Examples of connections between upper and lower plate faulting, fluids, megathrust properties, and slip behavior from seismic imaging in the Alaska, Aleutian and Mexico subduction zones

Donna J. Shillington

Alaska: Anne Bécel, *Jiyao Li, Jacob Clarke, Yinchu Li, Josh Burstein,* Samer Naif, Demian Saffer, Mladen R. Nedimović, and many others

Aleutians: *Valeria Cortés-Rivas*, Daniel Lizarralde, Hannah Mark

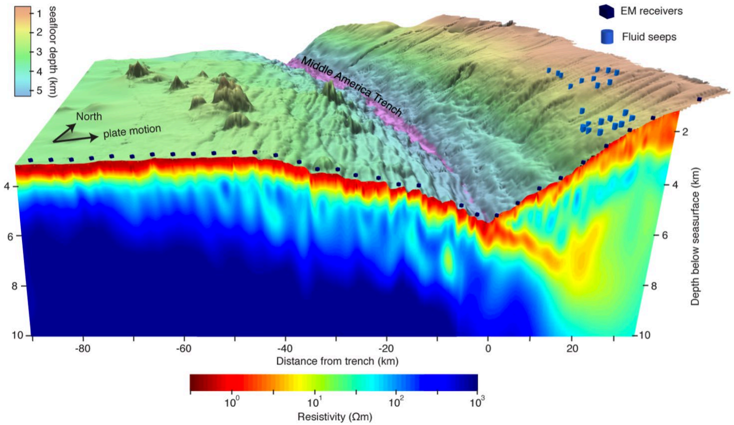
Mexico: Anne Bécel, *Grace Ward*, Victor Cruz-Atienza, *Tanner Acquisto, Davis Hagemeier,* and many others

Subduction comparison: Dan Bassett, Laura Wallace, Julie Elliott

Northern Arizona University; Lamont-Doherty Earth Observatory of Columbia University; Georgia Tech; University of Texas Institute for Geophysics ; Dalhousie University; Woods Hole Oceanographic Institution; Universidad Nacional Autónoma de México; GNS Science; GEOMAR Helmholtz Centre for Ocean Research; Michigan State University

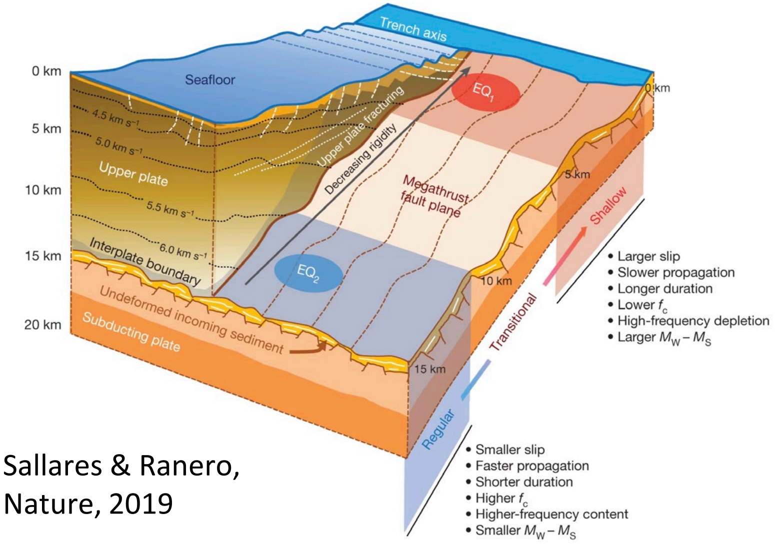
What explains downdip and along strike variations in properties and behavior of the megathrust?

- **Subducting plate:** Sediments, fluids, and topography may influence fluids and heterogeneity along plate boundary and upper plate deformation



Naif, Key et al, *G3*, 2016

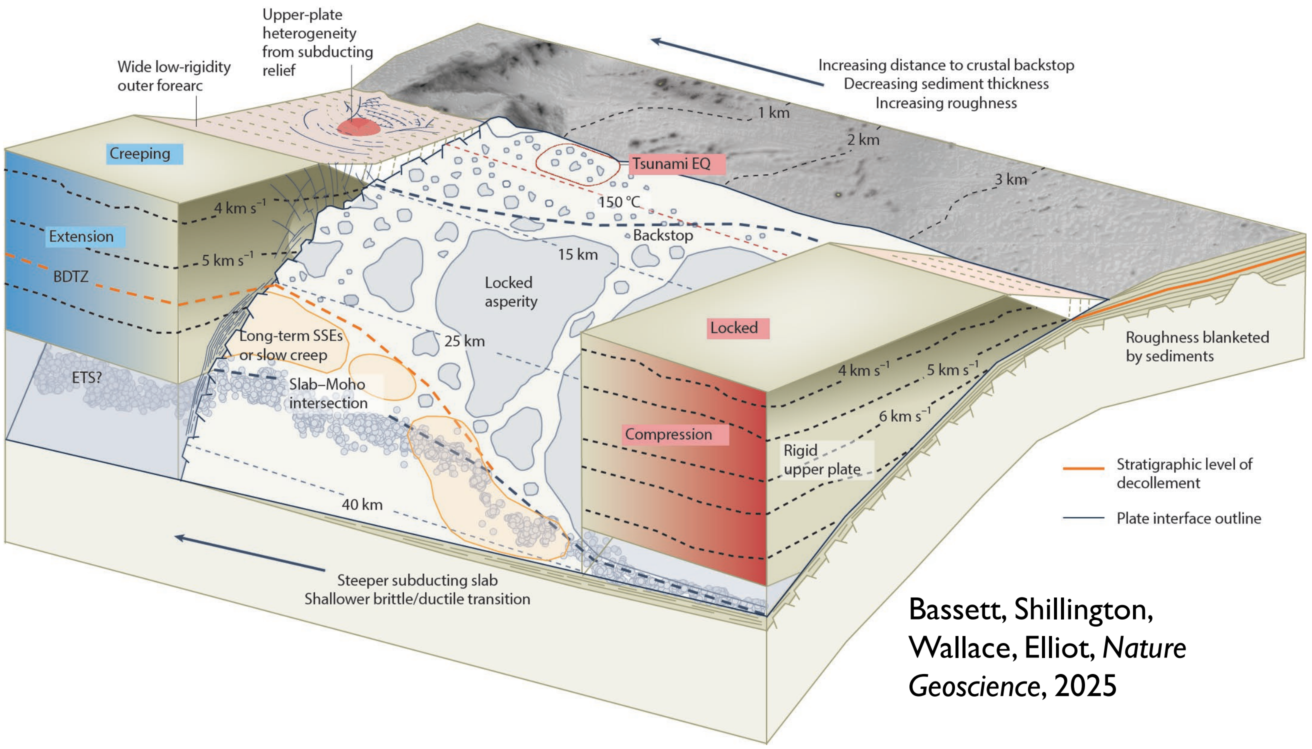
- **Overriding plate:** Rigidity and permeability of overriding crust may influence asperities, plate boundary properties and distribution of fluids



Sallares & Ranero, Nature, 2019

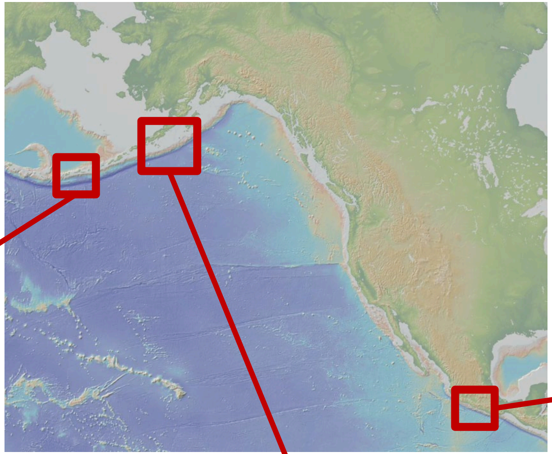
Takeaway: Multiple physical factors control megathrust slip behavior

Studies from subduction zones with along-strike variations in slip behavior showcase the suite of physical parameters that conspire to influence megathrust behavior

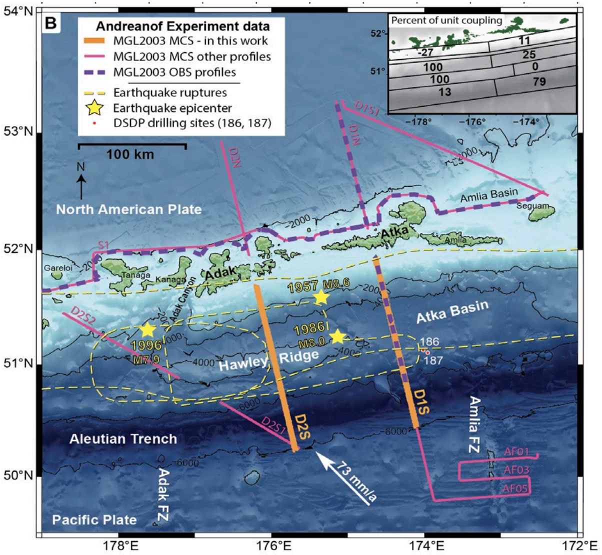


Bassett, Shillington, Wallace, Elliot, *Nature Geoscience*, 2025

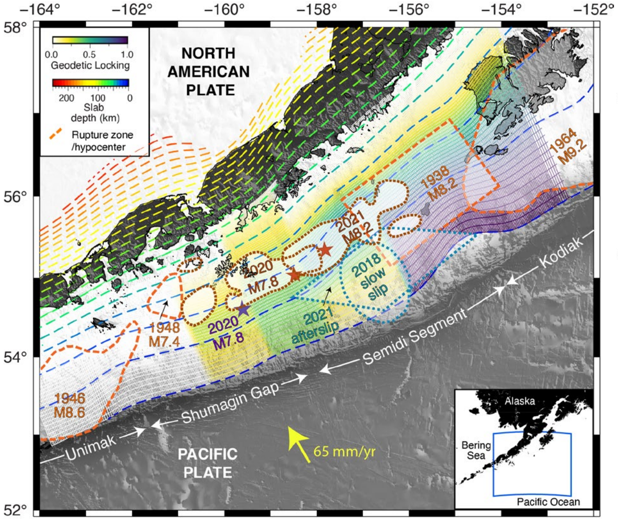
Vignettes from three subduction zones



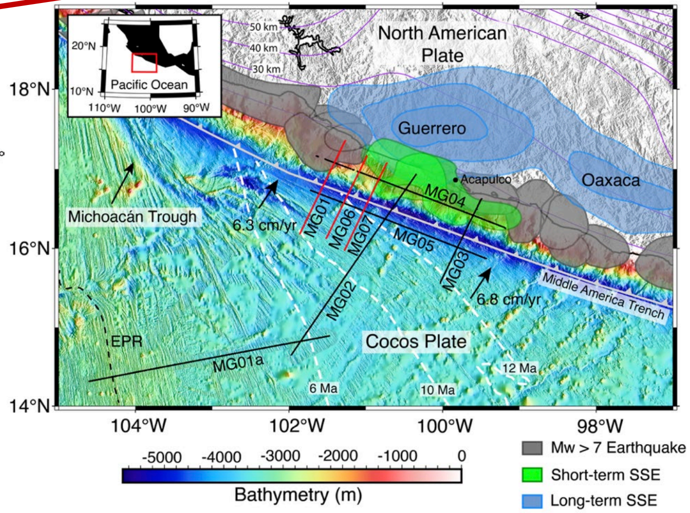
Aleutians



Alaska Peninsula

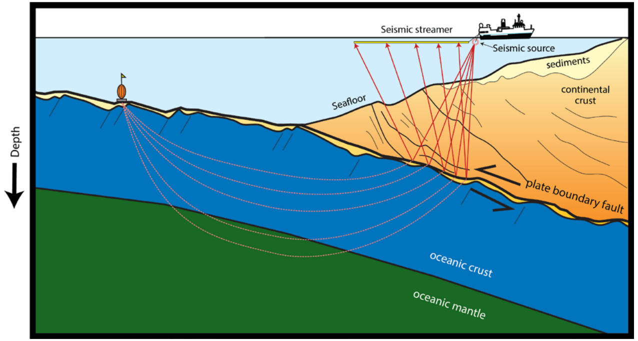


Mexico

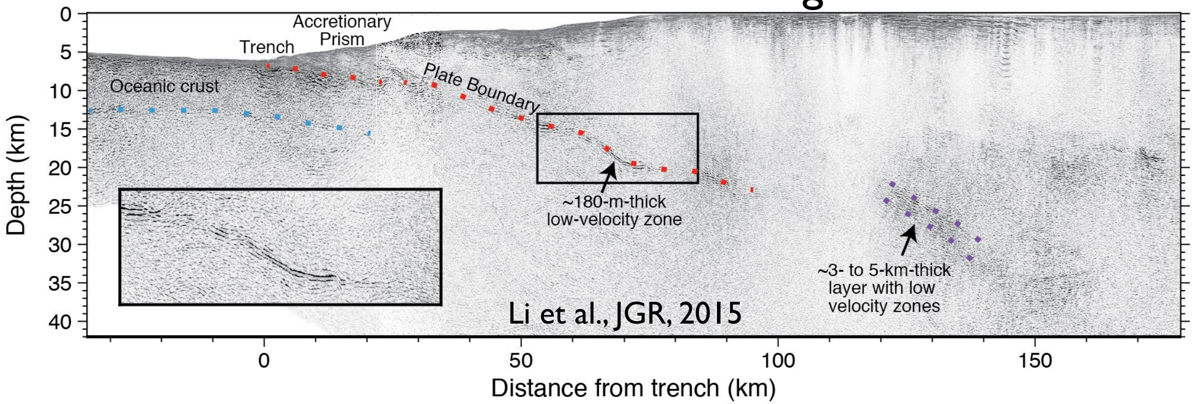


Active-source seismic data can image subduction zone structure

- High resolution characterization of sediments and faults
- Plate boundary geometry and properties

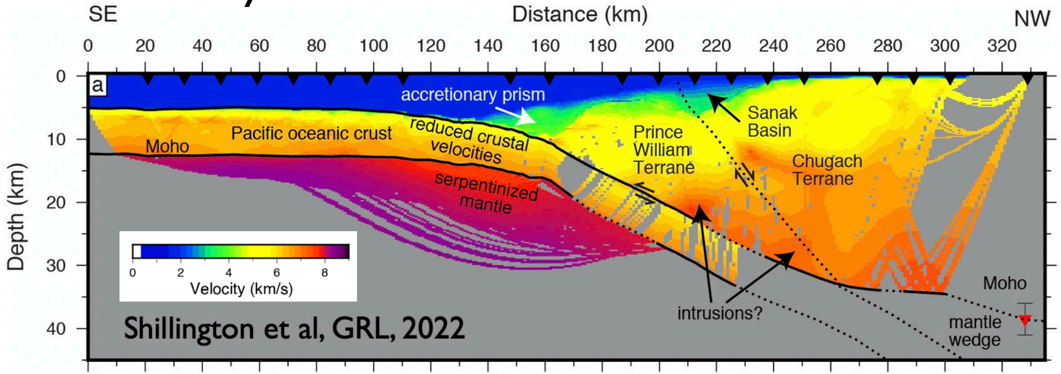


Seismic reflection image



- Large-scale architecture of subducting and overriding plates
- Changes in crustal and upper mantle composition

Velocity model based on seismic refraction data



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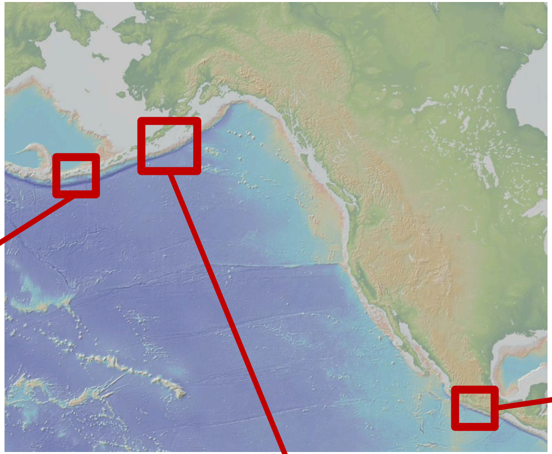

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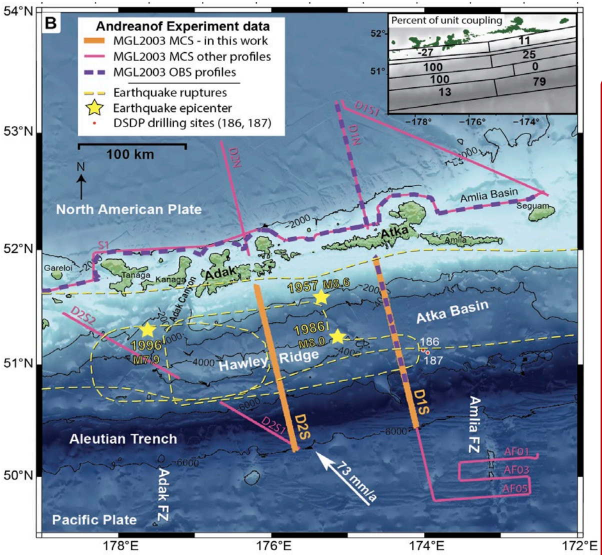
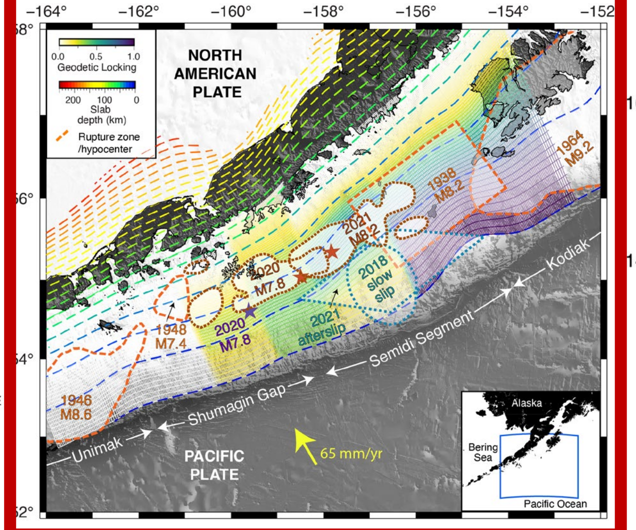
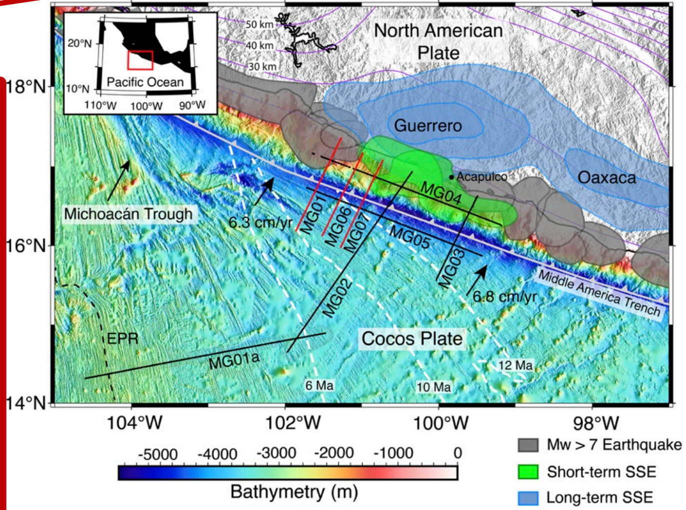


Alaska Peninsula



Mexico



What explains downdip and along strike variations in properties and behavior of the megathrust?

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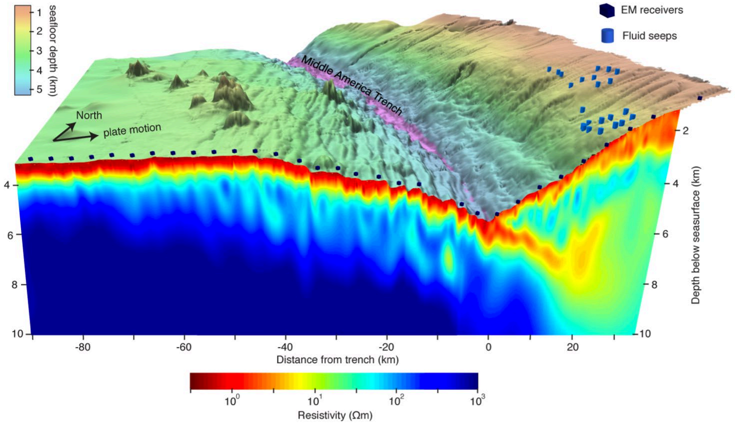
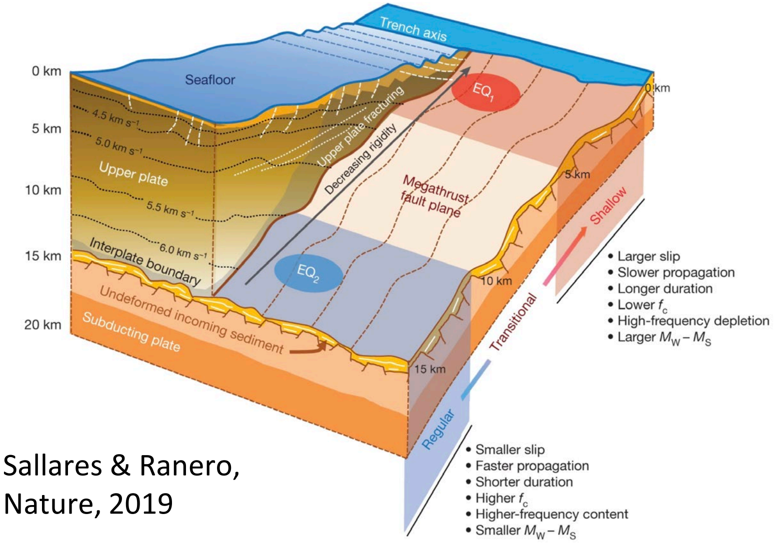
- **Overriding plate:** Rigidity and permeability of overriding crust may influence asperities, plate boundary properties and distribution of fluids



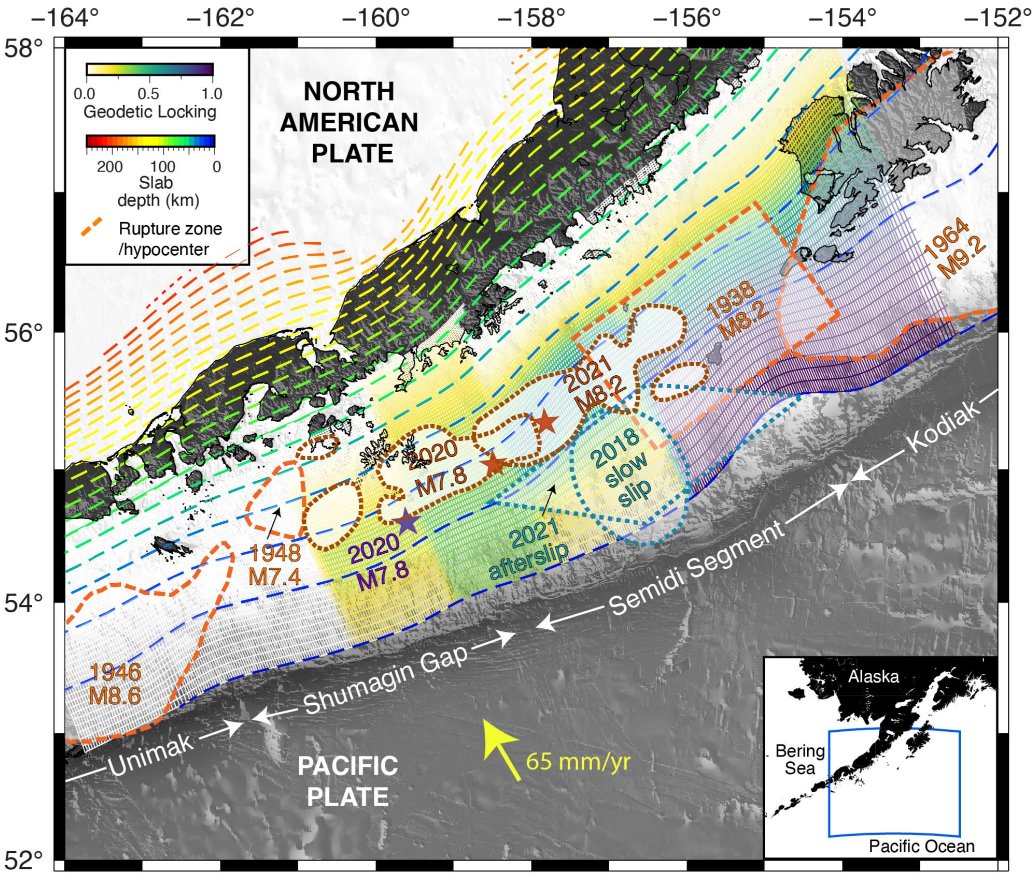
Naif, Key et al, *G3*, 2016



Sallares & Ranero, Nature, 2019

Variations in seismicity, locking and earthquake rupture history around the Alaska Peninsula

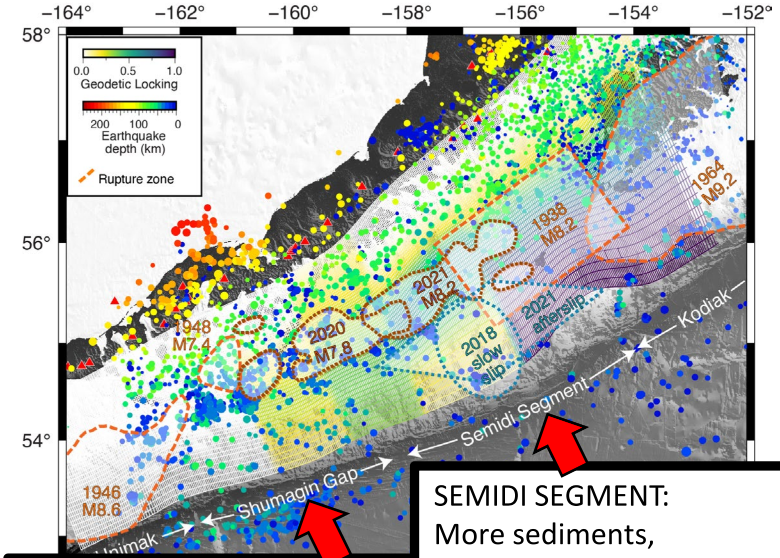
- Semidi segment
  - Regular M>8 earthquakes
  - Strong coupling in east, decreasing west.
  - Low levels of seismicity
  - *Shallow slow slip*
- Shumagin Gap
  - Last M>8 earthquake at least 150 yrs ago, possibly longer
  - Weak coupling
  - Higher levels of seismicity at depths >20 km
  - Regular M7.x earthquakes



Rupture patches: Tape & Lomax, 2022; Liu et al., 2023, Bai et al., 2025

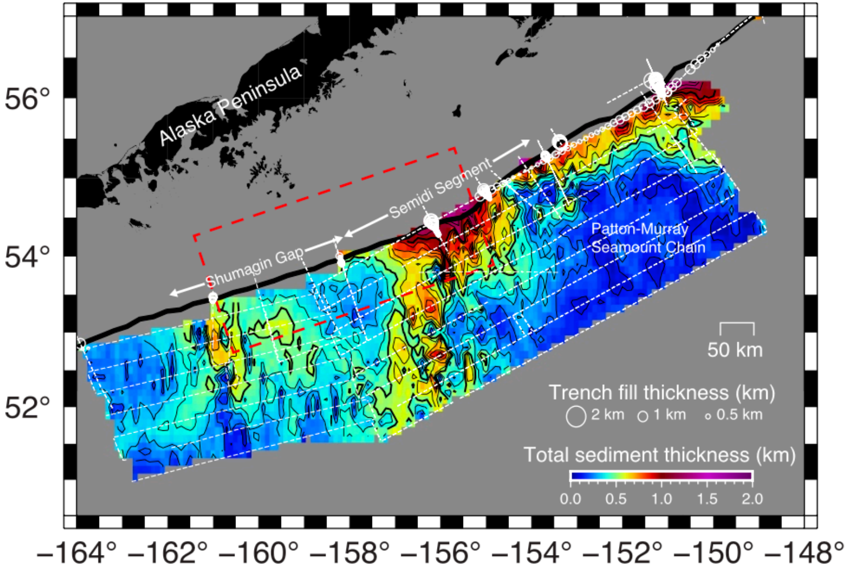
Slow slip/afterslip: He et al., 2018; Brooks et al., 2023

GPS: Xiao et al., 2021
Slab depth contours: Slab2.0, Hayes et al (2018)

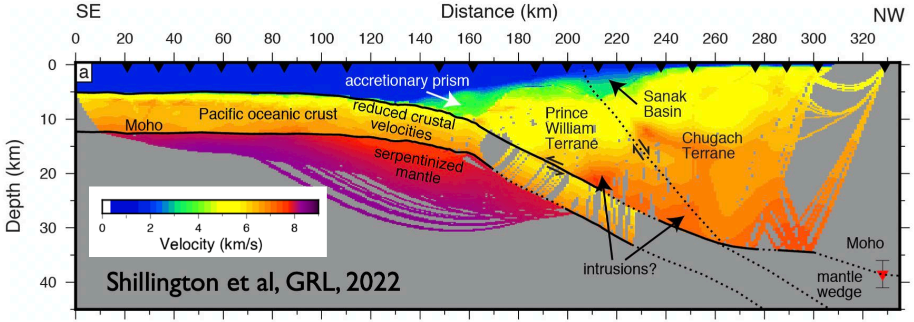


SEMIDI SEGMENT:
More sediments,
Less top-basement roughness
Less oceanic plate hydration

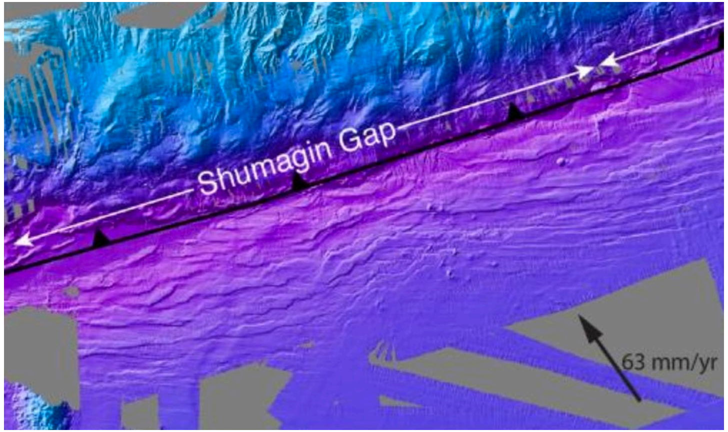
SHUMAGIN SEGMENT:
Less sediments
More top-basement roughness
More oceanic plate hydration



Clarke, Shillington et al., G3, 2024

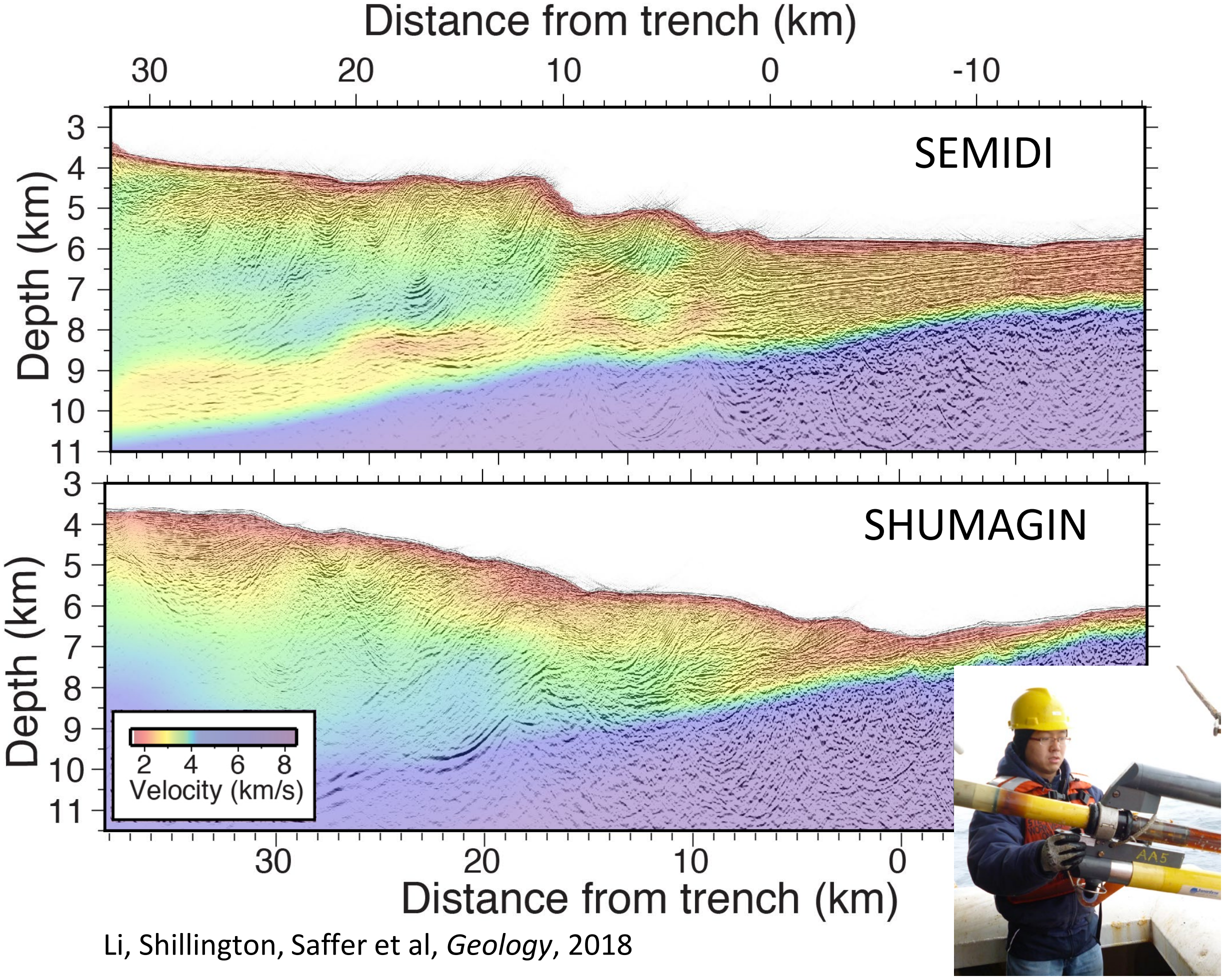


Shillington et al, GRL, 2022

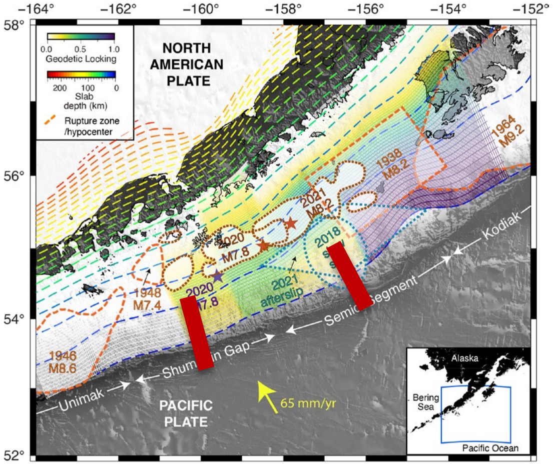


Work by
Jake Clarke,
former NAU
MS student

Structure of shallow part of megathrust



Li, Shillington, Saffer et al, *Geology*, 2018

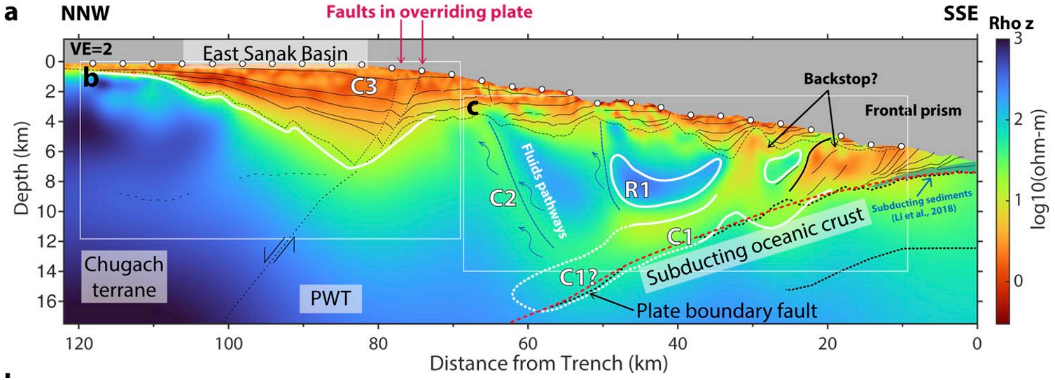


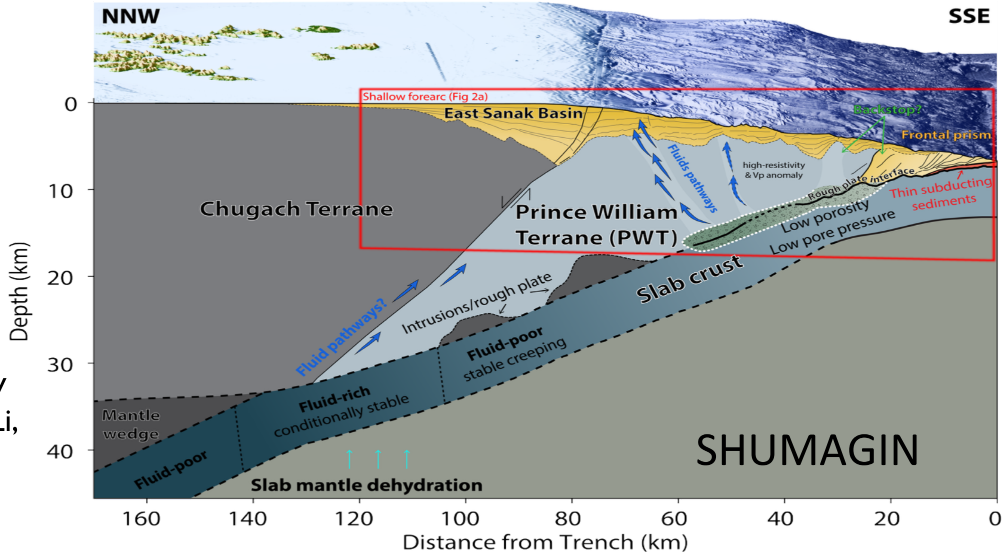
- Semidi: Thicker, continuous layer of low-velocity sediment along shallow plate boundary
- Shumagin: Small accretionary complex, limited subducting sediment, heterogeneous plate boundary

Work by Jiyao Li, former LDEO/Columbia PhD student

Source of fluids controls depth distribution of fluids along megathrust

- In Shumagin segment, main fluid sources are oceanic crust and mantle.
  - Fluids liberated from hydrated slab near base of seismogenic zone
  - On shallow megathrust, absence of pervasive elevated pore-fluid pressure
- In Semidi segment, main fluid source is sediment.
  - Shallow megathrust is fluid rich and overpressured





Y. Li, Naif, et al., *Nature Comm.* 2026

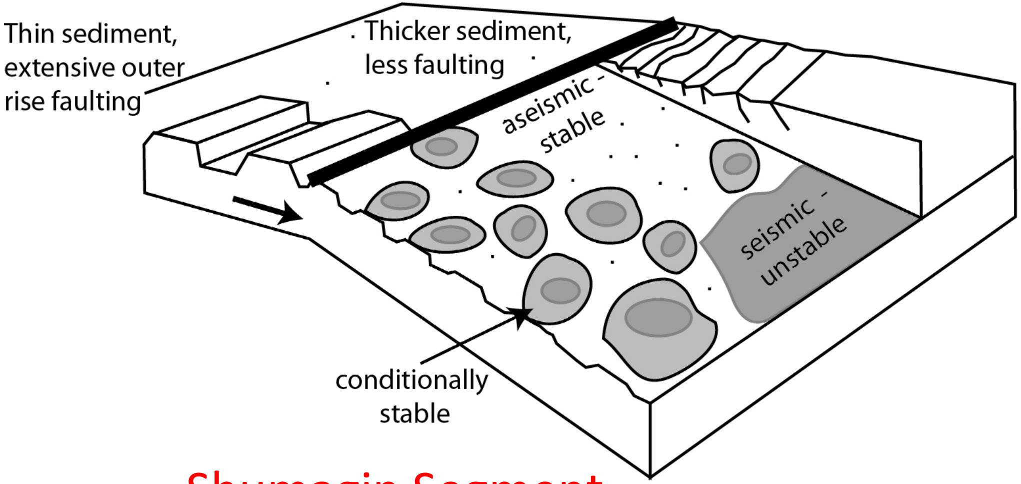
Shillington et al., 2015, Bécel et al., 2017; J. Li et al., 2018; Acquisto et al., 2022; Cordell et al, 2023; Y. Li et al, 2026

Work by Yinchu Li, Ga Tech PhD student

How do variations in inputs influence megathrust properties and behavior off the Alaska Peninsula?

- Semidi segment:
  - Thicker subducted sediment layer
  - Continuous overpressured sediment layer on shallow megathrust, which may inhibit shallow rupture and facilitate shallow slow slip (J Li et al., 2018)
- Shumagin segment:
  - Thinner sediments and more bend faulting
  - Heterogeneous plate boundary at all depths, which may explain abundant seismicity and creeping
  - Conditions for shallow slip and tsunamigenesis…? (Bécel et al, 2017)

Semidi Segment

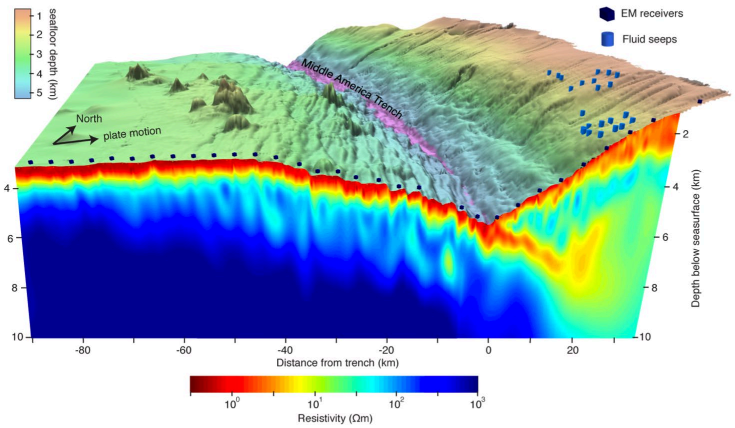


Shumagin Segment

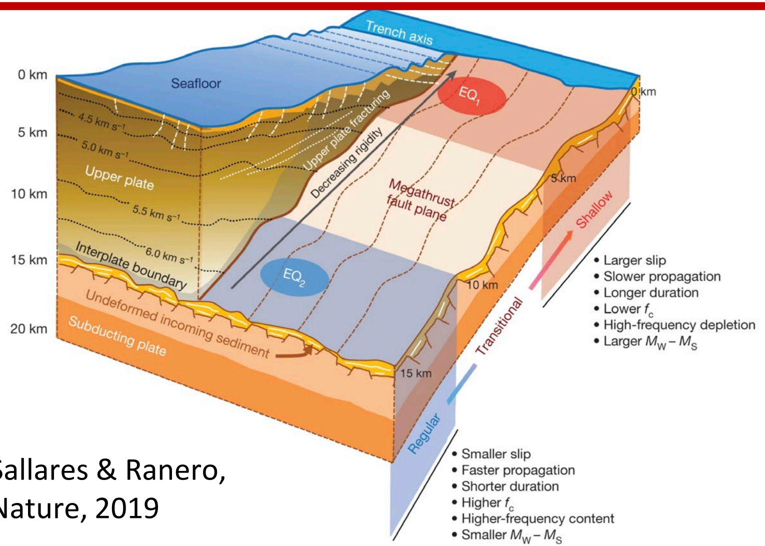
There is an upper plate story here too!

What explains downdip and along strike variations in properties and behavior of the megathrust?

- **Subducting plate:** Sediments, fluids, and topography may influence fluids and heterogeneity along plate boundary
- **Overriding plate:** Strength and permeability of overriding crust and depth of Moho may influence asperities, plate boundary properties and distribution of fluids



Naif, Key et al, *G3*, 2016



Sallares & Ranero, Nature, 2019

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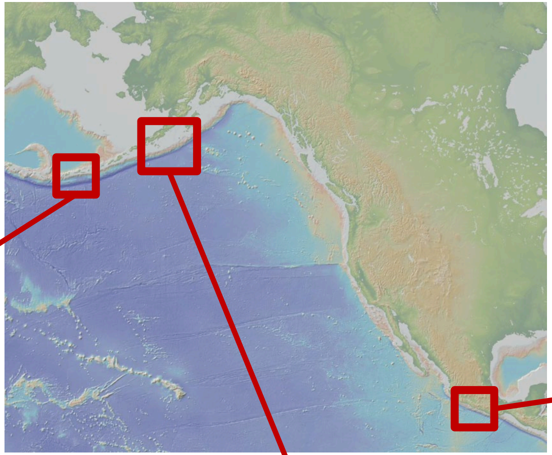
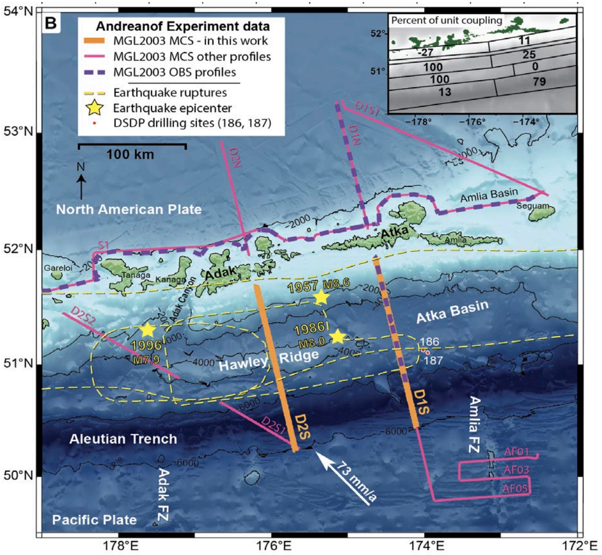
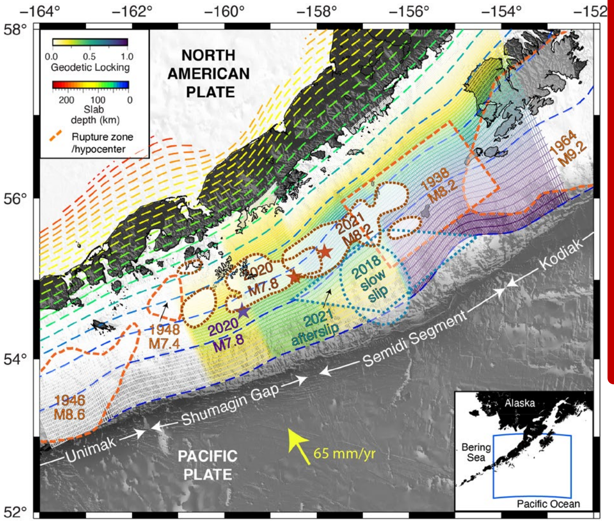


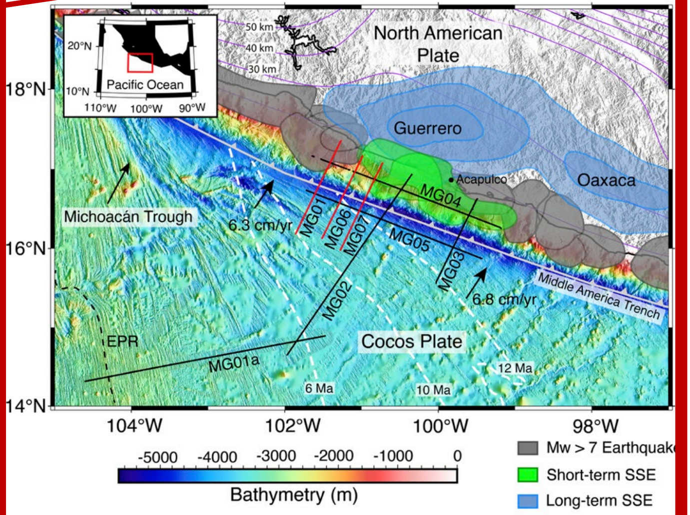
Aleutians



Alaska Peninsula

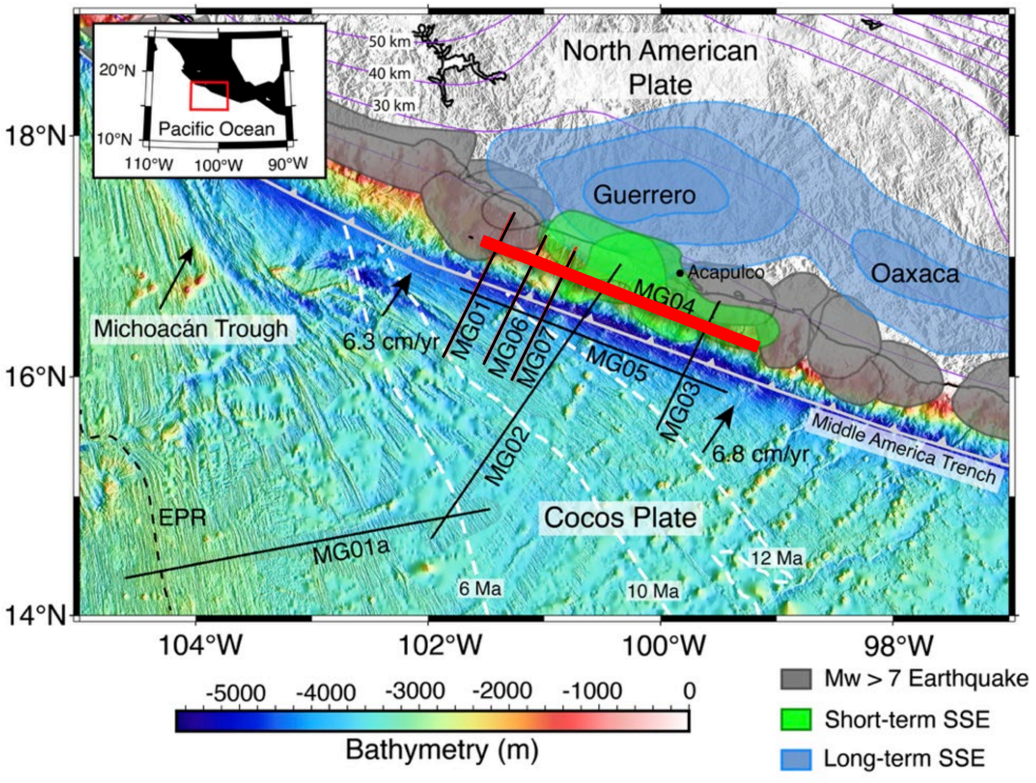


Mexico



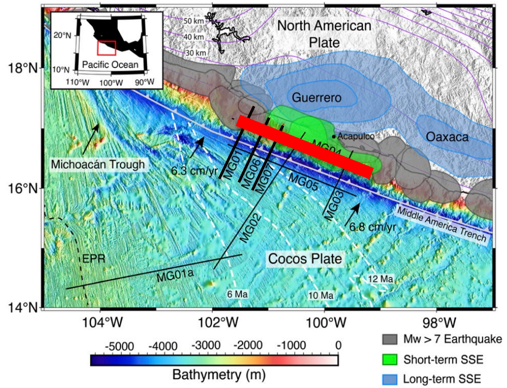
Variations in earthquake rupture and slow slip history offshore Mexico

- Most of the margin experiences regular Mw>7 earthquakes except Guerrero Gap, which has not ruptured in ~115 years
- Deep slow slip events every ~4 years
- Recent offshore geodetic work also reveals shallow slow slip

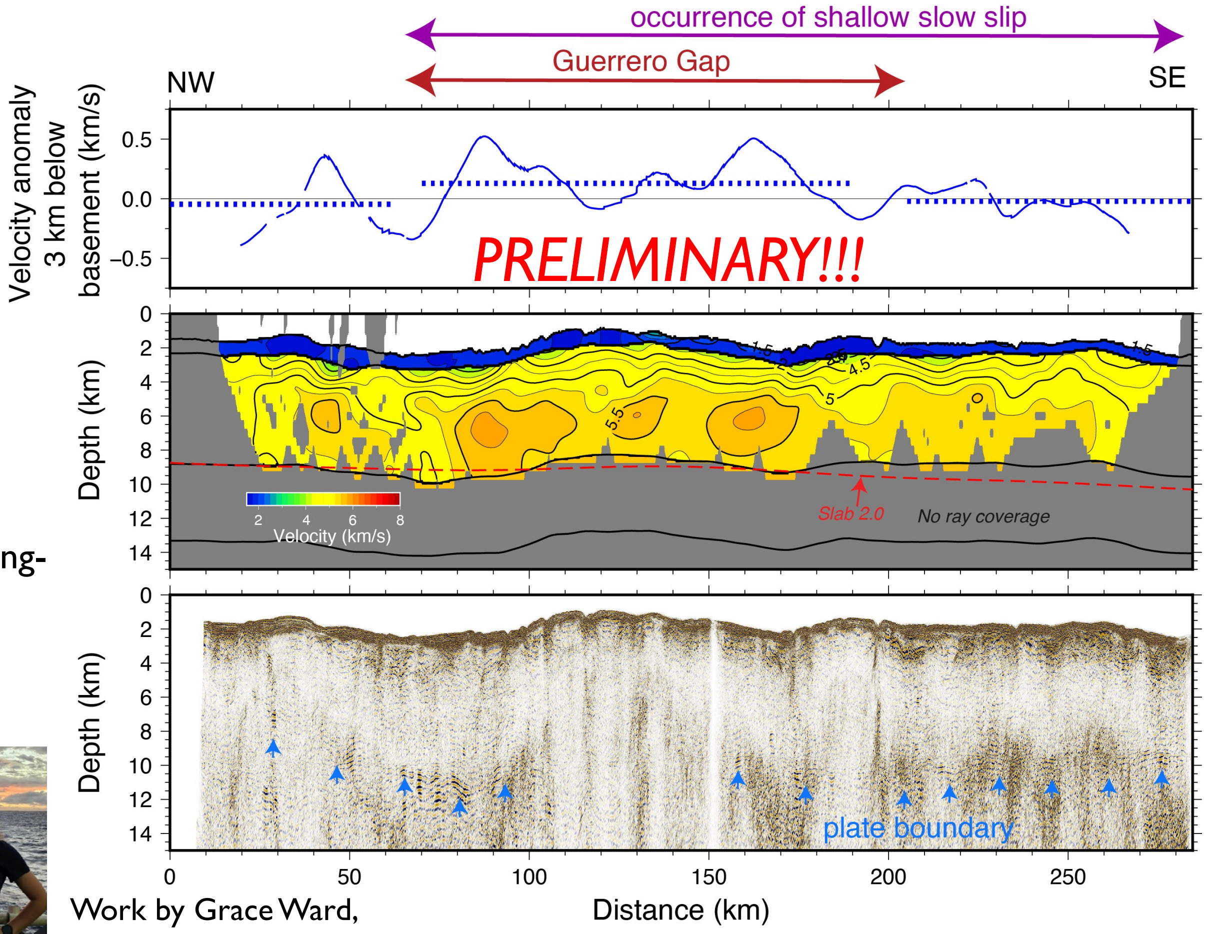


Large (Mw>7) earthquakes: Cruz-Atienza et al., 2021. Slab depth: Hayes et al., 2018. Long-term slow-slip events and short term slow-slip events: Cruz-Atienza et al., 2025b. Plate convergence: DeMets et al, 2010. Cocos plate age: Müller et al., 2008. From Hagemeier, Bécel et al, in review

Variations in upper plate permeability influence shallow slow slip?

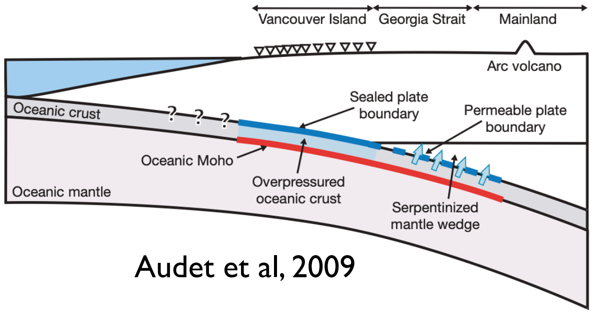


- Reduced forearc permeability due to long-lived mafic magmatism is proposed as a contributor to poor drainage and deep slow slip in Mexico
- Higher velocities in forearc crust in Guerrero – similar mechanism contributing to shallow slow slip??

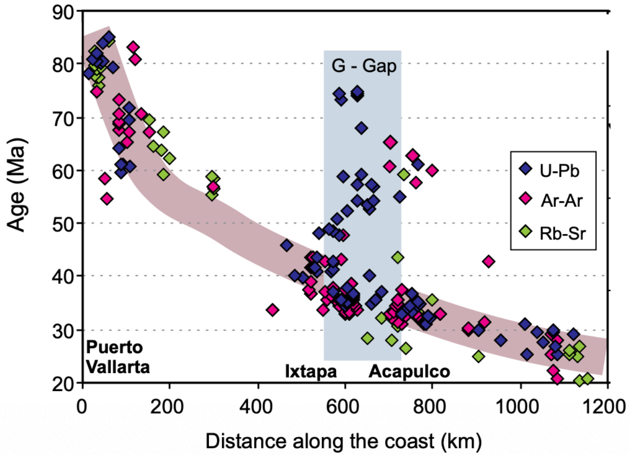


Work by Grace Ward, NAU MS student

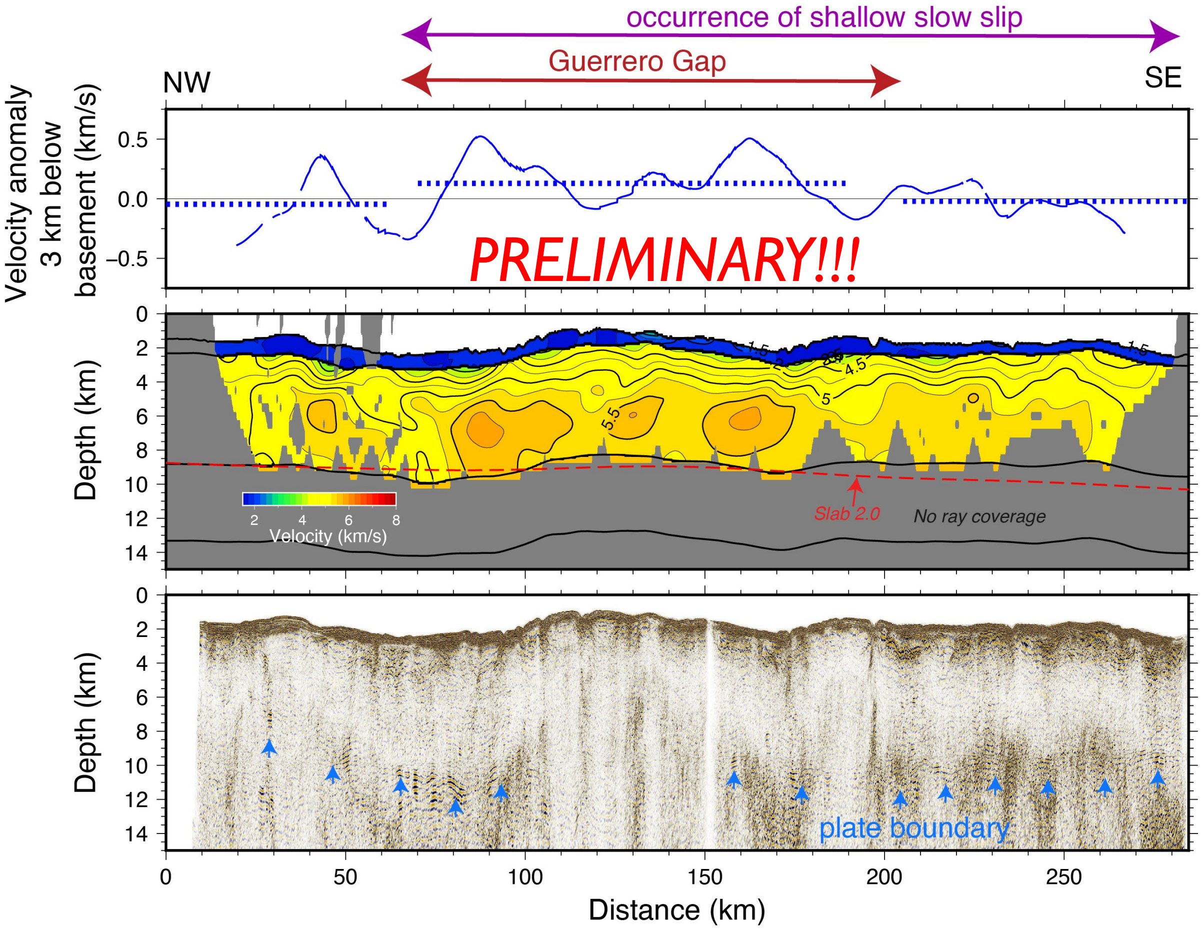
Variations in upper plate permeability influence shallow slow slip?



Audet et al, 2009



Husker et al, 2018



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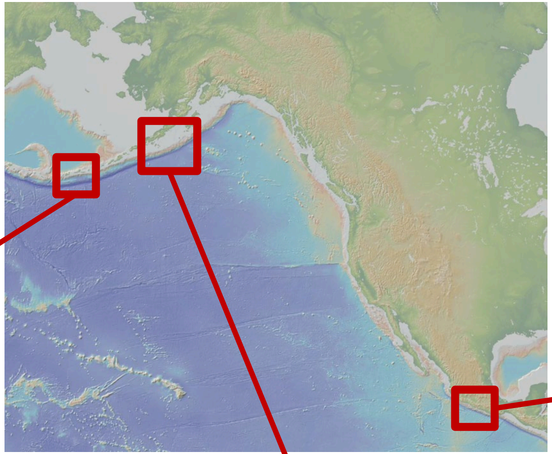
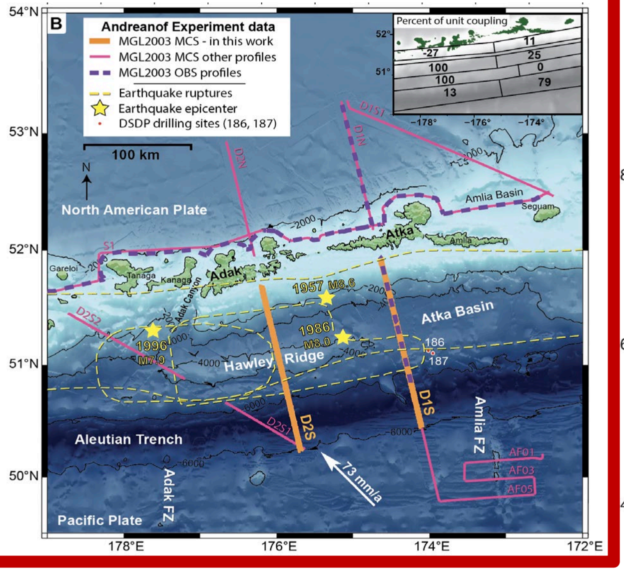
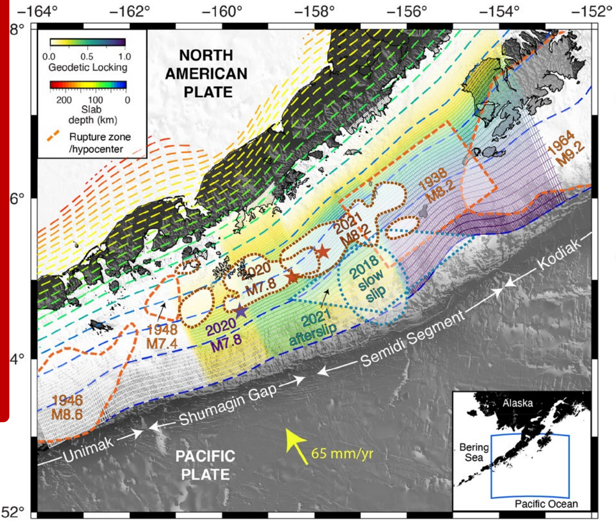


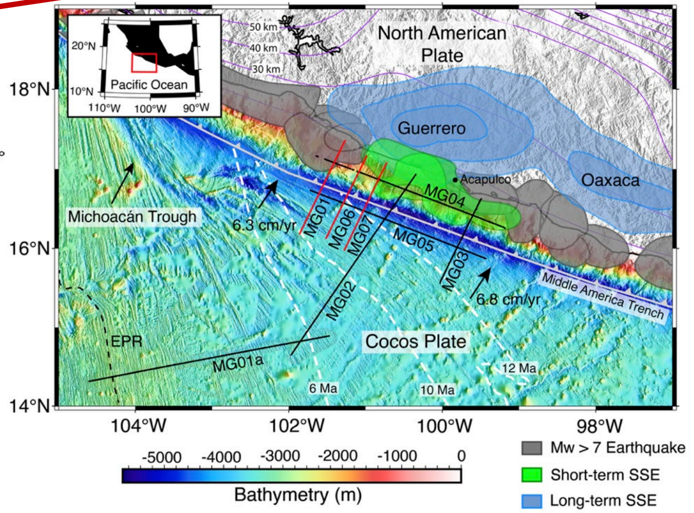
Aleutians



Alaska Peninsula



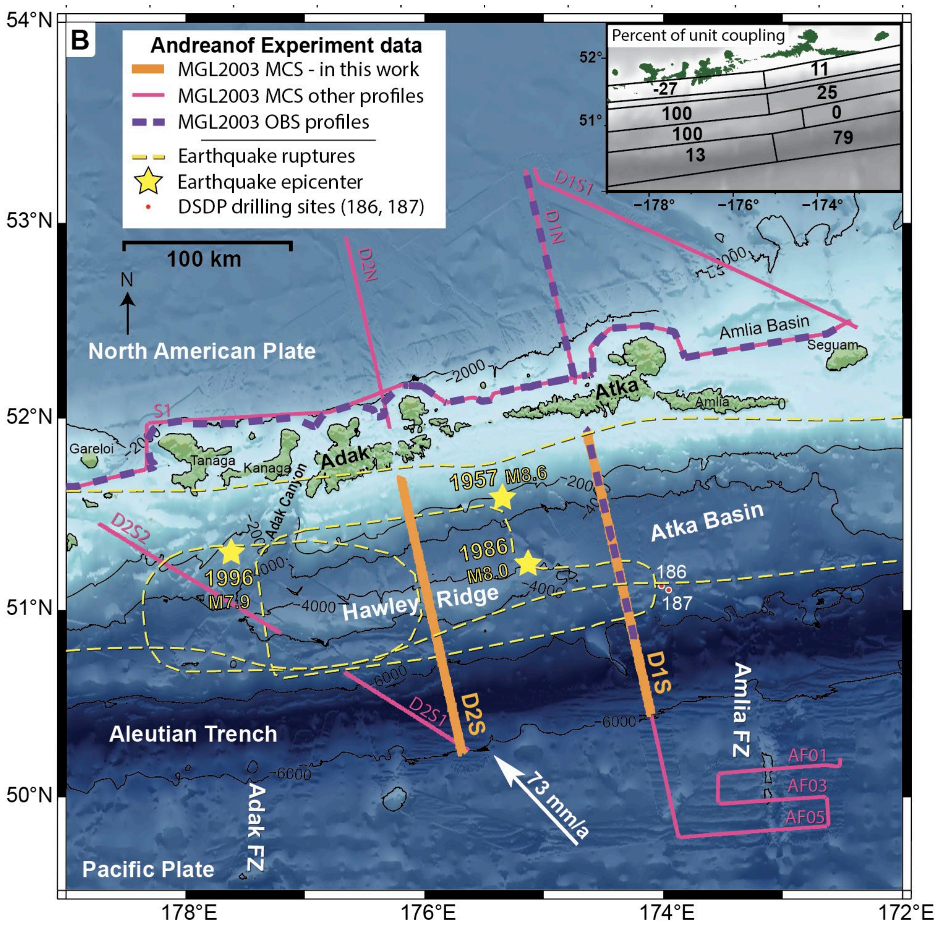
Mexico



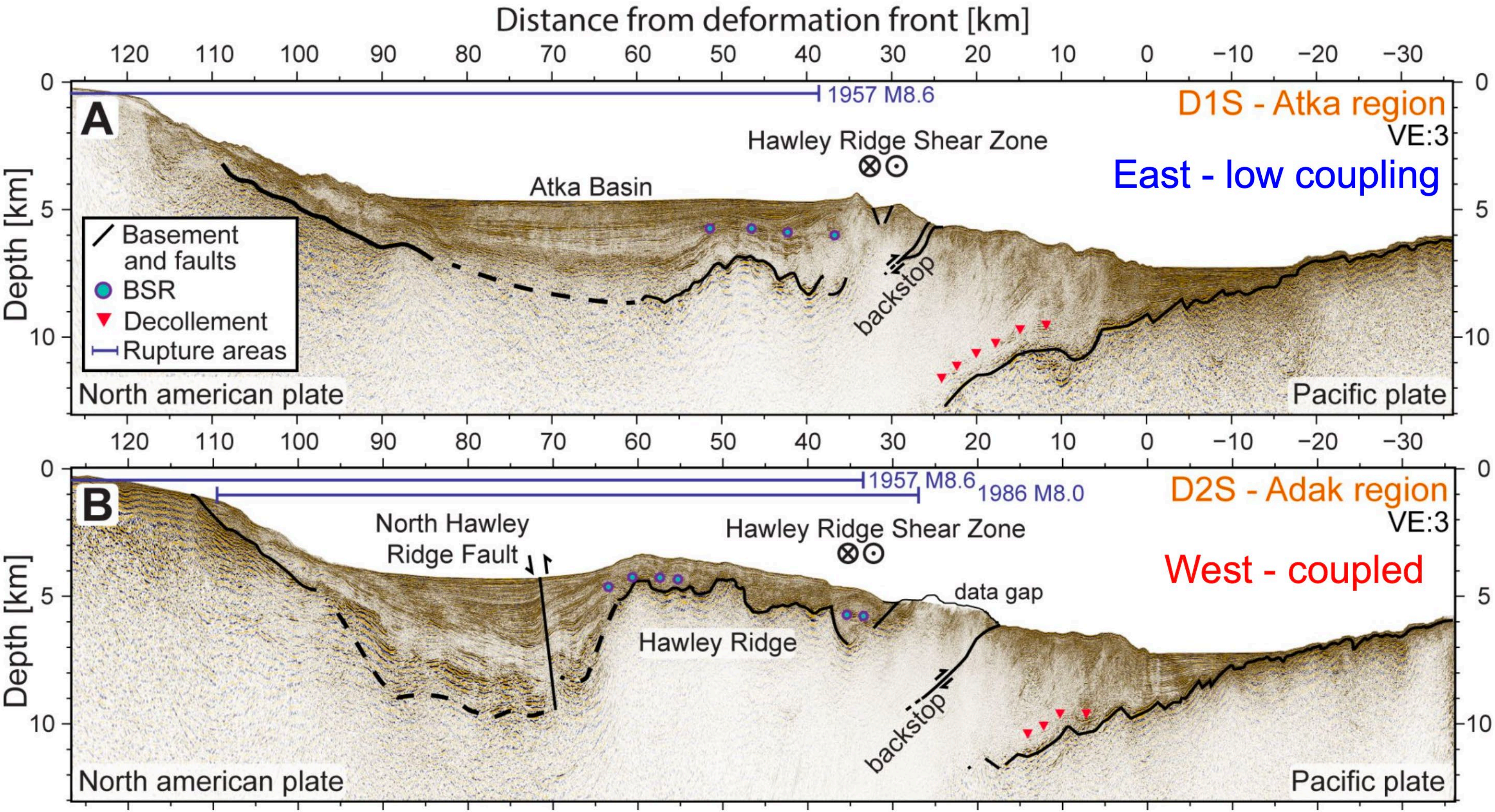
Variations in seismicity, locking and earthquake rupture history in the Andreanof region

- Offshore Adak:
  - Higher coupling
  - More frequent large earthquakes
- Offshore Atka:
  - Lower coupling
  - Less frequent large earthquakes

Work by Valeria Cortés Rivas, former NAU PhD student, currently postdoc at Pontificia Universidad Católica de Chile

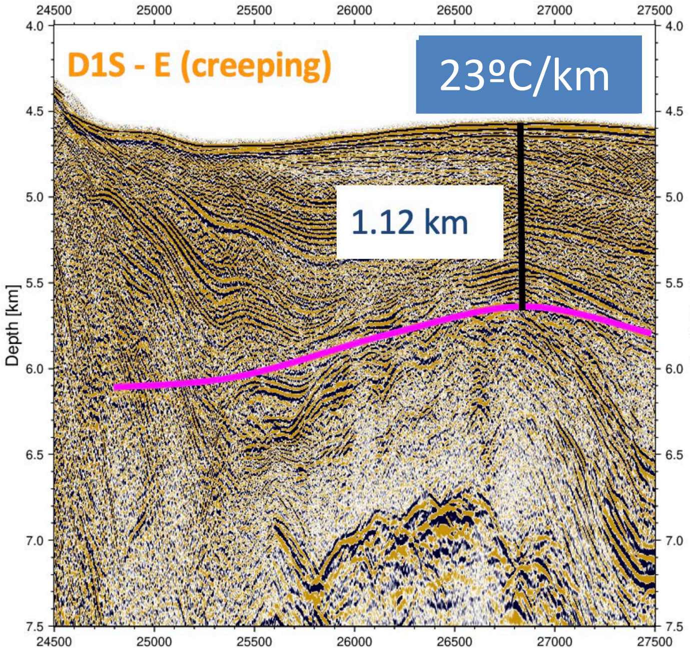


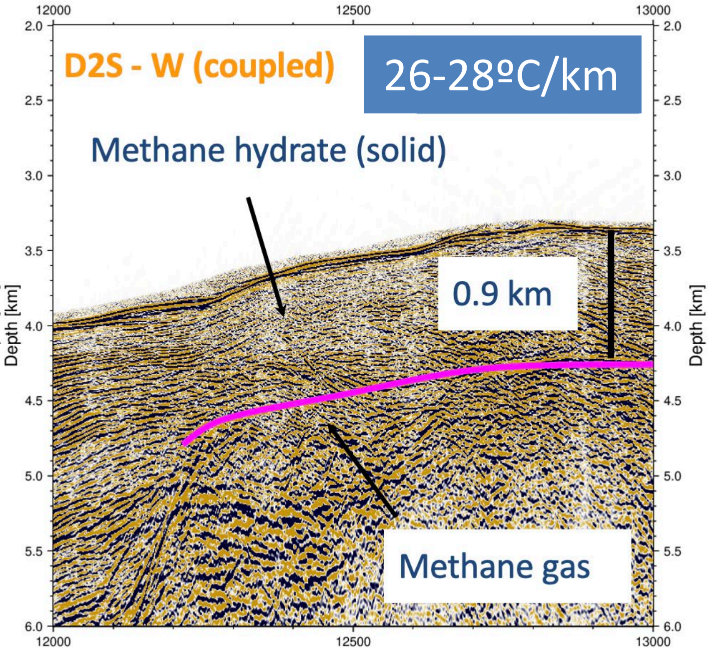
Cortés-Rivas, Shillington et al, 2025, Ruptures: Yamazaki et al., 2024; Engdahl et al., 1989; Tanioka and Gonzalez, 1998. Coupling: Cross & Freymueller, 2007



Cortés-Rivas, Shillington et al, *Geology*, 2025

Clues on forearc permeability from the BSR

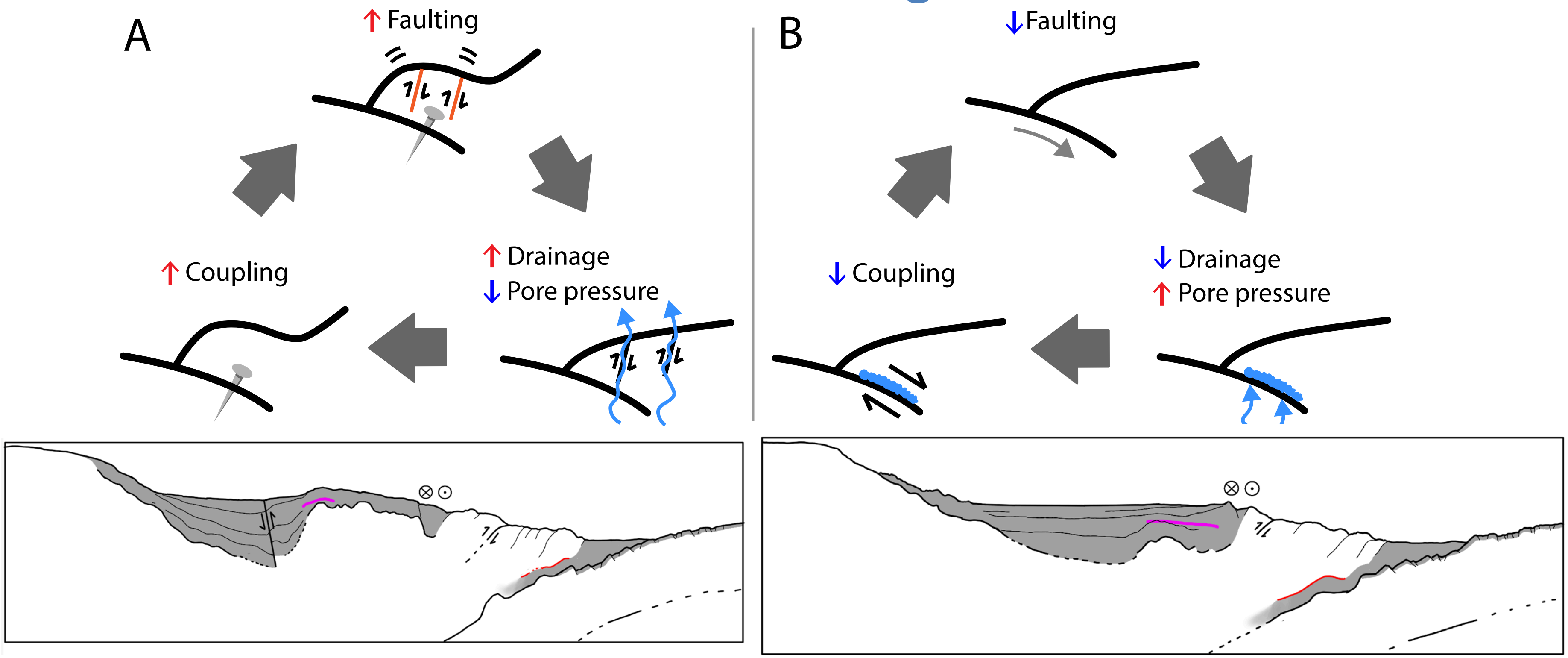




- BSR is a phase boundary between methane hydrate ('ice') and methane gas, and thus is a way to estimate temperature

- Large differences in subduction zone temperature structure not expected here, so changes interpreted to reflect greater heat advection due to fluid flow offshore Adak compared to Atka.
- Implies greater retention of fluids along the plate boundary in the creeping Atka region.

Forearc deformation and permeability influence fluid retention on megathrust



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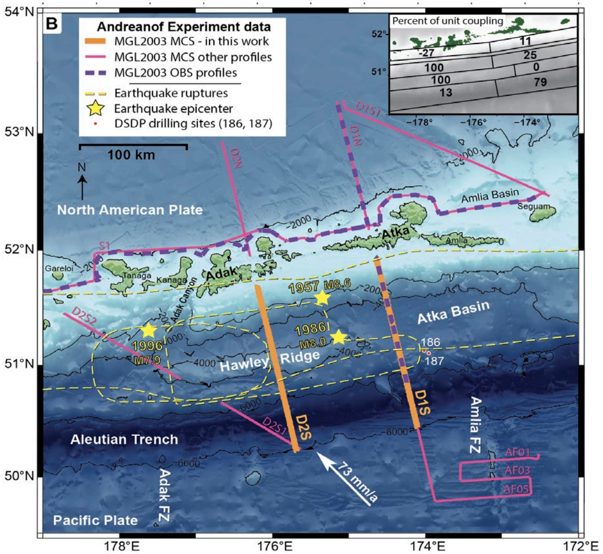
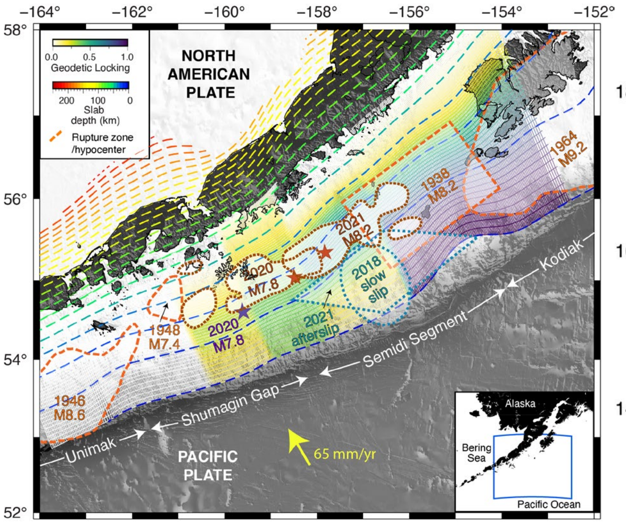


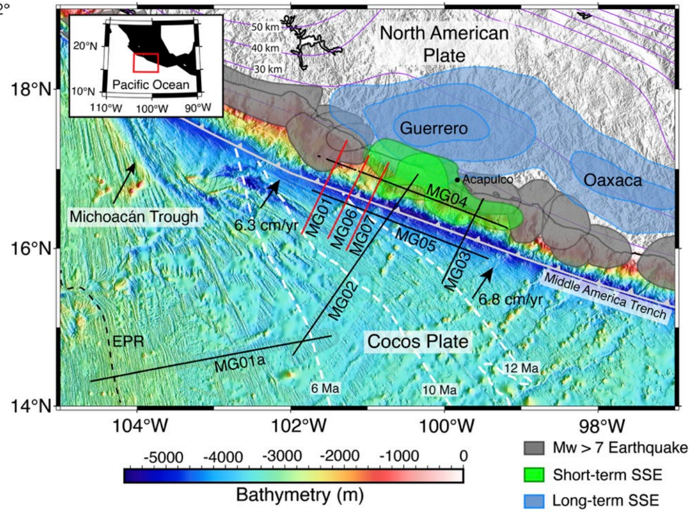
Feedbacks between coupling, forearc deformation, permeability and drainage

Alaska Peninsula



Subduction zone inputs and upper plate rigidity influence along-strike and downdip changes in slip behavior

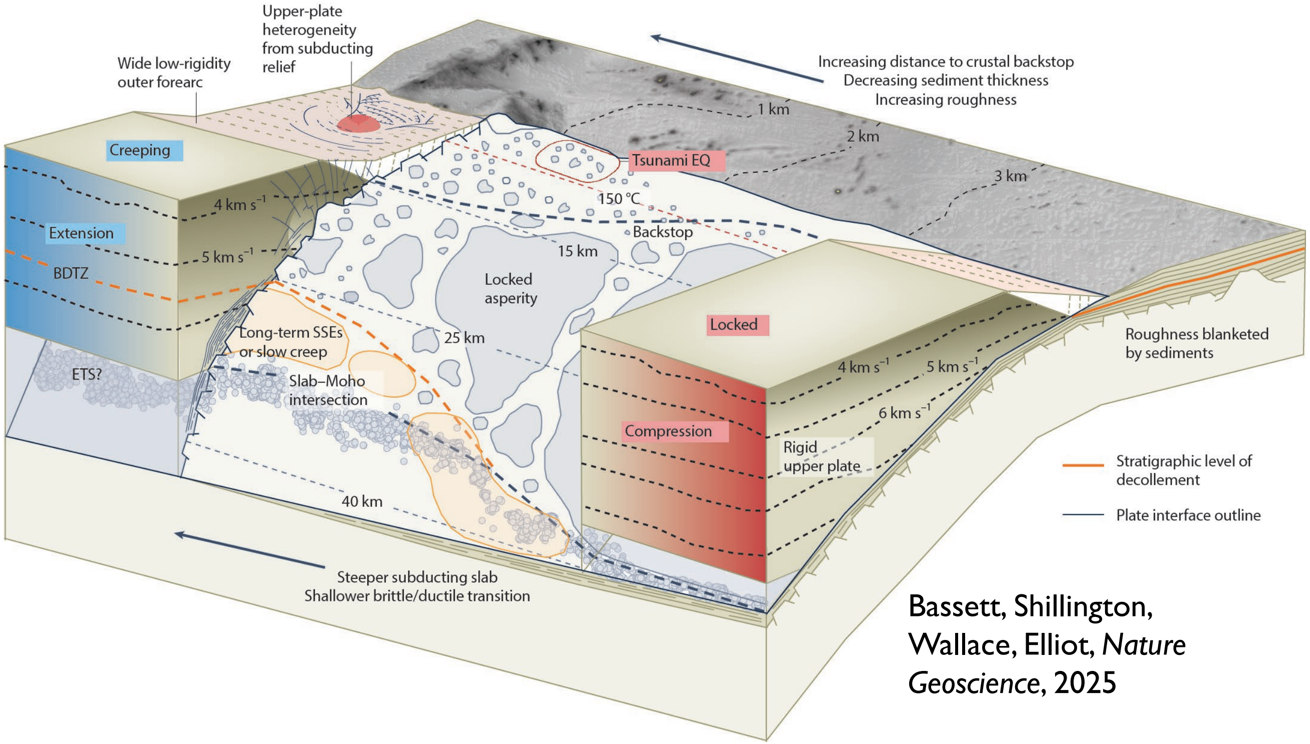
Mexico



Preliminary! Upper plate permeability promotes shallow slow slip?

Takeaway: Multiple physical factors control megathrust slip behavior

Studies from subduction zones with along-strike variations in behavior showcase the suite of physical parameters that conspire to influence megathrust behavior



Bassett, Shillington, Wallace, Elliot, *Nature Geoscience*, 2025