Constraining interseismic deformation processes in subduction zones through simple mechanical models

Matthew W. Herman[1], Kevin P. Furlong[1], Rob Govers[2]

[1]The Pennsylvania State University, [2]Utrecht University

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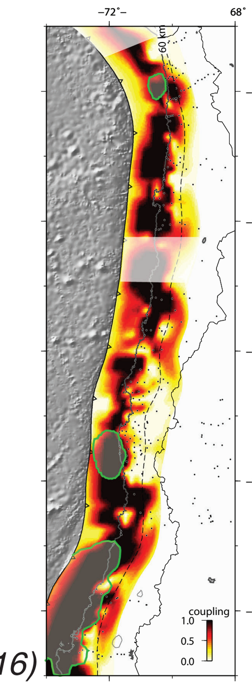
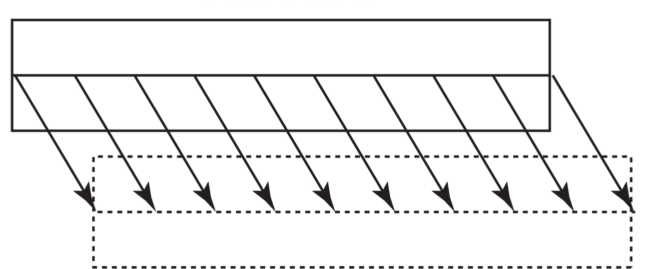
Introduction

In between earthquakes (the interseismic period), plates are frictionally locked at asperities. One way to model deformation around asperities is with dislocations embedded in an elastic half-space (e.g. Okada, 1992). In this framework, deformation generated by a slip deficit patch is represented with back-slip (opposite the direction of plate motion; Savage, 1983), and the rest of the system deforms as an unbroken elastic medium. This approach has led to misconceptions, such as:

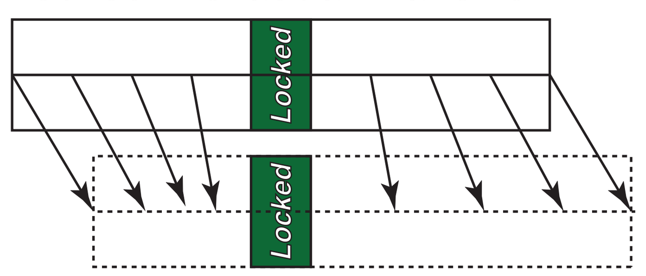
Locked regions accumulate full slip deficit, while unlocked regions accumulate zero slip deficit.

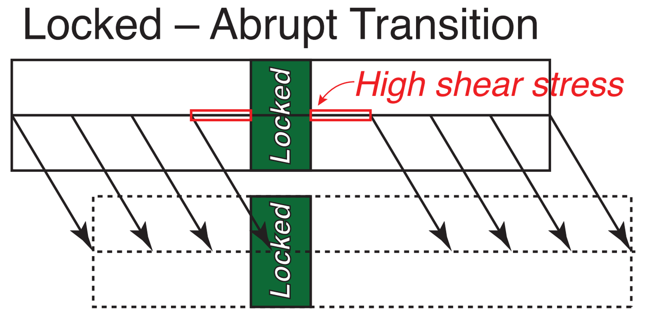


Metois et al. (2016)



Consider a schematic plate moving in the direction of the arrows. In a totally unlocked system, the plate moves uniformly without deforming.



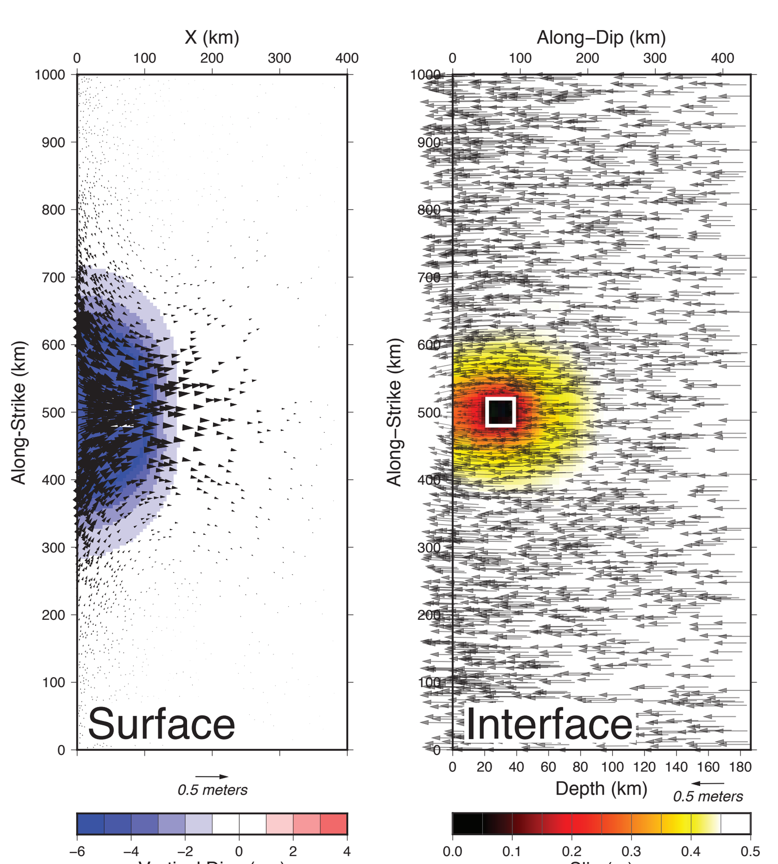


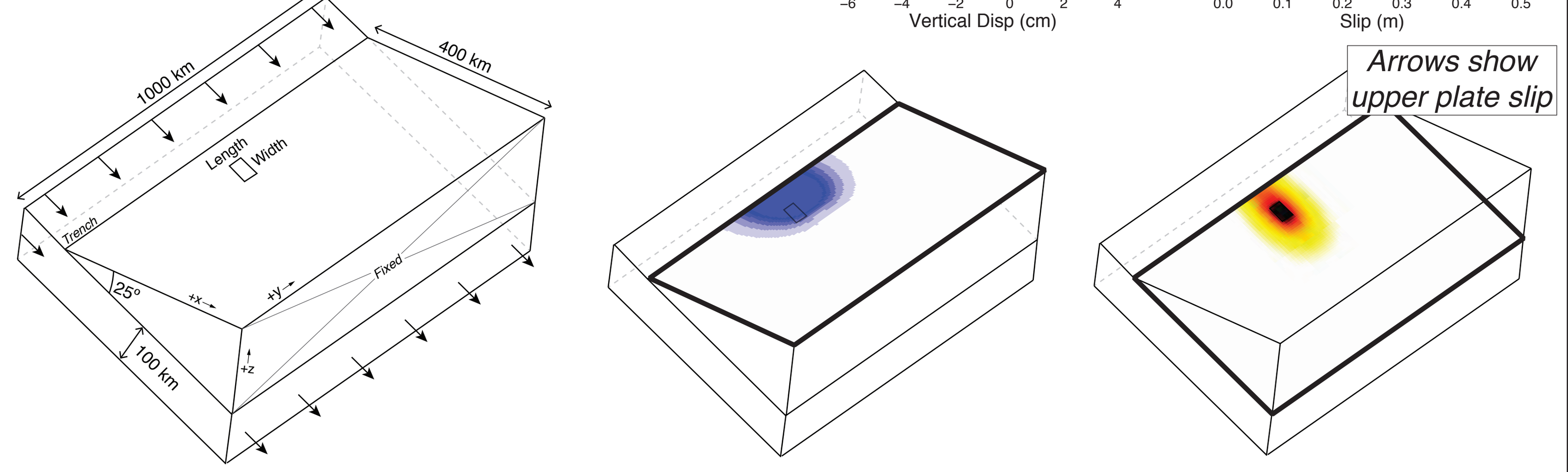
At a locked segment, the plate is restricted from moving. Outside the locked zone, the material deforms in response to the locking, so there is a transition zone over which slip goes from zero to plate rate.

If slip goes from zero inside the locked patch to the plate rate immediately outside, large stresses accumulate at the edge. However, the interface can slide in response to these stresses.

Model Setup

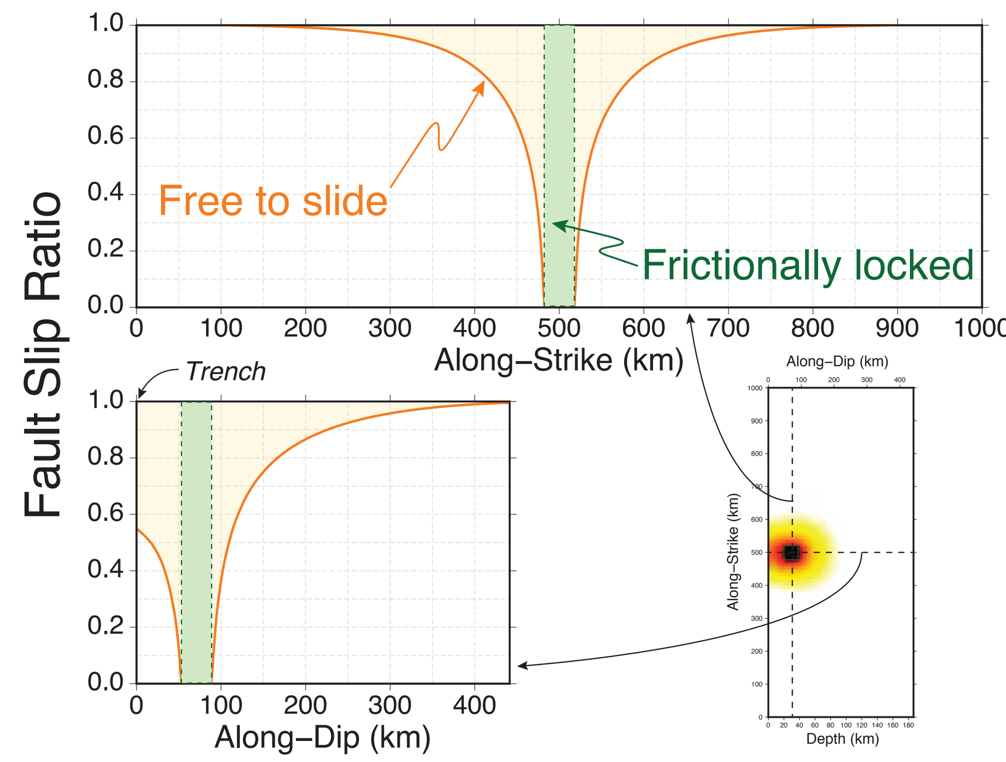
We use a 3-D finite element model of a subduction zone to explore how elastic strain accumulates around a locked asperity. Deformation is driven by relative motion: down-dip displacement is applied to both ends of the subducting plate and the back of the upper plate is held fixed. At rectangular asperities, the plates are locked together, while the rest of the plate interface is allowed to slide freely. The finite element approach allows us to apply these boundary conditions that are representative of the first-order frictional state of the megathrust.

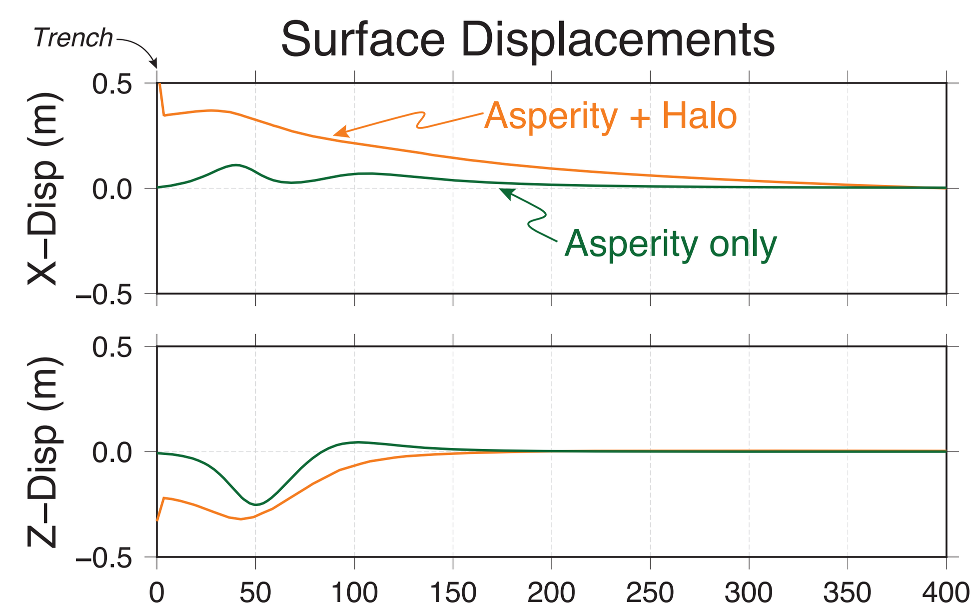




Single Fault Results

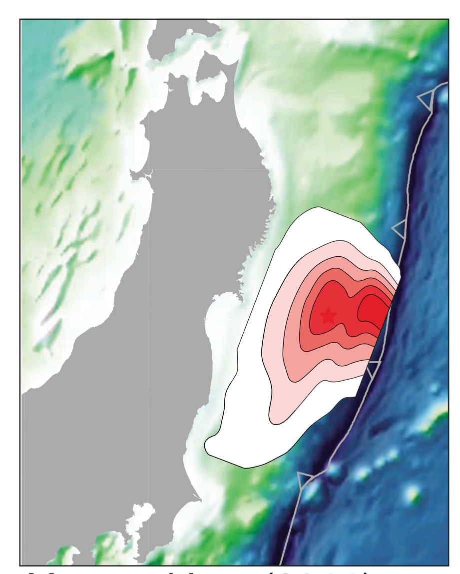
We take transects along the megathrust (dashed lines) and plot the fault slip along these paths. The frictionally locked zone (green) has zero slip by definition. The region outside the asperity is able to slide freely (orange), and as a result of the locking, slip is reduced near the asperity. With increasing distance from the asperity, fault slip recovers to the full plate motion rate. This appears as a "halo" of reduced slip surrounding the asperity.



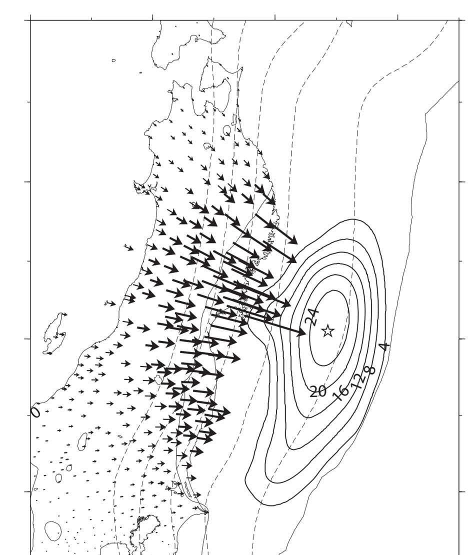


If we model only the effects of the asperity, the predicted deformation is incomplete (green). The halo of reduced slip also contributes to surface displacements (orange). An inversion of the full signal sees the halo as a zone of partial coupling. This coupling is due to proximity to the asperity, rather than being indicative of frictional characteristics at that point.

A consequence of this increased area of slip deficit is that the eventual earthquake rupture can be larger than expected based on the asperity alone (perhaps like Tohoku?). The total moment deficit is 2-3x greater than the deficit within the locked zone. This is critical up-dip of the locked patch; although this area may not be frictionally locked, slip deficit near the trench may approach full plate motion if adjacent to a shallow asperity.



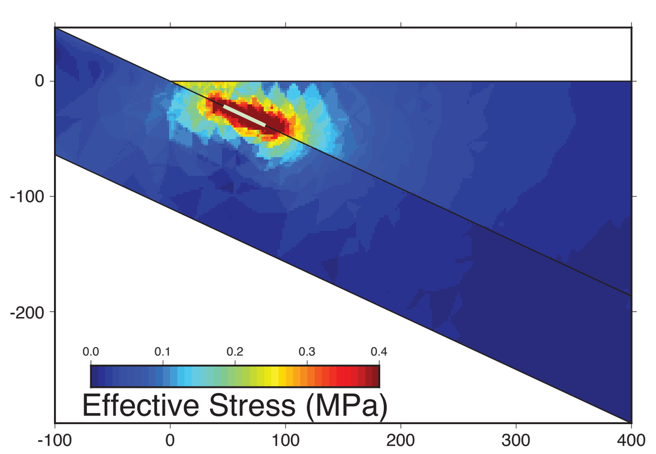
Yue and Lay (2011)



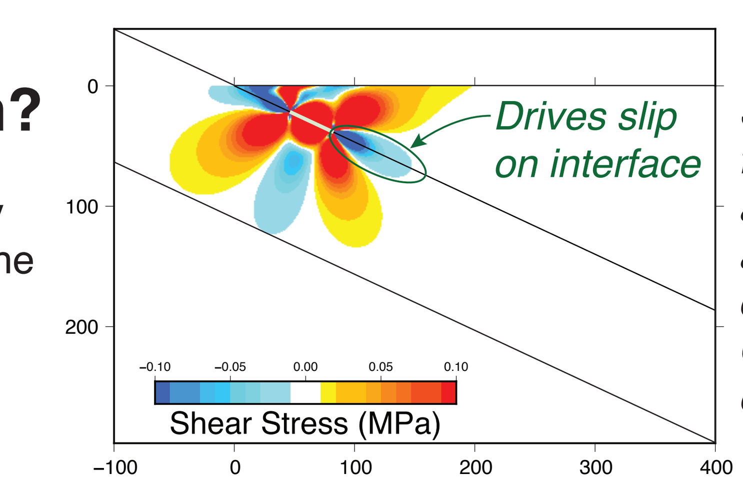
Ozawa et al. (2012)

Stresses - What controls the observed deformation?

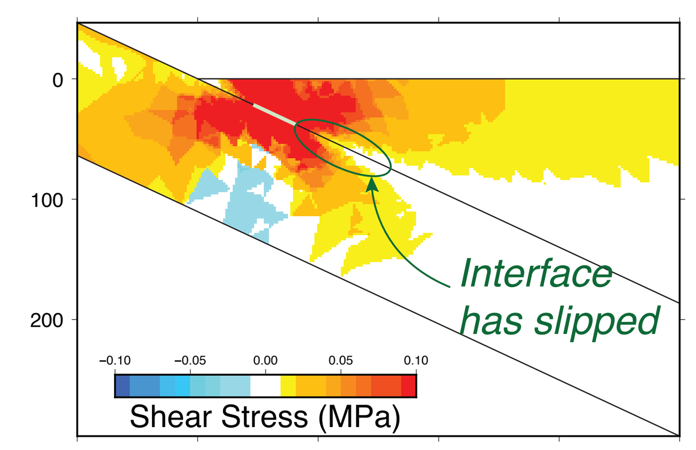
Resistance to plate motion at the asperity causes shear stress to increase around the locked patch. This drives slip on the adjacent freely sliding region, which we model as a plane of zero shear stress resolved on it.



Effective stress is a measure of the amplitude of the stress tensor



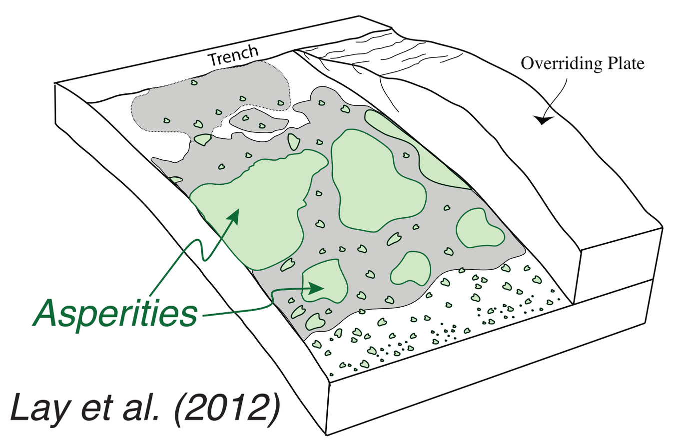
Shear stress from back-slip on a locked fault in a half-space, computed using Okada (1992) equations



Modeled shear stress after freely sliding interface has slipped to resolve on shear stress

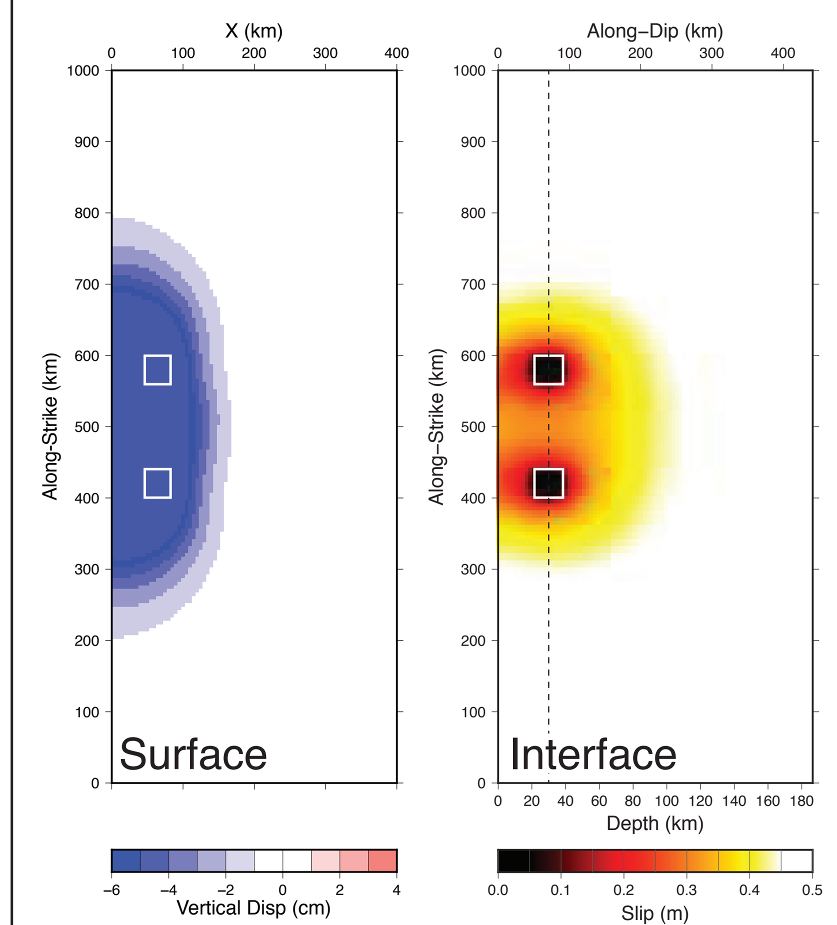
Multiple Asperity Interactions

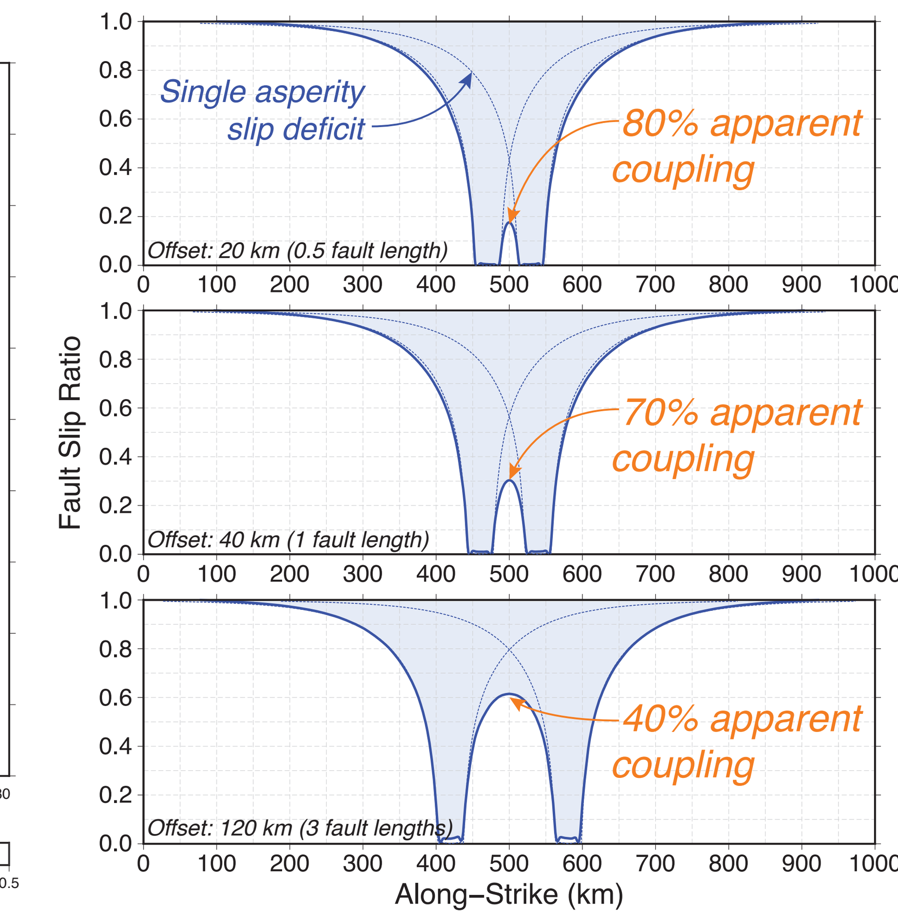
Current models of the subduction interface have numerous asperities within the seismogenic zone (depths of 10-50 km). This interpretation is based on the distribution of seismicity on the plate boundary and seismological analyses of large megathrust earthquakes. If these asperities are close enough, their slip reduction halos will overlap.

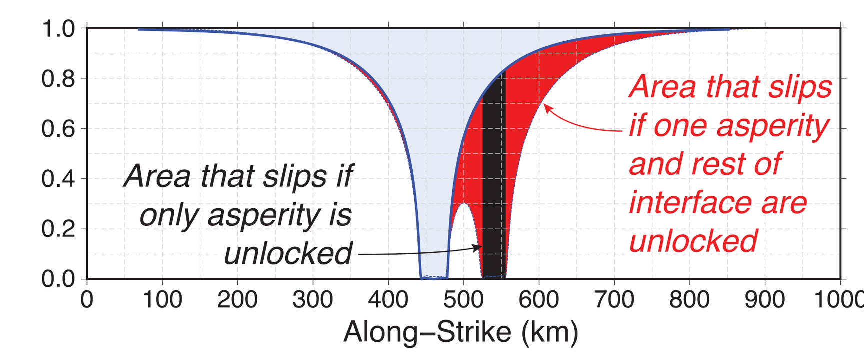


Lay et al. (2012)

First, we consider two equal-size asperities at the same depth on the megathrust, separated along strike (the y-direction).



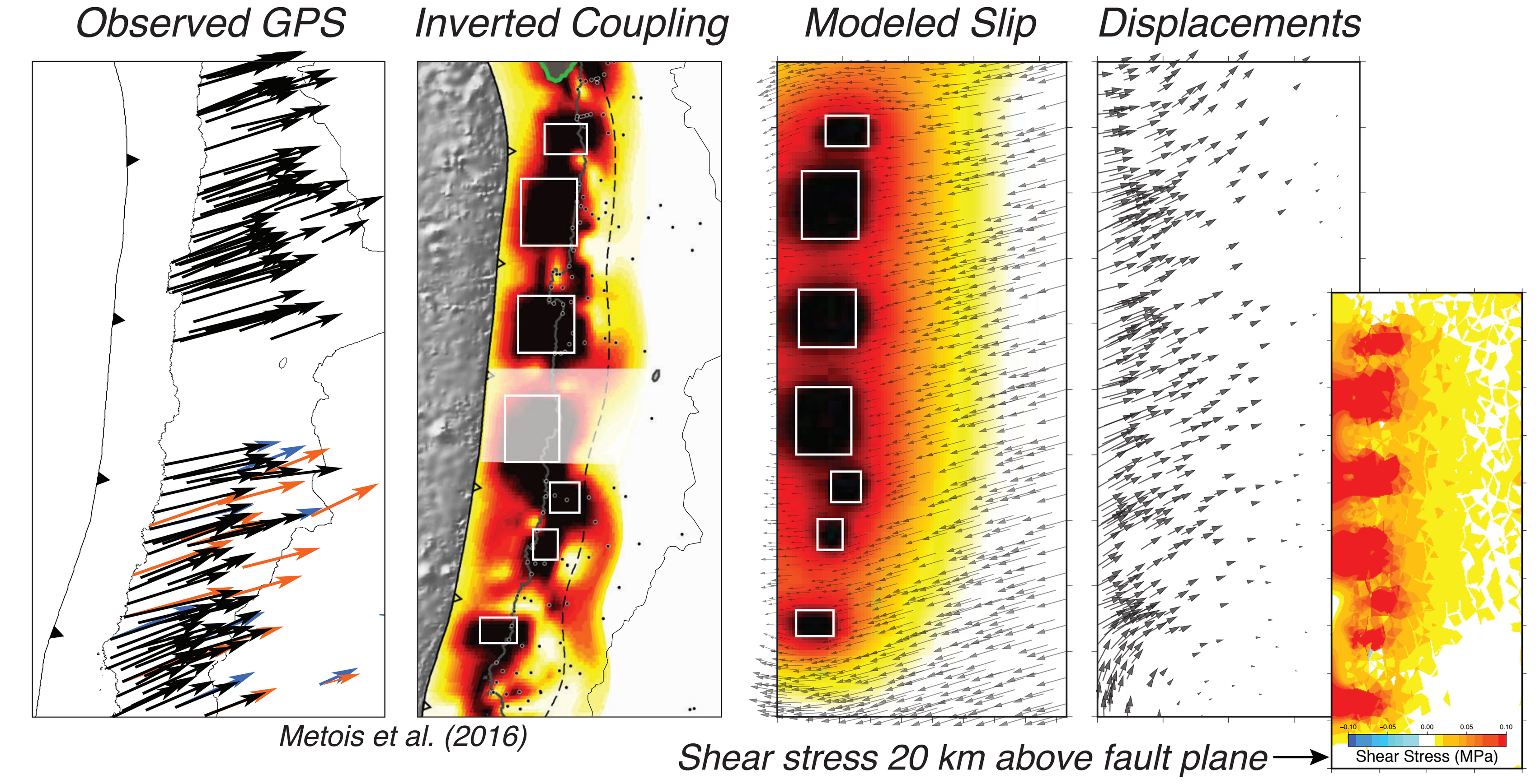




If an earthquake ruptures one asperity only the excess slip deficit can contribute to the event, while the rest of the boundary is held in place by the other locked area.

Summary

Interpretations of interseismic coupling should consider how locked asperities affect the slip in the adjacent frictionally weak regions. The common interpretation of full slip deficit within asperities and zero slip deficit outside is physically unreasonable. Instead, a halo of apparent partial coupling should surround asperities. To first order, this halo effect around smaller asperities can explain much of the observed coupling patterns (e.g. in the subduction zone offshore Chile).



Metois et al. (2016)

Shear stress 20 km above fault plane

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