Resolving locked asperities and slip deficit in unlocked regions: A new inversion method applied in the South America subduction zone

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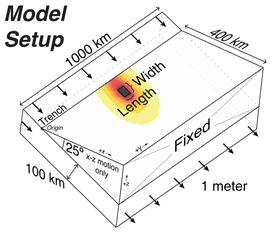
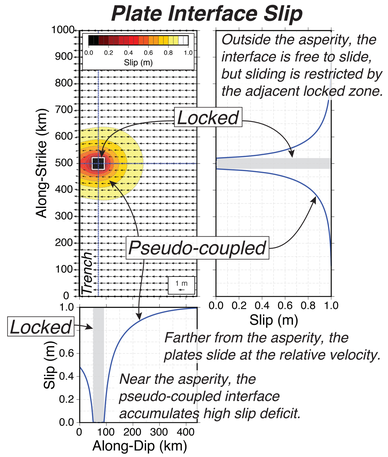
Pseudo-coupling Model

The continuous nature of tectonic plates implies that inter-seismic slip deficit must be continuous on the plate boundary. As a result, areas outside mechanically locked asperities can accumulate slip deficit even in the absence of shear resistance. We call this “pseudo-coupling” to distinguish it from mechanical coupling. Previously, we quantified its effect conceptually (Herman et al., 2018).



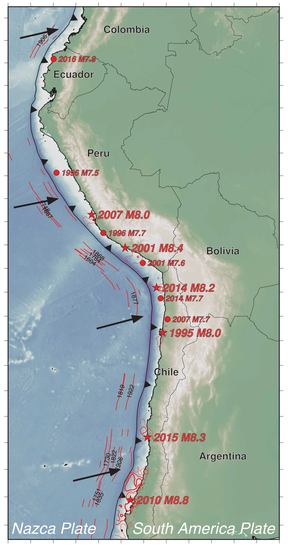
We displace the top and bottom of the subducting plate 1 meter while holding the backstop of the upper plate fixed. No slip is allowed in locked asperities, but the rest of the interface is unlocked and can thus slide freely.



In this study, we incorporate the physics of pseudo-coupling into an inter-seismic inversion so that we can determine:

Where and how much of the subduction plate interface is locked?
What is the corresponding slip deficit accumulation rate?

South America Subduction Zone



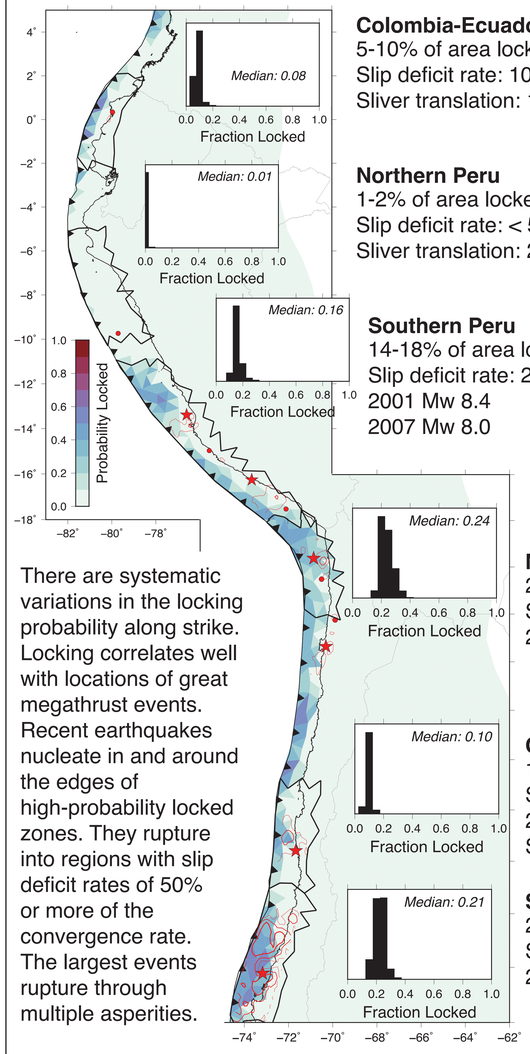
Seismotectonics

The oceanic Nazca plate subducts eastward beneath the continental South America plate from Chile to Colombia. This subduction zone has hosted 12 Mw 7.5+ earthquakes in the past 25 years (red symbols indicate these earthquake epicenters and red lines show 2, 5, and 10 meter slip contours). There is also a centuries-long historical record of great earthquakes (Kelleher, 1972) (rupture extents of these events are indicated by red bars west of the trench; Mw 8.0+ events are labeled with their dates).

Geodetic Observations

The upper plate is densely instrumented by continuous and campaign GNSS stations measuring surface motions. We use the inter-seismic velocity field (measured before the Mw 7.5+ earthquakes) as the constraints on the plate interface locking distribution. We also test how much of the velocities can be explained by forearc sliver motions.

Locking Probability



There are systematic variations in the locking probability along strike. Locking correlates well with locations of great megathrust events. Recent earthquakes nucleate in and around the edges of high-probability locked zones. They rupture into regions with slip deficit rates of 50% or more of the convergence rate. The largest events rupture through multiple asperities.

Colombia-Ecuador
5-10% of area locked
Slip deficit rate: 10-60 mm/yr
Sliver translation: 1-2 mm/yr

Northern Peru
1-2% of area locked
Slip deficit rate: < 5 mm/yr
Sliver translation: 2-3 mm/yr

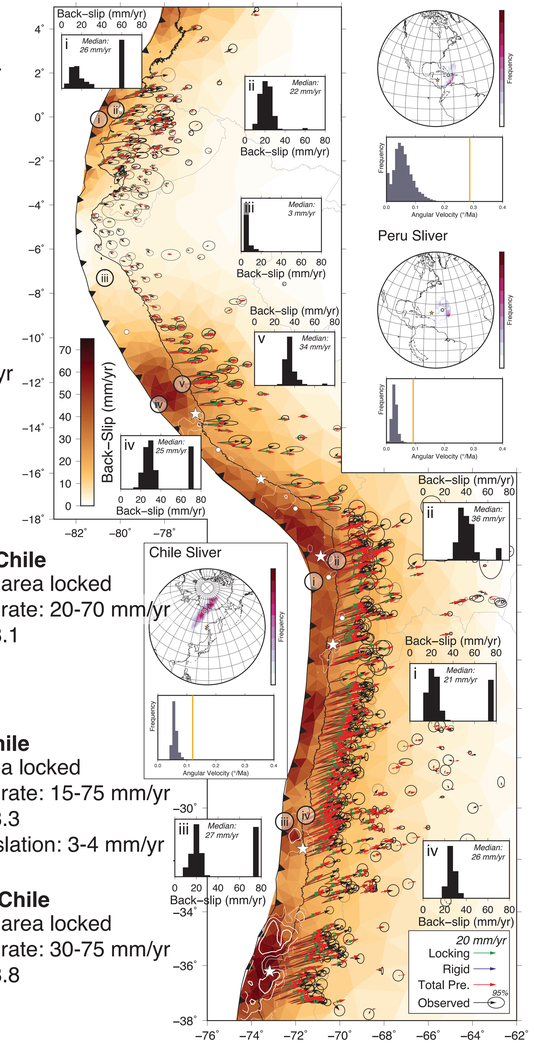
Southern Peru
14-18% of area locked
Slip deficit rate: 25-70 mm/yr
2001 Mw 8.4
2007 Mw 8.0

Northern Chile
20-30% of area locked
Slip deficit rate: 20-70 mm/yr
2014 Mw 8.1

Central Chile
10% of area locked
Slip deficit rate: 15-75 mm/yr
2015 Mw 8.3
Sliver translation: 3-4 mm/yr

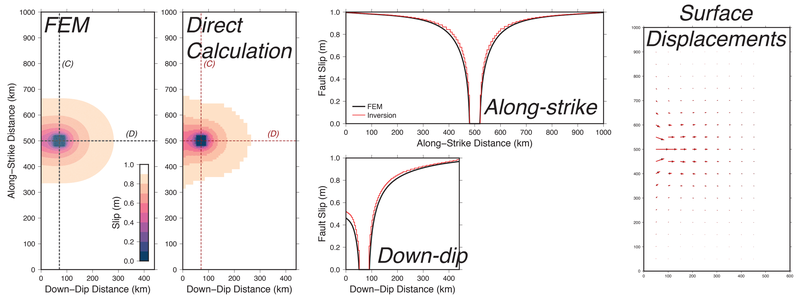
Southern Chile
20-30% of area locked
Slip deficit rate: 30-75 mm/yr
2010 Mw 8.8

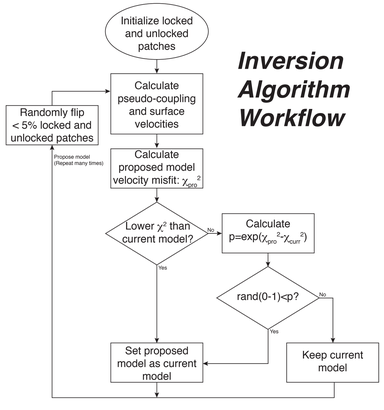
Slip Deficit Rate



Inversion Approach

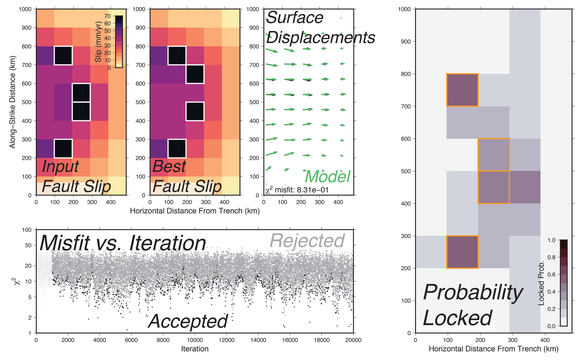
We search for distributions of locked and unlocked patches that produce good fits to inter-seismic surface velocities. Since there are potentially many good fitting solutions, we implement an algorithm (Metropolis-Hastings) to determine the probability that each patch is locked. Key to this approach is that the fault slip distribution and corresponding velocities are based on the physics of pseudo-coupling in every iteration of the search.





Inversion Algorithm Workflow

Proof of Concept

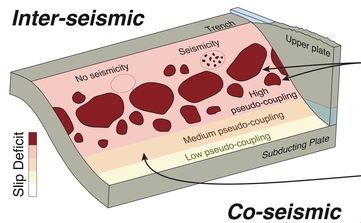


The search involves running 10,000+ models. Each requires calculating the slip distribution and computing the misfit with respect to the observed velocities. To accelerate the search, we use an analytical solution for directly minimizing the shear stresses to calculate slip around locked patches instead of an FEM . This produces similar fault slip and horizontal surface motions as the FEM. Biases associated with vertical displacements preclude their use in this model.

Conclusions

- Maximum of 30% of plate interface area is locked
- Earthquakes initiate inside or near edges of high probability locked zones
- Mw 8+ earthquakes occur in regions with at least 10% of fault area locked
- Large earthquakes may propagate outside of high-probability locked zones into regions with slip deficit rate ≥ 25-50% of convergence rate
- Slip deficit rate near trench is ≥ 25% of convergence rate
- Forearc sliver motion ~1/2 that of previous studies

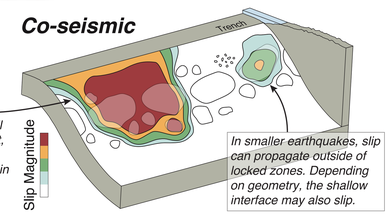
Inter-seismic



Fully locked asperities accumulate slip deficit at the convergence rate. Earthquakes begin in and around these regions.

Outside asperities, the interface appears partially coupled over a large area, accumulating slip deficit at a significant rate.

Co-seismic



Large, multi-asperity ruptures release the full accumulated slip deficit, allowing other pseudo-coupled regions to slip in concert with the seismogenic zone.

In smaller earthquakes, slip can propagate outside of locked zones. Depending on geometry, the shallow interface may also slip.