Life in the stress shadow:

Stress-constrained inversion for interseismic coupling on shallow megathrusts

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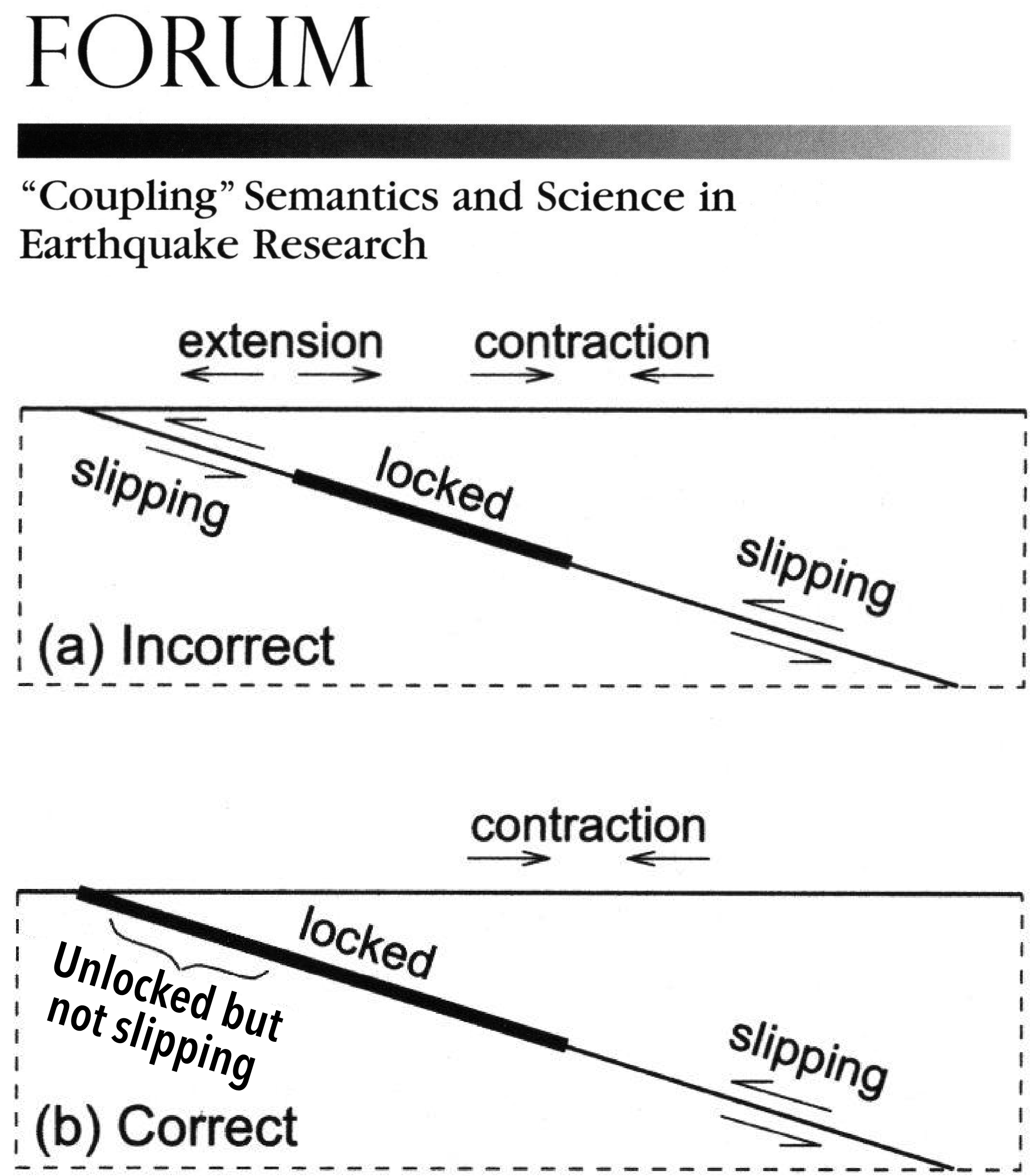
Key point for this talk:

The shallow part of a megathrust above a locked zone is **highly coupled.**

Is **locking** the same as **coupling**?



Wang & Dixon, 2004

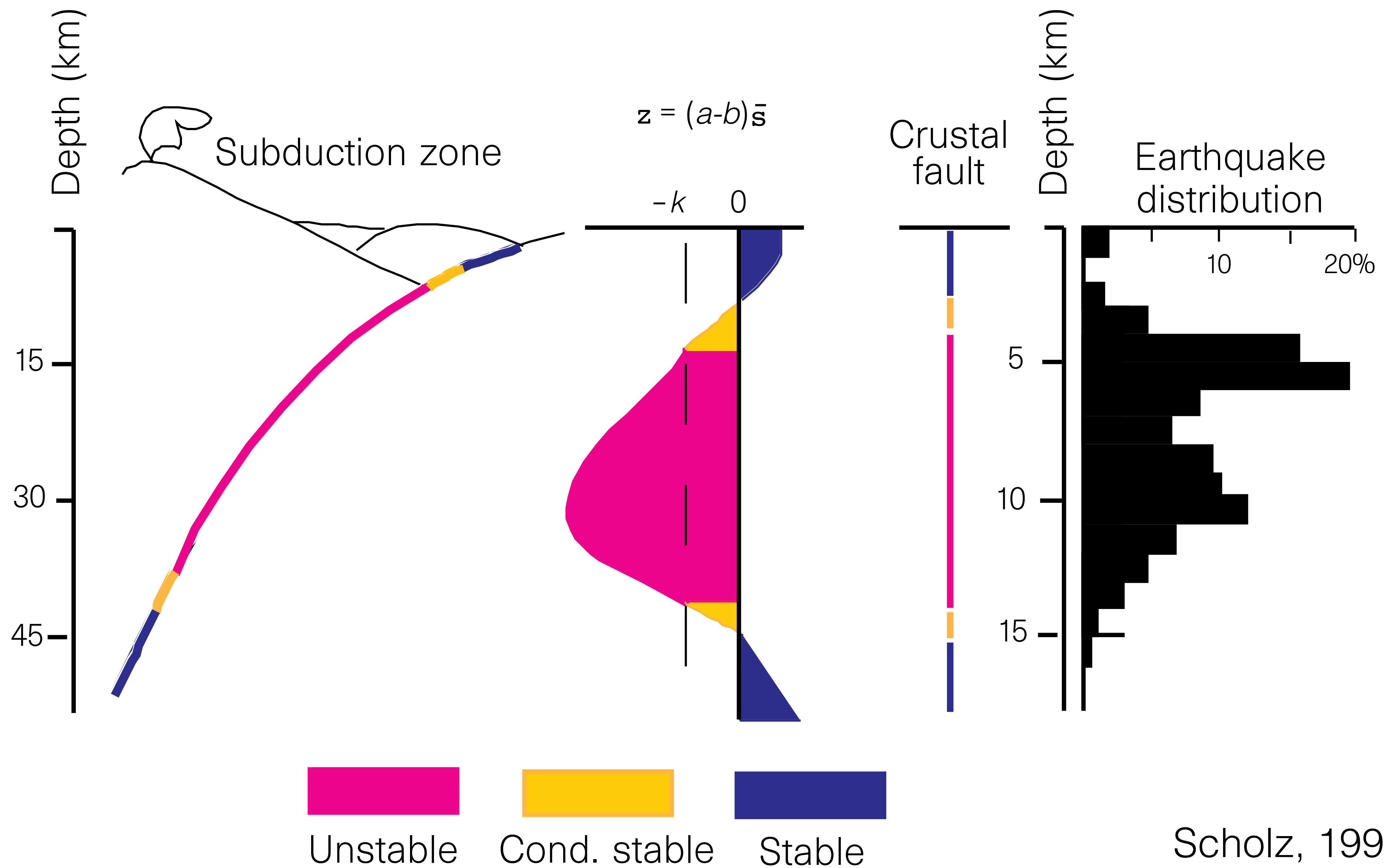
Locking: a physical term describing the fault's response to stress.

Coupling (or **Slip Deficit**): a kinematic term describing the slip rate on the fault.

Fault creep is the expected behaviour for shallow faults.

1. Lab studies have shown **velocity strengthening** behavior is common at low temperature and pressure.

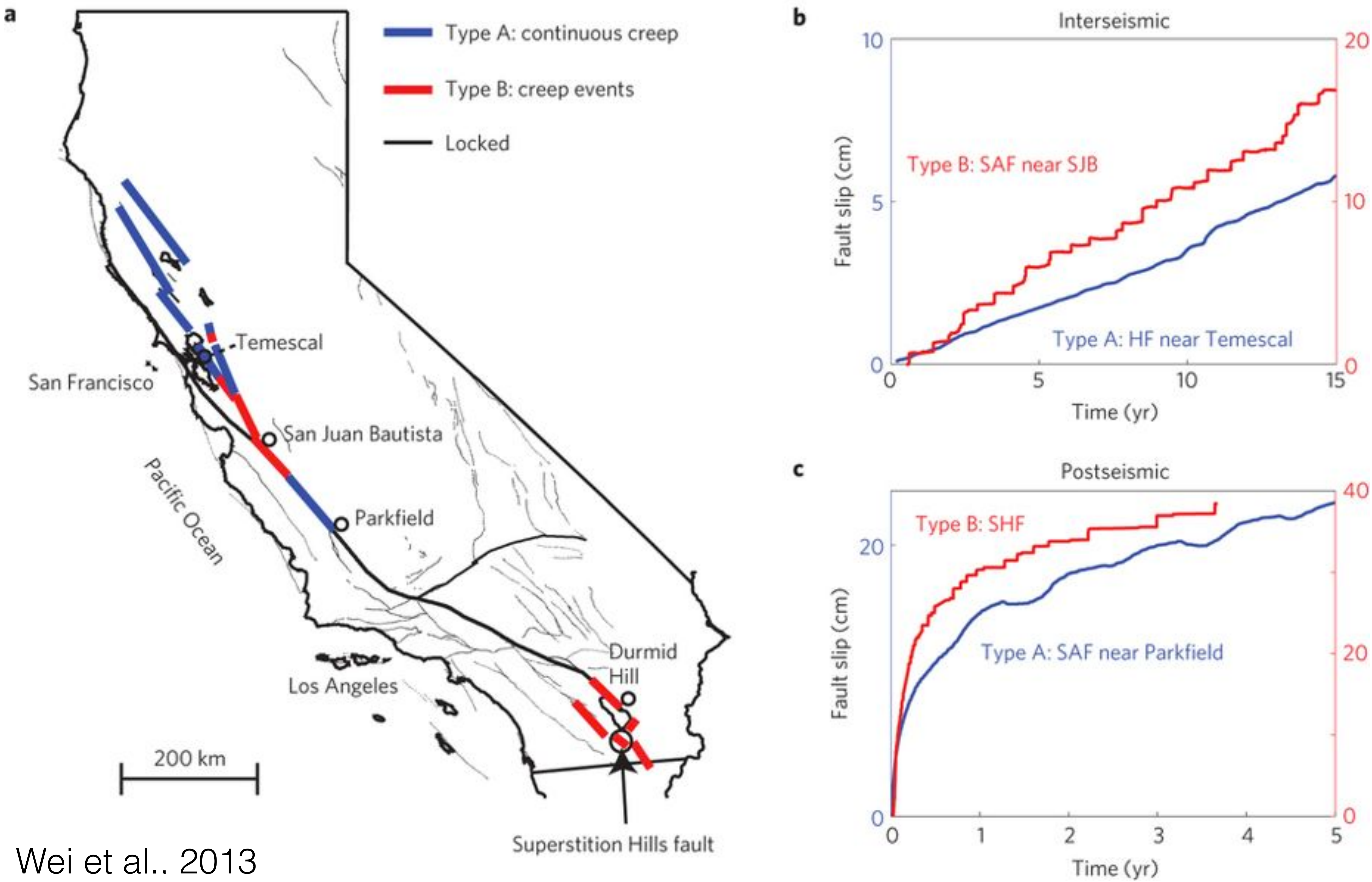
2. There is a relative **lack of microseismicity** on the shallow part of faults.



Scholz, 1998

Fault creep is diverse, and not present everywhere

Note: the shallow creep rate is almost always **less than the long-term rate.**



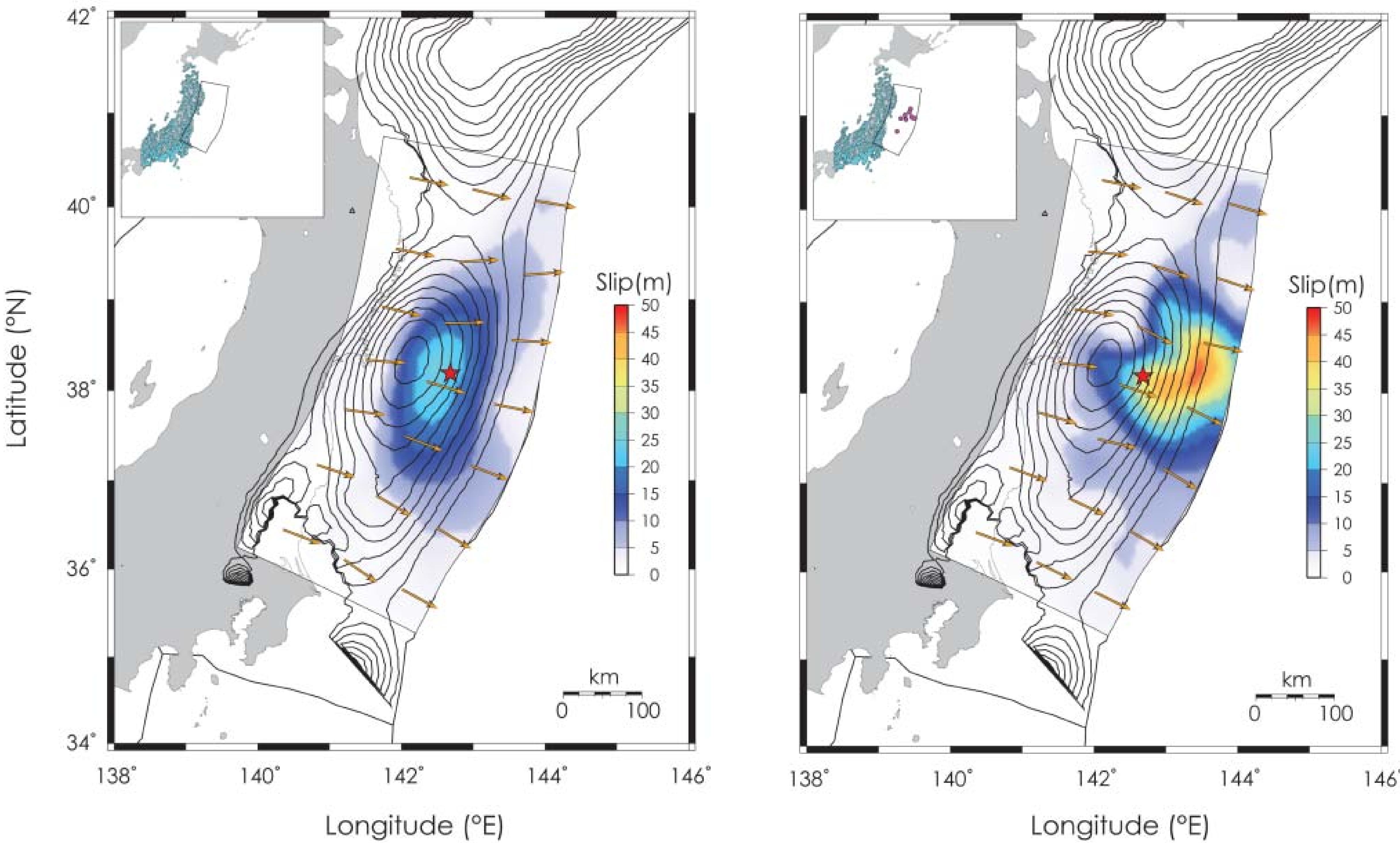
Wei et al.. 2013

Are shallow megathrusts locked or unlocked?

There is evidence for a wide range of frictional behavior on megathrusts. However, geodetic data has almost no resolution…

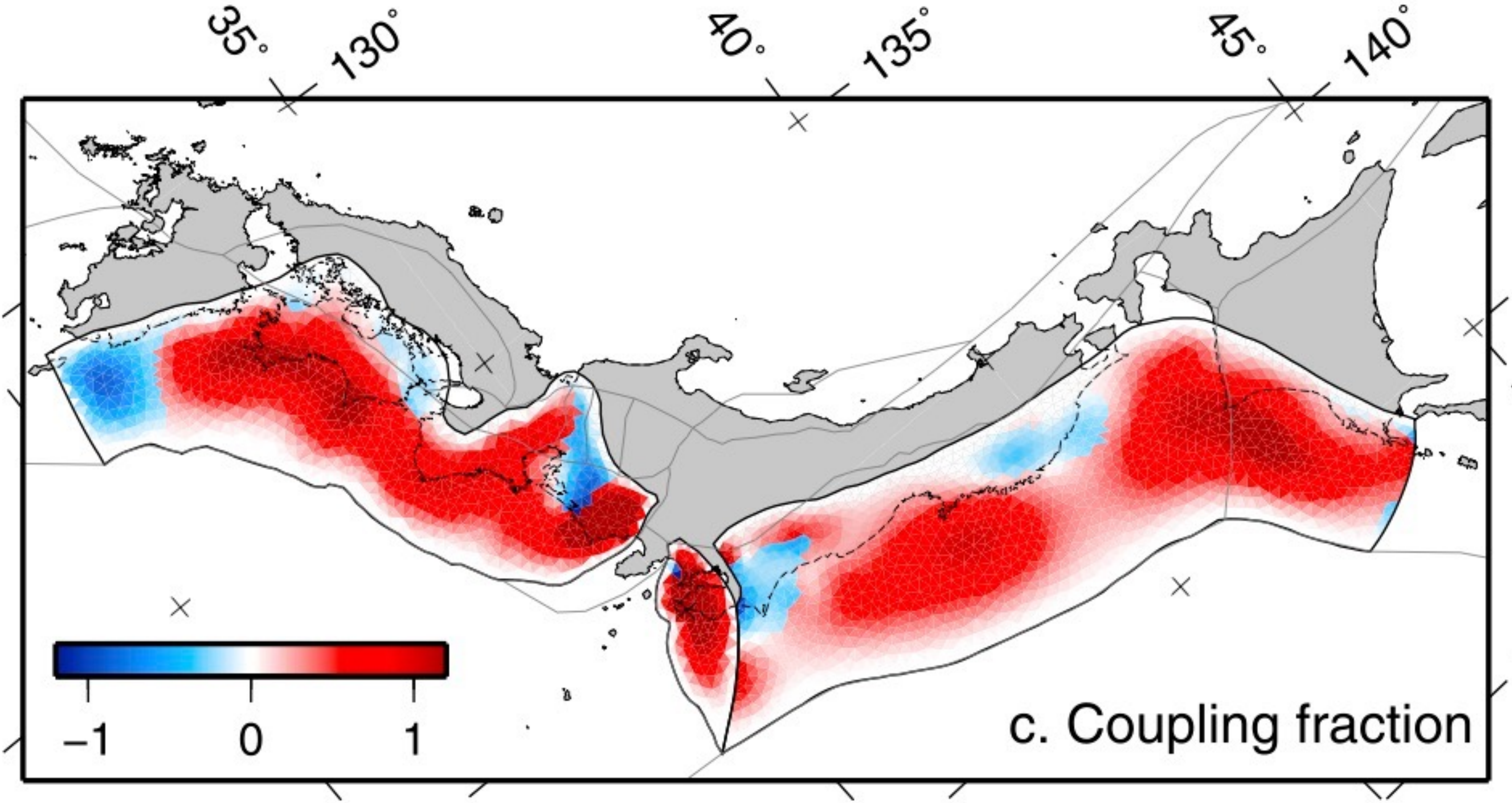
Coseismic slip: GPS-only

Coseismic slip: GPS + Tsunami



Romano et al., 2012

Many models infer low or zero coupling at the trench: **Japan**, Sumatra, Ecuador, Cascadia



Loveless & Meade, 2010

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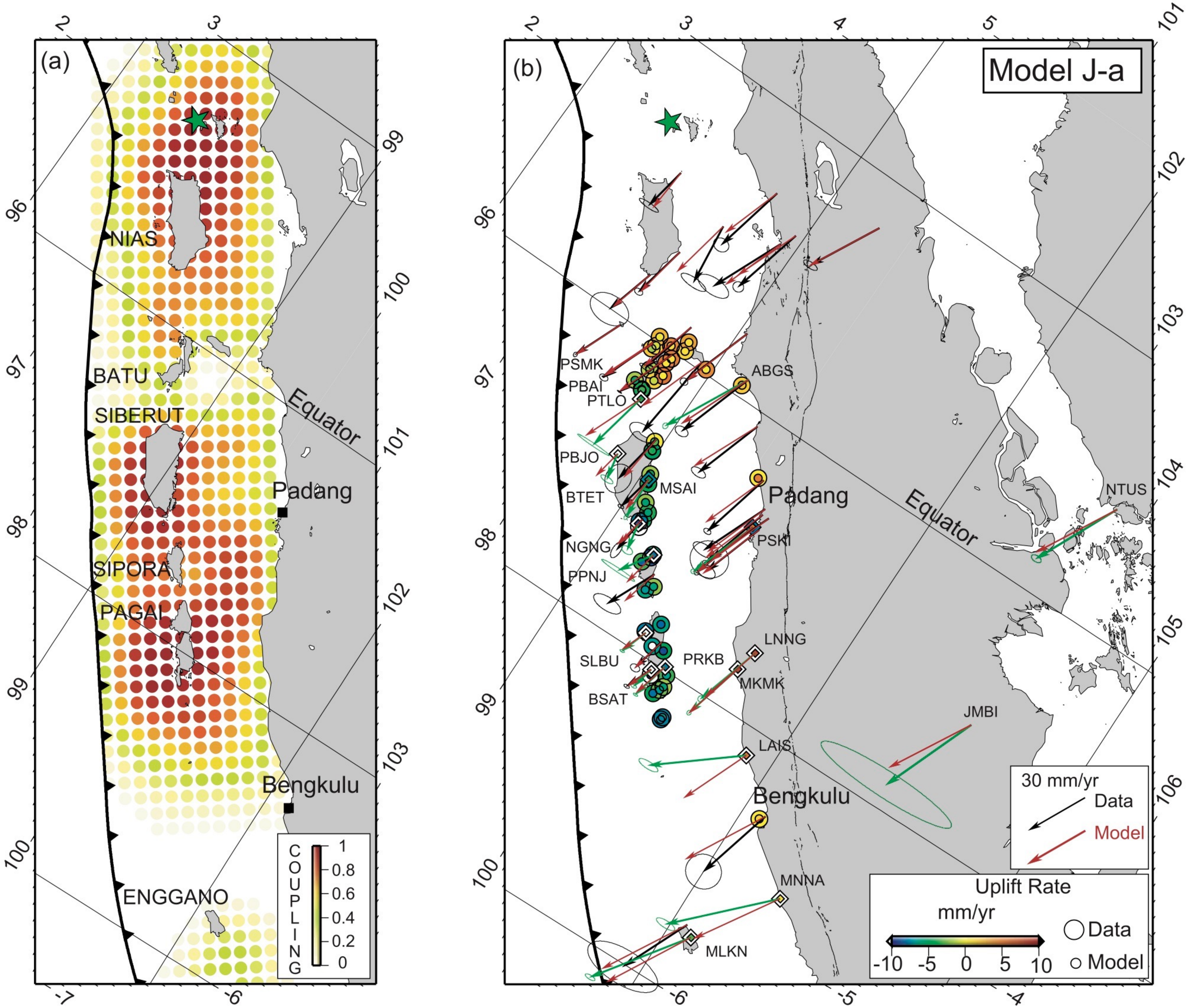

Chlieh et al., 2008

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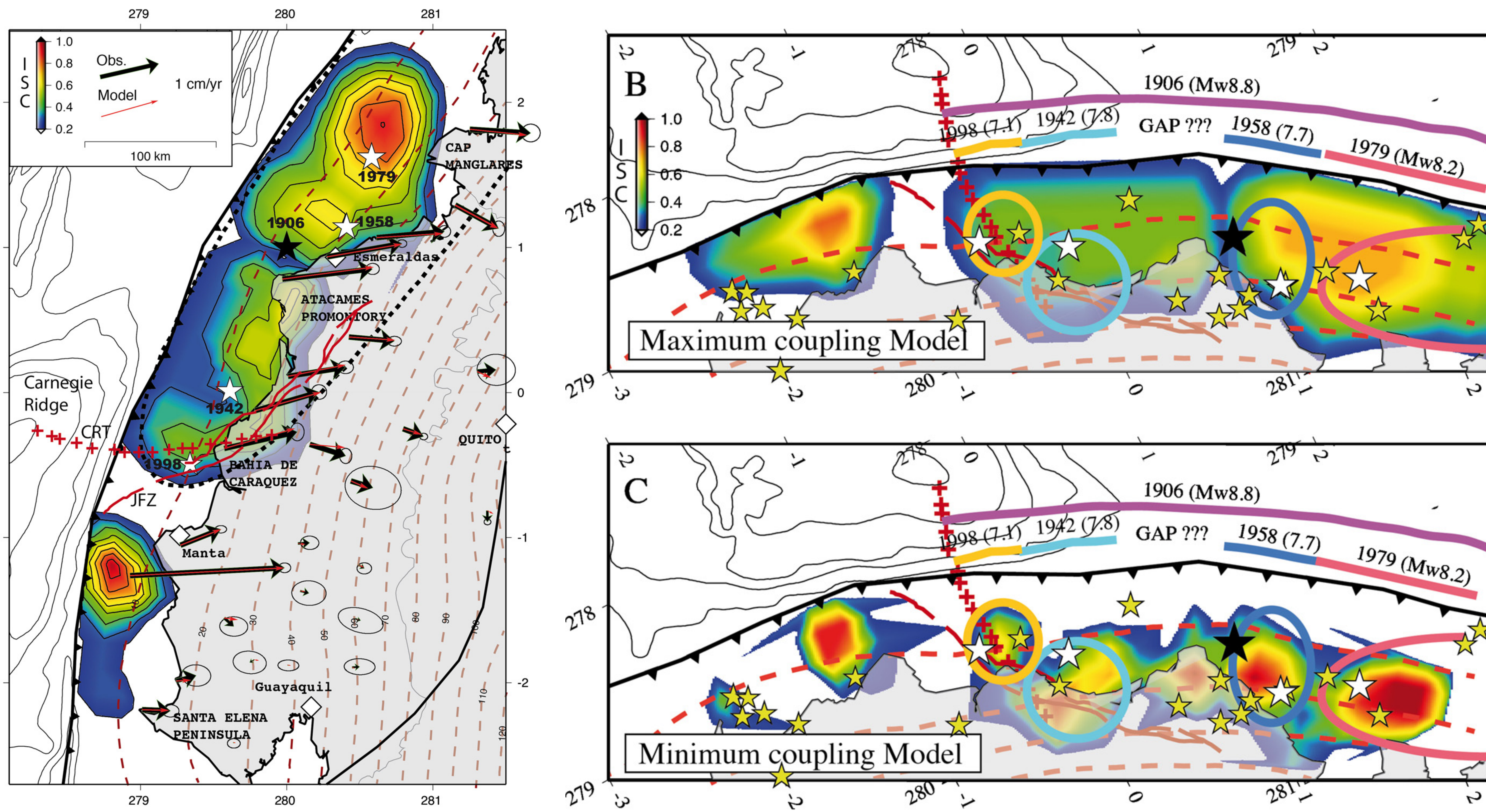

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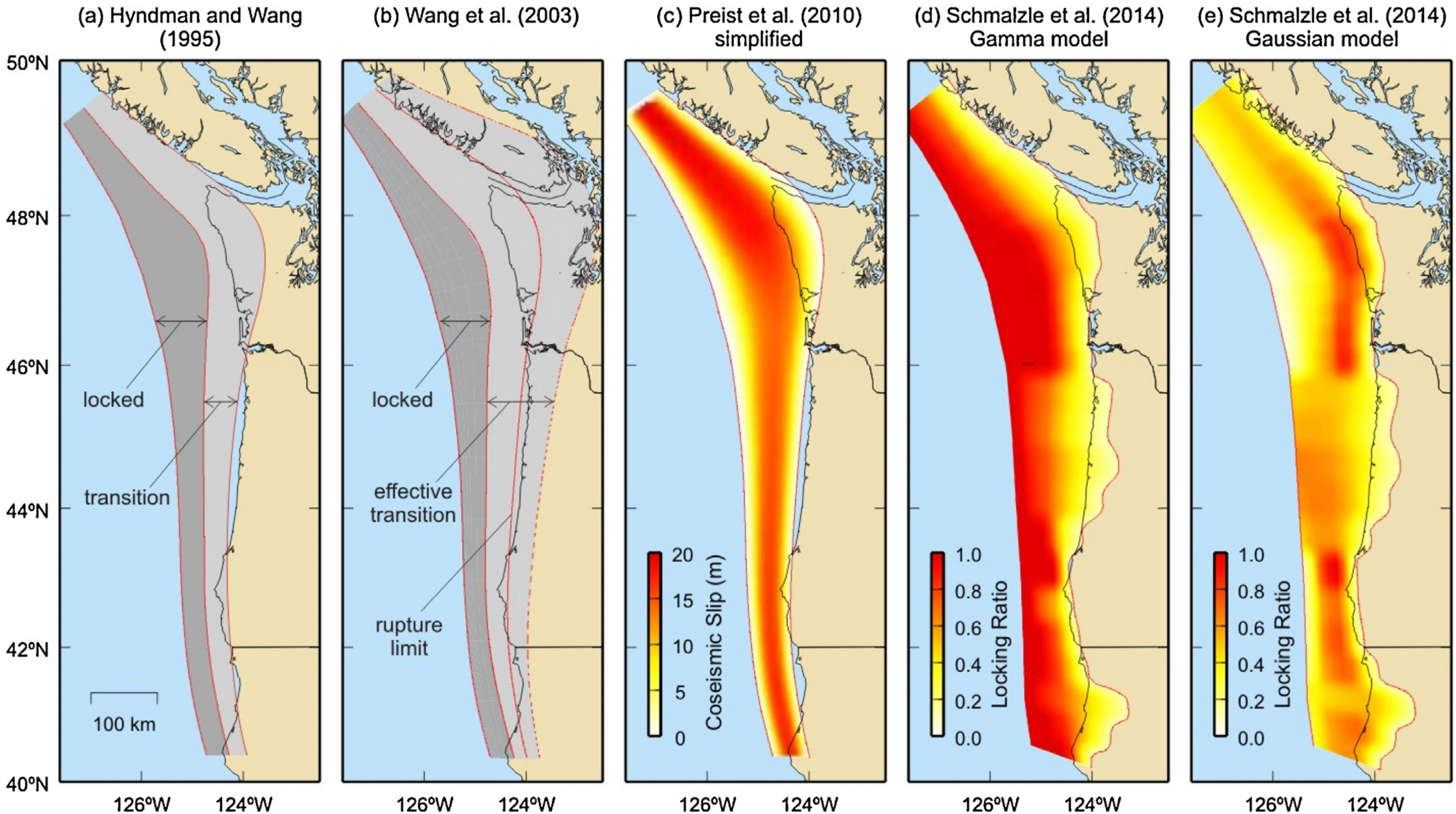
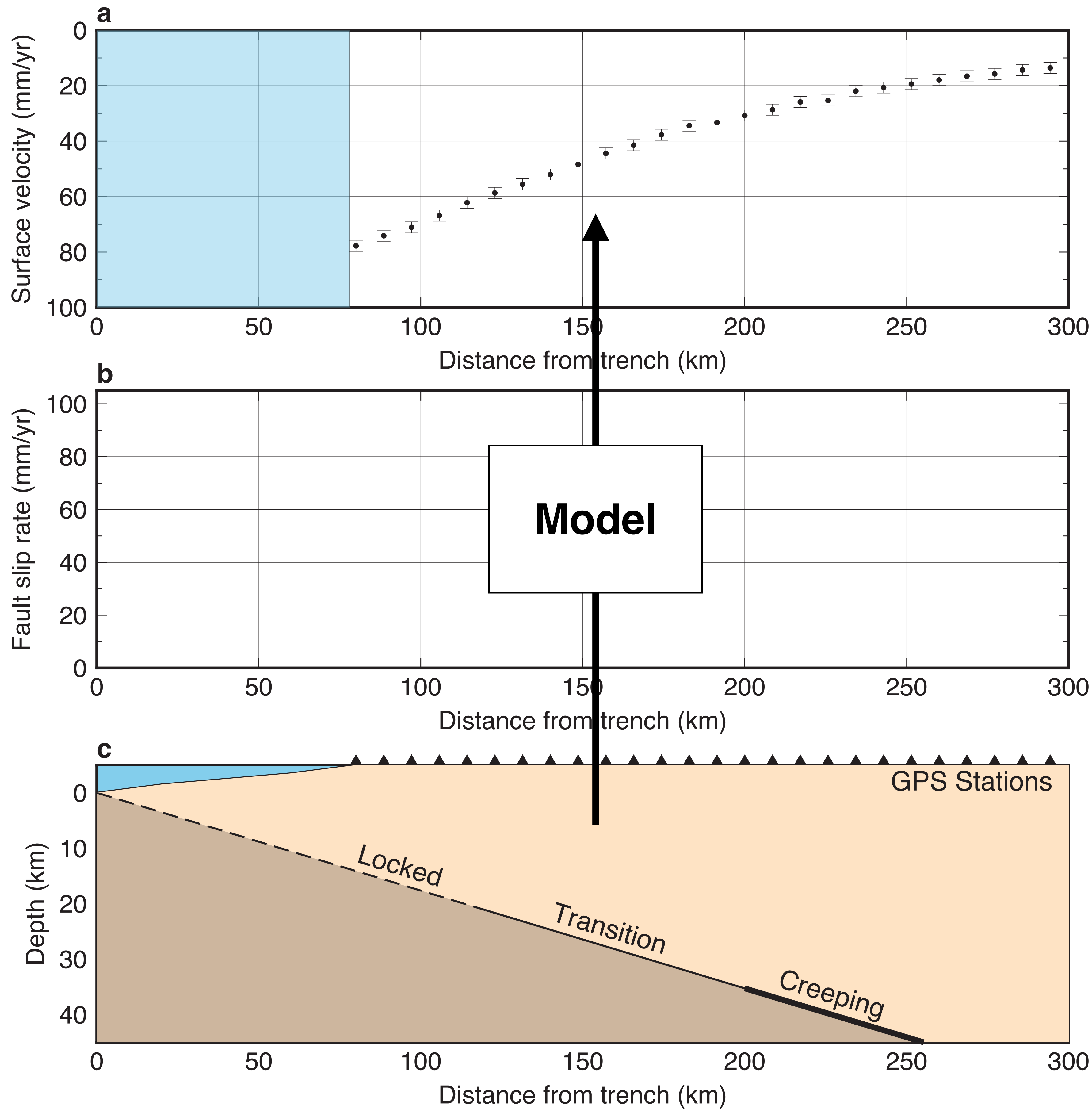


Wang & Trehu, 2016

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

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

misfit = residual + smoothing + model norm minimization



Result: large uncertainty near the trench

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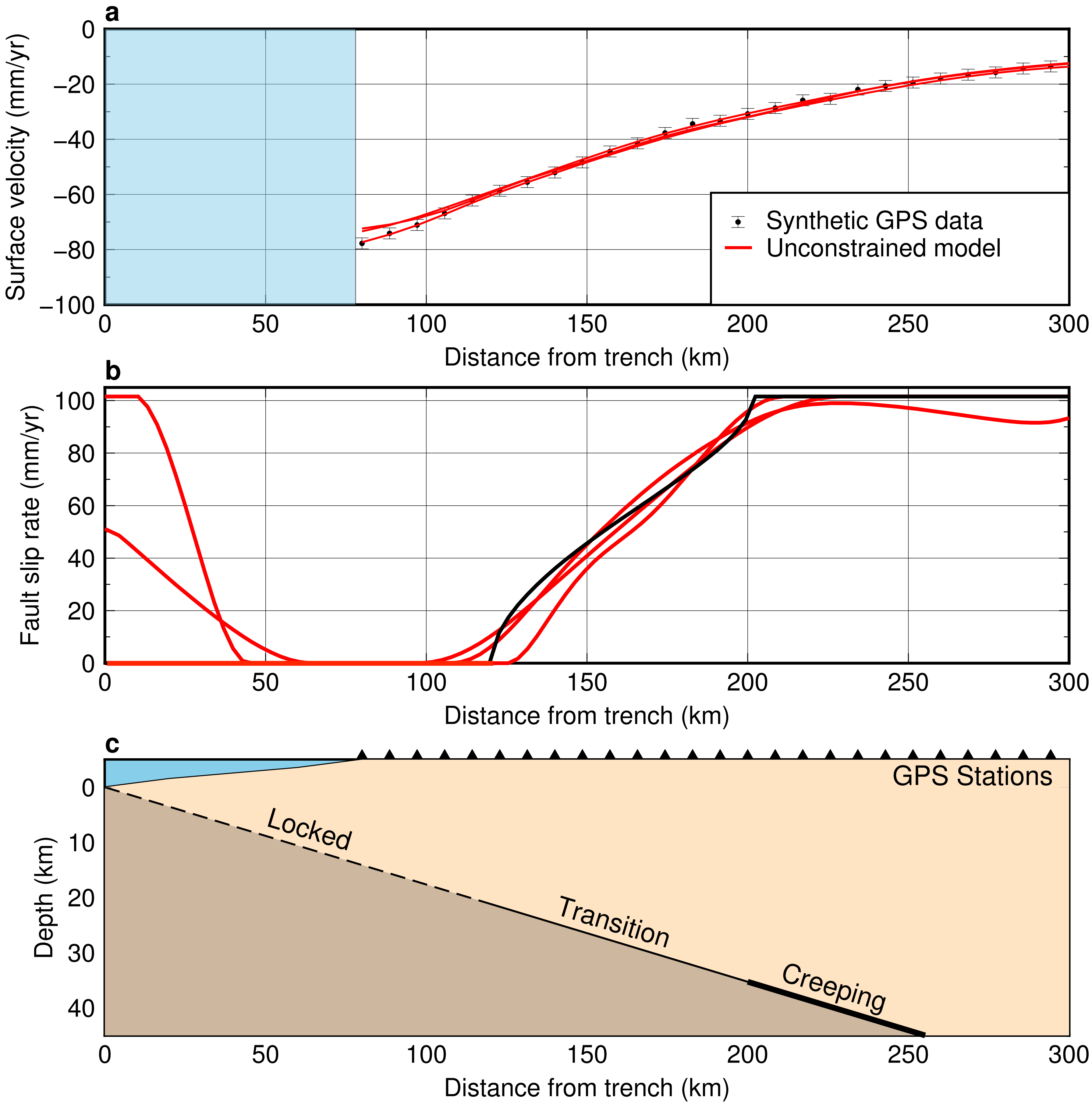
Near the trench, uncertainty is ~100%: we have **no ability to resolve** the coupling.



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Shaded area:
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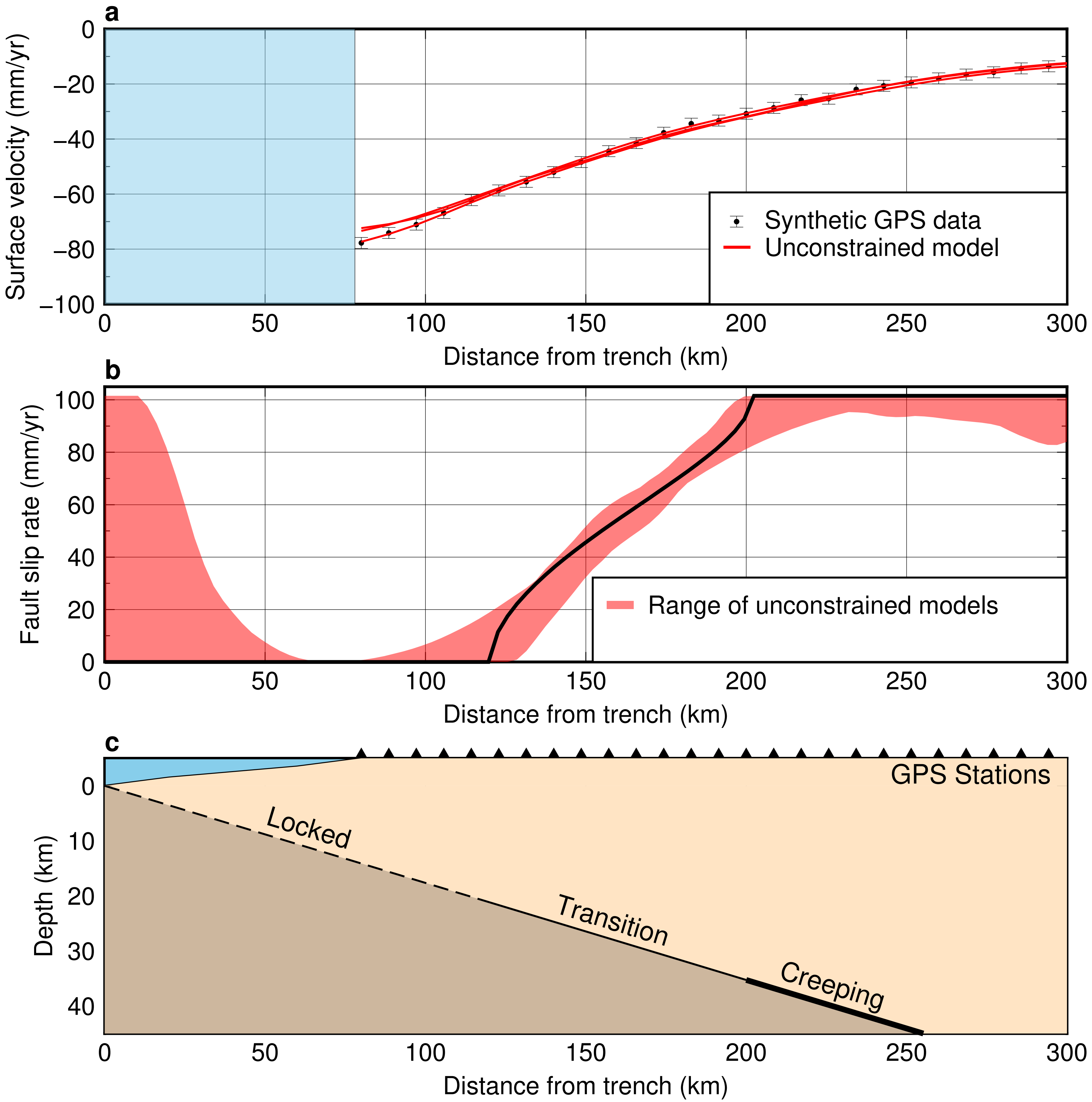

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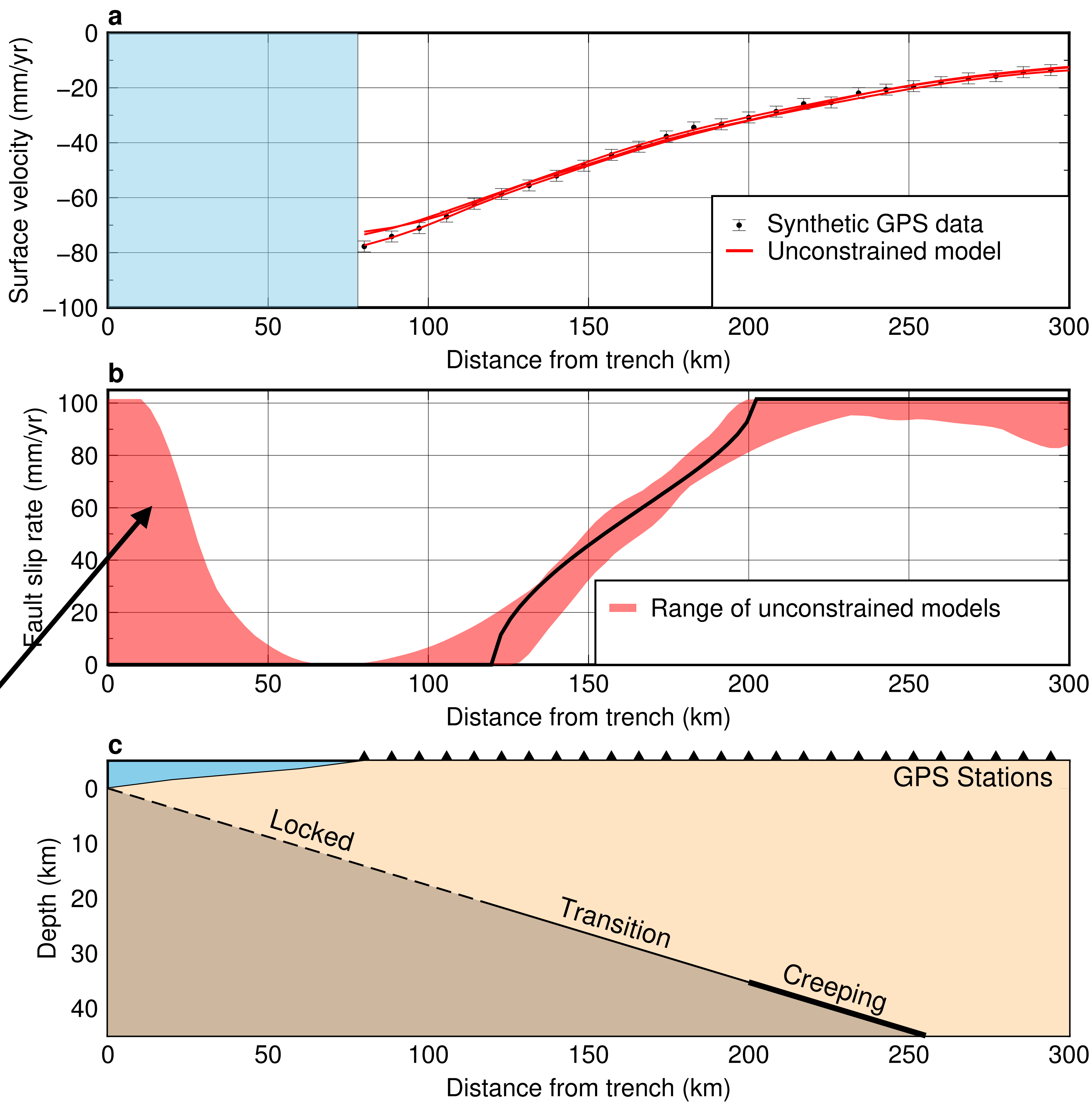
Question: what source of stress could drive this slip?



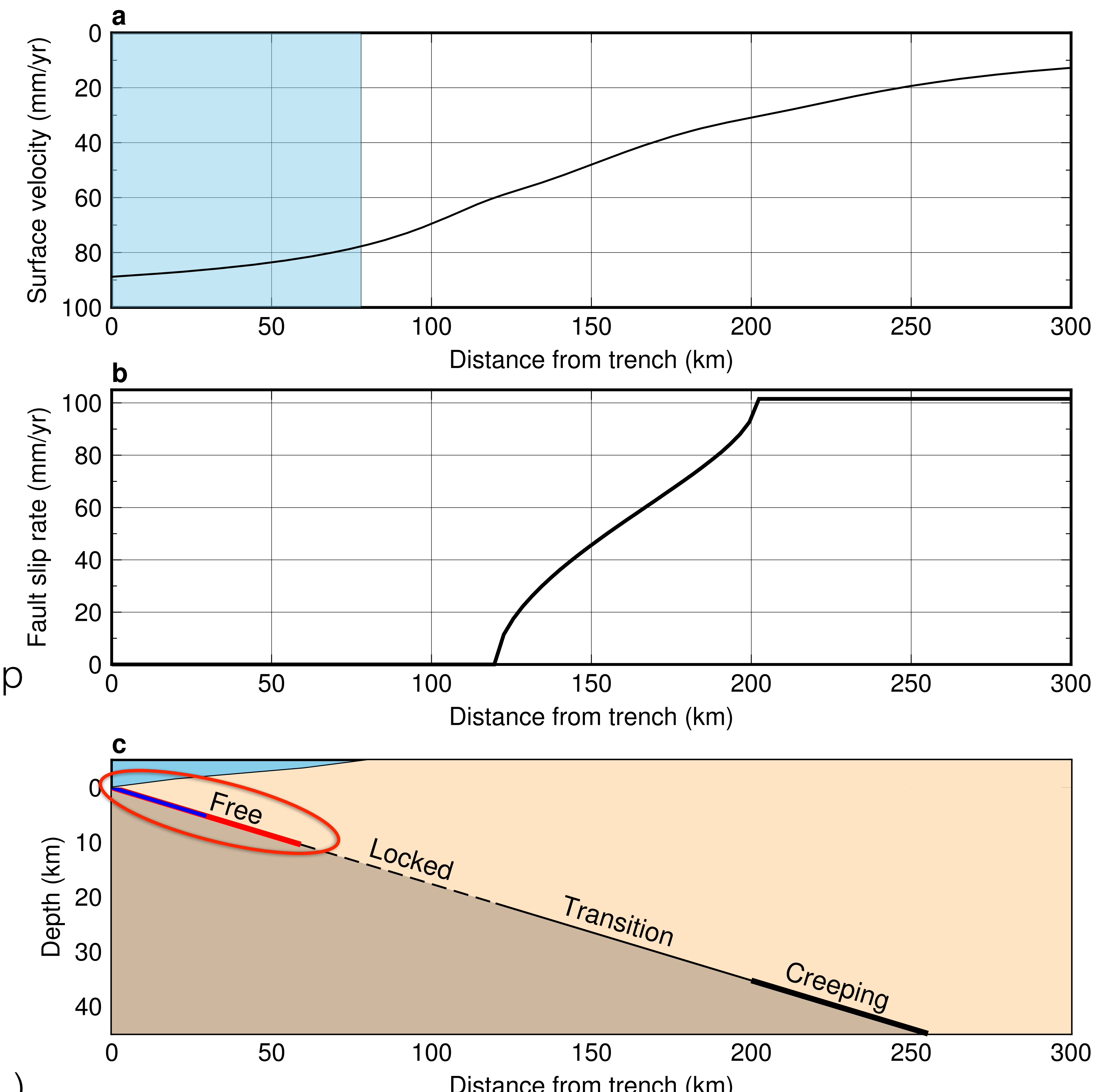
Use a physical model to predict shallow slip rates

Model assumptions:

- 2D, planar thrust fault dipping 10°
- Homogeneous elastic half space
- Driving stress is far-field
- Fault slips at the convergence rate below some depth

Locking/unlocking

- Locked patches cannot slip at all
- Unlocked patches slip in response to any applied stress



Almeida, Lindsey et al., 2018 (GRL)

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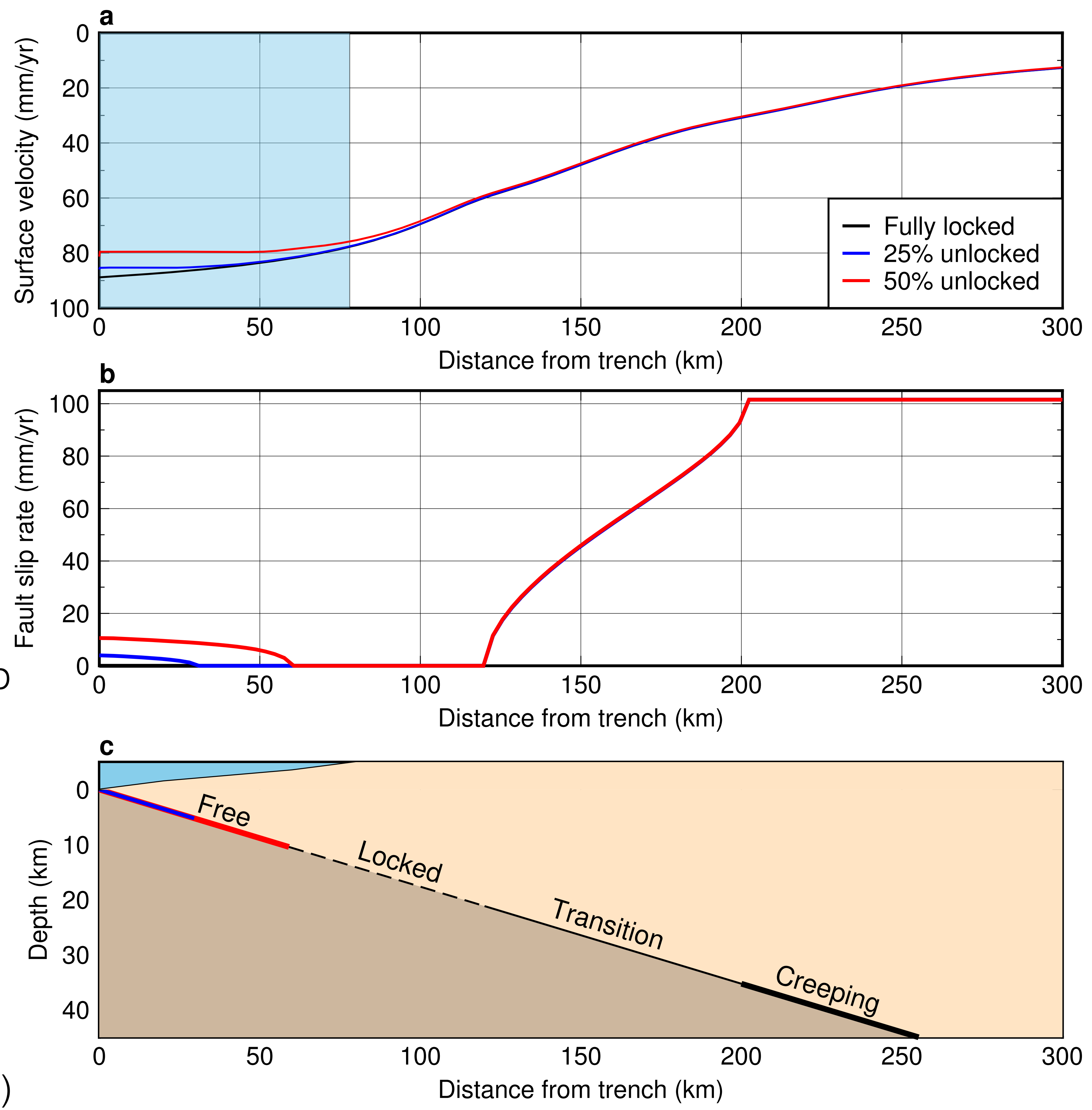

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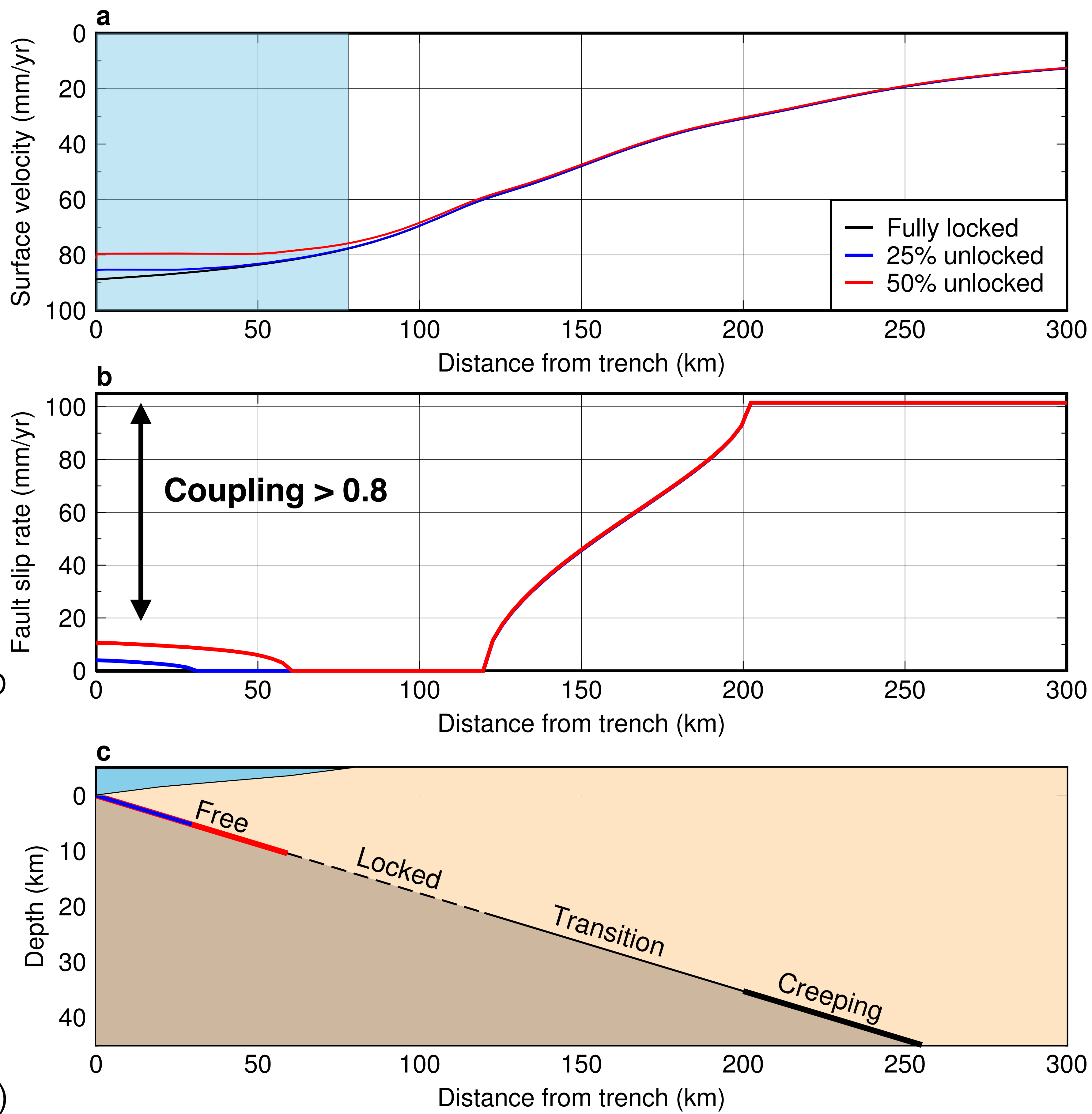


Almeida, Lindsey et al., 2018 (GRL)

How can we use this knowledge to improve our inversion?

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

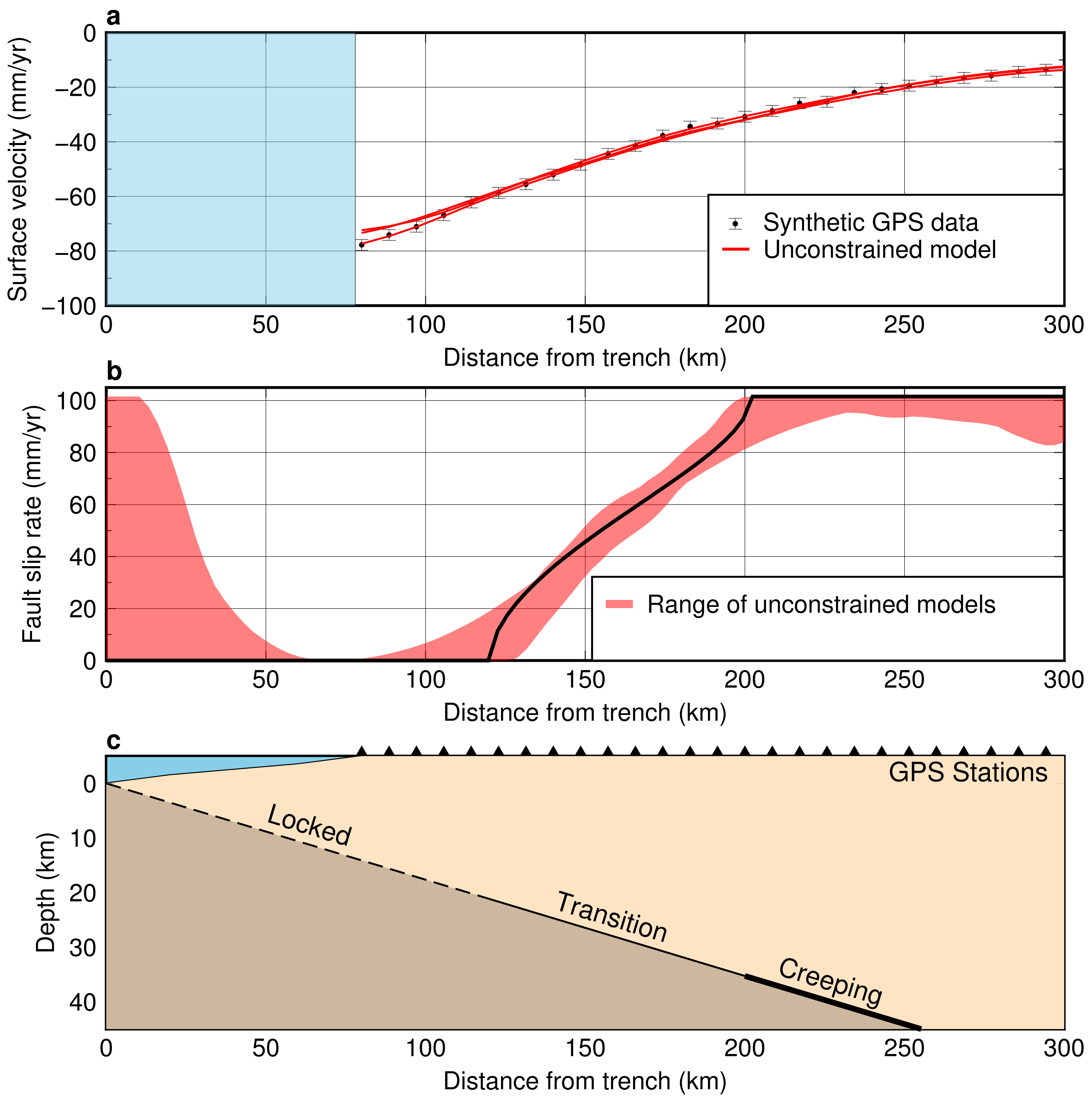
Stresses are a linear function of slip:

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

Balance with the far-field loading stress rate:

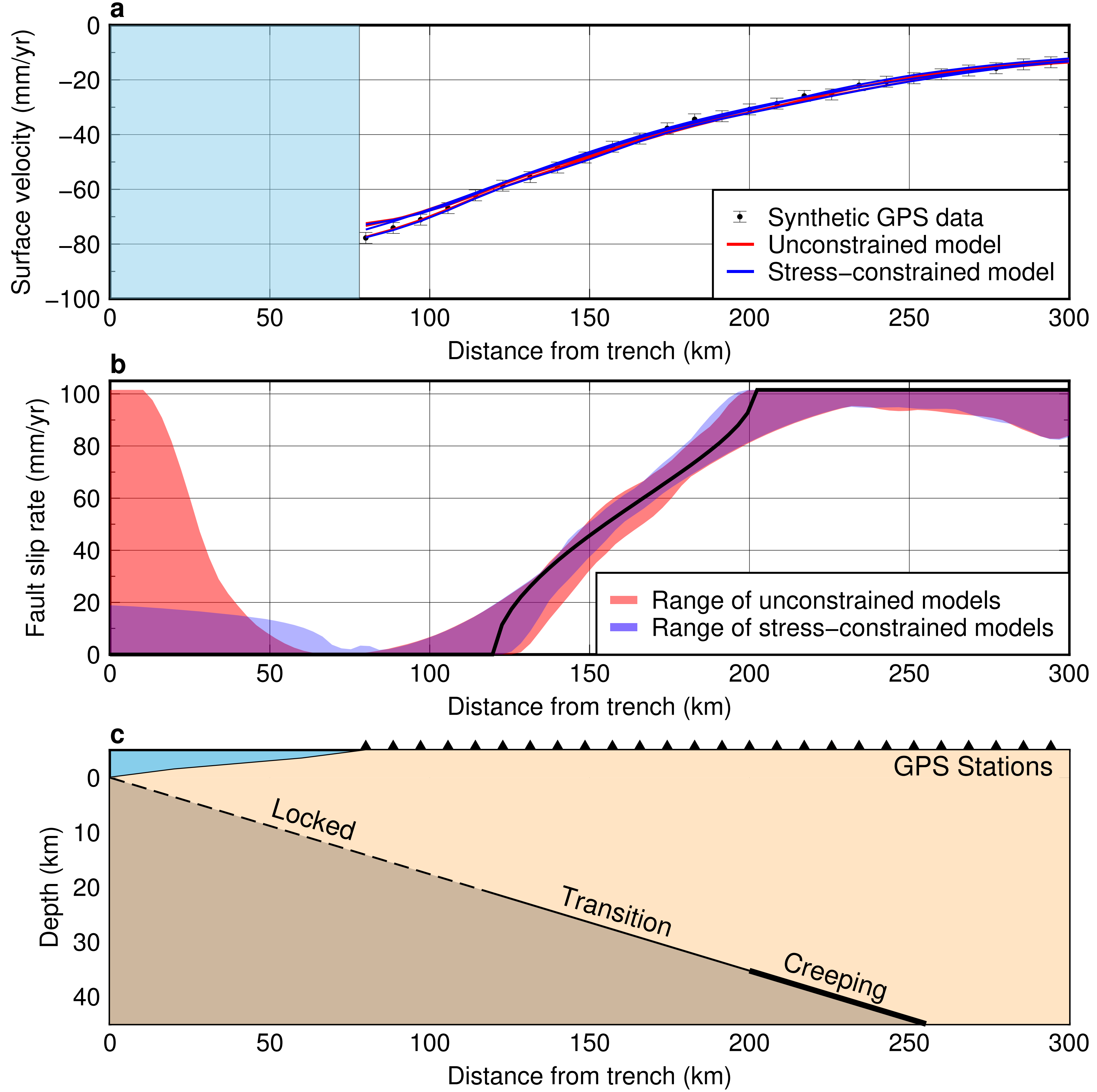
$$2\,\mu\,E_{ij} \cdot \dot{s}_j \leq \dot{\sigma}_j^0$$

We implement this as a linear constraint in the inversion.



Stress-constrained inversions cannot over-predict creep rates.

→ Much less uncertainty at the trench!



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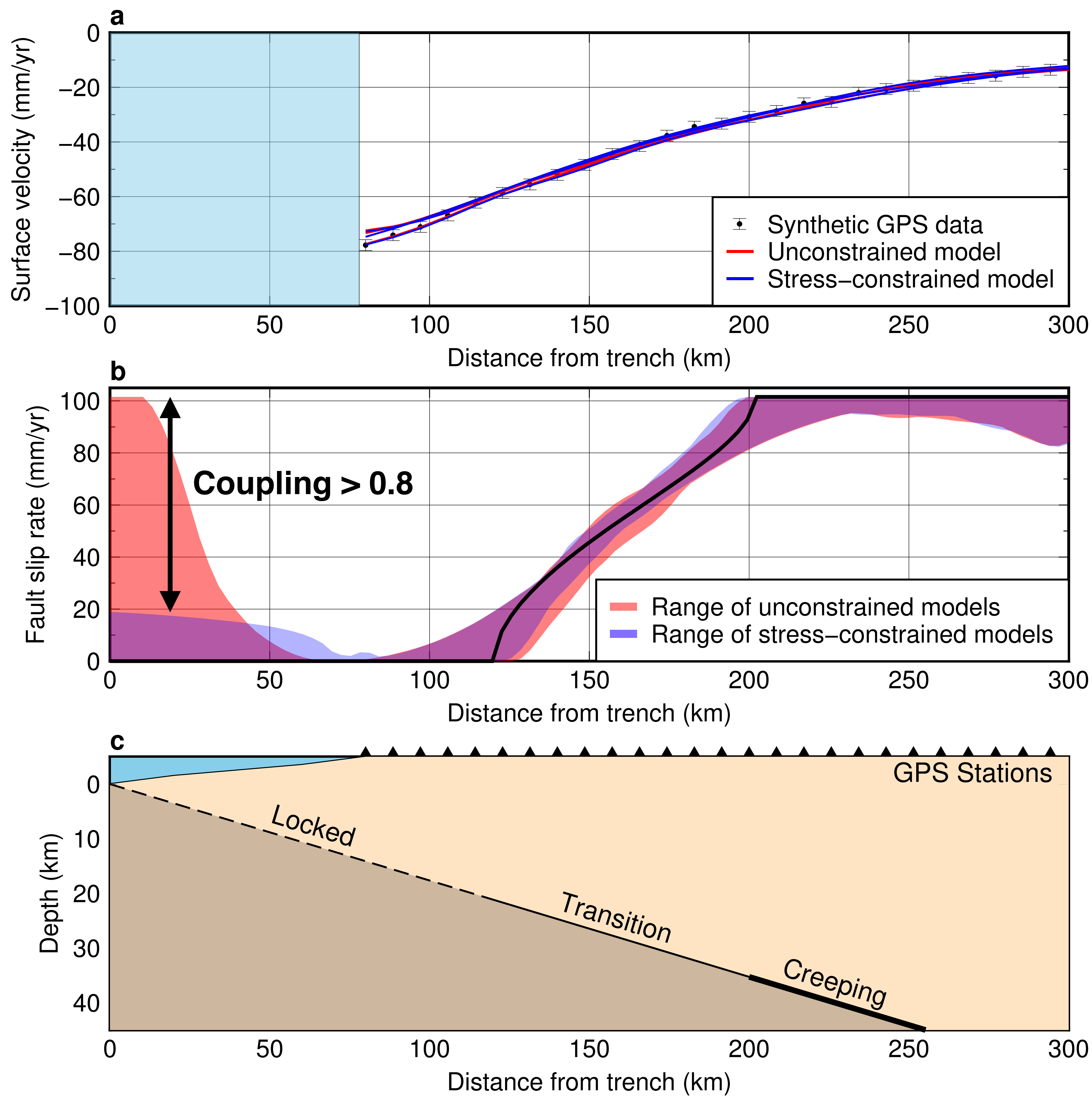
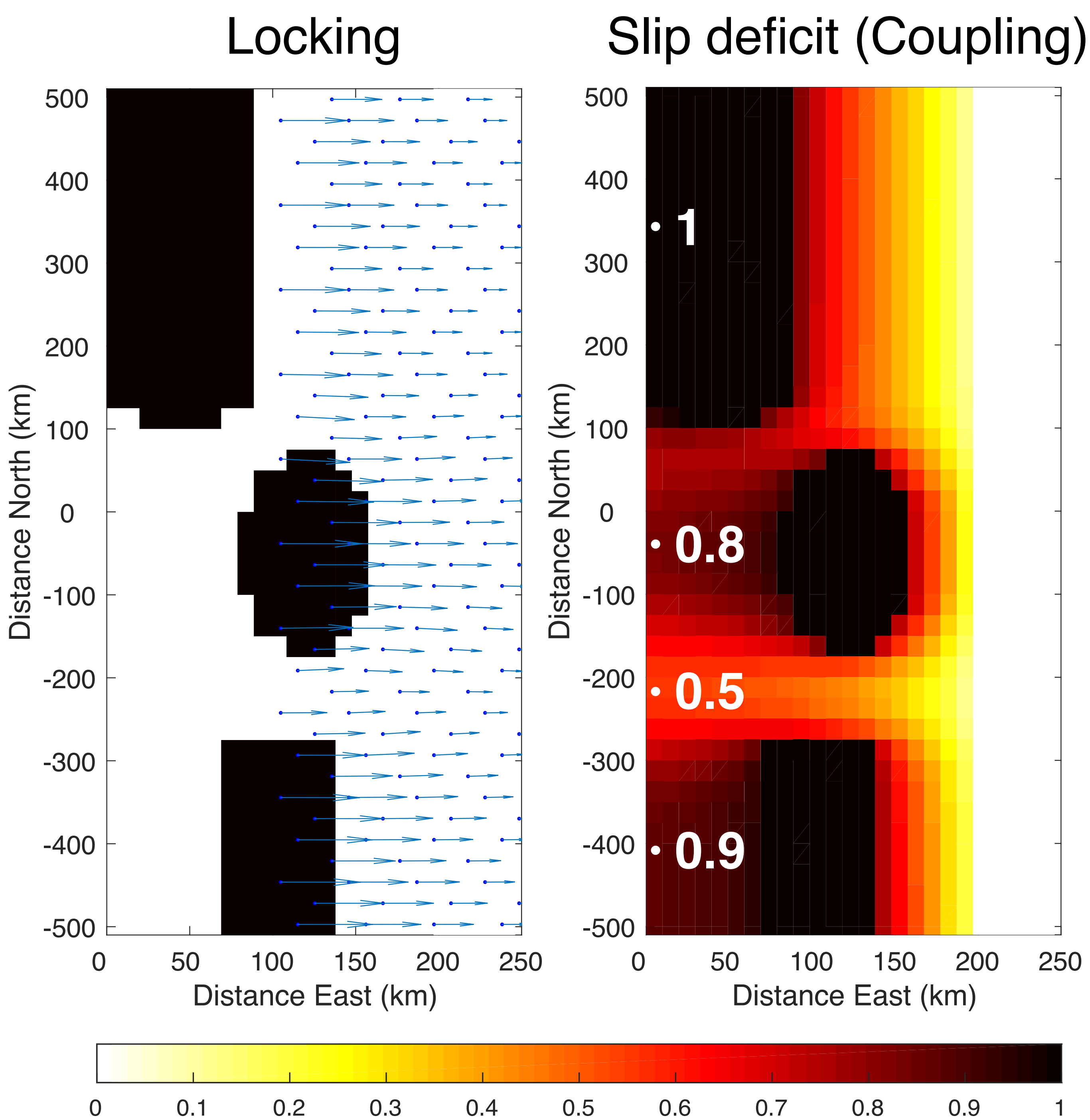


Visualising locking vs. coupling in 3D



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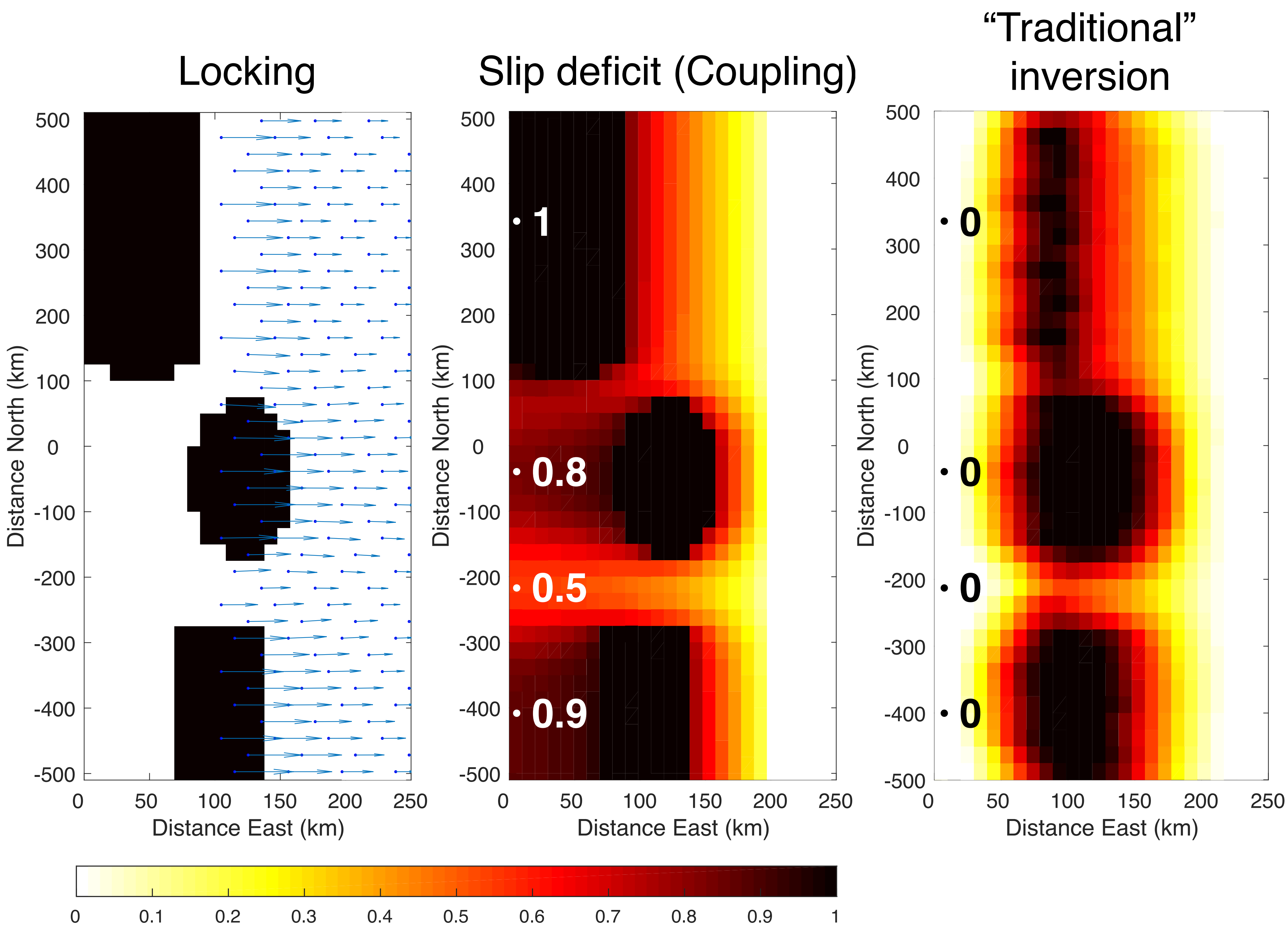

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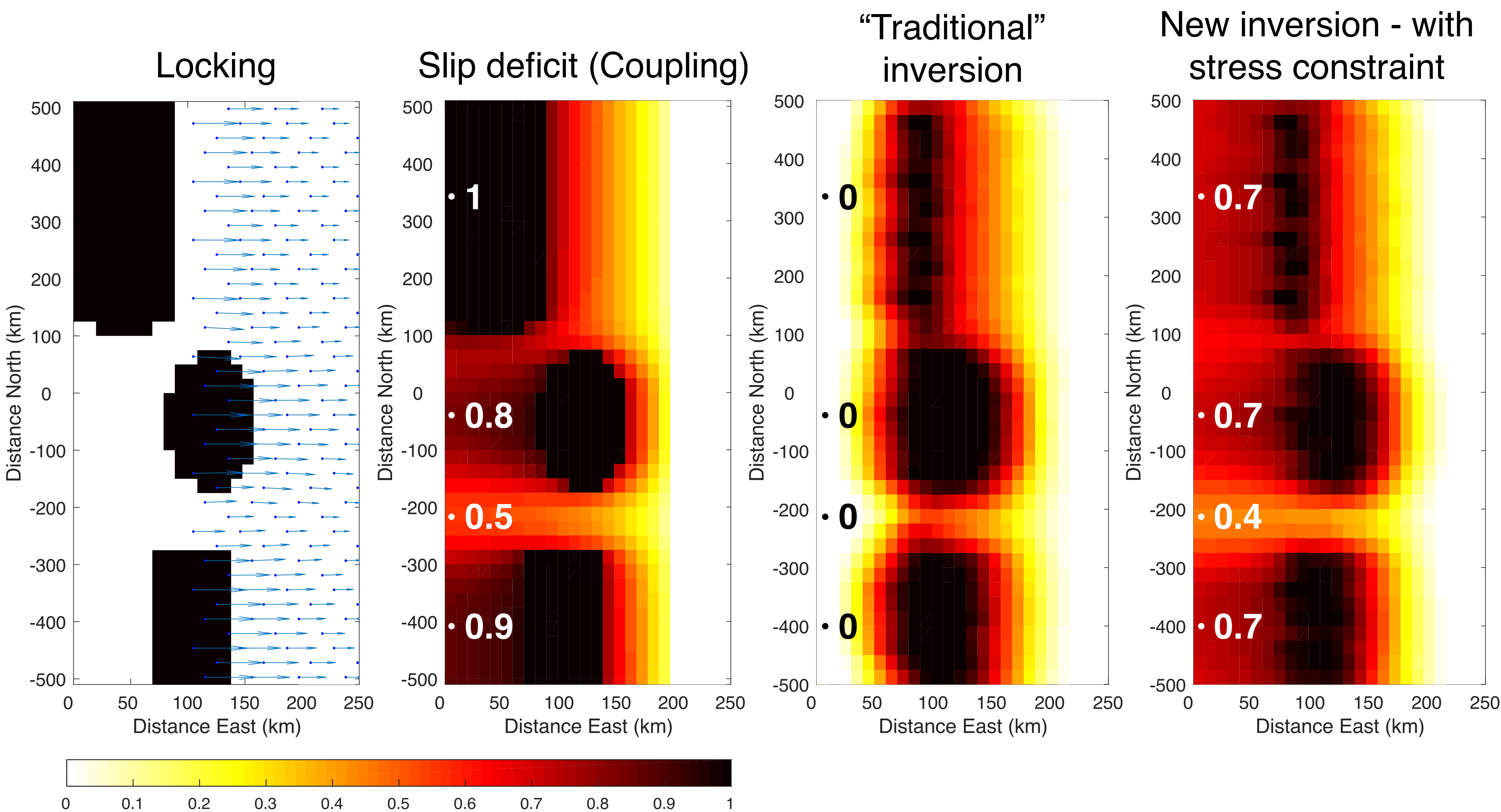
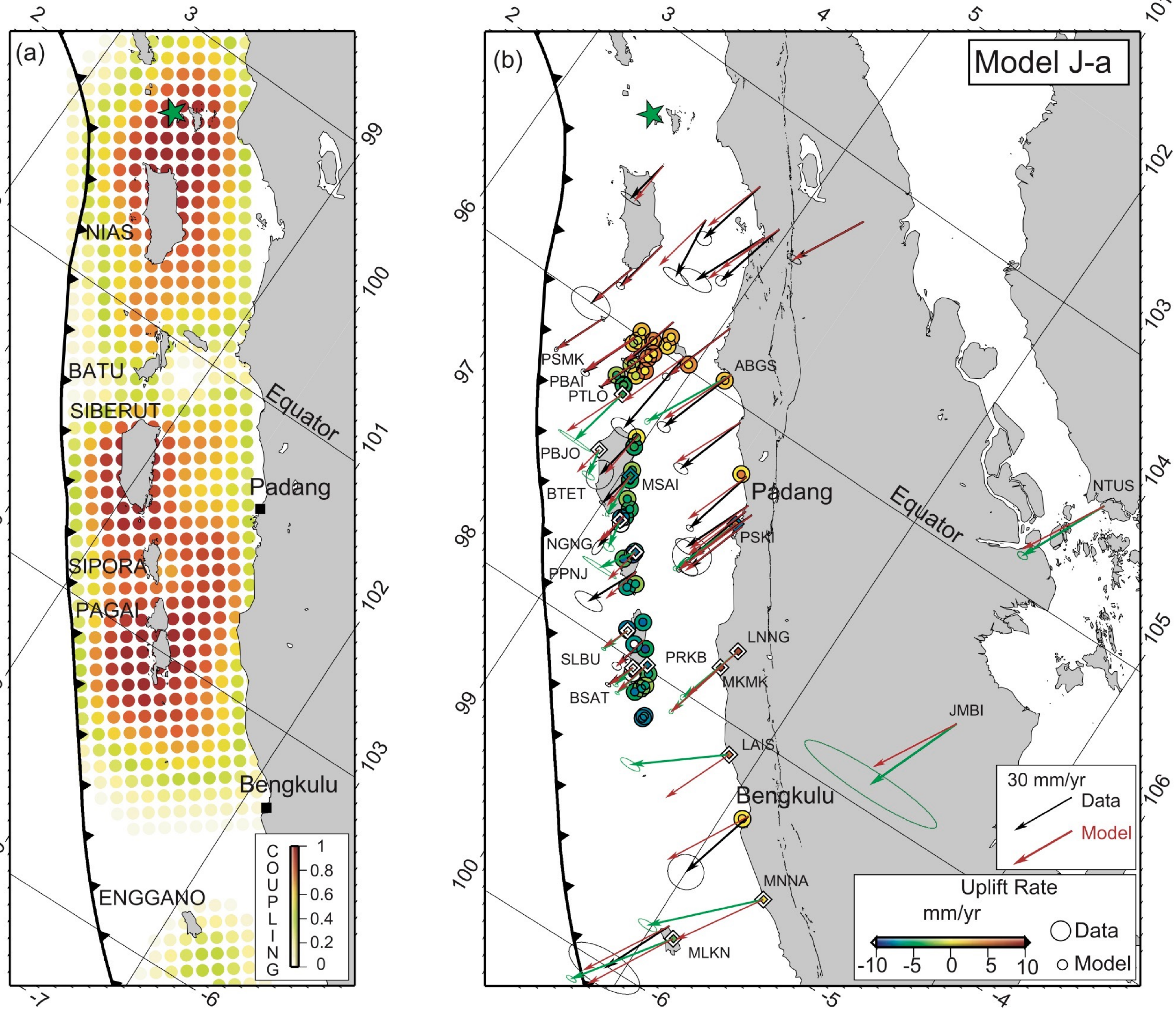


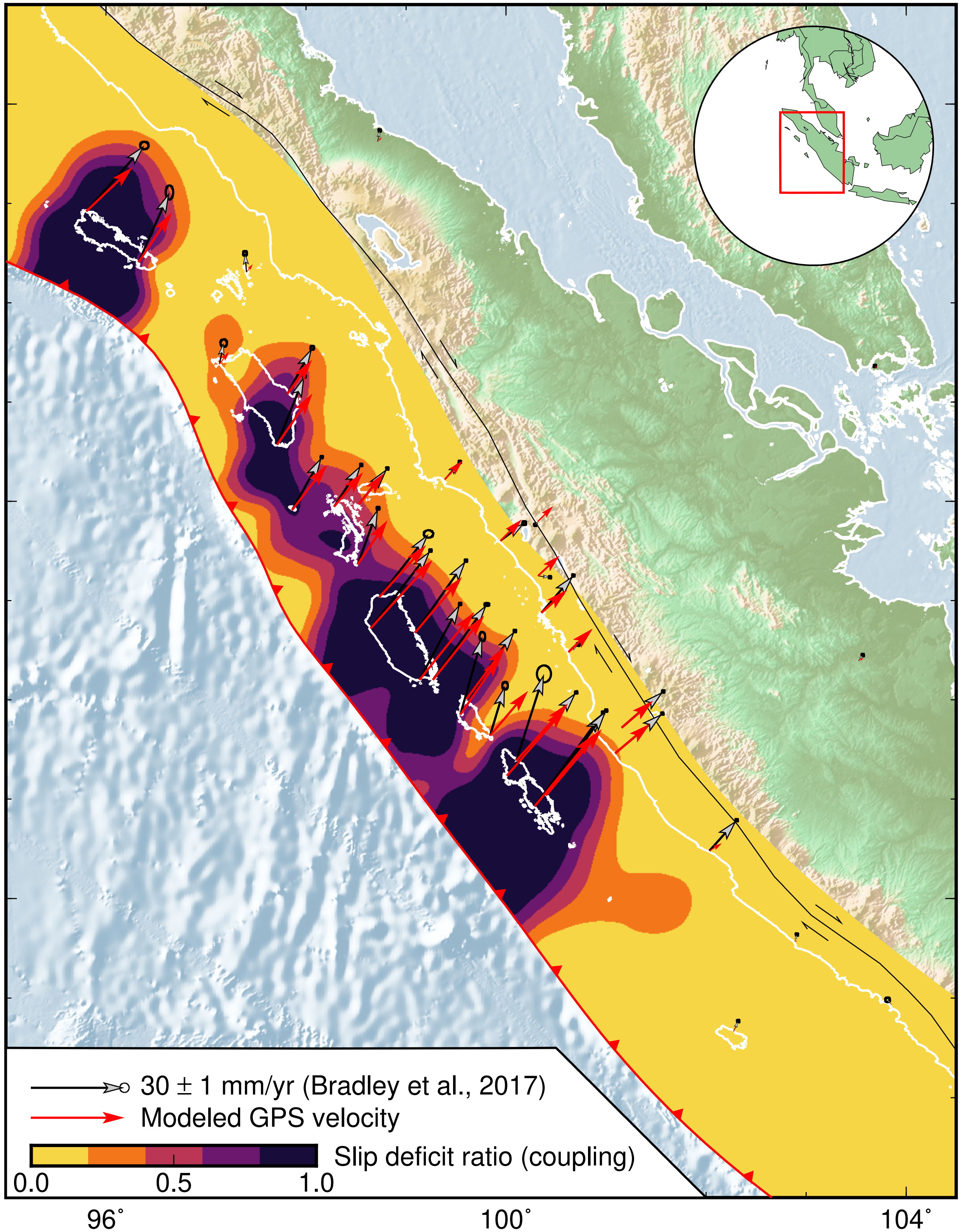
What do we really know about coupling in Sumatra?



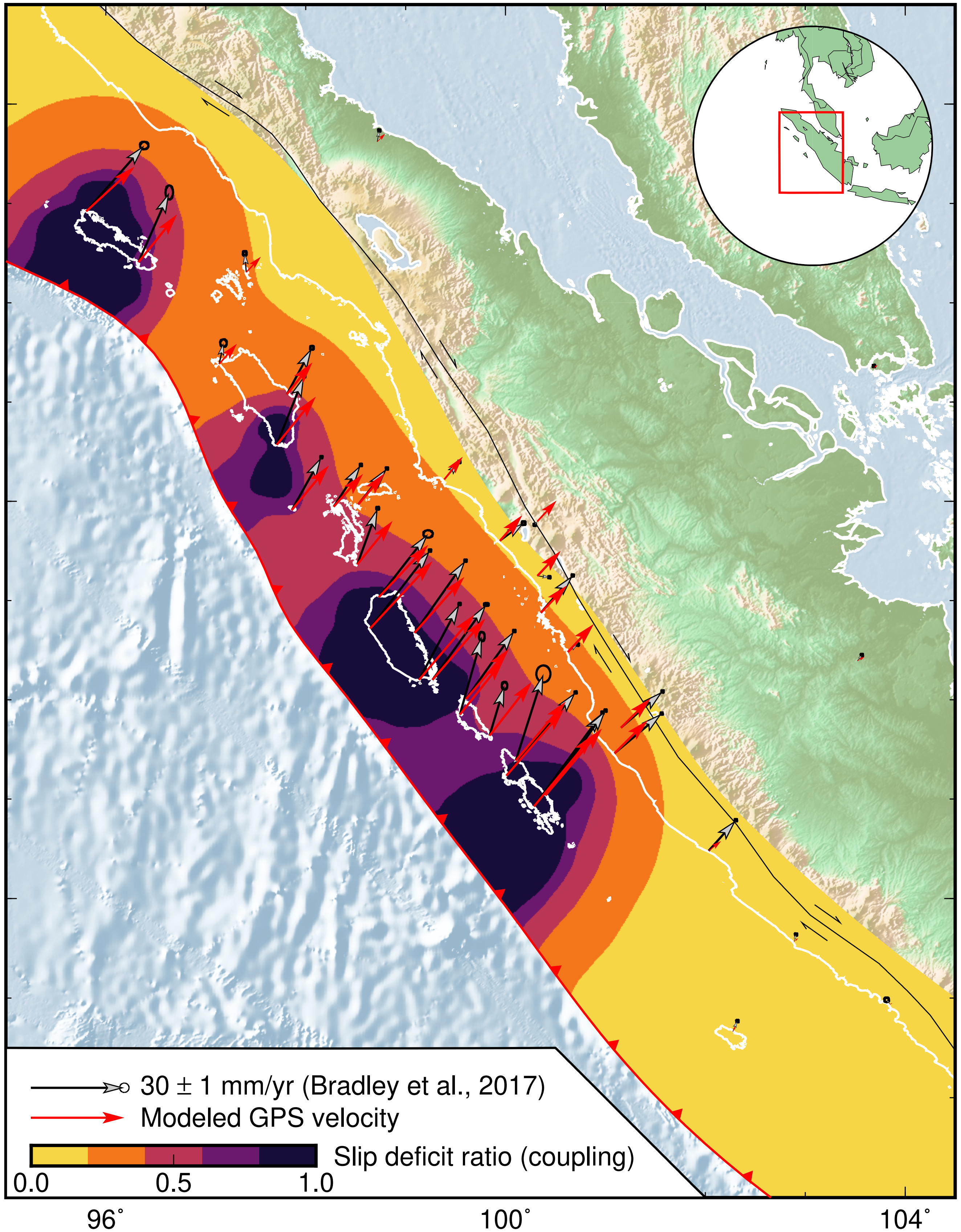
Chlieh et al., 2008

Slip deficit extends to the trench.

No stress constraints, norm minimization

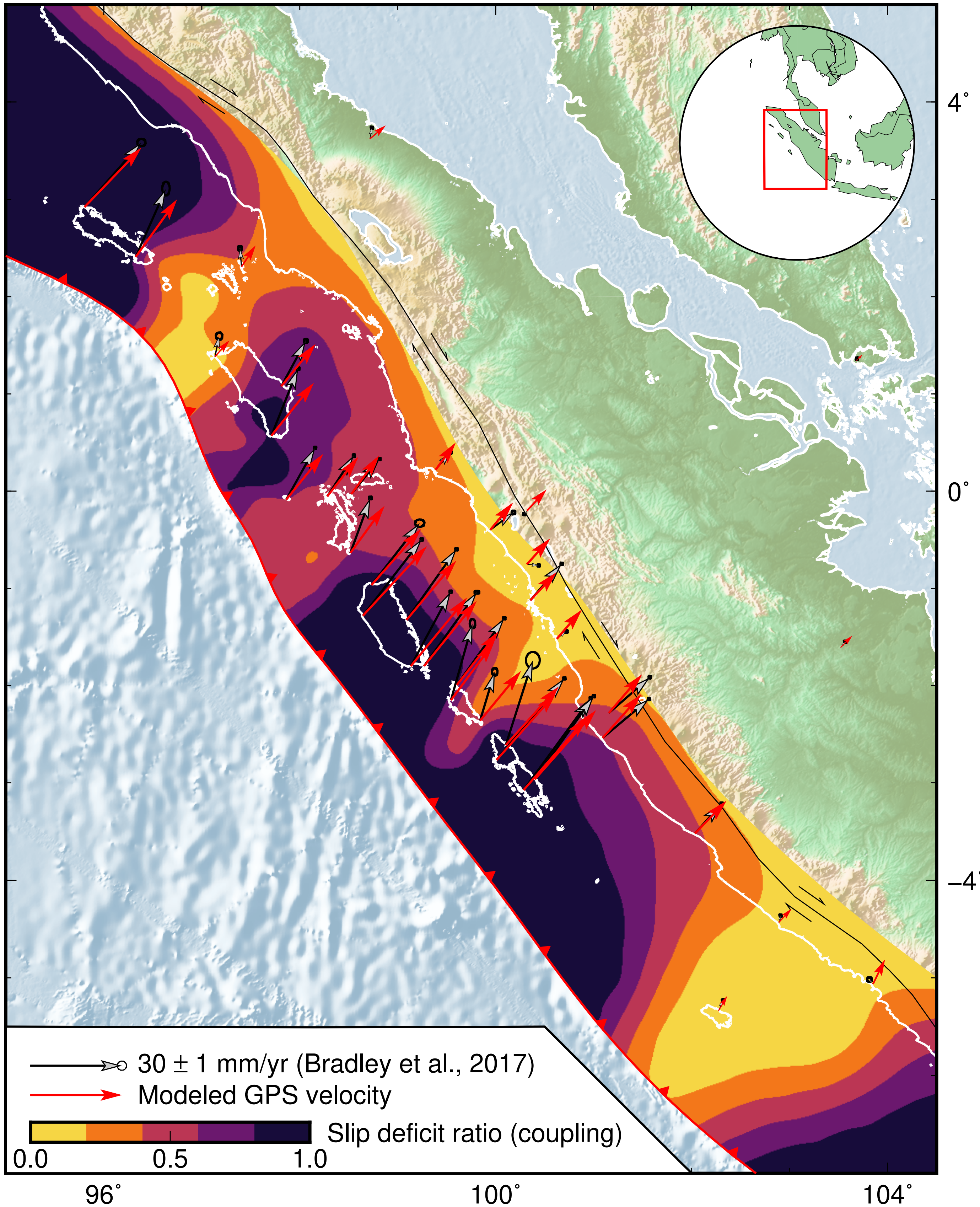


With stress constraints, norm minimization



It may be much higher than estimated using norm minimization.

No stress constraints, norm **maximization**



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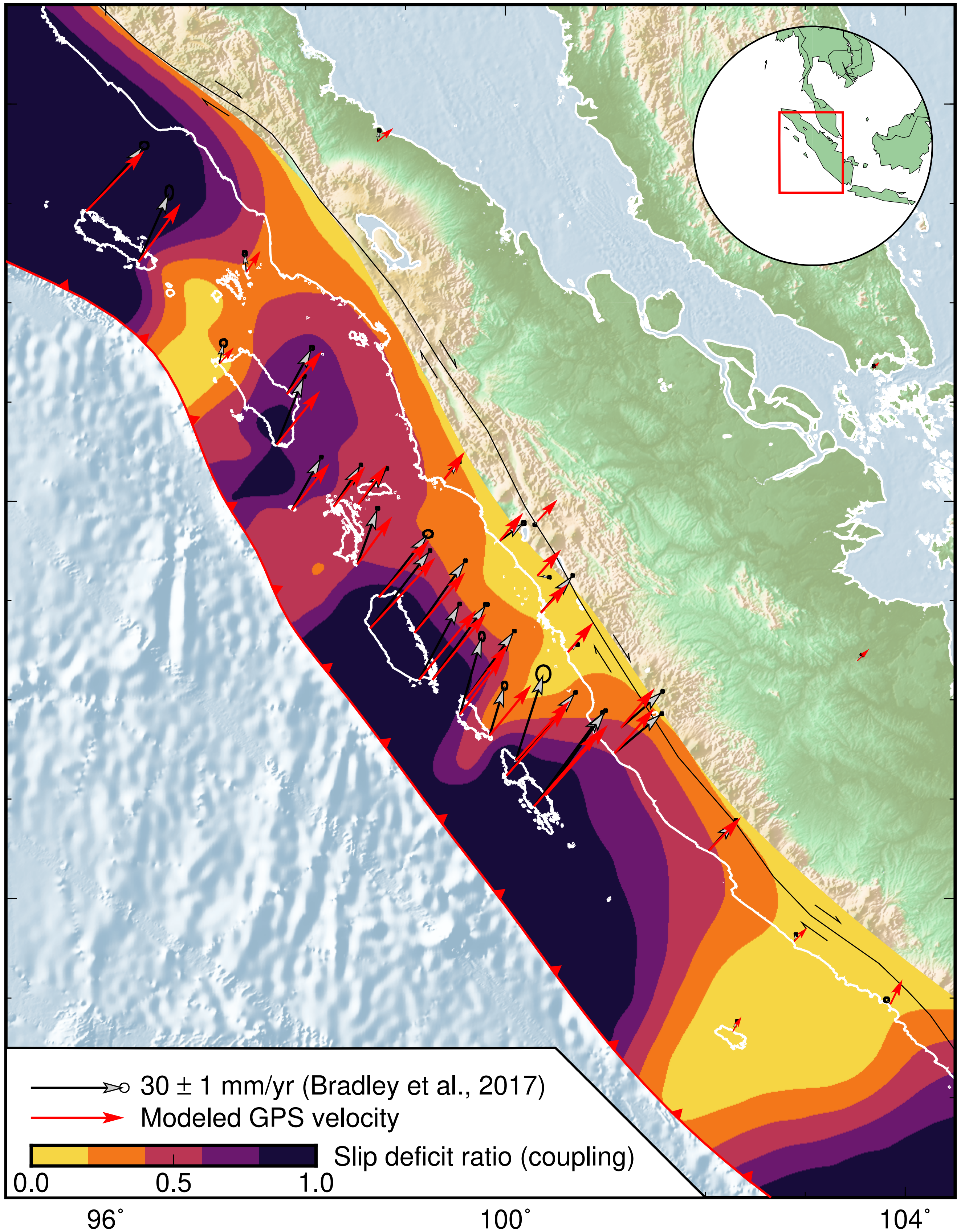
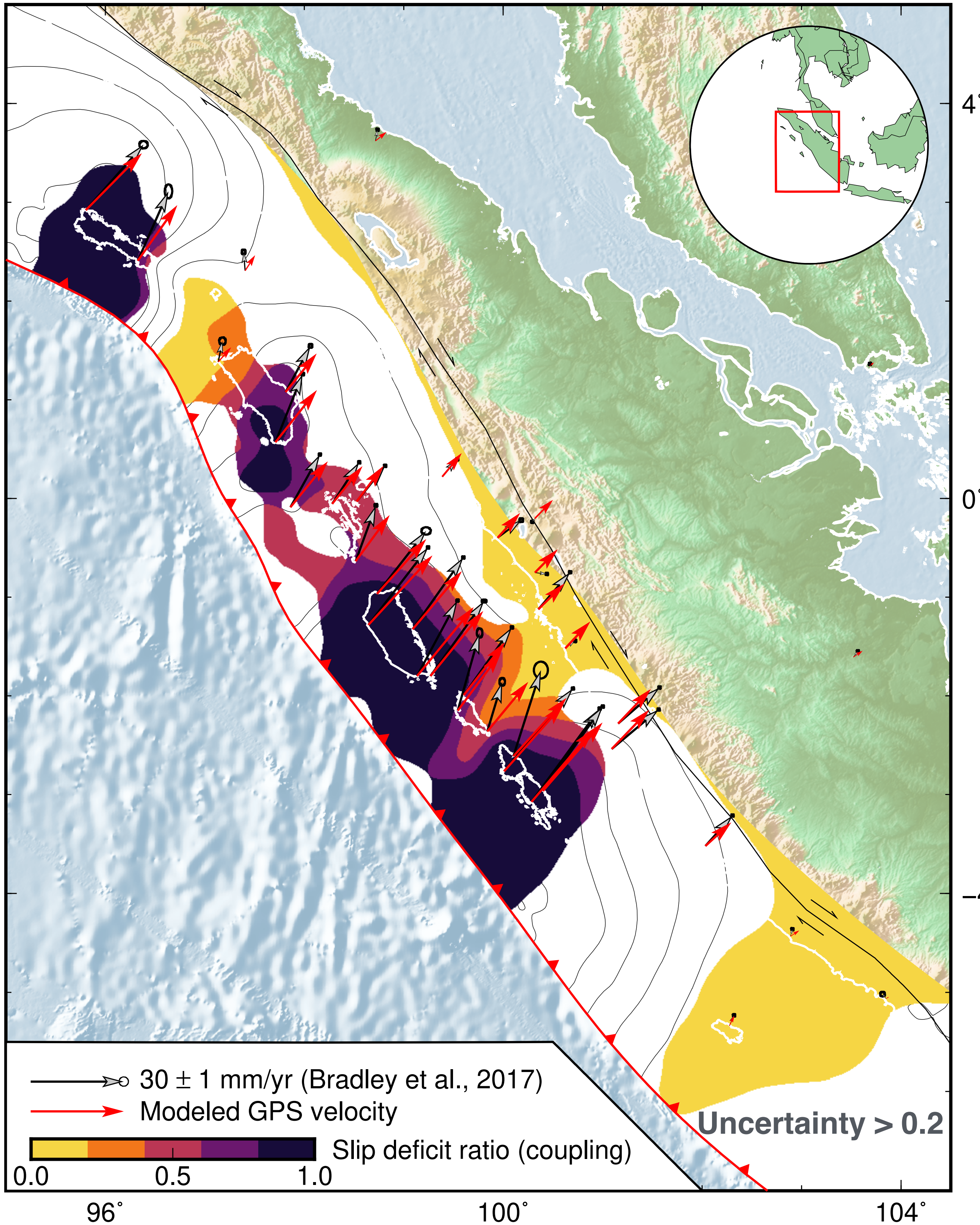


Stress constraints reduce our uncertainty on the possible slip deficit.

No stress constraints, no norm penalty



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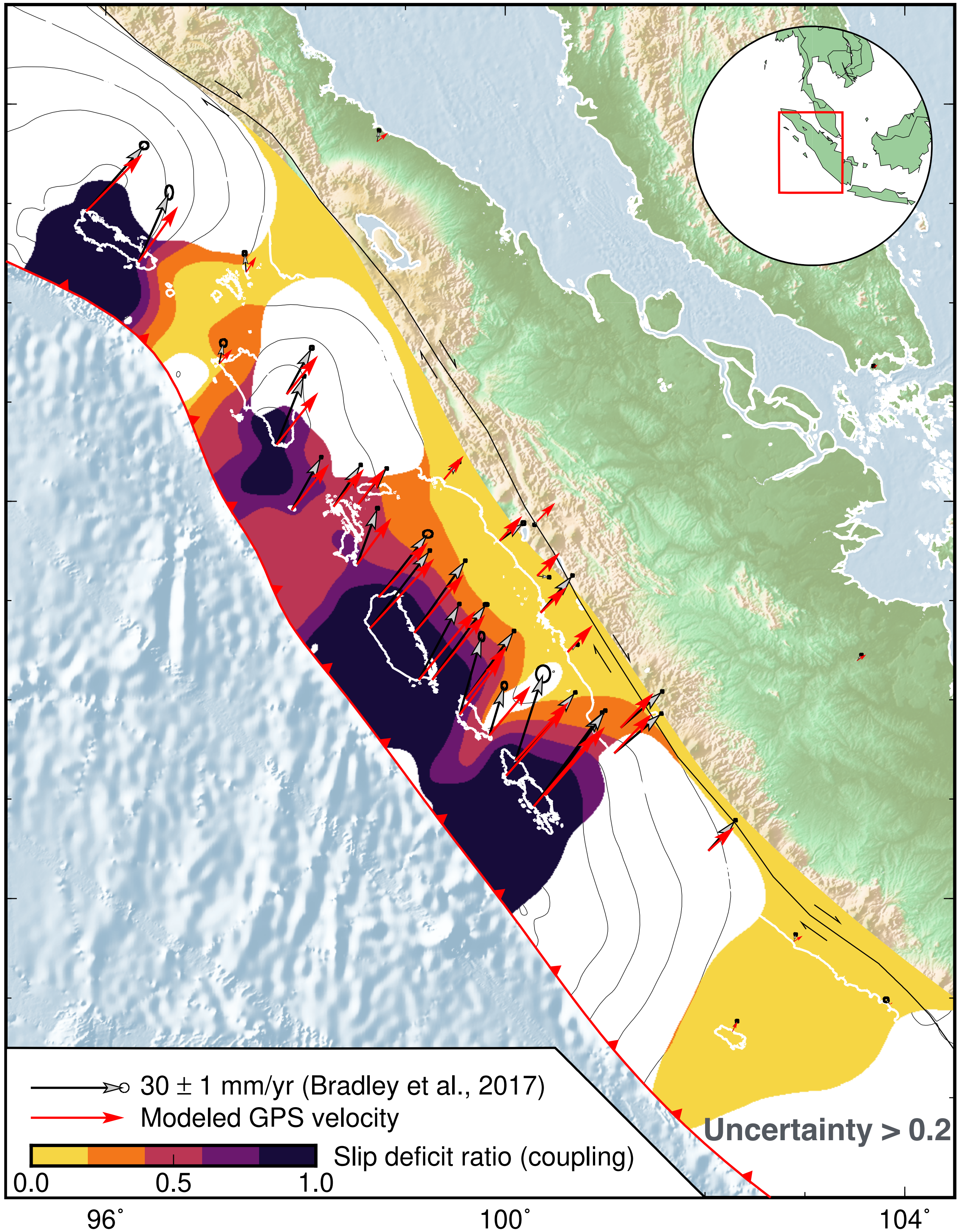
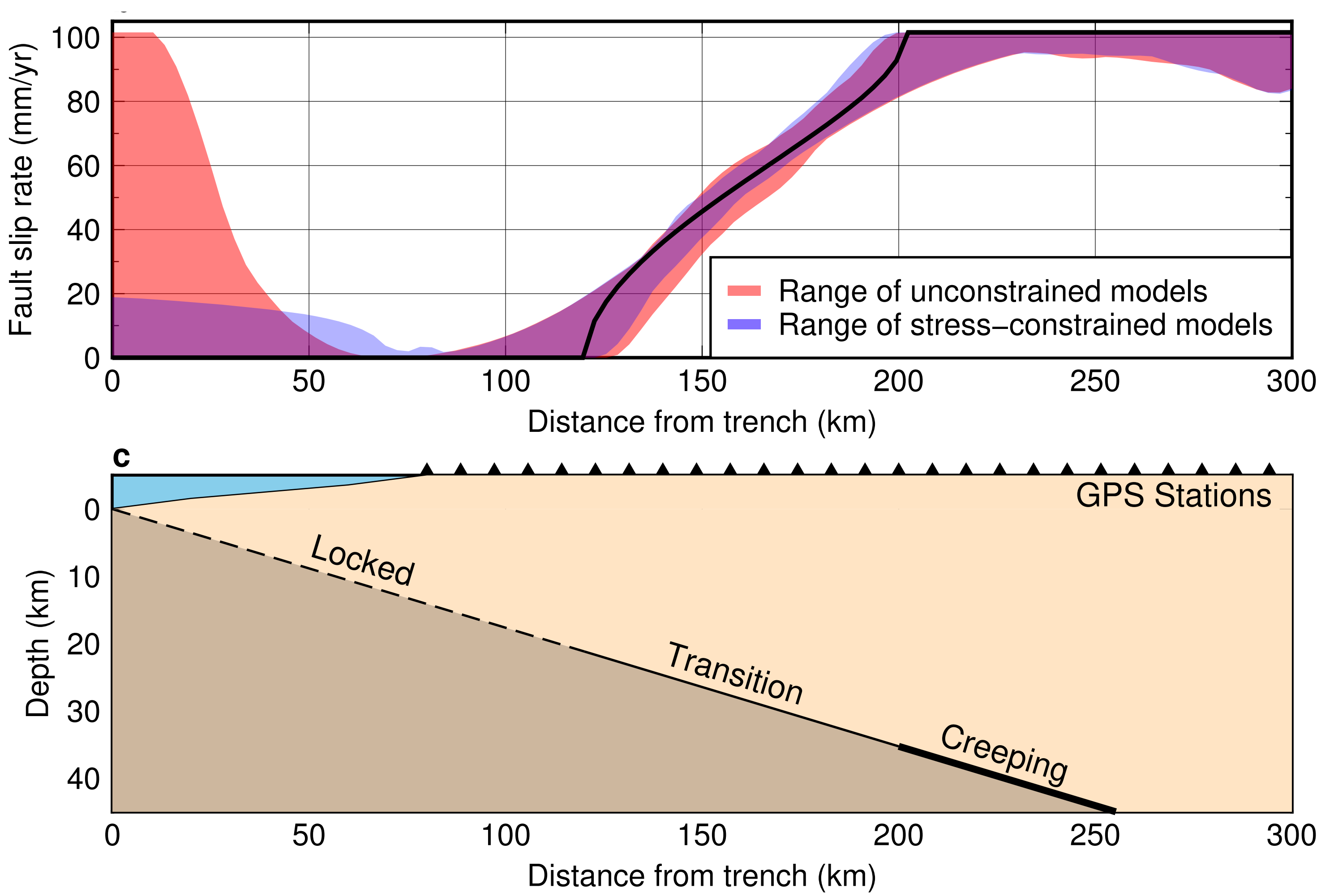


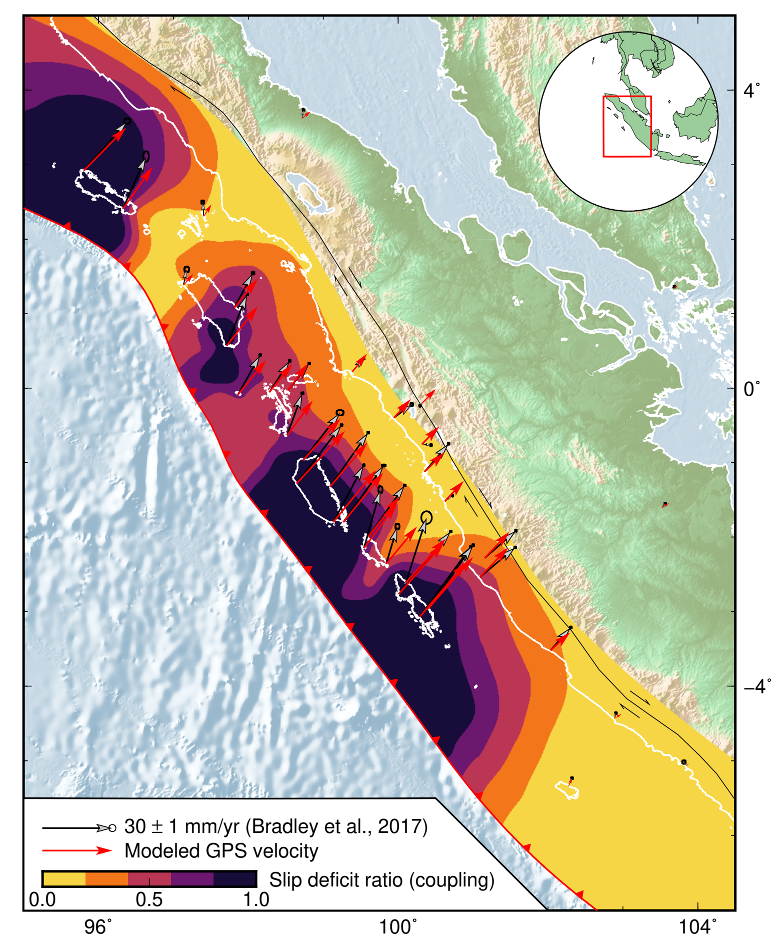
Conclusions

The shallow part of a megathrust above a locked zone has a **high slip rate deficit.**

We can incorporate this knowledge into our kinematic inversions in a simple way.

Results reduce show that the shallow megathrust has **more slip potential** than commonly assumed.





Thank you!
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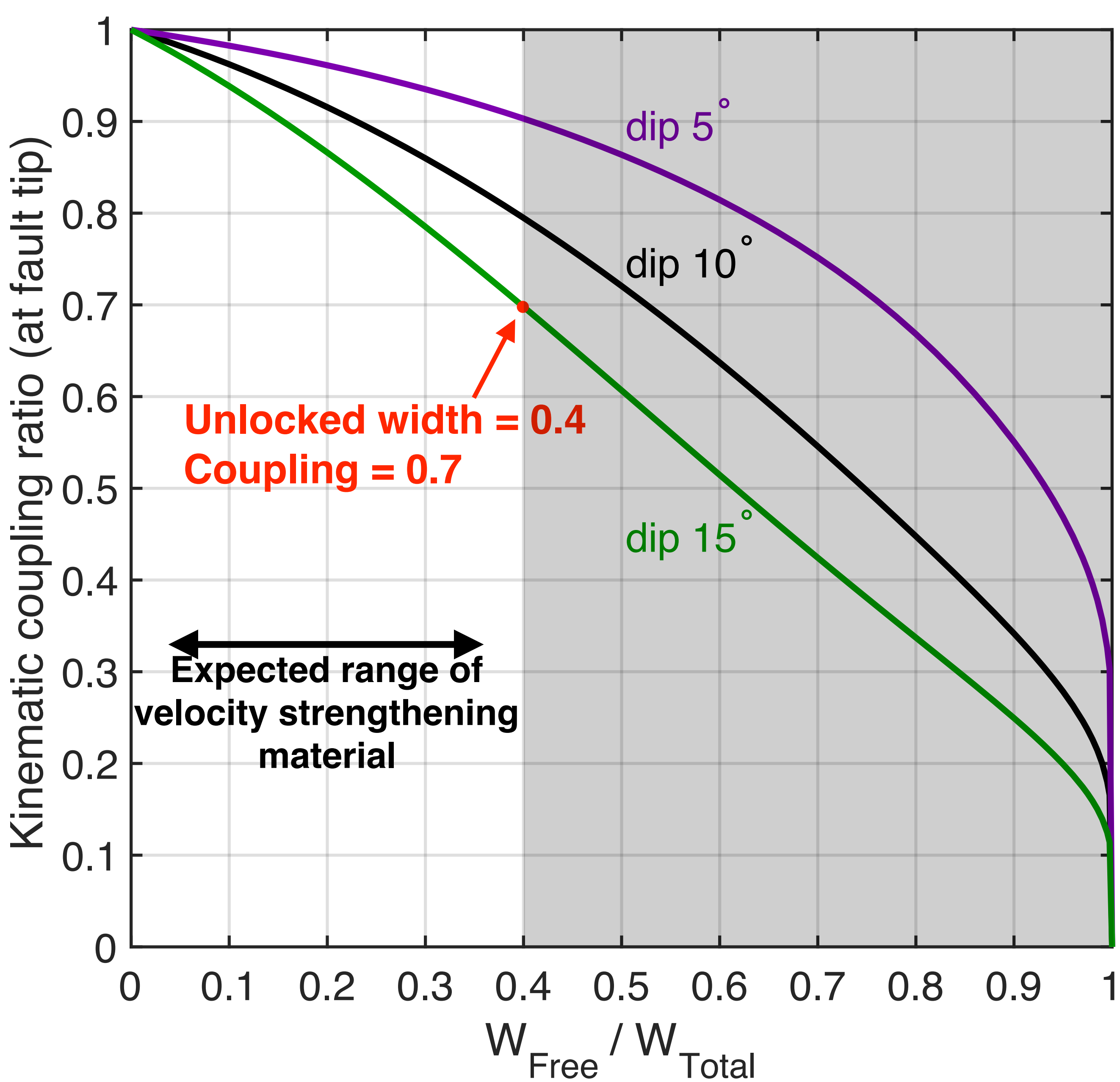
Moderate sensitivity to fault dip — due to the proximity of the free surface



Dip has the strongest influence on the shallow stress shadow.

Deep transition width does not affect the shallow coupling ratio

Effects not included:

- Fault curvature
- Elastic heterogeneity
- Shallow SSEs or time dependence
- Lateral variations in coupling

See discussion in:
Almeida et al. (2018), *GRL*

Why do we think the shallow fault is **uncoupled**?

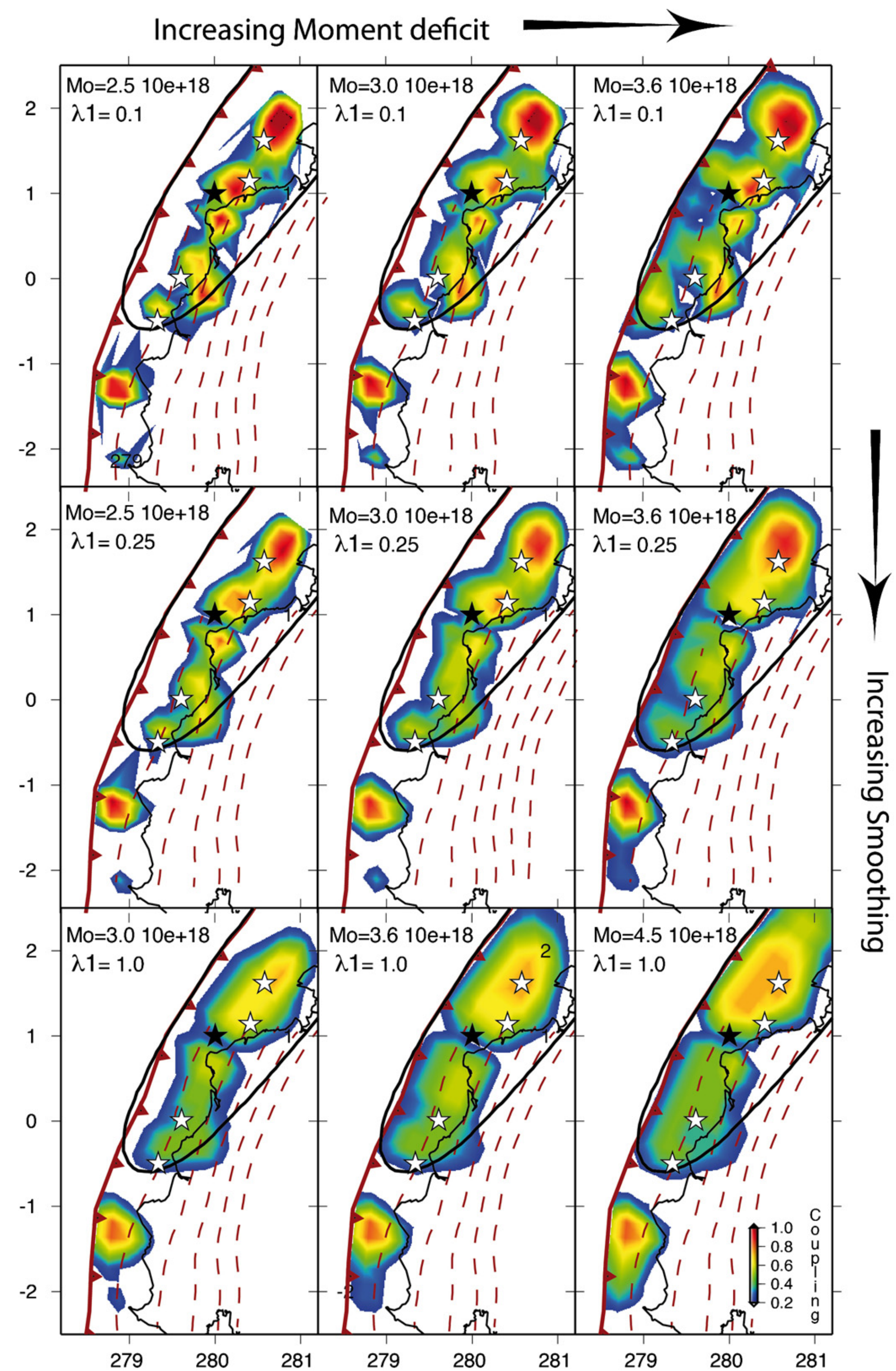
A penalty applied to the total moment deficit (e.g. Chlieh et al., 2014):

$$\text{Cost} = \text{wrms}^2 + \lambda 1\ \text{Dc}^2 + \lambda 2(\text{Mo} - M_d)^2 \quad (1)$$

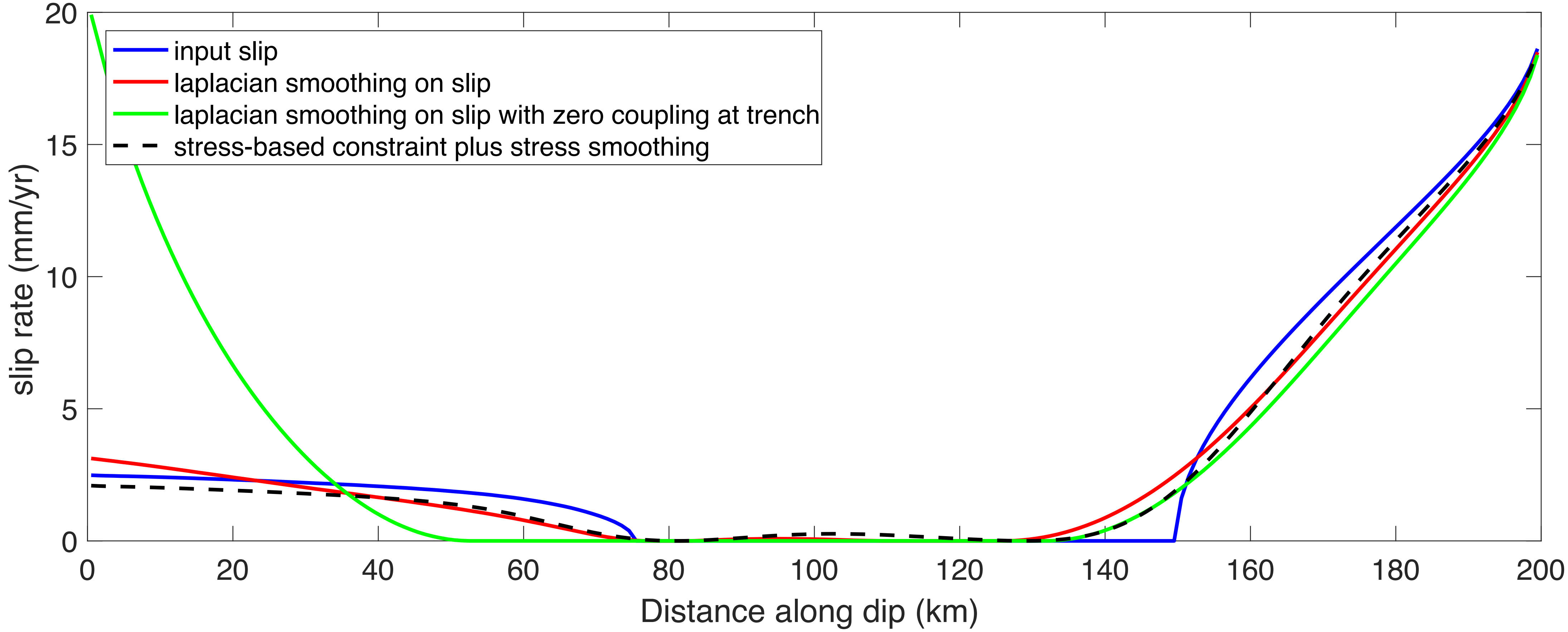
Note that zero coupling also means:

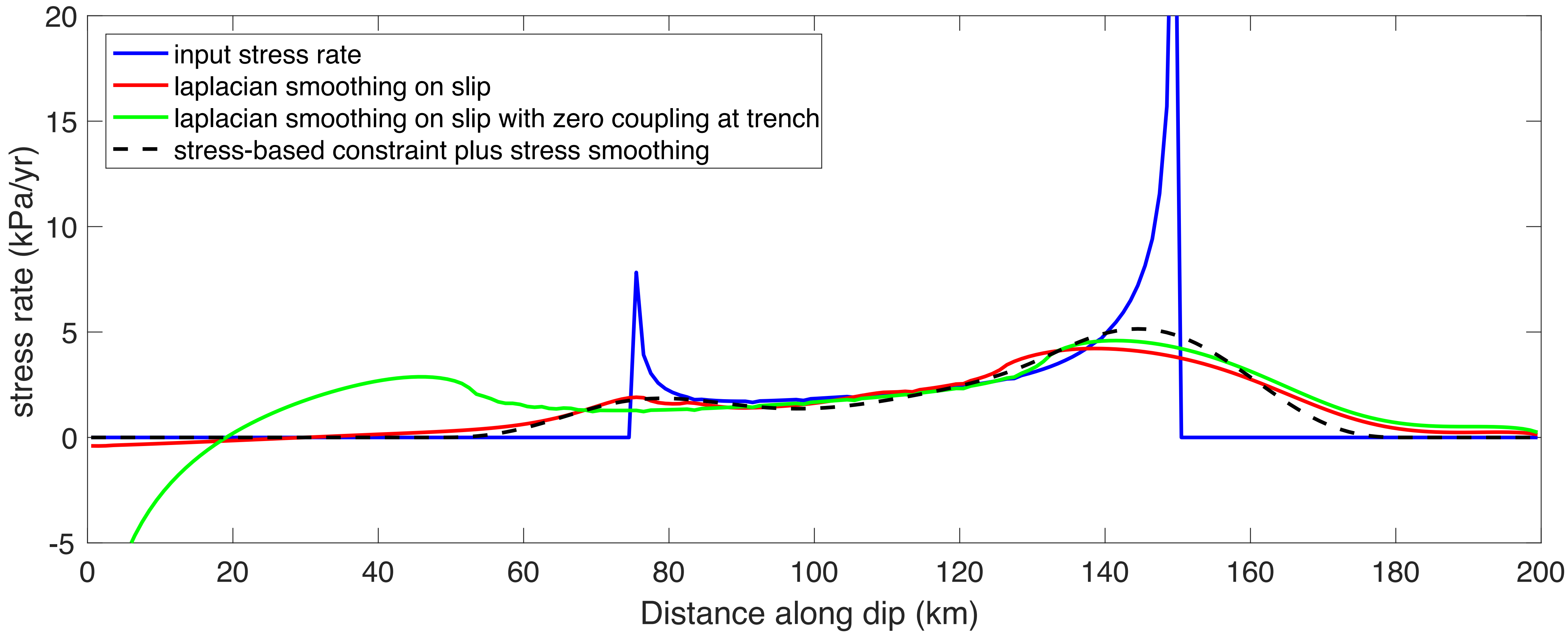
“creep at the full plate convergence rate.”

What stresses could drive this slip?



Chlieh et al., 2014


input slip
laplacian smoothing on slip
laplacian smoothing on slip with zero coupling at trench
stress-based constraint plus stress smoothing
slip rate (mm/yr)
Distance along dip (km)
0
5
10
15
20
0
20
40
60
80
100
120
140
160
180
200


input stress rate
laplacian smoothing on slip
laplacian smoothing on slip with zero coupling at trench
stress-based constraint plus stress smoothing
stress rate (kPa/yr)
Distance along dip (km)
-5
0
5
10
15
20
0
20
40
60
80
100
120
140
160
180
200