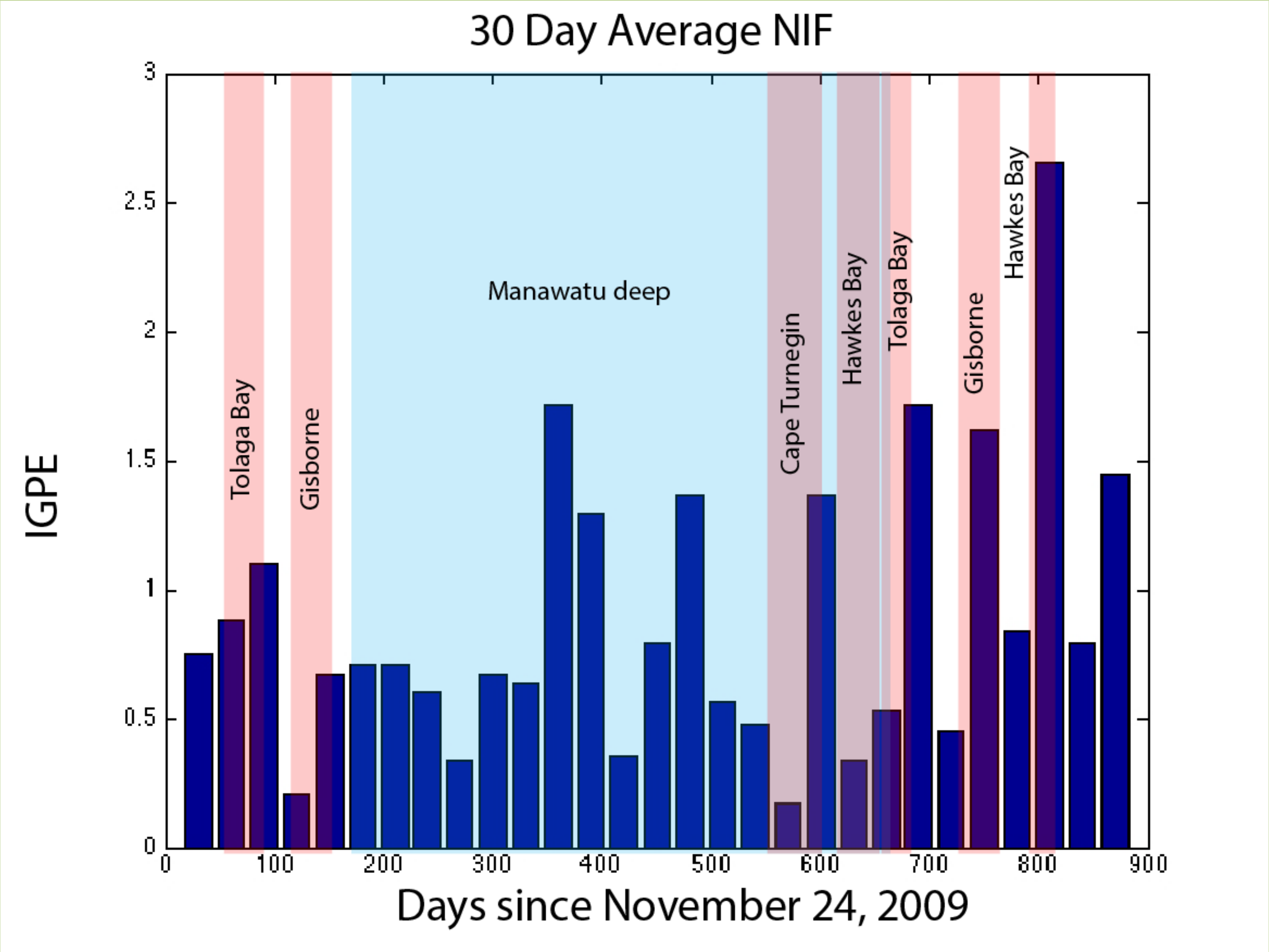


Time independent tests (only optimize once)



Testing 100 day intervals (train for 100 days, predict the next 100 → time dependent models)





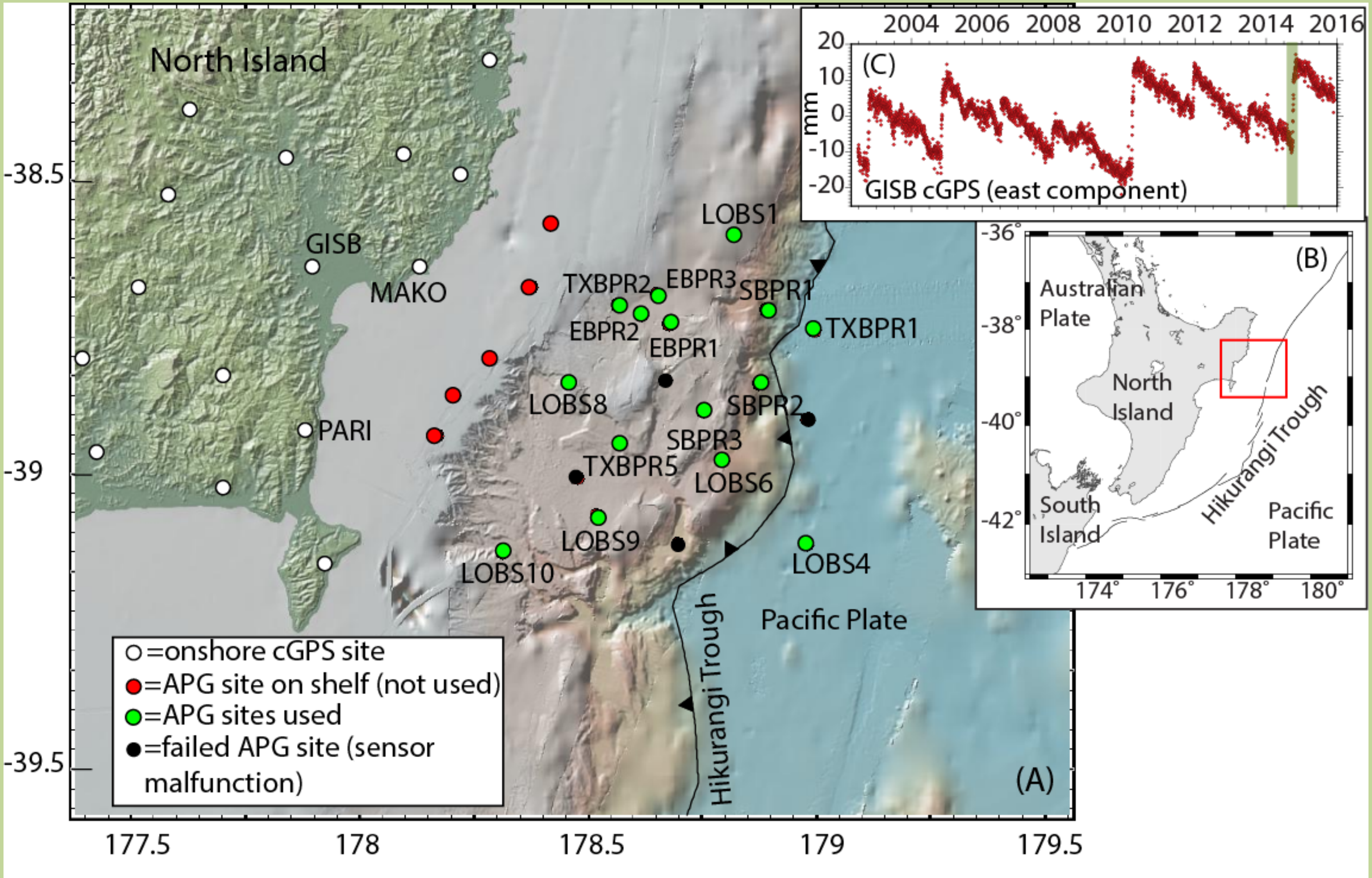
Multiplicative hybrid approach of Rhoades et al., 2014

Part 1 is over!

Part 2. Hypotheses:

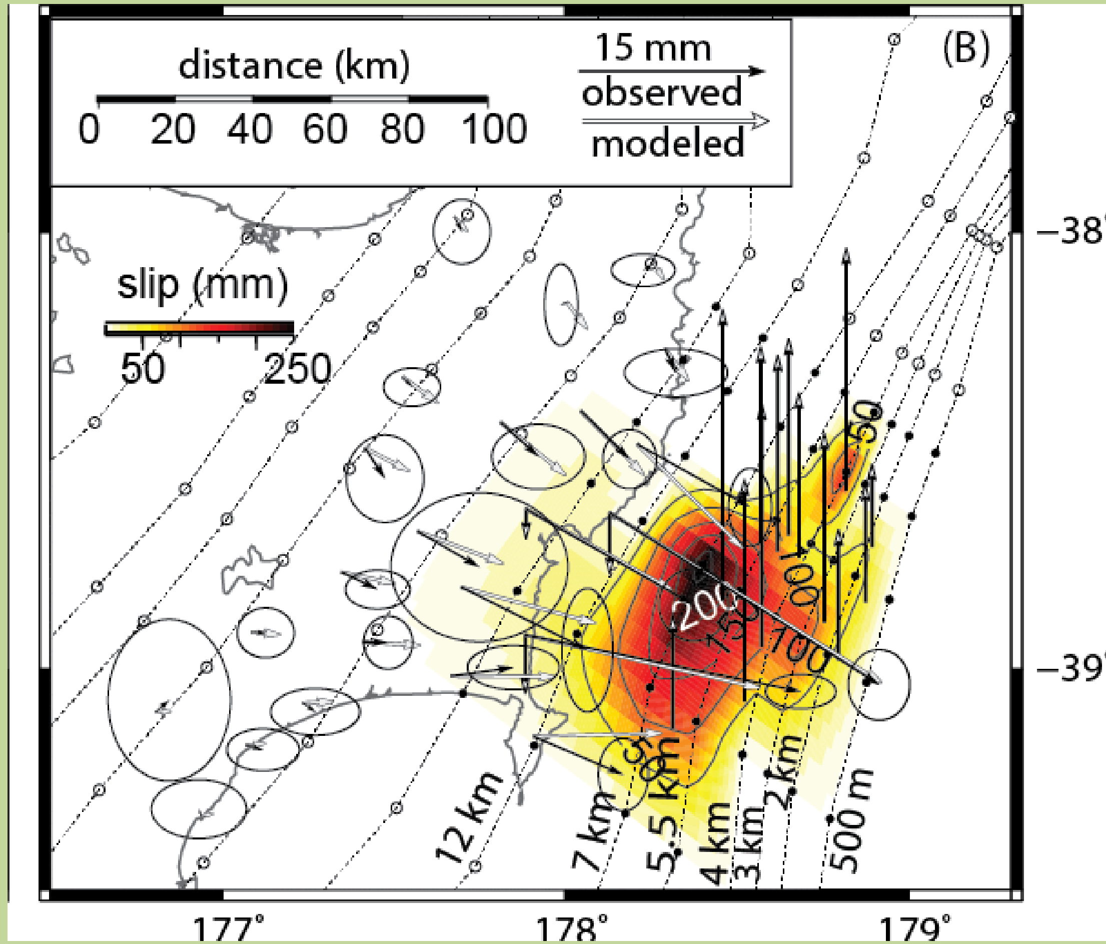
SSE are associated with changing stress conditions that sometimes increase rates of seismicity. The ambient noise wavefield responds to changes on or around megathrust faults during the SSE and this change *is measureable over short time scales*

SSEs recur here every 1-2 years, with very large ones every 4-5 years.



Wallace et al., 2016

Increased seismicity around the periphery of the SSE



Wallace et al., 2016

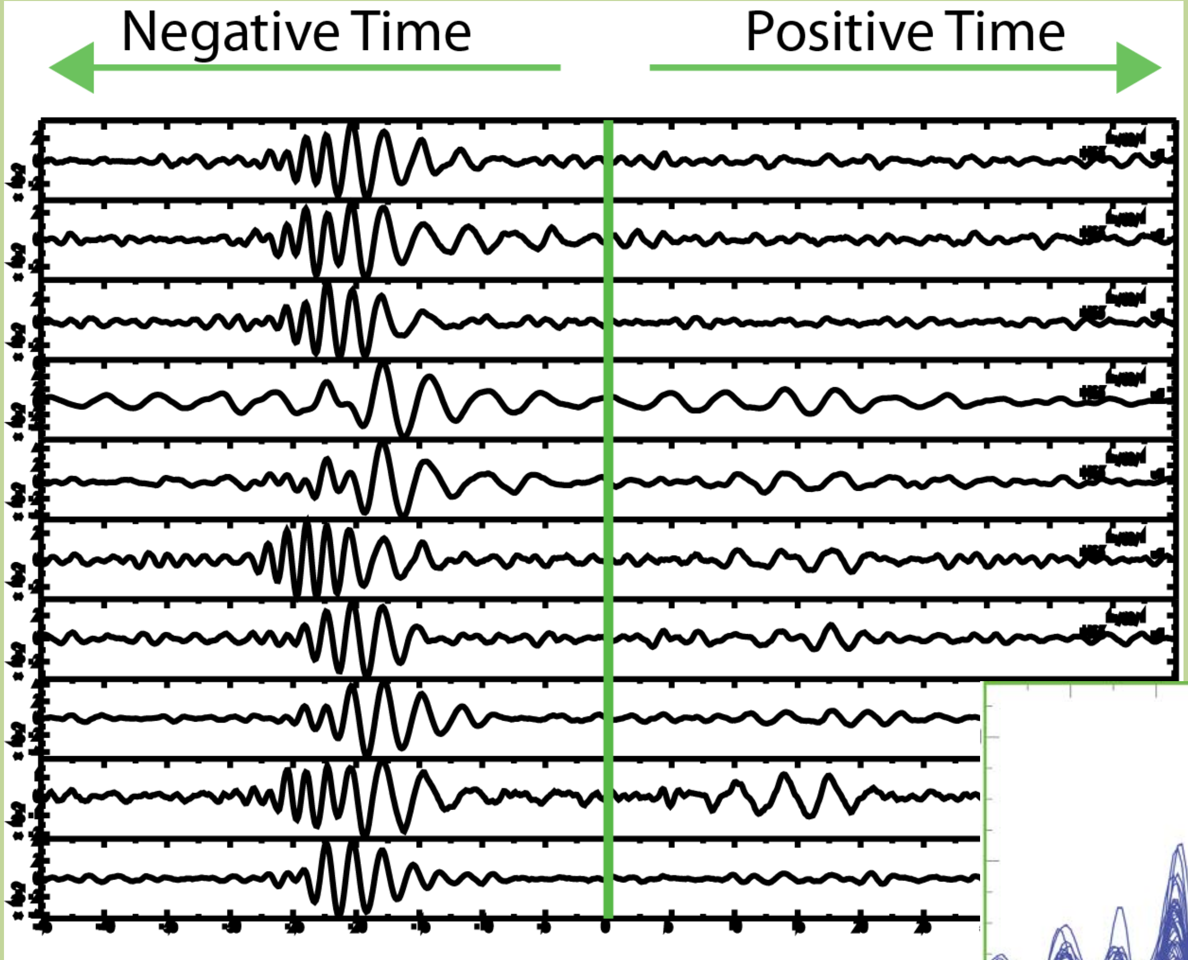
Cross correlations and Green's Functions

Assumptions: Equipartitioning of energy and non-degenerate modes

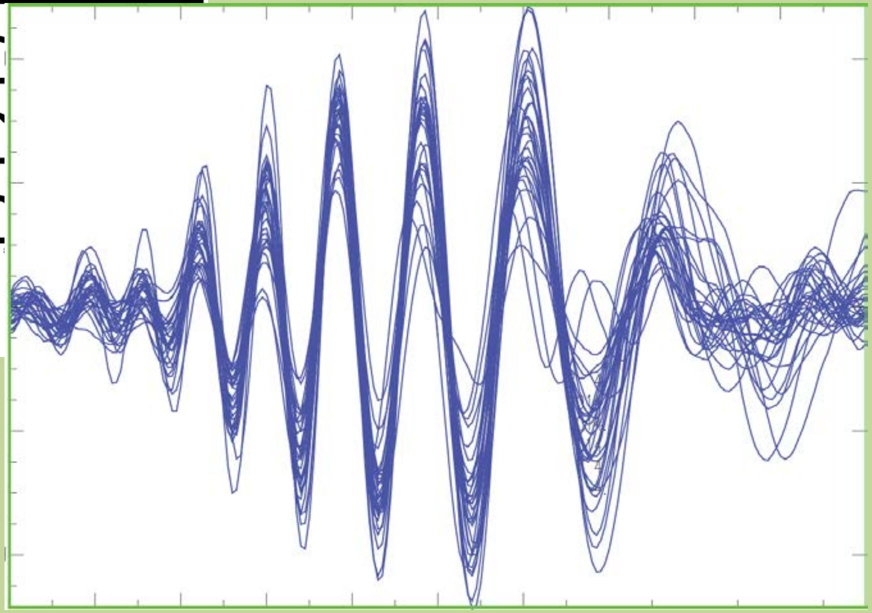
$$C_{U1,U2}(t) = A\left(\frac{dG(U1,t;U2,0)}{dt}\right)$$

Lobkis and Weaver (2001), Wapenaar (2004), Roux et al., (2005)

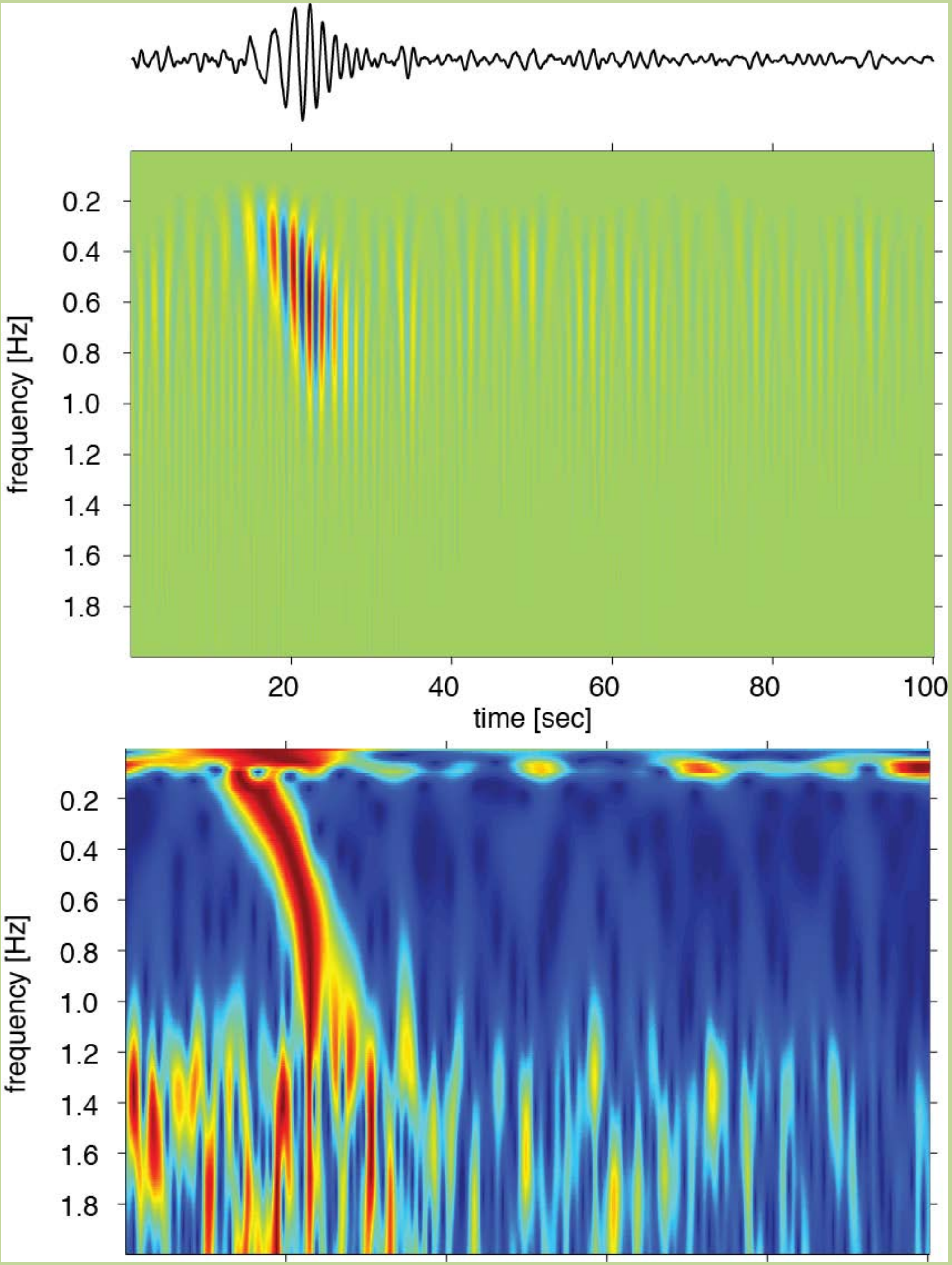
Daily EGF from ERI OBS

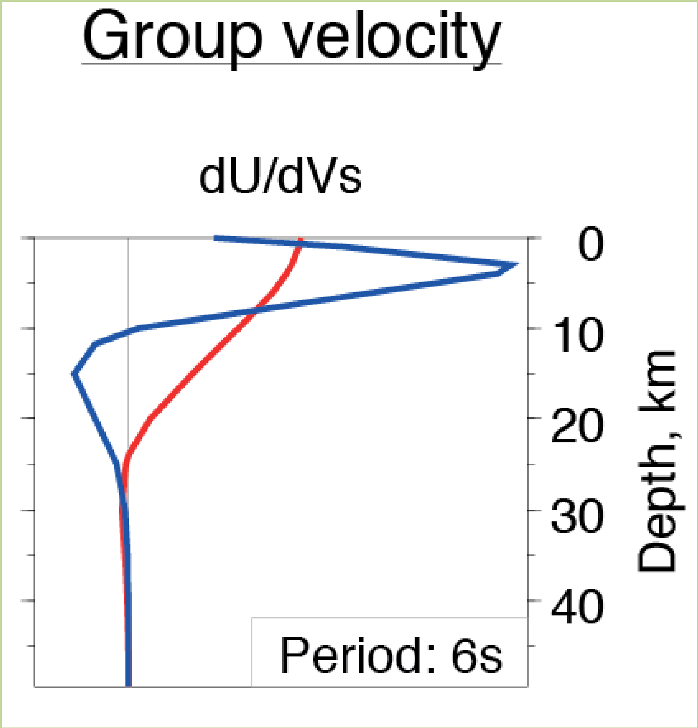


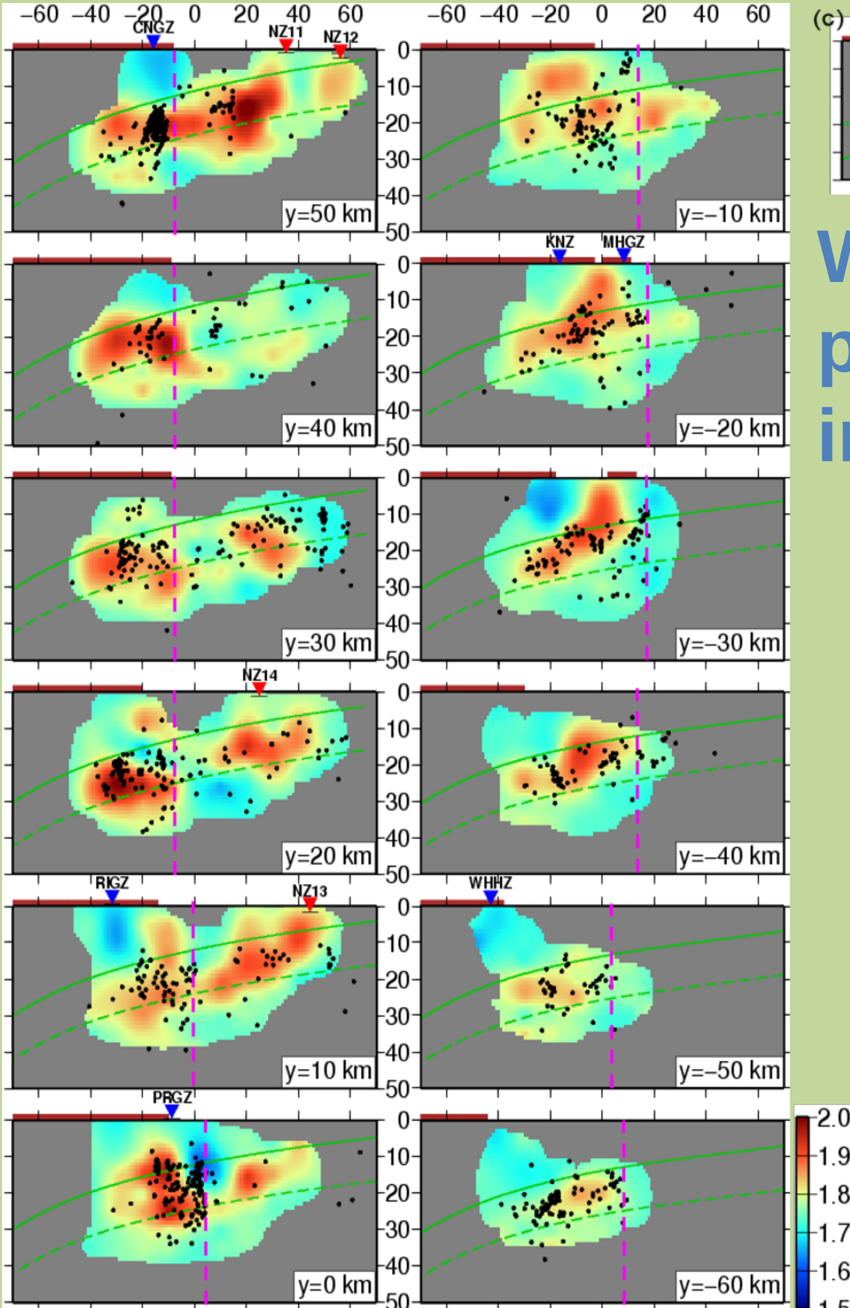
1-Day stacks from EBS1-EBS3

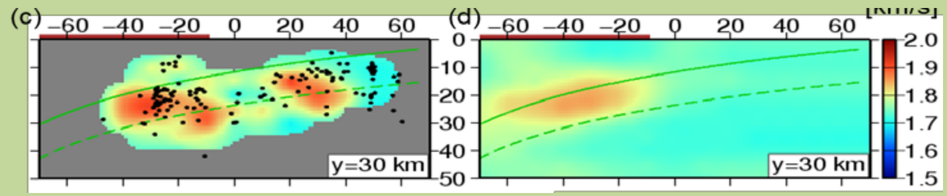


Analysis of disersion (frequency dependent velocity) gives us information about depth-dependent seismic velocity

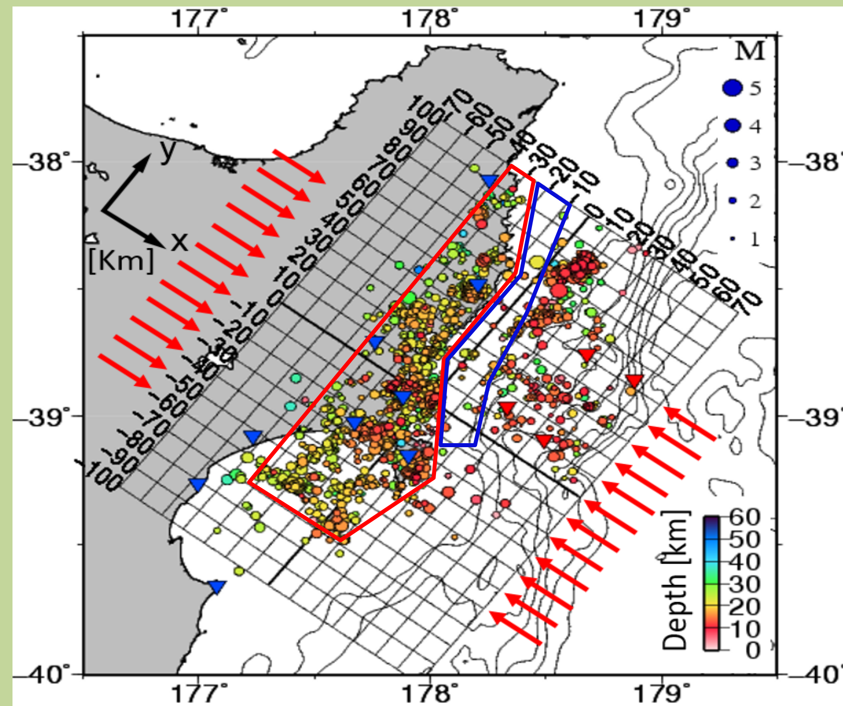






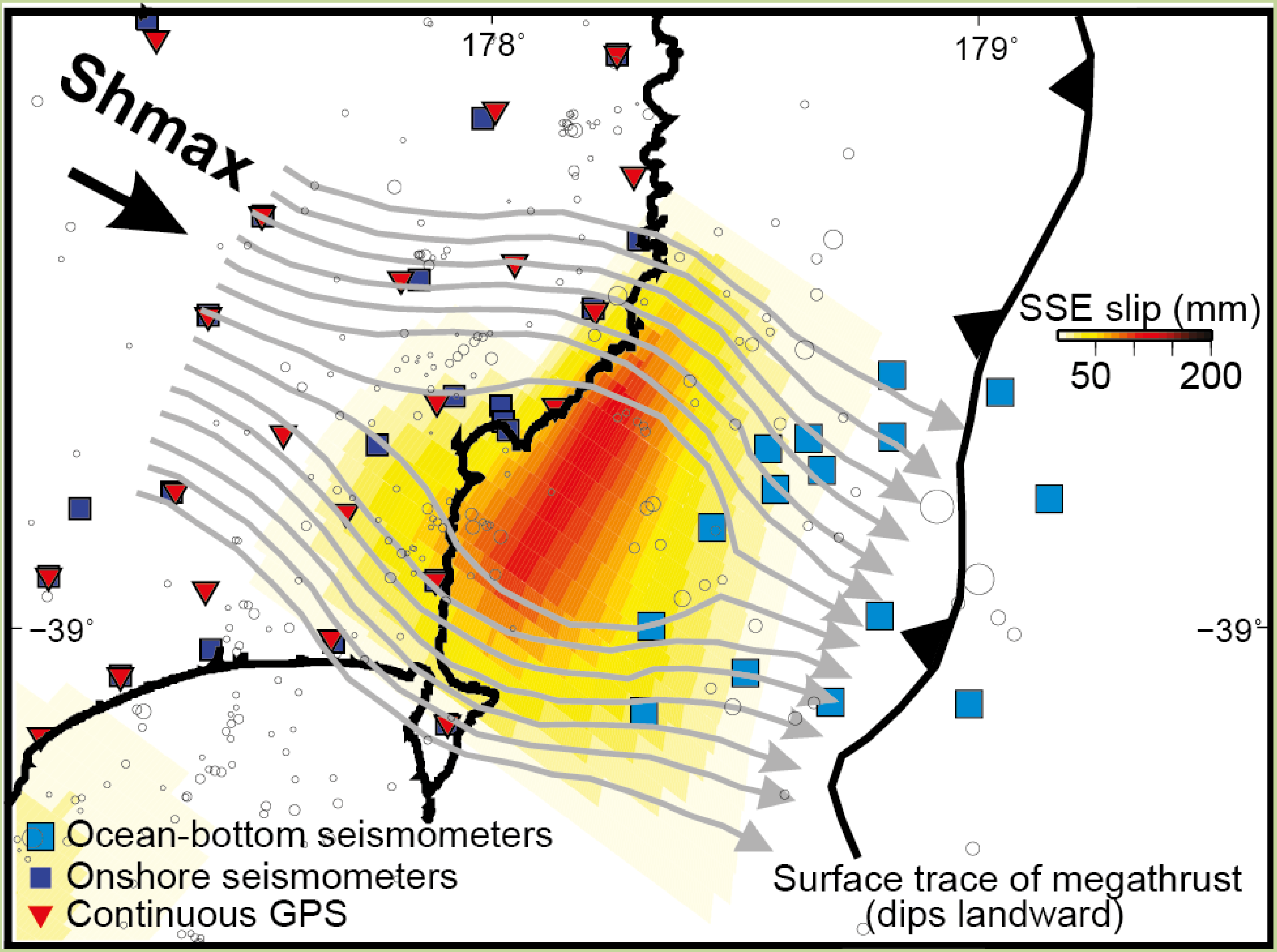


We don’t understand fluid pressures and their influence on seismicity

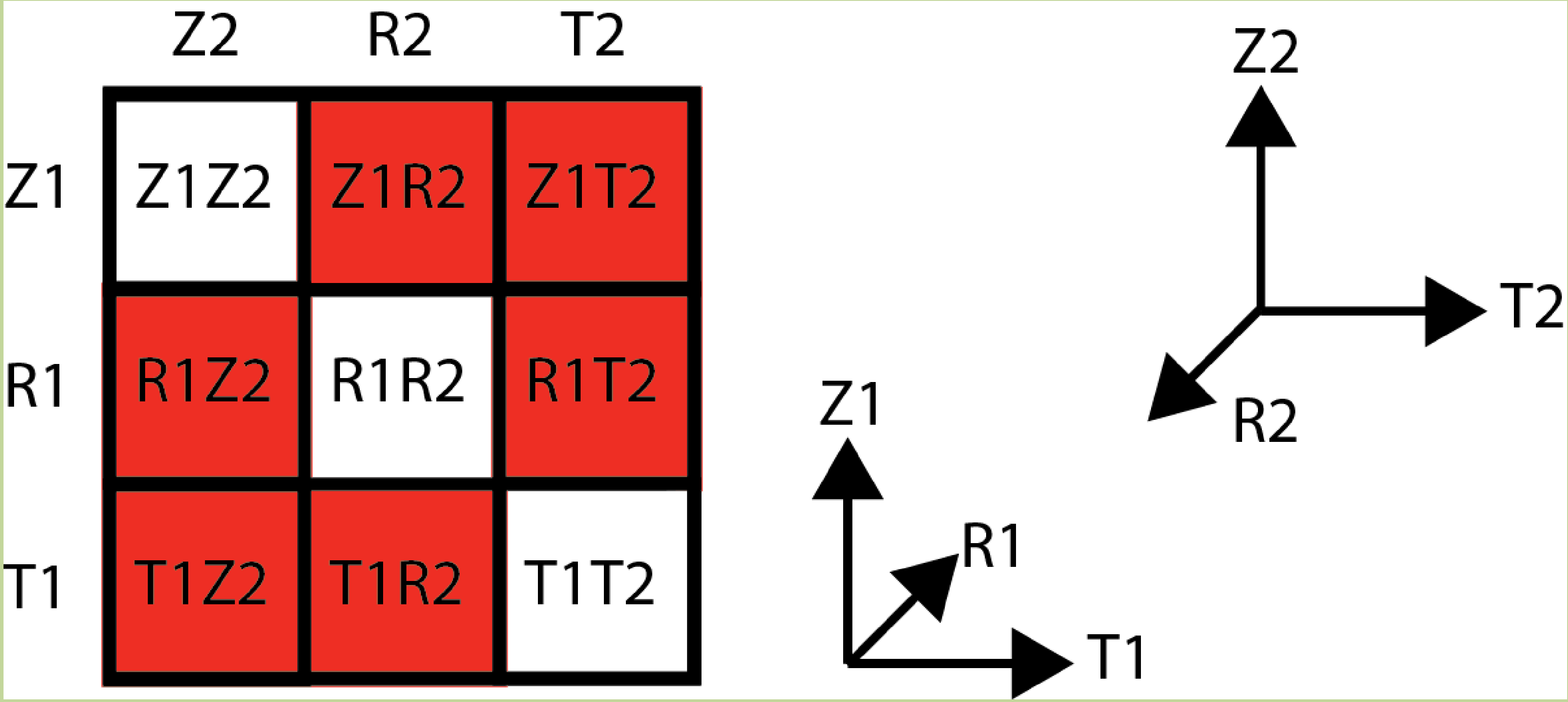


Mochizuki

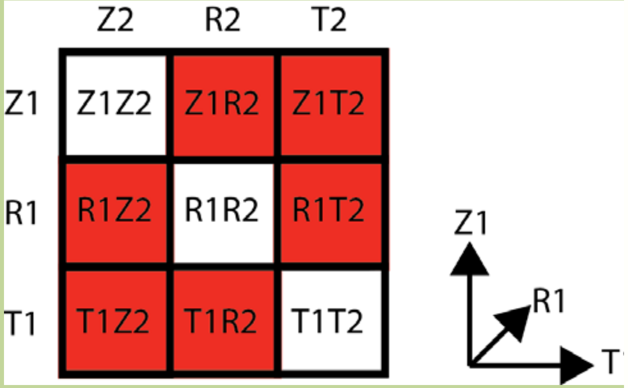
Conceptual model for potential reorientation of principal stresses

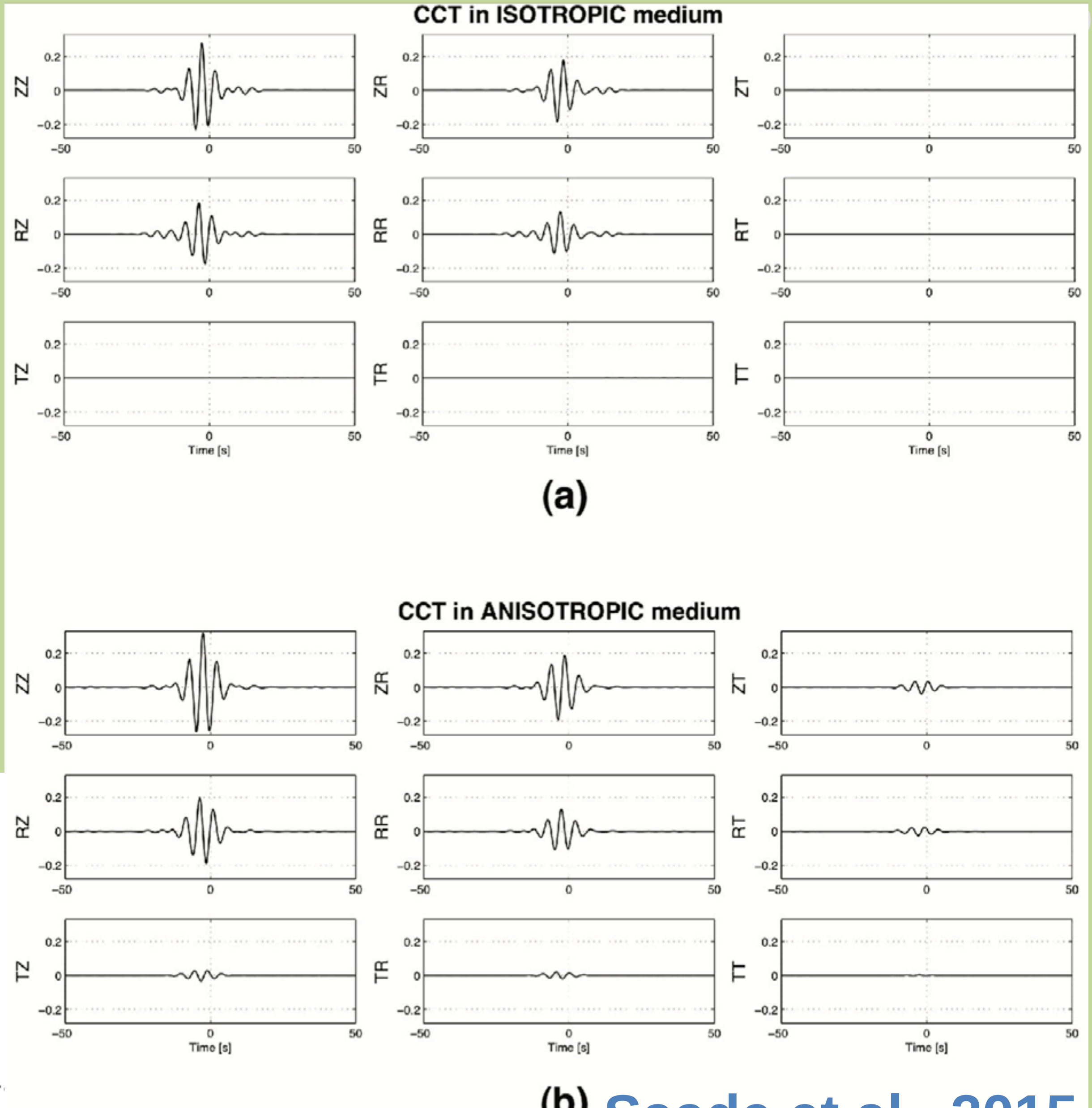


Perhaps seismic anisotropy is more sensitive to changes than isotropic velocity.



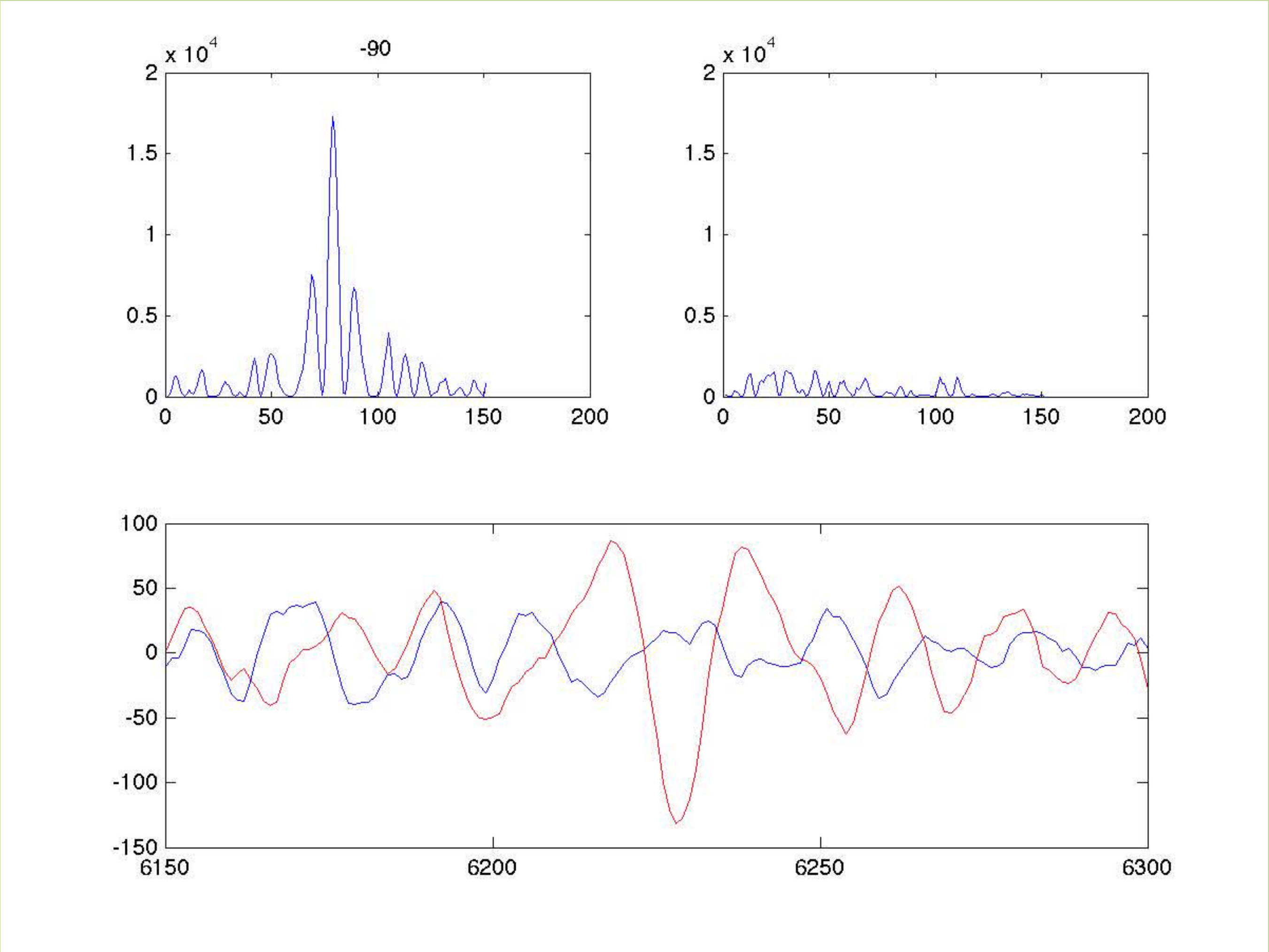
Cross tensor components (ZT and RT) contain information about anisotropy / surface wave polarization



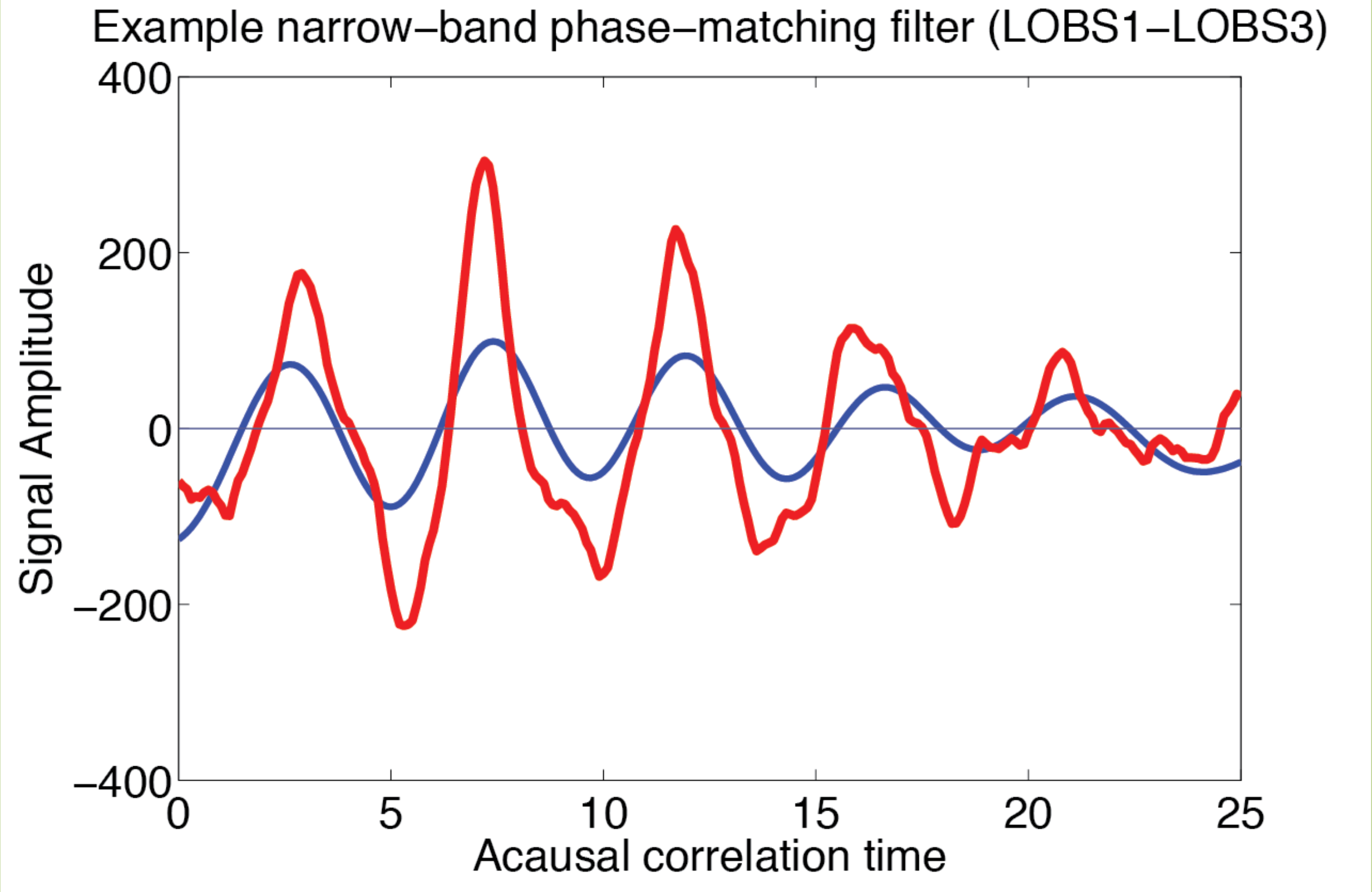


Saade et al., 2015

We establish a baseline orientation of maximum energy by rotating the horizontal components until energy on one is maximized and energy on the other is minimized.

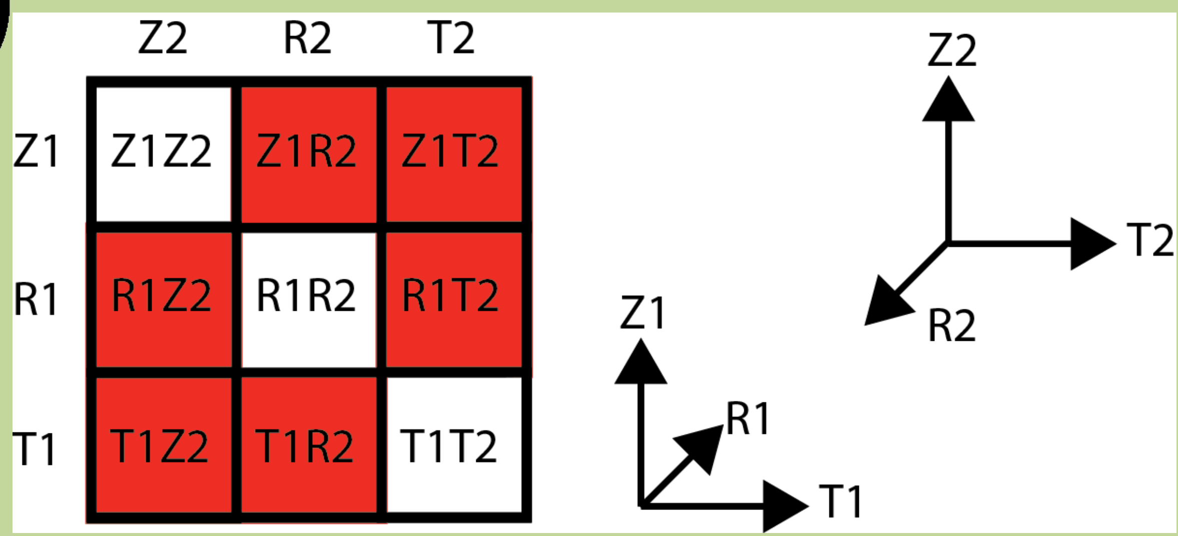


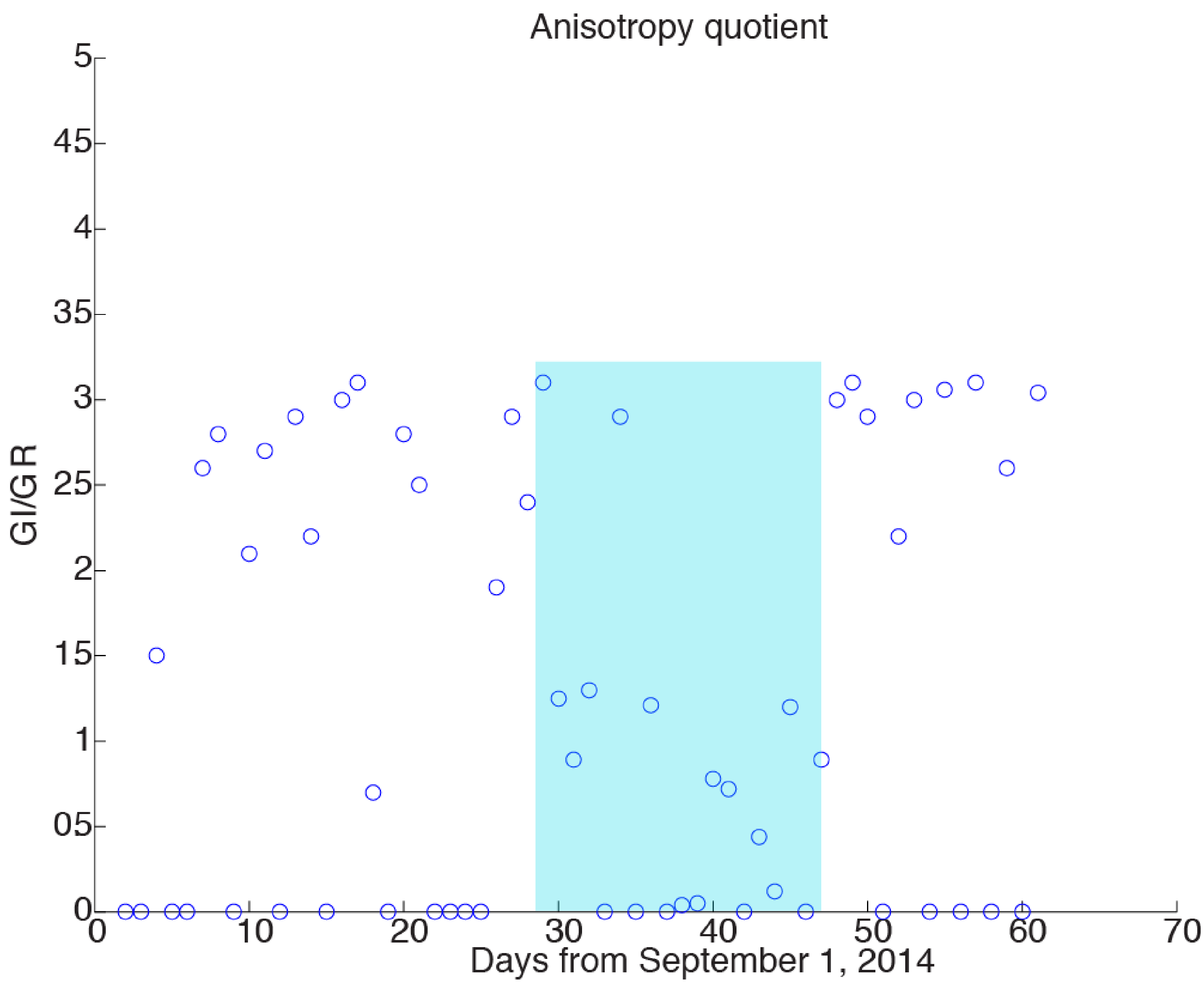
We apply an optimization process for designing a phase-matched filter by minimizing the misfit between our filter and the signal over a narrow bandwidth



We determine a quotient of the real and imaginary phase of the rotated TT correlation time windowed around Love waves.

$$\frac{\left\langle \mathrm{G}_{ij}(I) \right\rangle}{G_{ij}(\mathrm{Re})}$$



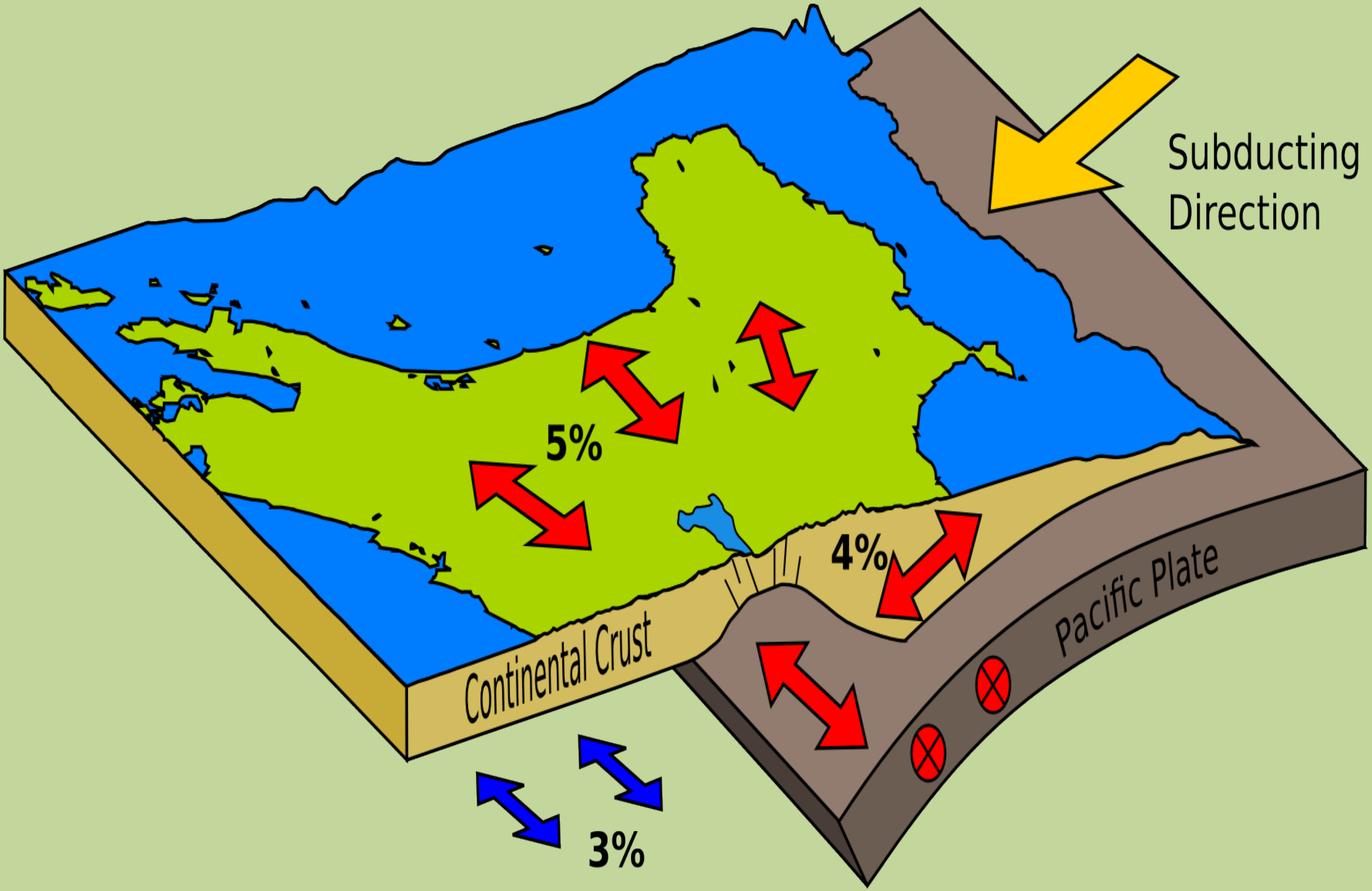


Anisotropy quotient
GI/GR
5
45
4
35
3
25
2
15
1
05
0
0
10
20
30
40
50
60
70
Days from September 1, 2014

Conclusions to take away

- Earthquake rates respond to transient megathrust aseismic deformation in a quantifiable way.
- Surface wave polarization anisotropy appears to be sensitive to short-term shallow stress transients and therefore provides an enticing method for megathrust monitoring and mapping changes during the slow-slip cycle.

The End
(with a beautiful model from Yifan Yin)



$$\int_{\theta}\int_{\phi} K(\theta,\phi)\,\delta U(\omega,\theta,\phi)\,d(\theta)\,d(\phi) = \delta Ui(\omega)$$

$$\delta U(\omega) = \delta Uiso(\omega) + A1(\omega)\cos(2\psi) + A2(\omega)\sin(2\psi)$$
$$+A3(\omega)\cos(4\psi) + A4(\omega)\sin(4\psi)$$