BLOOMINGTON

Estimation of the Fully Coupled and Transitional Creep Zones at Nankai and Cascadia Using Probabilistic Inversion Methods

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Background & Motivation

This work aims to improve assessment of earthquake and tsunami hazard at subduction zones.

- We are trying to **better estimate** the spatial distribution of **the fully coupled or "locked" zone** because:
  - the length and width determine the overall size of an earthquake,
  - the updip extent has implications for tsunami generation, and
  - the downdip slip has implications for more intense ground shaking near populations.

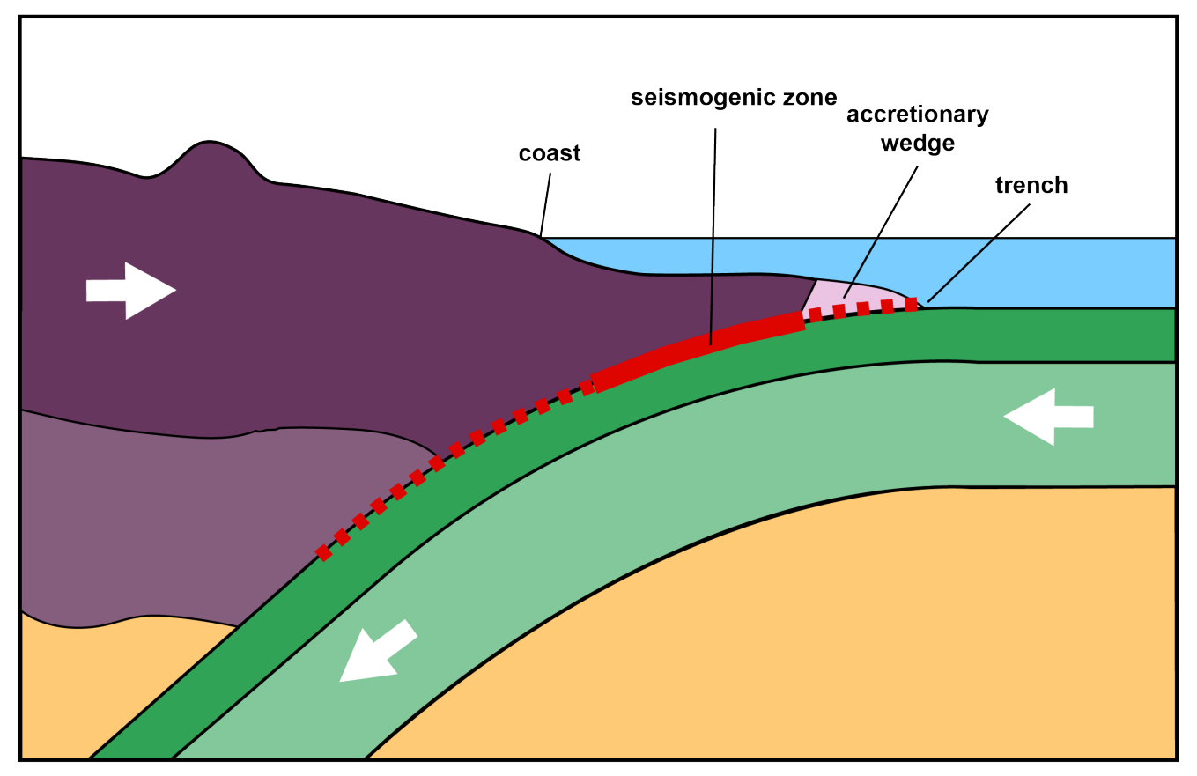


Figure. A subduction zone in cross section showing an idealized view of the fully coupled or "locked" zone (solid red) and the transitional creep zones (dashed red).

- We also want to **estimate** the spatial distribution and shape of **the shallow and deep transitional creep zones.**
- There is a **spectrum of slip behaviors** observed at subduction zones including: coseismic slip, postseismic slip, slow slip, and steady creep.

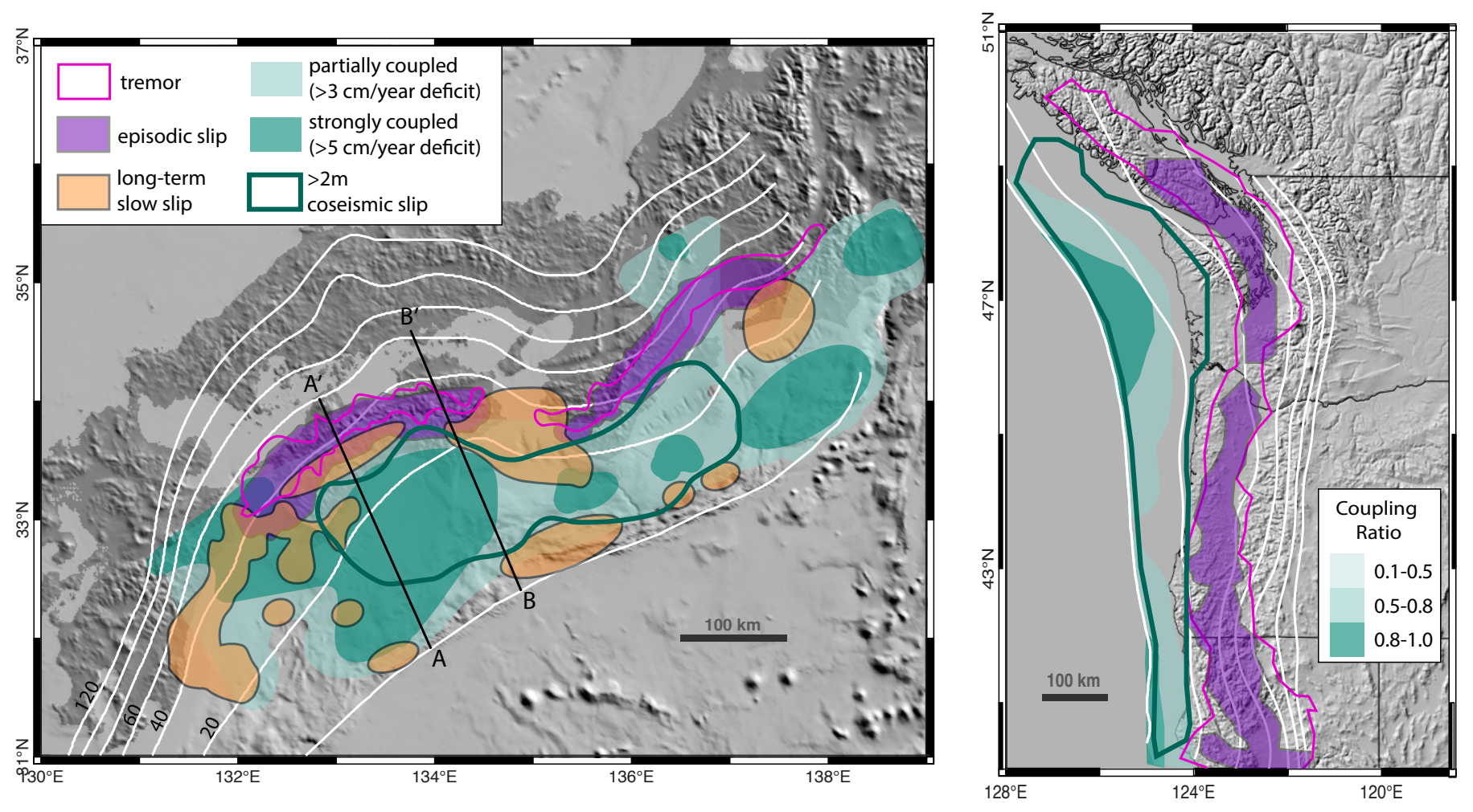
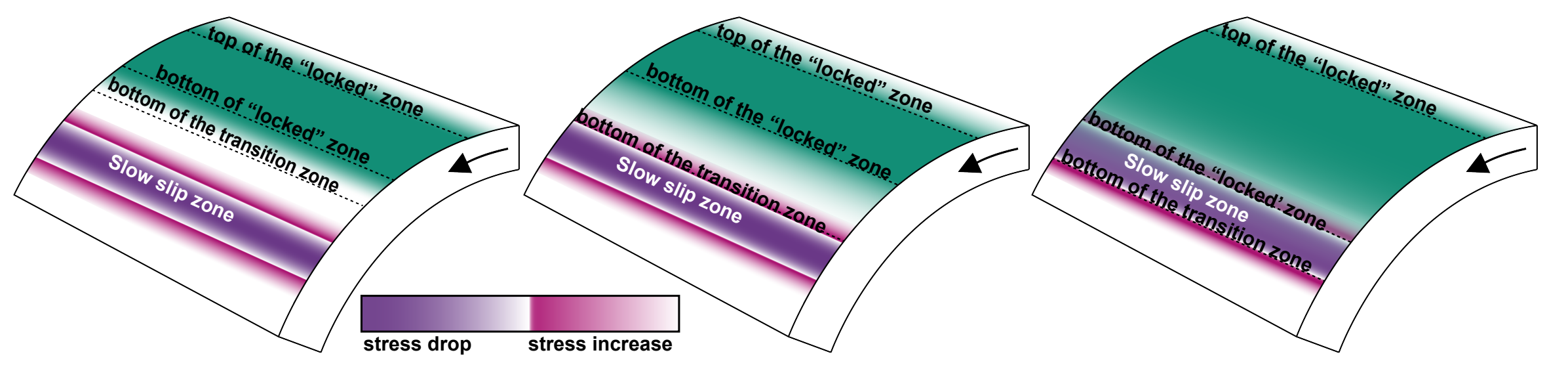


Figure. (a) Tectonic setting of the Nankai subduction zone showing locations of tremor (Obara et al., 2010), episodic short-term SSEs (Nishimura et al., 2013), long-term SSEs (Hirose et al., 2010; Kobayashi, 2017; Ozawa, 2017; Ozawa et al., 2016; Takagi et al., 2015), the inferred partially and strongly interseismically coupled regions (Yokota et al., 2016), and the coseismic slip region for the 1944/46 earthquakes (Sagiya & Thatcher, 1999). White contour lines represent slab depth at Nankai in 20 km increments (Hayes et al., 2012). Cross-sections A-A' and B-B' are for slip budget estimates in Figure 6. (b) Tectonic setting of the Cascadia subduction zone showing locations of tremor (Bartlow, 2020), episodic short-term SSEs (Bartlow, 2020), estimated coseismic slip region for the 1700 earthquake (Wang et al., 2013), and the inferred interseismic coupling ratio (Lindsey et al., 2021). White contour lines represent slab depth at Cascadia in 20 km increments (Hayes et al., 2018).

- Numerical simulations indicate that slow slip events can evolve into megathrust rupture. It is important to know the spatial relationship of the slow slip zone and the fully coupled zone when assessing seismic hazard.



- Slip inversions that employ smoothing make it difficult to assess where the downdip and updip edge of the fully coupled, transitional creep, and slow slip zones are located.
- The method presented here helps to address this limitation.

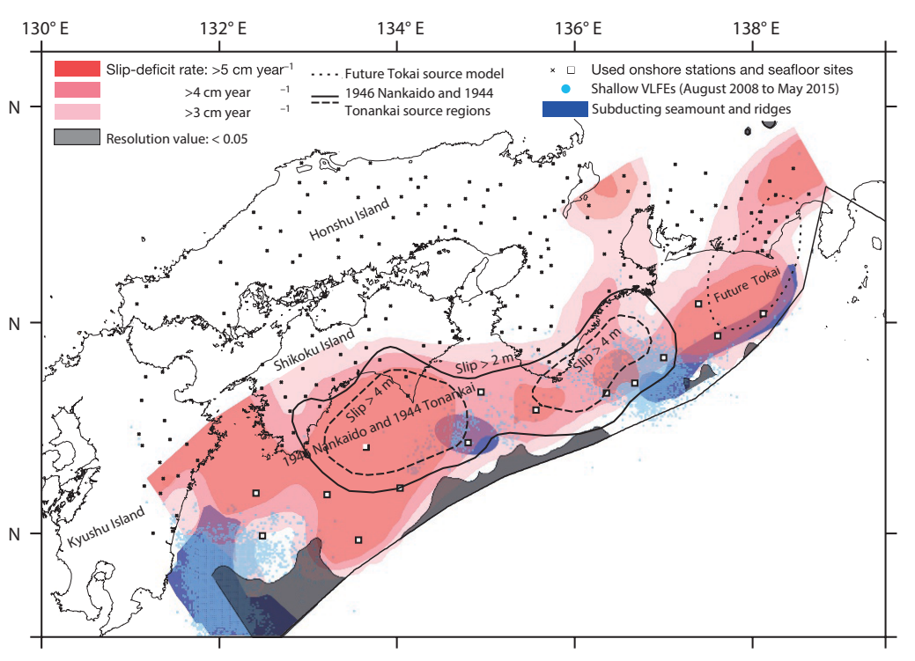
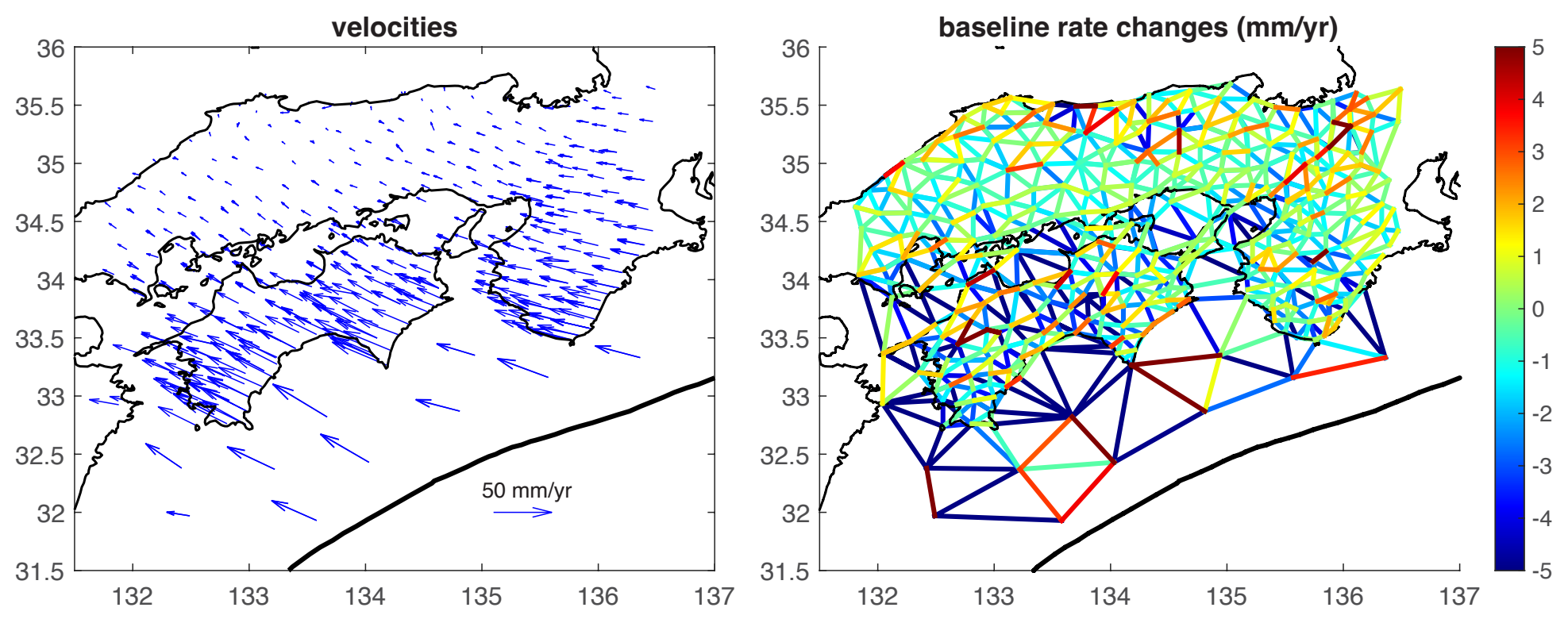


Figure. Yokota et al. (2016) interseismic coupling estimate for Nankai, Japan shown in shades of red. Dark red indicates areas that are fully coupled. This is an example of a slip inversion where it is difficult to delineate the bottom or top edge of the fully coupled zone.

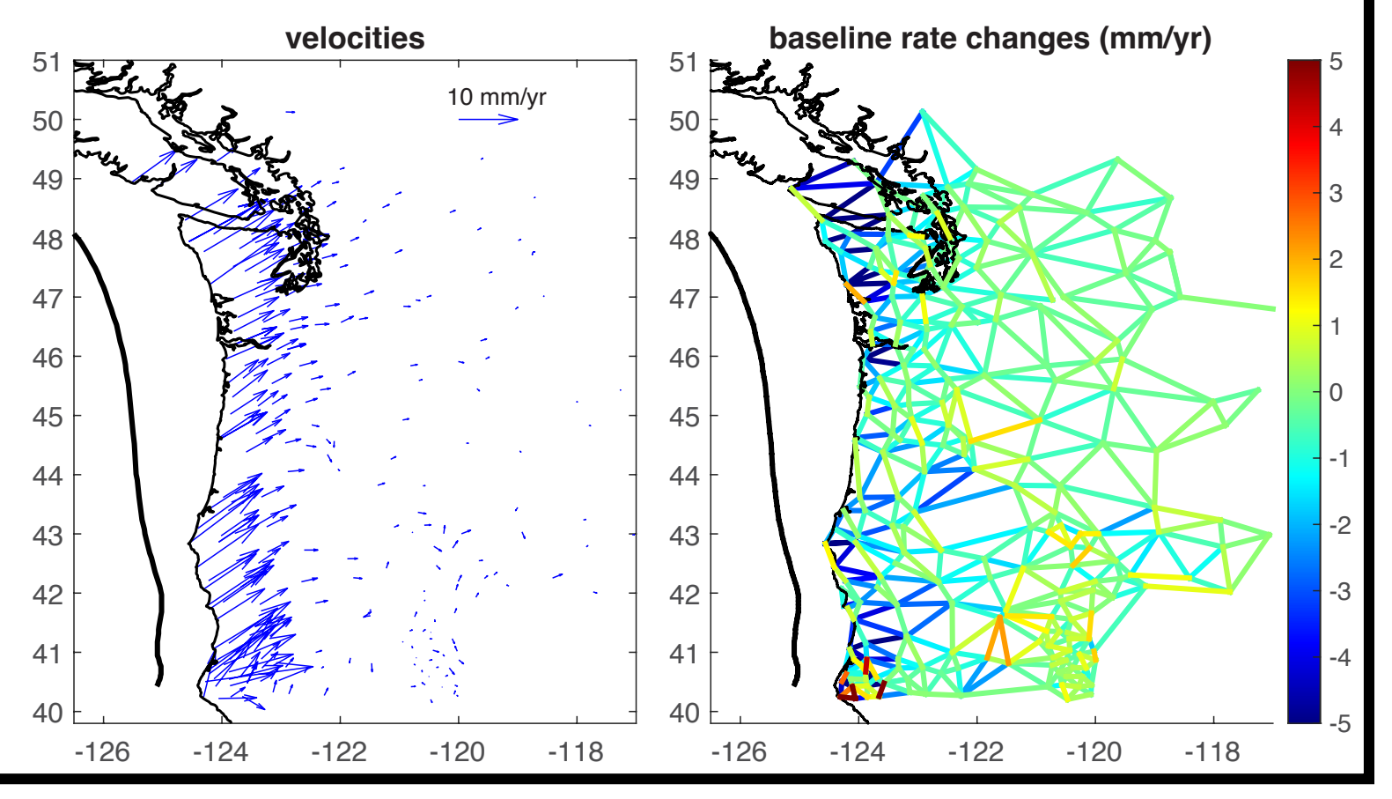
Interseismic Data

- Interseismic velocities are projected onto baselines connecting the GNSS stations.
- The rate changes of these baselines are inverted for interseismic coupling.
- This method removes the need to estimate the contribution of rigid body motion to the velocity field.
- The Cascadia field came from Rob McCaffrey.
- The Nankai field came from Yokota et al. (2016).

Nankai



Cascadia



Boundary Inversion Method

Details about the inversion:

- Markov chain Monte Carlo inversion of interseismic baseline rate changes for the node depths that define:
  - the upper boundary of the fully coupled zone (red line in Figure)
  - the lower boundary of the fully coupled zone (blue line in Figure), and
  - the lower boundary of the deep transitional creep zone (green line in Figure).

Fully Coupled Zone

- The traditional "backslip" model of Savage (1983) is used, where slip deficit is modeled with imposed slip in the opposite sense of long-term motion.
- A patch is defined as fully coupled if the backslip rate equals 1.
- Thus, that patch is not slipping in the interseismic period.

Shallow Transitional Creep Zone

- Cannot assume the trench is fully creeping.
- Boundary element calculation to estimate stressing rate on a patch based on the backslip rate of the other patches.
- Similar to Lindsey et al. (2021).

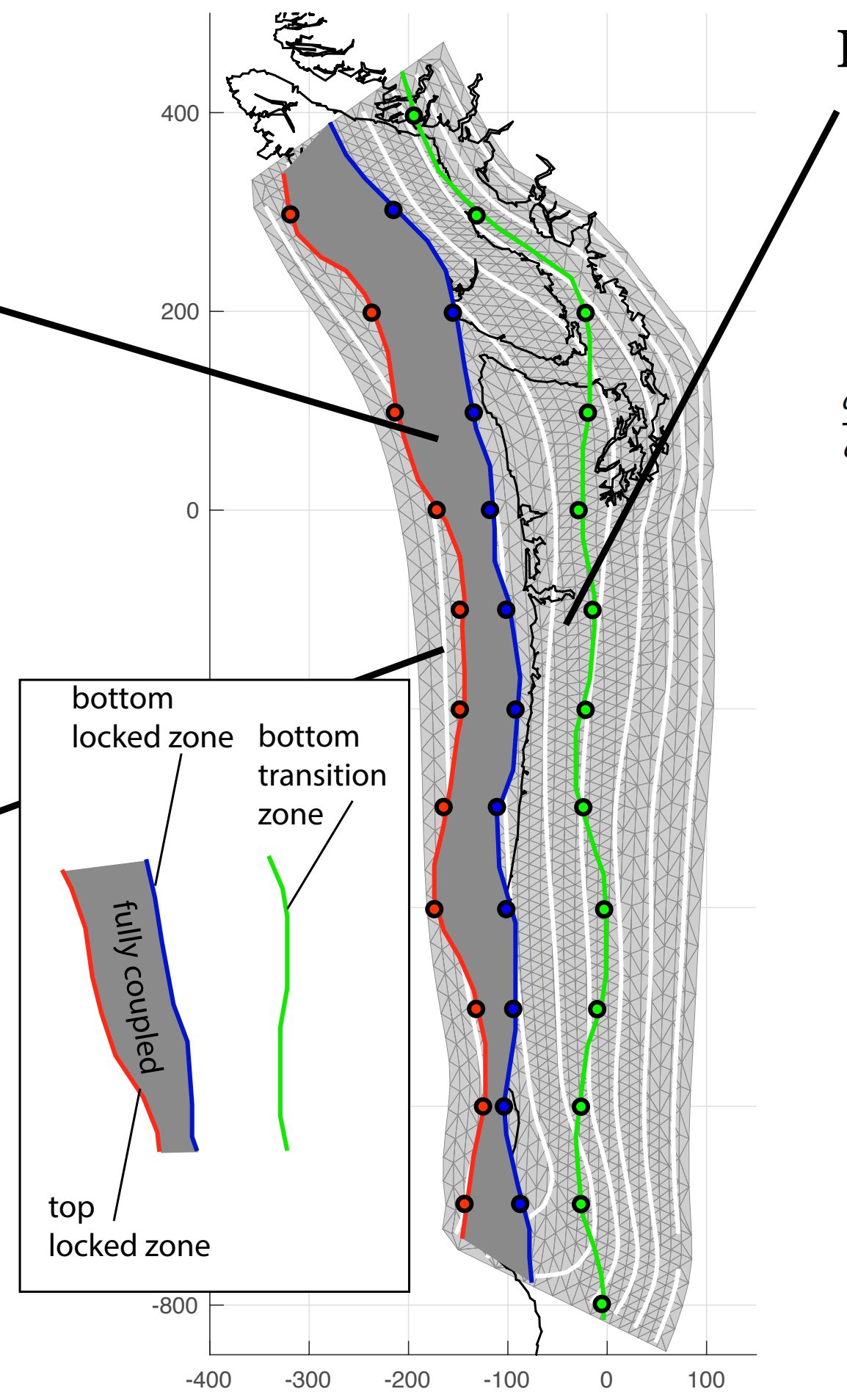


Figure. Schematic of the Cascadia subduction zone with the boundaries that the inversion solves for shown in red (top of locked), blue (bottom of locked), and green (bottom of deep transition).

Deep Transitional Creep Zone

- Define the deep transition zone distribution from fully coupled to fully creeping using Bruhat & Segall (2017) equation 13d.

$$\frac{ds}{dt}(\xi,t) = \frac{v^{\infty}}{\pi}\left[\xi\sqrt{1-\xi^2} + \arcsin(\xi) + \frac{\pi}{2}\right] + \dot{a}\frac{2v^{\infty}t}{a\pi}(1-\xi)\sqrt{1-\xi^2}.$$

- Inversion solves for propagation rate ($\dot{a}$) at each node.

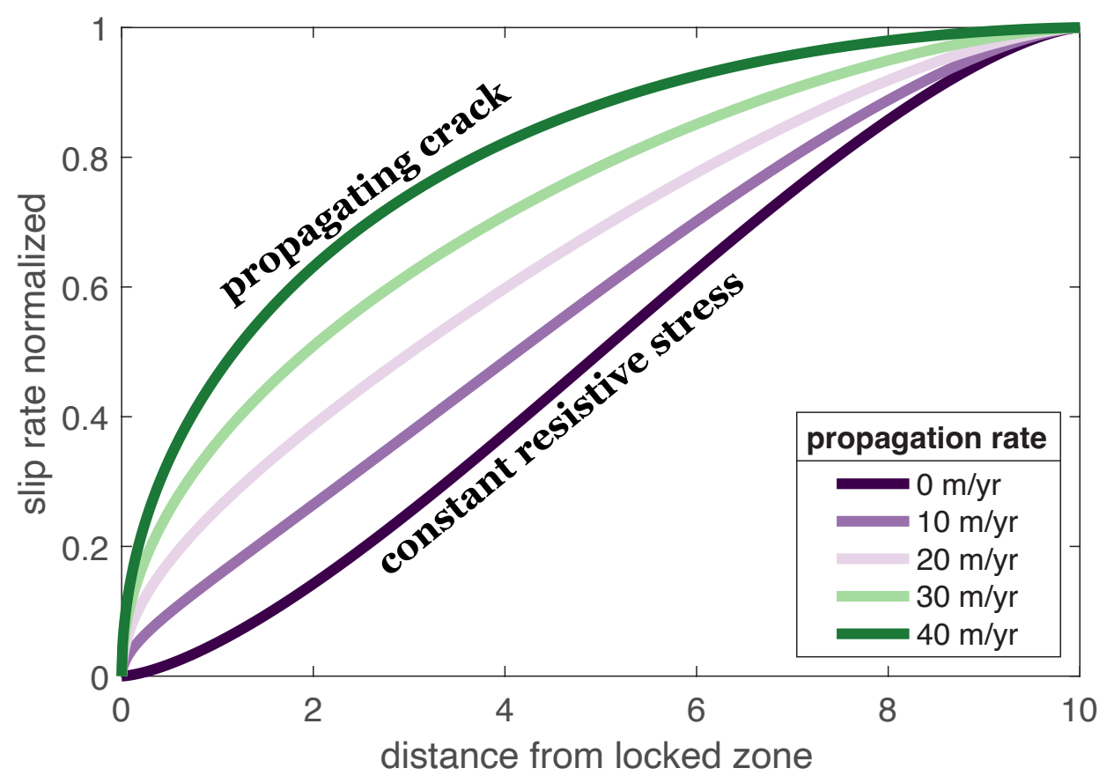
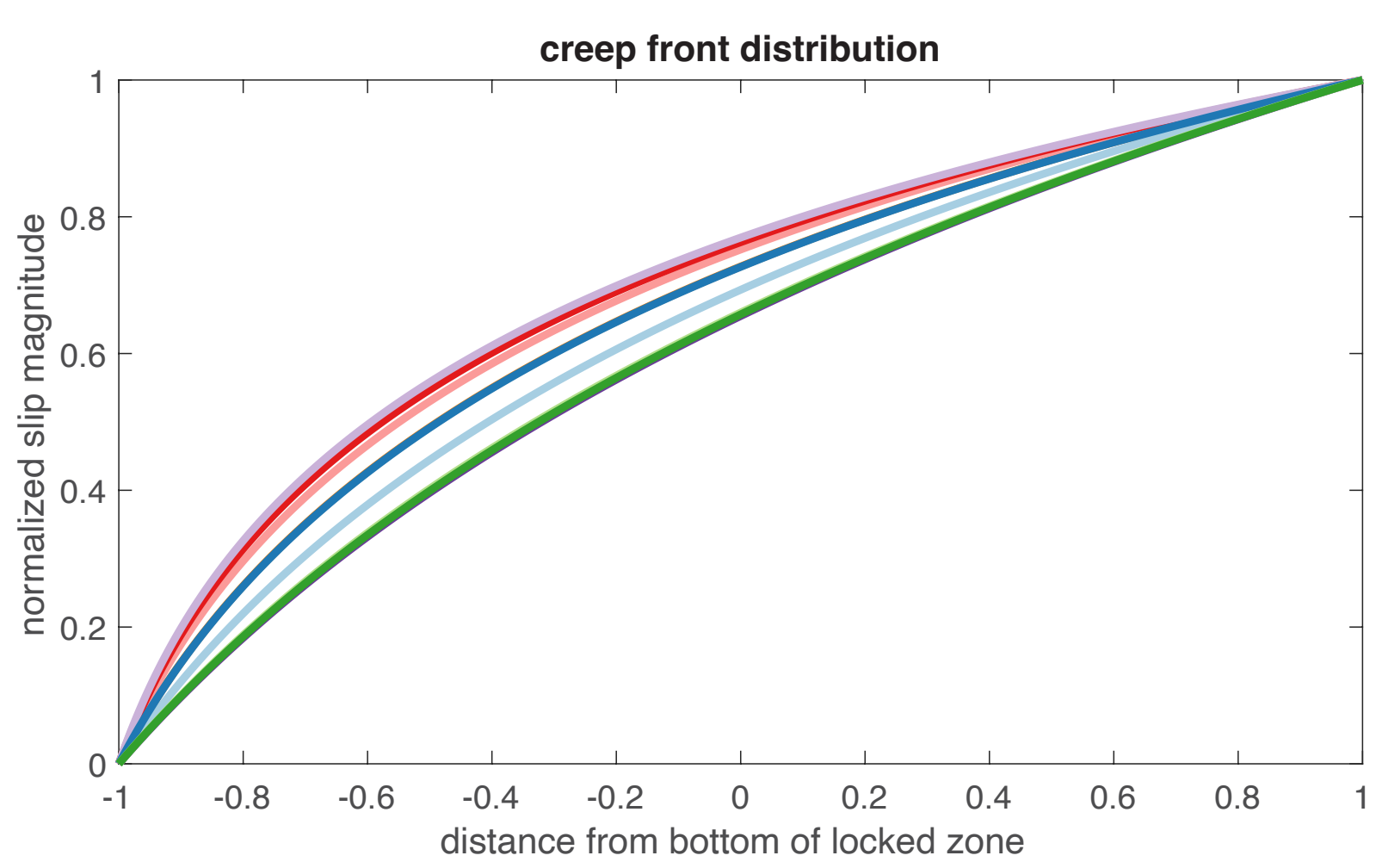
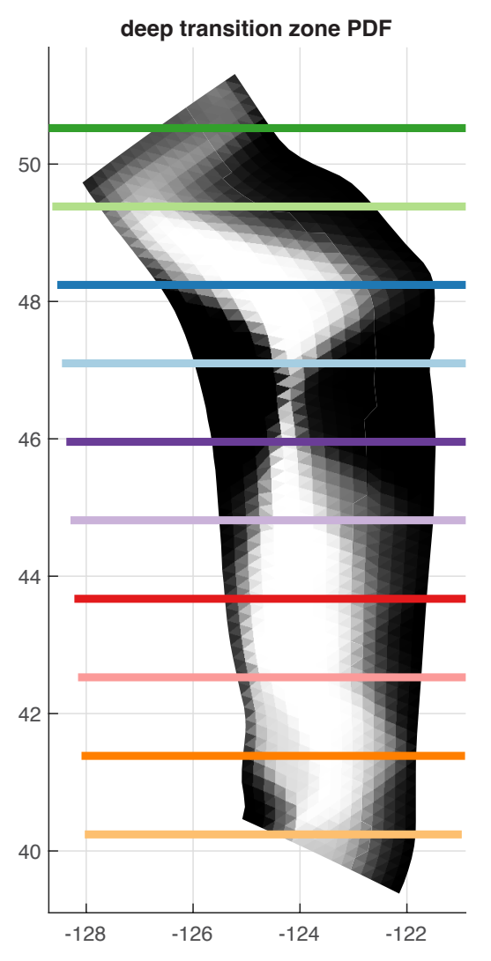


Figure. Illustration of various slip rate profiles using the Bruhat & Segall (2017) equation. A slip rate of 0 is fully coupled and a slip rate of 1 is fully creeping. The different colored lines represent different propagation rates of the creep front.

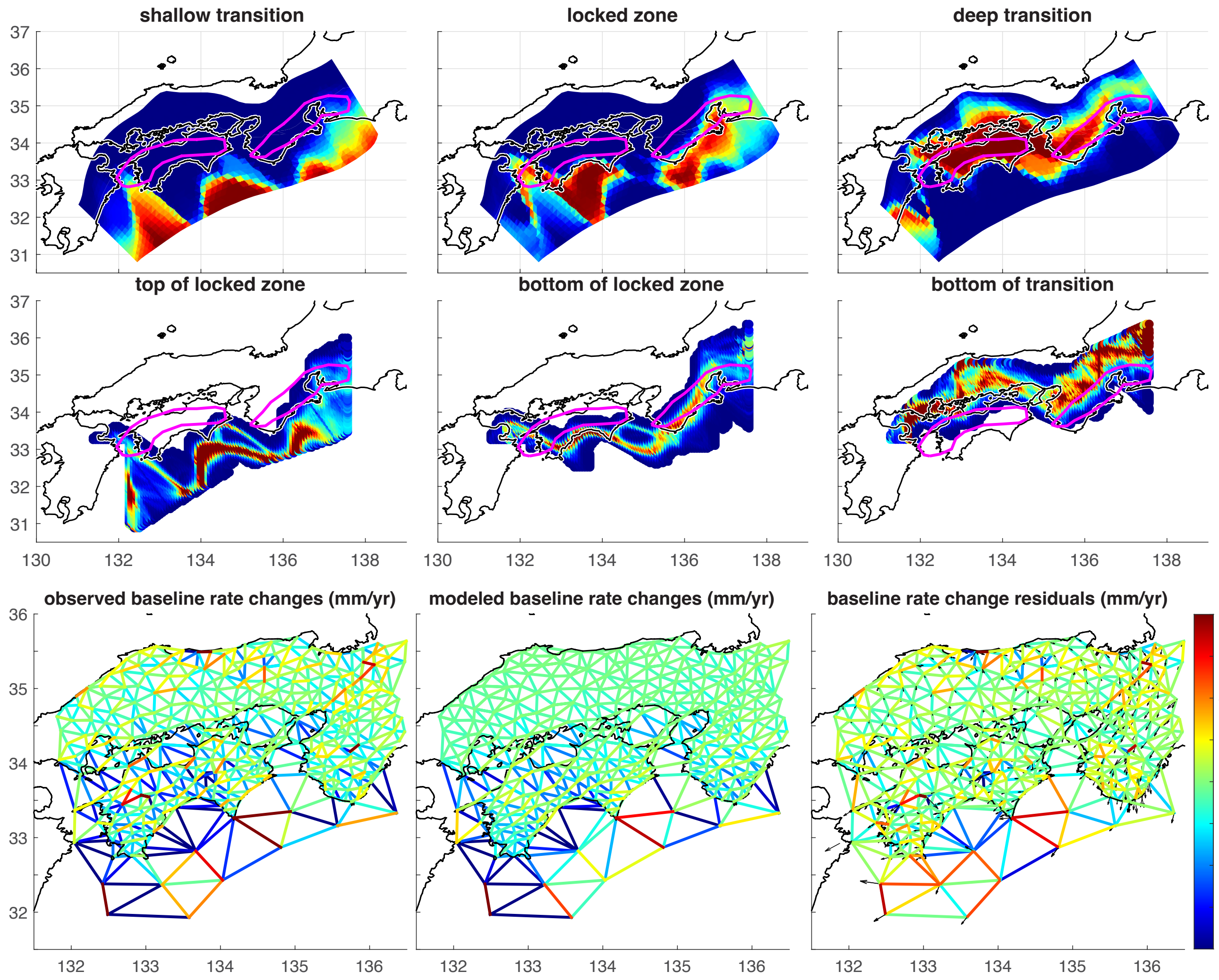
Propagating Creep in Deep Transition Zone

- Preliminary results for the propagation rate at Cascadia are shown in the two figures to the right.
- The slip rate profiles shown on the left are from cross sections of the deep transition zone shown on the right.
- The purple and red cross sections around 43-46°N have the highest propagation rates.
- The green profiles are closer to constant resistive stress.



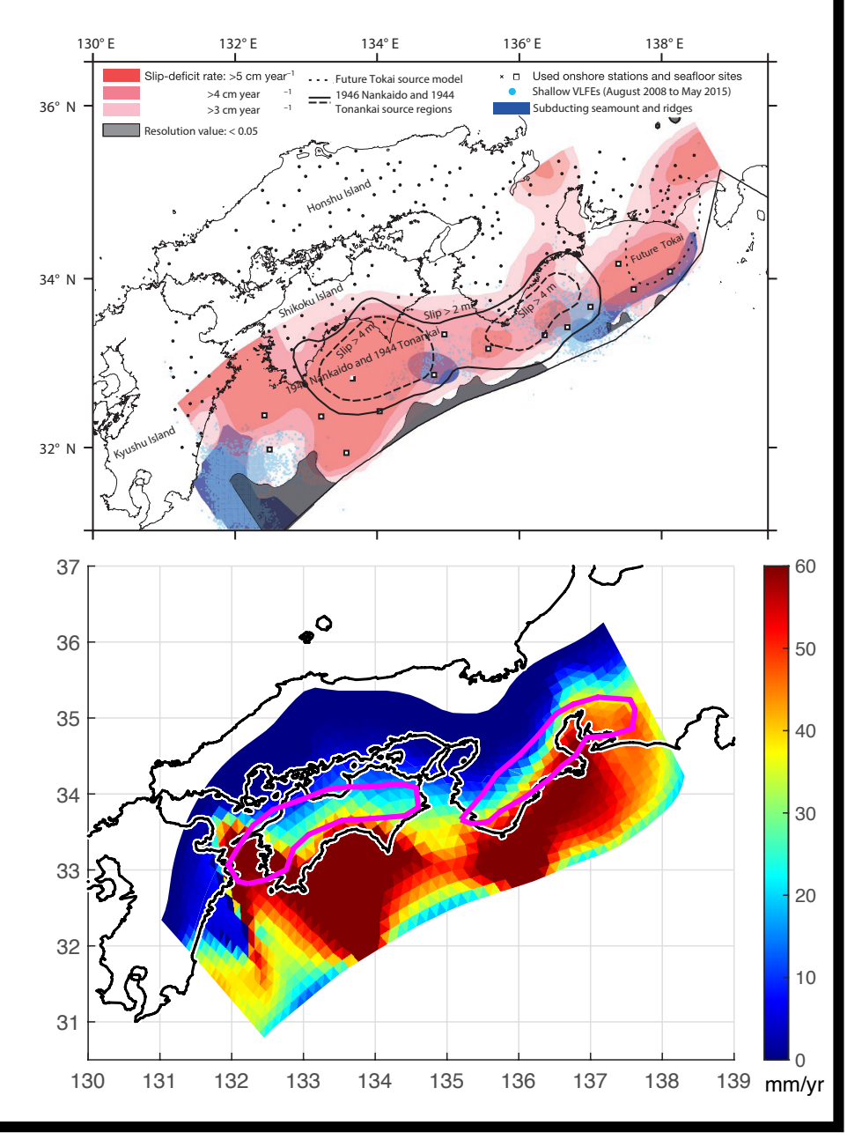


Nankai Results



low high
probability
☐ slow slip zone

Figure. (top left) Probability distribution functions for the best-fitting Nankai trail. Grey lines are 20km contours from Slab 2.0. (bottom left) Observed, modeled, and residual baseline rate changes for the best-fitting trial for Nankai. (bottom right) Comparison of the best-fitting backslip distribution to the Yokota et al. (2016) interseismic coupling estimate.



Cascadia Results

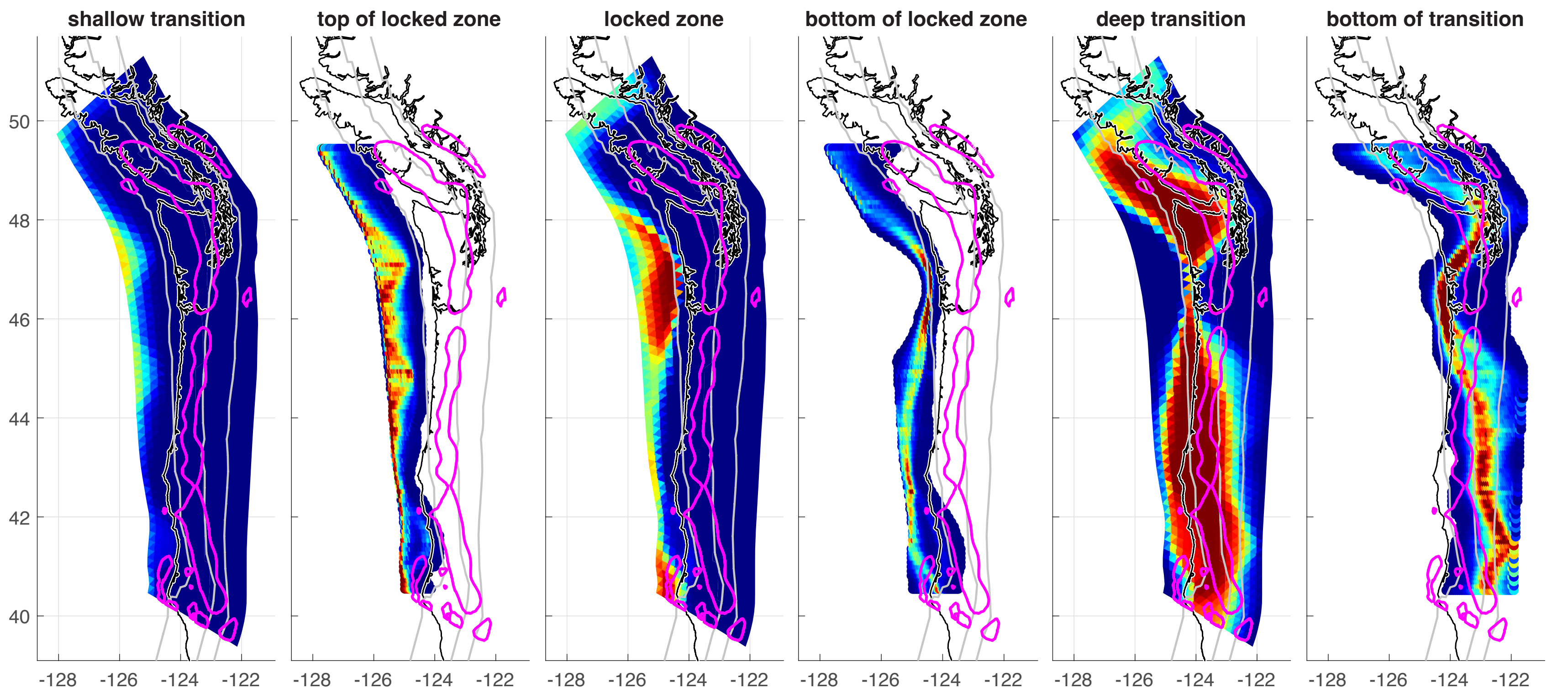


Figure. Probability distribution functions for the best-fitting Cascadia trial. Grey lines are 20km contours from Slab 2.0.

low high
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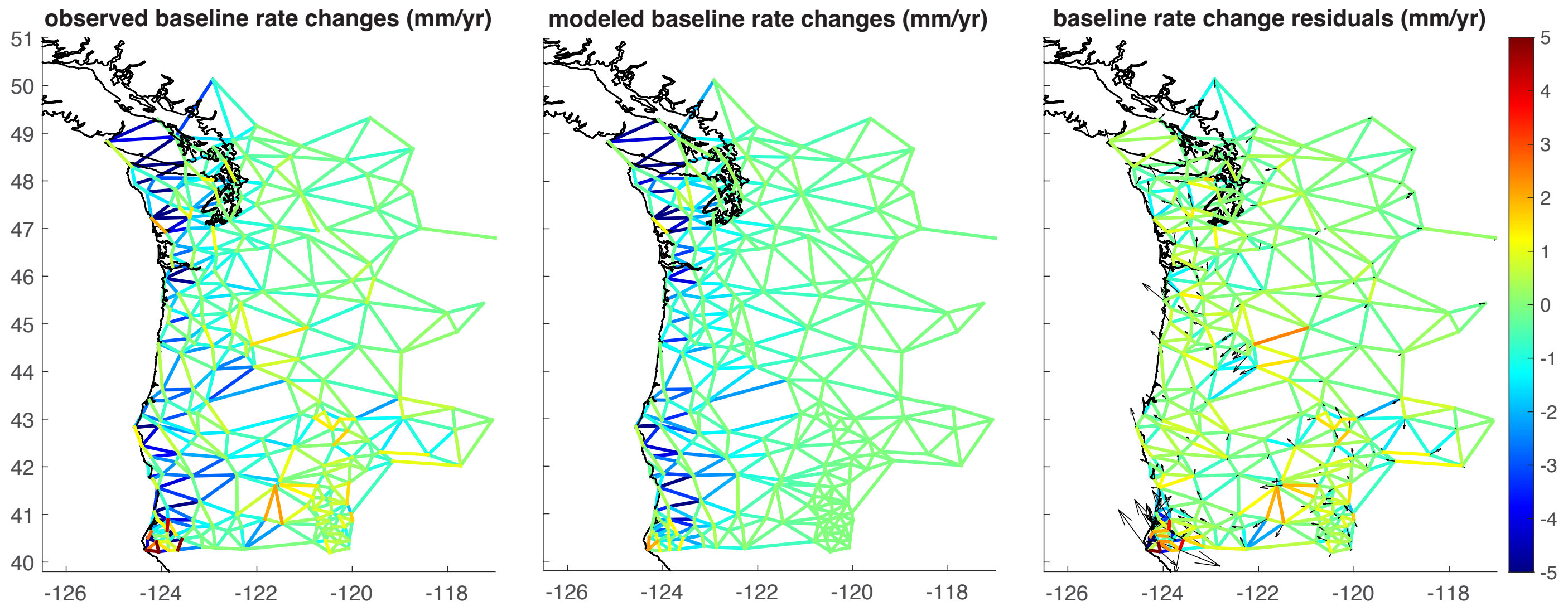


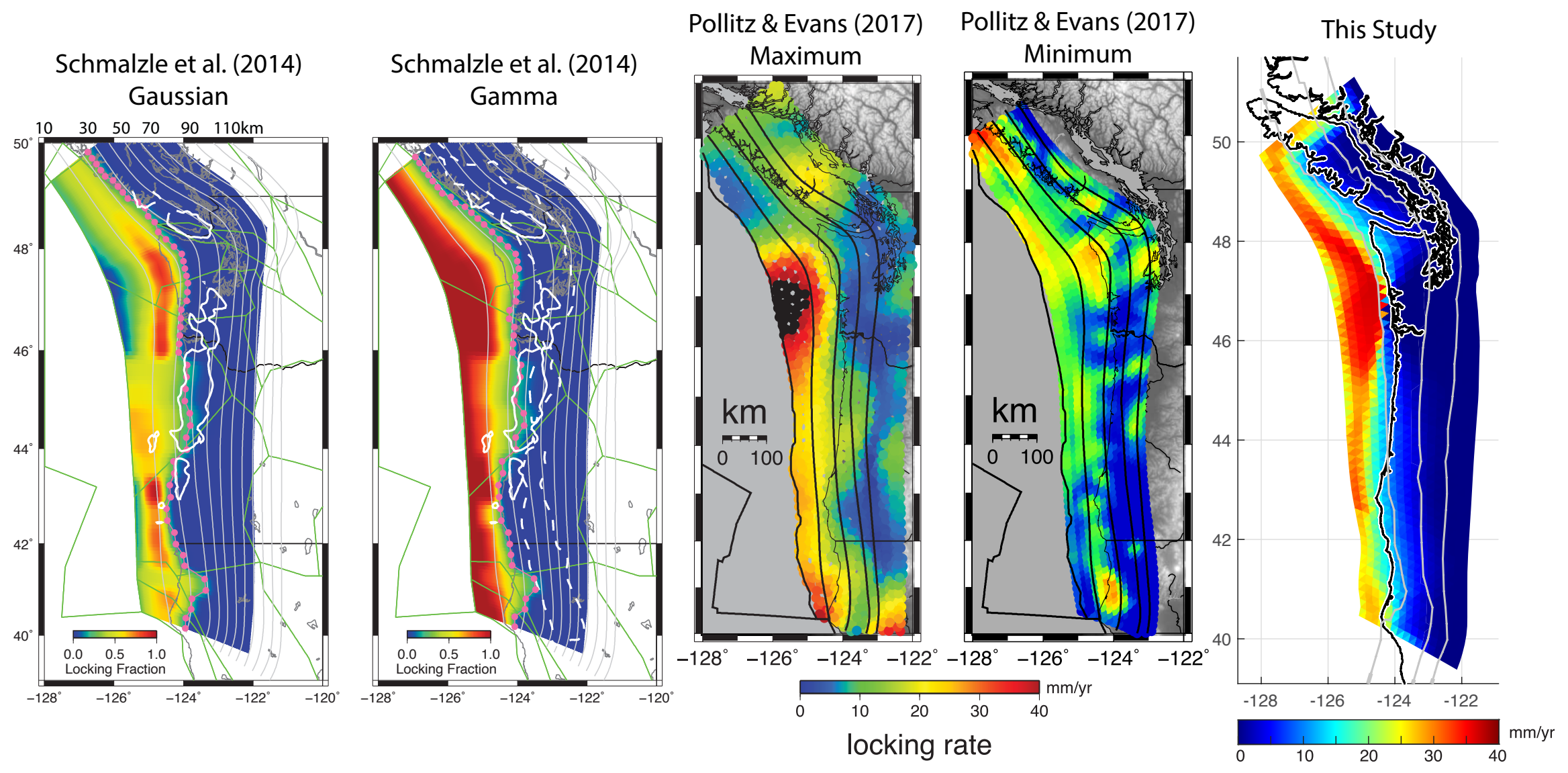
Fit to data

The observed (left), modeled (middle), and residual (right), baseline rate changes for our best fitting Cascadia trial.

Comparison to other models

Our best-fitting backslip distribution compared to Schmalzle et al. (2014) and Pollitz & Evans (2017) locking estimates.

Deeper locking between 46-48°N and shallow locking between 43.5-46°N are common features of all estimates.



Conclusions & Next Steps

Conclusions

1. There appears to be a gap between the bottom of the fully coupled zone and the top of the deep transition zone at Cascadia.
2. The bottom of the fully coupled zone is right next to the top of the deep transition zone at Nankai.
3. The slow slip zone seems to be fully contained within the transition zone at Nankai and Cascadia.
4. Results are very preliminary, but the creep front appears to be propagating towards the bottom of the locked zone in southern Washington and northern Oregon.
5. Elastic only inversions seem to match similar non-probabilistic inversions. It is likely viscoelasticity will improve fit, especially to vertical data.

Next Steps

1. Incorporate elastic heterogeneity
2. Viscoelastic cycle modeling
3. Develop a similar inversion for slow slip zone using long-term average slow slip velocities

Figure. Viscoelastic cycle and elastic models of horizontal and vertical velocity data at Cascadia (Johnson, in prep). a) Vertical data at Cascadia. b) 2D model c) results for the horizontal and vertical, viscoelastic and elastic. Viscoelasticity is critical for matching the vertical data and improves the fit to horizontal data.