Locked or Coupled? The semantics and science of future earthquake potential on the shallow megathrust

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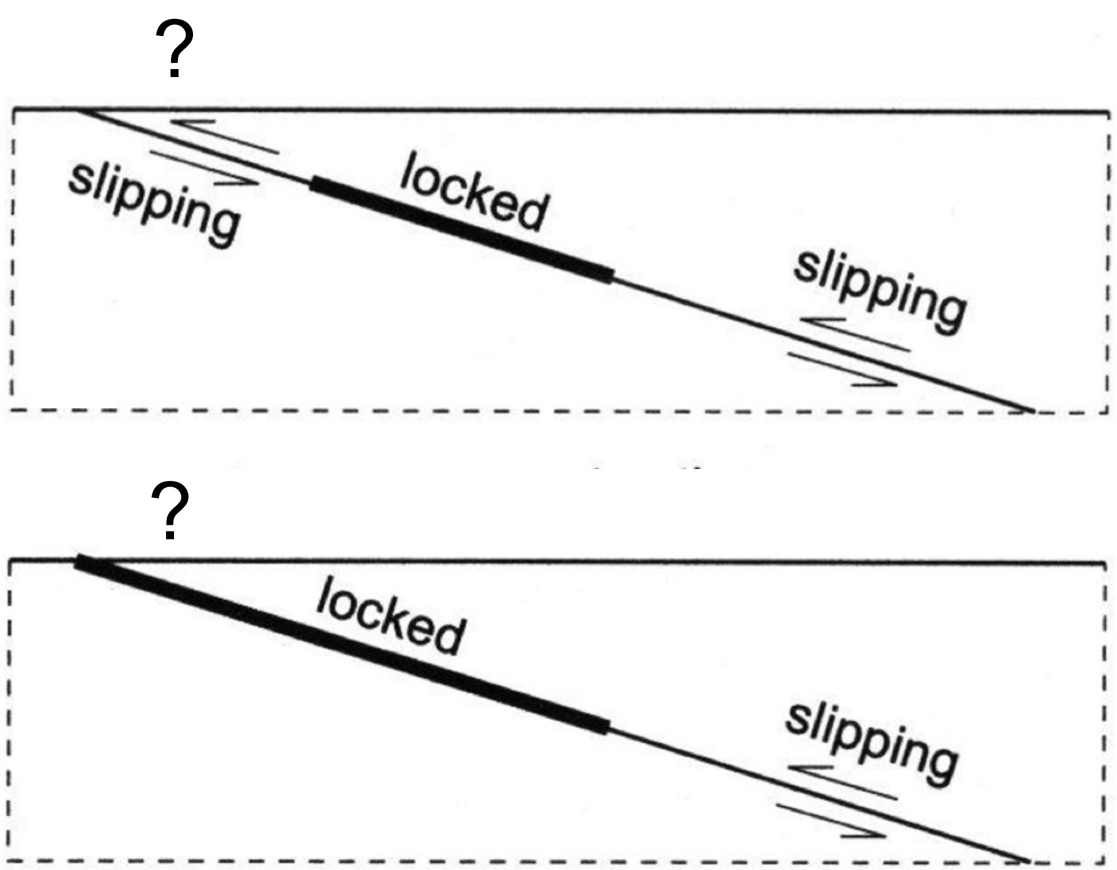
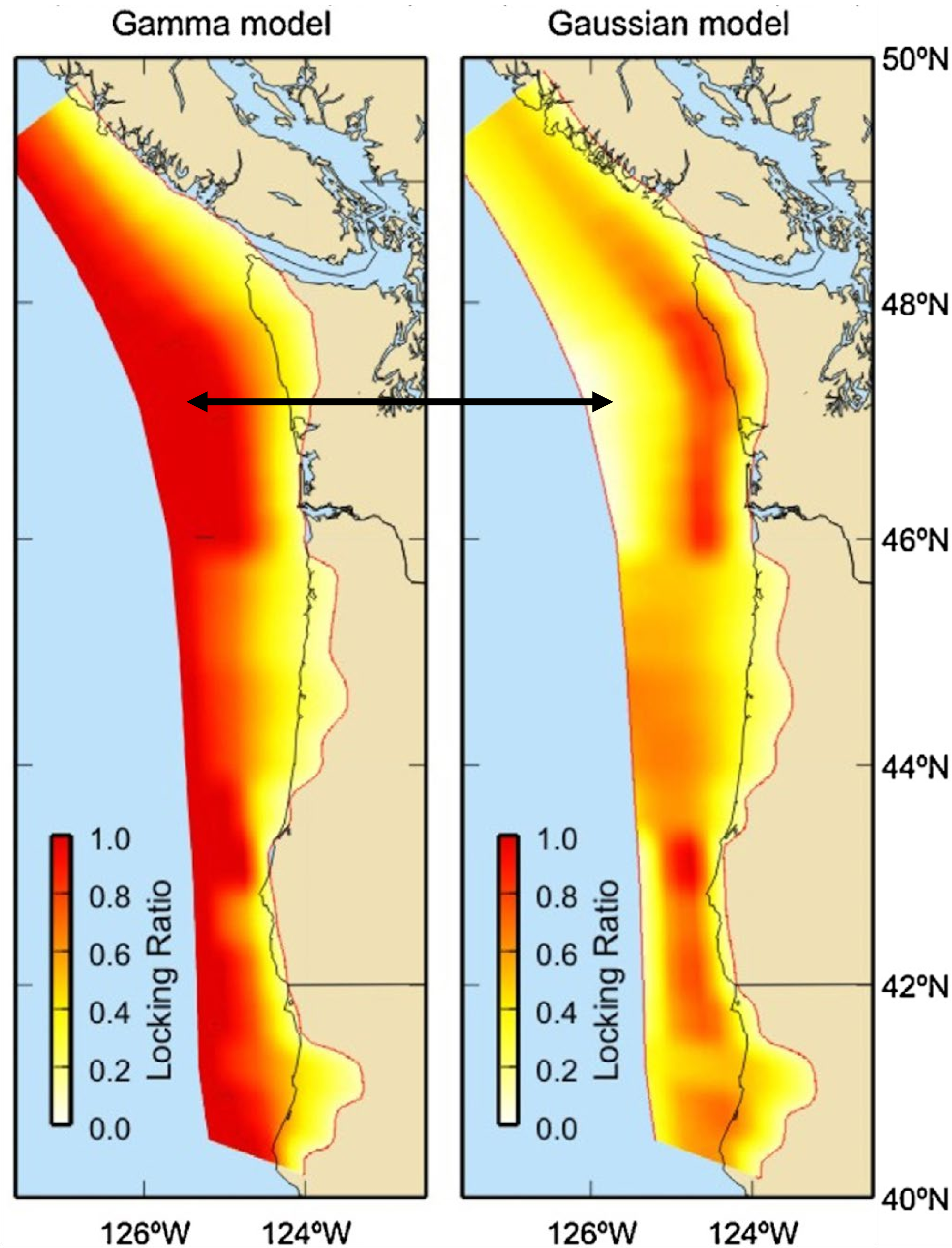
Tsunami hazard comes from the shallow part of the fault.

What can land-based geodesy tell us about this part of the fault?

Not much by itself - the data has nearly zero resolution near the trench.

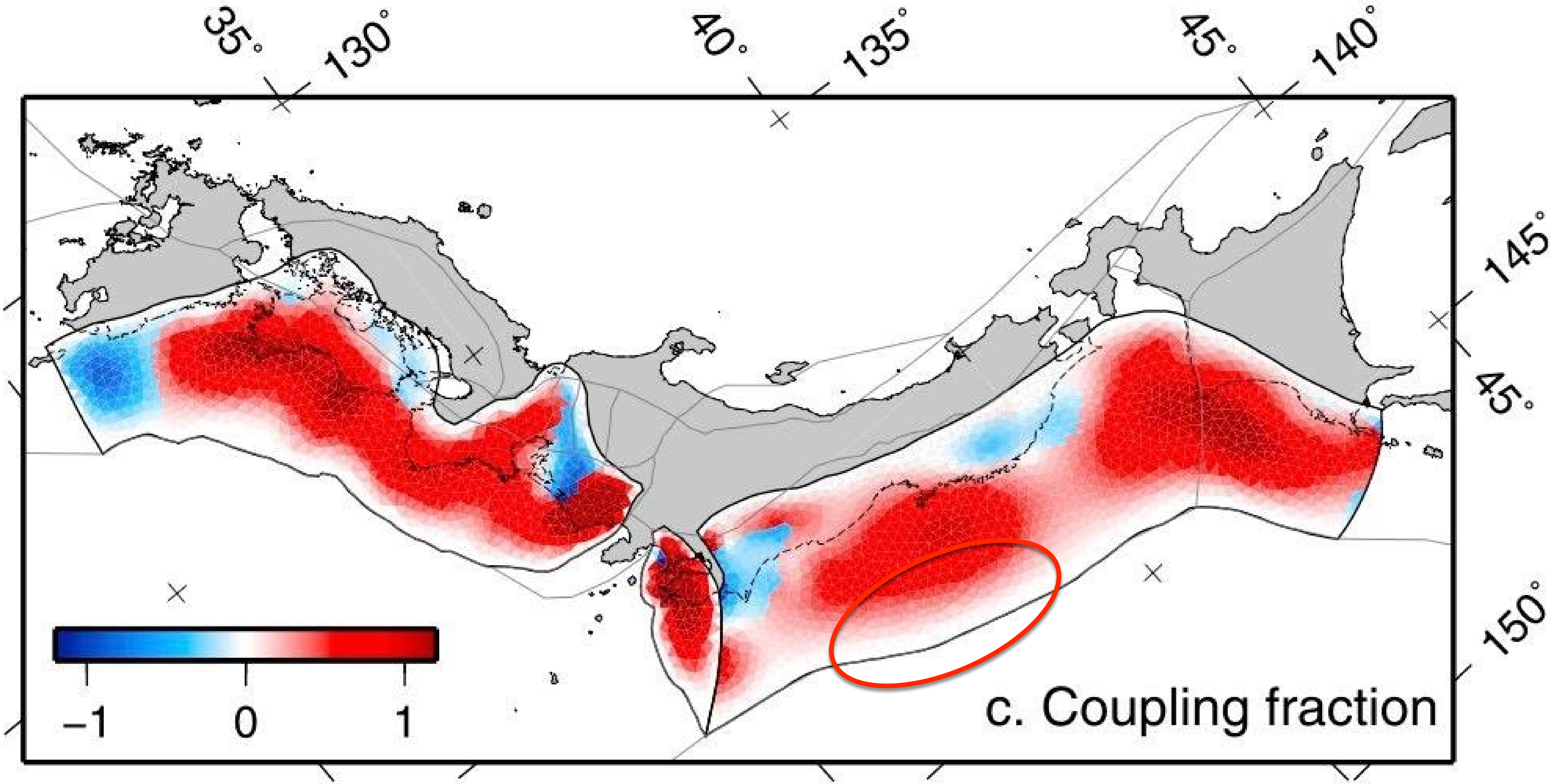


Wang & Dixon, 2004



Schmalzle et al., 2014; Wang & Trehu, 2016

Shallow subduction zones are hard to measure geodetically: many models assume low **kinematic** coupling



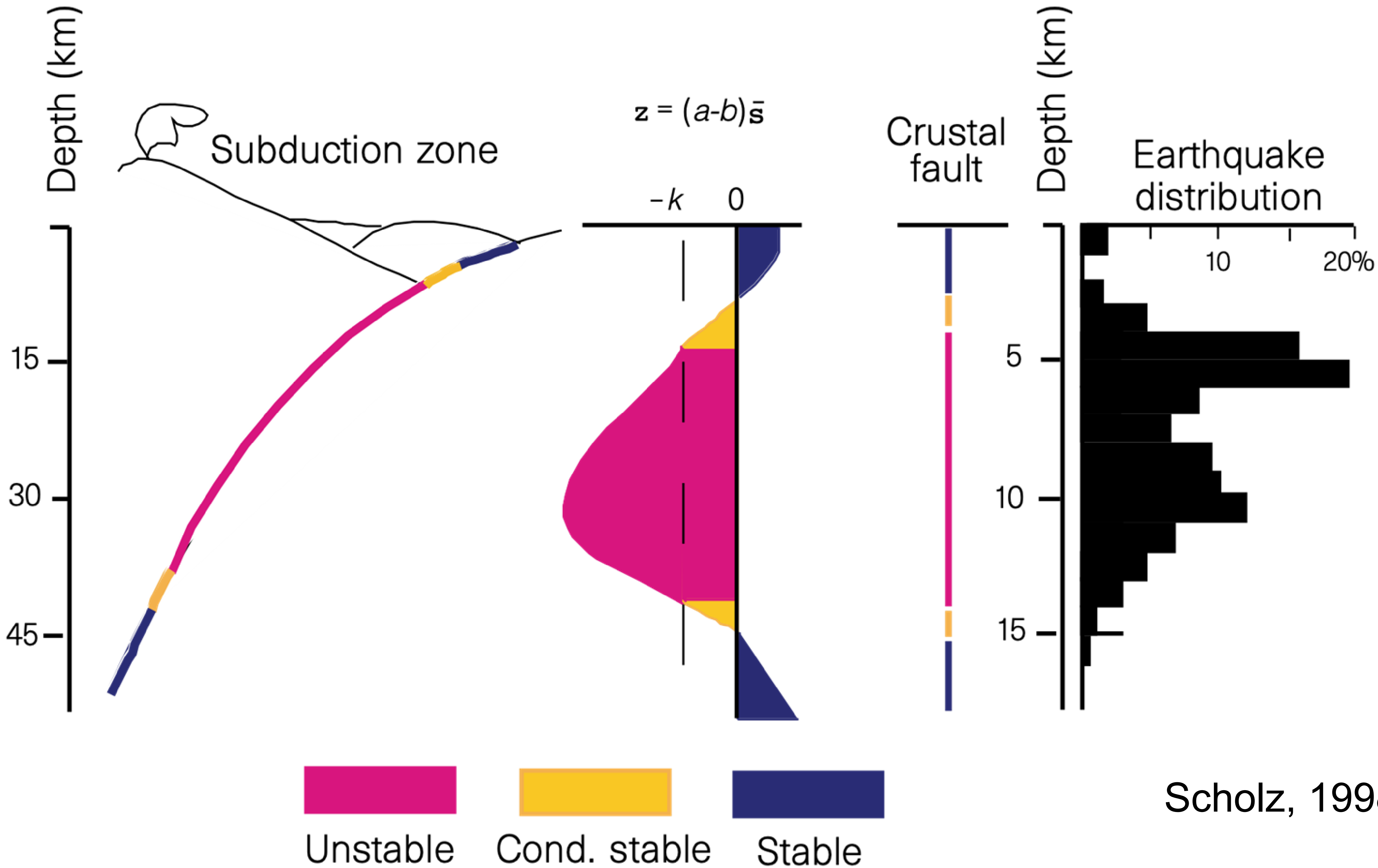
Japan: Loveless & Meade, 2010

Fault creep is the expected behavior for shallow faults

1. Lab studies have shown velocity strengthening behavior is common at low temperature and pressure (fault may be frictionally unlocked).

2. There is a relative lack of microseismicity on the shallow part of faults.

→ low **seismic coupling** (Kanamori, 1971)



Scholz, 1998

Many published models make a key error: they confuse **seismic coupling** and **kinematic coupling**.

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"Coupling" Semantics and Science in Earthquake Research

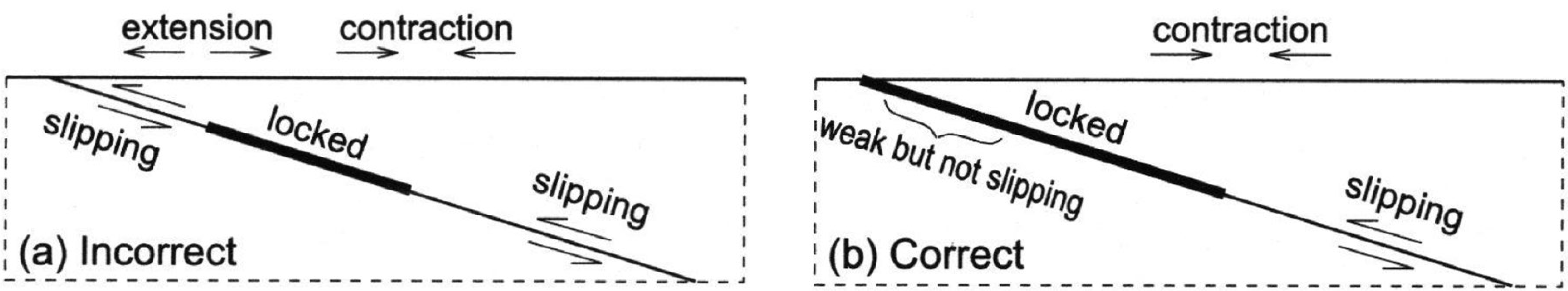
The confusion comes from historical misuse of terminology.

Slip rate deficit: the difference between the current slip rate and the long-term average

Kinematic coupling: ratio of slip deficit to long-term slip rate (1=not slipping)

Seismic coupling: fraction of slip released seismically (1=totally seismic)

Frictional locking: the fault's response to slip (locked=unstable)

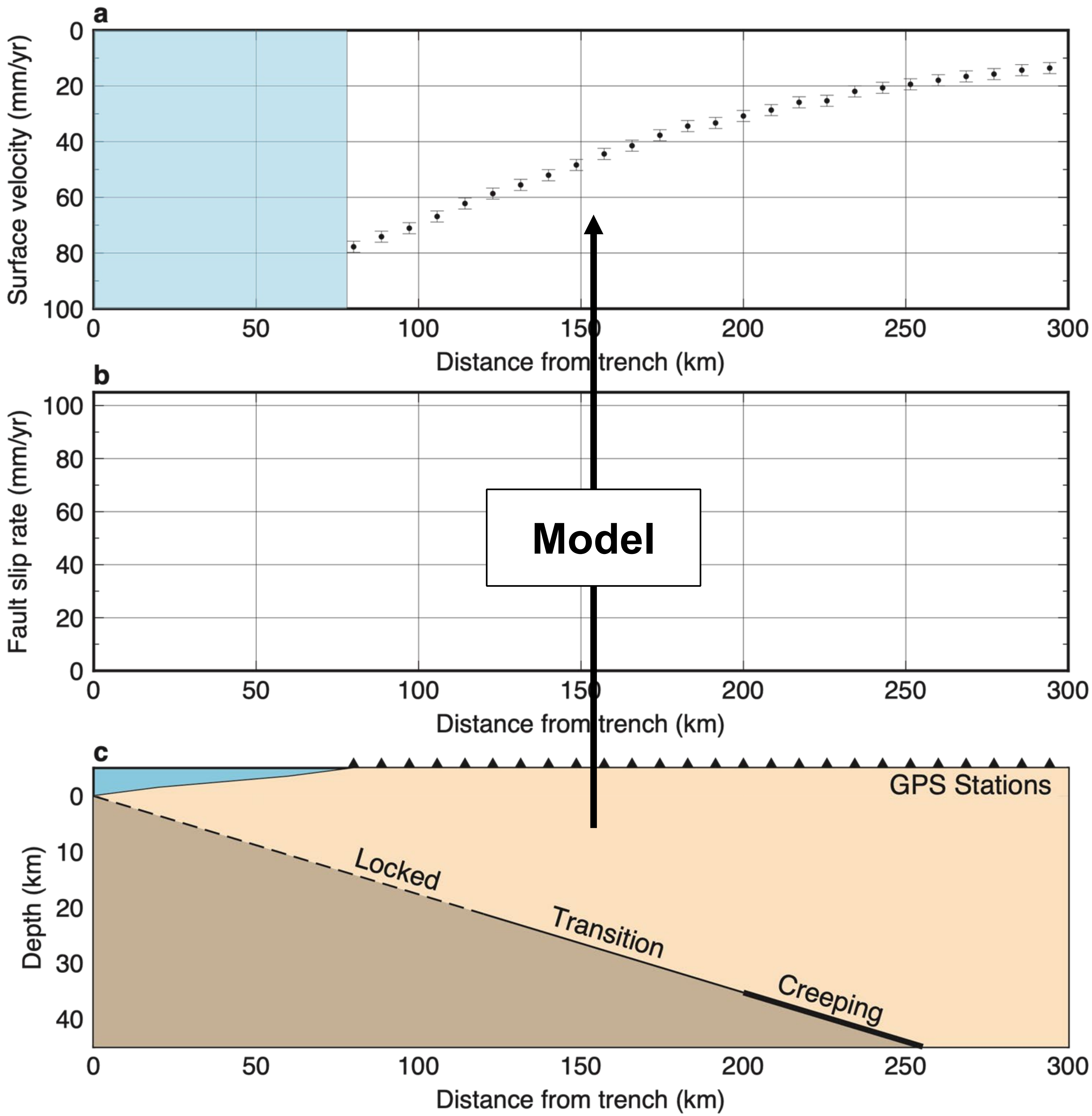


Wang & Dixon (2004); Almeida et al. (2018); Herman et al. (2018); Lindsey et al. (2021)

What is the range of models that can fit the data?

Use a traditional least-squares technique (Chlieh et al., 2008; 2014).

misfit = data residual
+ smoothing penalty
+ model norm prior



Result: large uncertainty near the trench

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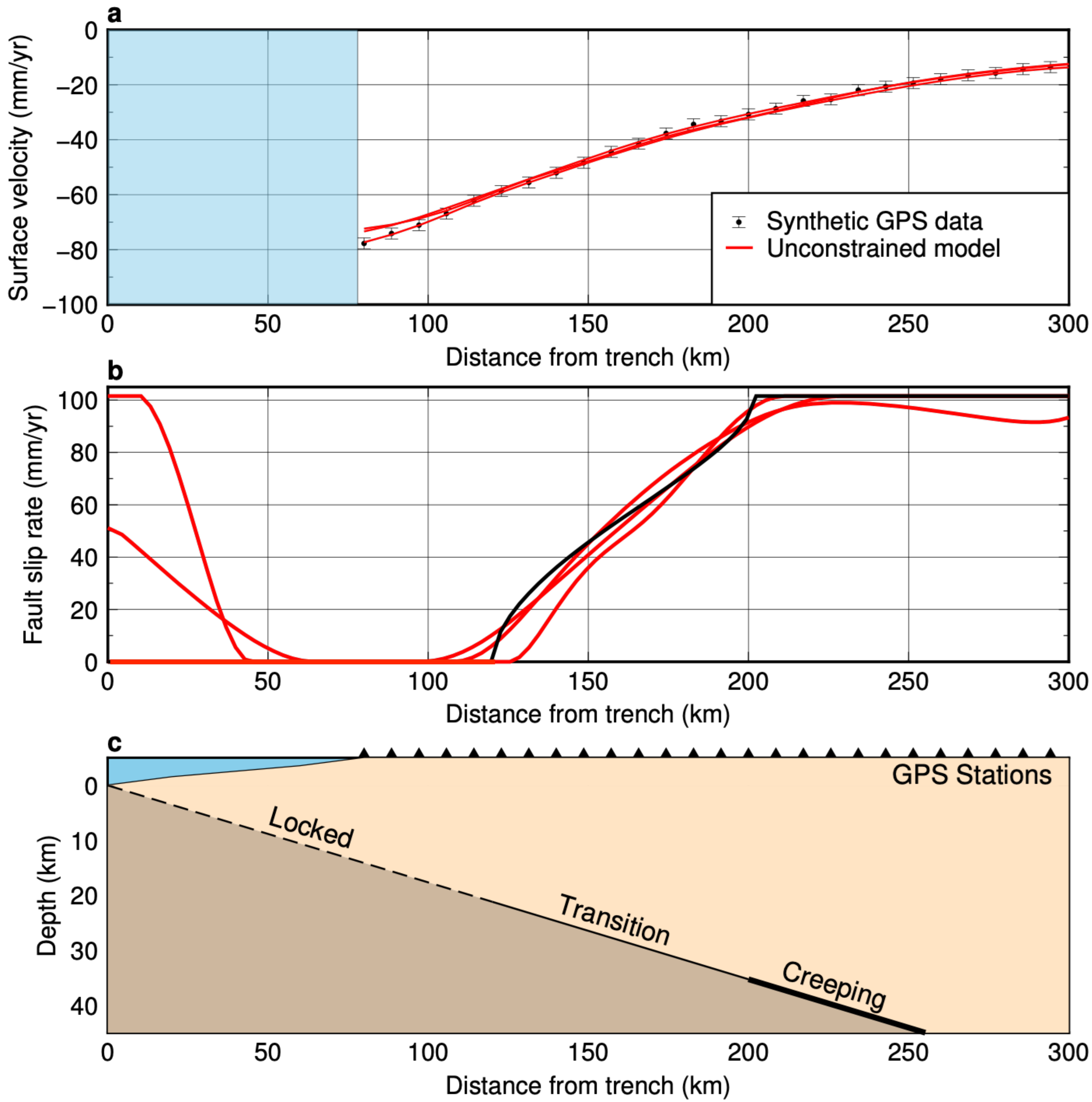
Near the trench, uncertainty is ~100%: we have **no ability to resolve** the coupling.



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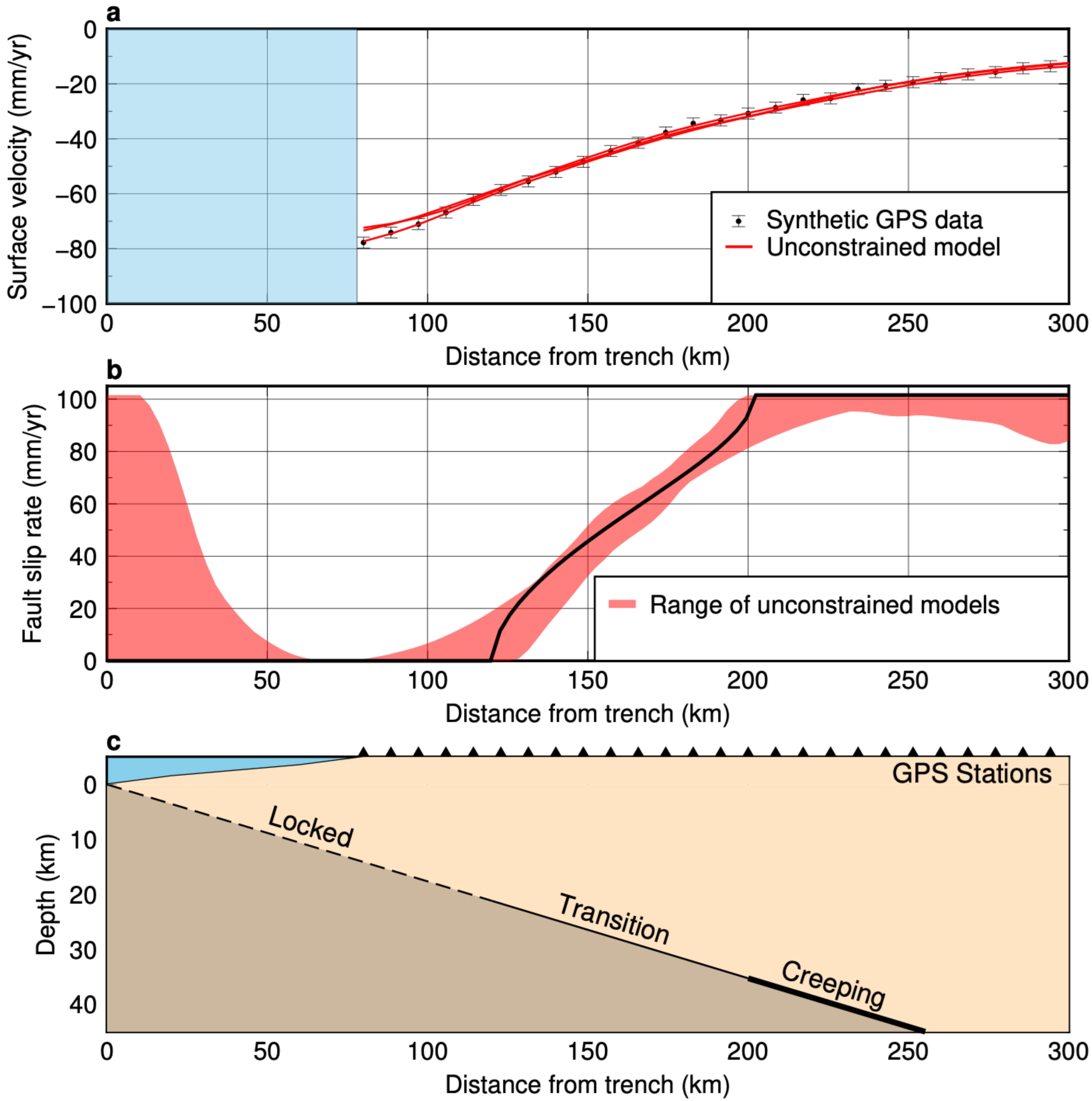
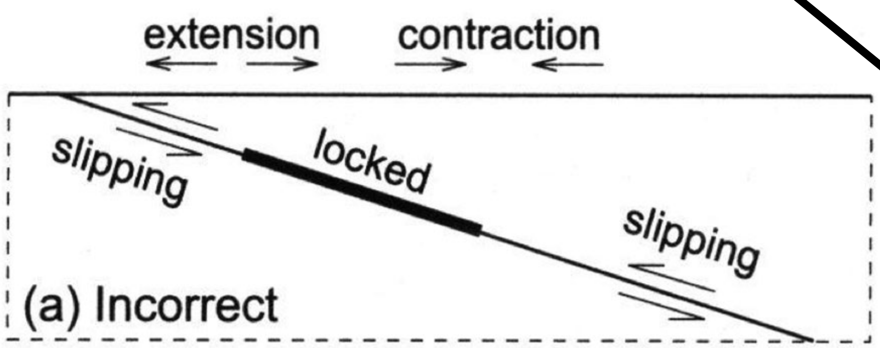
Shaded area: all "acceptable" models (χ^2/d.o.f. = 1.0)

We need some other source of information about the shallow fault!



Does a high slip rate (low coupling) near the trench make sense?

These models predict extension in the shallow wedge!



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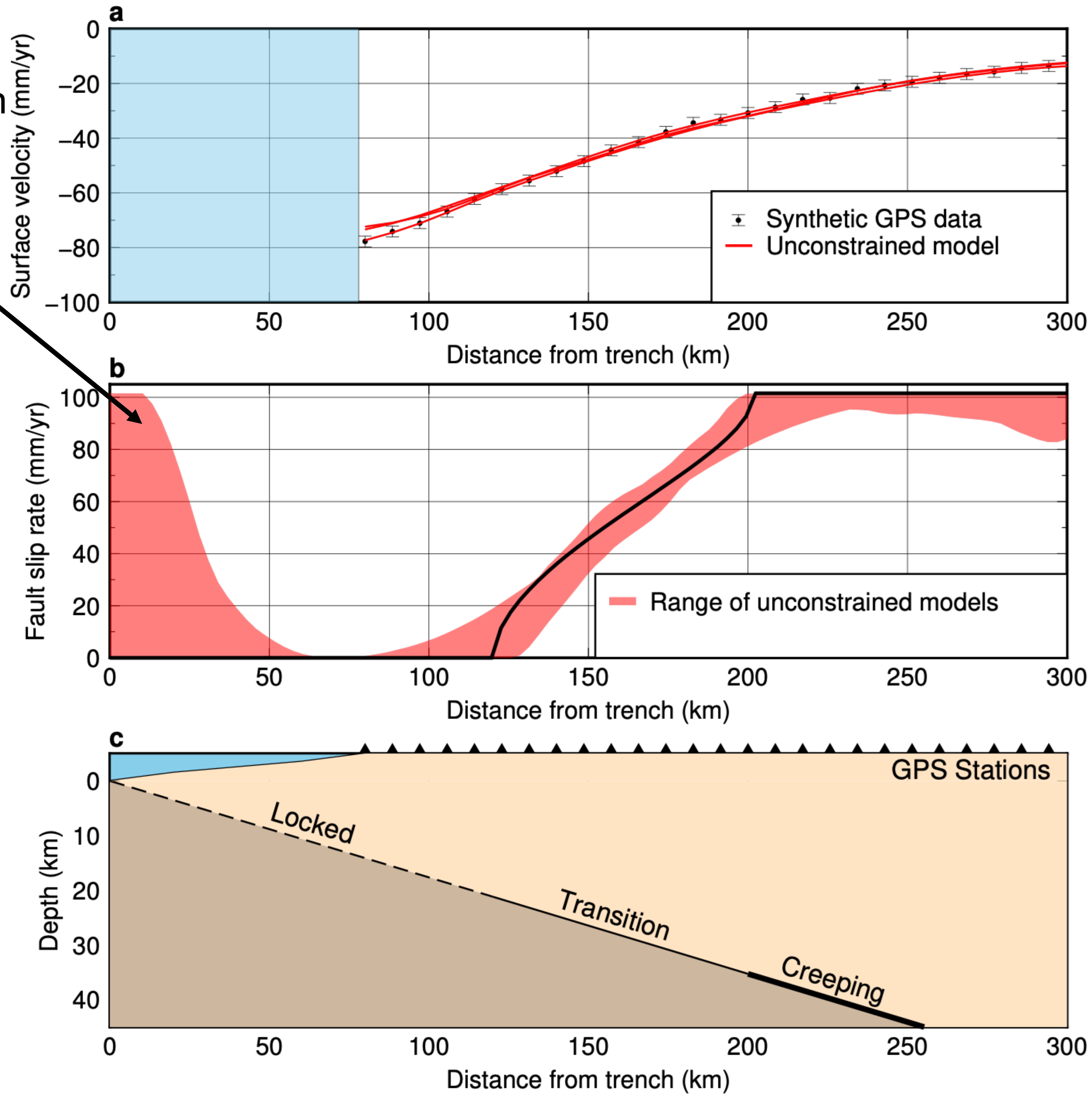
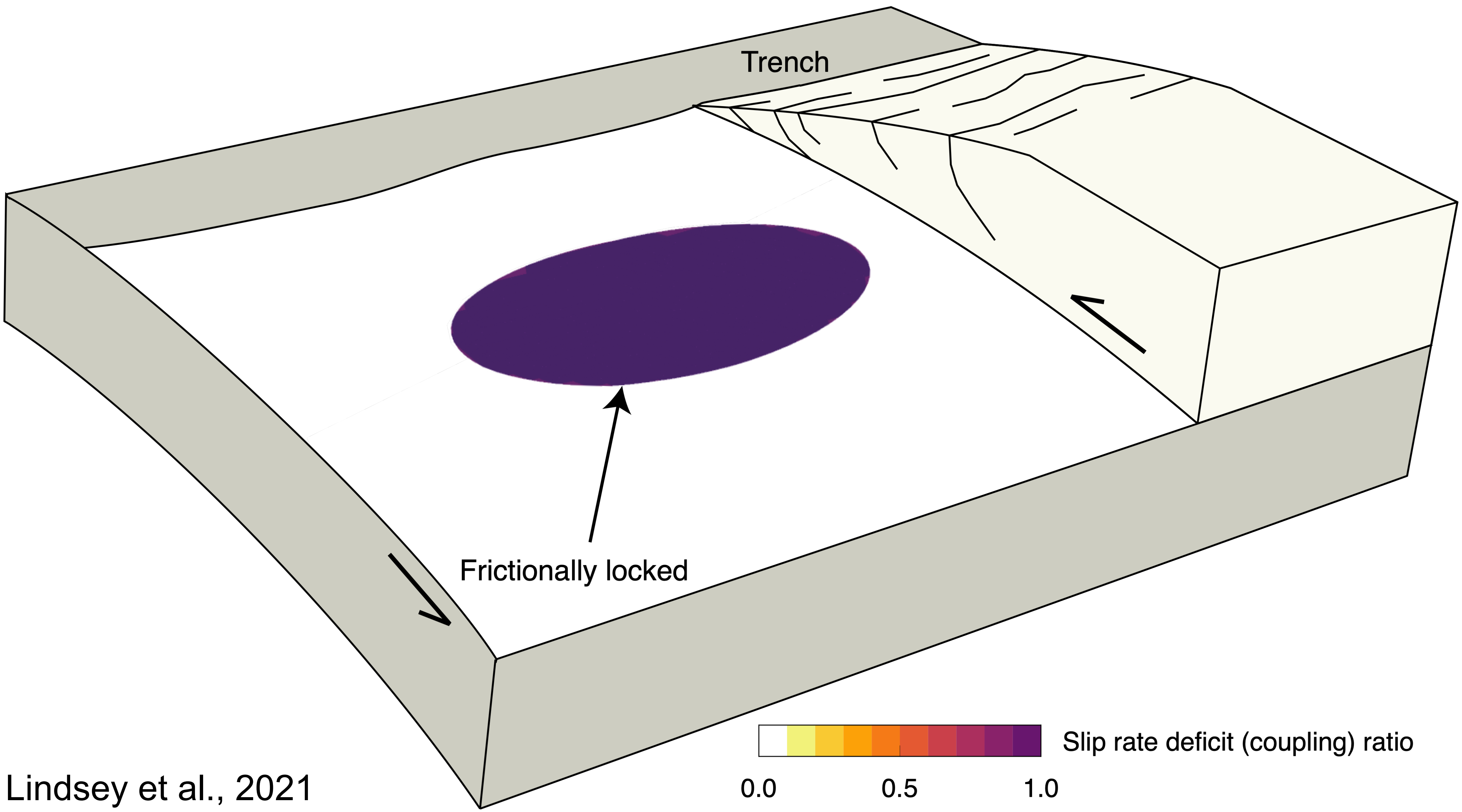


A physics-based way to think about slip rates:

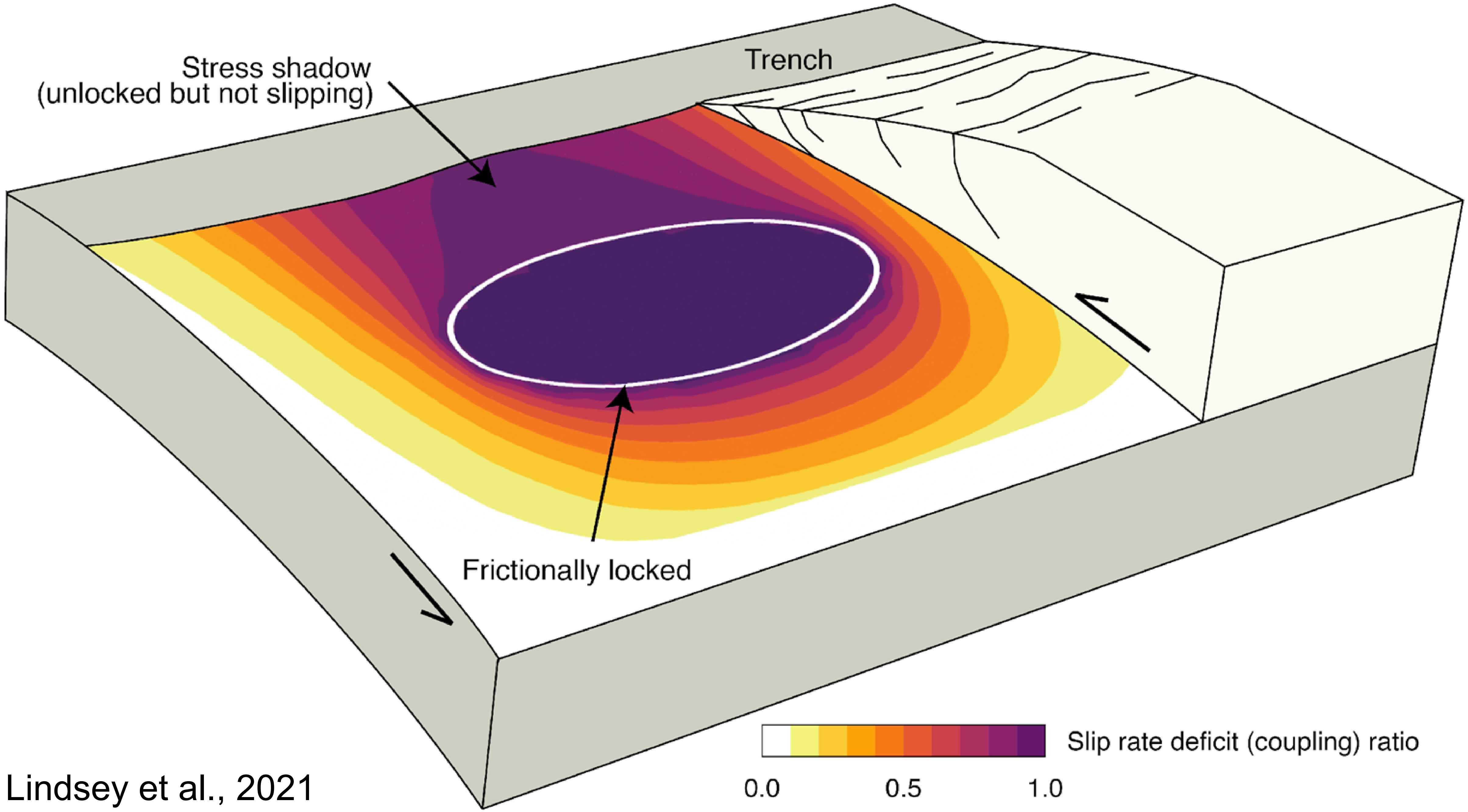
Does this picture make sense?



Lindsey et al., 2021

A physics-based way to think about slip rates:

There is a **stress shadow** around frictionally locked areas.



Lindsey et al., 2021

Key idea: **slip rate** is controlled by fault loading (**stress rate**), which is limited by interactions with the rest of the fault.

Stress (rate) is a linear function of slip (rate):

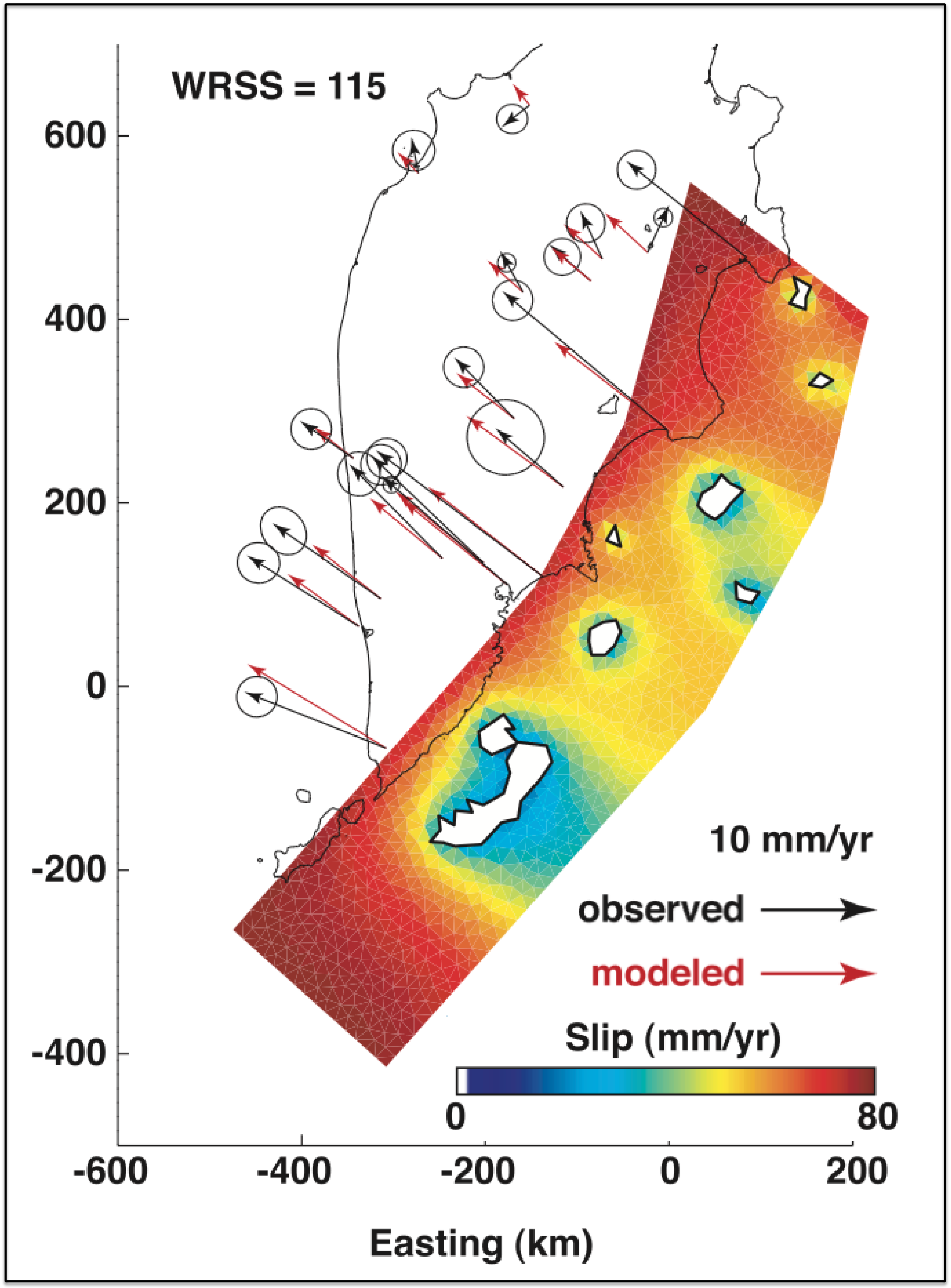
$$\dot{\sigma}_i = 2\,\mu\,E_{ij}\cdot\dot{s}_j$$

The stress shadow: stresses either **increase** or **stay the same** during the interseismic period.

This amounts to a simple requirement:

$$2\,\mu\,E_{ij}\cdot\dot{s}_j \geq \dot{\sigma}_j^0$$

Idea: incorporate this into a linear inversion



Burgmann et al., 2005

The stress-constrained inversion

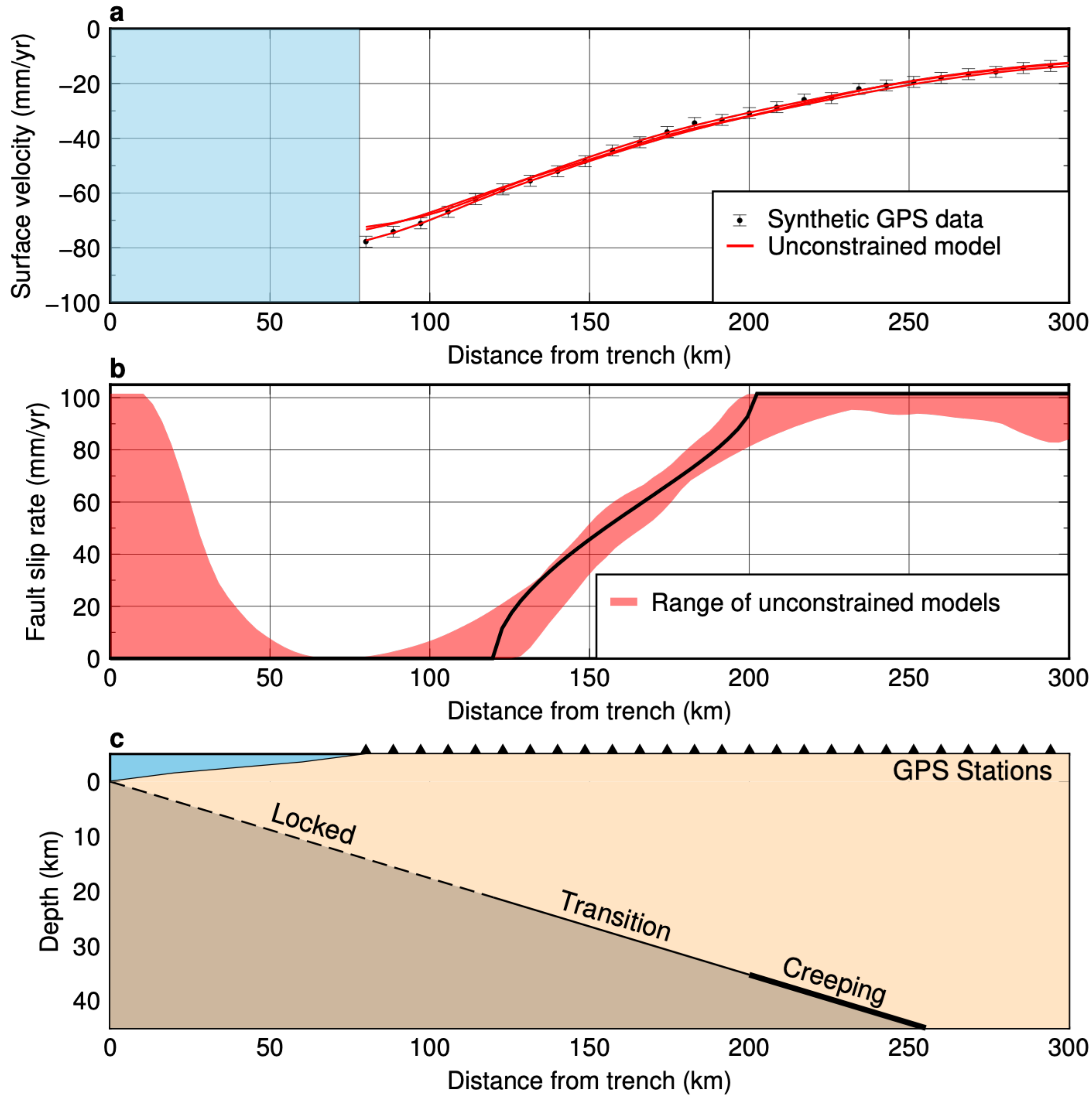
Idea: stresses either **increase** or **stay the same** during the interseismic period.

Balance slip with the far-field loading stress rate:

$$2\,\mu\,E_{ij}\cdot\dot{s}_j\;\geq\;\dot{\sigma}_j^0$$

This is a **linear** constraint!

Straightforward to implement.



Lindsey et al. (2021)

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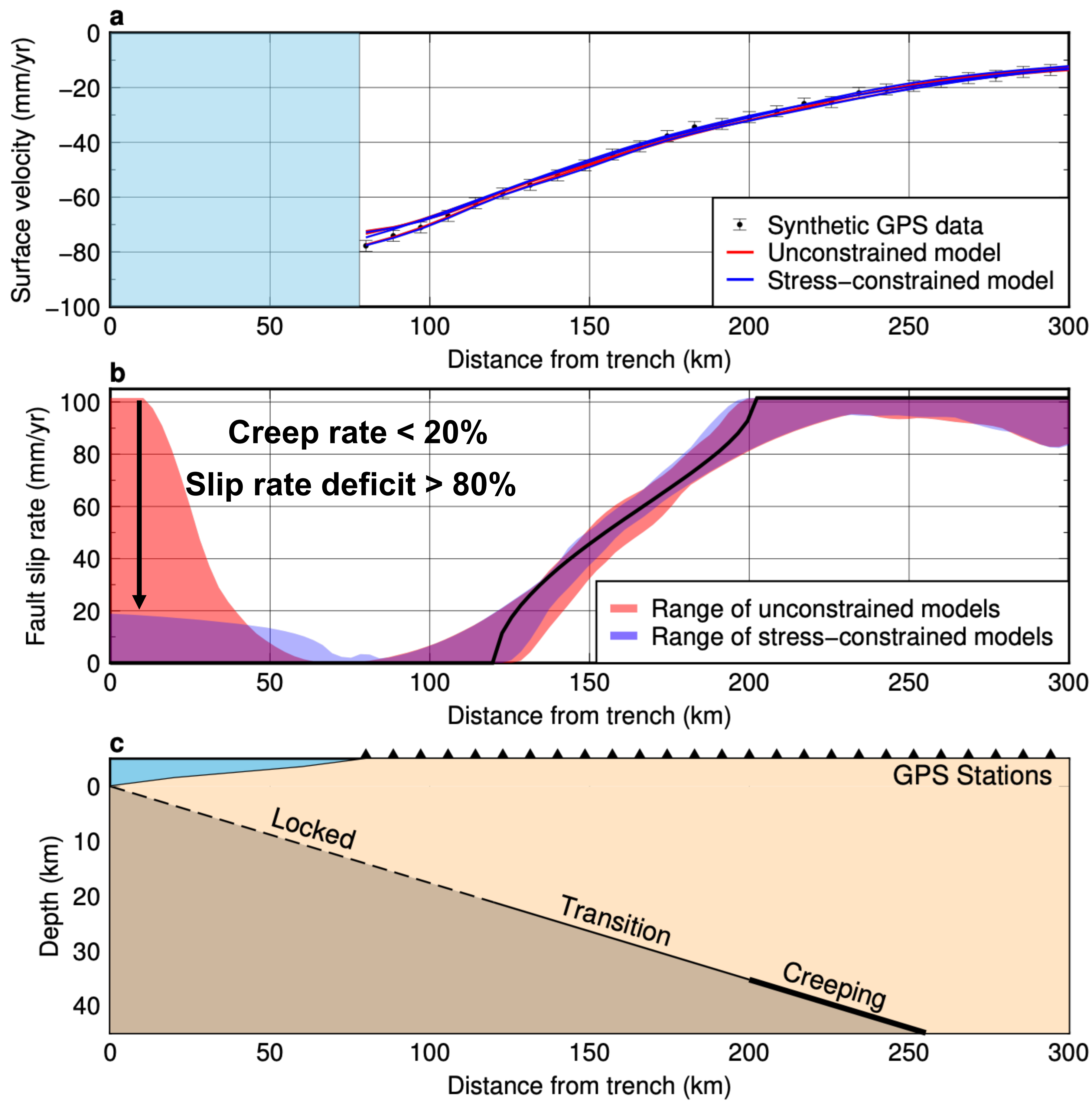
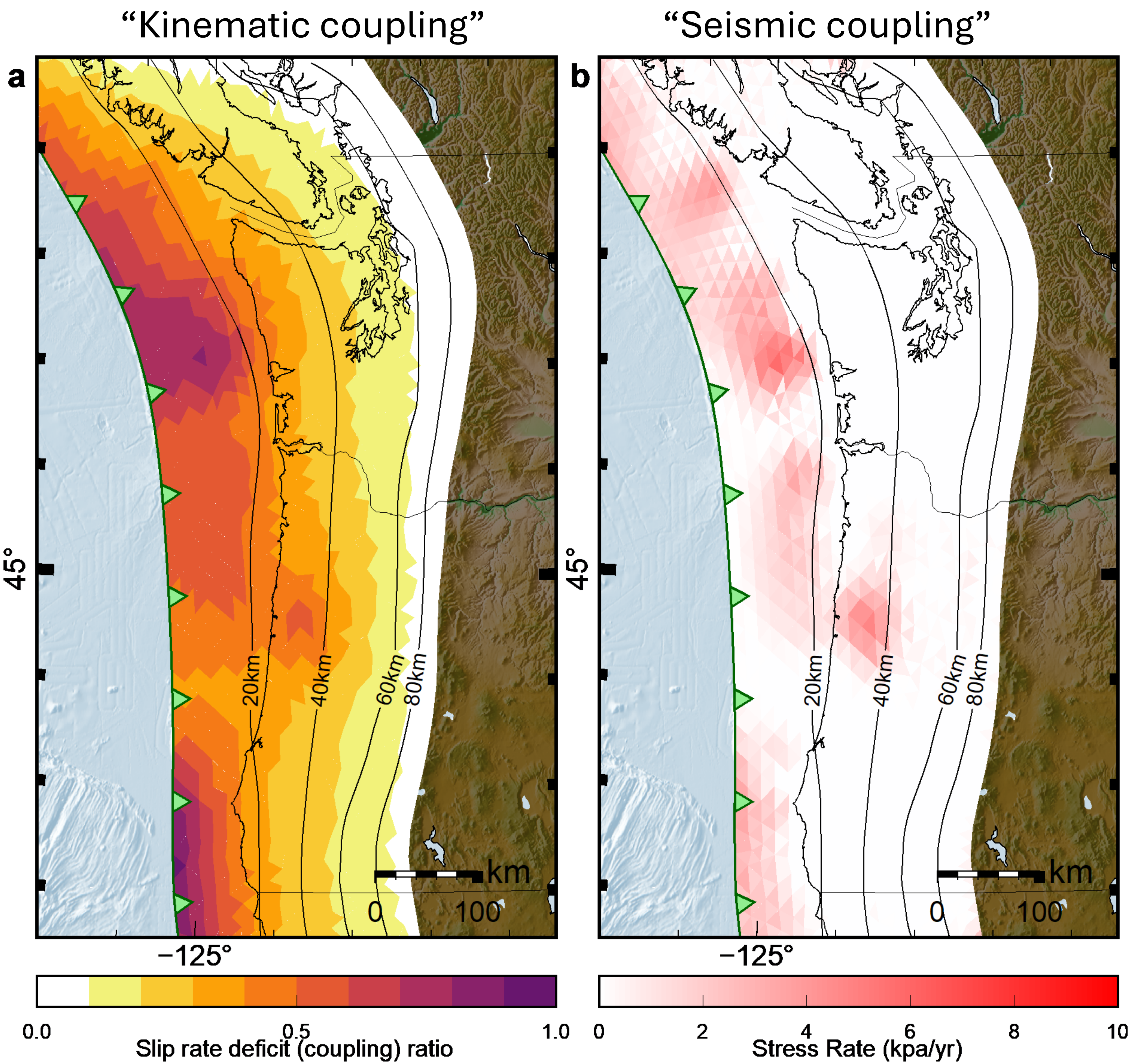
Straightforward to implement.

Result: much less uncertainty at the trench!



Lindsey et al. (2021)

Cascadia: Visualizing the effect of stress constraints



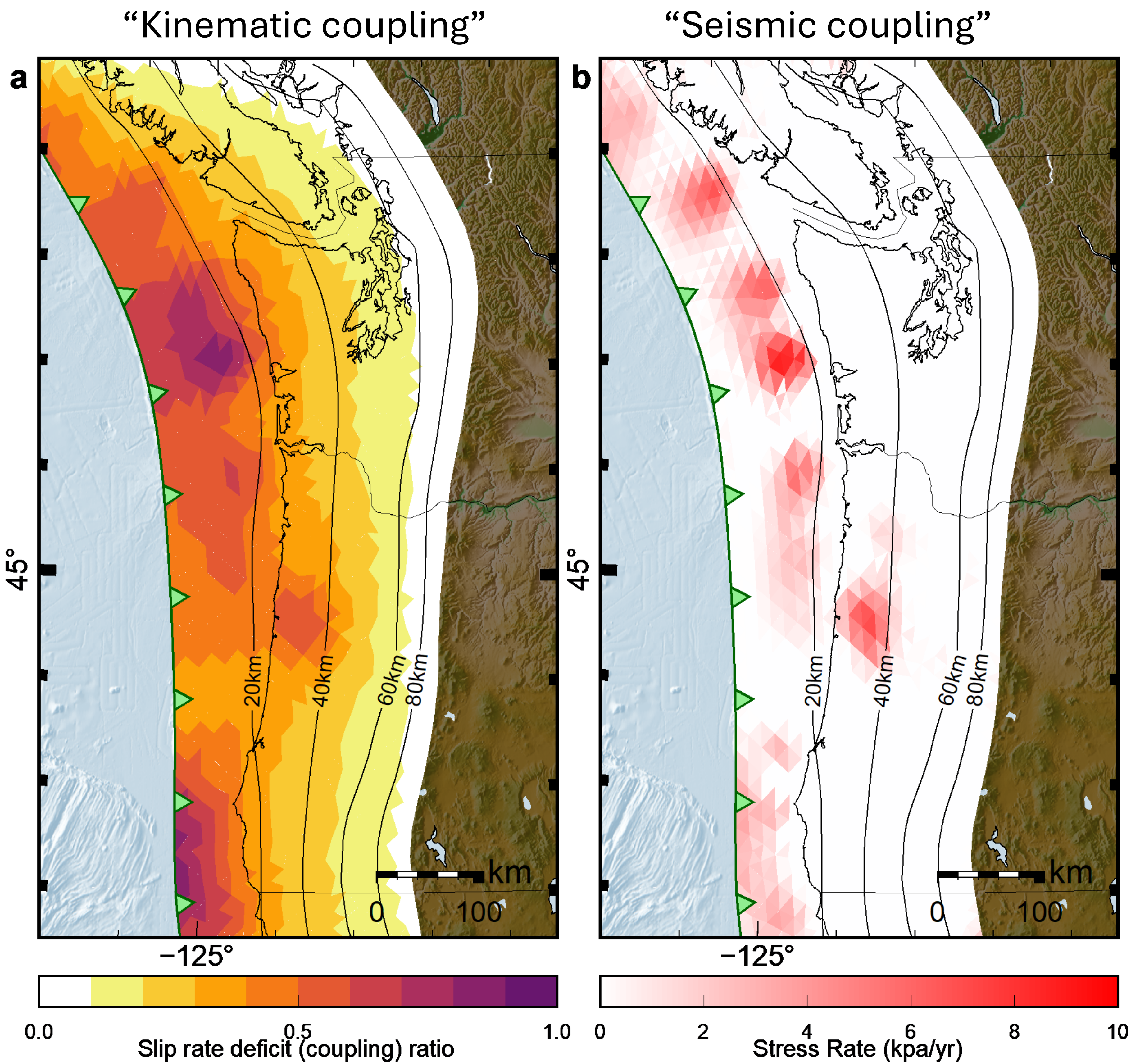
Smoothing factor: 0.7

Panel on left shows slip rate deficit.

On the right shows stress rates resulting from this model.

Different smoothing values change the model, but the two plots are never the same.

Cascadia: Visualizing the effect of stress constraints



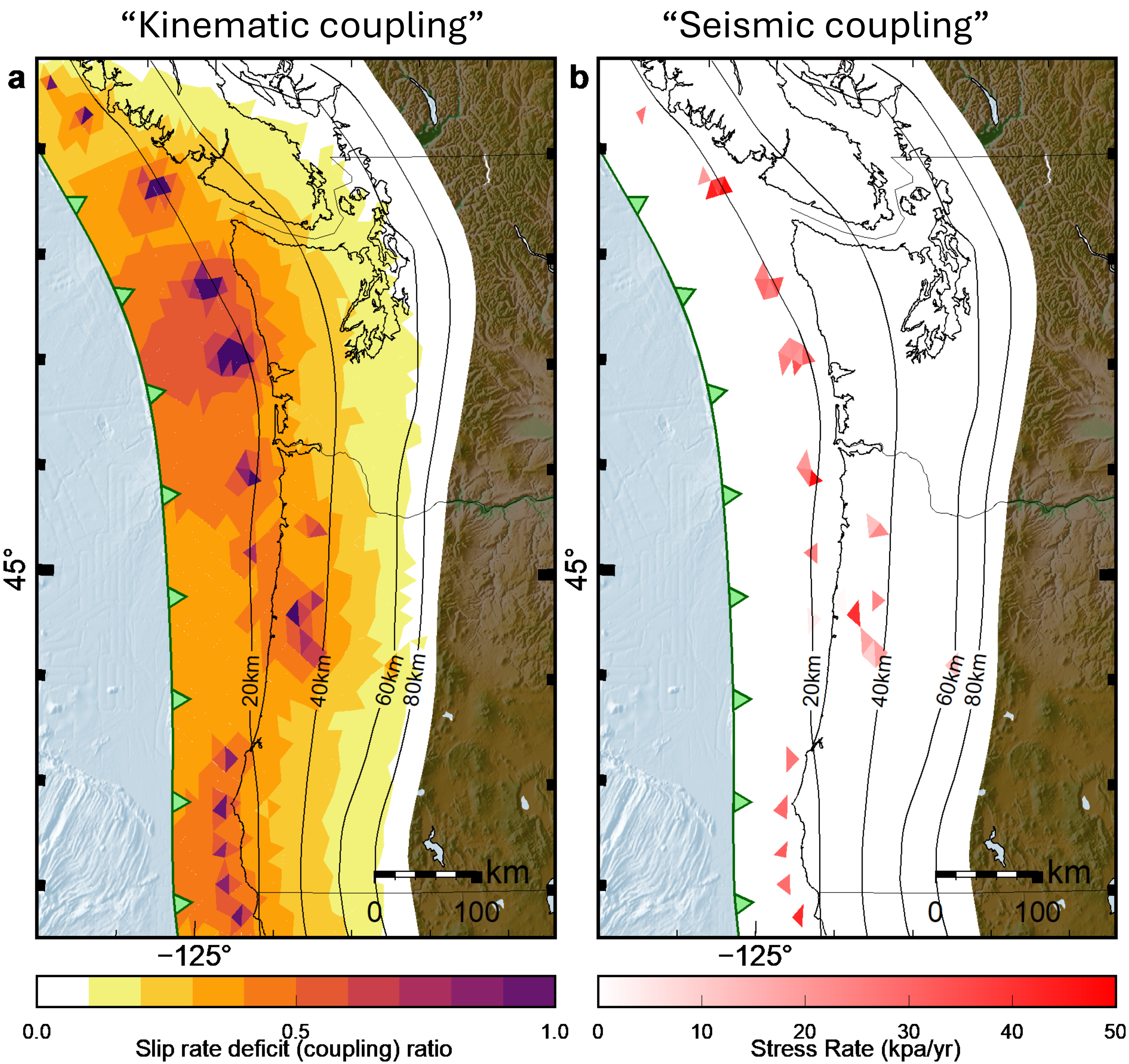
Smoothing factor: 0.3

Panel on left shows slip rate deficit.

On the right shows stress rates resulting from this model.

Different smoothing values change the model, but the two plots are never the same.

Cascadia: Visualizing the effect of stress constraints



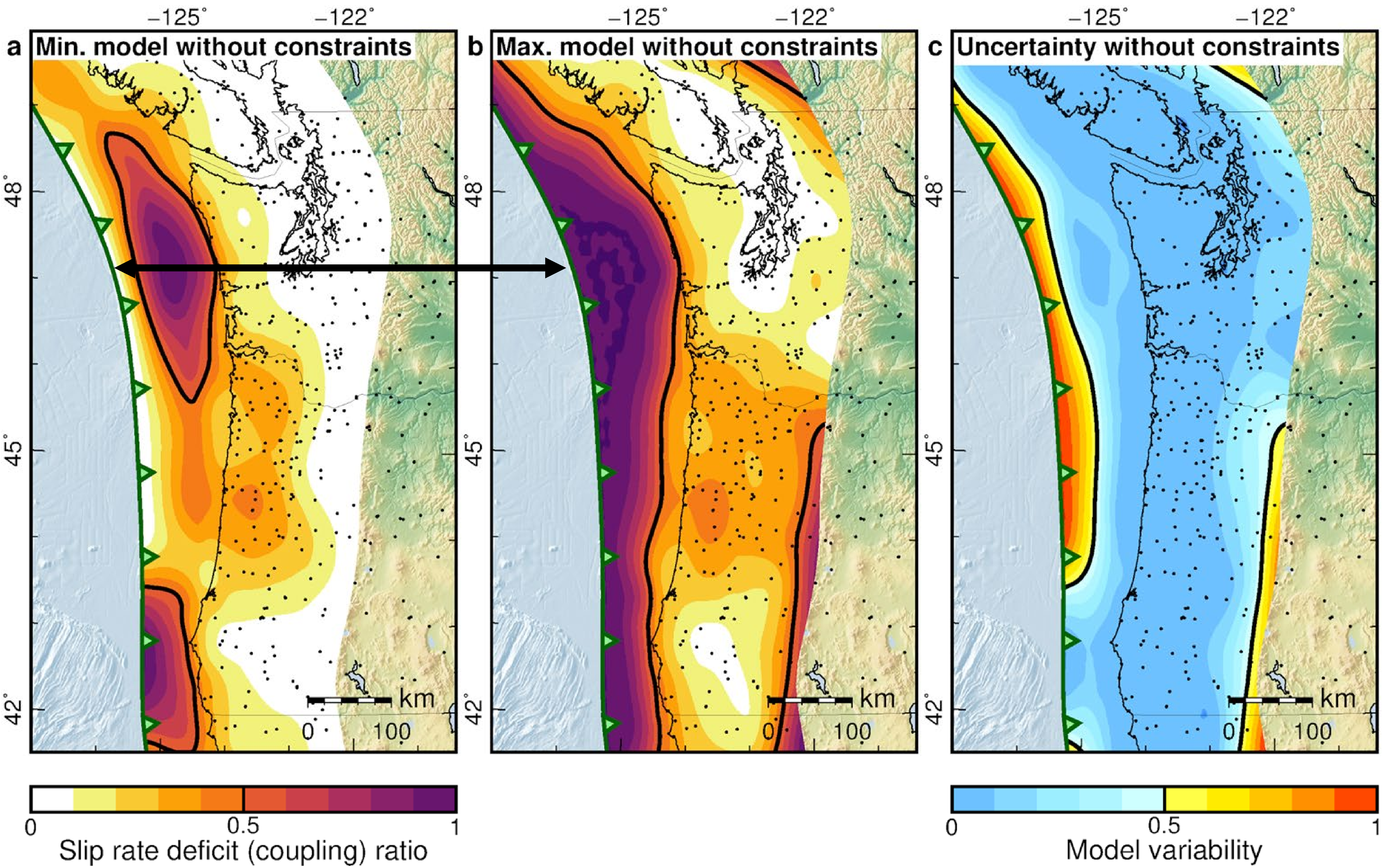
Smoothing factor: 0 (really!)

Panel on left shows slip rate deficit.

On the right shows stress rates resulting from this model.

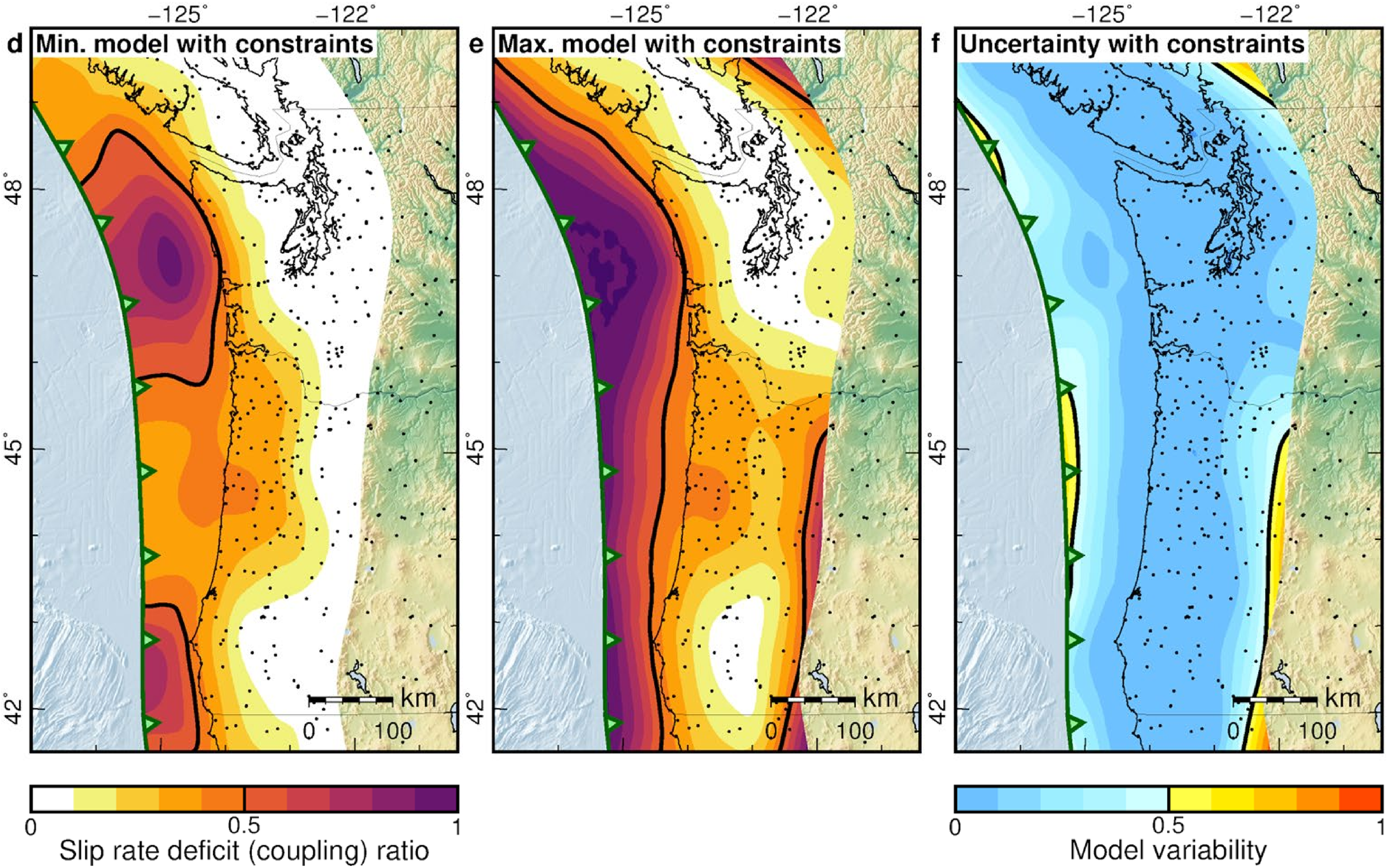
Different smoothing values change the model, but the two plots are never the same.

Can the shallow fault have zero coupling? Example: Cascadia



Lindsey et al. (2021)

Cascadia: 40 - 80% reduction in uncertainty with stress constraints



Lindsey et al. (2021)

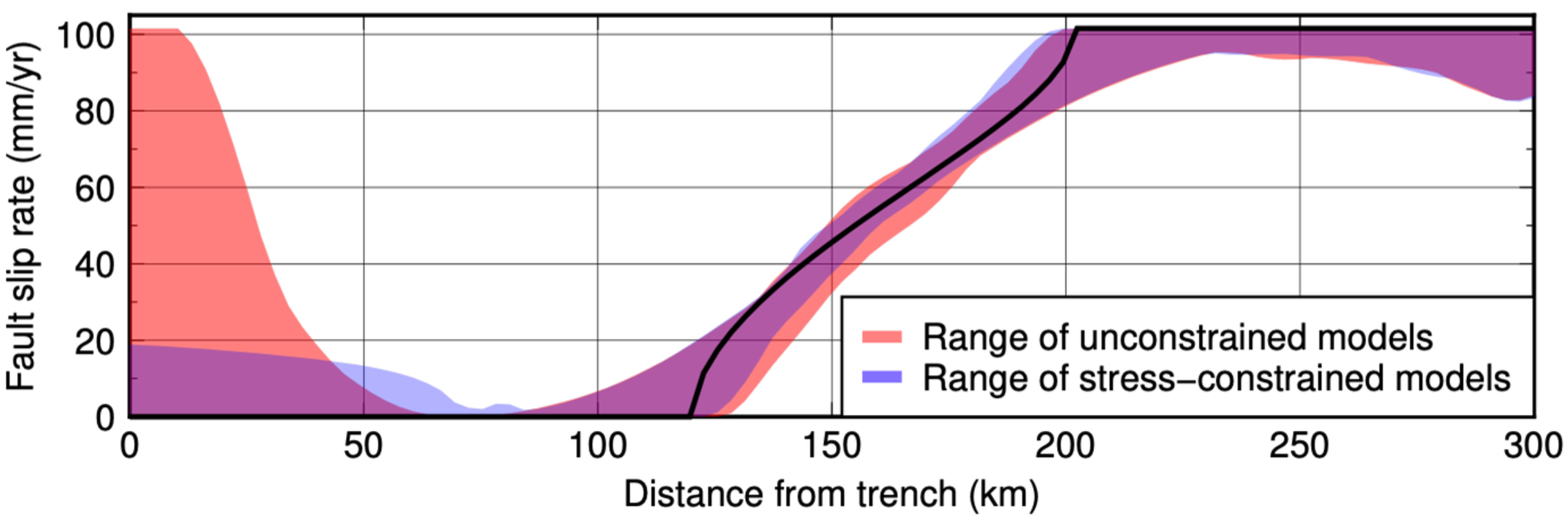
Why is this important?

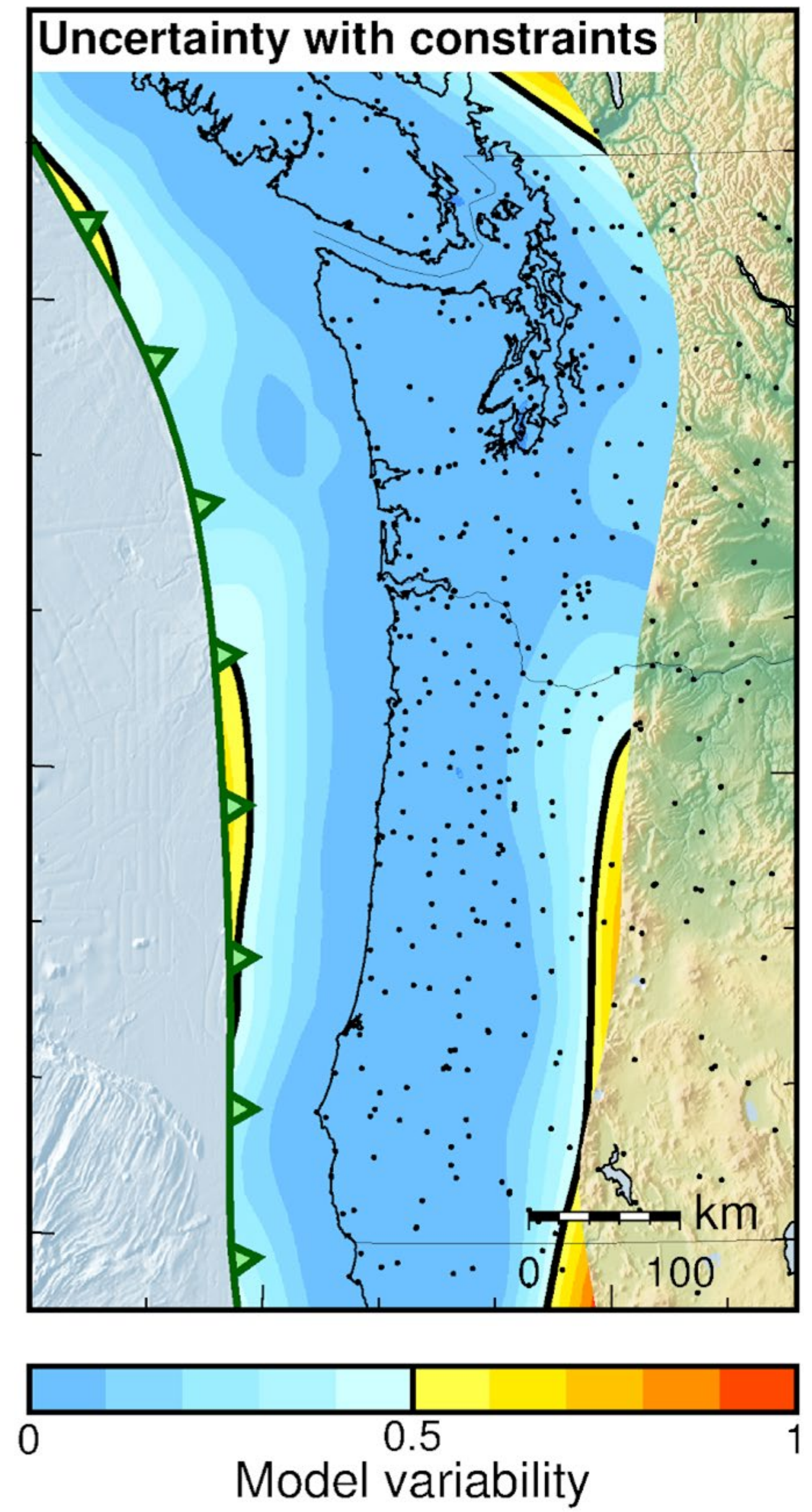
Most geodetic models of megathrusts are lacking fundamental physics.

With an improved model, we find that *kinematic* coupling (slip rate deficit) is generally high close to the trench.

We can accurately infer this value *without offshore data,* and the model helps us better plan any offshore sites.

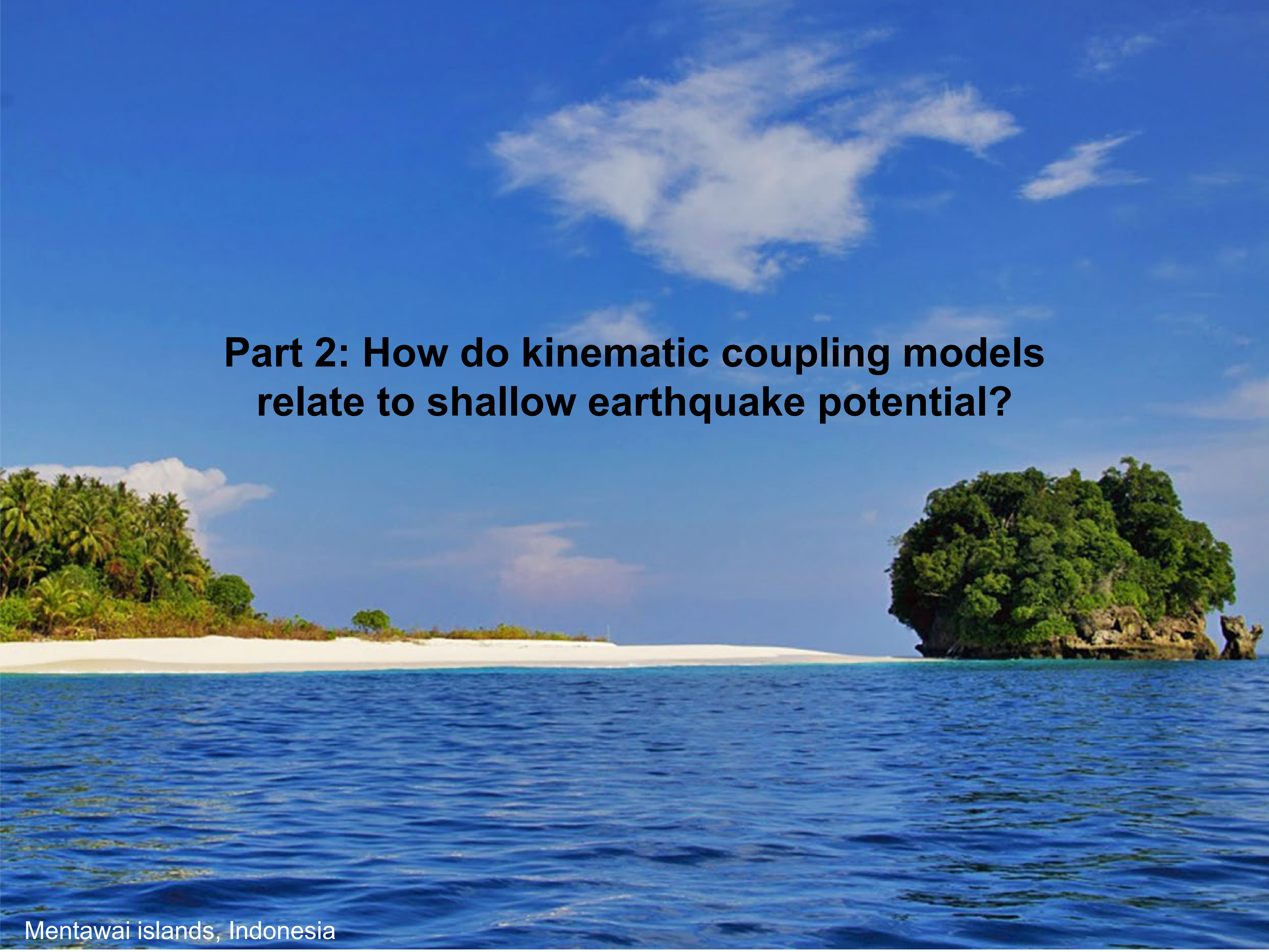
Global tsunami hazard may be underestimated at present.





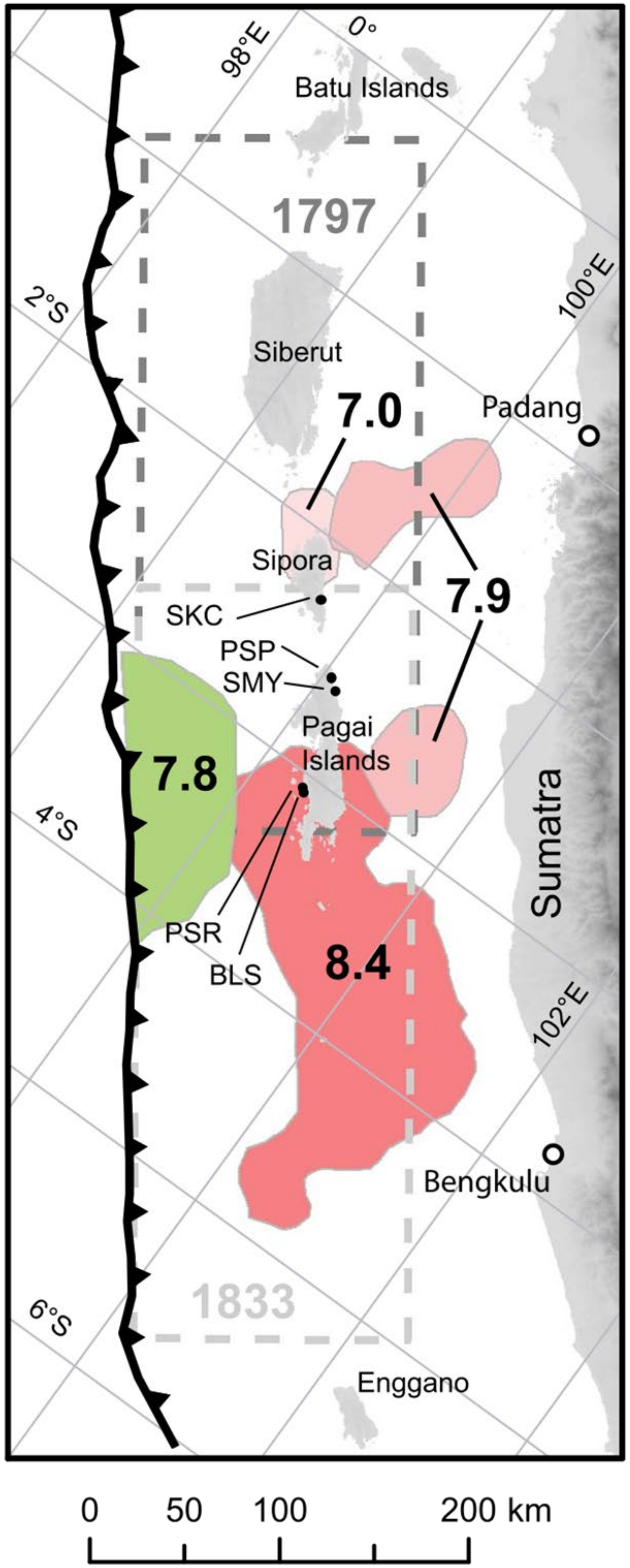
Lindsey et al. (2021)

Part 2: How do kinematic coupling models relate to shallow earthquake potential?



Mentawai islands, Indonesia

Lessons from the Mentawai Patch



The central segment of the Sunda megathrust is known as the **Mentawai Patch**.

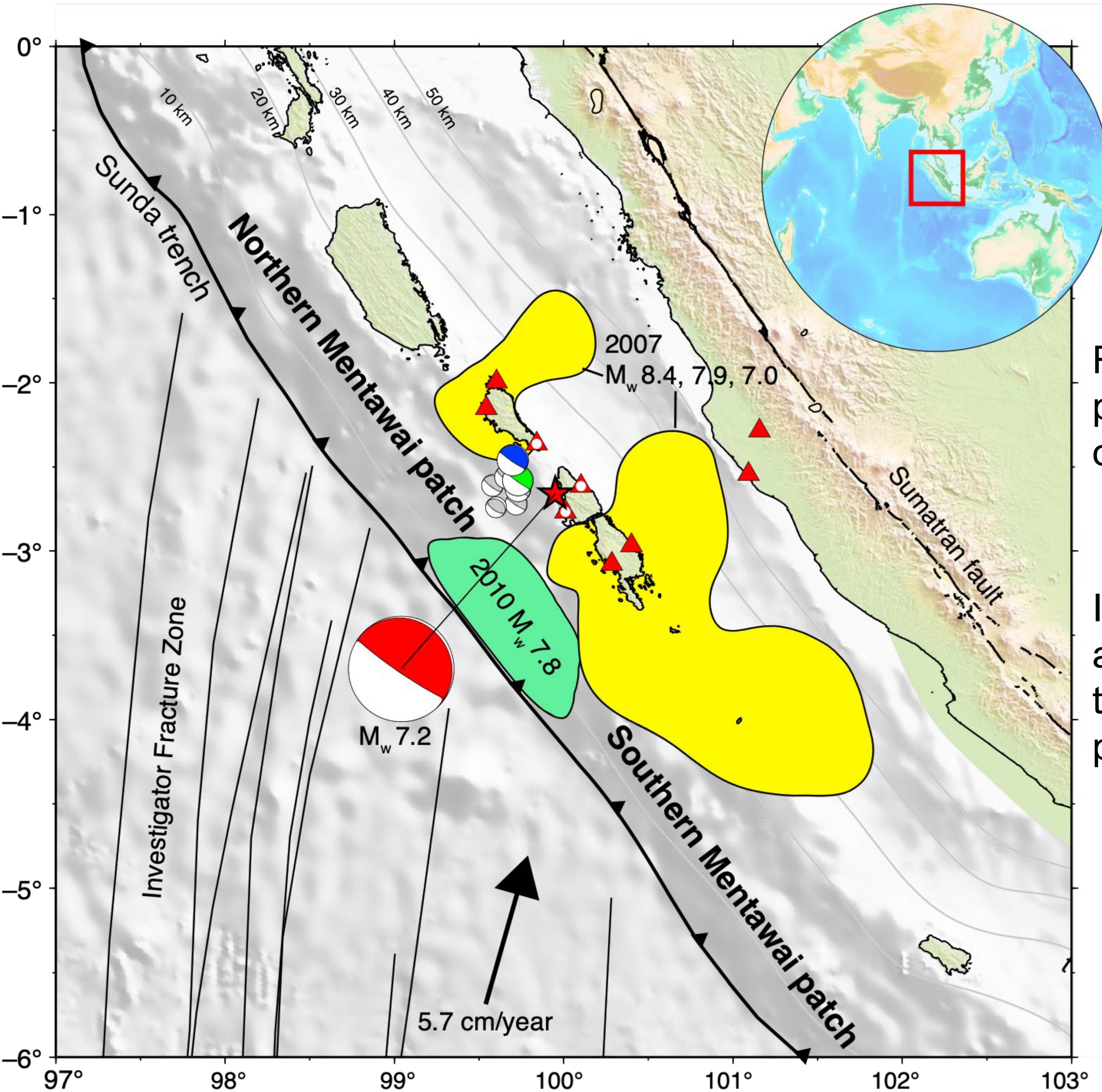
Historically, it ruptured in M~8 – 9 earthquakes soon after the northern segment (e.g. Philibosian et al., 2012).

From 2007 – 2010, a sequence of M 7 – 8 earthquakes occurred in this patch, but still left most of the fault area unruptured.

Why didn't these events rupture the whole fault?

Philibosian et al., 2012

The 2008 Pagai earthquake

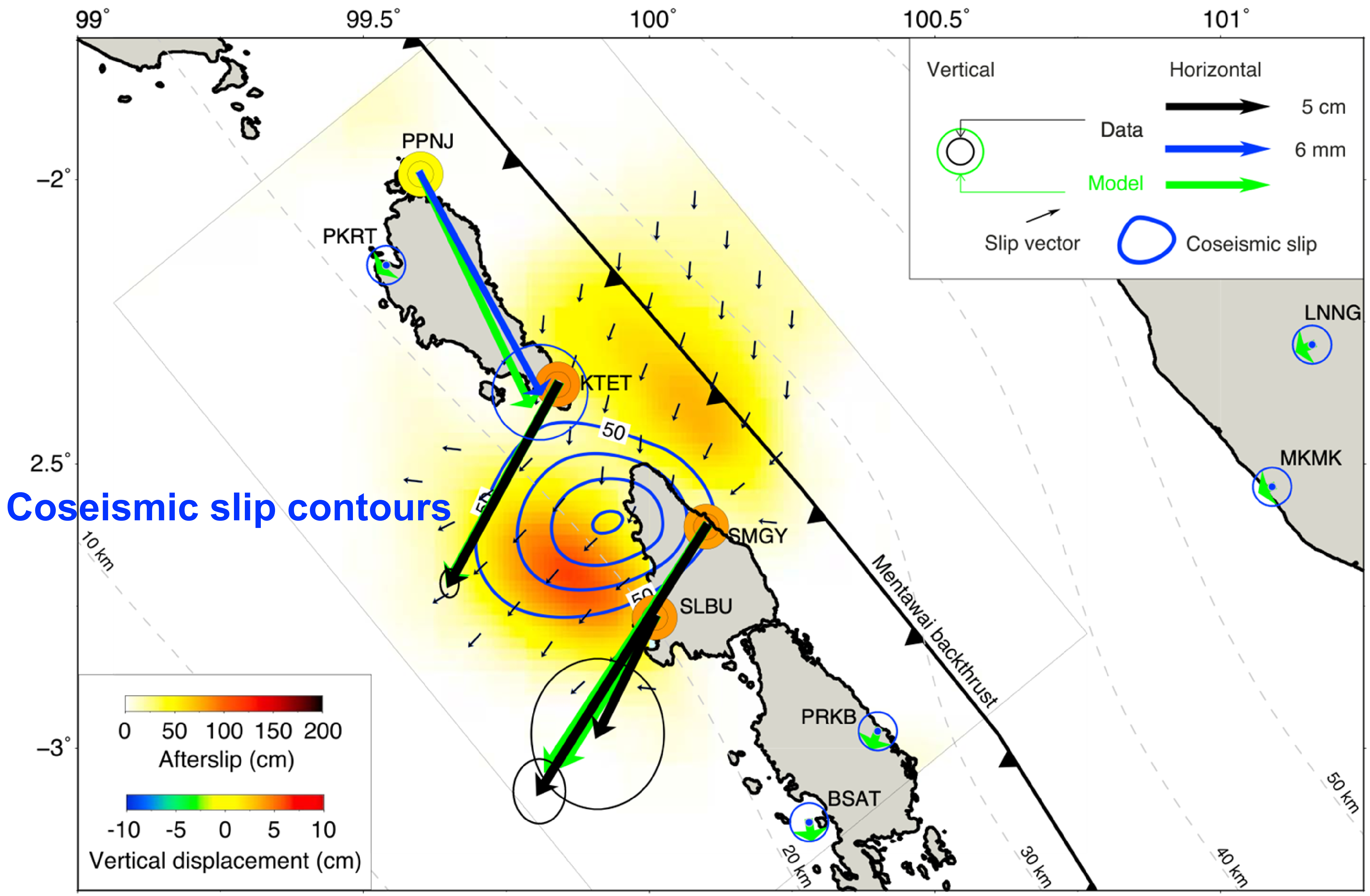


Right in the middle of this patch, a M7.2 earthquake occurred in 2008.

It was well recorded by GPS and InSAR - a perfect chance to probe the mechanical properties of the fault.

Salman, Lindsey et al. (2017)

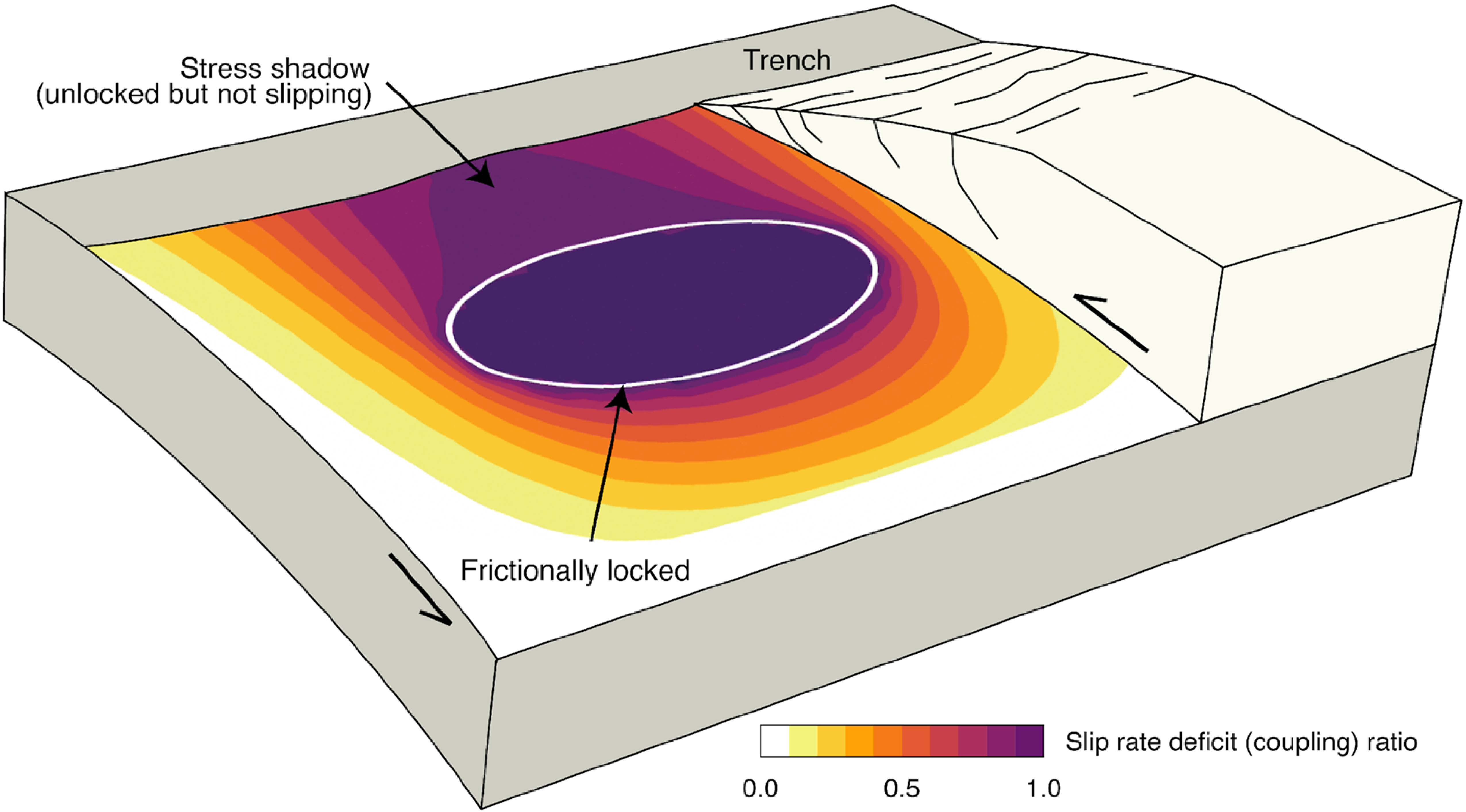
Oddly, postseismic afterslip significantly overlapped with the coseismic slip. How is this possible?



Salman, Lindsey et al. (2017)

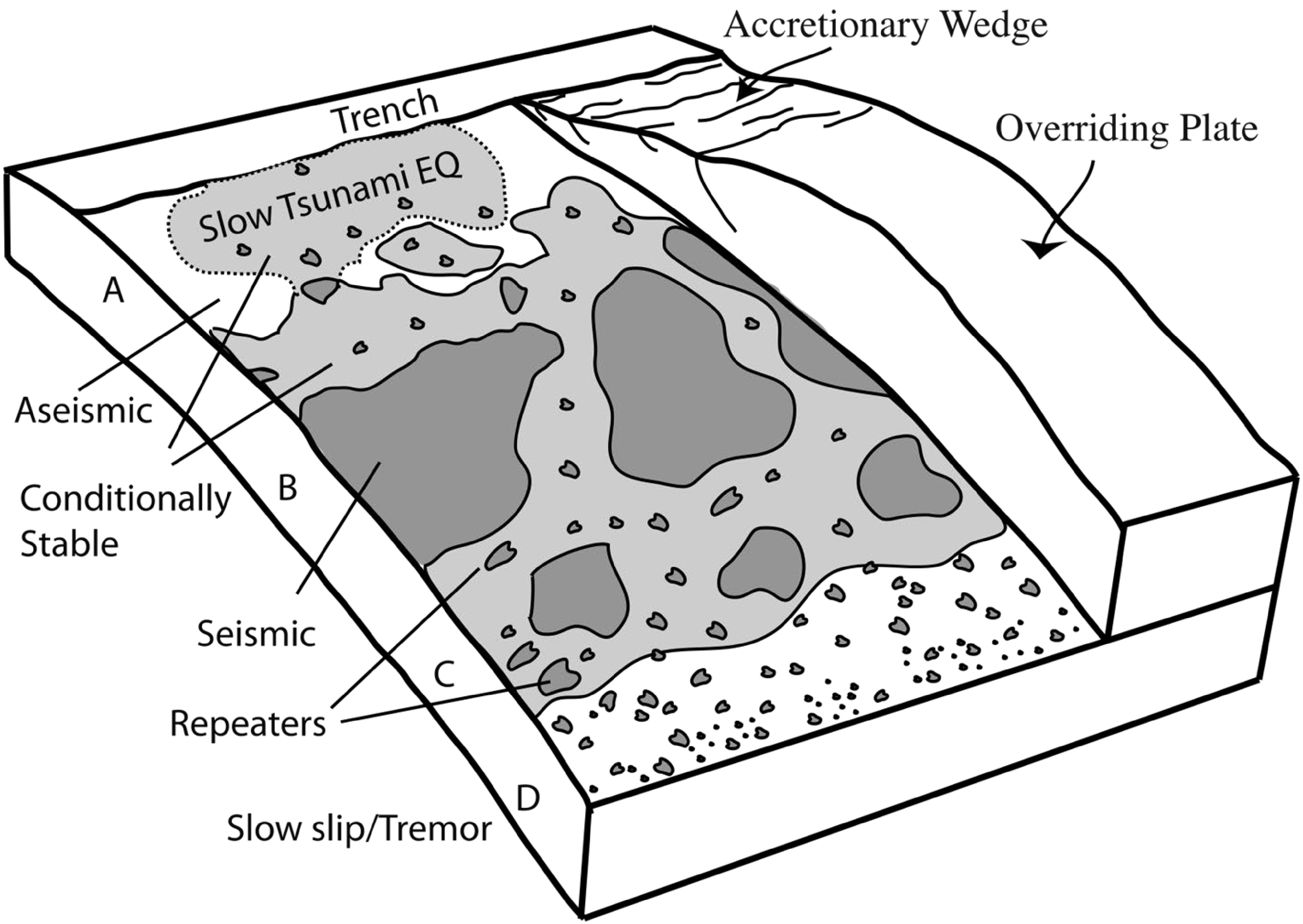
Recall the stress shadow: there is a slip deficit in nearby *unlocked* areas

Co- / postseismic slip overlap is expected if the fault has small, isolated asperities



Lindsey et al. (2021)

Are the Mentawai seismic asperities rupturing in a piecemeal fashion?



Lay et al., 2012

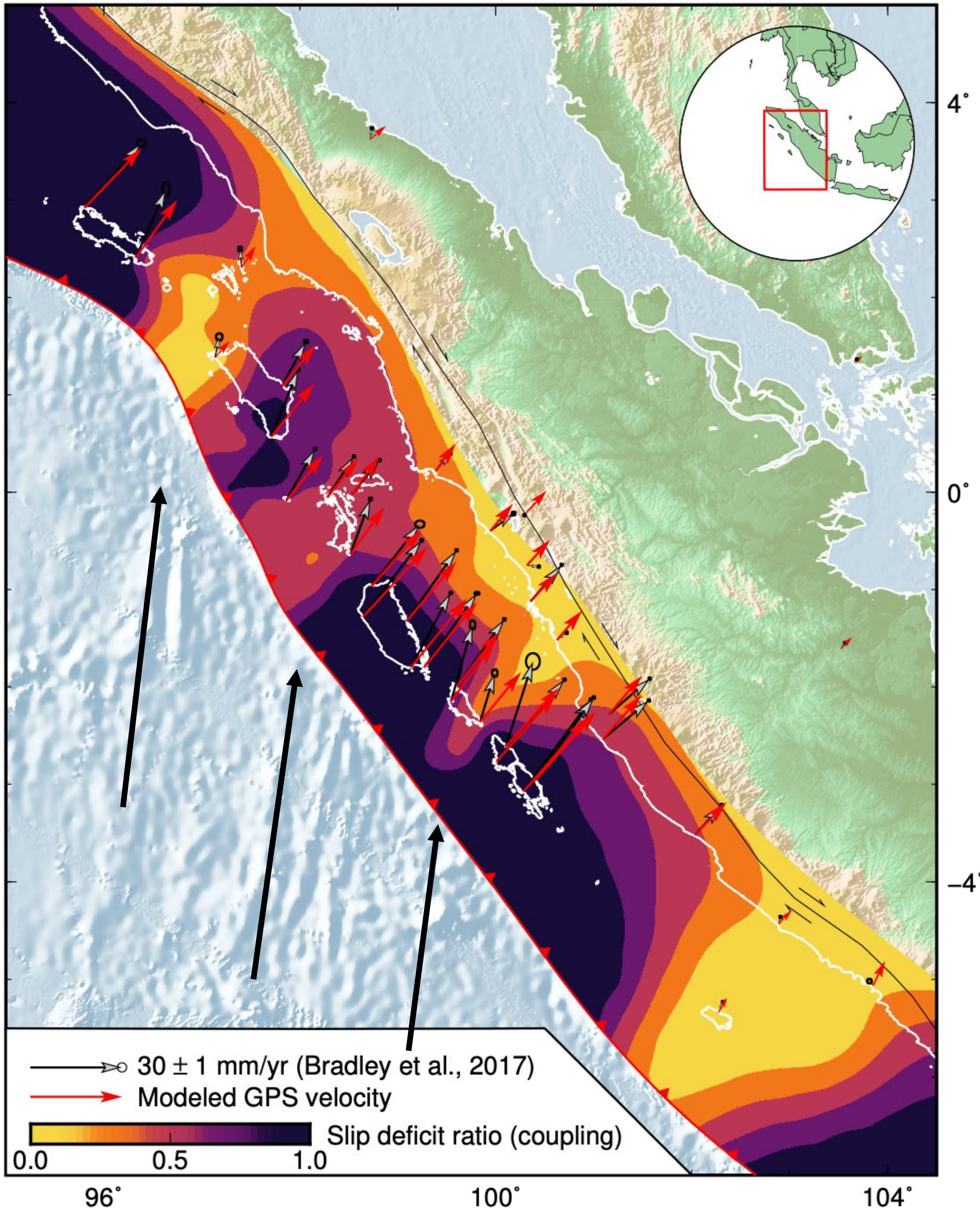
Question: can we tell where the tsunami hazard lies from a kinematic coupling model?

My answer: unfortunately no.

(At least, not very well). A “coupled” zone may be locked & unstable, or it may just be up-dip of a locked zone.

Better in-situ data are needed, or some other method to probe fault friction (e.g. afterslip).

Slip rate deficit ≠ Frictional locking



Key takeaway: don't confuse
seismic coupling and **kinematic coupling**.

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"Coupling" Semantics and Science in
Earthquake Research

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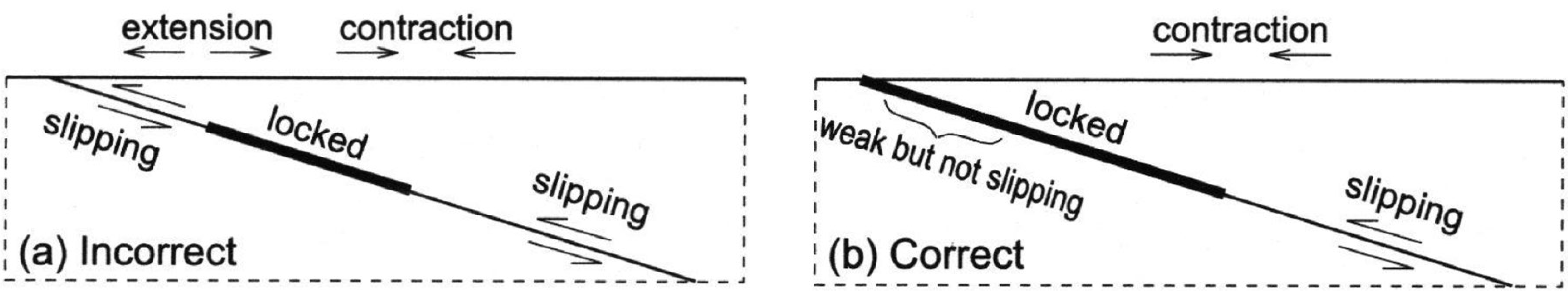


Wang & Dixon (2004); Almeida et al. (2018); Herman et al. (2018); Lindsey et al. (2021)

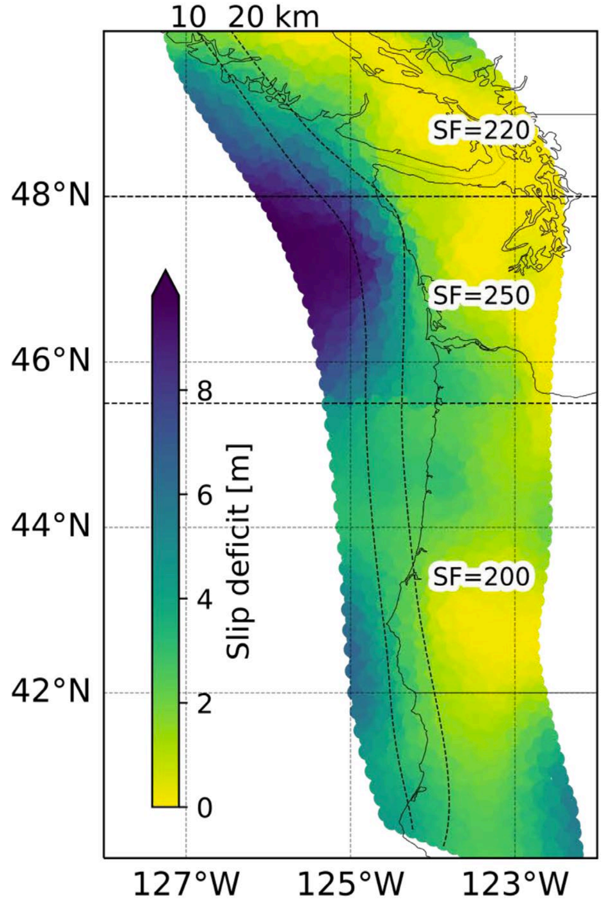
Thank you!

Idea: can we use our slip deficit model to run dynamic simulations?

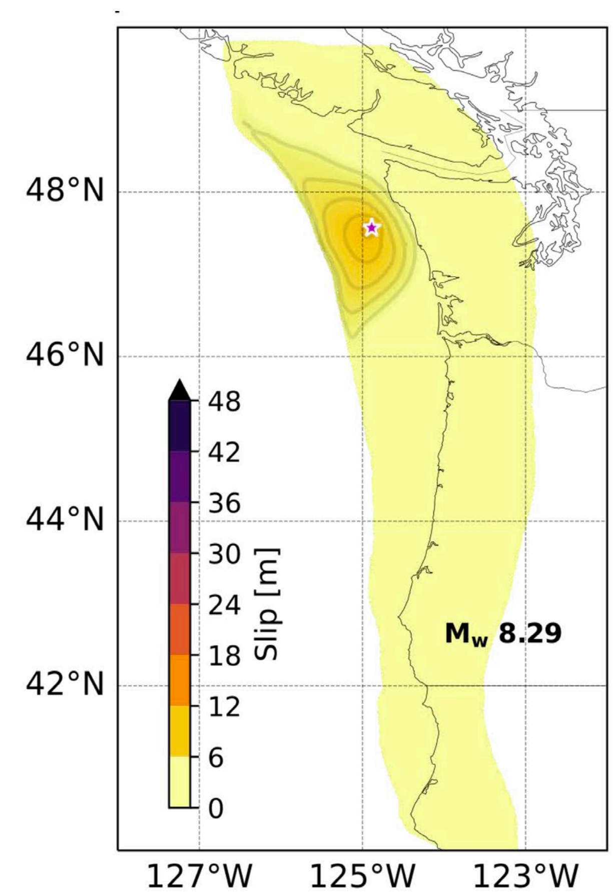
Stress-constrained models are generally smoother than others due to the added constraint.

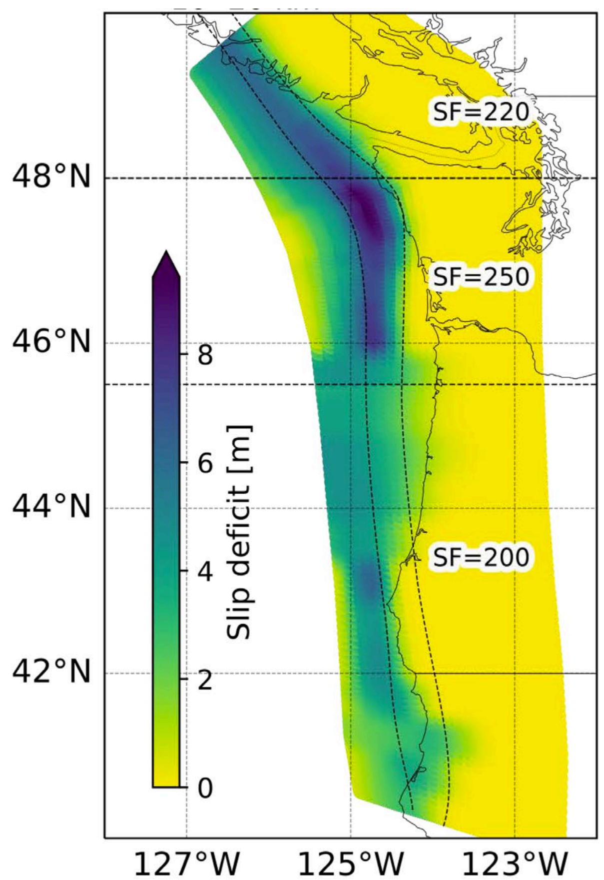
This causes problems when using them to simulate future earthquake ruptures.

Are we thinking about this problem in the right way?

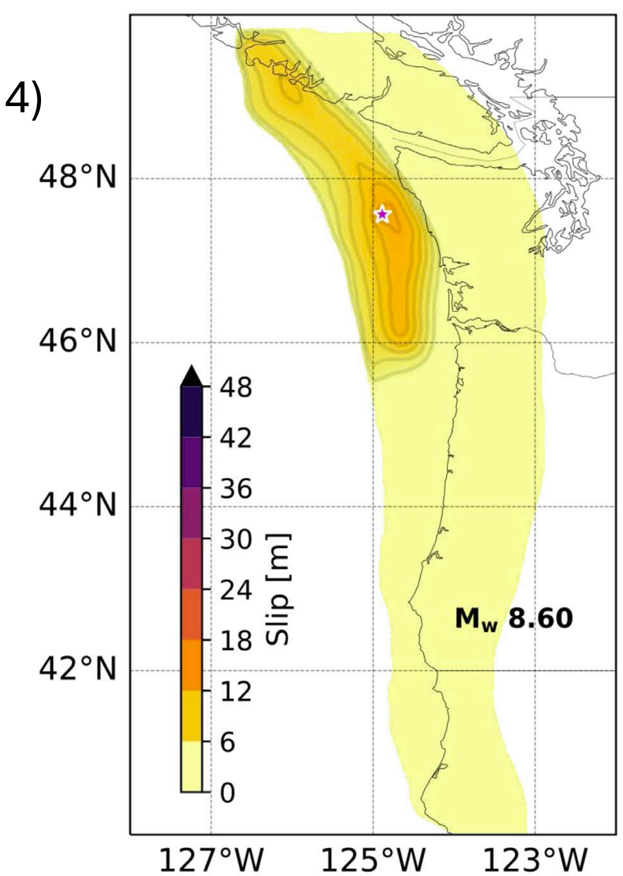


Stress-constrained
(Lindsey et al., 2021)





"Gaussian" model
(Schmalzle et al., 2014)



Glehman et al., in review

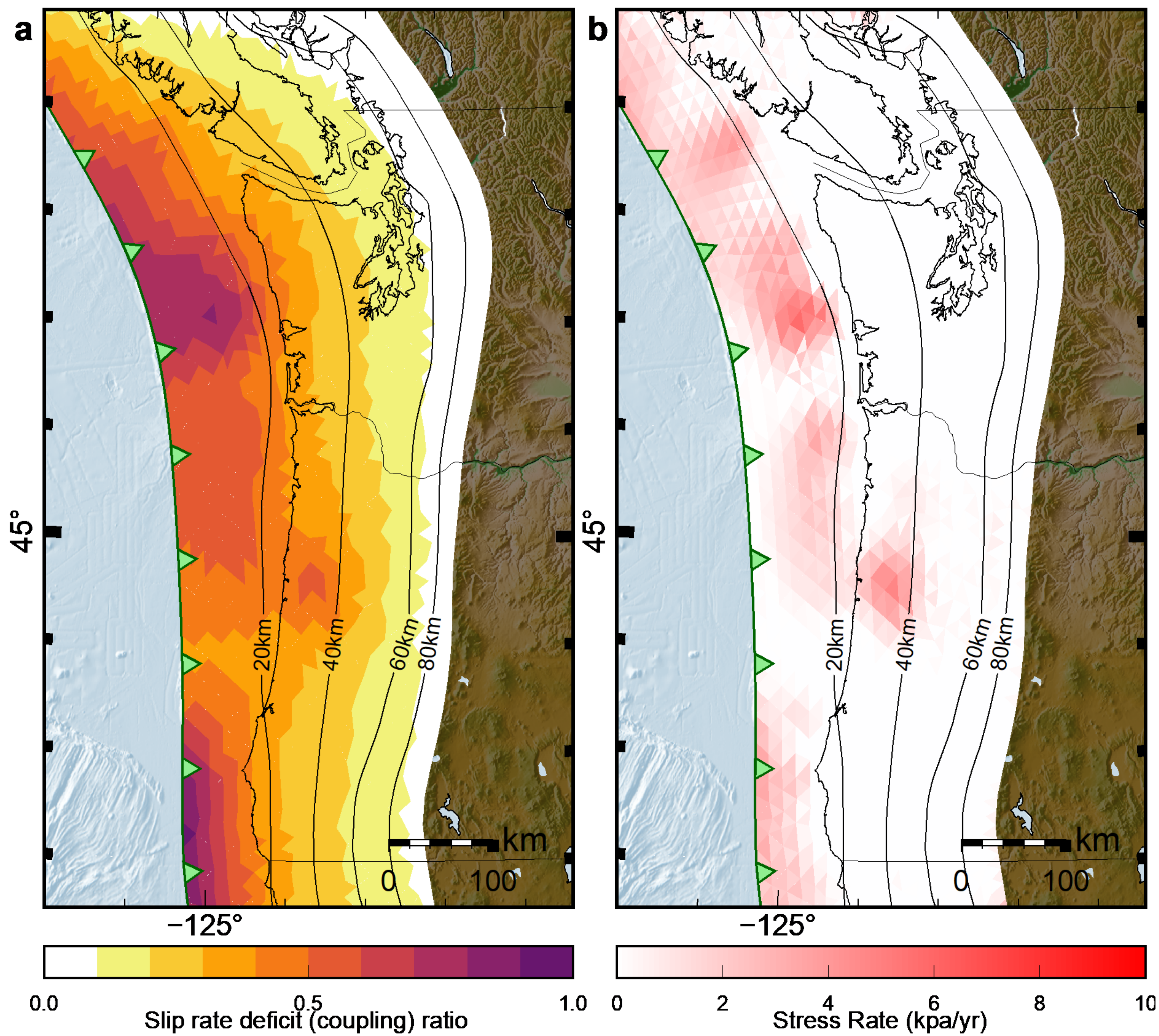
Modifications needed for realistic input to dynamic models

Stress-constraints make the model more stable.

We can use less smoothing while the model remains physically plausible!

The results are still sensitive to data noise, however.

Smoothing factor: 0.7



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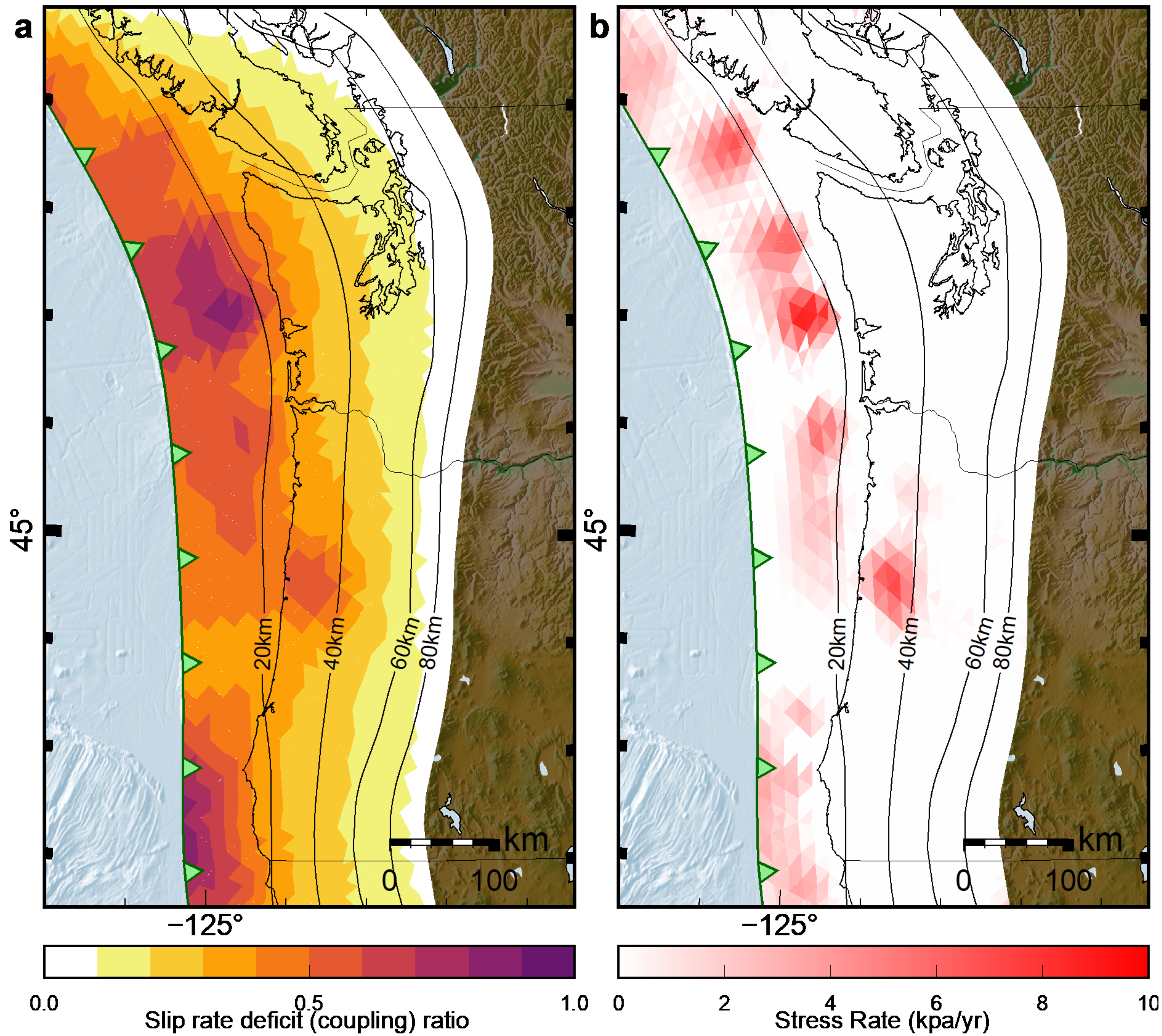

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