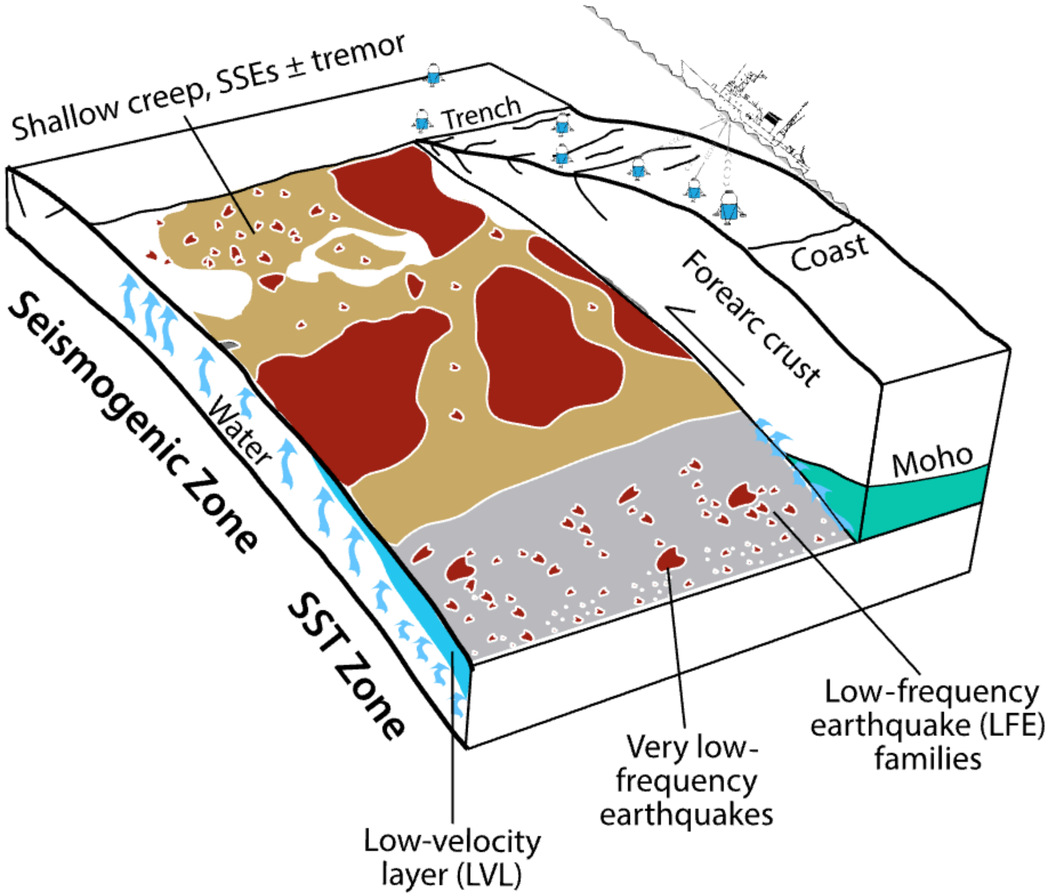
The relationship between interseismic locking, slow slip, and afterslip at subduction zones

(and implications for the role of fluids in faulting)

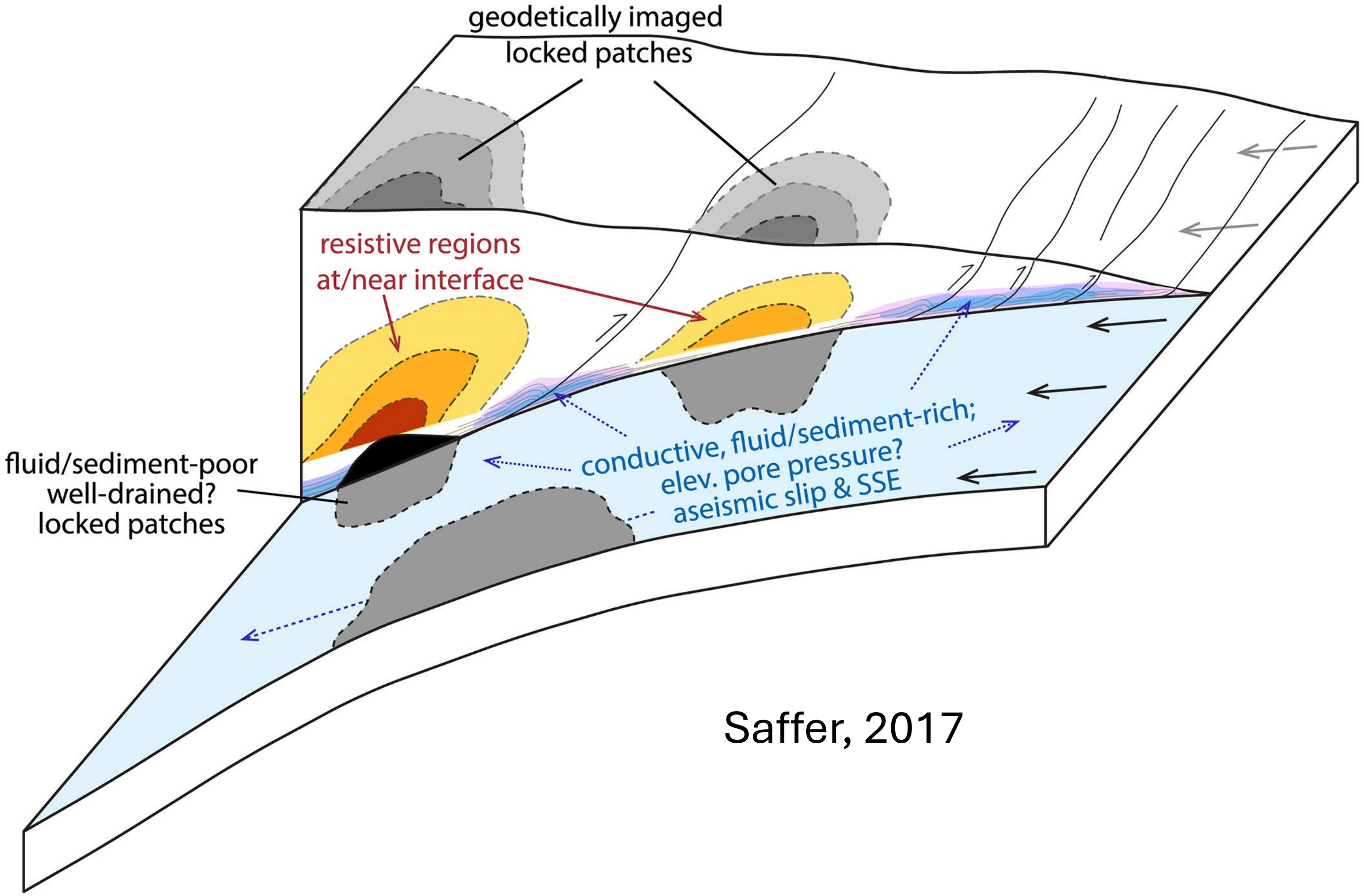


Kaj M. Johnson
Indiana University

with
Elizabeth Sherrill, GEOMAR, Germany
Eric Burton, Indiana University
Durga Acharya, Indiana University

Hypotheses about fluids and interface sliding

- Locking corresponds with high effective normal stress

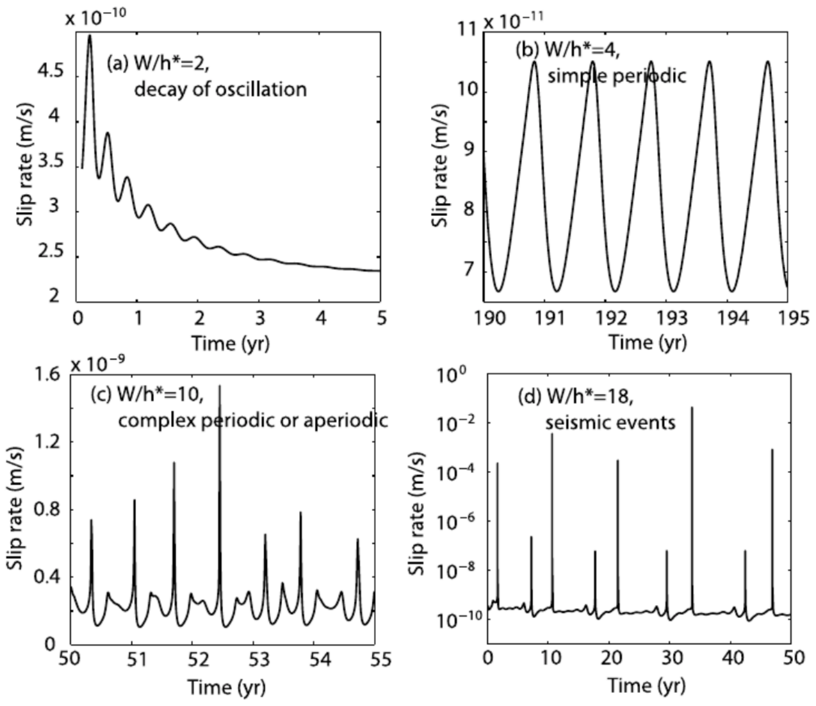


Saffer, 2017

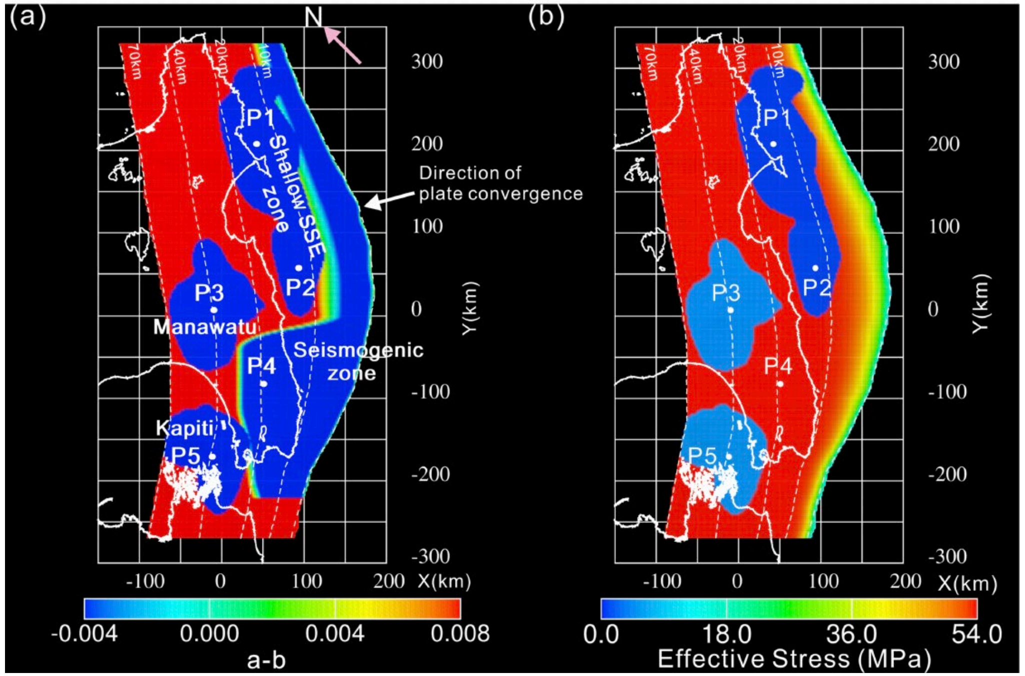
Hypotheses about fluids and interface sliding

- Locking corresponds with high effective normal stress
- Episodic slow slip requires very low effective normal stress

Liu and Rice, 2007; 2009

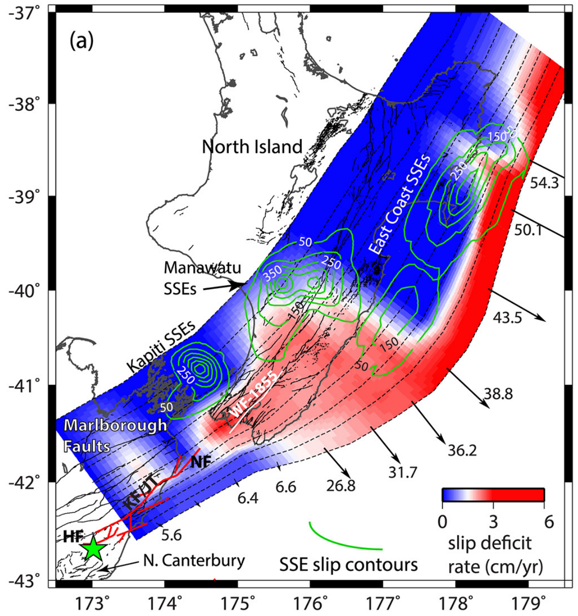


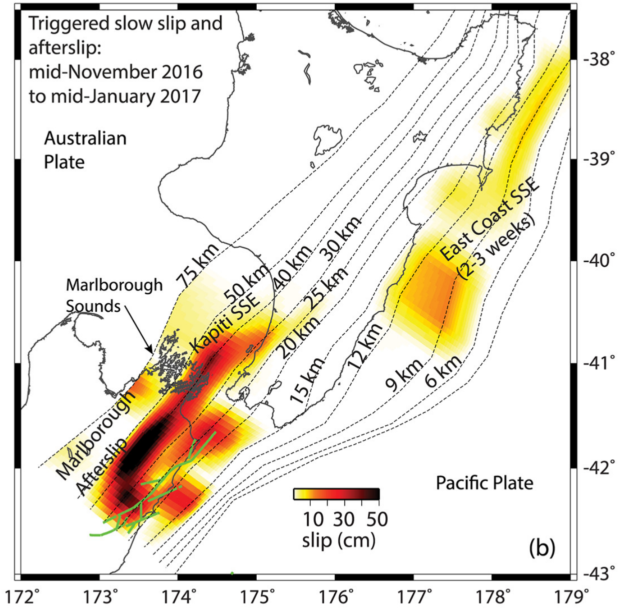
Shibazaki, 2019



Hypotheses about fluids and interface sliding

- Locking corresponds with high effective normal stress
- Episodic slow slip requires very low effective normal stress
- Distant triggering of slow slip requires very low effective normal stress





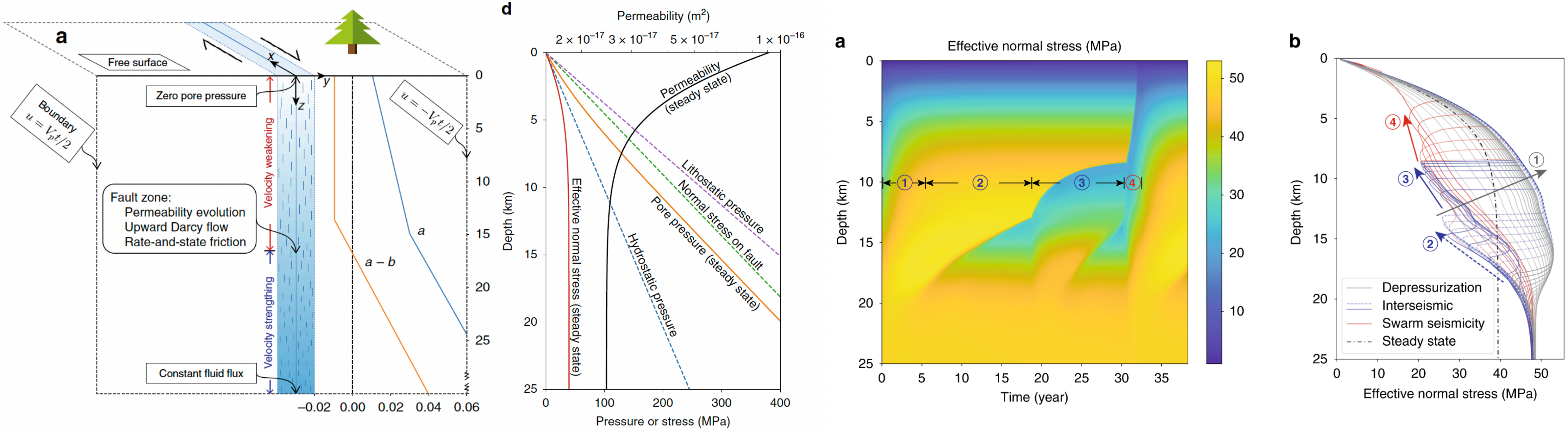
Wallace et al., 2018
Shibazaki et al., 2019

Hypotheses about fluids and interface sliding

- Locking corresponds with high effective normal stress
- Episodic slow slip requires very low effective normal stress
- Distant triggering of slow slip requires very low effective normal stress
- Transient slow slip is driven by fluid flow along the interface

Fault valving – fluid flow along the interface

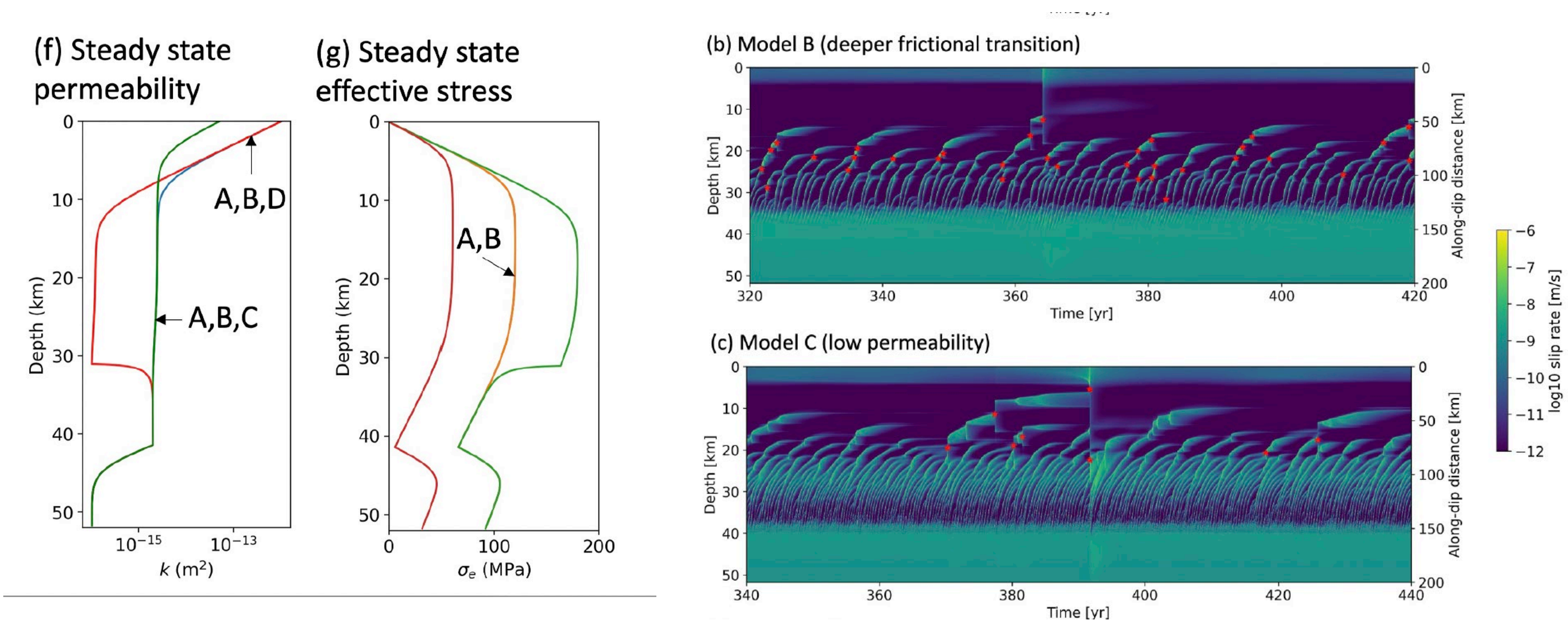
Zhu et al., 2020



Produces late interseismic fault unlocking, slow slip and creep transients ***without extremely low effective normal stress***

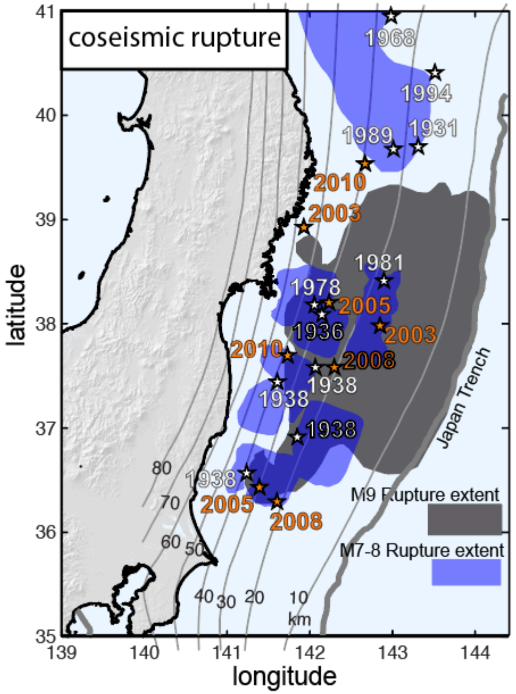
Fault valving – fluid flow along the interface

Ozawa et al., 2024



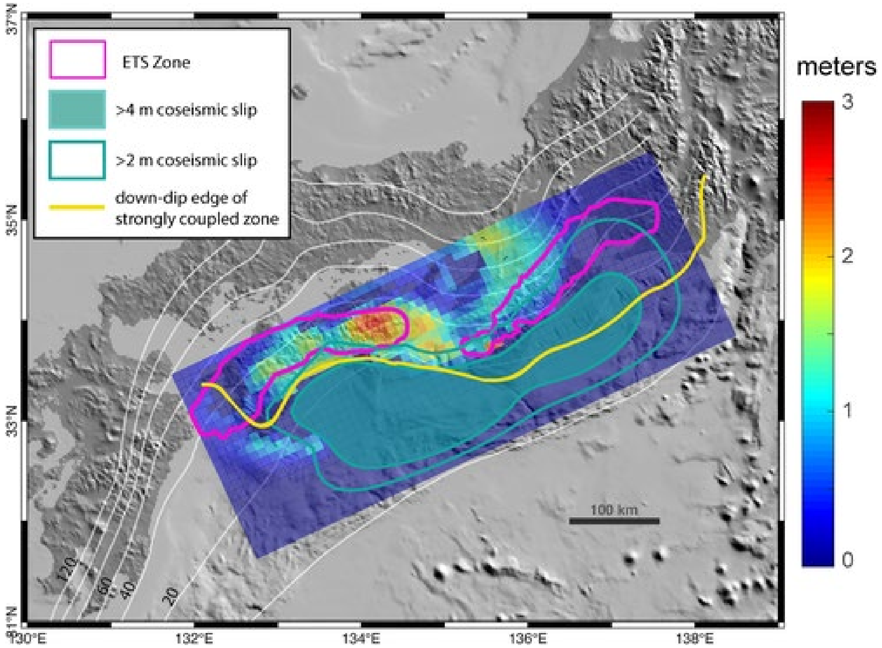
Three Main Messages

First point



Overlapping aseismic and seismic slip – moderate effective normal stress

Afterslip in ETS zone

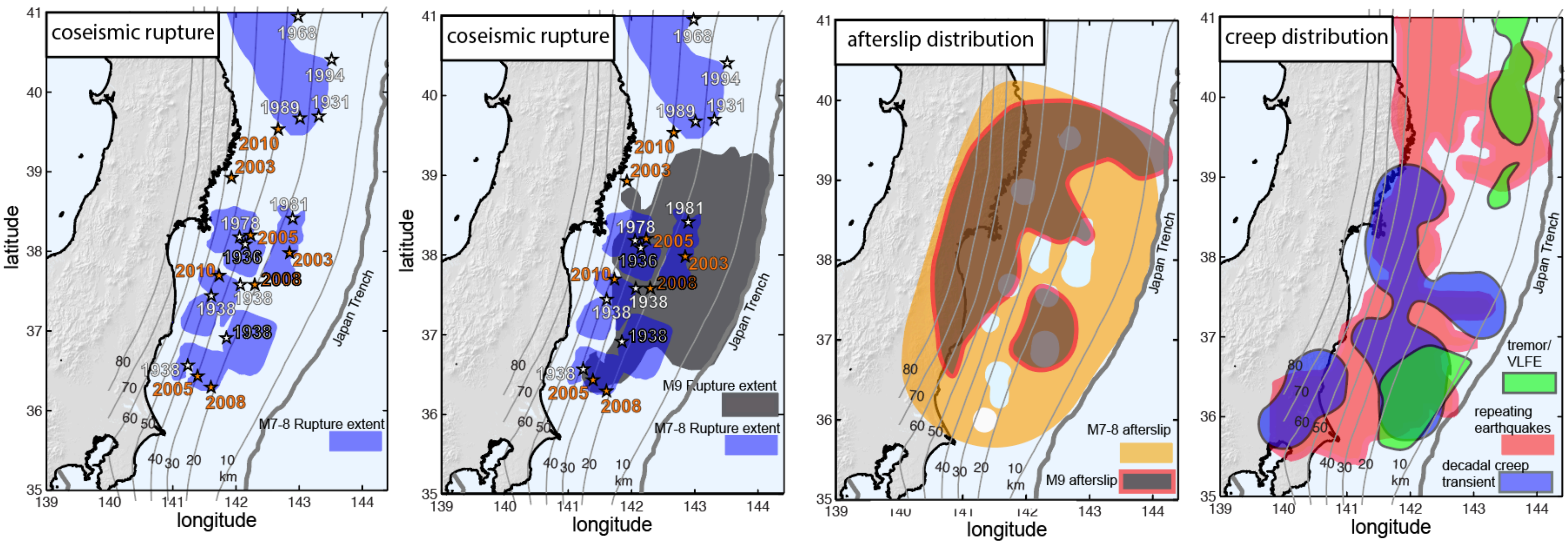


Long-duration (decades) afterslip inconsistent with very low effective normal stress

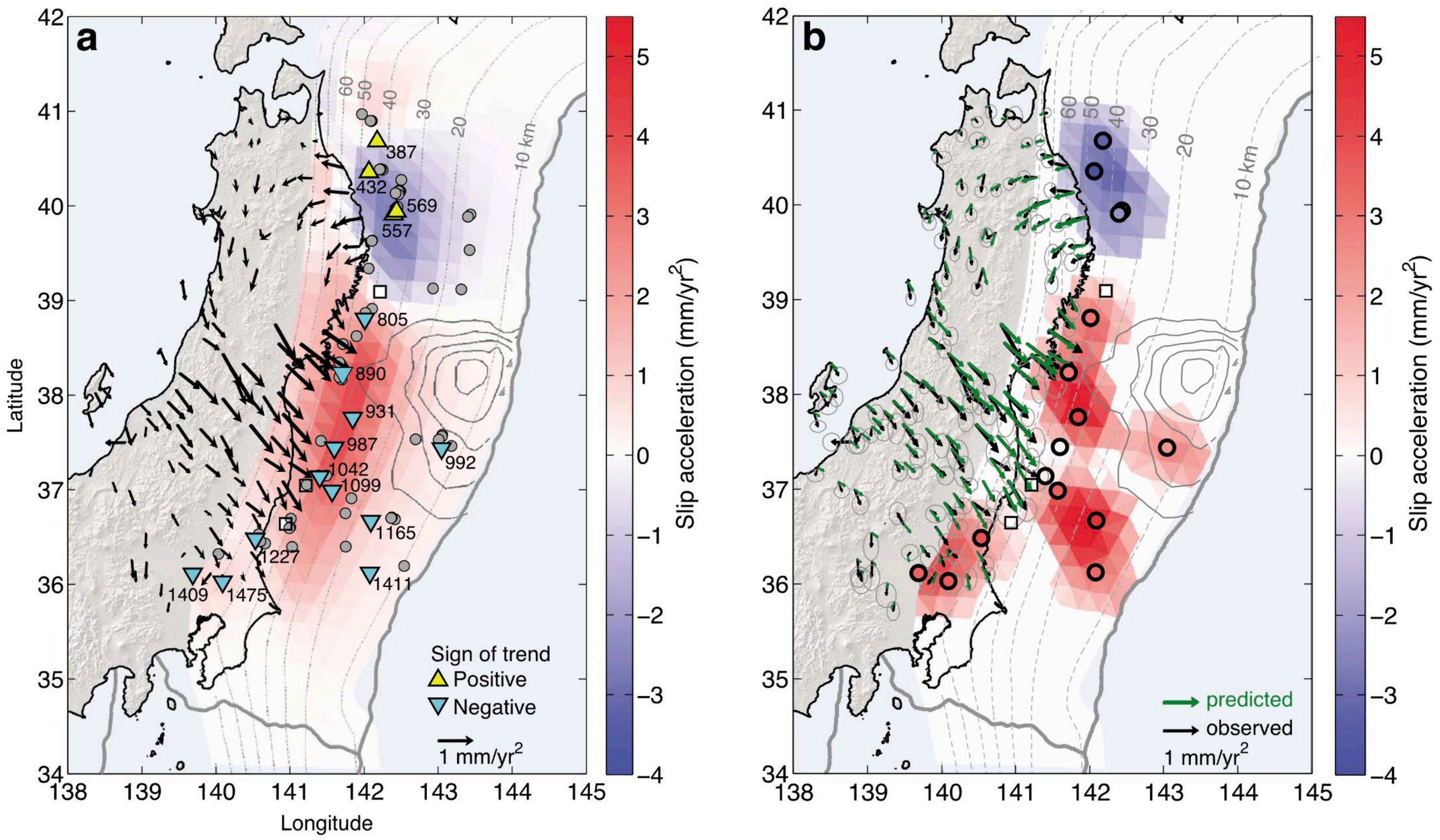
Heterogeneous locking

Locked asperities of various sizes. Probably non-stationary. Slow slip adjacent to locked patches.

1. Japan Trench Displays Overlapping Slip Behaviors



Decadal Creep Transient

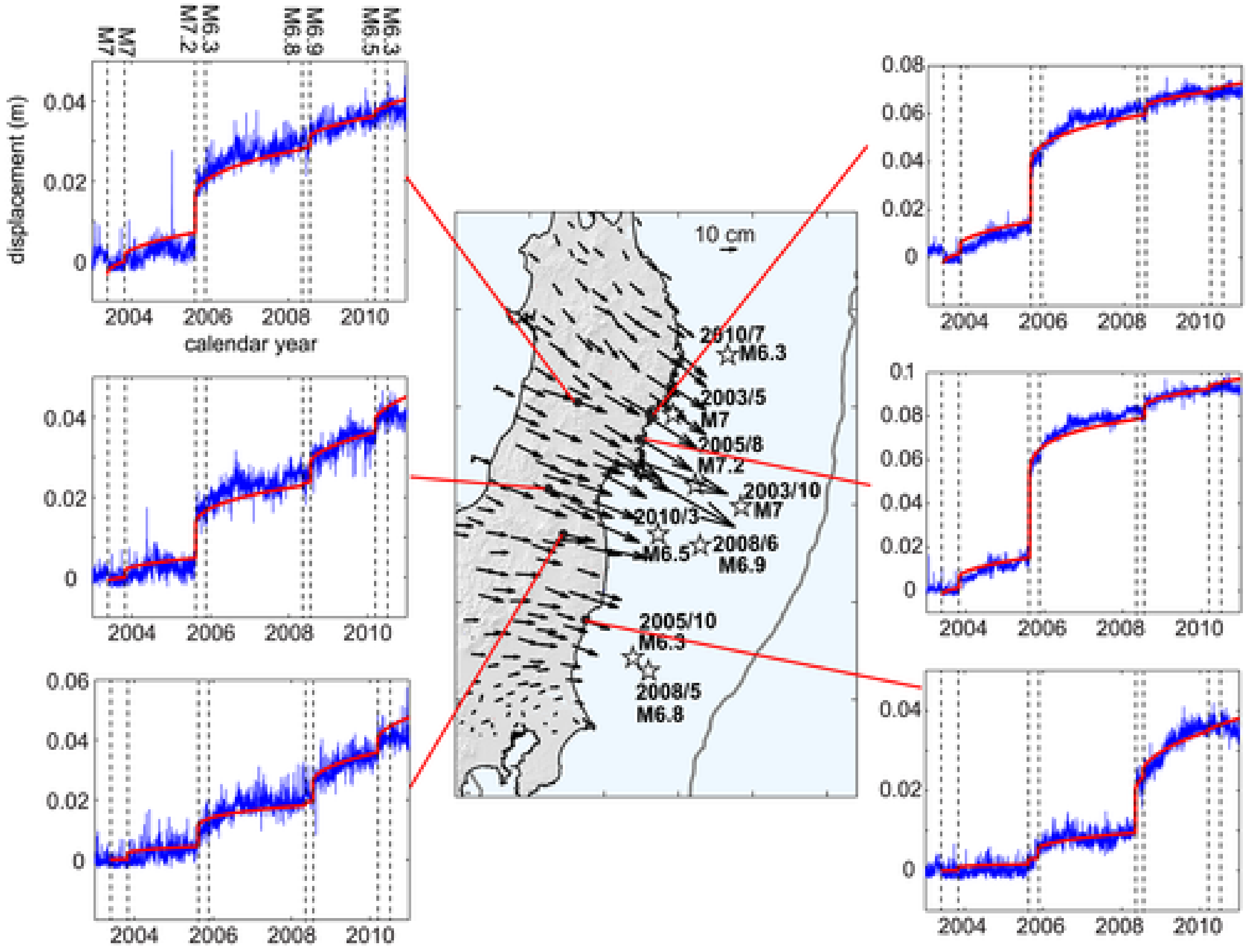


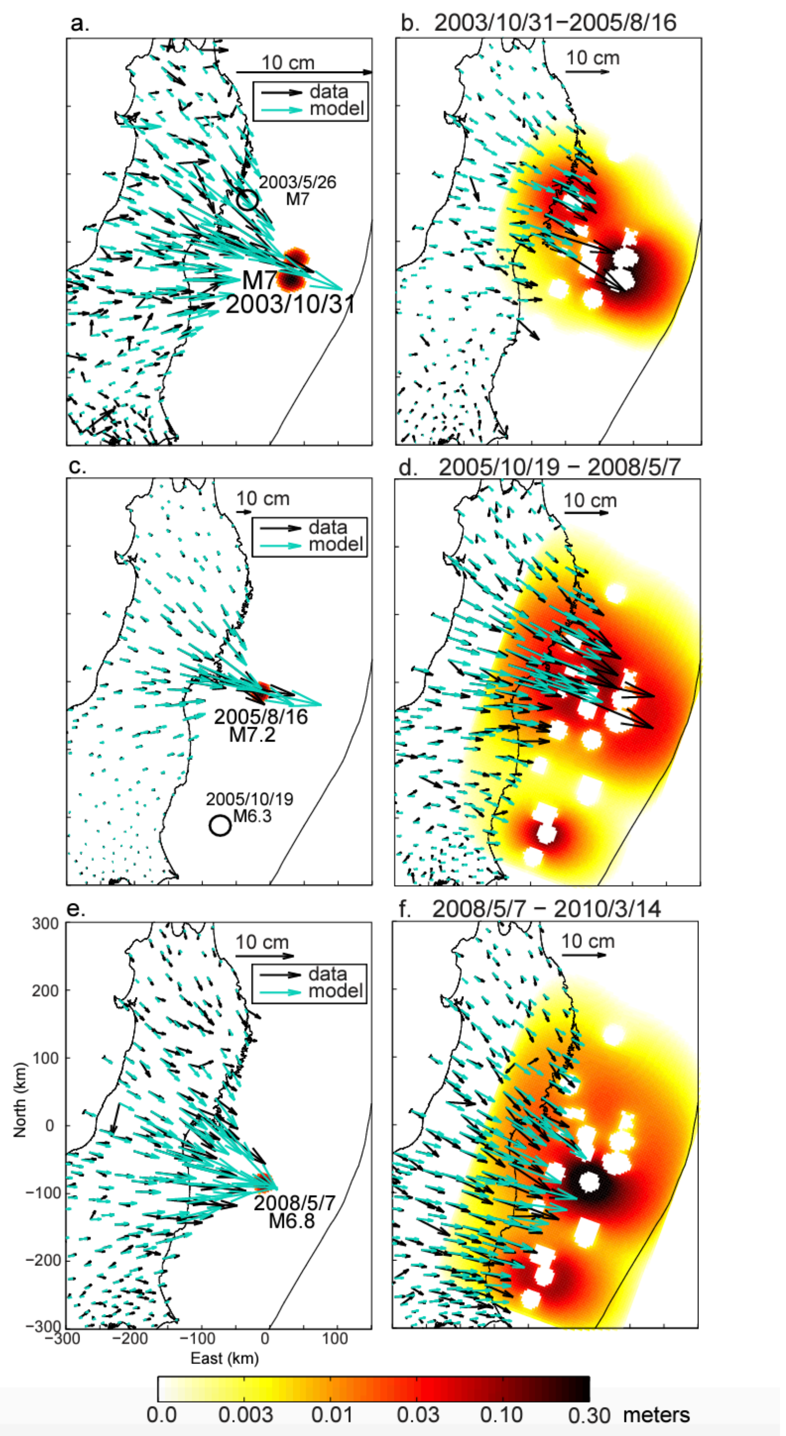
At least 15 years of accelerating creep on the interface prior to the 2011 M9 Tohoku-oki earthquake

Mavrommatis et al., 2015; See also Yokota et al., 2015 and Marill et al., 2021

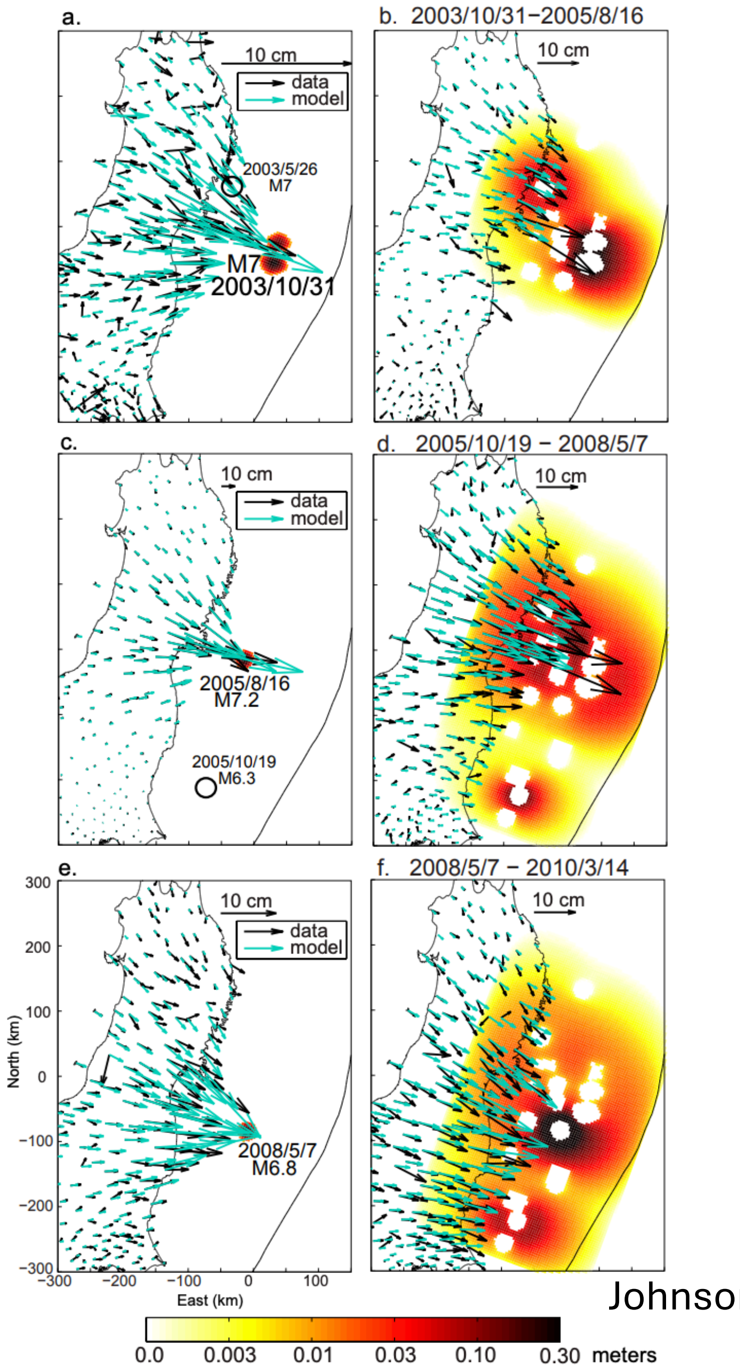
Abundant Afterslip Following M7 Earthquakes

Johnson et al., 2016



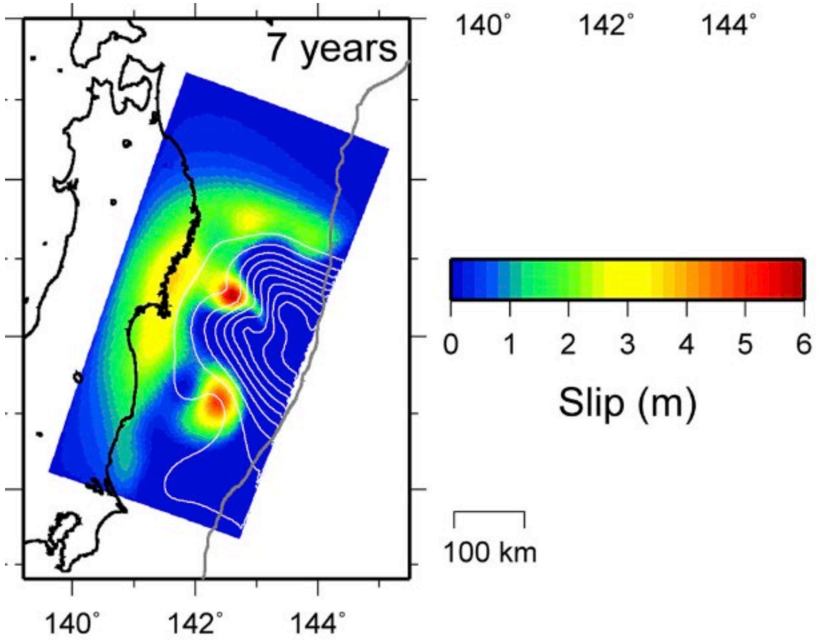


Afterslip Modeling Implies Moderate Effective Normal Stress



Johnson et al., 2016

Afterslip: M9 Tohoko earthquake



Fukuda and Johnson, 2021

Rate-strengthening friction:

$$\tau = \sigma\mu_* + \sigma(a-b)\ln\left(\frac{V}{V_*}\right),$$

M7 afterslip: $\sigma_{eff}(a\text{-}b) = 0.08$

M9 afterslip: $\sigma_{eff}(a\text{-}b) = 0.8$

Within seismogenic zone:

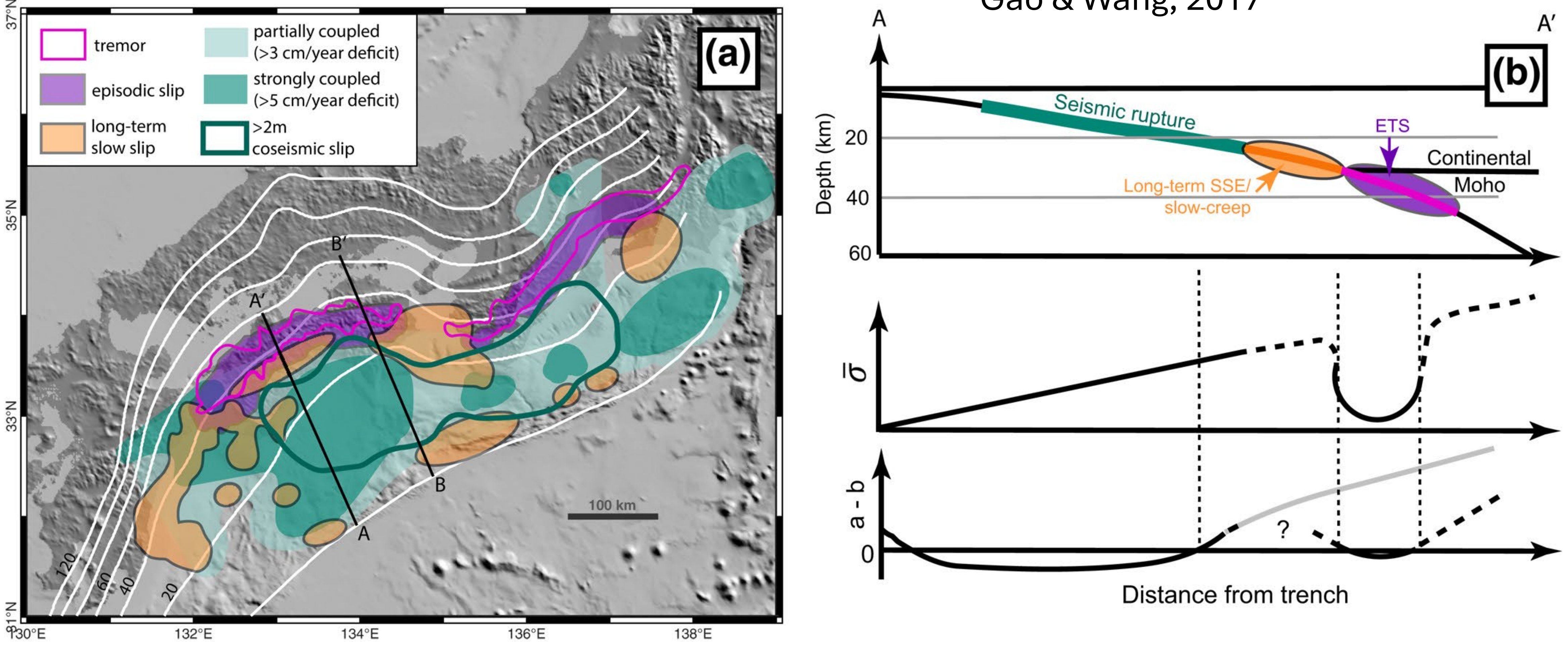
σ_{eff} = 20-200 MPa

Below seismogenic zone

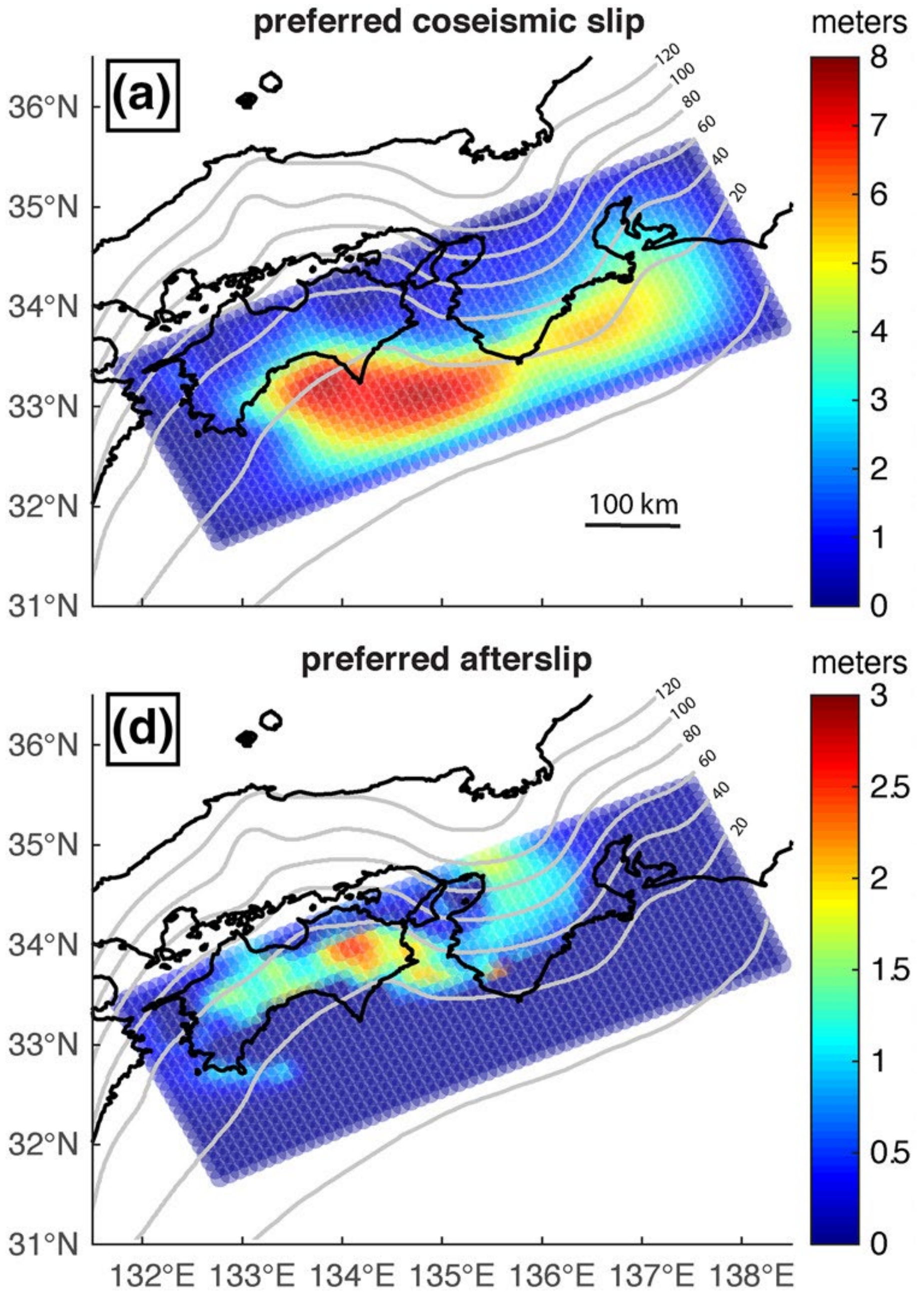
σ_{eff} = 80 - 800 MPa

2. Does ETS Zone Rupture in Earthquakes?

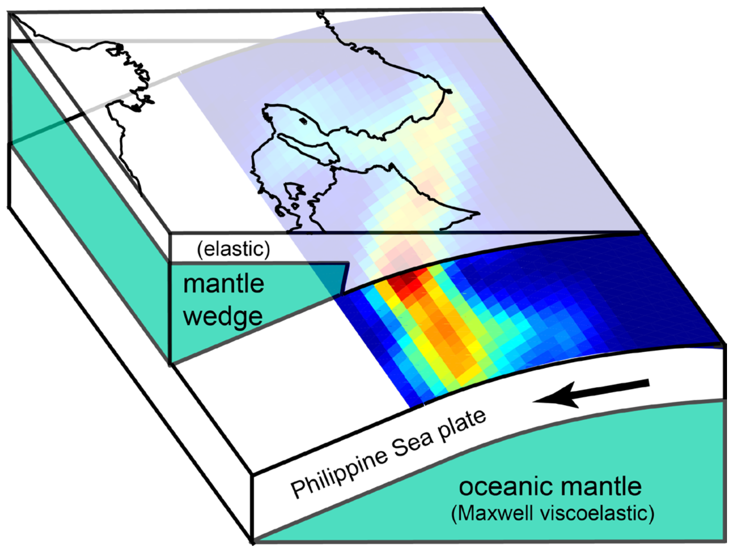
Gao & Wang, 2017



ETS Zone at Nankai Displayed Afterslip, Not Coseismic Slip



Sherrill & Johnson, 2021



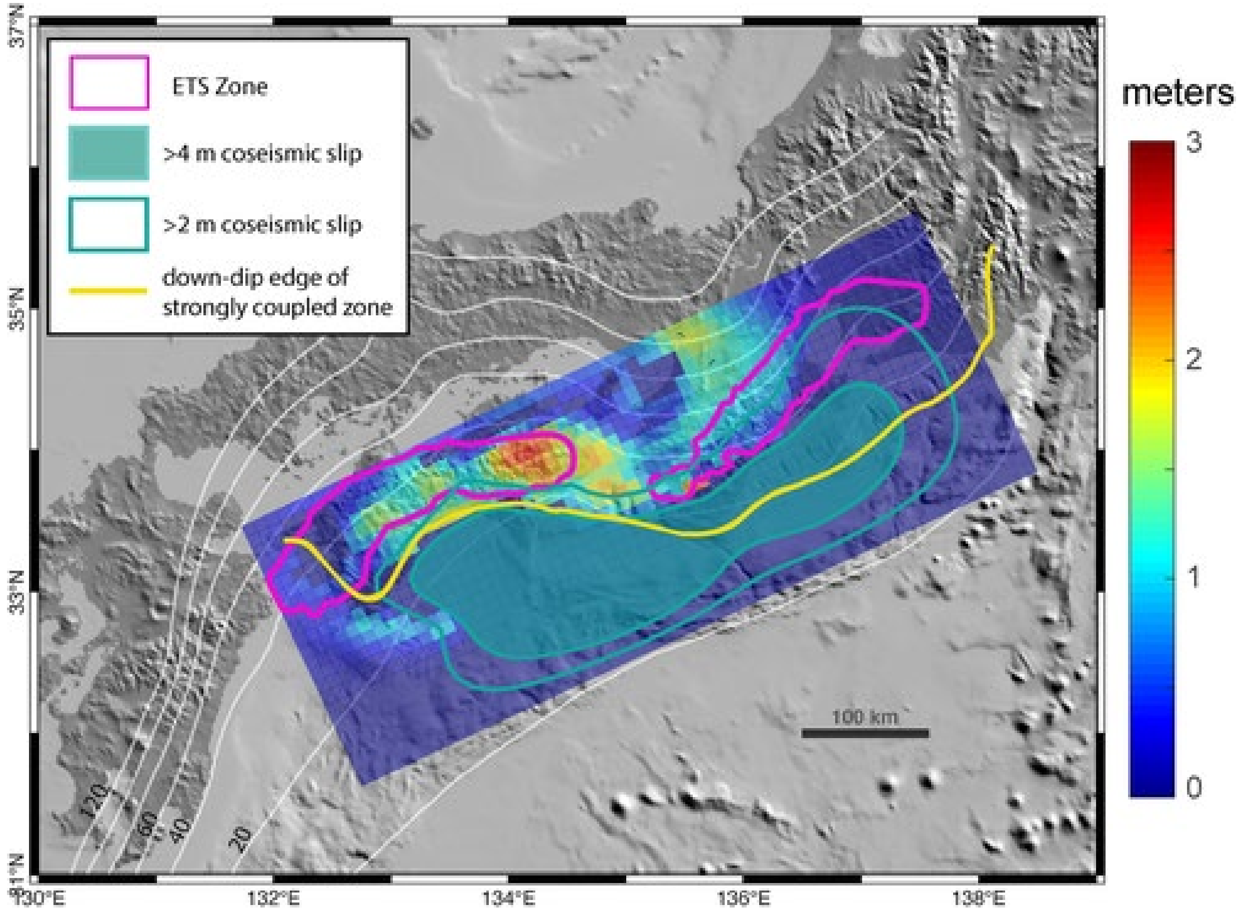
Constraints from leveling and tide gauge data

Postseismic mantle flow and afterslip contributed to postseismic deformation

Afterslip largely within the ETS zone

ETS Zone at Nankai Displayed Afterslip, Not Coseismic Slip

Sherrill & Johnson, 2021



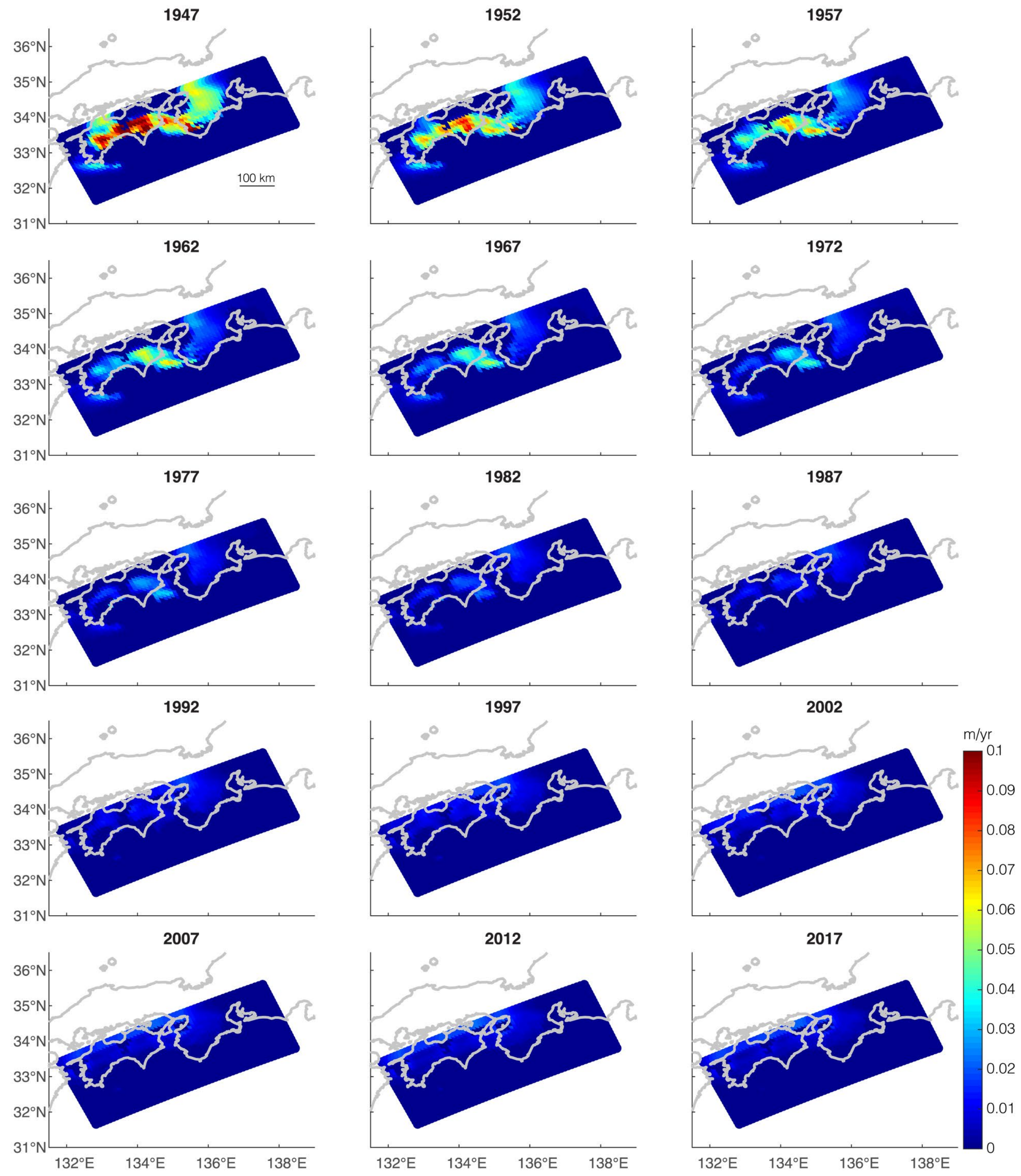
Constraints from leveling and tide gauge data

Postseismic mantle flow and afterslip contributed to postseismic deformation

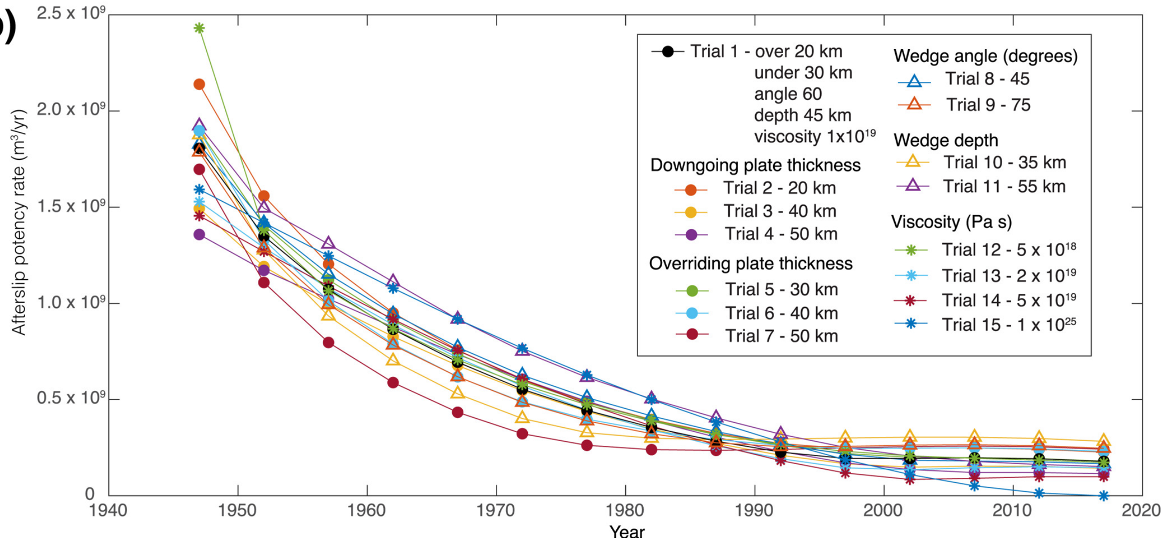
Afterslip largely within the ETS zone

Nankai Afterslip Duration was decades

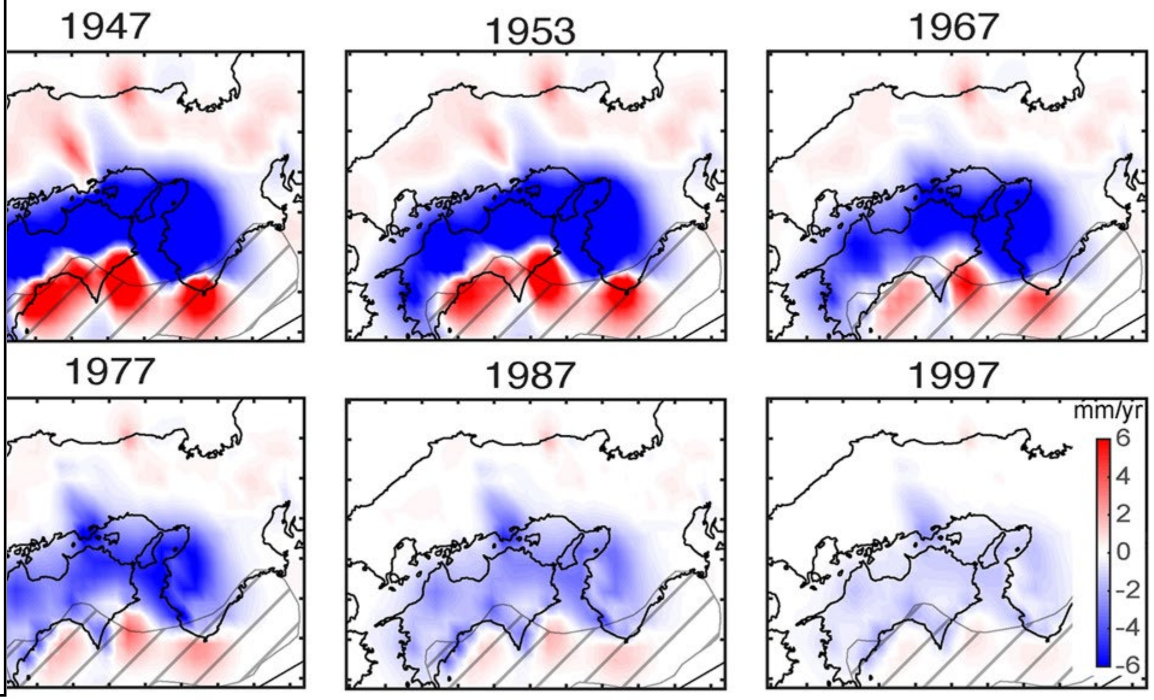
a)



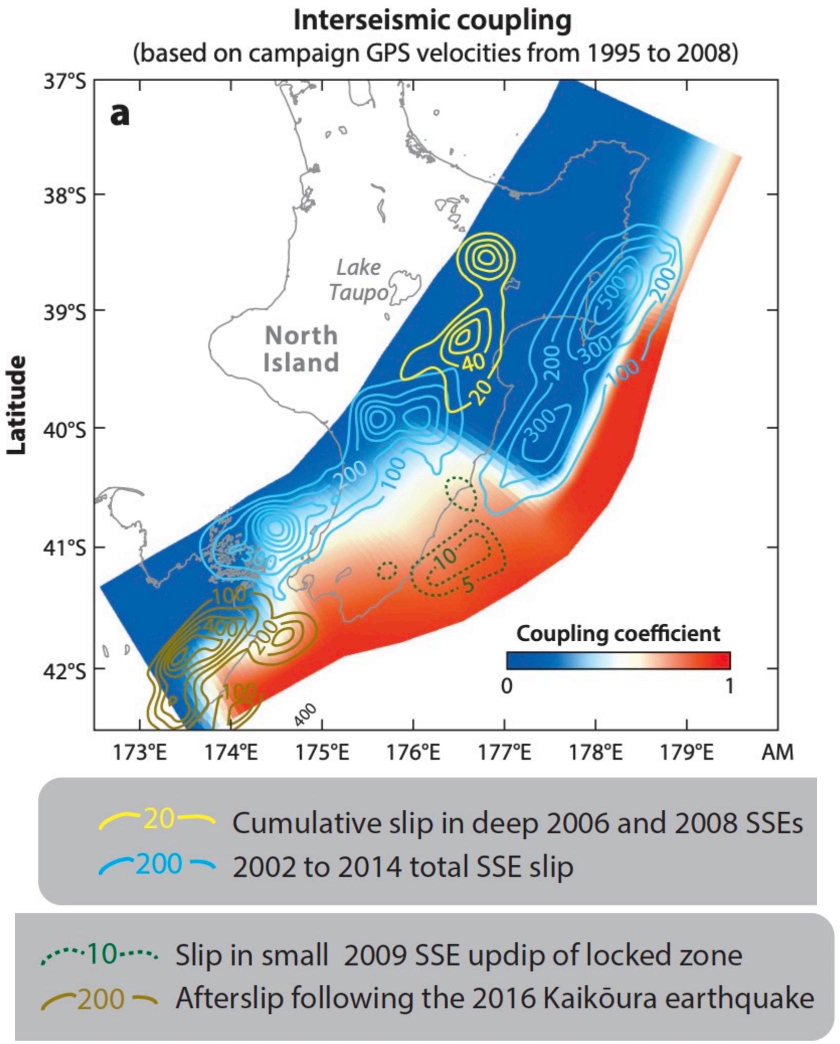
(b)

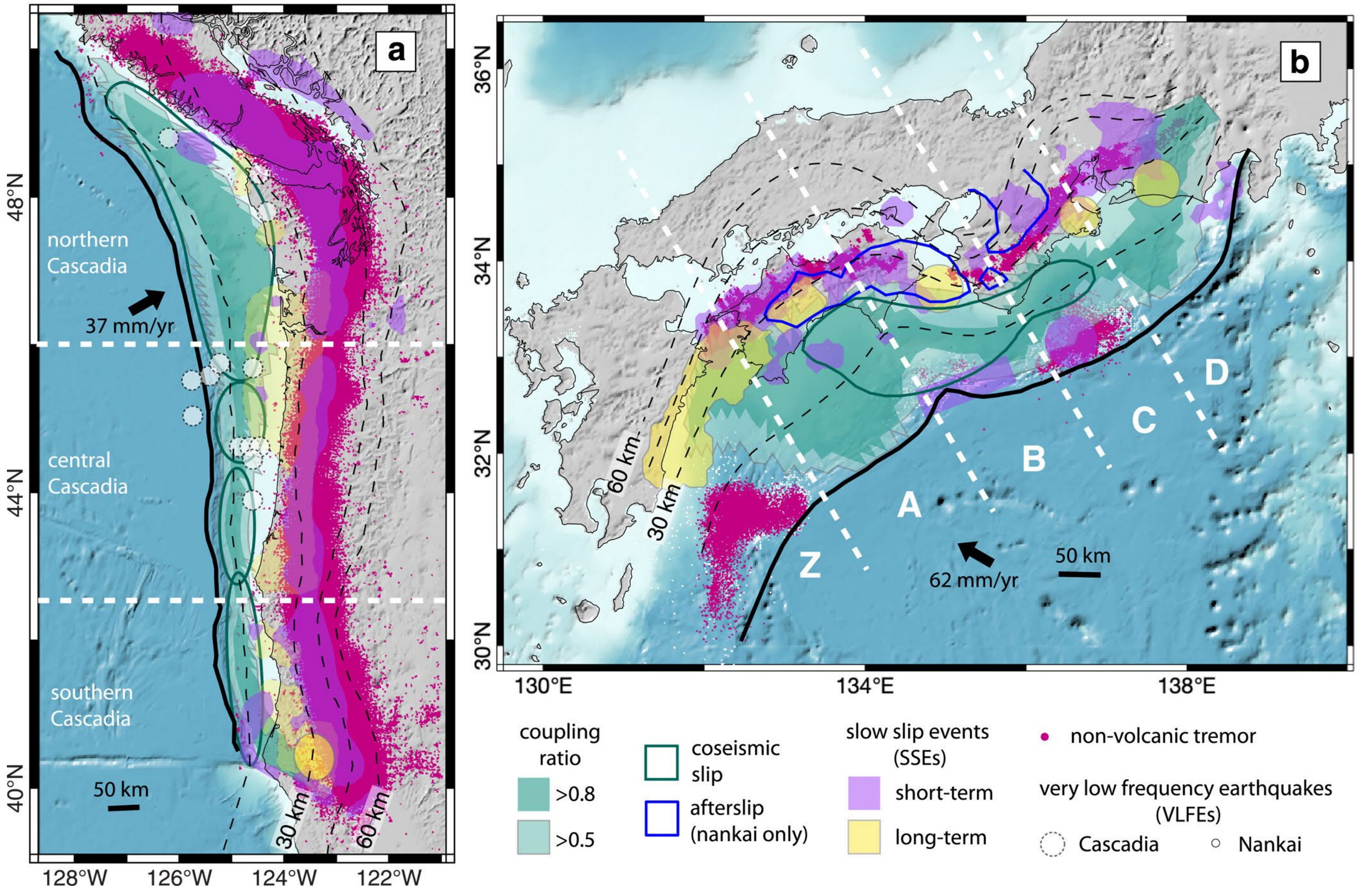


Postseismic Vertical Velocities
1944-46 Earthquakes
Nankai Trough



3. What is the spatial relationship of slow slip and locking?





Resolution is Poor, Uncertainty is High

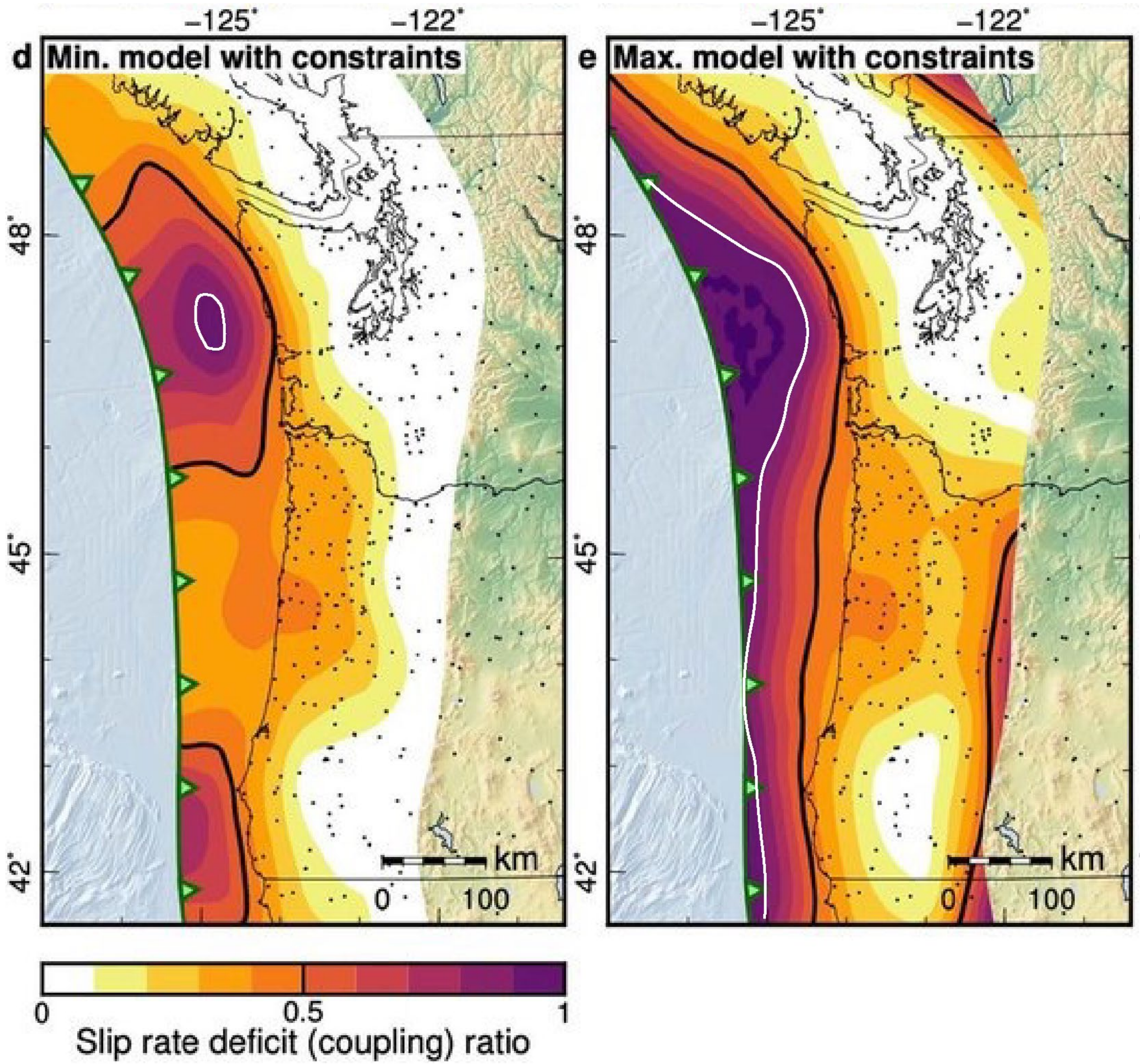
Smoothed kinematic slip inversions do not resolve fully locked areas of the interface

Article | Published: 03 May 2021

Slip rate deficit and earthquake potential on shallow megathrusts

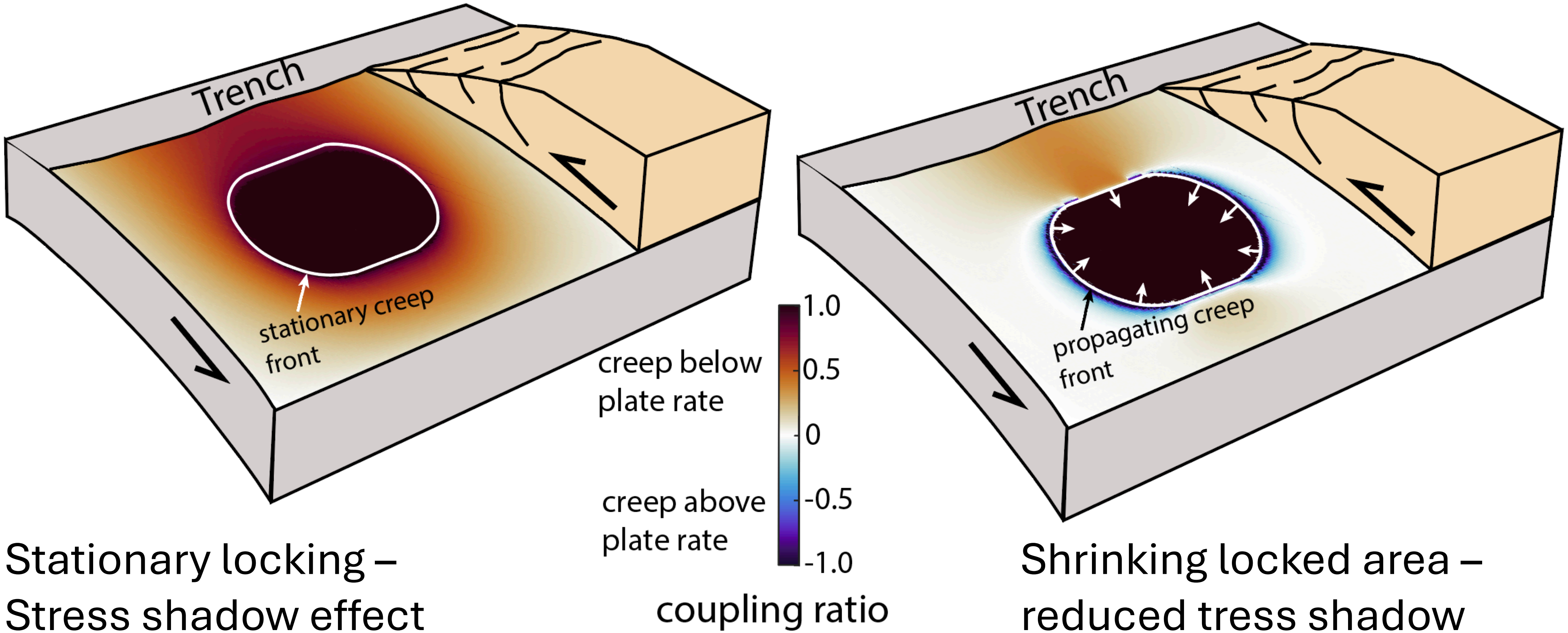
Eric O. Lindsey, Rishav Mallick, Judith A. Hubbard, Kyle E. Bradley, Rafael V. Almeida, James D. P. Moore, Roland Bürgmann & Emma M. Hill

Nature Geoscience **14**, 321–326 (2021) | Cite this article



Non-stationary Asperities and Surrounding Interseismic Creep

simple physical constraints on coupling



Stationary locking – Stress shadow effect (e.g., Lindsey et al. 2021)

Shrinking locked area – reduced tress shadow effect (e.g., Lindsey et al. 2021)

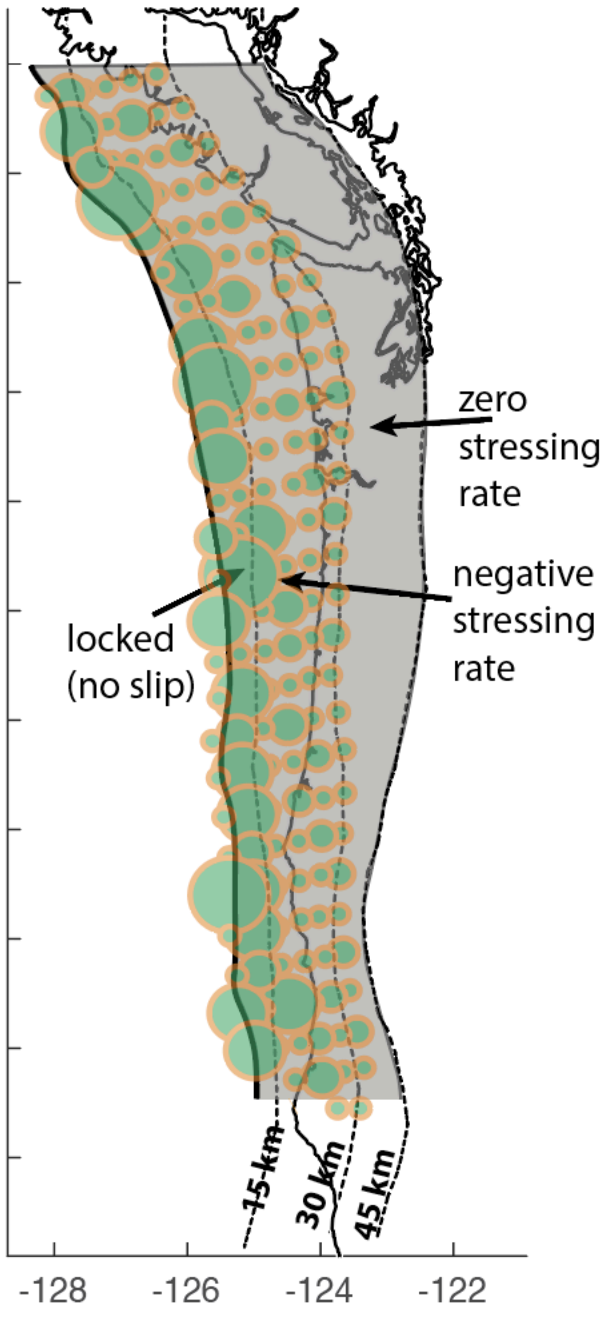
Asperity Inversion With "Ring Stress" for interseismic locking

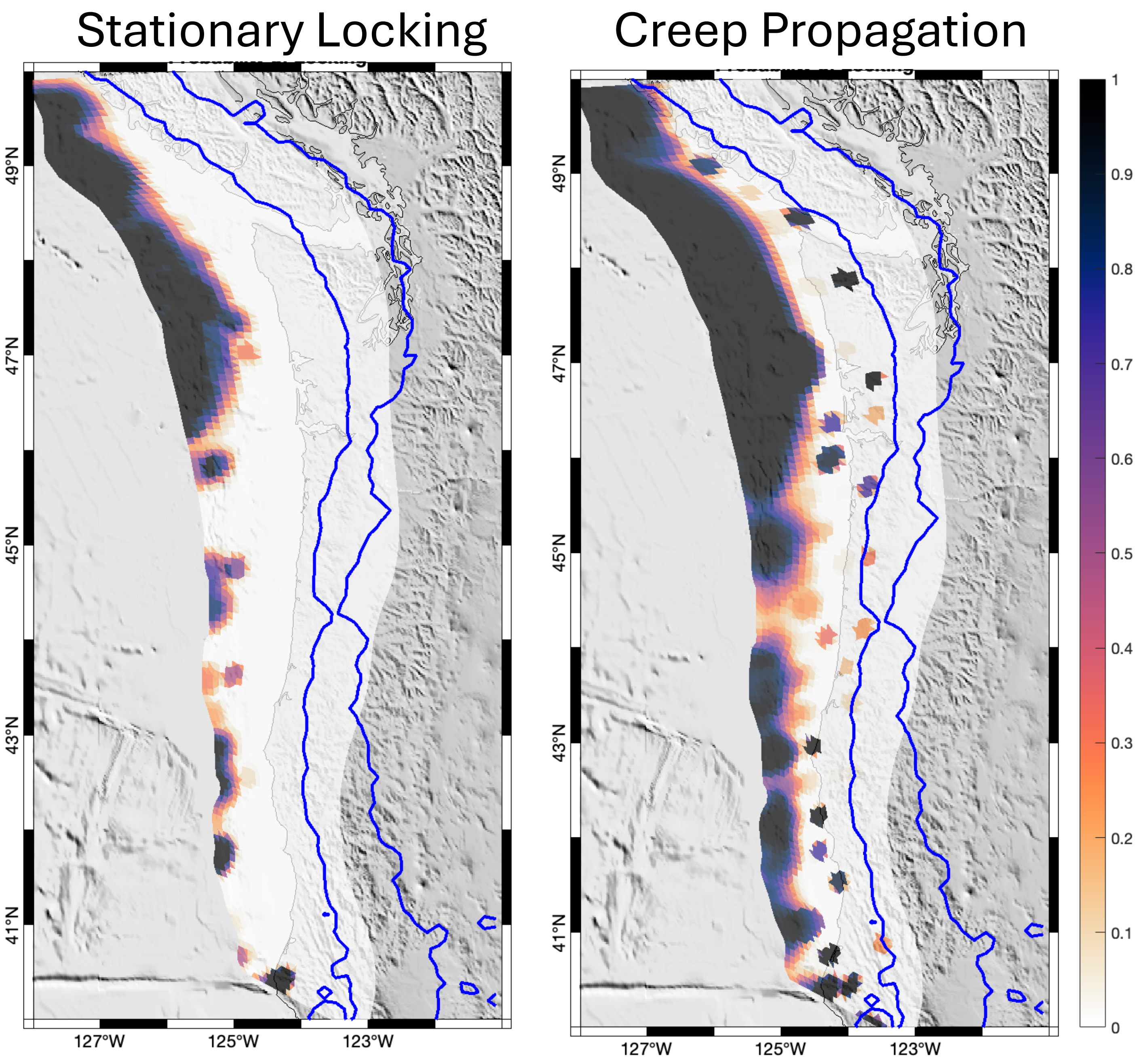
Forward Model

1. Grid of circular asperities. Zero creep imposed within boundaries. Specify radius of each asperity.
2. Imposed "Ring" of negative stressing rate at edges of locked asperities.
3. Creep at zero stressing rate (constant stress) outside of locked asperities (gray area).

Inversions

1. Metropolis-Hastings MCMC inversion
2. Solve for radii of asperities
3. Solve for "ring stress" (negative stressing rate) around asperities

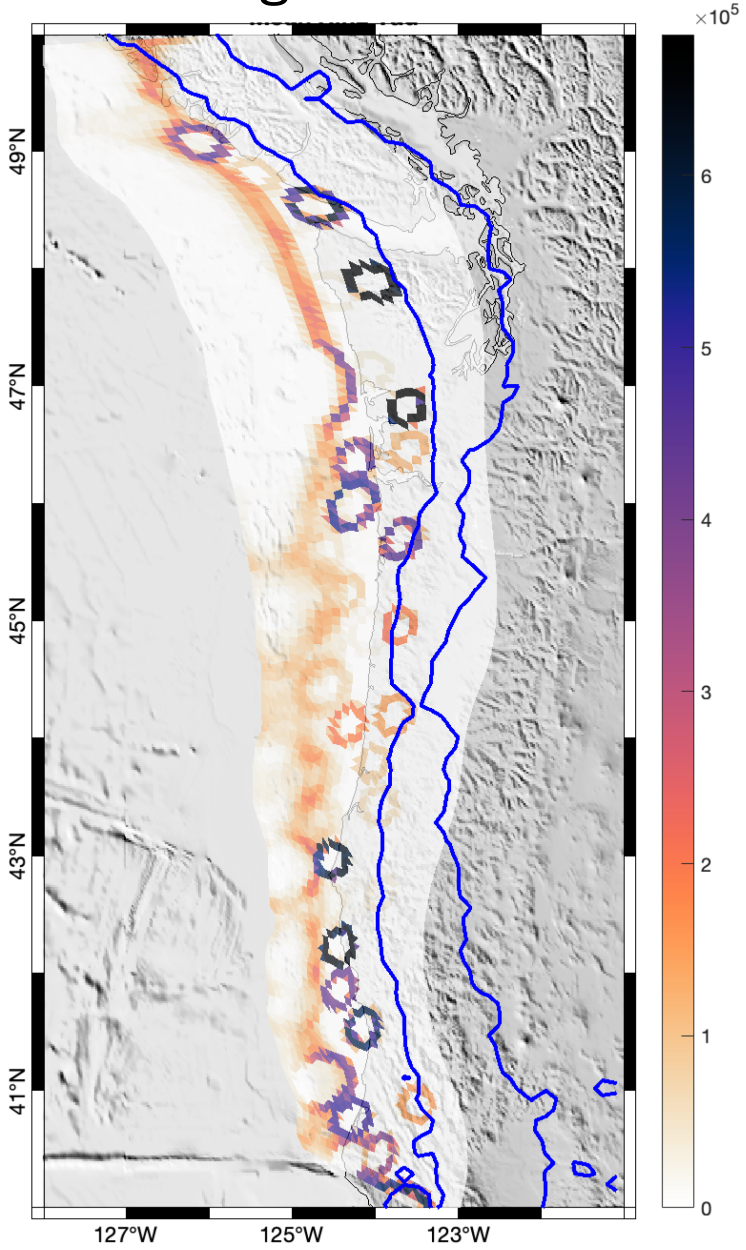




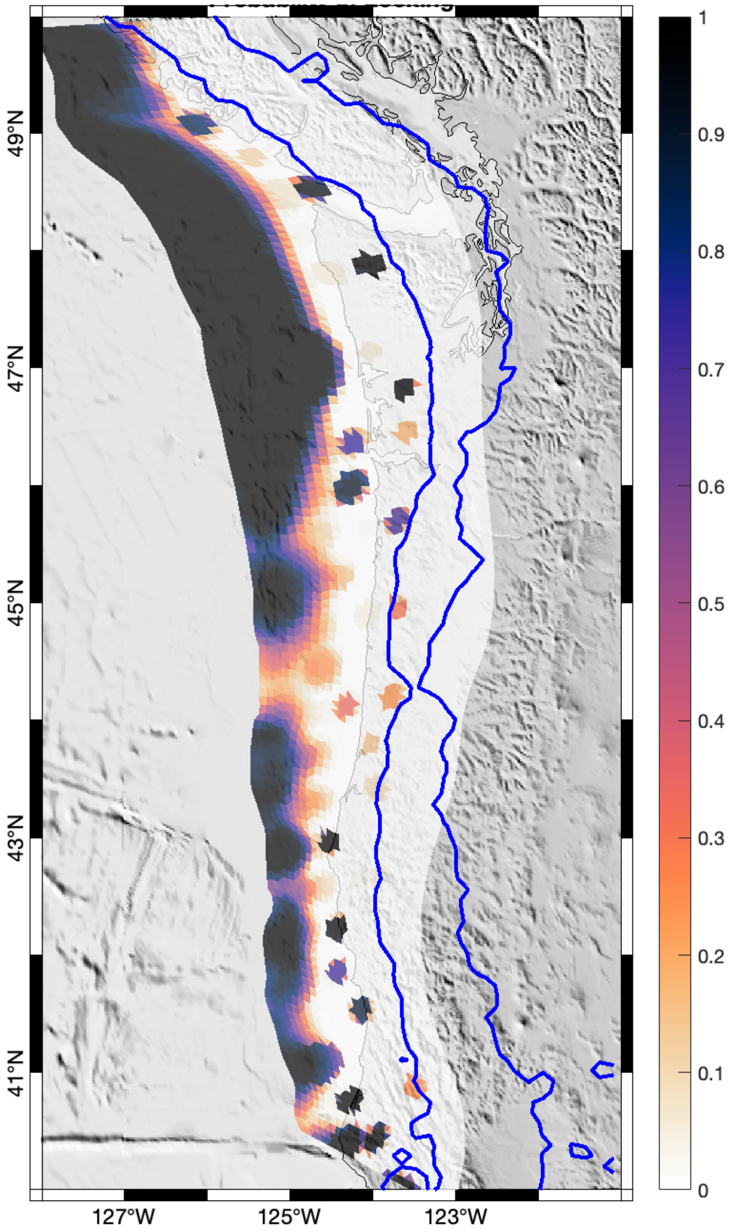
Cascadia Inversions

Probability of Locking

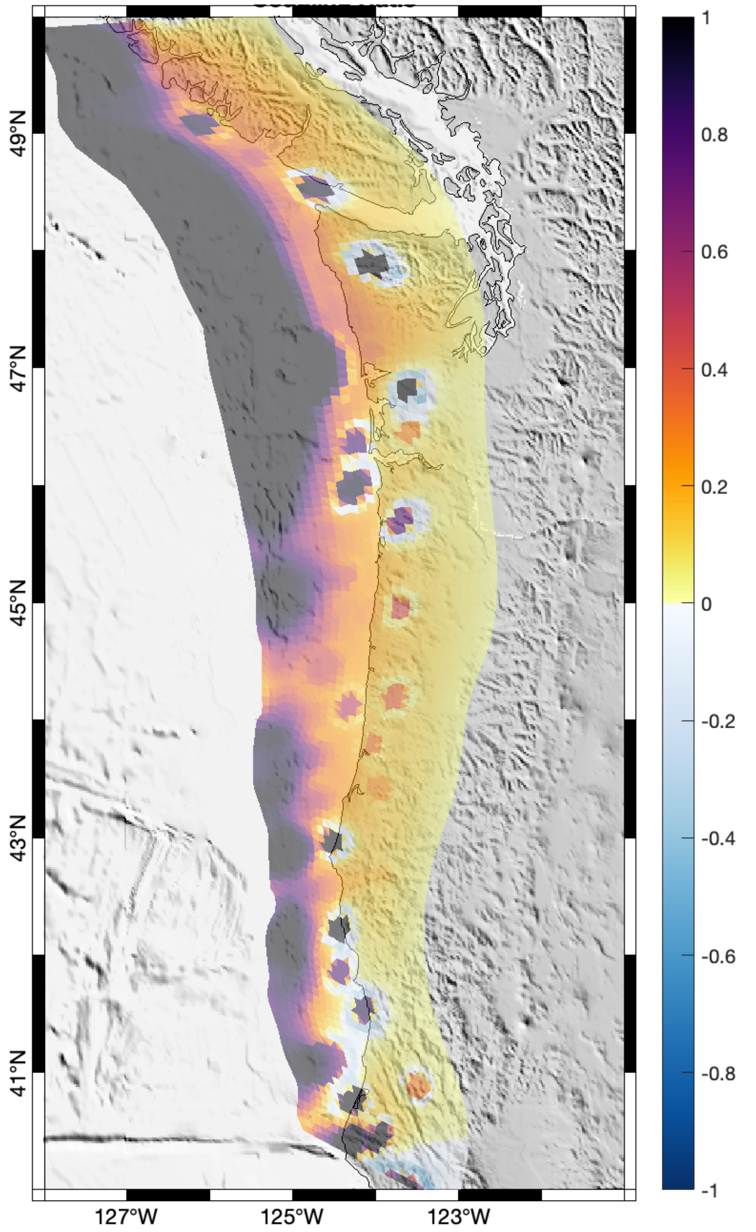
Ring Stress



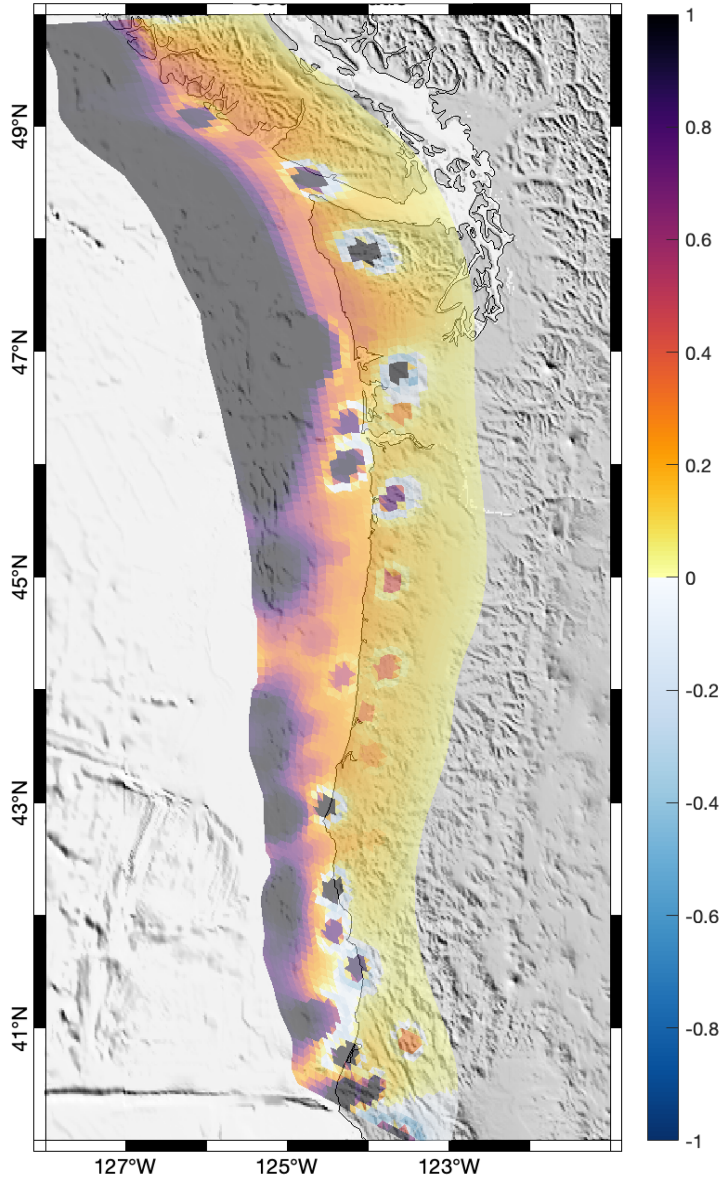
Locking Probability



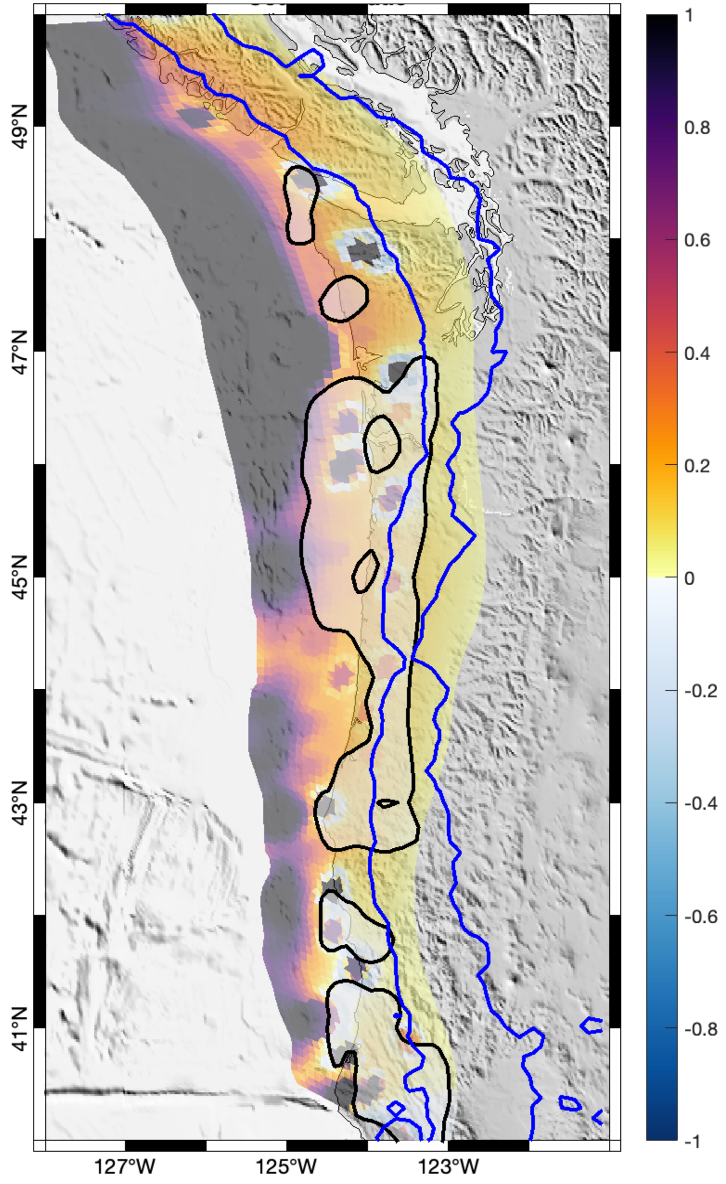
Coupling Ratio



Coupling Ratio



Slow Slip Zones



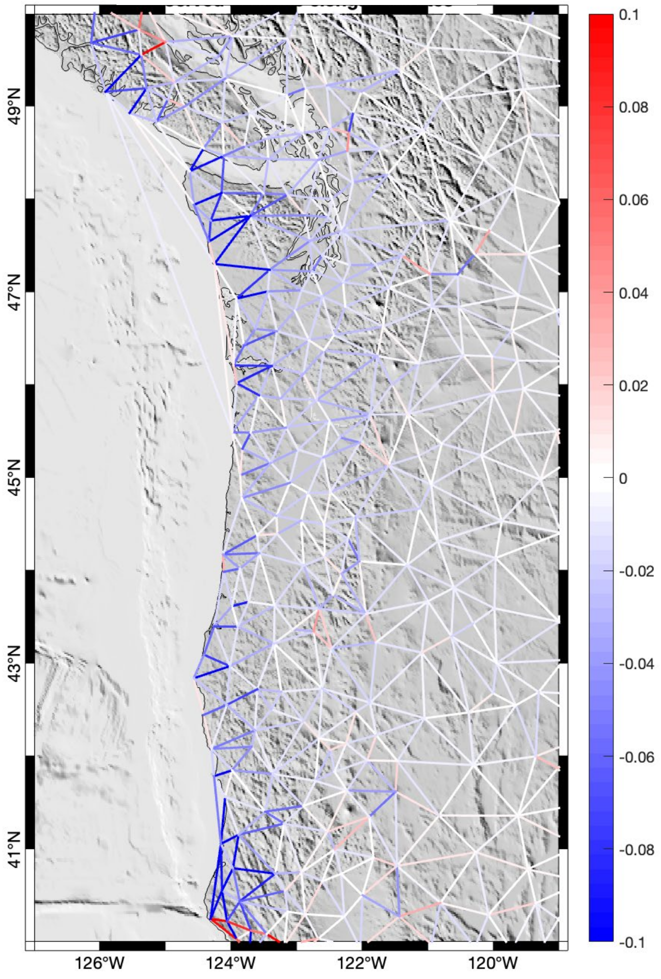
Nuyen & Schmidt, 2021

Maximum Depth Coseismic Slip

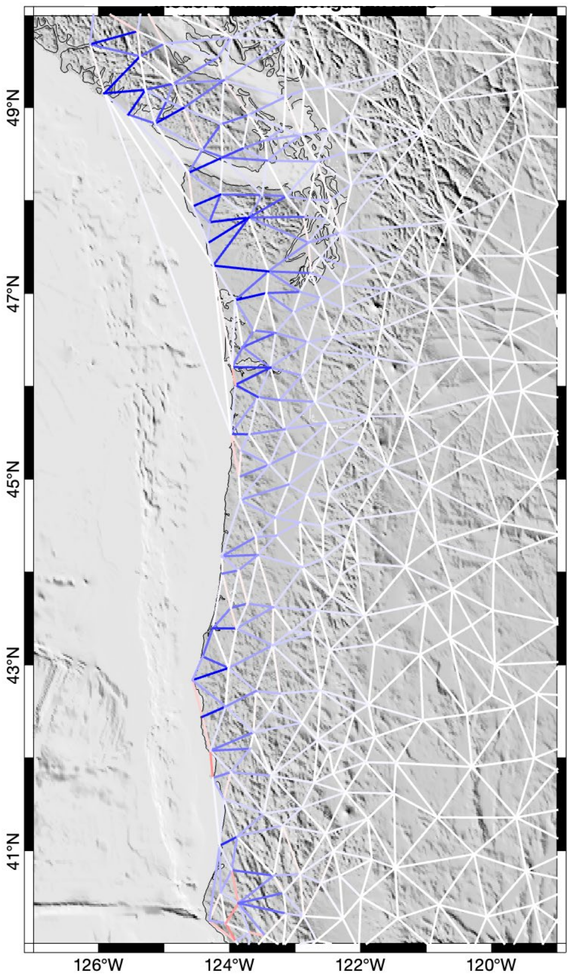
Sherrill & Johnson, in prep

Fit to Geodetic Data is Reasonably Good

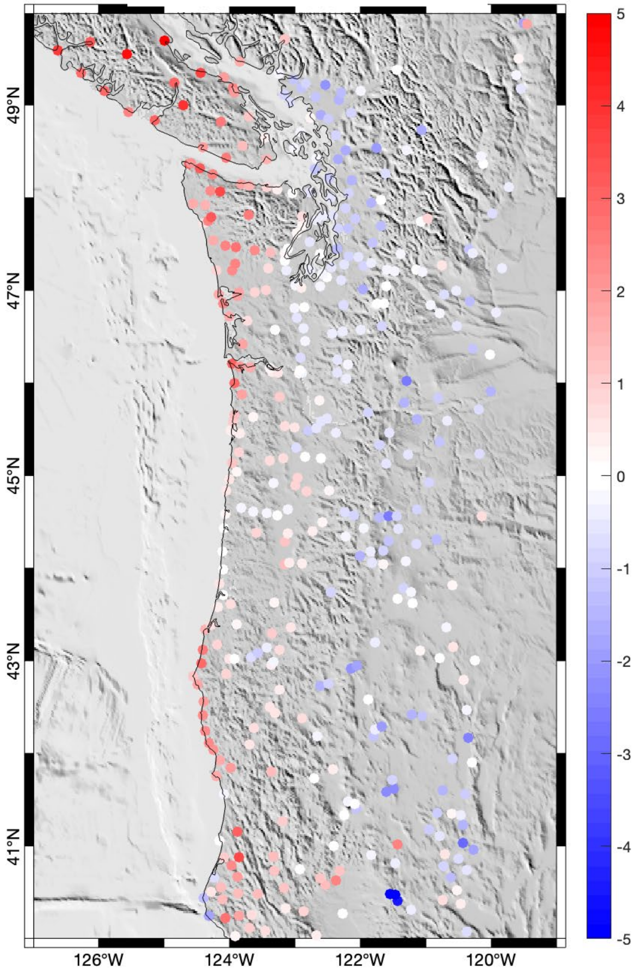
Observed Baseline Elongation Rates



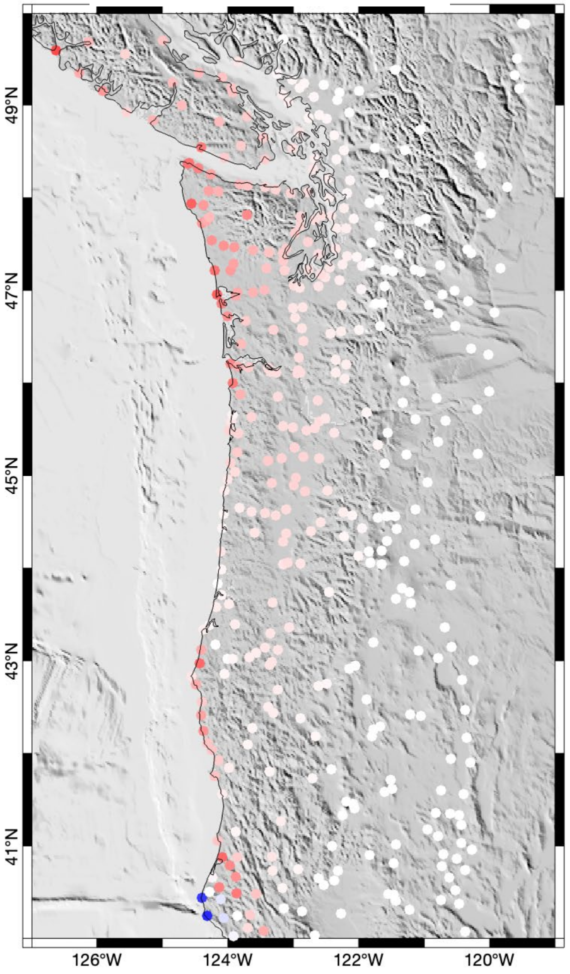
Model Baseline Elongation Rates



Observed Vertical Velocities

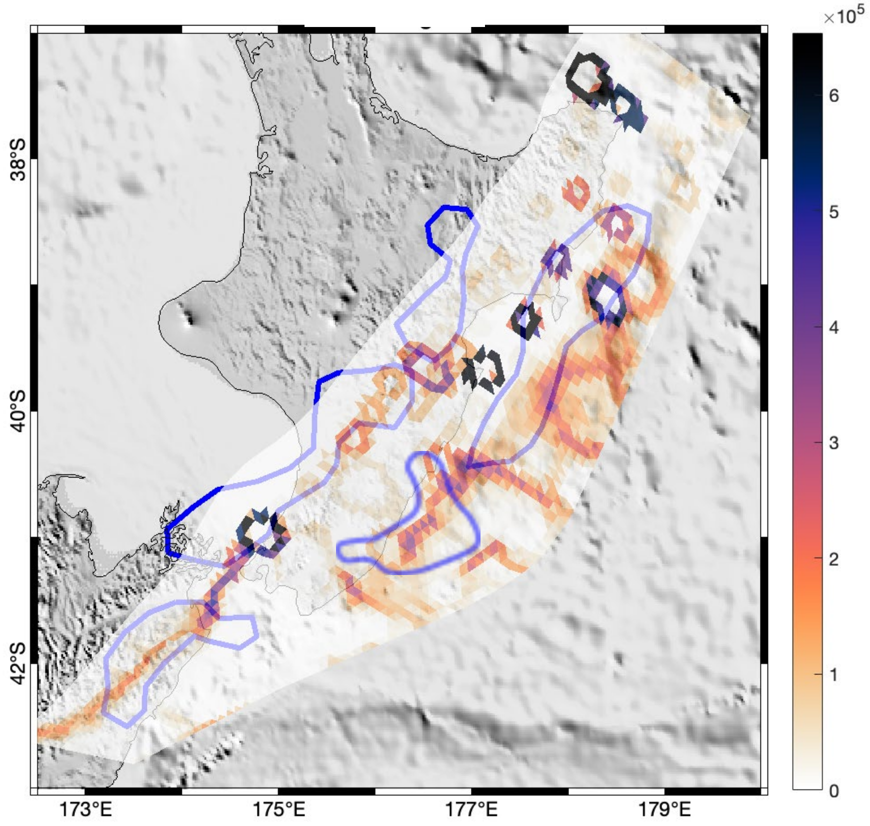


Model Vertical Velocities



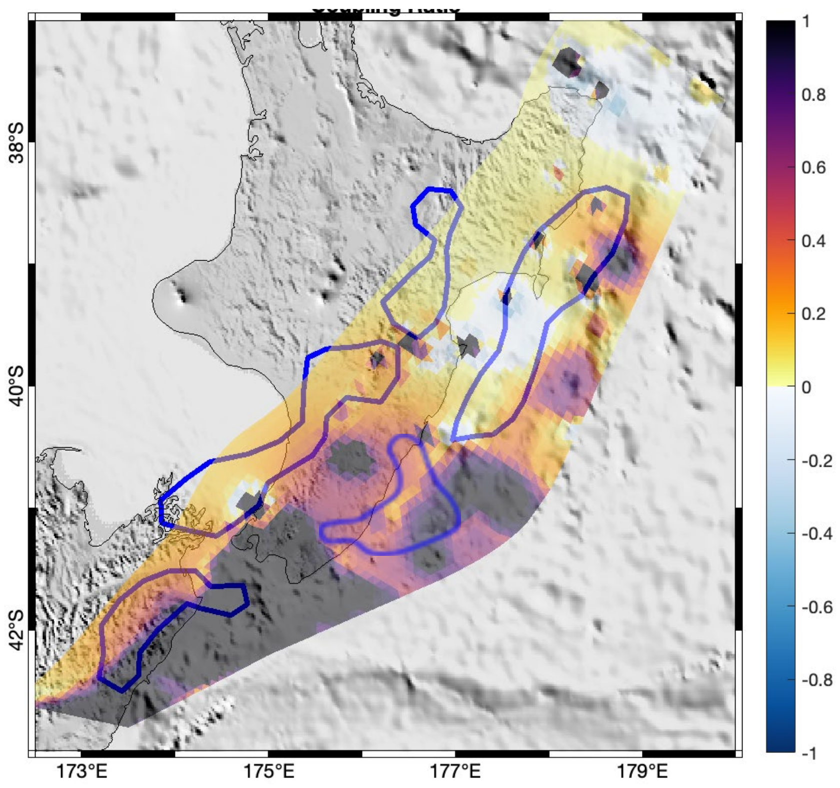
Hikurangi Inversions

Ring Stress



Locking Probability

Coupling Ratio

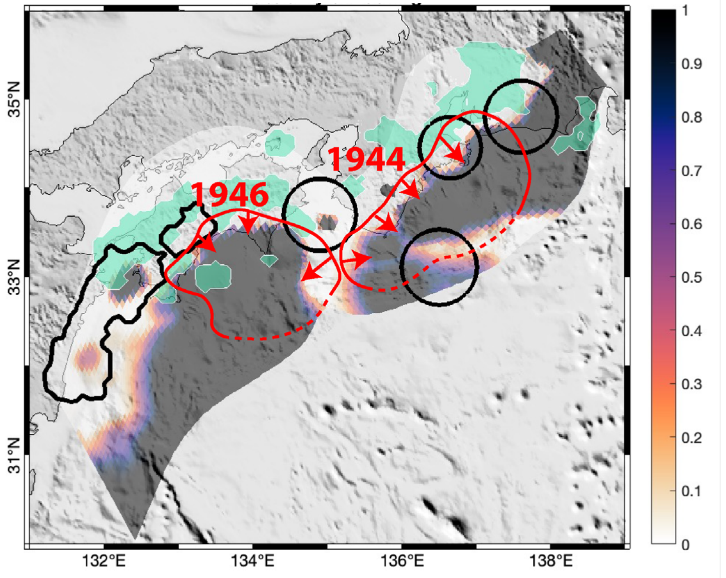


Final Thought (a hypothesis)

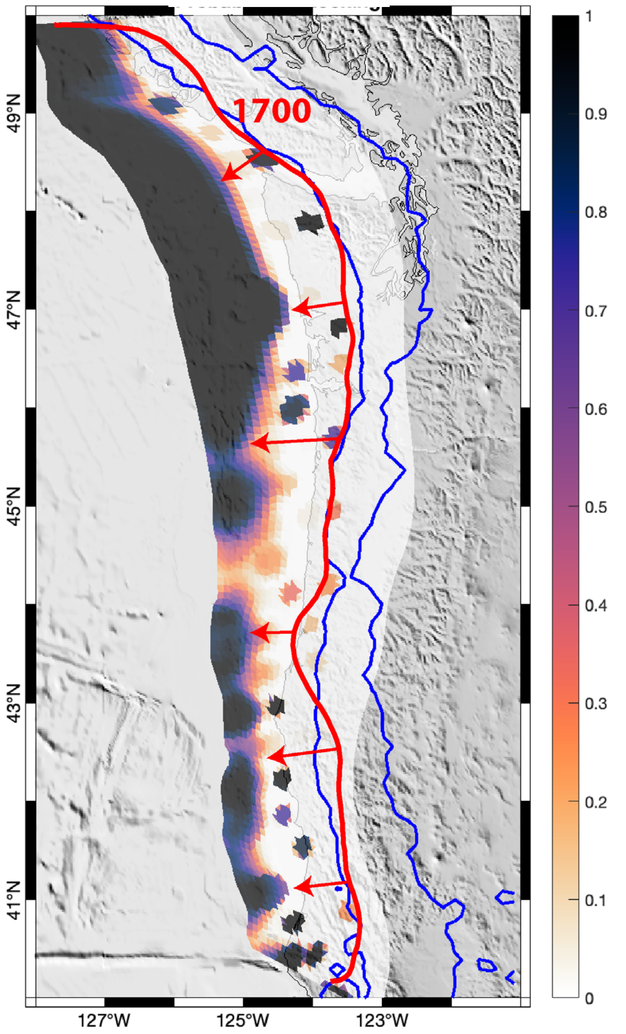
We infer heterogenous coupling consistent with nonstationary (shrinking) locked patches.

Observations/inferences of resent-day distribution of locking and slow slip may reflect a snapshot in time of a highly transient process.

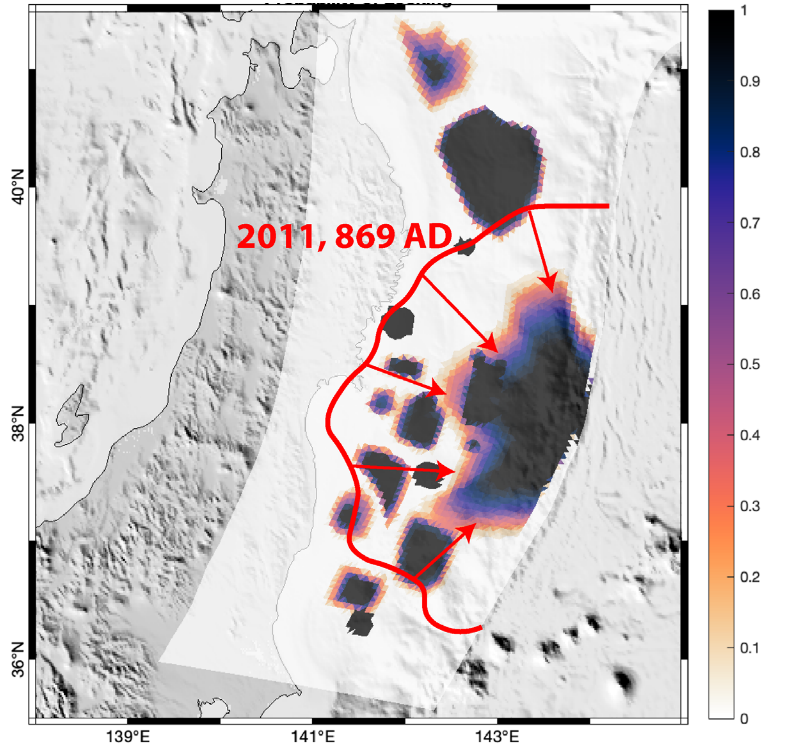
Nankai



Cascadia



Japan Trench



Hikurangi