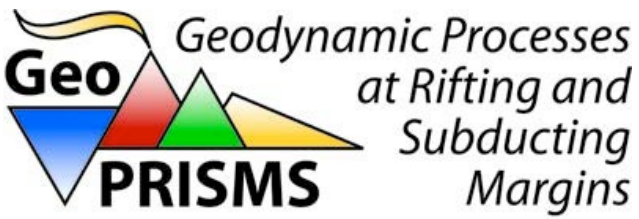
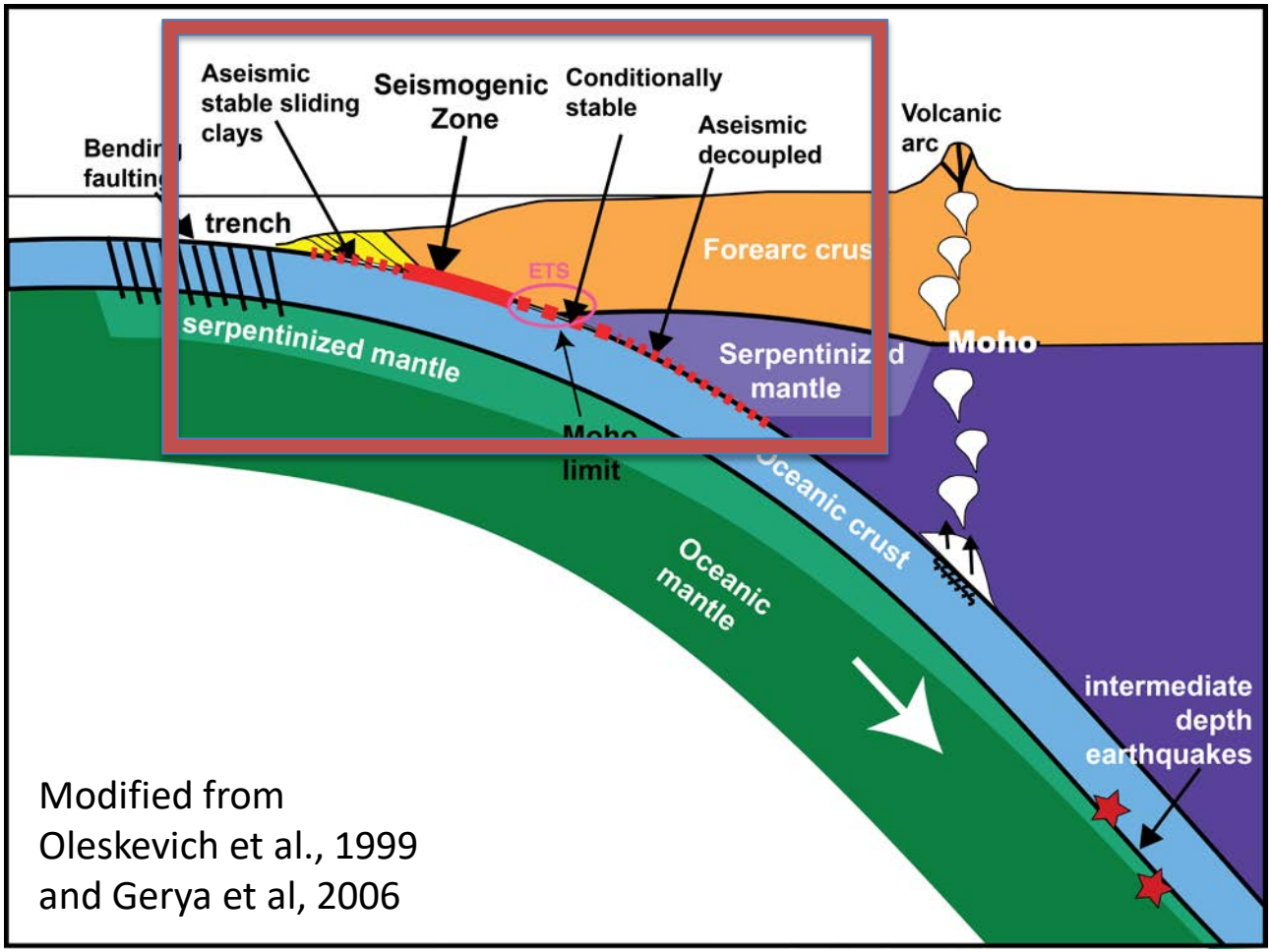


How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?

Jeff Freymueller

MICHIGAN STATE UNIVERSITY

Deformation in the Subduction Plate Boundary

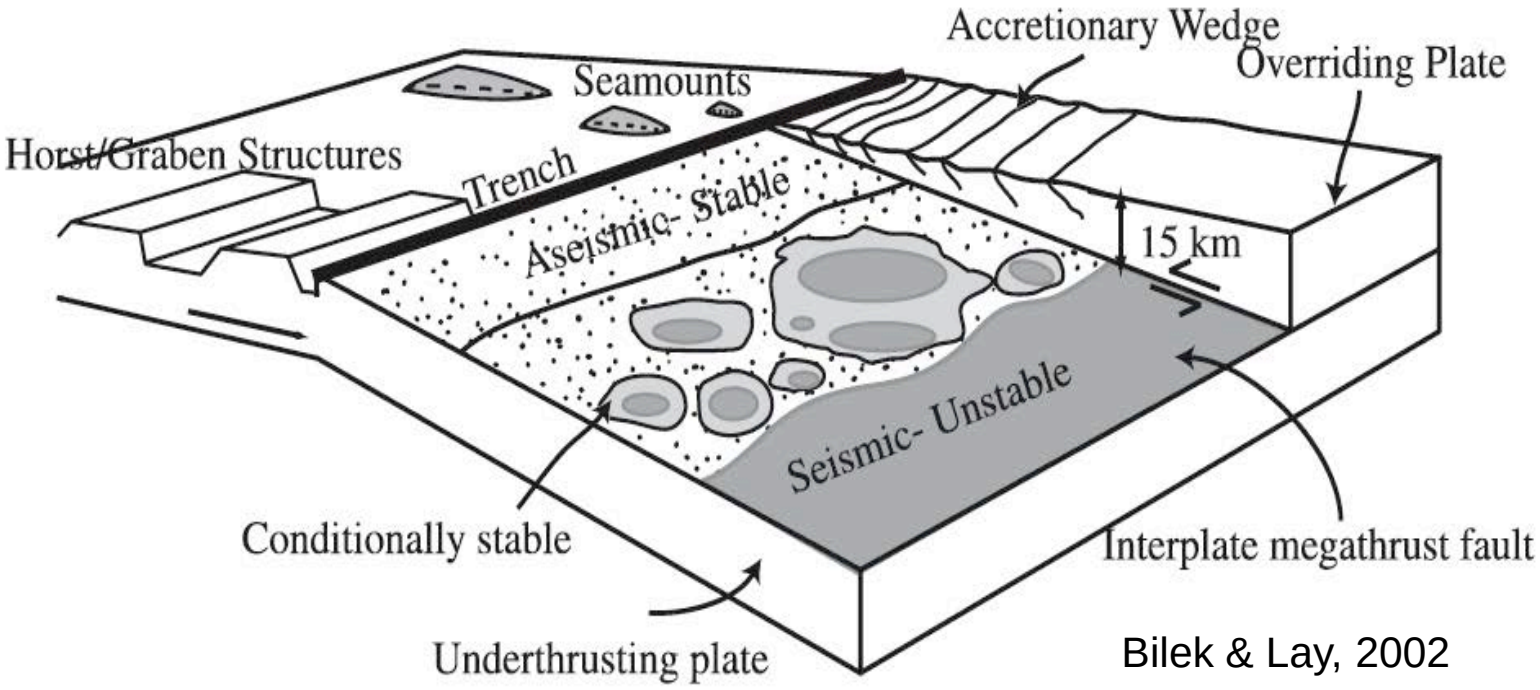


- Study of the Seismogenic zone is about both ***seismic*** and ***aseismic*** slip behavior
- Slip budget and controls on modes of slip

SCD Key Questions

- What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?
- How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?
- What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?

The Seismogenic Zone



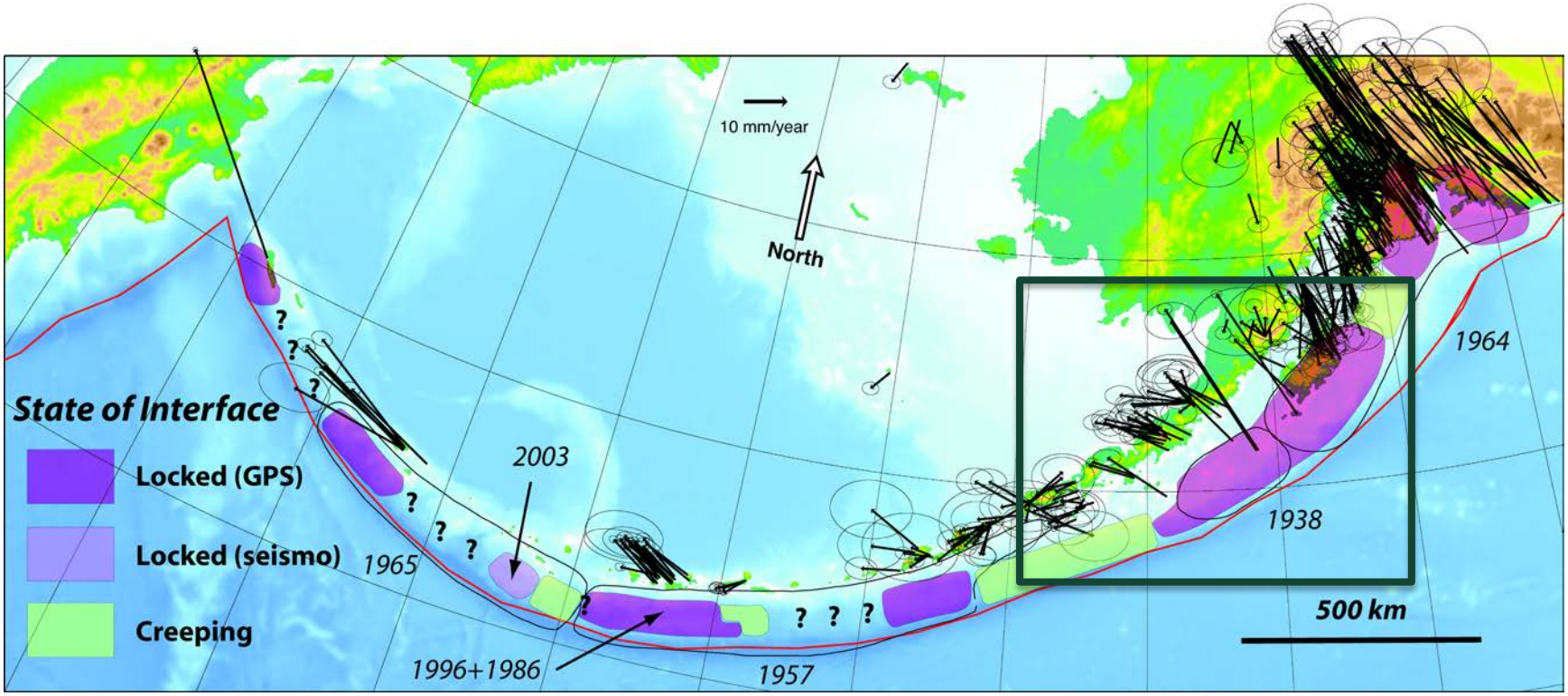
Bilek & Lay, 2002

- Where do/can large earthquakes occur?
- How does this system evolve over time?

Complexity of Subduction Zone Slip

- Along-strike variations
  - Extent of slip deficit varies along strike: how, why?
    - ***Slip deficit*** is the difference between long-term slip rate and the slip that is occurring steadily.
- Slow slip events and transient slip
  - Do we understand where slow slip events can occur?
    - Yes: at the edges of patches that are frictionally locked
  - How long can slow slip events last?
    - At least a decade!
- Common theme: slip along interface varies with space and time – ***not just interseismic + coseismic in cross section.***

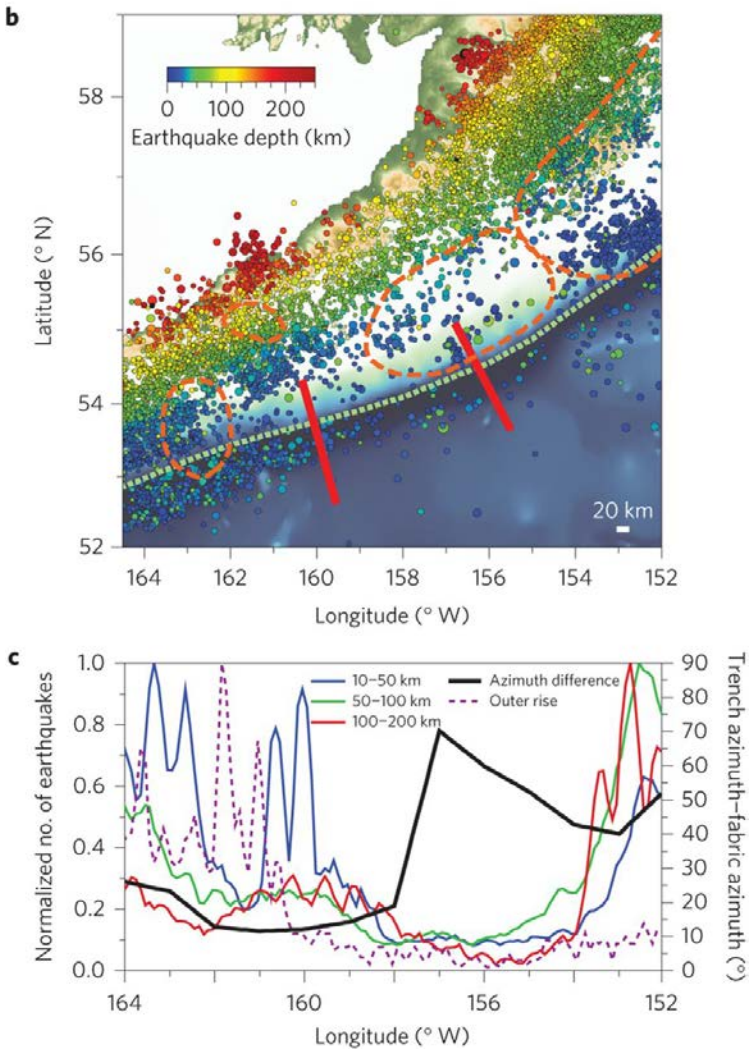
Along-Strike Variations: Alaska Peninsula



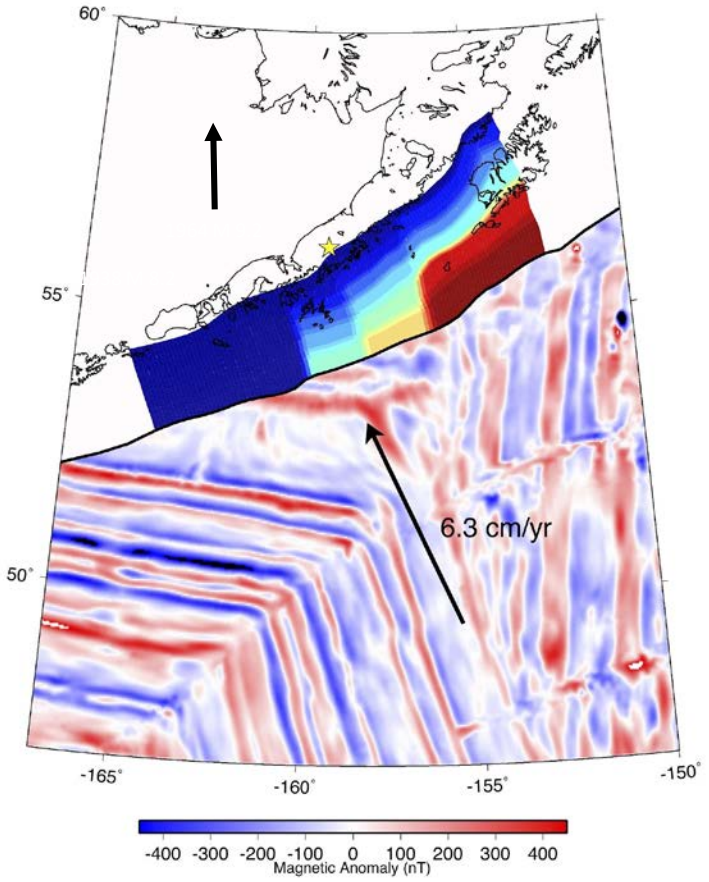
Freymueller et al. (2008)

Along-Strike Variations

Shillington et al (2015)



Li and Freymueller (2018)



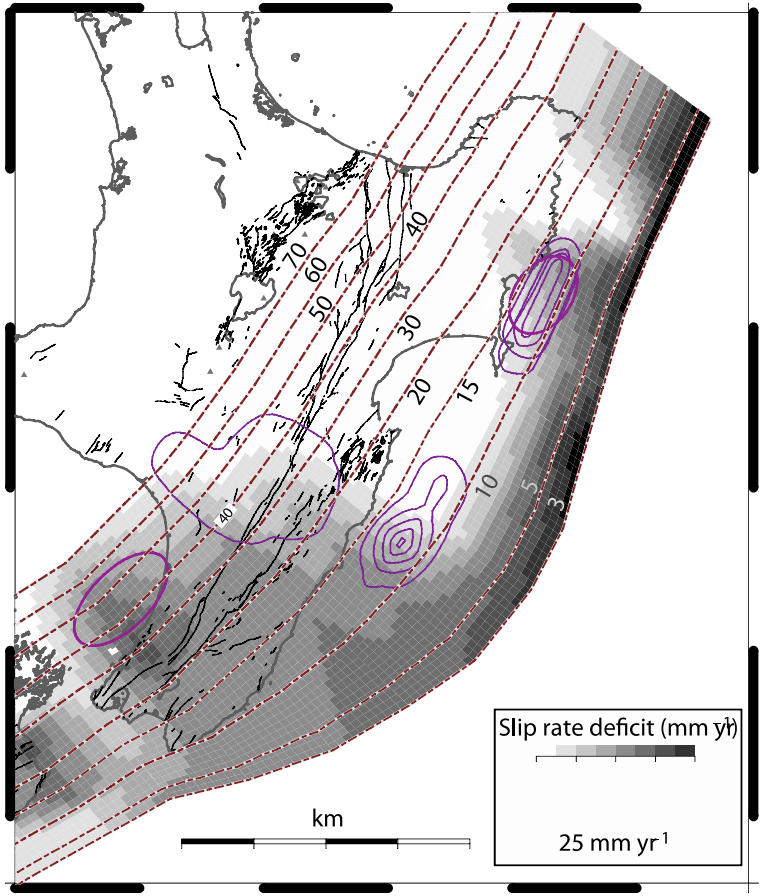
There are along-strike variations in:

- Fabric orientations in the downgoing Pacific Plate
- Slip deficit in shallow seismogenic zone
- Seismicity at a range of depths

Along-Strike Variations

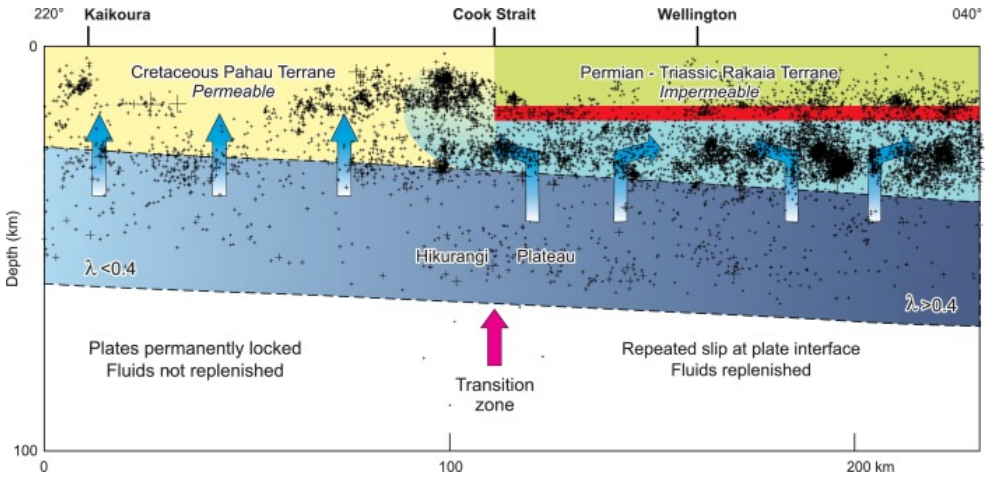
- Alaska Peninsula: Position of changes in slip deficit, earthquake distribution strongly correlated with a change in the fabric of the downgoing plate
  - Resulting from intensity of bending faulting and thus hydration, roughness of incoming plate
  - Changes in New Zealand suggest that hydration, fluids may be a generally controlling factor
- Does this apply to other locations?

Hikurangi: Along-Strike Variations may be Controlled by Fluids



McCaffrey et al. (2008)

- Strong along-strike variations in slip deficit
- Upper plate geology and stress state may control the flow of fluids and thus fluid pressures at interface
  - Low pore fluid pressure on interface == LOCKED



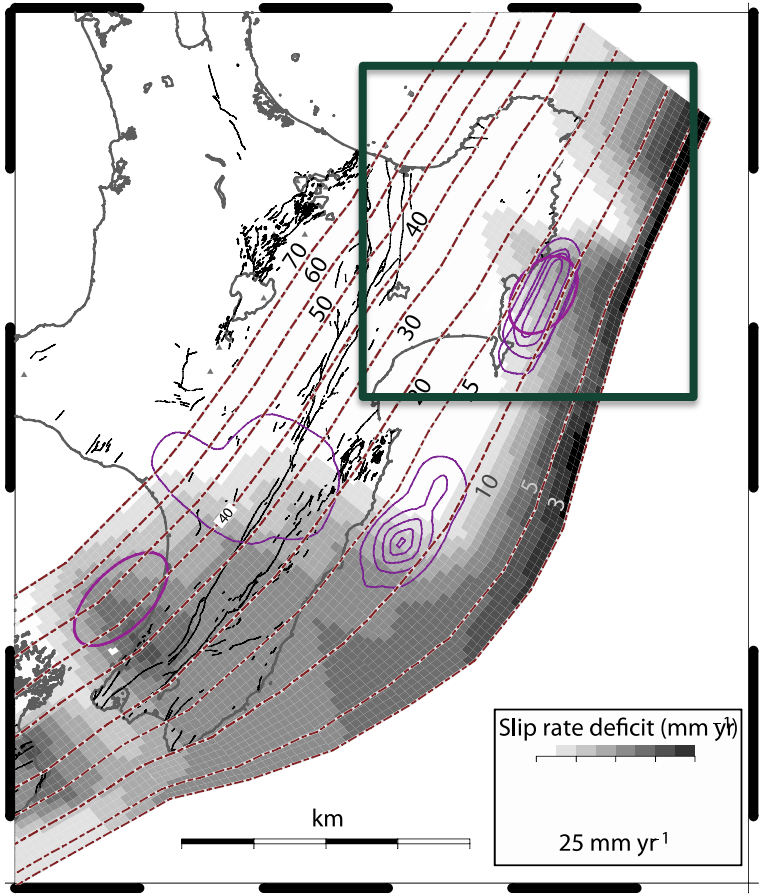
Wallace et al. (2012)
Reyners et al. (2017)

Slow and Aseismic Slip

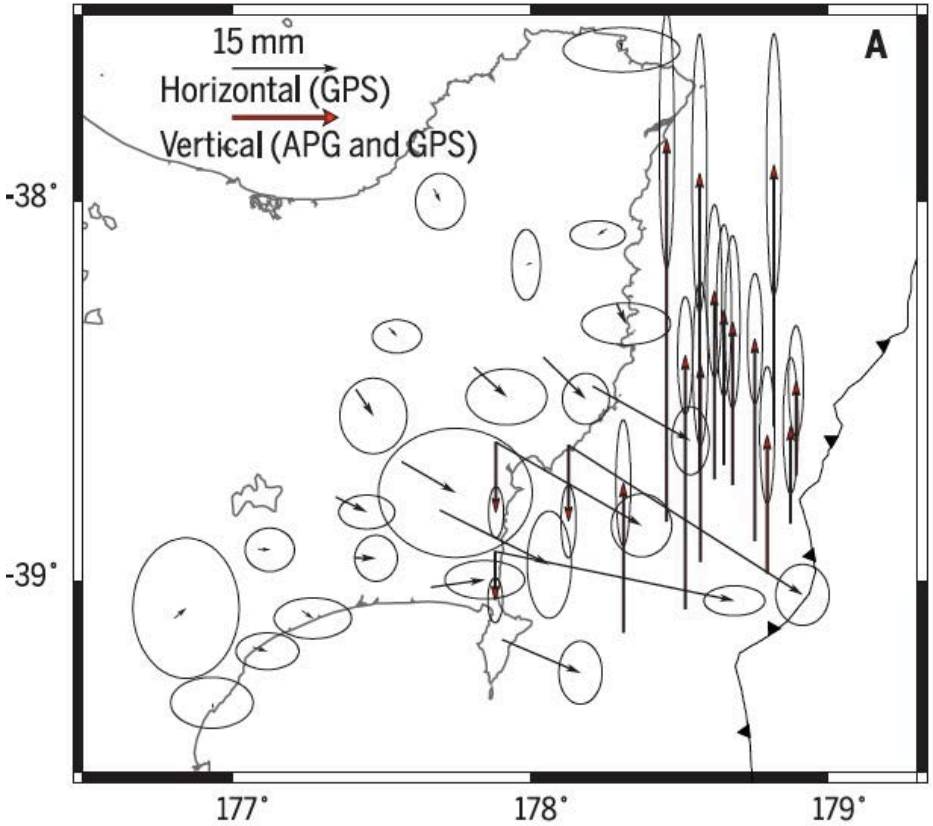
- Slow slip events of various sizes observed in Cascadia, Alaska, Mexico, Japan, Costa Rica, ….
  - Durations of weeks to a few years
- Located at edges of the locked zones, especially downdip edge
- Transient Slip Events may precede earthquakes

Slow Slip: Hikurangi

McCaffrey et al. (2008)



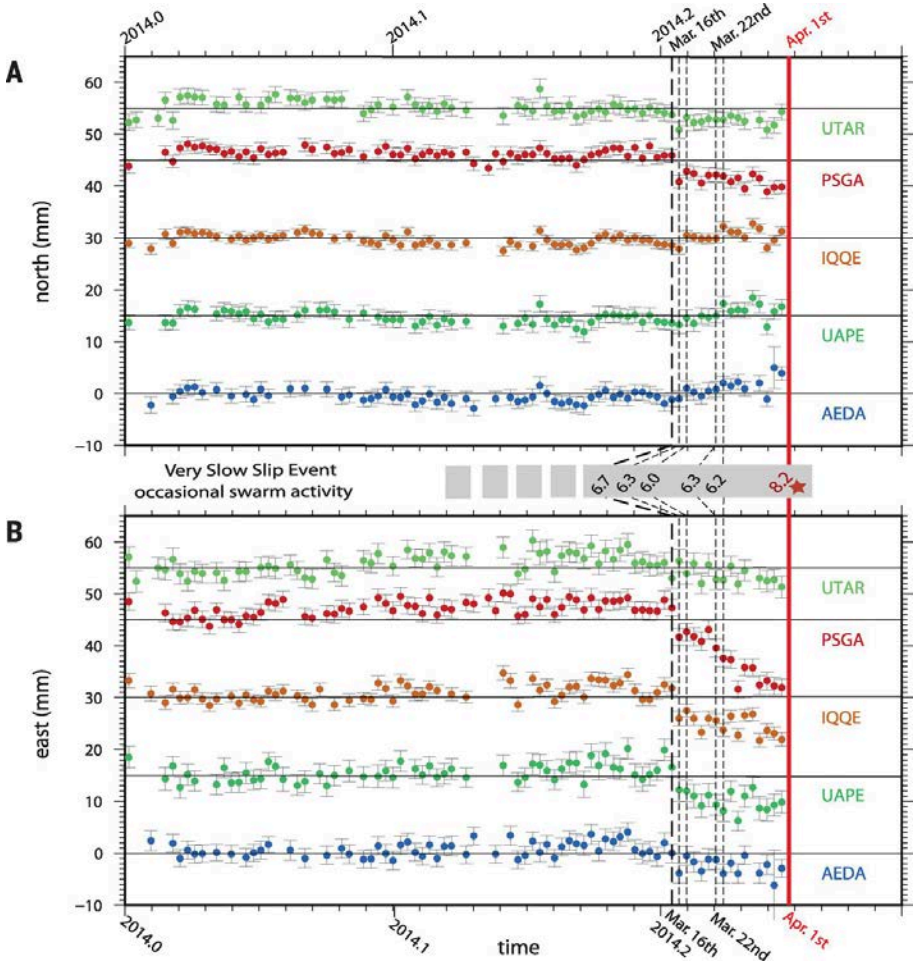
Wallace et al. 2016

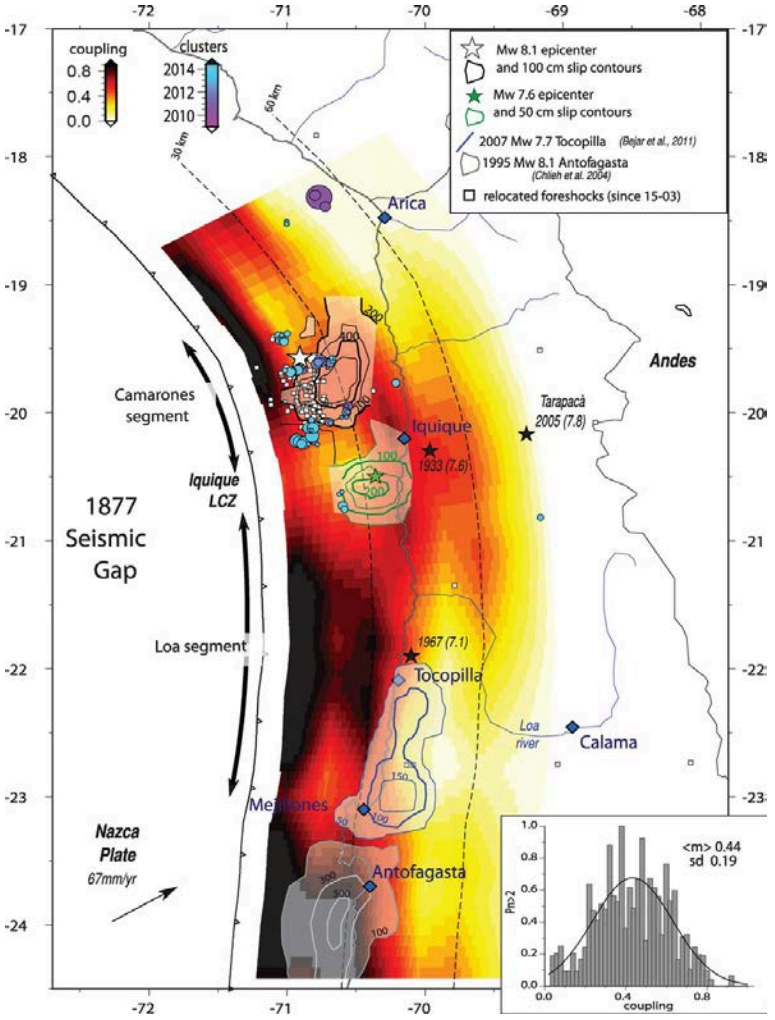


HOBITSS Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip (2014-2015) – SSEs occur on shallowest reaches of megathrust, within 2 km of seafloor.

Iquique Earthquake: Slow Slip Preceded Mainshock

Ruiz et al. (2014)

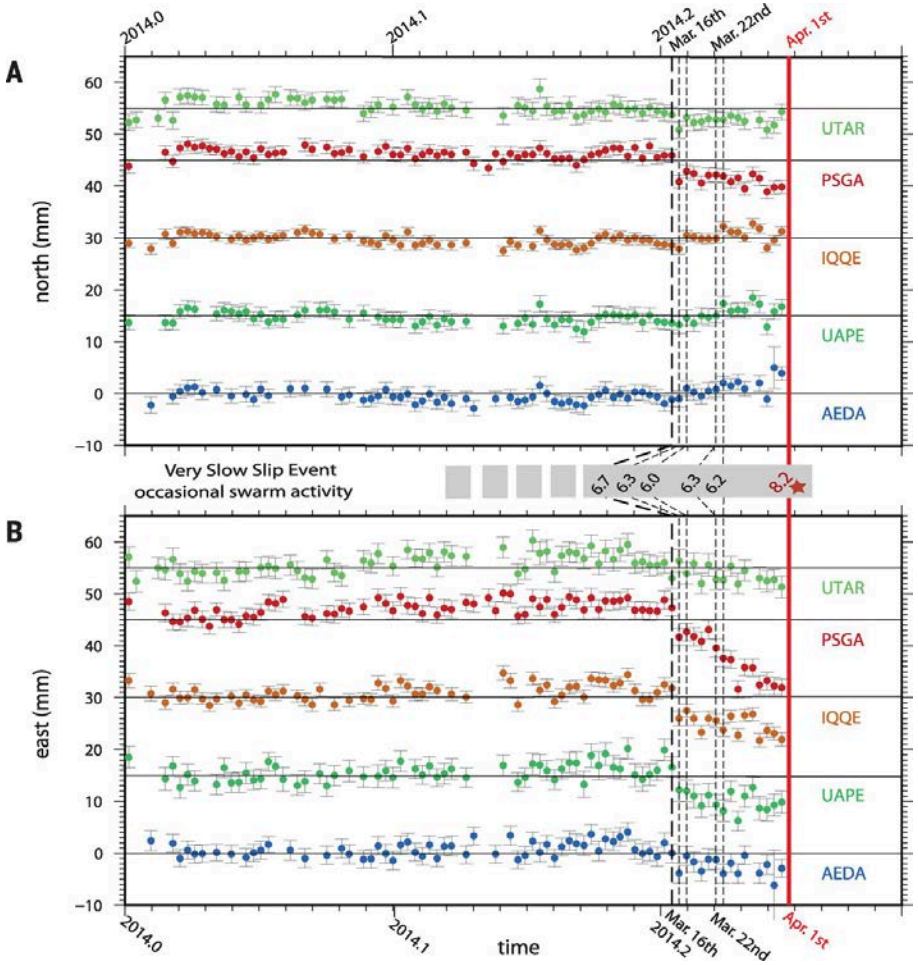


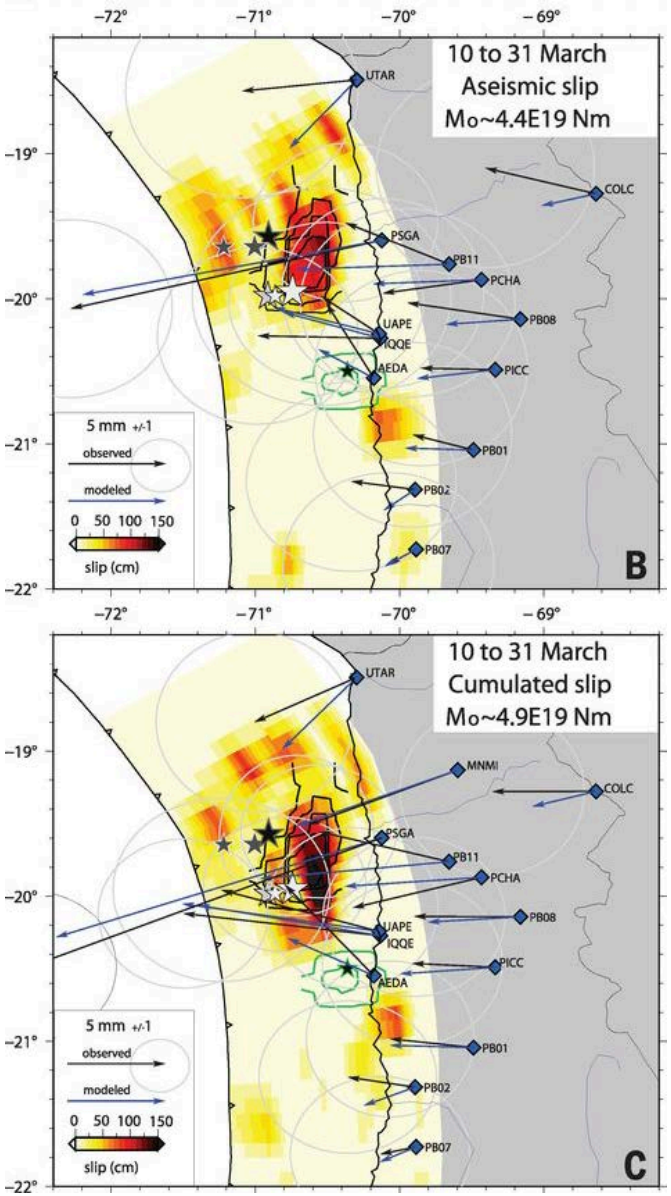


- Iquique earthquake preceded by slow slip and foreshock sequence

Iquique Result

Ruiz et al. (2014)





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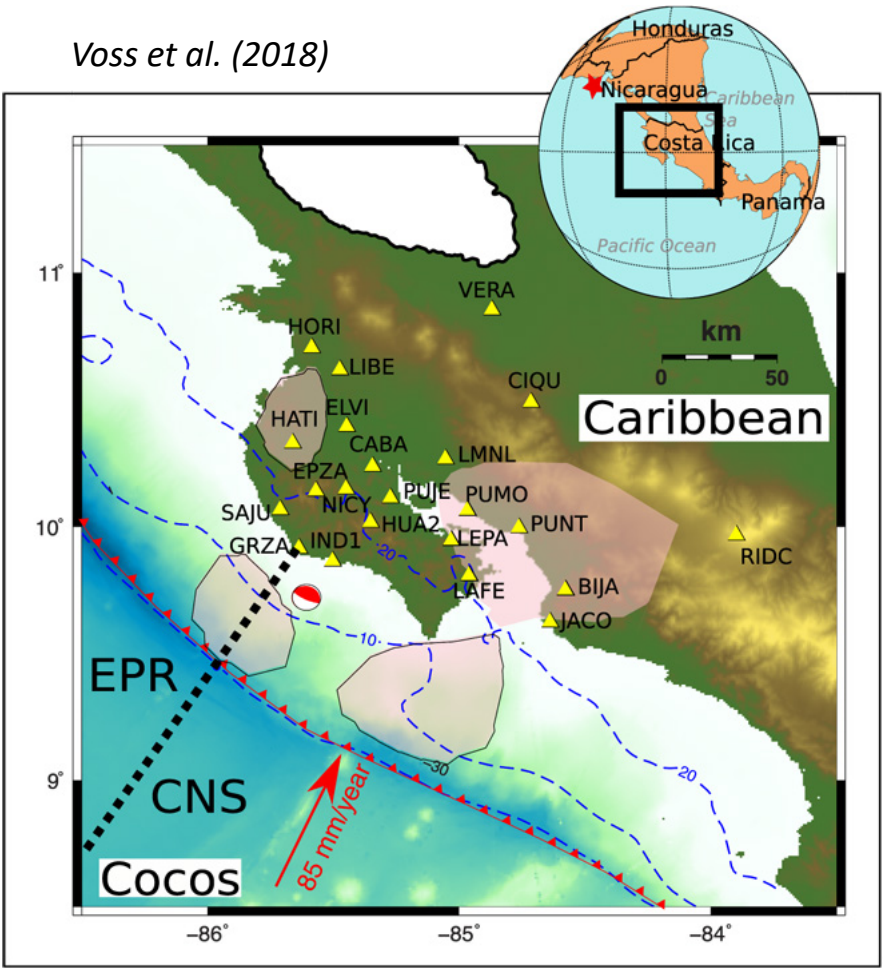
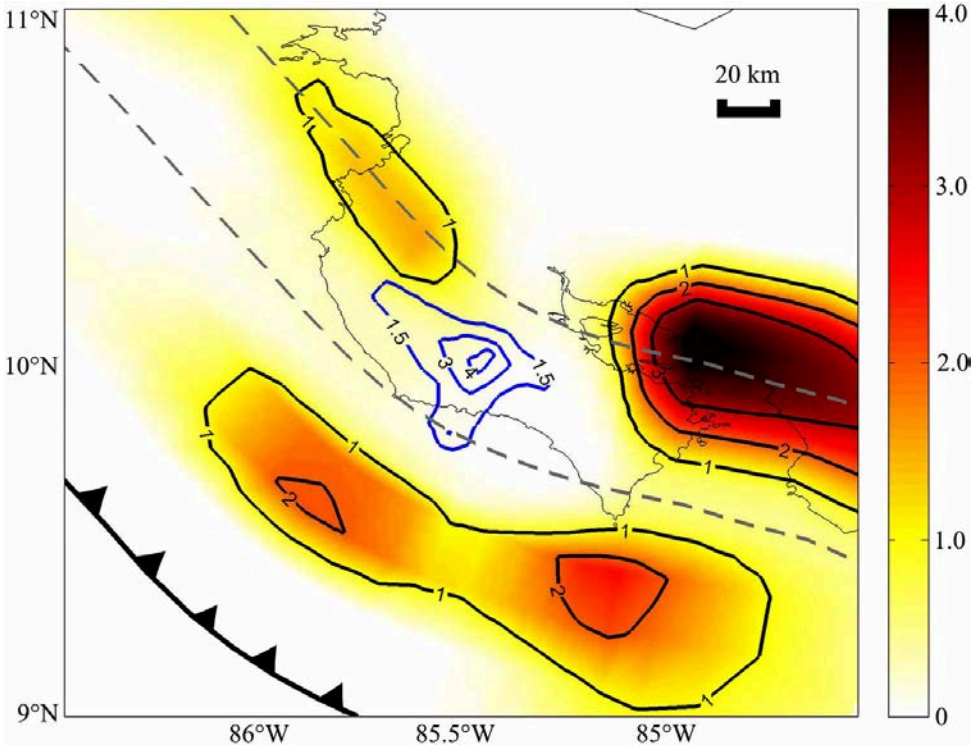
Costa Rica Earthquake and SSEs

Voss et al. (2018)



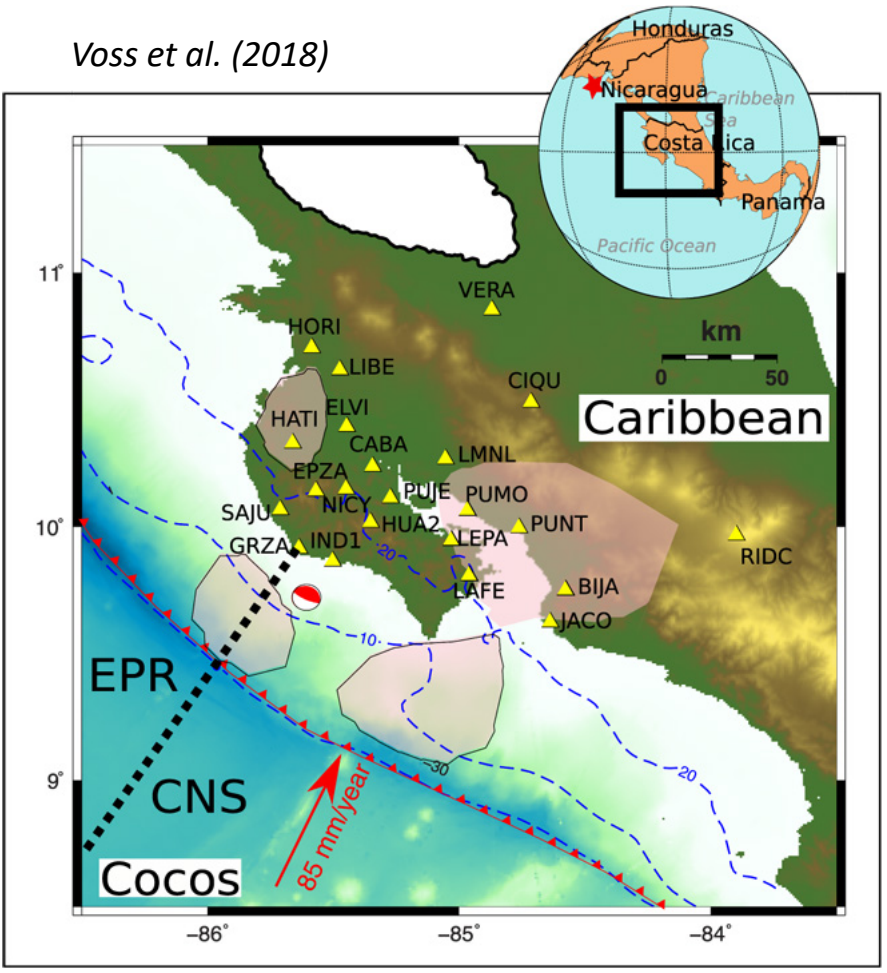
Dixon et al. (2014)



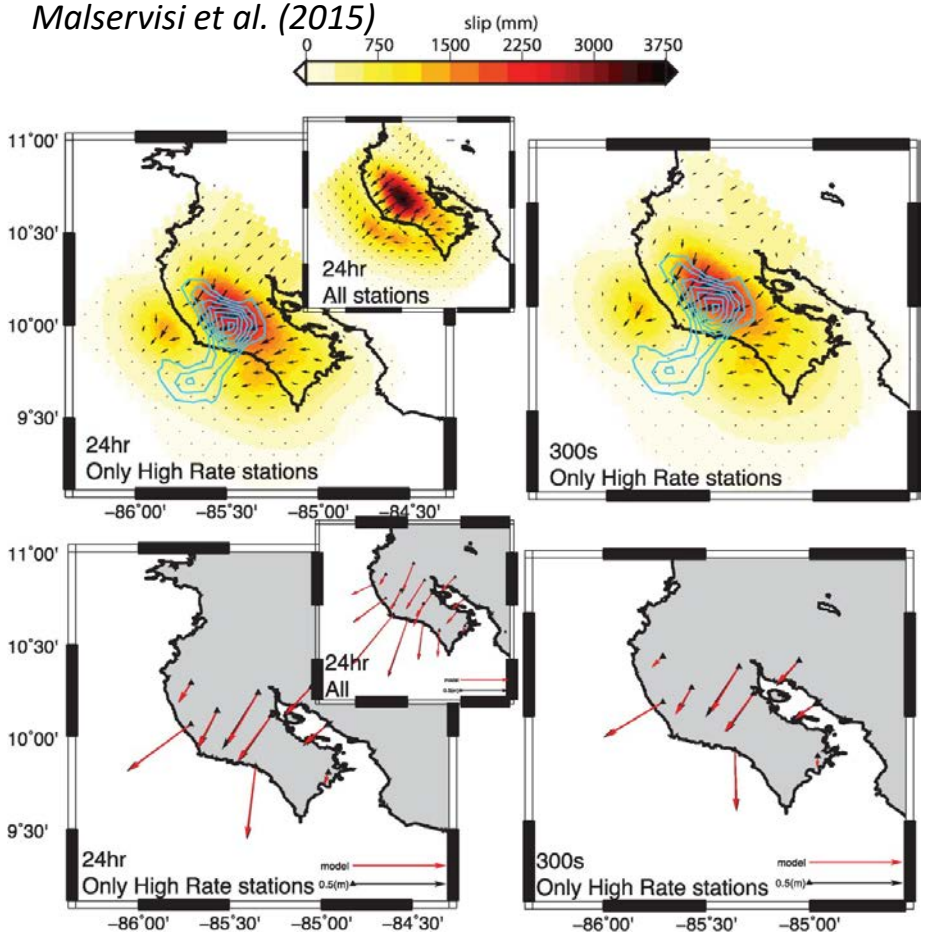
- The rupture area of the 2012 Nicoya earthquake was surrounded by areas of slow slip

Costa Rica Earthquake and SSEs

Voss et al. (2018)



Malservisi et al. (2015)

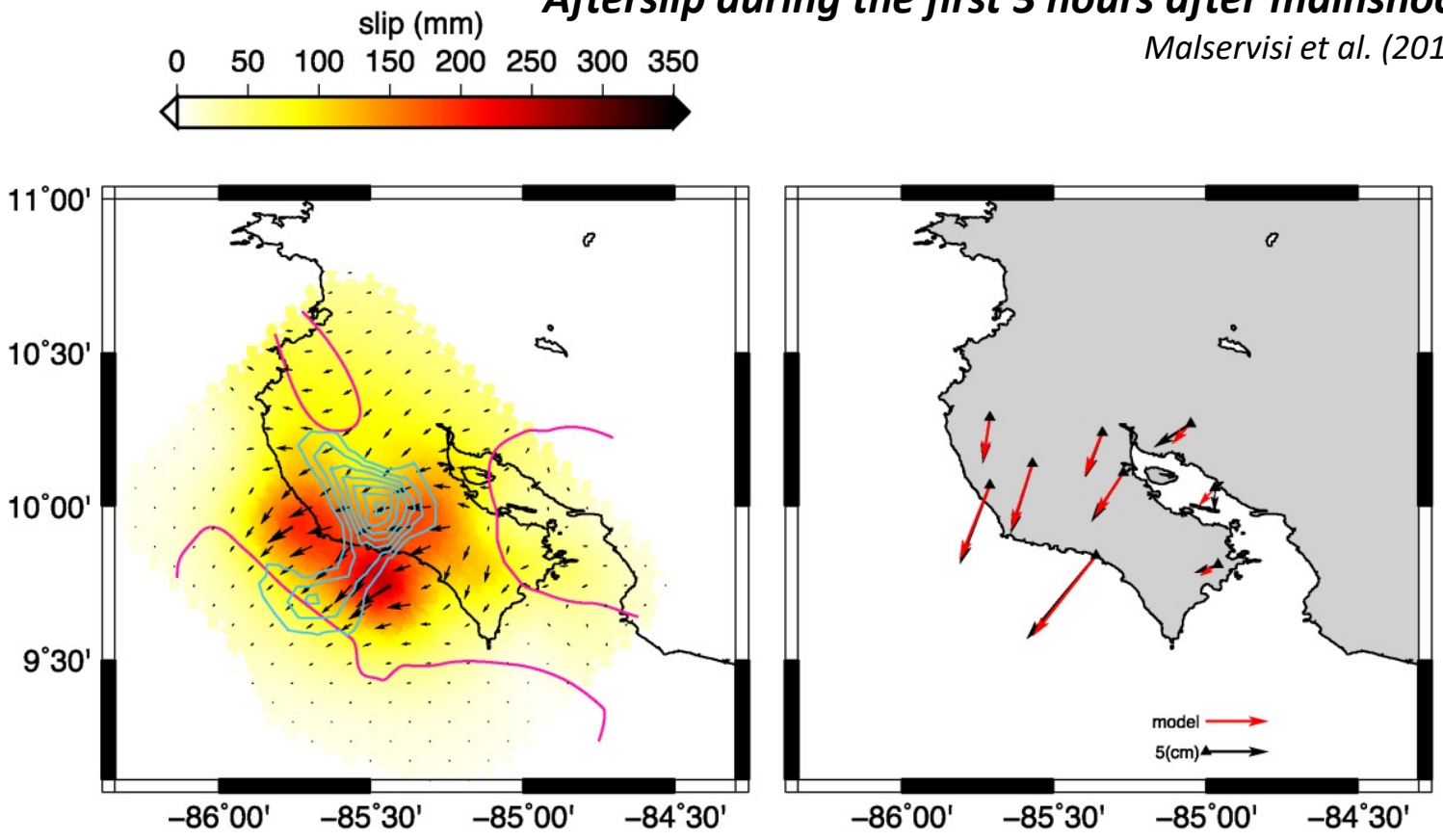


- Afterslip, including that within the first day, filled in some of the gaps between the coseismic rupture and the SSEs

Costa Rica Earthquake and SSEs

Afterslip during the first 3 hours after mainshock

Malservisi et al. (2015)

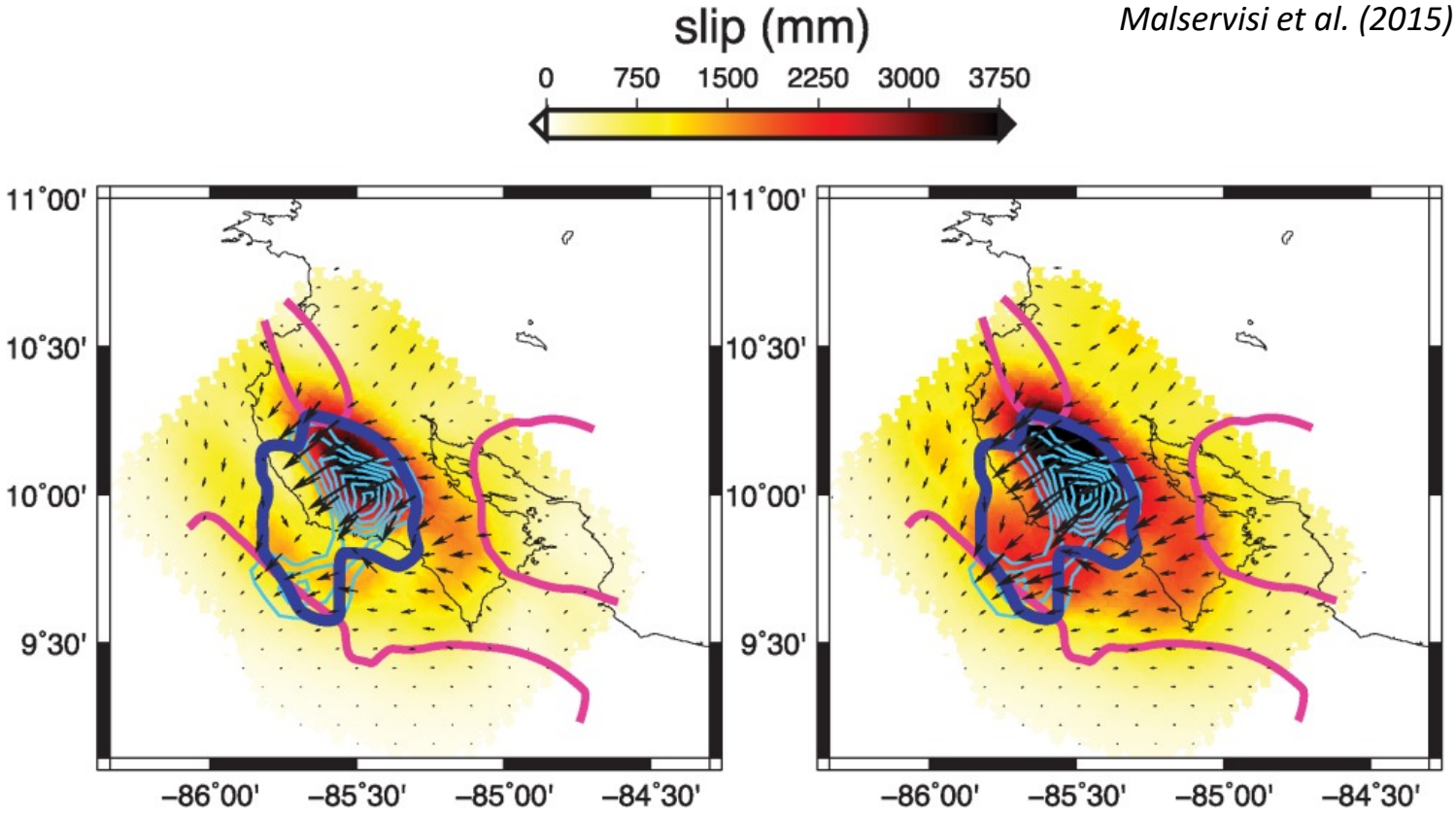


- Afterslip, including that within the first day, filled in some of the gaps between the coseismic rupture and the SSEs

Costa Rica Earthquake and SSEs

Coseismic (24 h) compred to Coseismic + aftershock + 71 days postseismic

Malservisi et al. (2015)

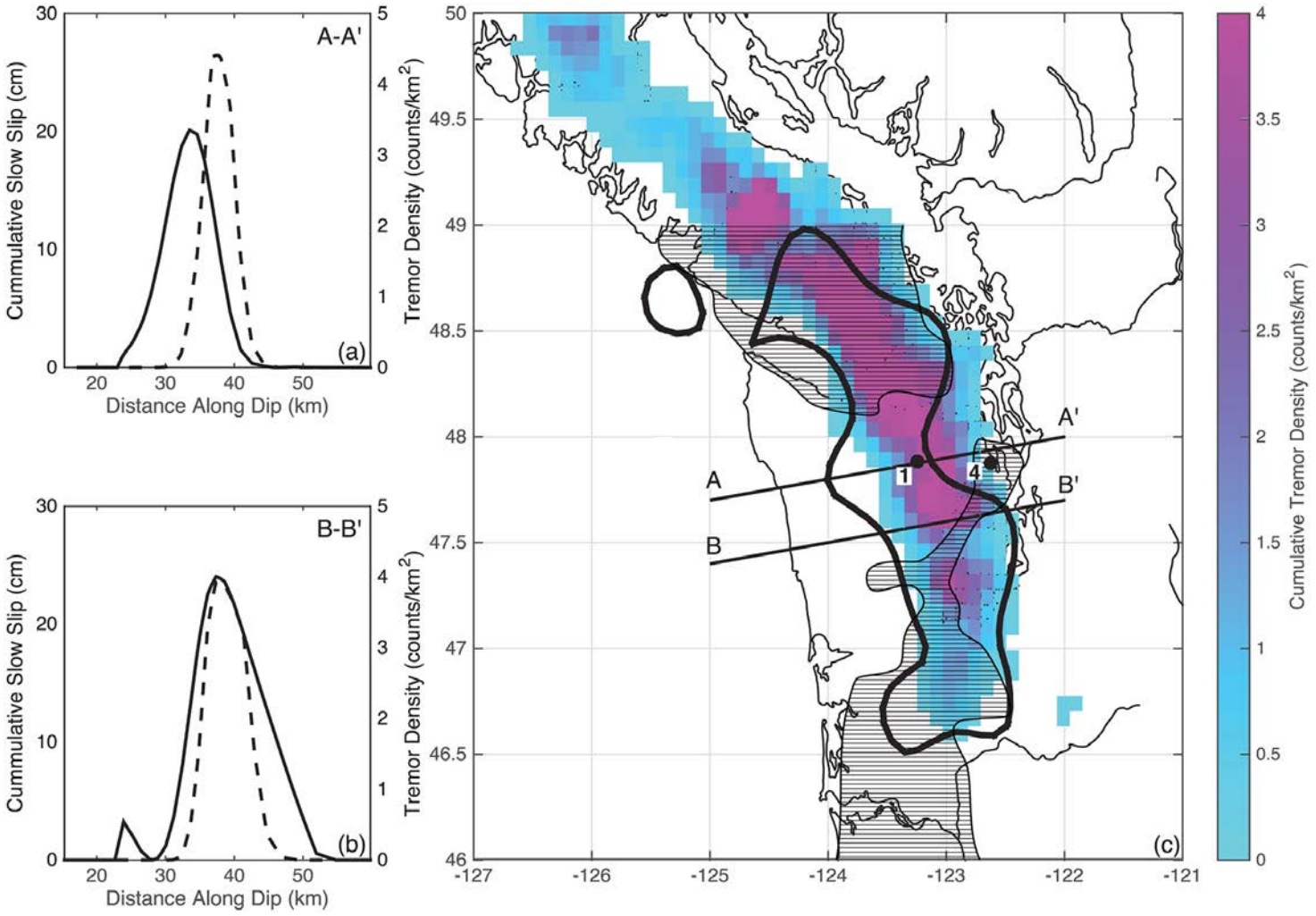


- Earthquake rupture area was defined by previous SSEs, but the slip that filled the gap was a combination of coseismic slip and postseismic afterslip

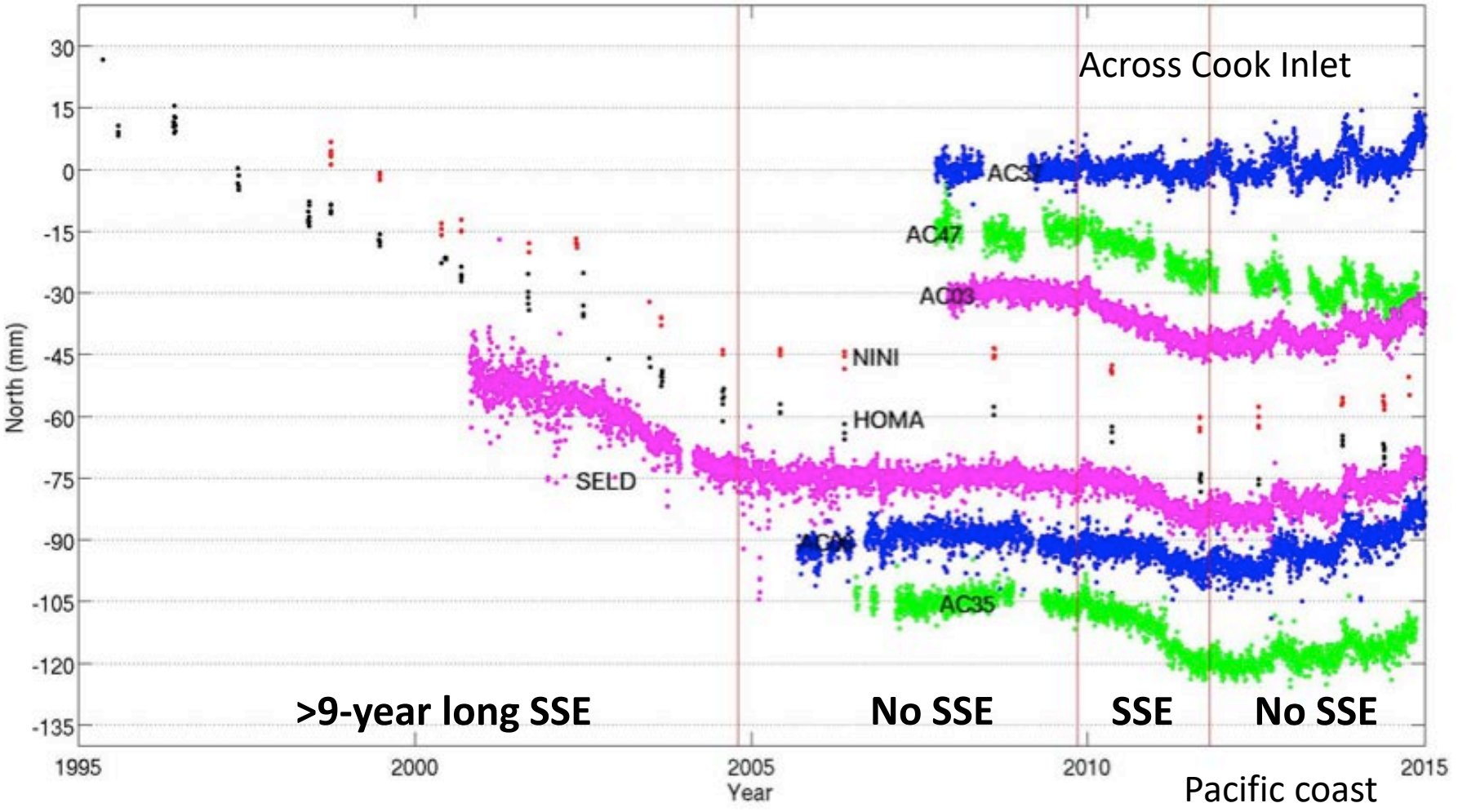
Cascadia: Slip Extends Updip of Tremor

Hall et al. (2018)

In some places



SSEs can be ~Decadal Scale



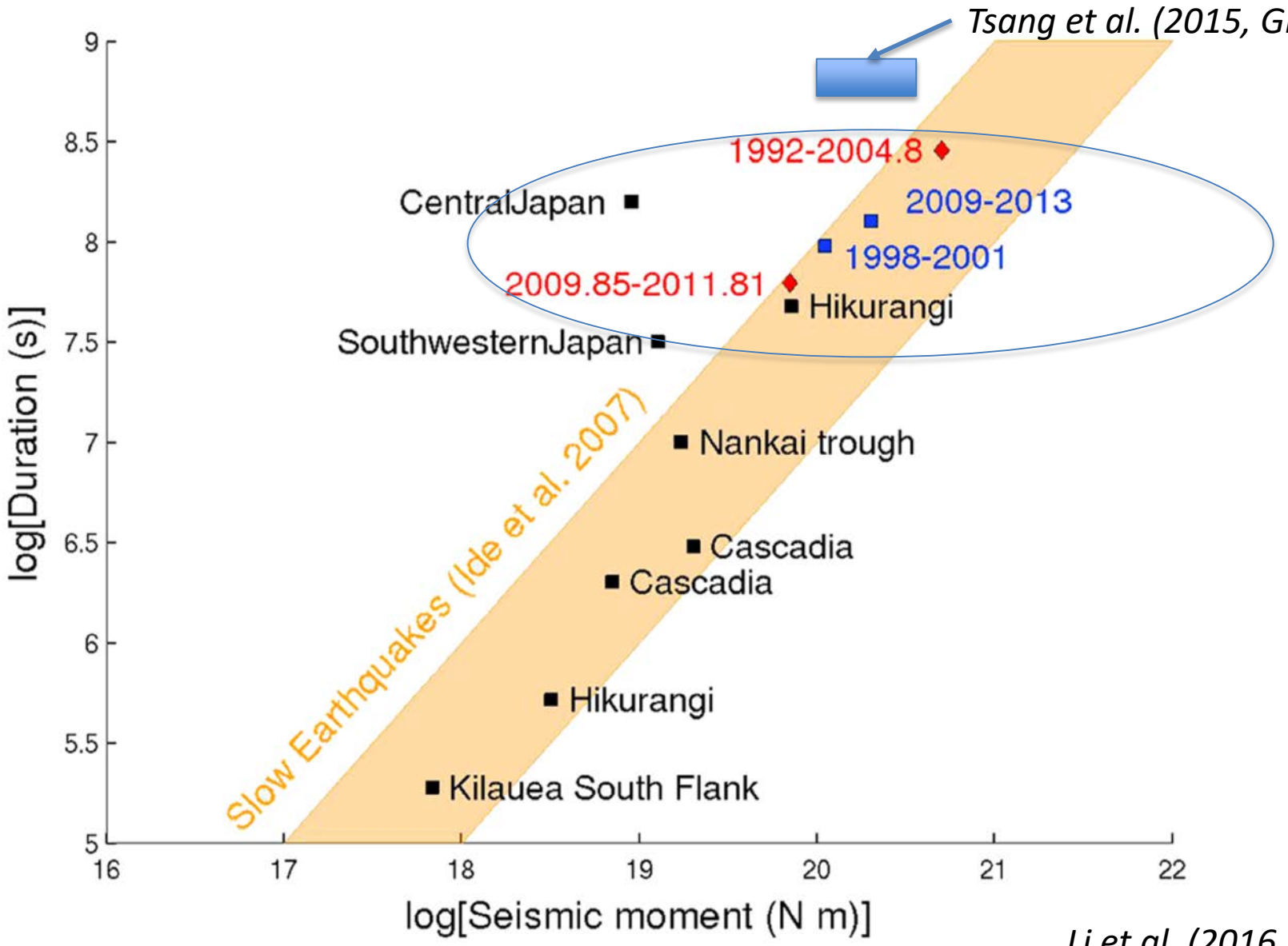
Li et al. (2016)

Key Outstanding Questions

- How much does the extent of seismogenic (unstable) and aseismic (stable) slip vary with time?
  - How well will present interseismic locked patches correspond to future earthquake rupture patches?
  - Can we use paleo-earthquake and paleo-tsunami data to look back in time?
  - Can we fully describe the slip budget for various segments of subduction zones?
- Relating short-term to long-term deformation
  - Can we develop mechanical models that include realistic rheology and stress transfer with seismic, aseismic, transient, etc behavior, and also predict long-term deformation of the forearc/arc region?

Bonus Slides!

Duration/Magnitude of SSEs

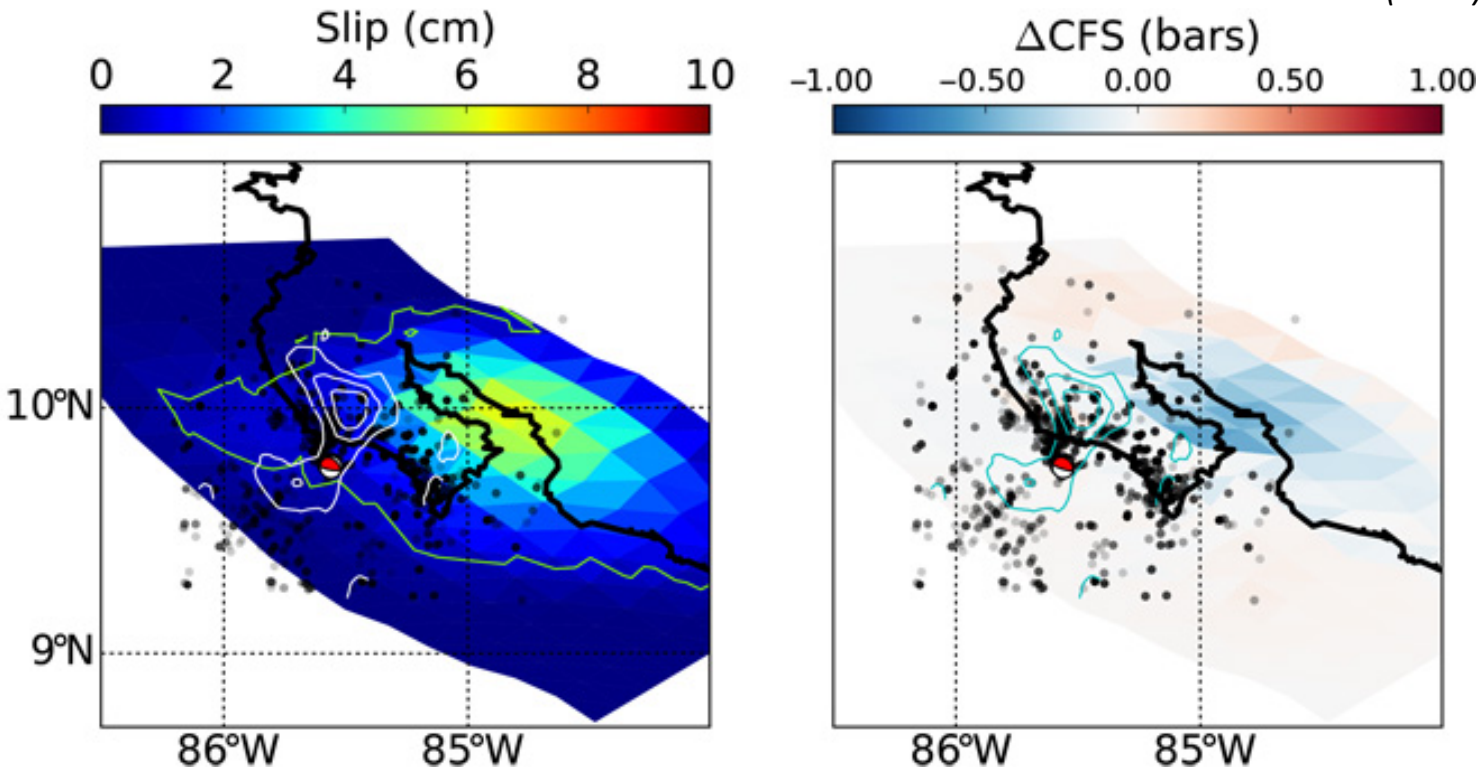


Li et al. (2016, JGR)

Costa Rica Earthquake and SSEs

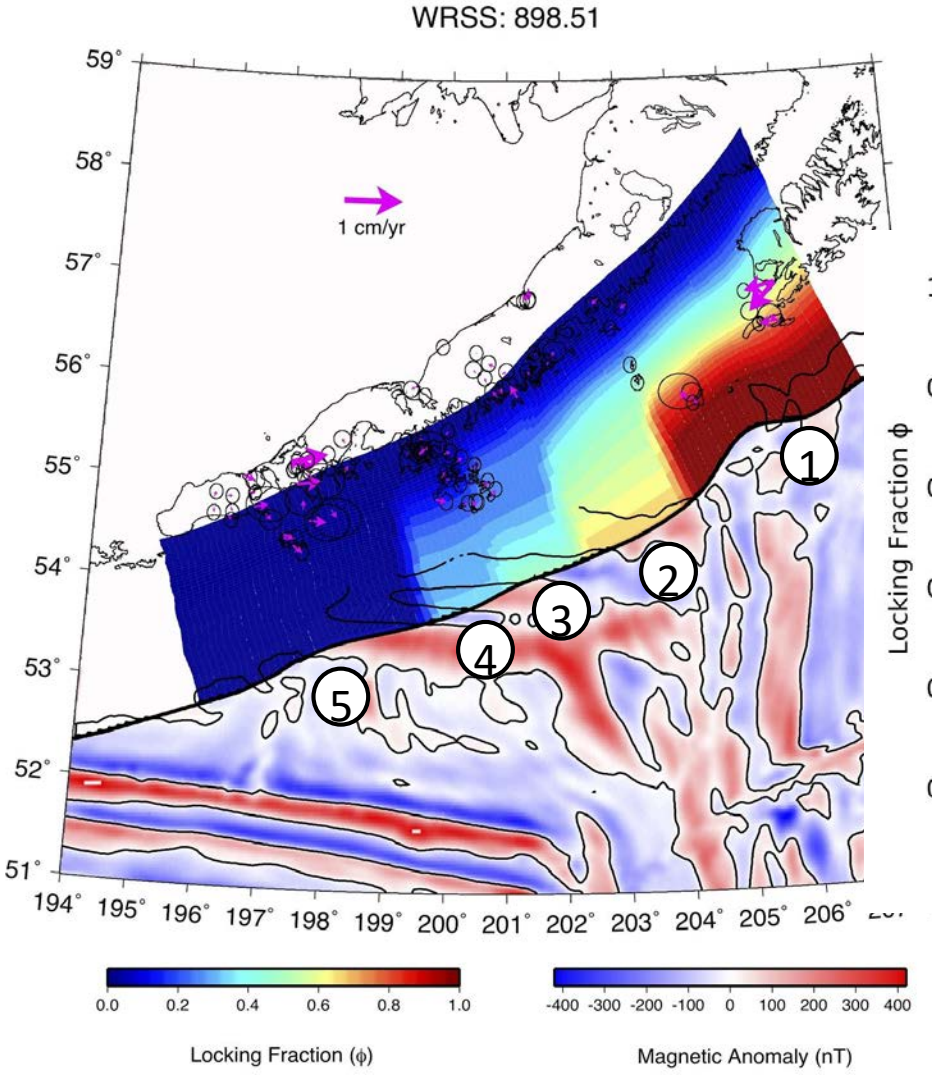
Coulomb stress changes caused by SSEs at rupture initiation point are small

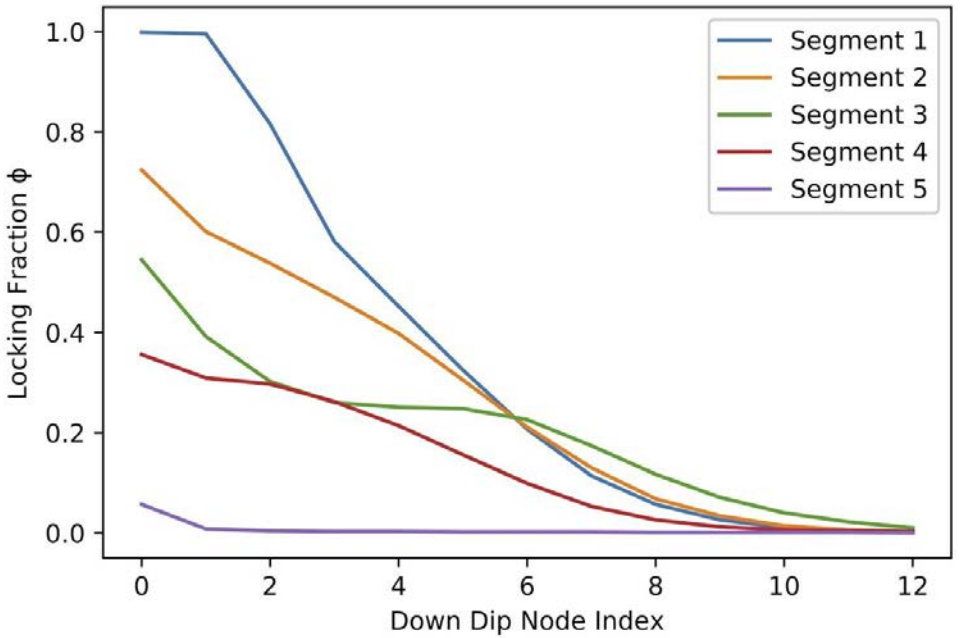
Voss et al. (2018)



- Evidence for triggering of Nicoya earthquake by the preceding SSEs is weak

Refining the Slip Deficit Model



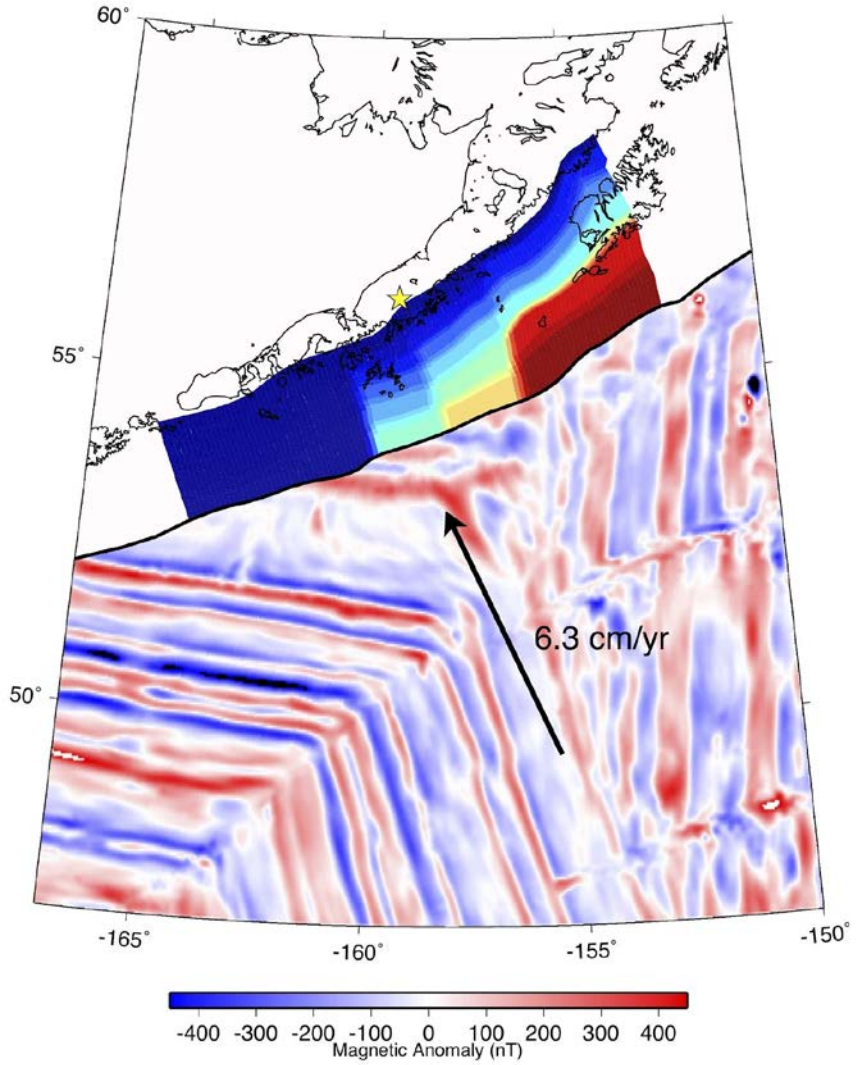


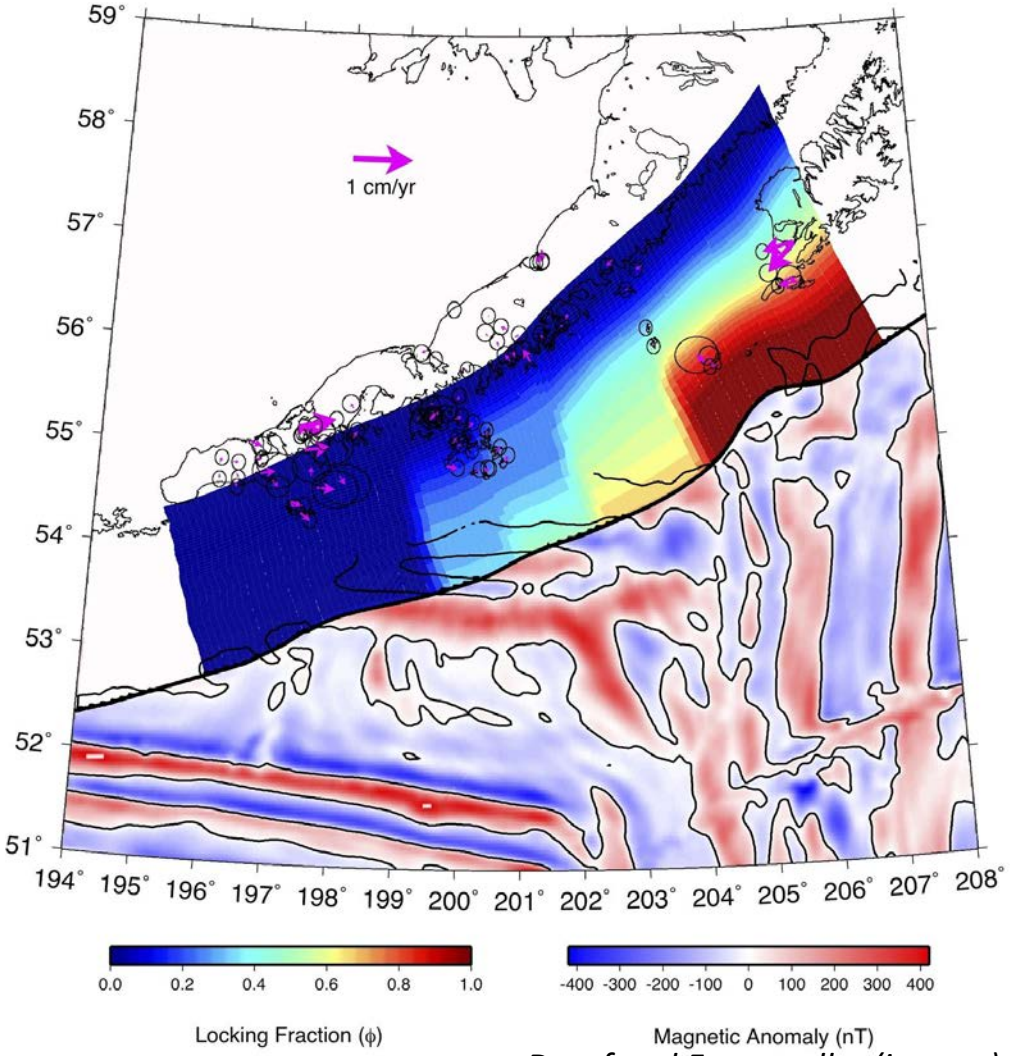
Droof and Freymueller (in prep)

- Remaining mystery: How does the 1946 tsunami earthquake fit into this picture?

Refining the Slip Deficit Model

- Added new data (Veniaminof volcano, corrected)
- Added another along-strike segment





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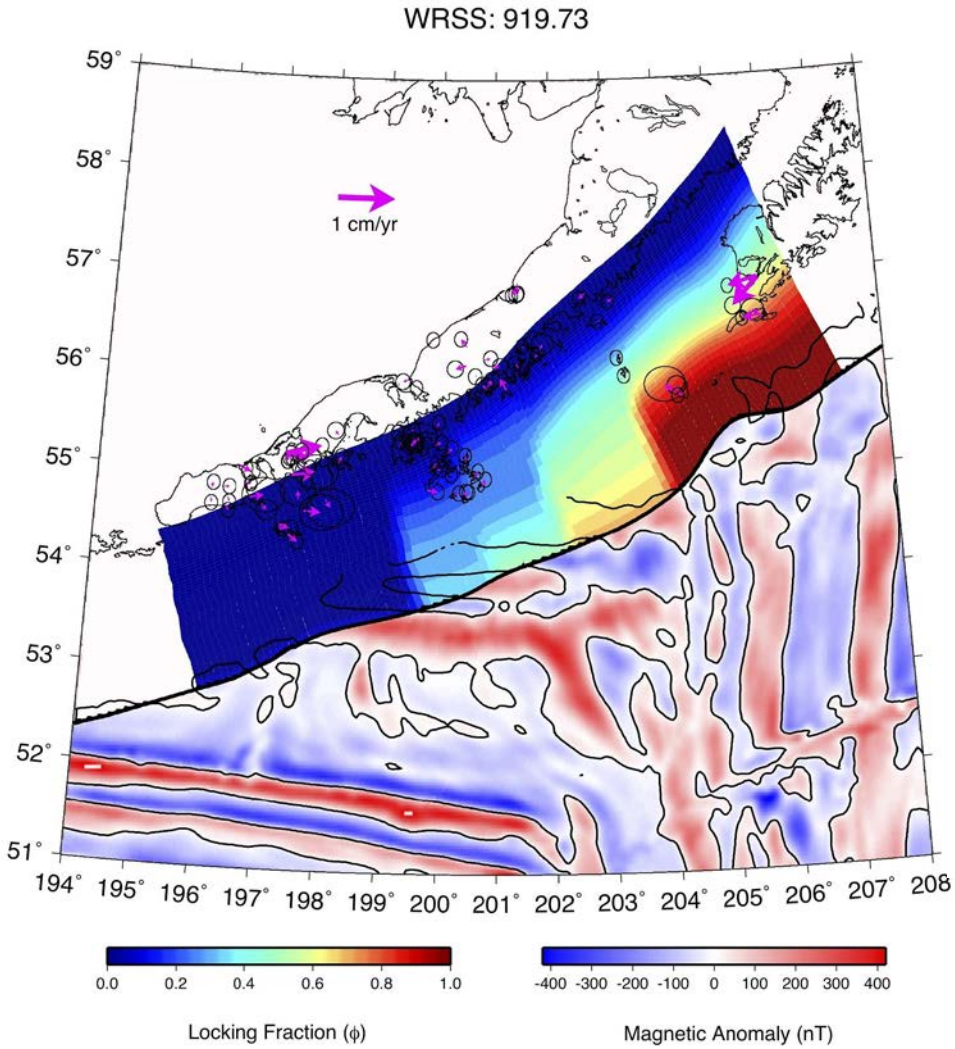
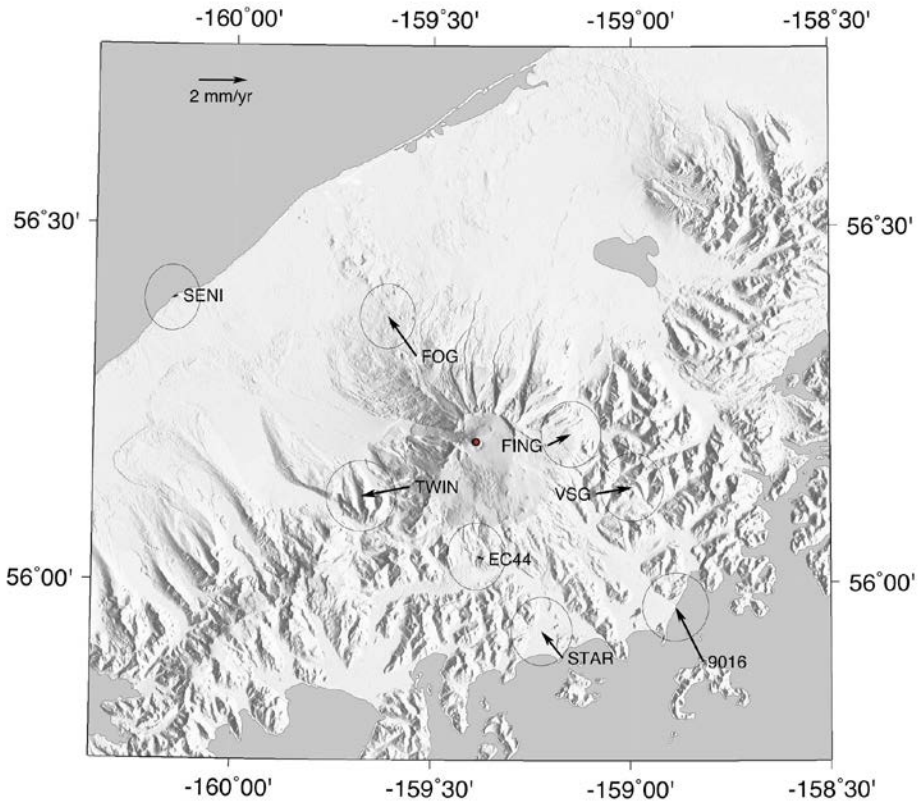
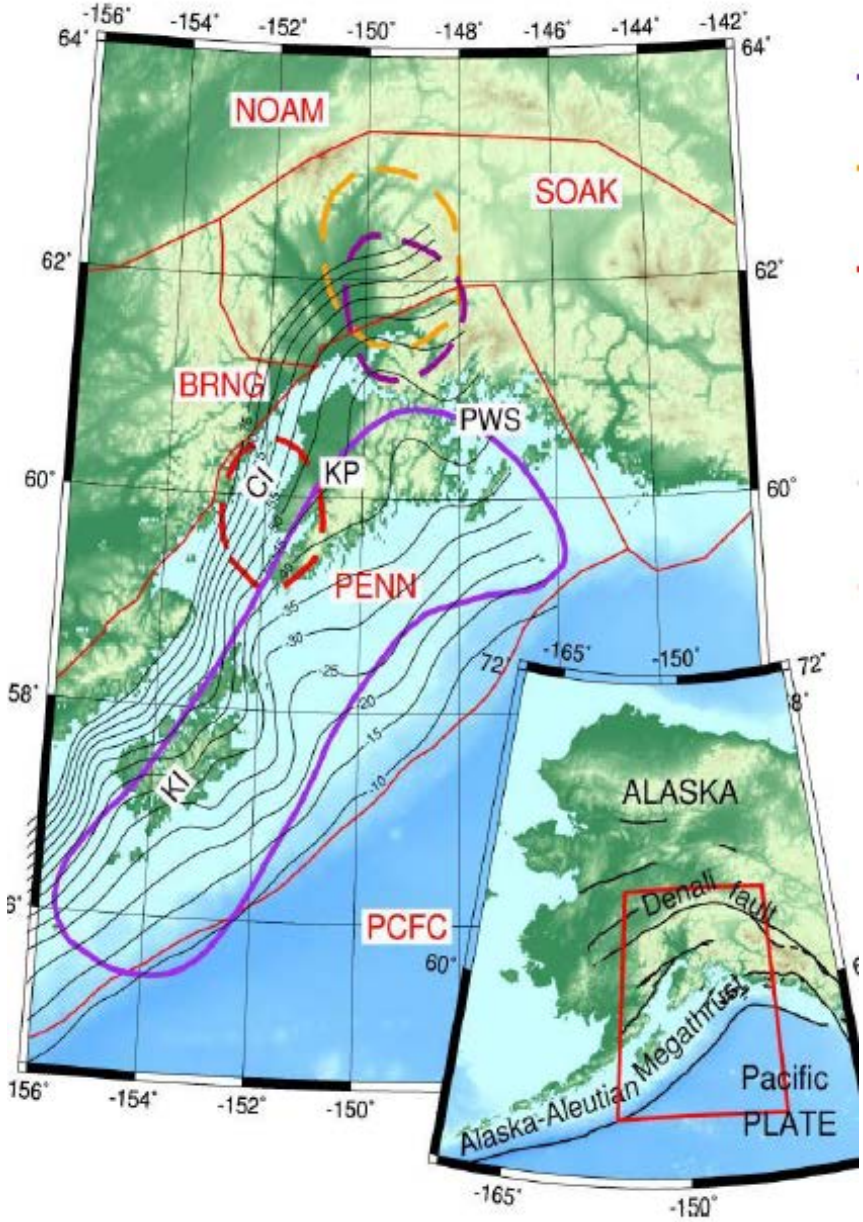




Droof and Freymueller (in prep)

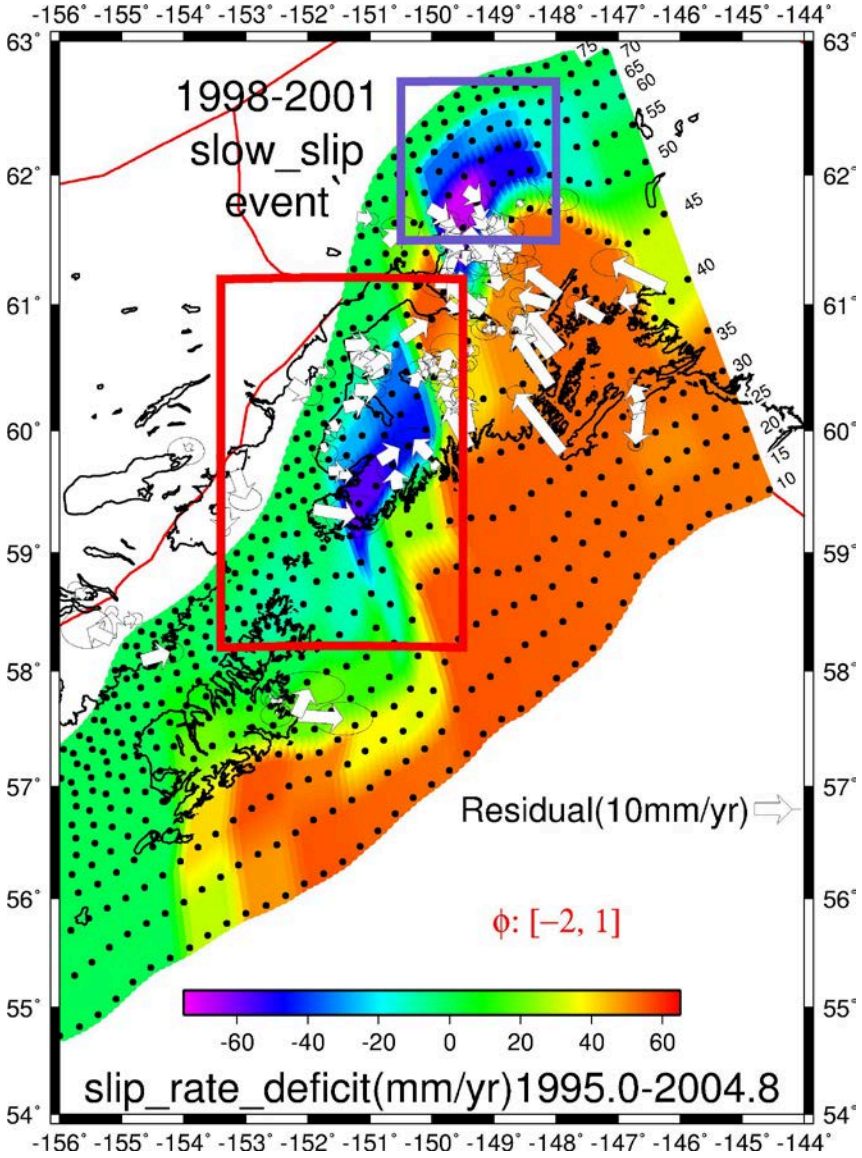
Slow Slip Events

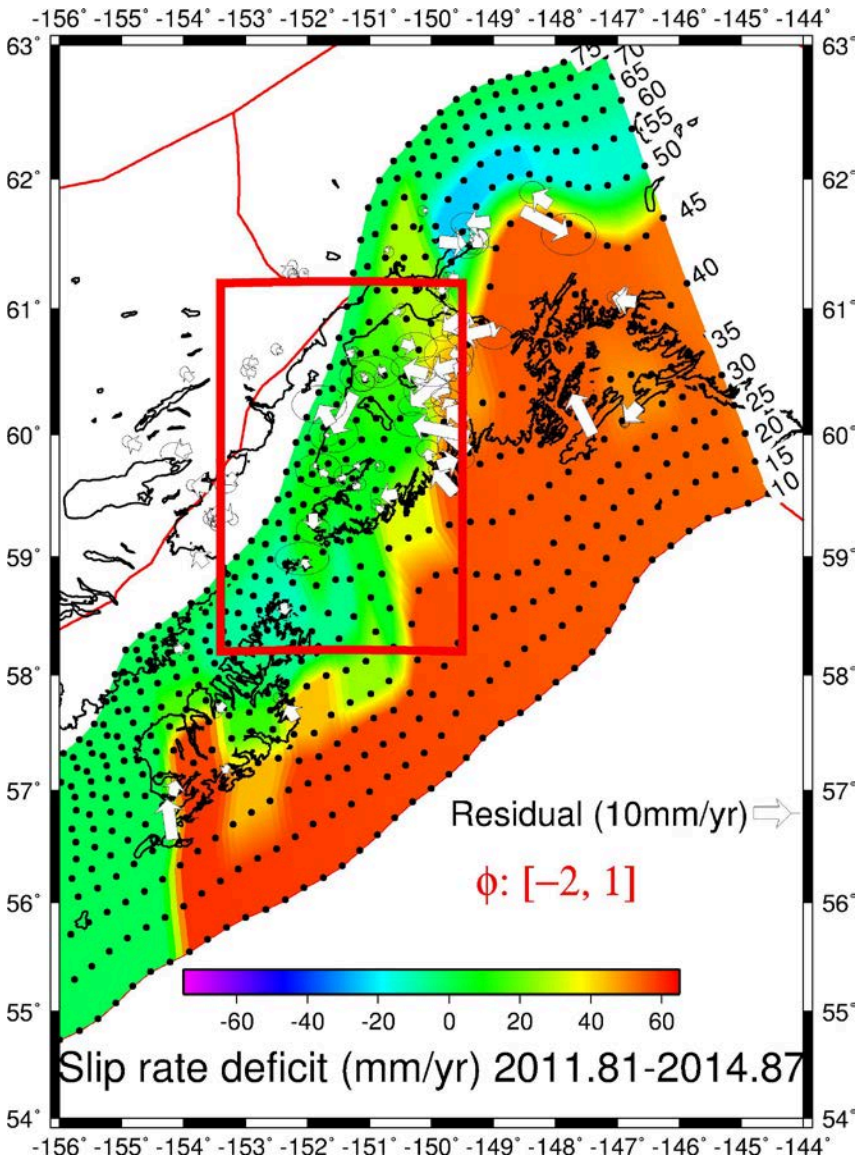


- Multiple slow slip events have been observed downdip of the 1964 earthquake (M9.3) rupture zone.
- SSE durations 2-9+ years.
- Equivalent magnitudes as large as M7.8

Li et al., (2016)

Slip Distribution of SSE vs Normal





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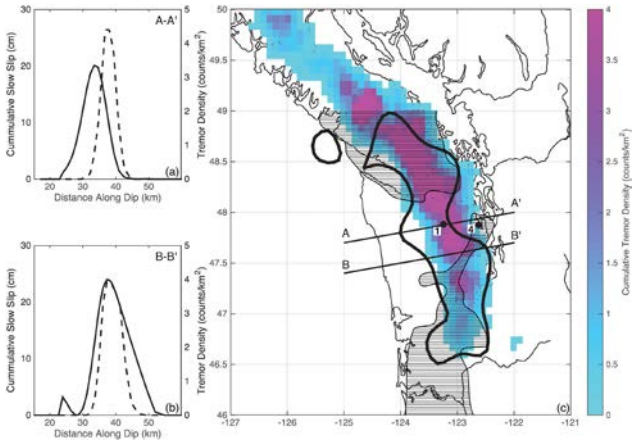

Stress perturbation from a slip event