Evidence for megathrust locking and shallow coseismic slip in the Cascadia accretionary wedge

Harold Tobin, Anna Ledeczi, Madeleine Lucas

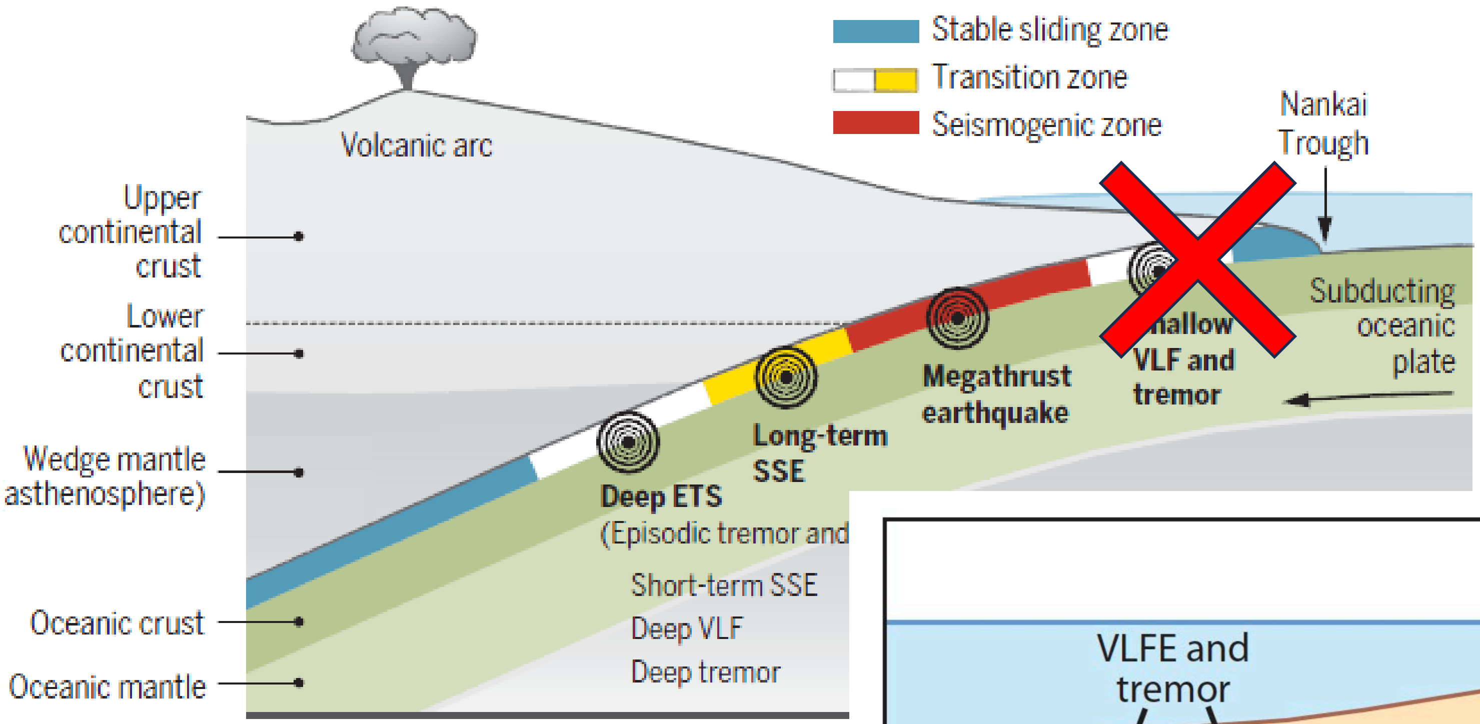
University of Washington

Fault Structure Stress & Tectonics at UW

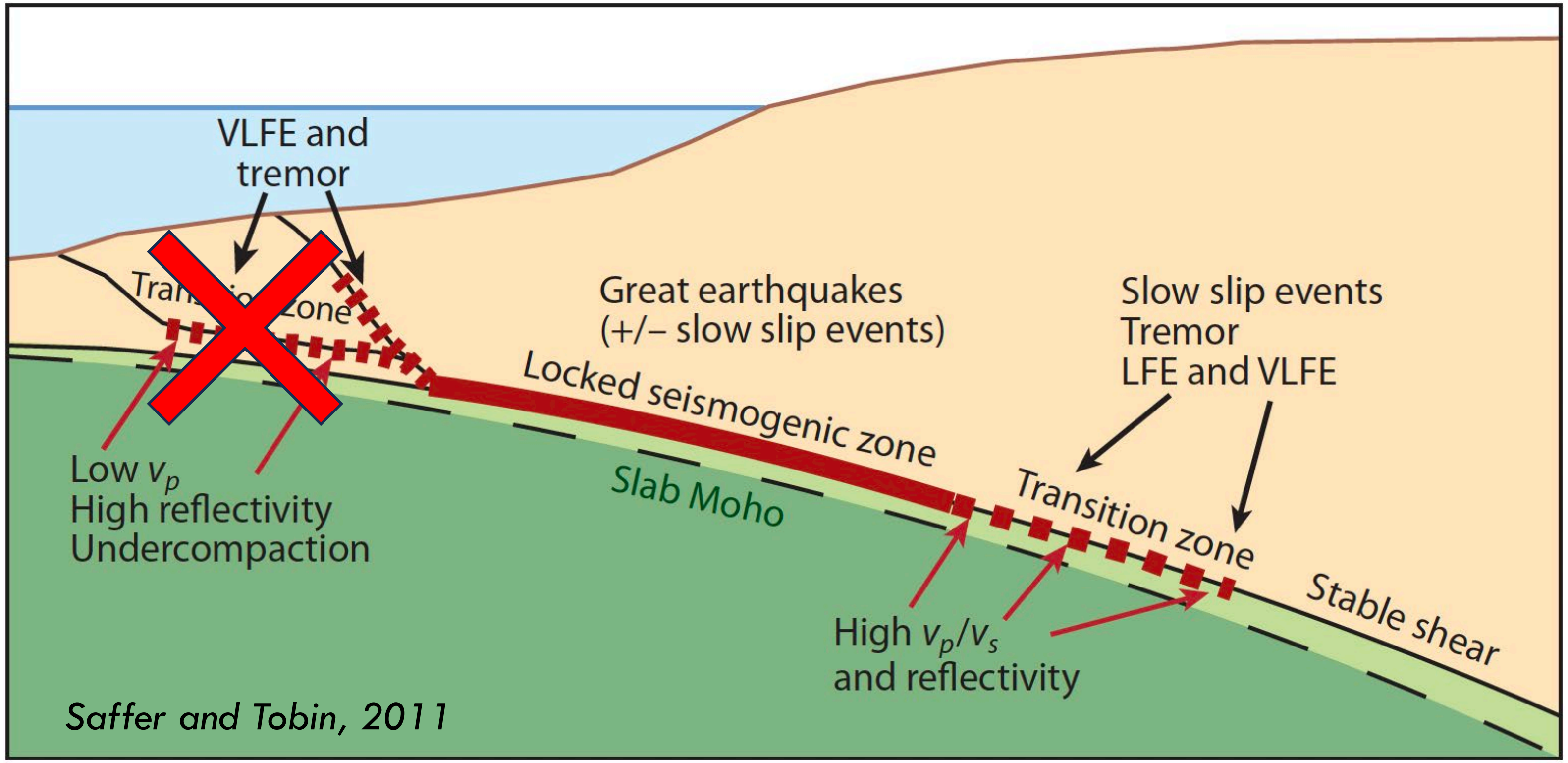
FaSST

Generic paradigm:
Locked seismogenic zone is flanked by aseismic or conditionally stable regions

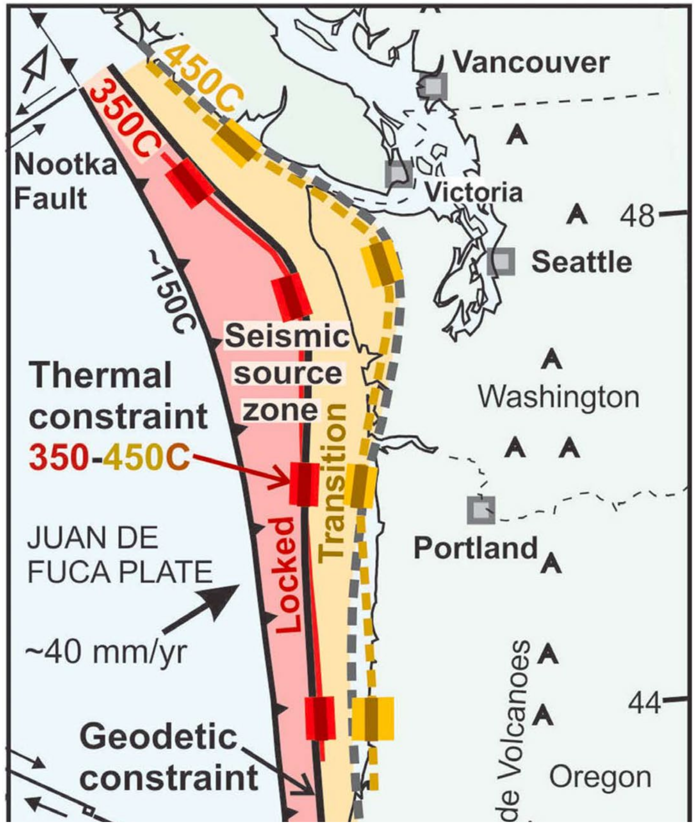
Cascadia is not typical!



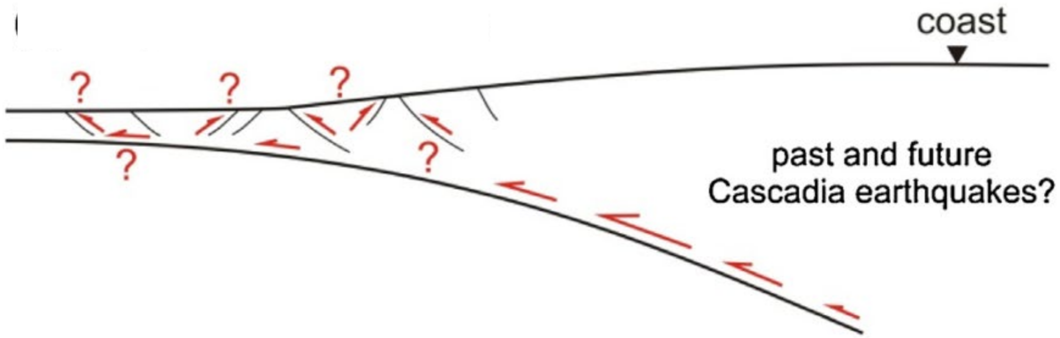
Obara and Kato, 2016



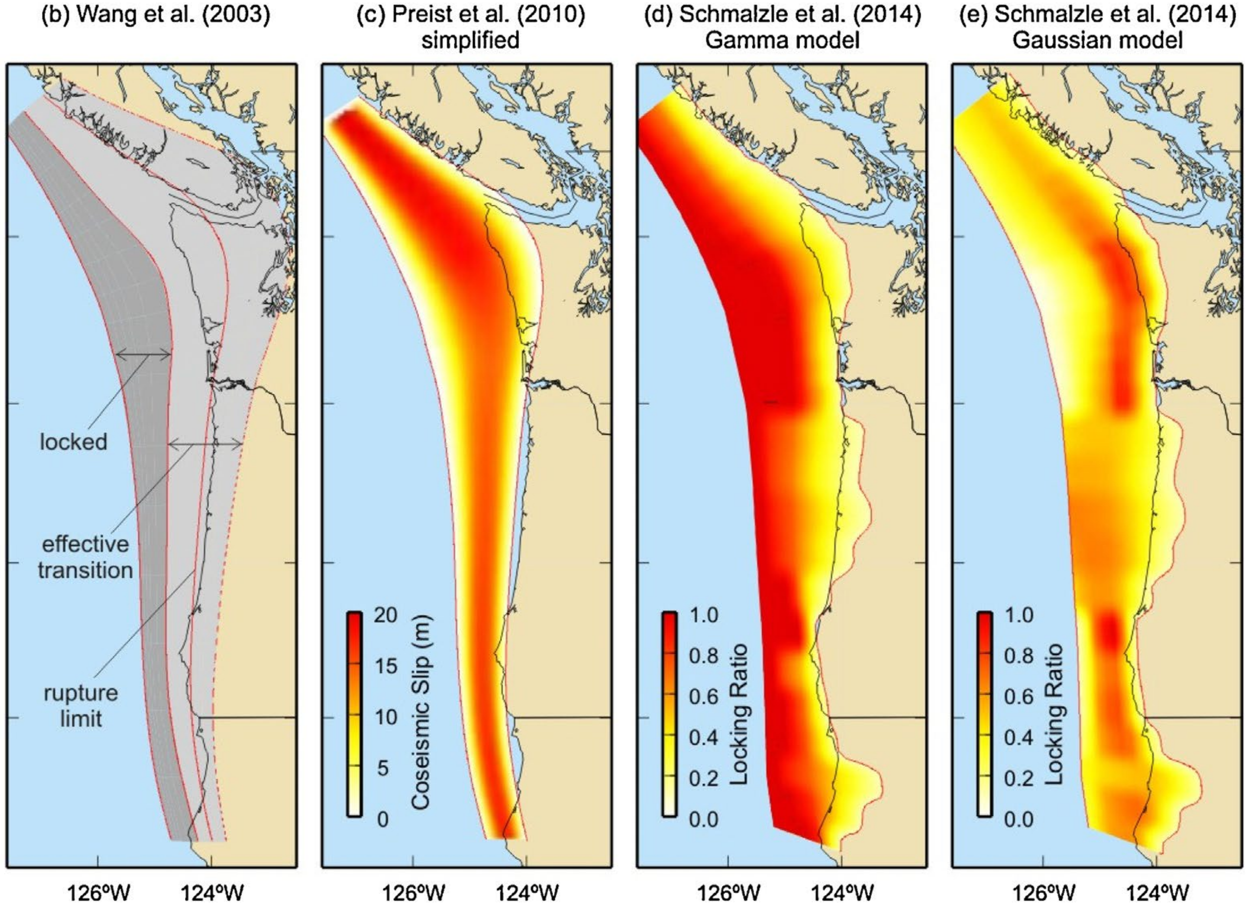
Thermal controls



Hyndman et al., 1995, 2015



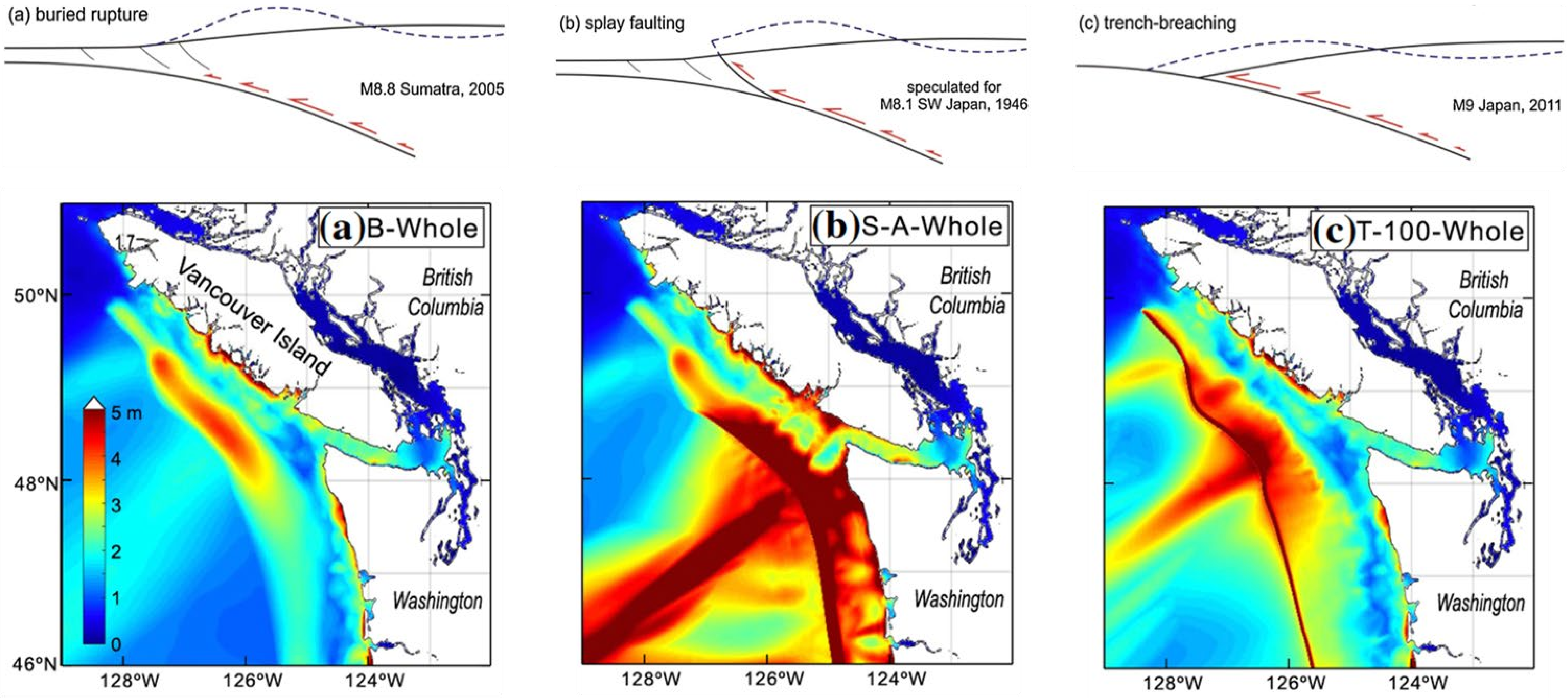
Wang and Trehu [2016]



From the earliest work on the up-dip limit (Hyndman 1993, etc.), Cascadia was recognized as being ≥150° at the deformation front

What is the shallow locking state in Cascadia? Where will rupture go?

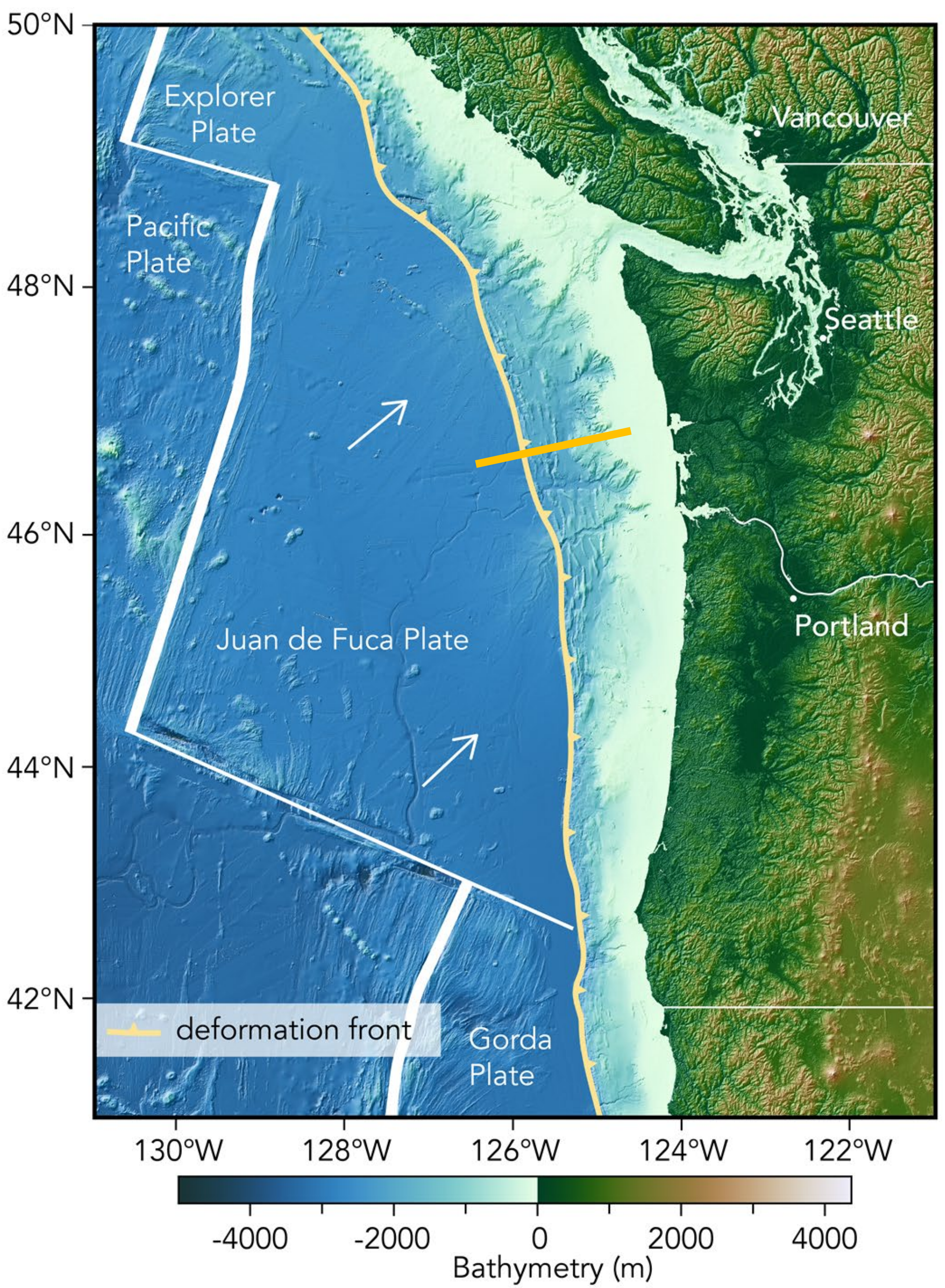
Shallow rupture and **megasplay** rupture both impact tsunami hazard



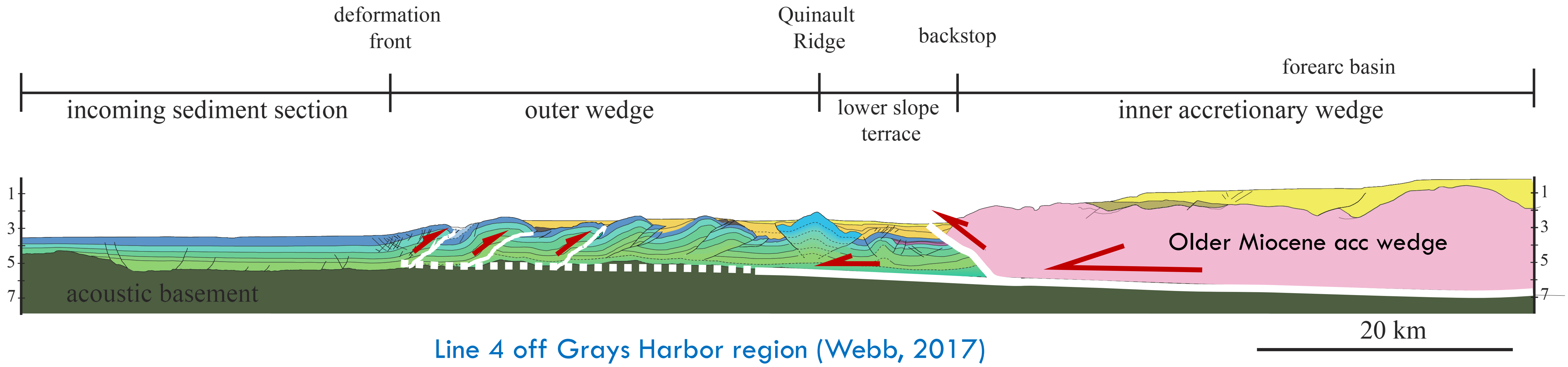
top: Wang & Trehu (2016) bottom: Gao et al. (2018)

Cascadia structure offshore

- Young, hot plate subducts ~40 mm/yr
- Potential for M9 class event:
  - Recurrence time ~450-500 years
  - Most recent was 325 years ago
- Wide & high-volume accretionary wedge of deformed sediments above the shallowly-dipping megathrust fault
- Widest and flattest off Washington state where it is also now accumulating the greatest elastic strain (*slip deficit*)



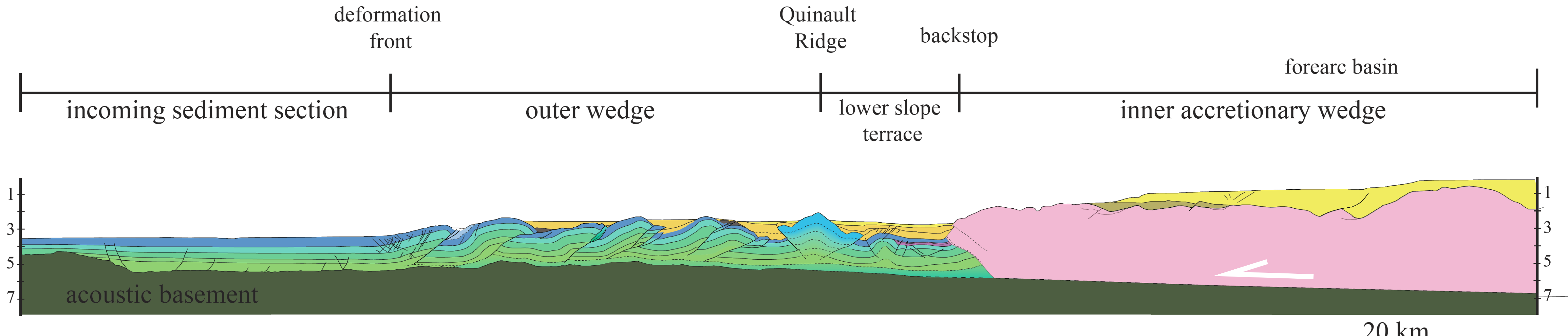
Central Cascadia: Evidence of outer wedge rupture and/or mega-splay fault slip



Line 4 off Grays Harbor region (Webb, 2017)

- *How far out to the deformation front does fast slip go on the megathrust décollement?*
- *What about shallow splay faults that reach the surface?*
- *Is there evidence of a mega-splay fault?*

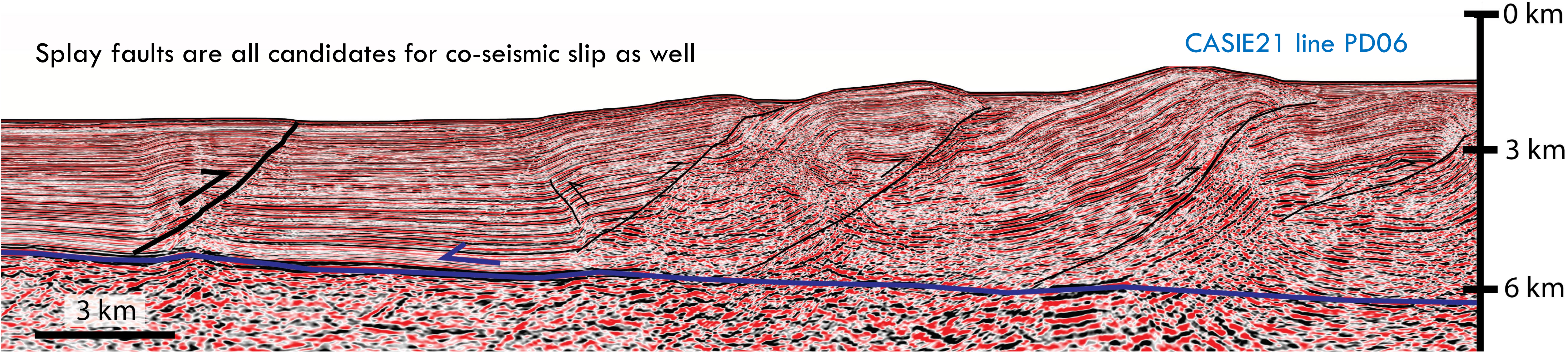
Cascadia's *landward-vergent* fold and thrust wedge

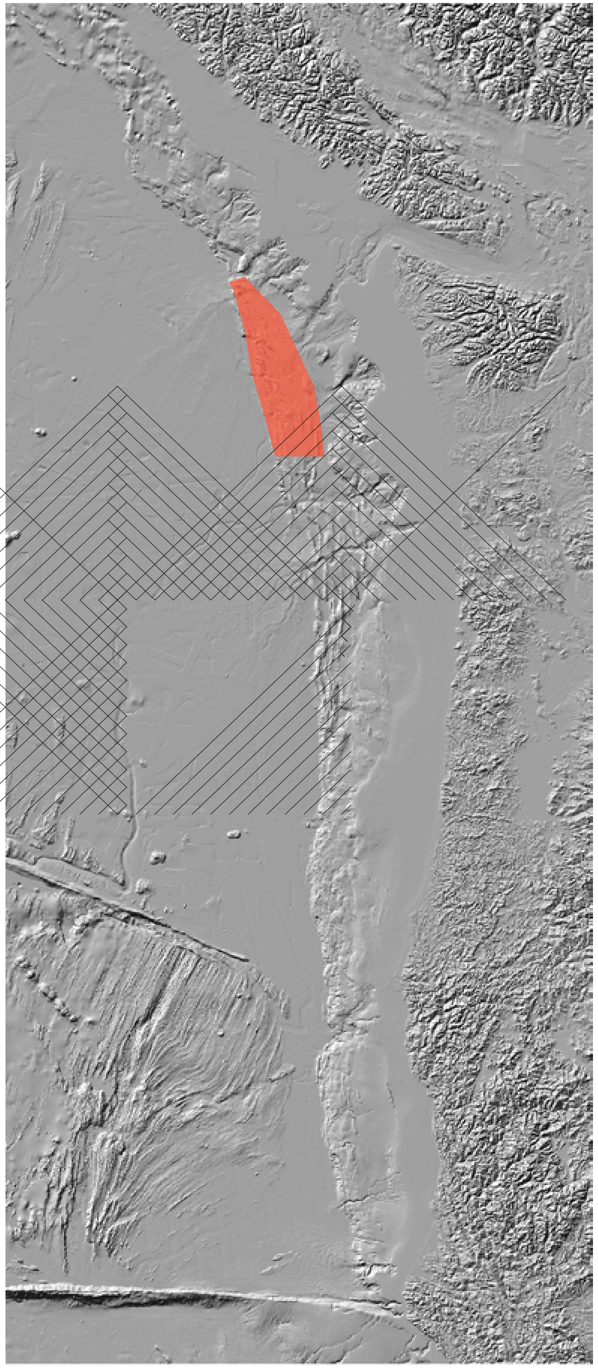


COAST line 4 off Grays Harbor region (Webb, 2017)

Decollement is the plate boundary, and lies **~3 km** below the surface <u>right at the deformation front</u>

Splay faults are all candidates for co-seismic slip as well





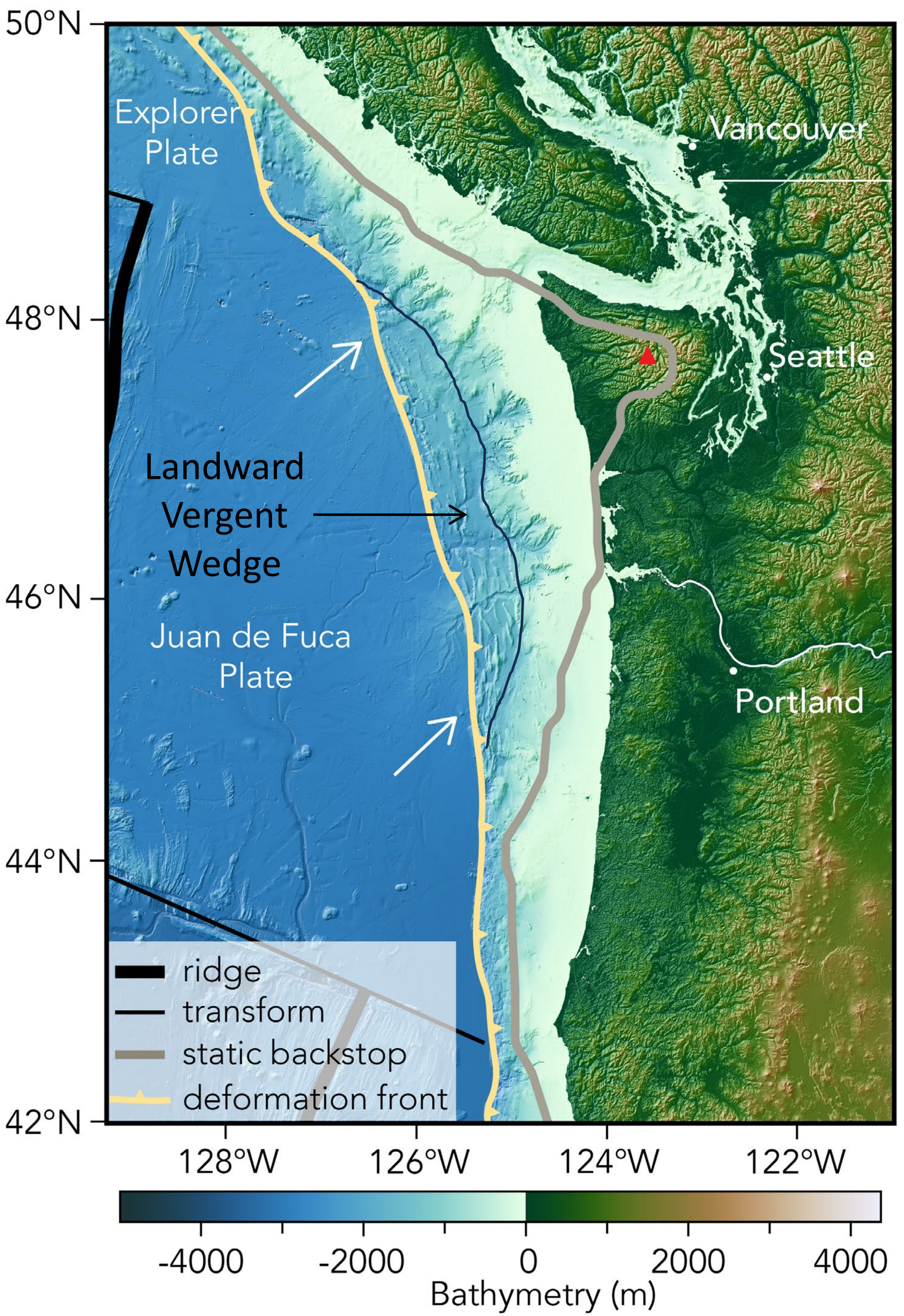
Landward Vergence Zone(s)

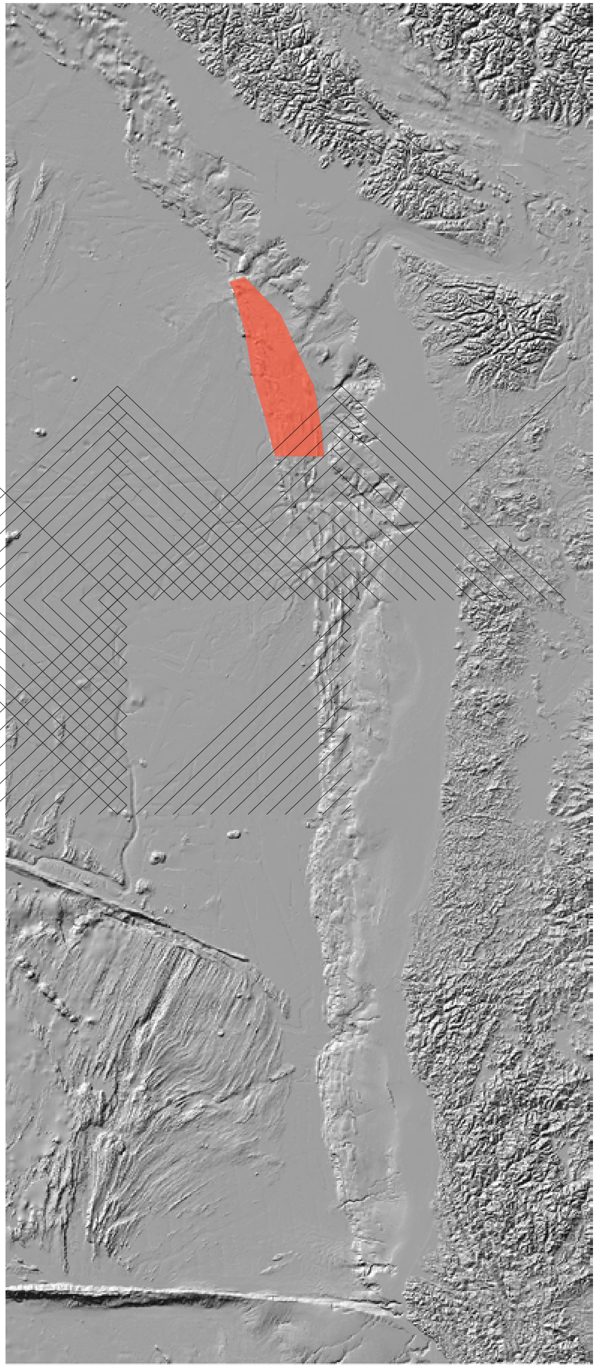
Landward vergence zone has been recognized since Seely, 1977 -- (also MacKay et al., 1995; Gulick et al., 1998; Adam et al., 2004, etc.)

Systematic LV is globally very rare – most extensively developed LVZ is Cascadia (also Sumatra 2004 M9)

Northern and southern patches at Cascadia

Watt & Brothers, 2021





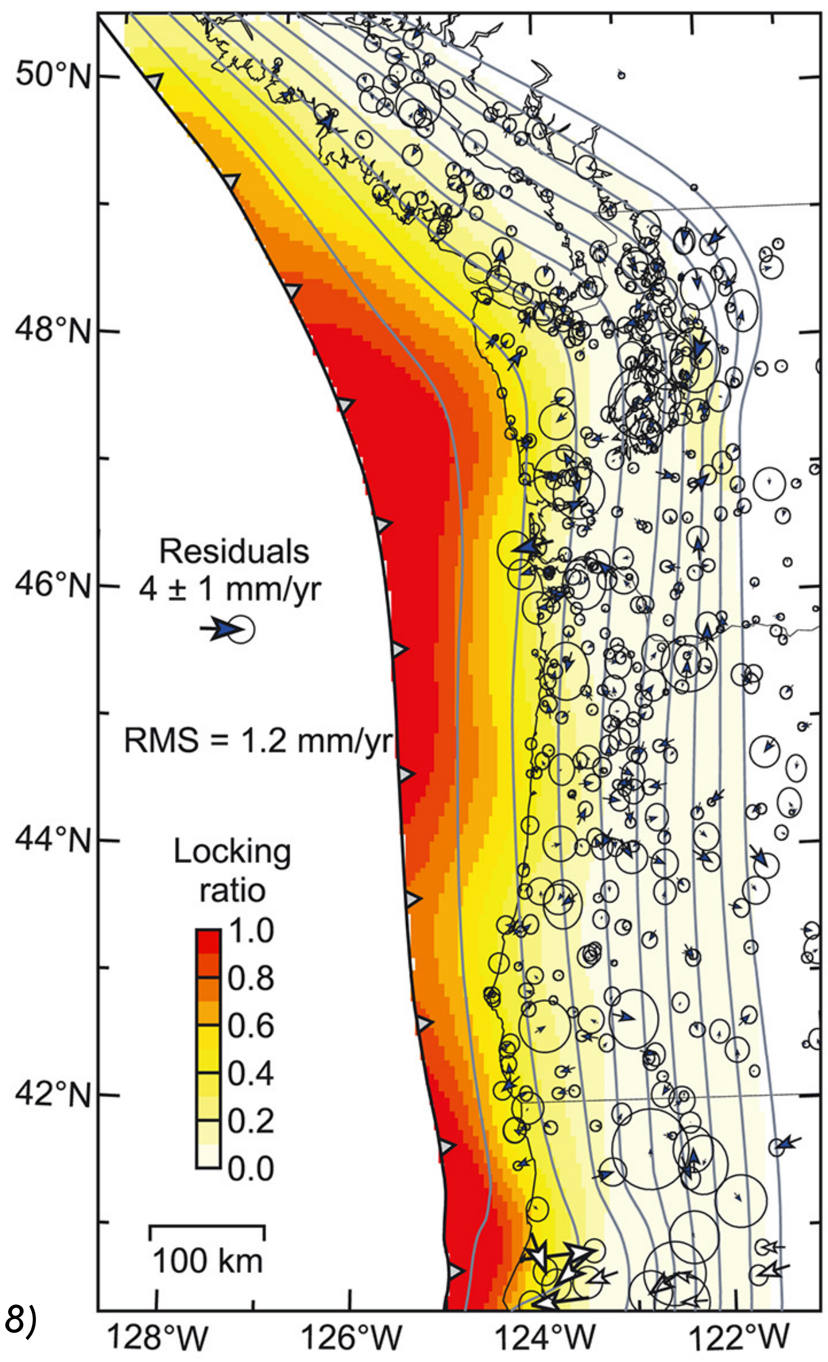
Landward Vergence and Geodetic Locking:

Coincidence?

Geodetic locking models for Cascadia suggest it is locked to the trench for most of the length

The extent of the LV dominated zone corresponds to this geophysical evidence of present-day locking and slip deficit of the plate boundary

Watt & Brothers (2021)



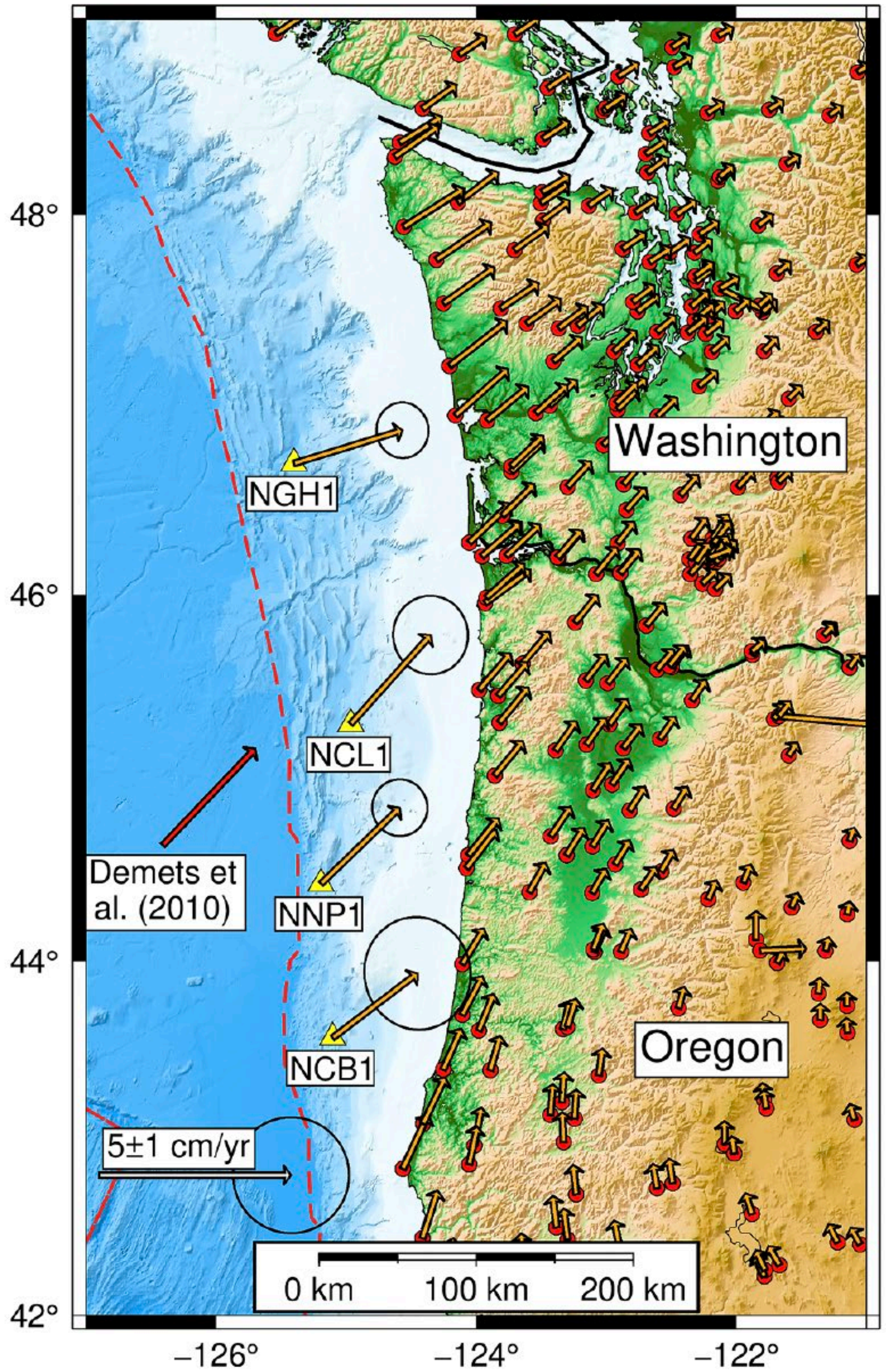
Li et al., (2018)

New offshore geodesy from GNSS-A

Consistent with models showing strong up-dip locking

Are conditions in the plate boundary consistent with shallow locking?

DeSanto et al., 2025 EPSL



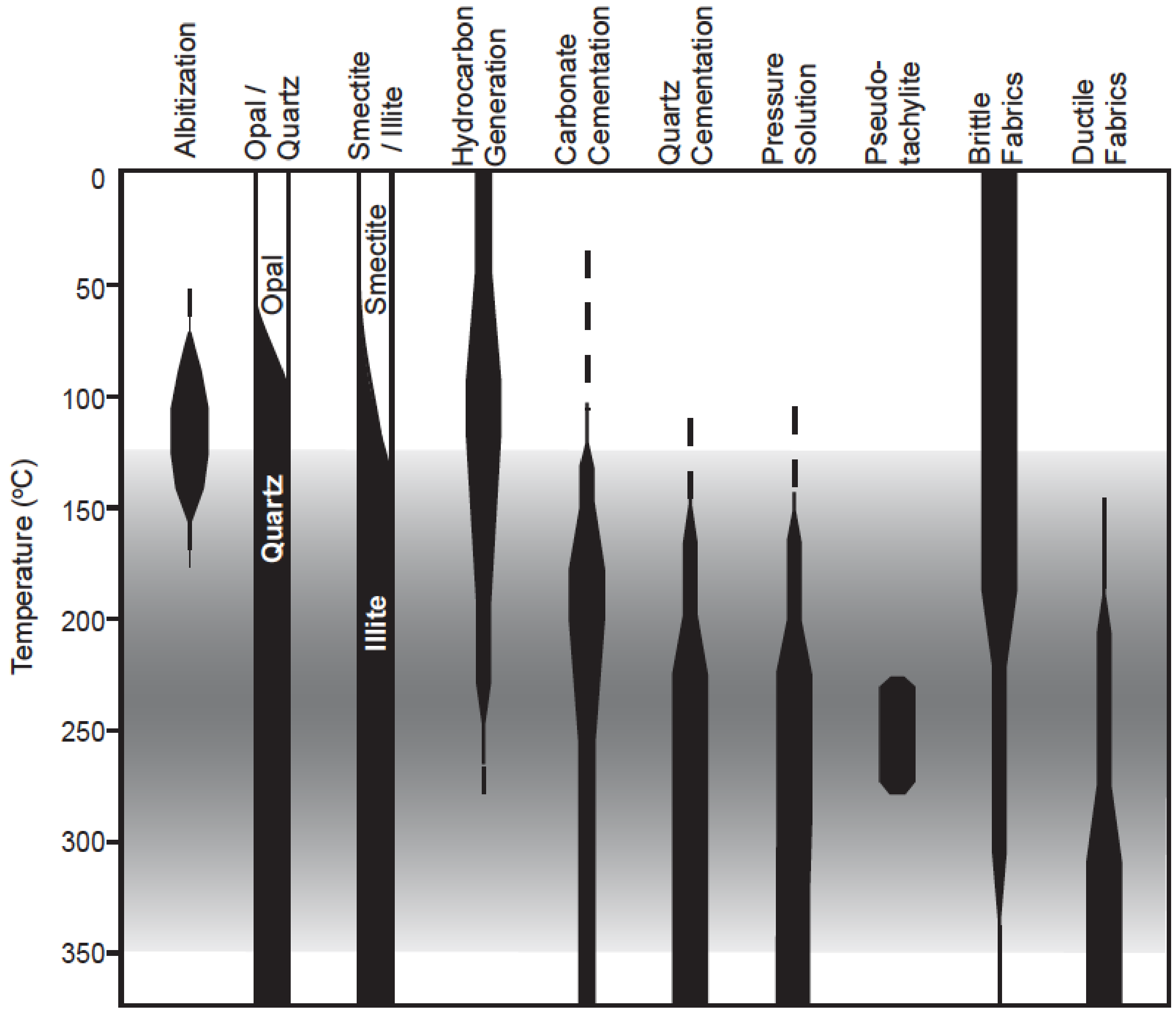
What controls <u>frictional locking behavior</u> of the shallow subduction zone decollement?

- **Fault-normal stress** magnitude (burial)
- **Strength** (rigidity) at fault depth: lithification and cementation
- **Pore fluid pressure**
- Wall-rock strength (compliance) especially the upper plate

Rate-state framework defining velocity-strengthening (stable creep) vs. velocity weakening (unstable & seismic)

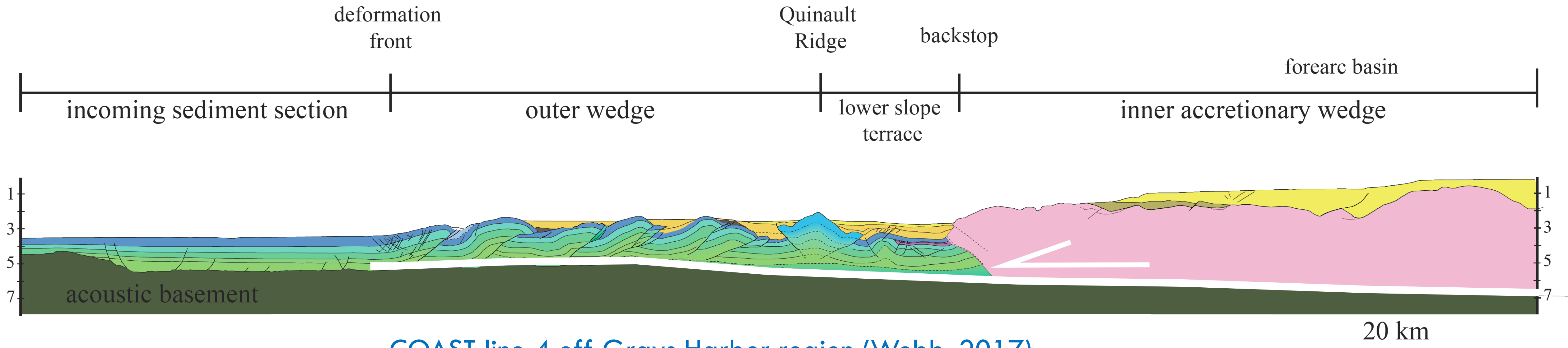
Mineralization and fluid sources change with temperature in typical s.z. sediments

→ ***~100 - 150˚ C is a transition for many processes***



Moore, 2007

“Slip to the trench” = slip to the toe at décollement depth



COAST line 4 off Grays Harbor region (Webb, 2017)

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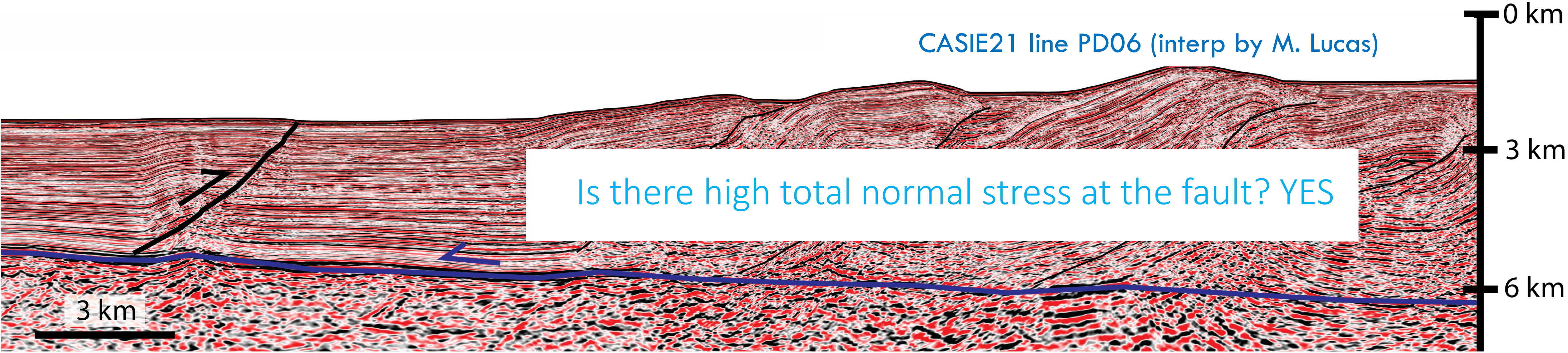


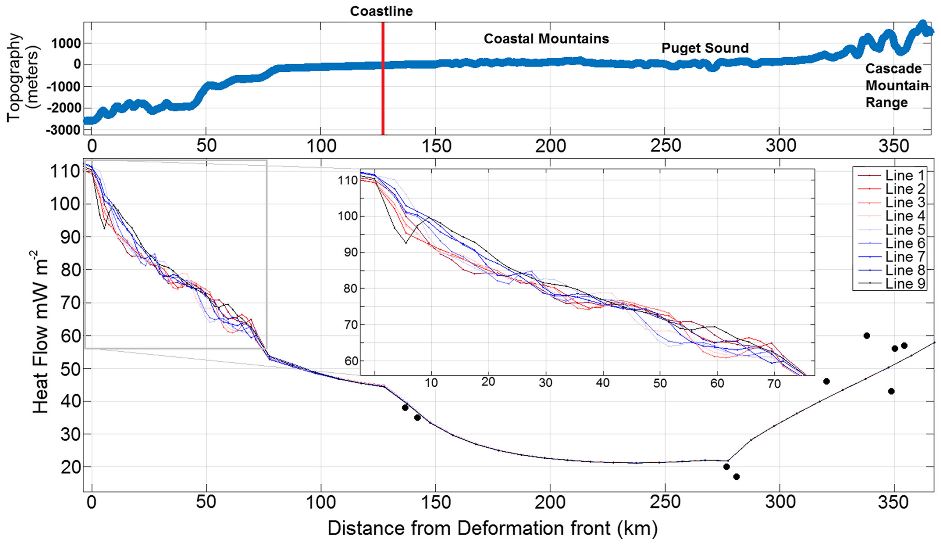
Is it hot enough? *YES*

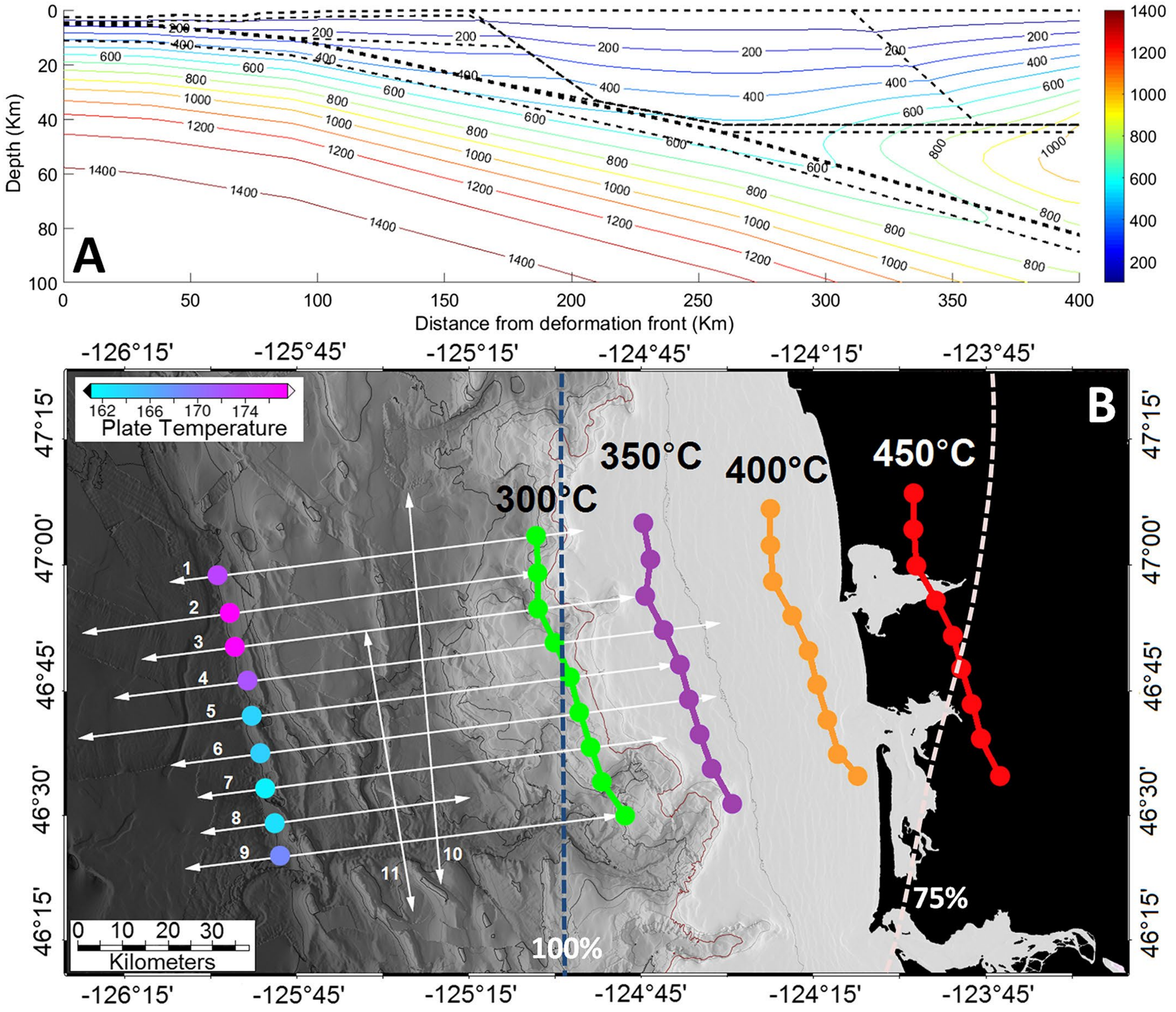
Cascadia thermal models agree that the temperature at the base of the sediment section at the front exceeds ~150°C

Salmi et al. (2017) heat flow data and BSR derived temperature gradient estimates to constrain a thermal model

→ At the def. front, **T = ~170+°C**

→ Heat flow = **110 mW/m²**

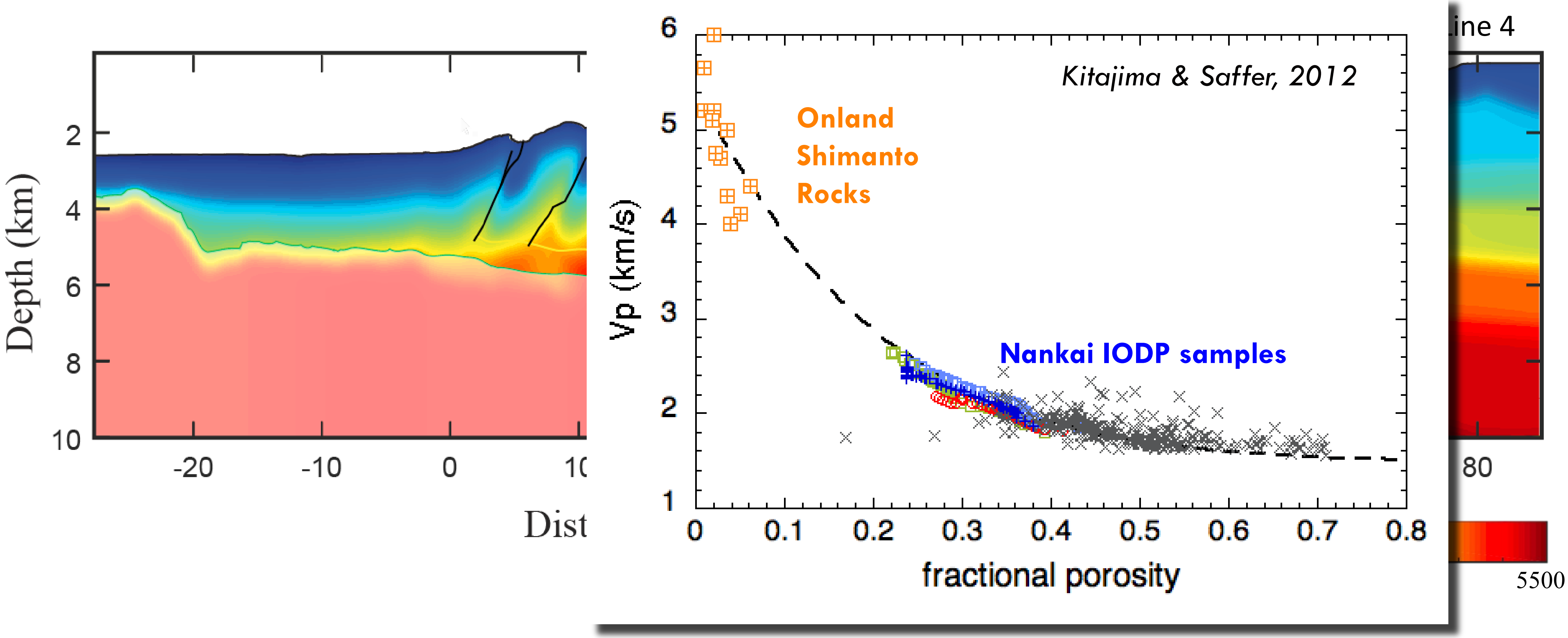




Salmi et al., 2017

Are the rocks lithified?

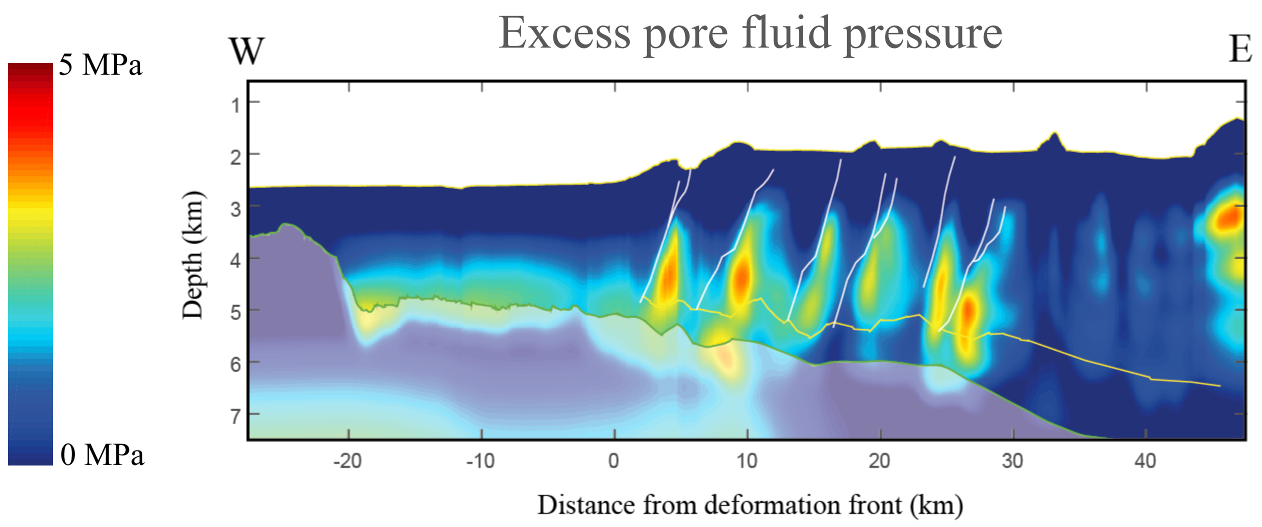
Vp interval velocity from horizon-based tomography for Prestack Depth Migration

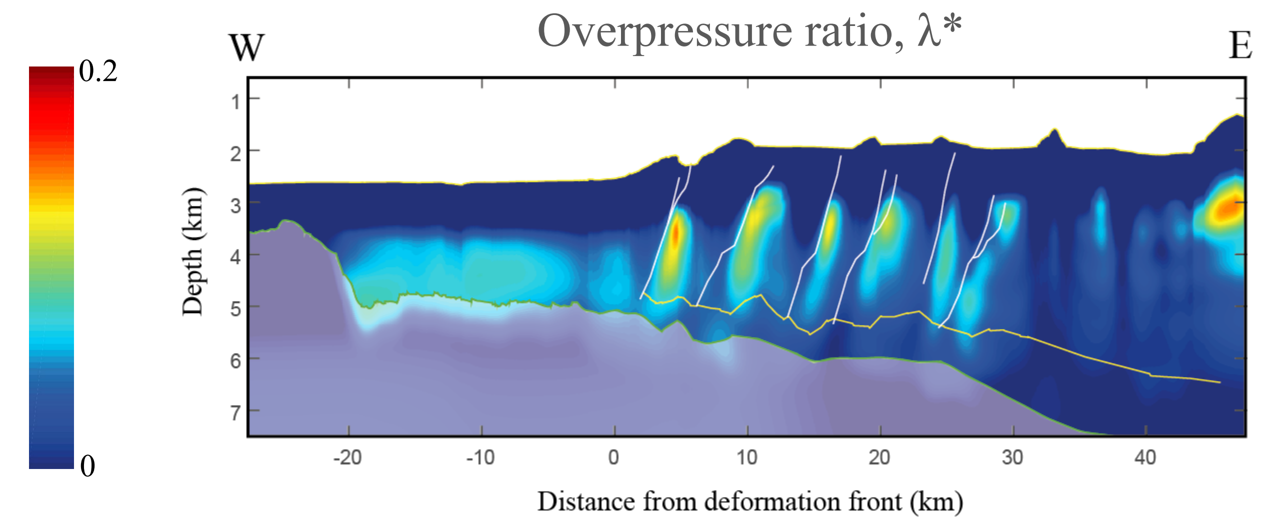


Decollement at the front is high Vp: $\geq 4000\ m/s$

PSDM by Susanna Webb, 2017

Is there pore fluid overpressure? NO





Calculated apparent underconsolidation and therefore pore fluid overpressure from seismic interval velocity

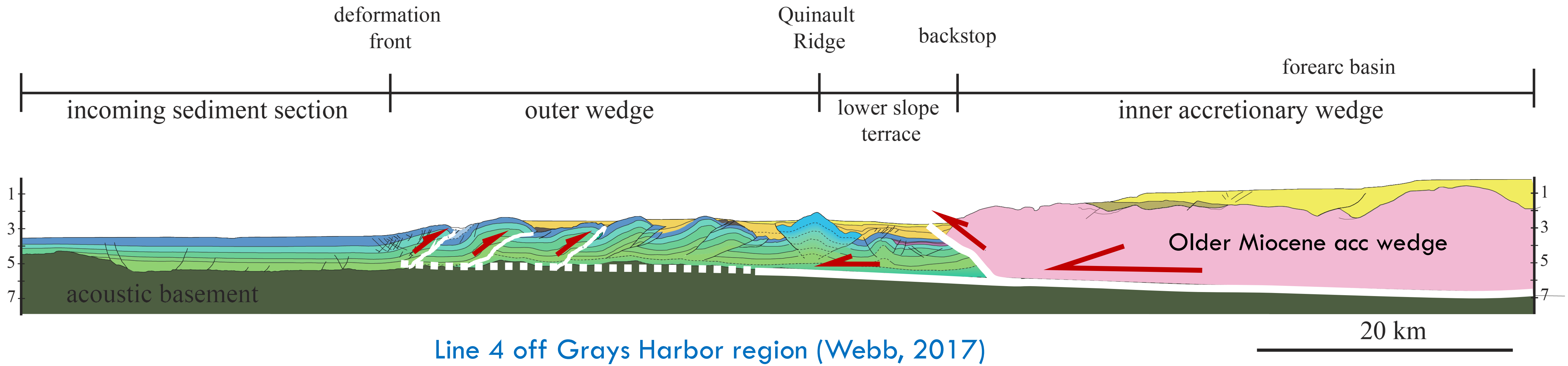
→ Evidence for only <u>very minor</u> overpressure at depth – close to hydrostatic

High seismic velocity, deep burial, normal pore pressure imply a <u>strong</u> wedge environment

→ Frictional locking and unstable fast slip behavior are *expected*

Consolidation analysis by Susanna Webb, 2017

Ok, so is there any <u>evidence</u> of shallow rupture and/or splay fault slip?



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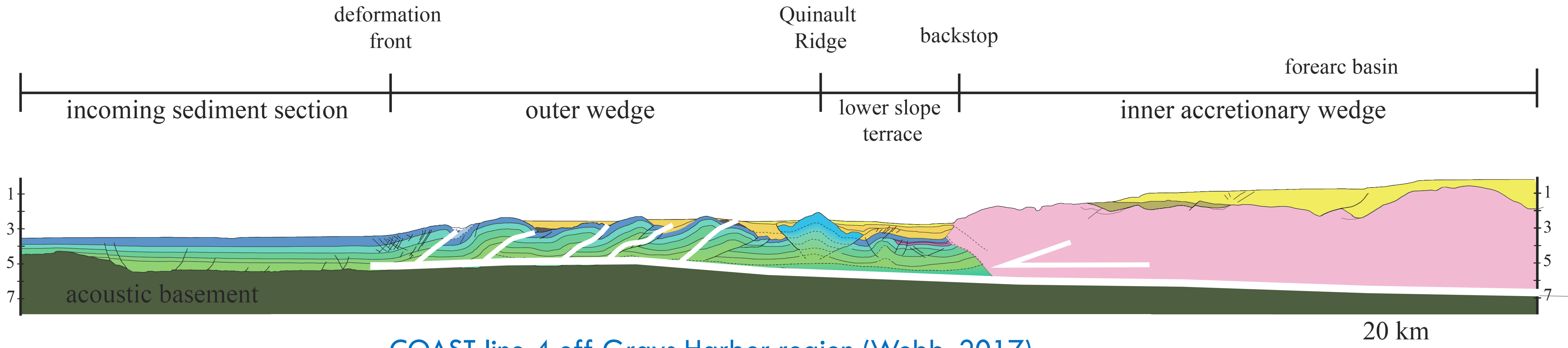
Is there *evidence* of shallow coseismic slip?



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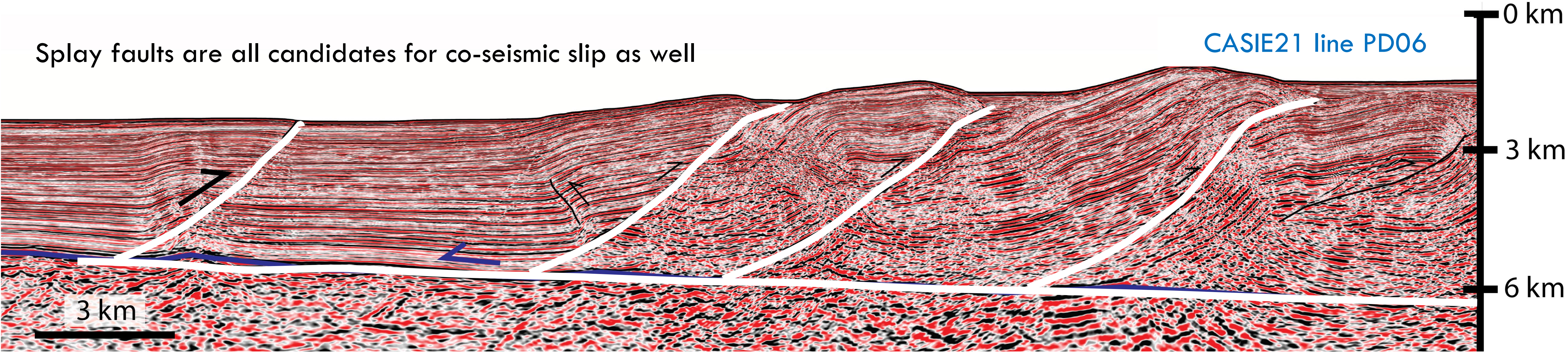
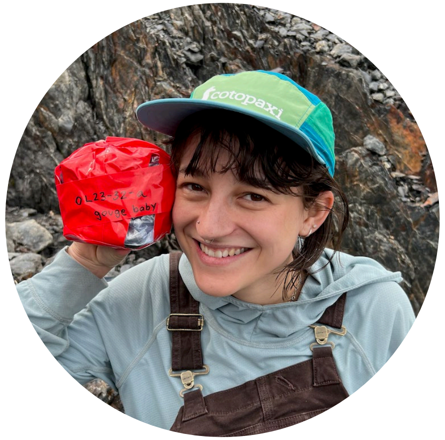
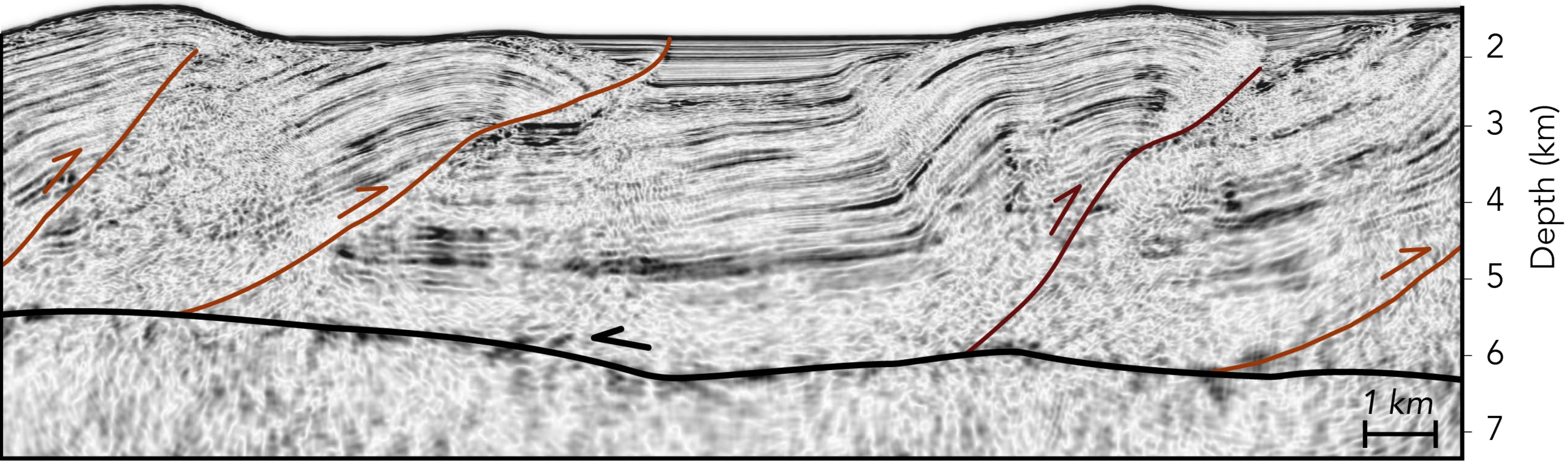


Anna Ledeczi: Joint interpretation of near surface (<1 km) and deeper (<10 km) imaging to map active faults



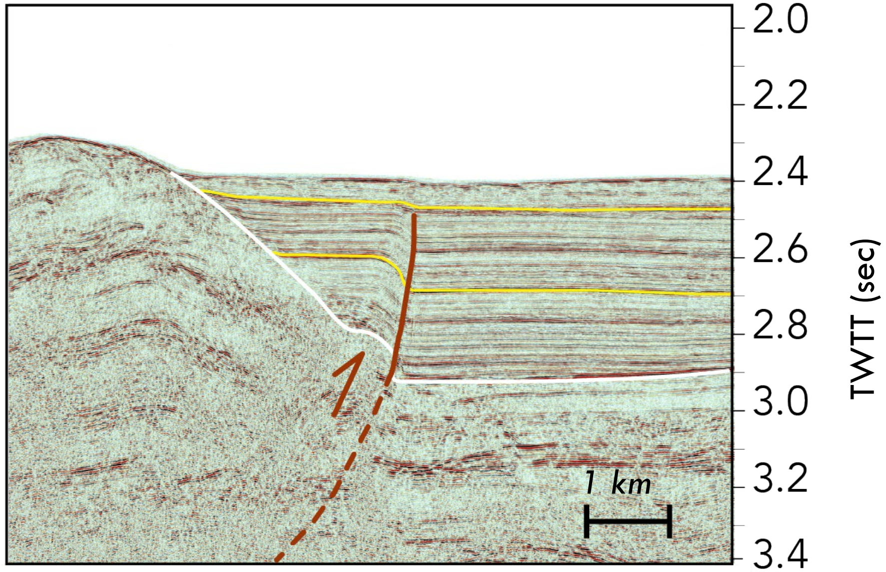
Anna Ledeczi

CASIE21 PD06B

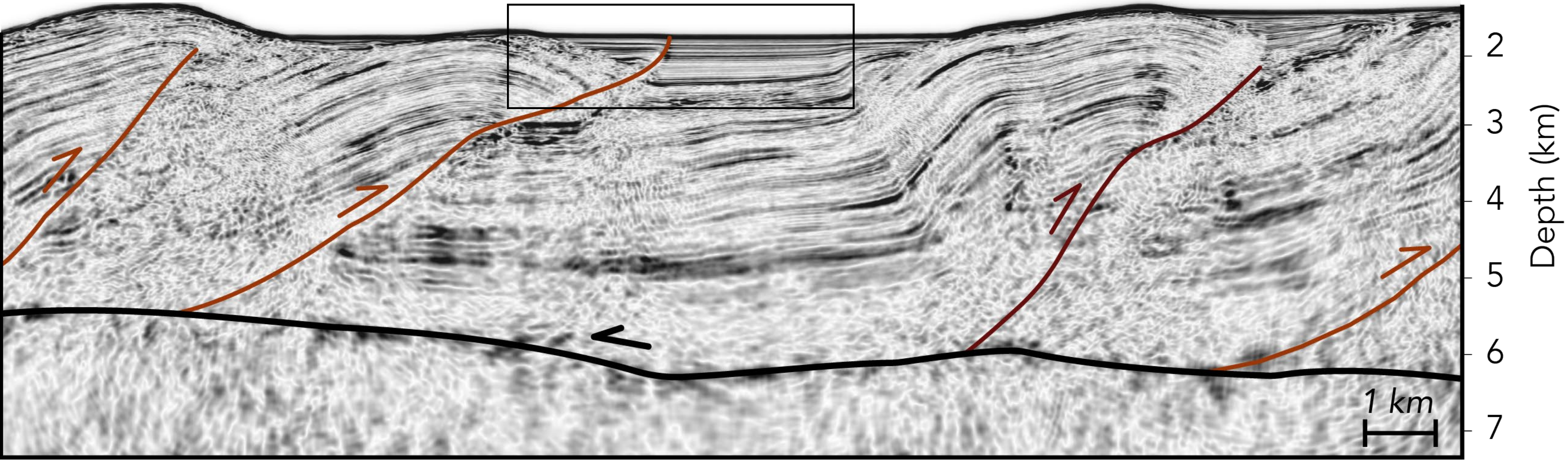


Ledeczi et al., 2024

Joint interpretation of near surface (<1 km) and deeper (<10 km) seismic reflection imaging



Higher resolution sparker seismic data



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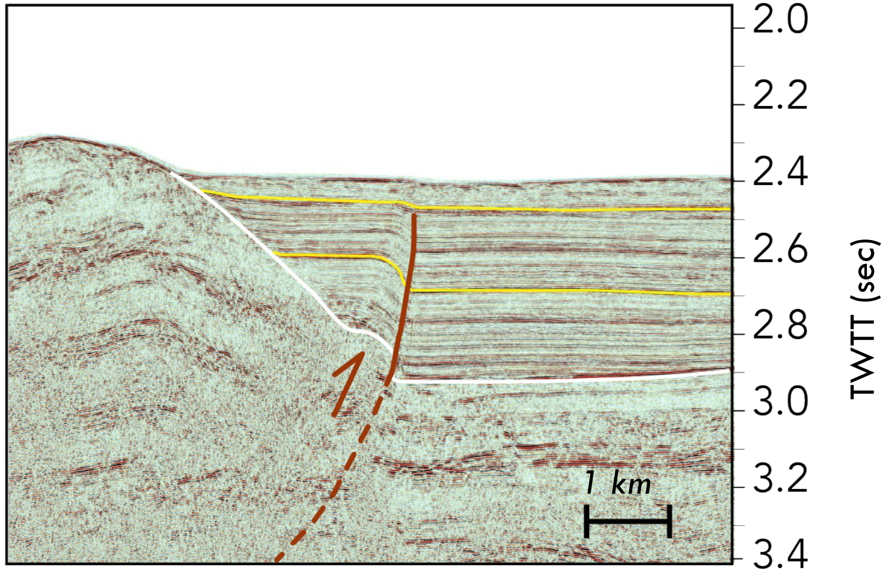
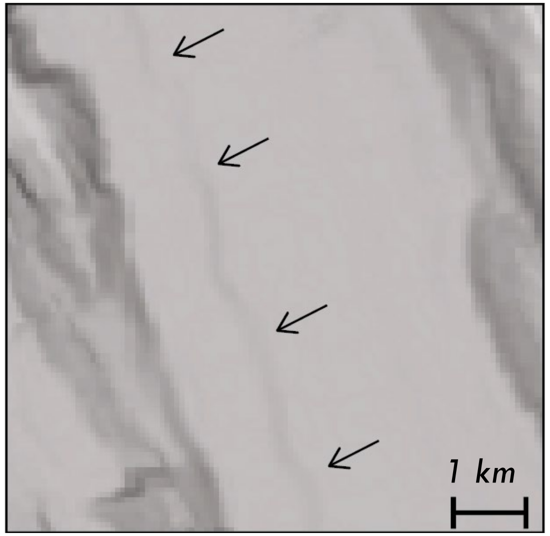
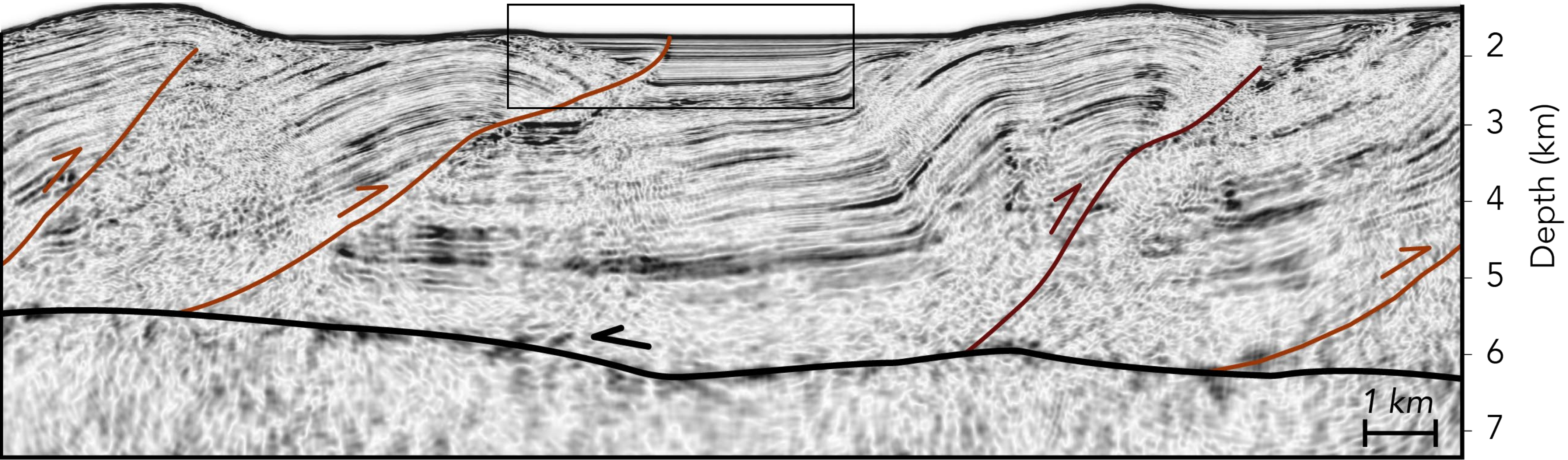




USGS 30-m bathymetry



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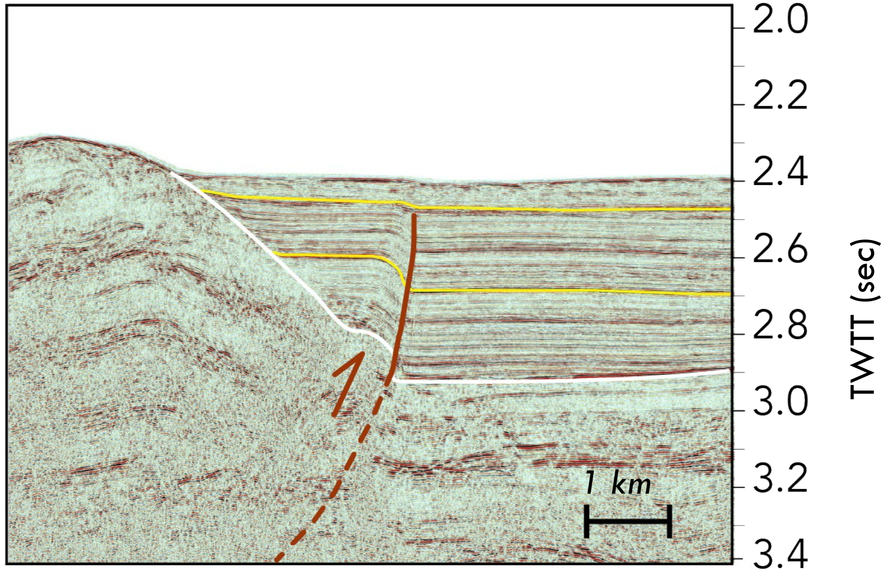
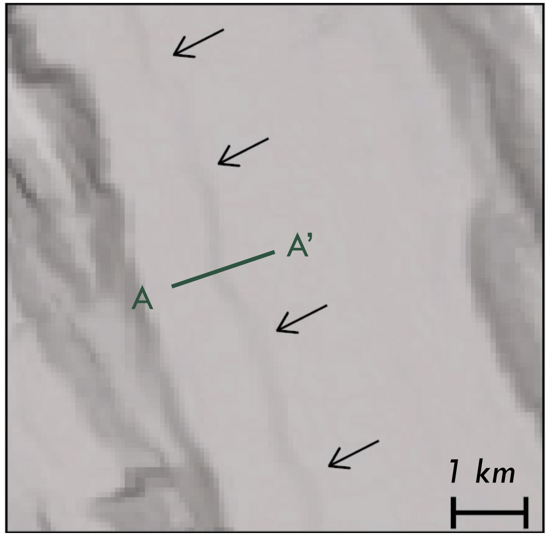
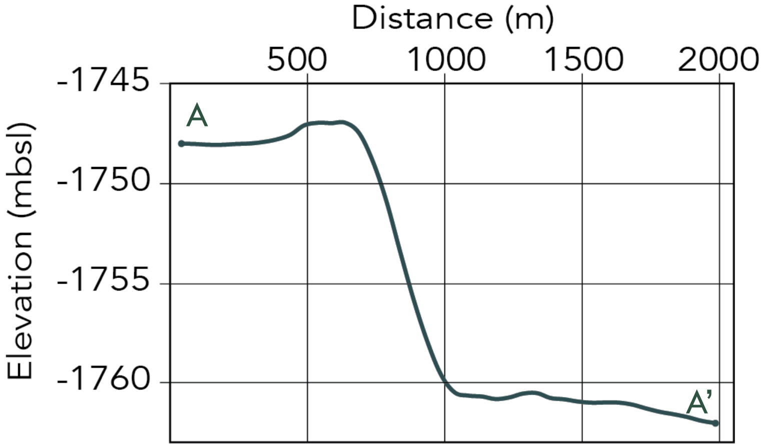
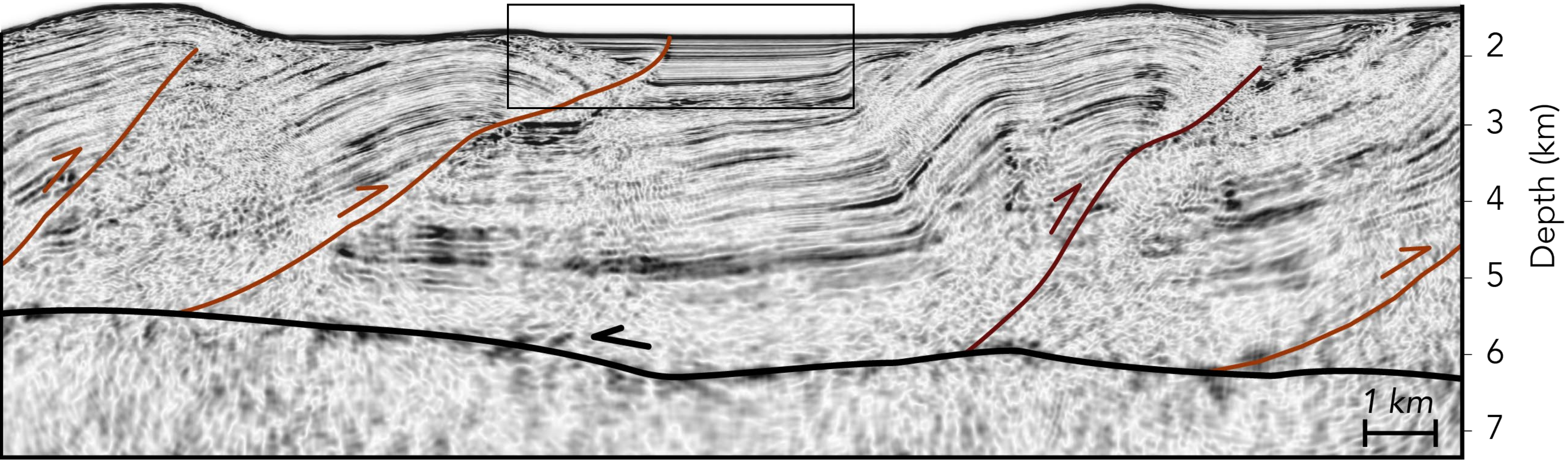


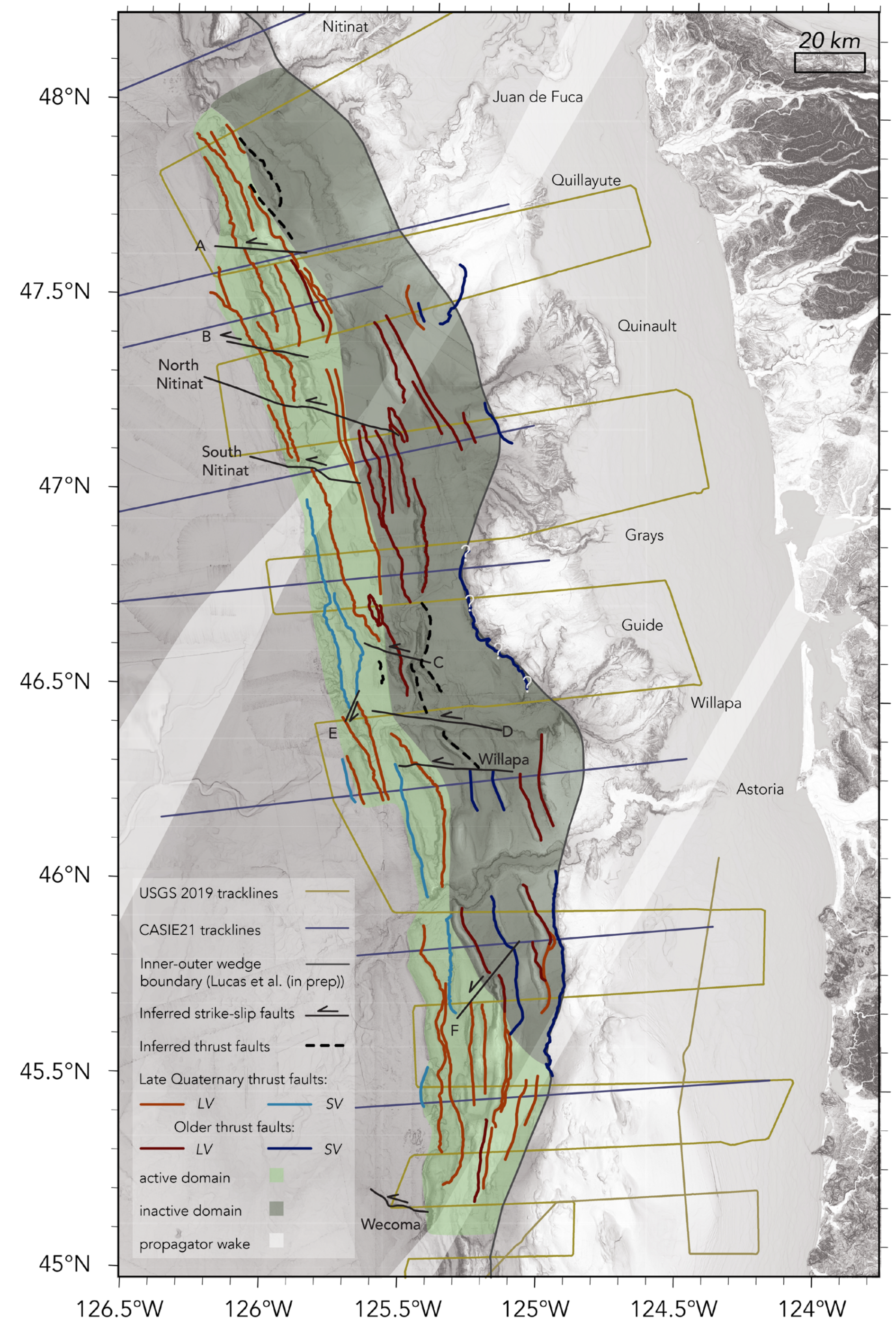




13 meter scarp!



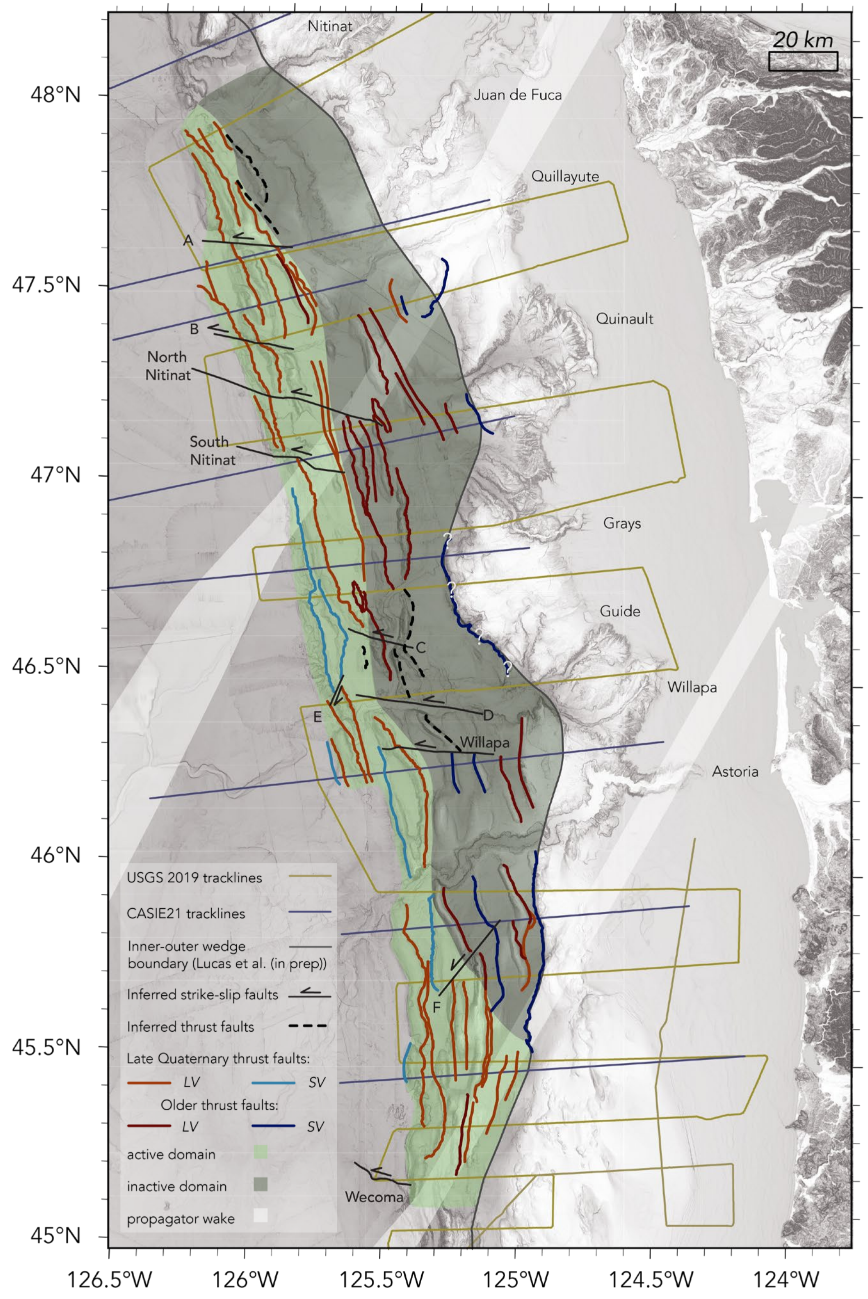
Ledeczi et al., 2024



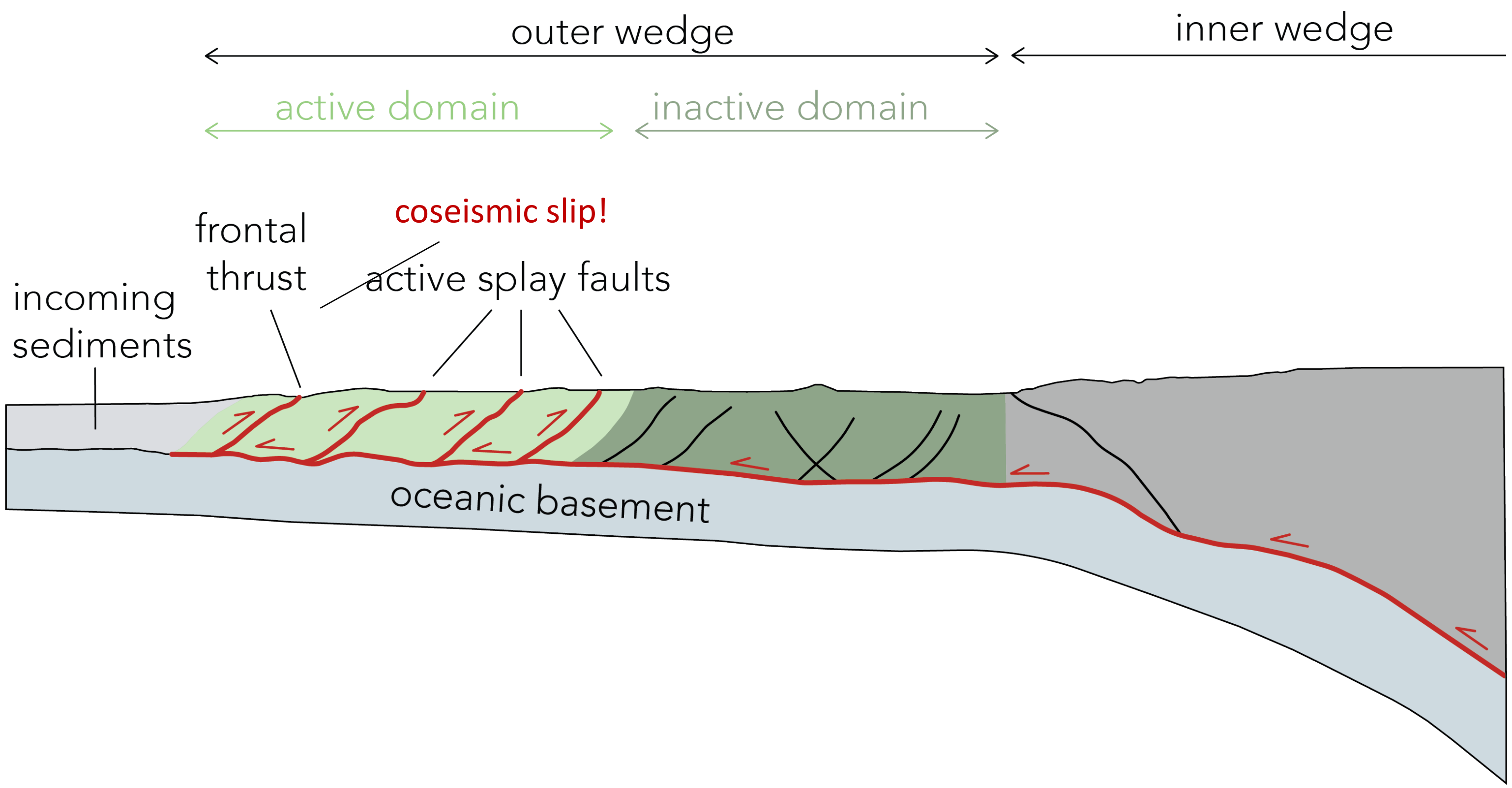
Widespread recent activity of splay faults within ~30 km of the deformation front

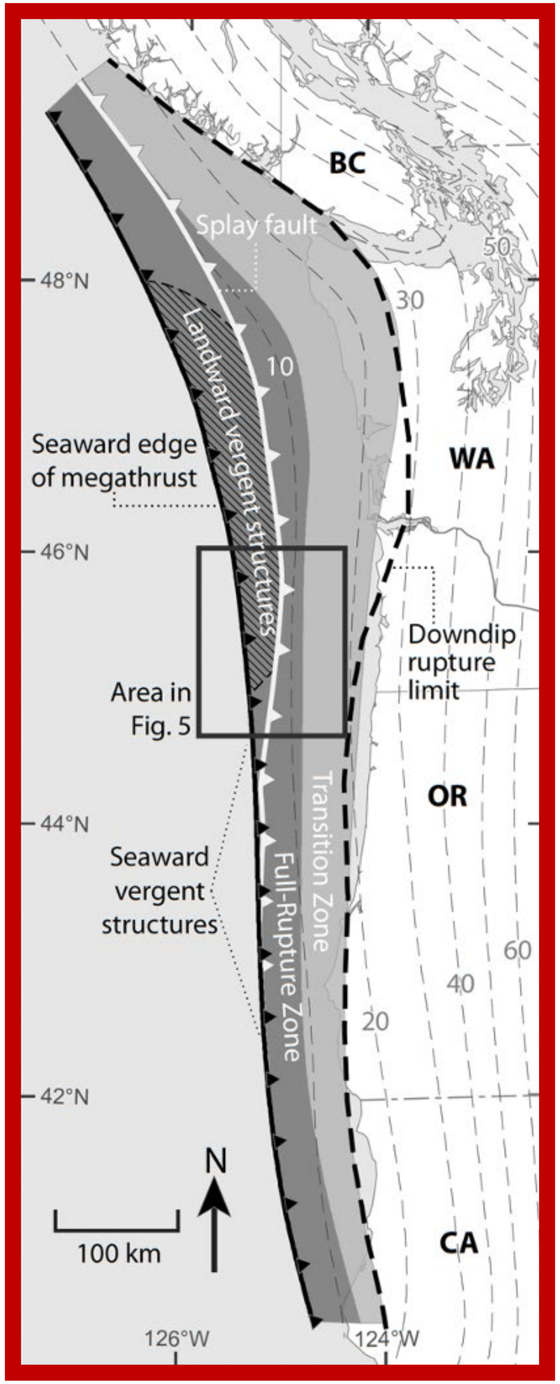
- New data resolution allows us to map out faults which are actually active
    - Previous work has identified similar faults, but all were called active
- Partitioning of recent activity into "active domain" and older activity into "inactive domain"
    - Active domain < 30 km wide
    - Inactive domain 10 to 40 km wide
- ***Recently active = potentially active in next M9***

Faults in the active domain are candidates for recent (and therefore future) coseismic slip



- During megathrust events, shallow slip is likely and distributed onto multiple splay faults in the active domain
- The inner wedge and the inactive domain may move as a rigid block

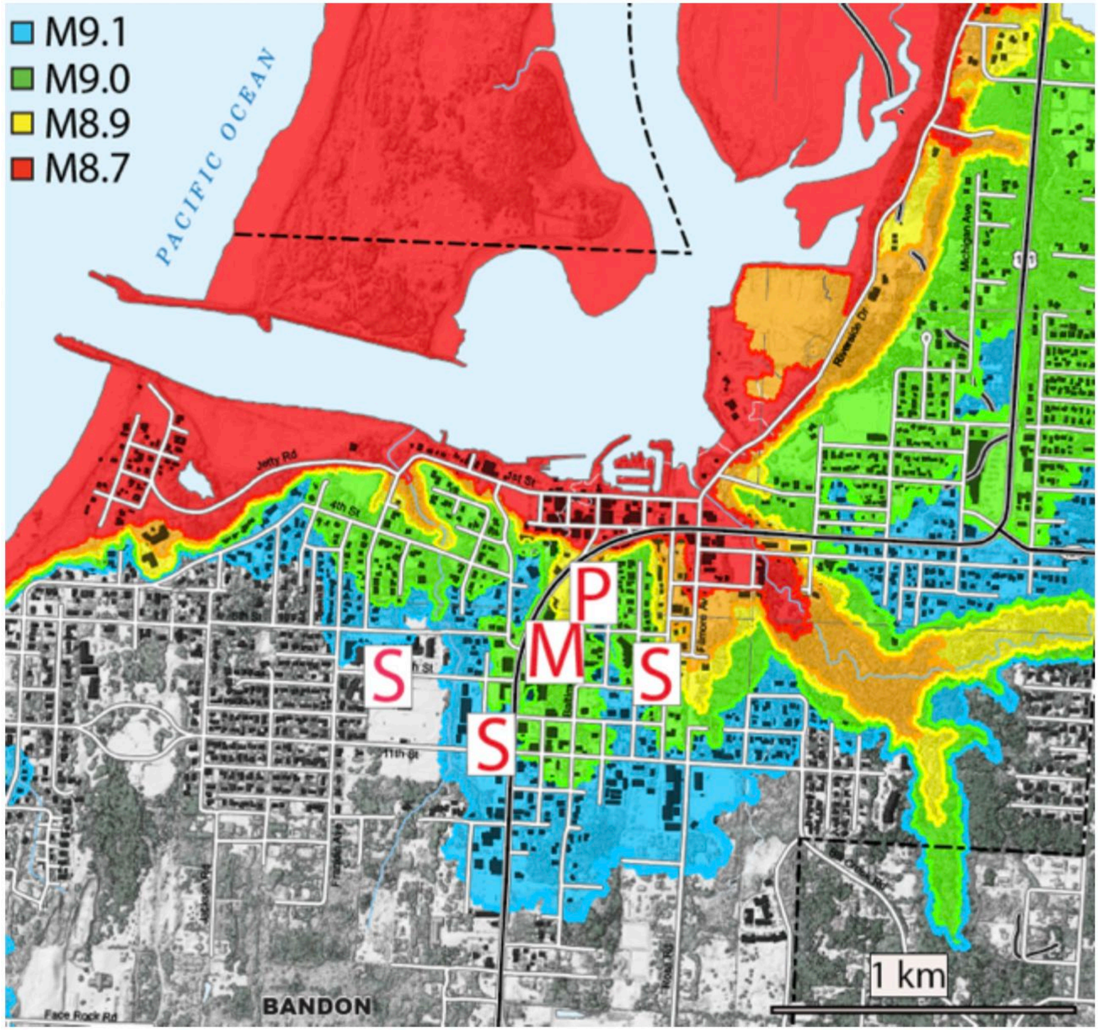




A megasplay fault at the inner wedge / outer wedge boundary has been proposed and is used as a preferred scenario in tsunami hazard models

Official tsunami inundation scenarios for Bandon, Oregon ranging from M8.7 – M9.1

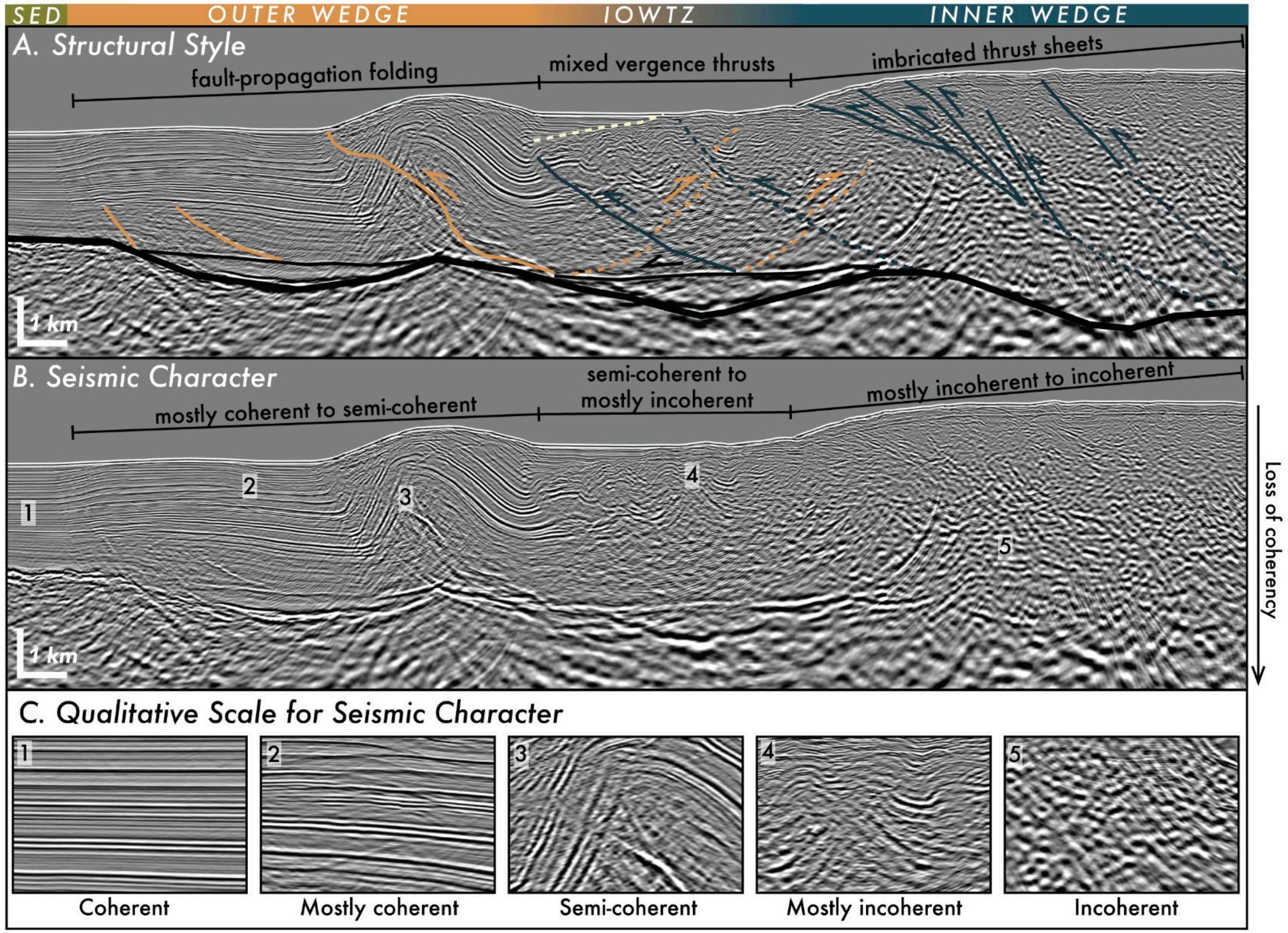
Uses models with megasplay rupture

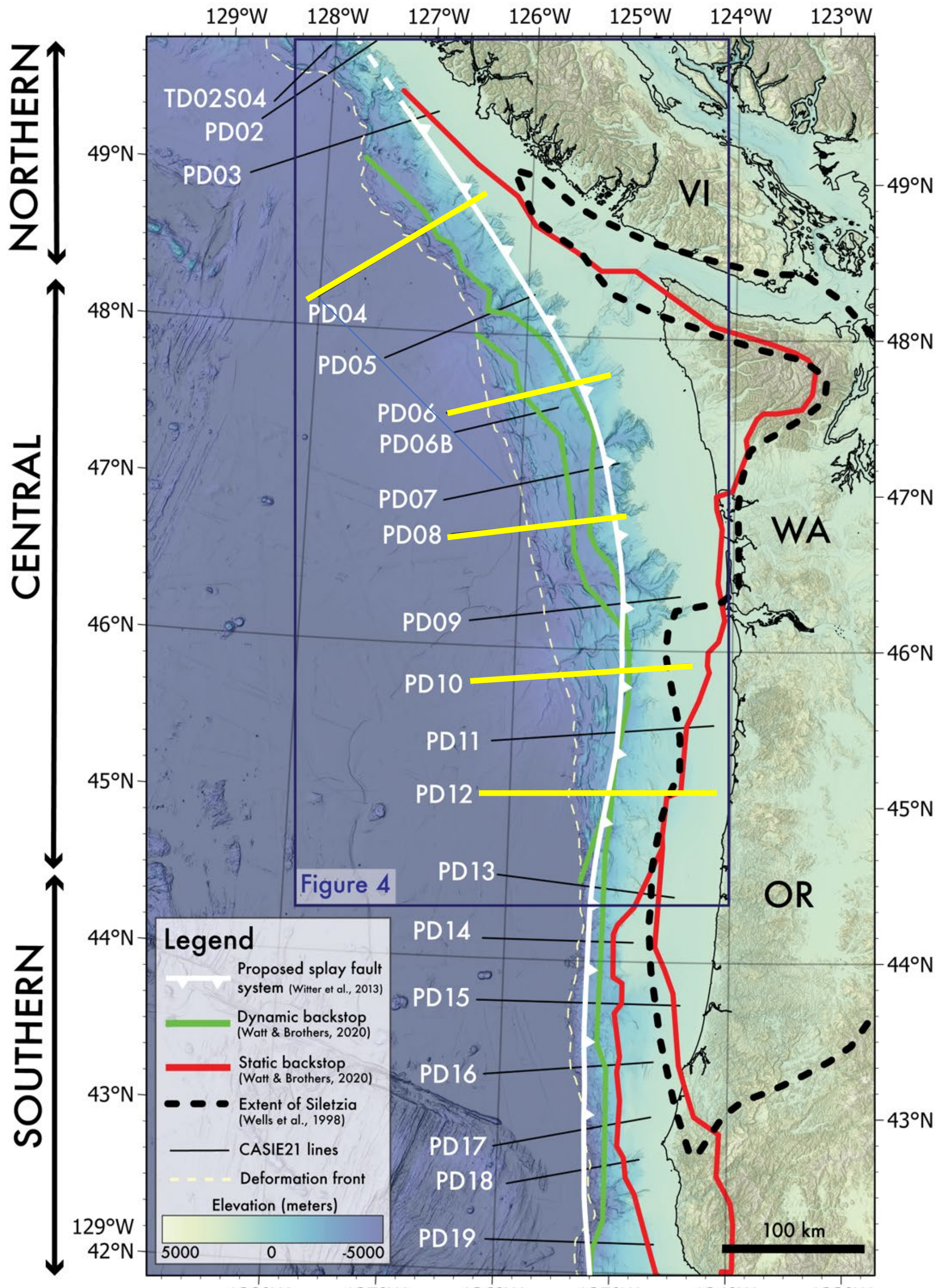


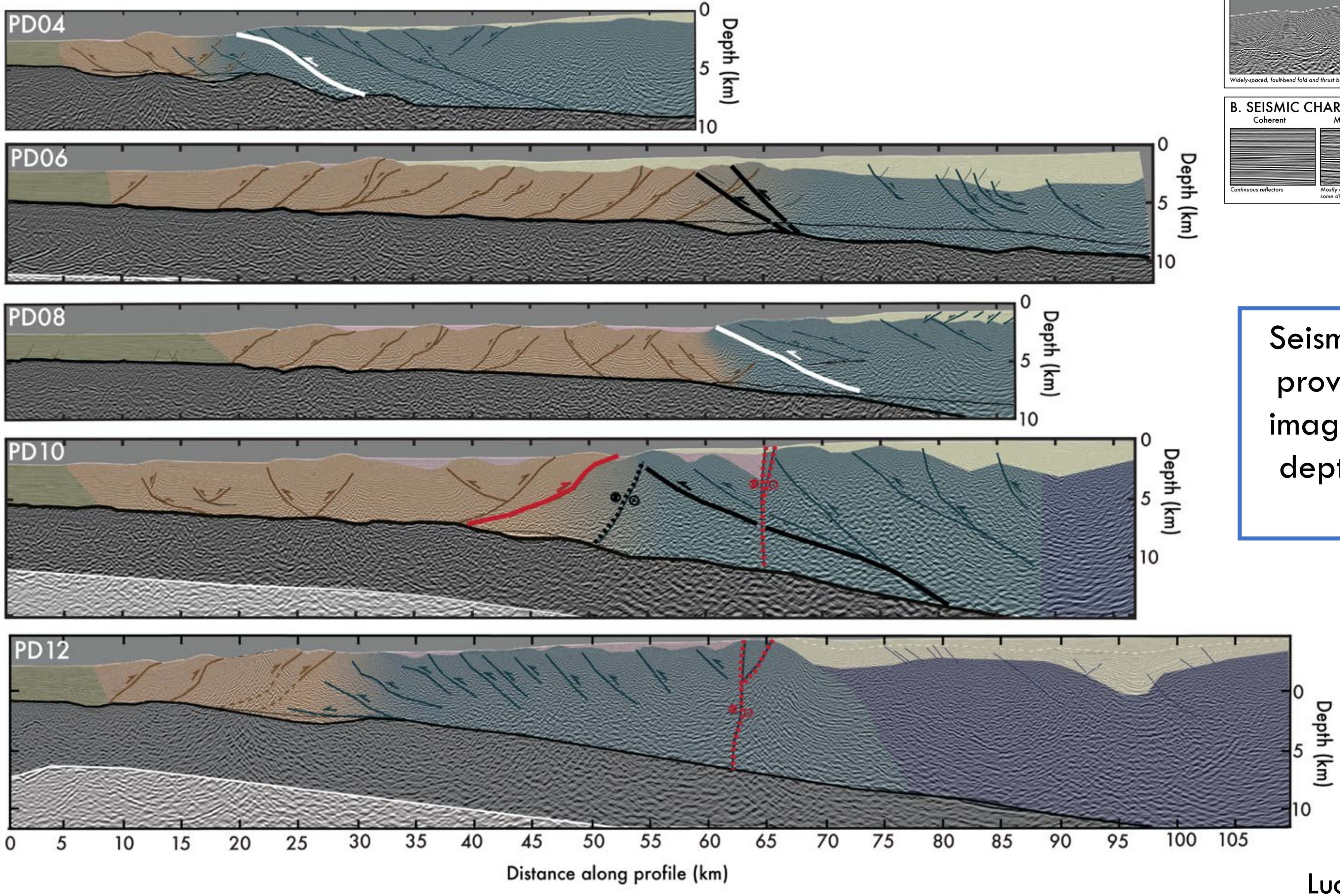
Witter et al. (2013)

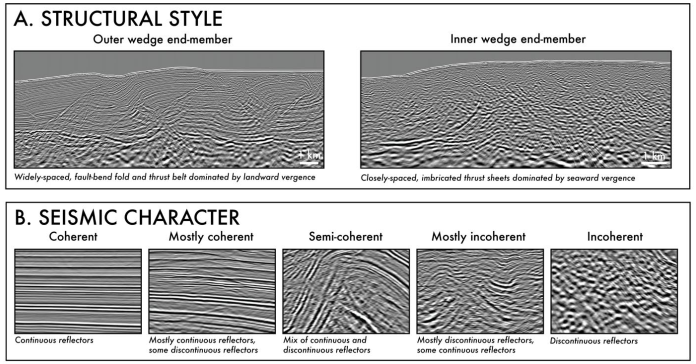
Evaluating potential seismic slip of the *megasplay* fault (inner-outer wedge boundary)

Lucas et al., 2025





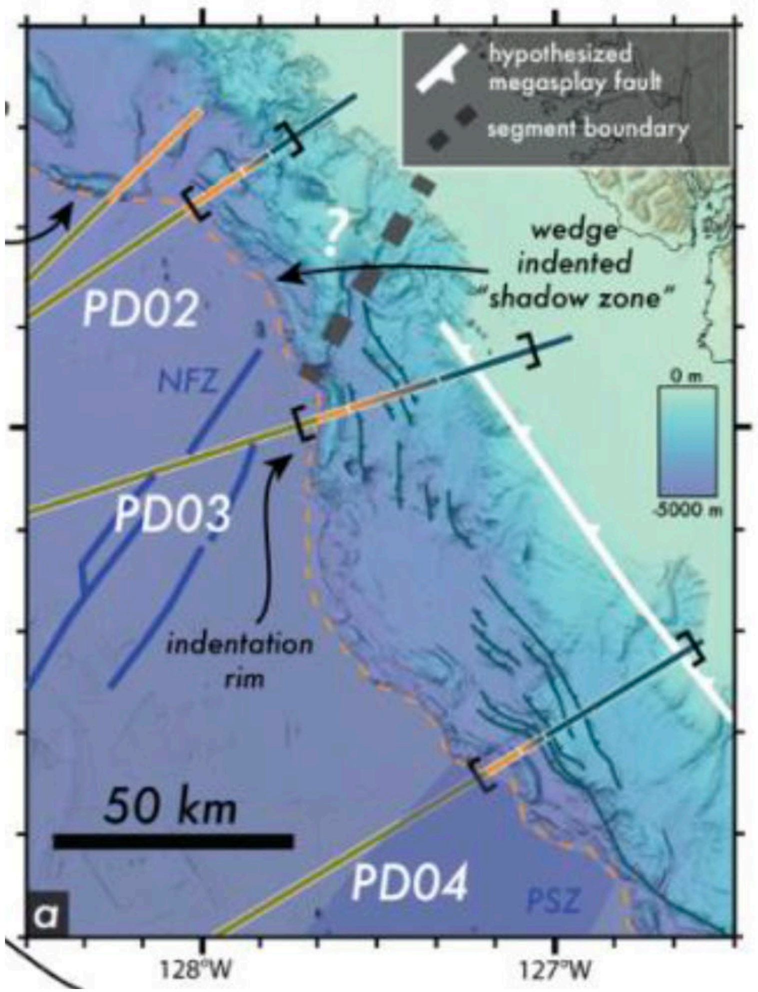


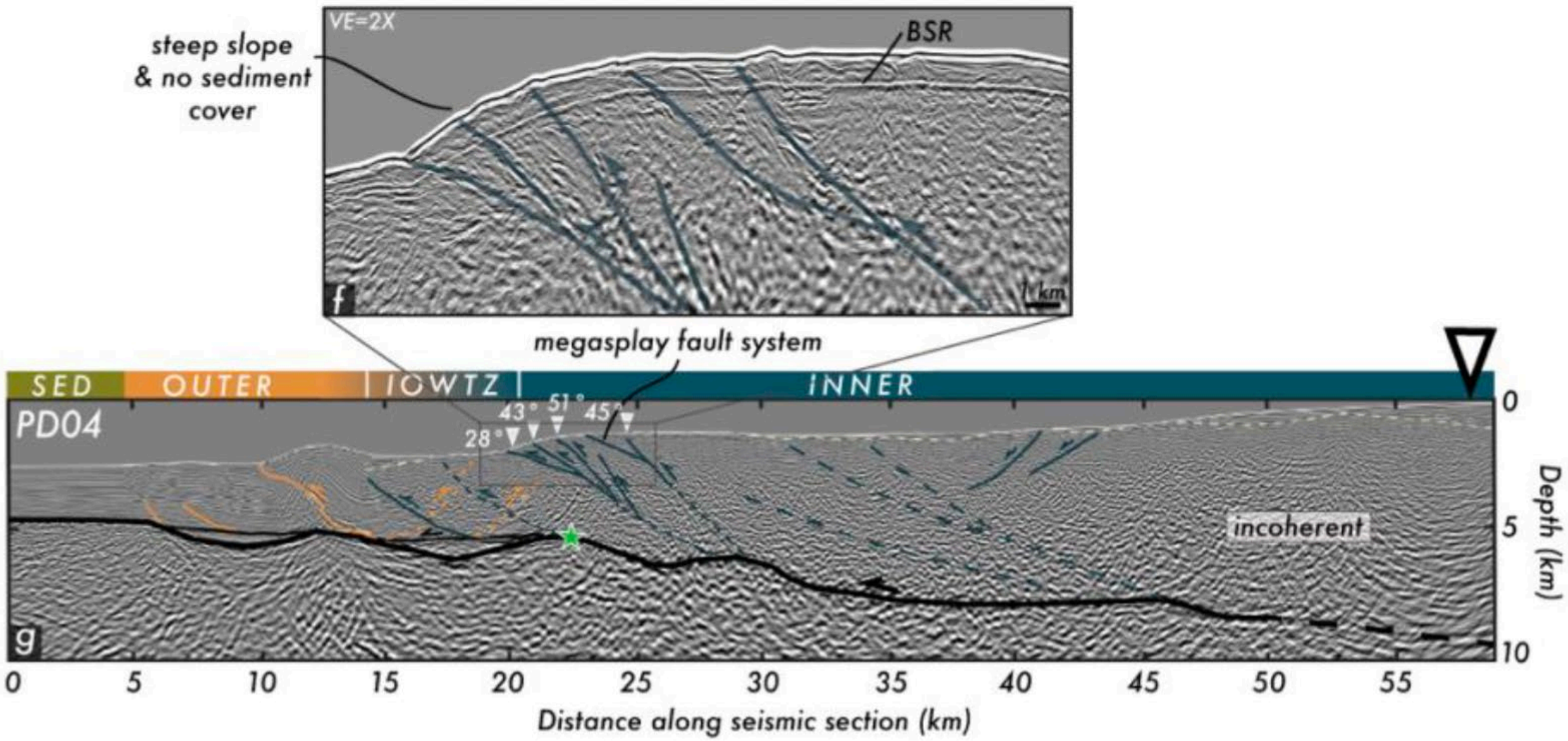


Seismic reflection profiles provide subsurface fault imaging down to ~15 km depth in unprecedented detail

Lucas et al., 2025

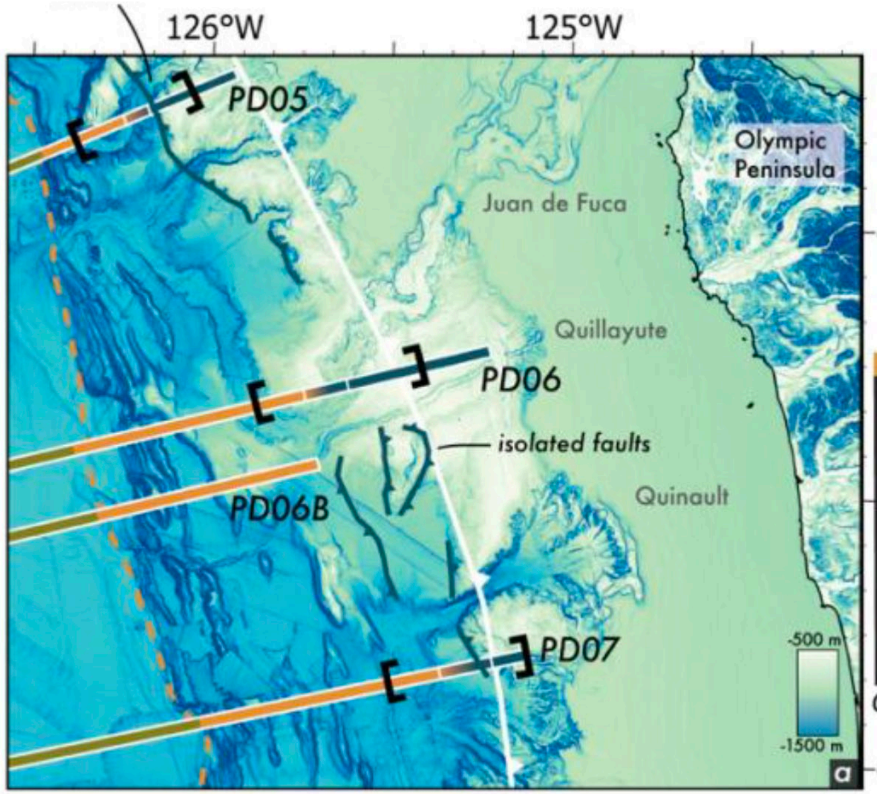
Off Vancouver Island, some areas show potentially active megasplay fault system

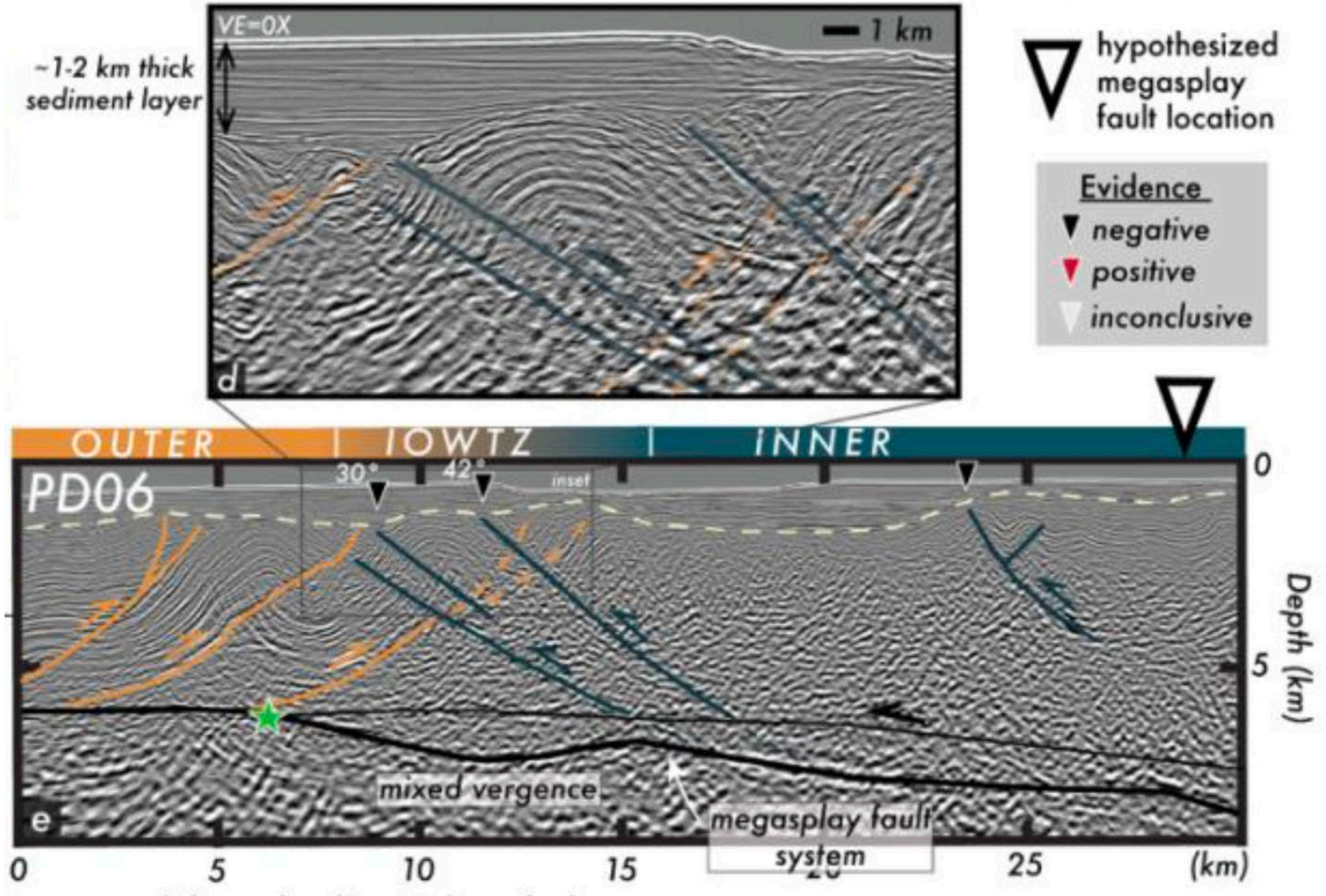




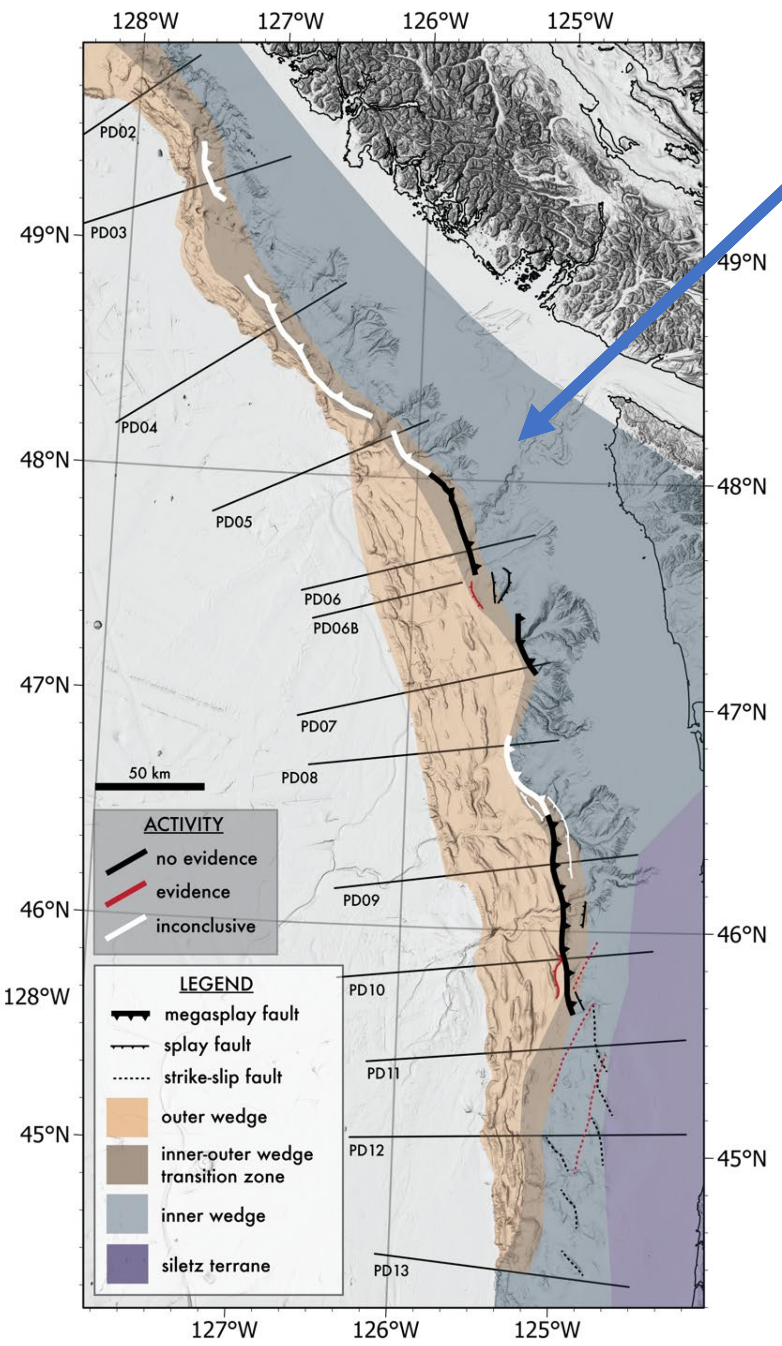
Lucas et al., 2025

Off Washington & N. Oregon, evidence is clear that there is no such active fault in most areas





Lucas et al., 2025



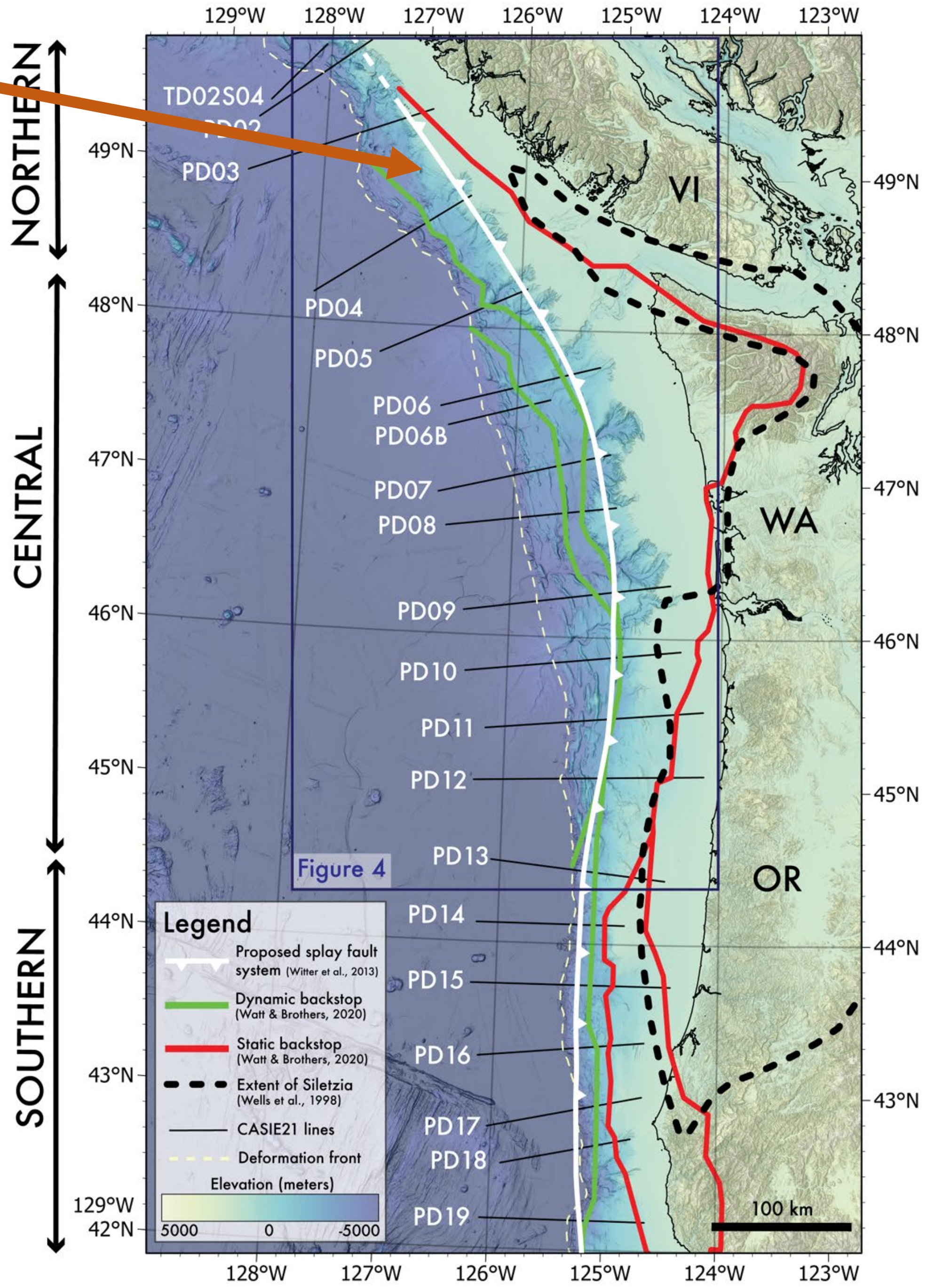
YES

NO

Bottom line:

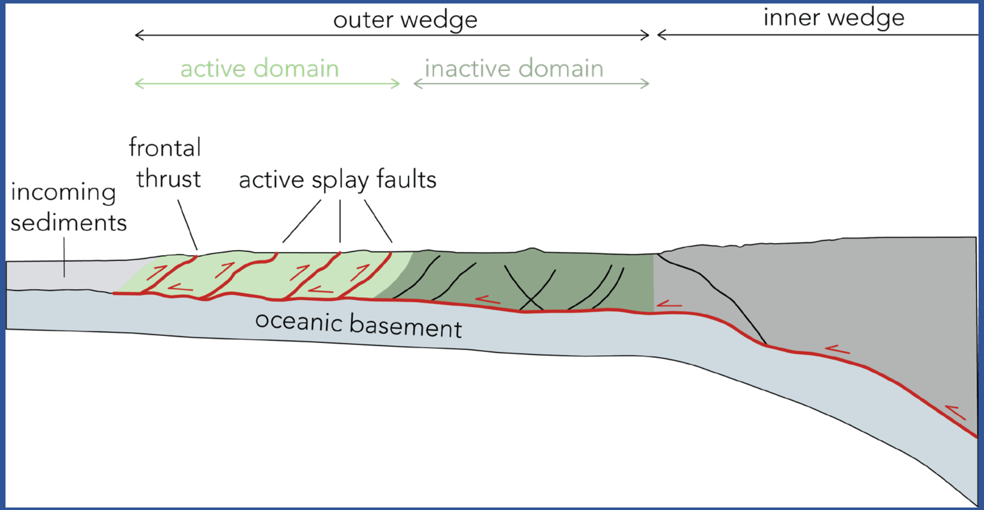
Strong evidence that there is **no through-going megasplay fault** off Washington or Oregon

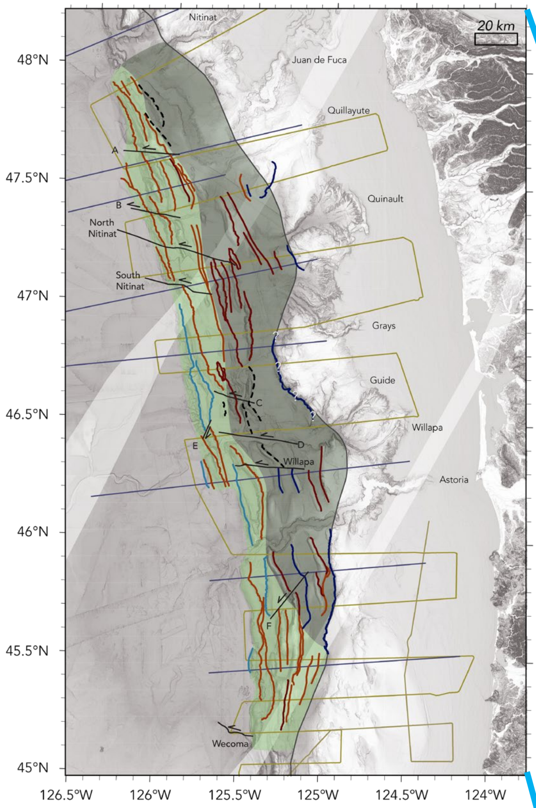
Lucas et al., 2025



Seismic slip distribution offshore

- Slip of the locked megathrust under the entire LVZ to the def. front is *likely*
- There is patchy evidence at best for a major megasplay fault – commonly-used tsunami scenarios need re-evaluation
- Slip *is* likely to occur on multiple LV splay faults in the outermost ~ 30 km, which may add to seafloor displacement

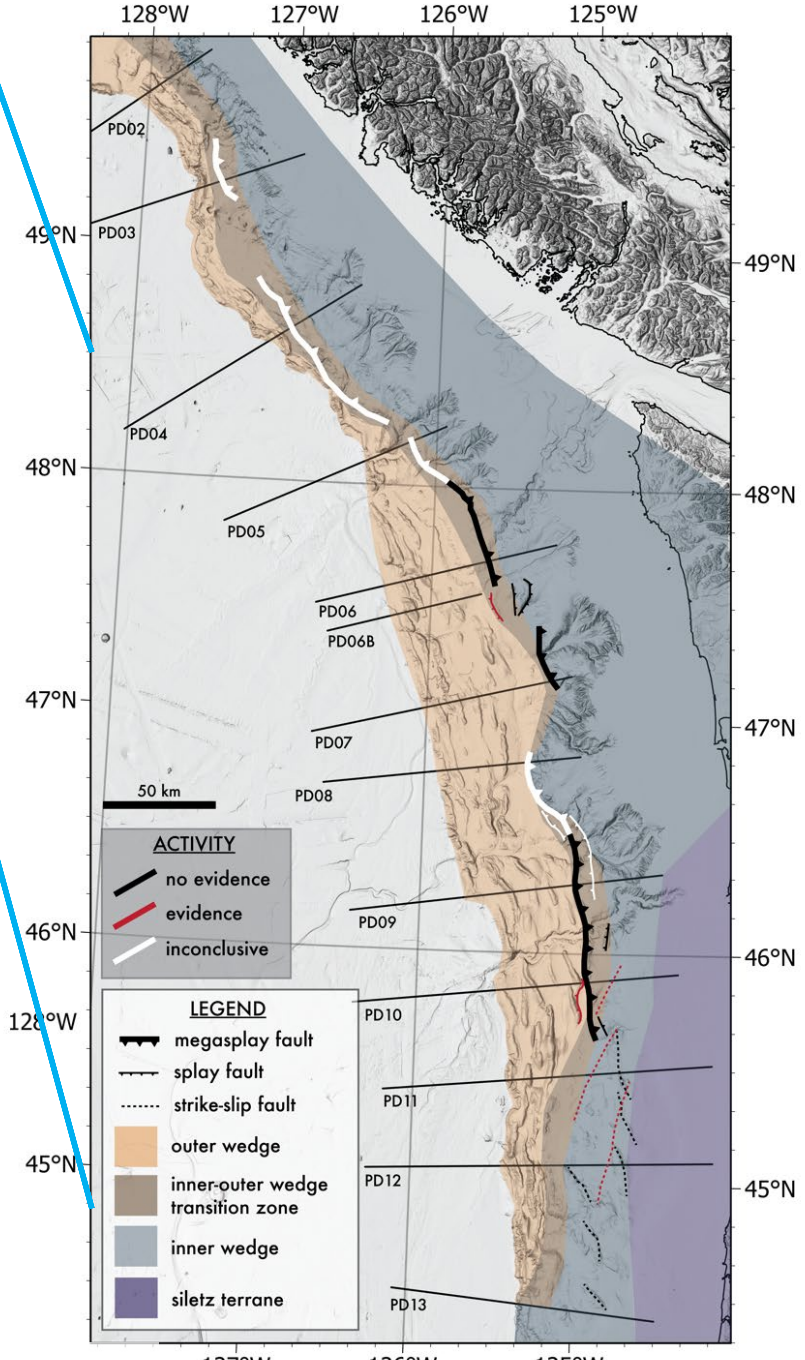




Ledeczi et al., 2024

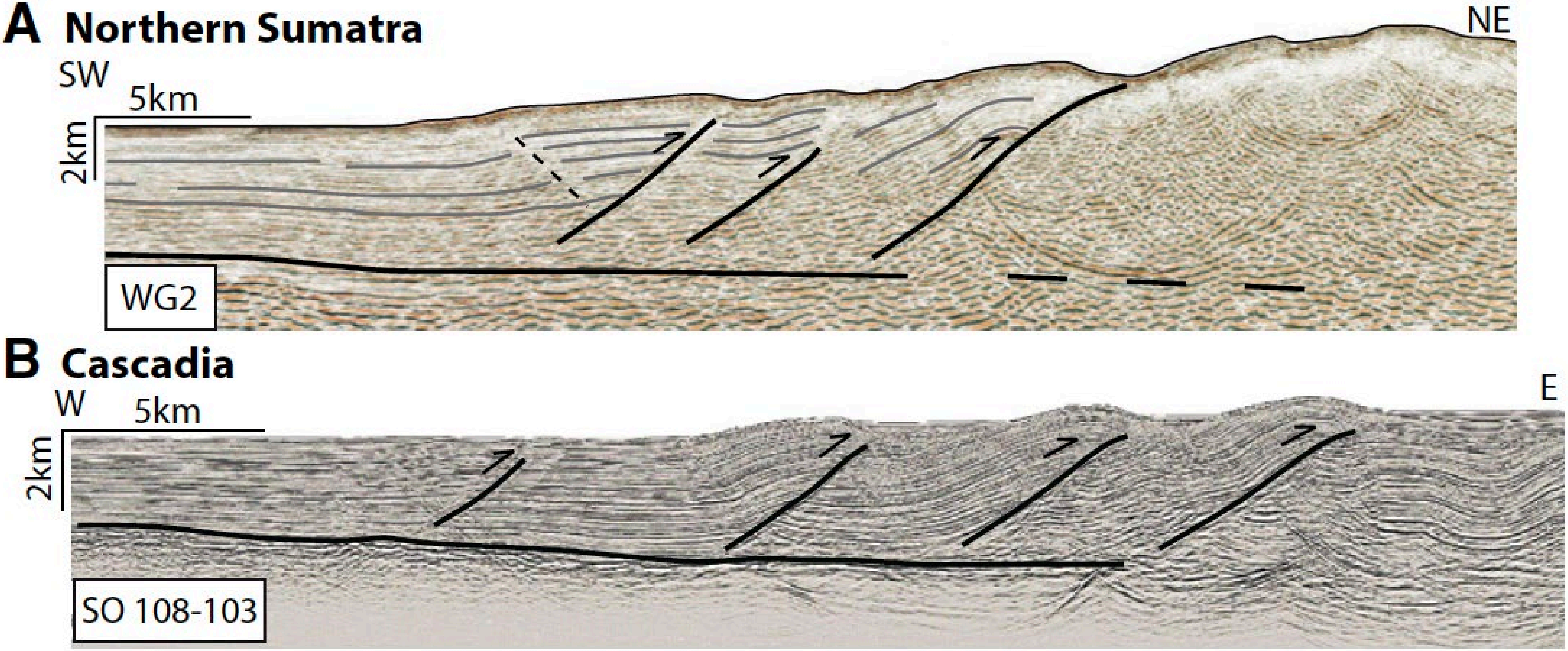
Many recently-active faults in outermost region (light green)

"Megasplay" fault is discontinuous to absent



Lucas et al., in review

Is the landward-vergent Cascadia wedge direct evidence of shallow co-seismic slip?



Cubas et al., 2016

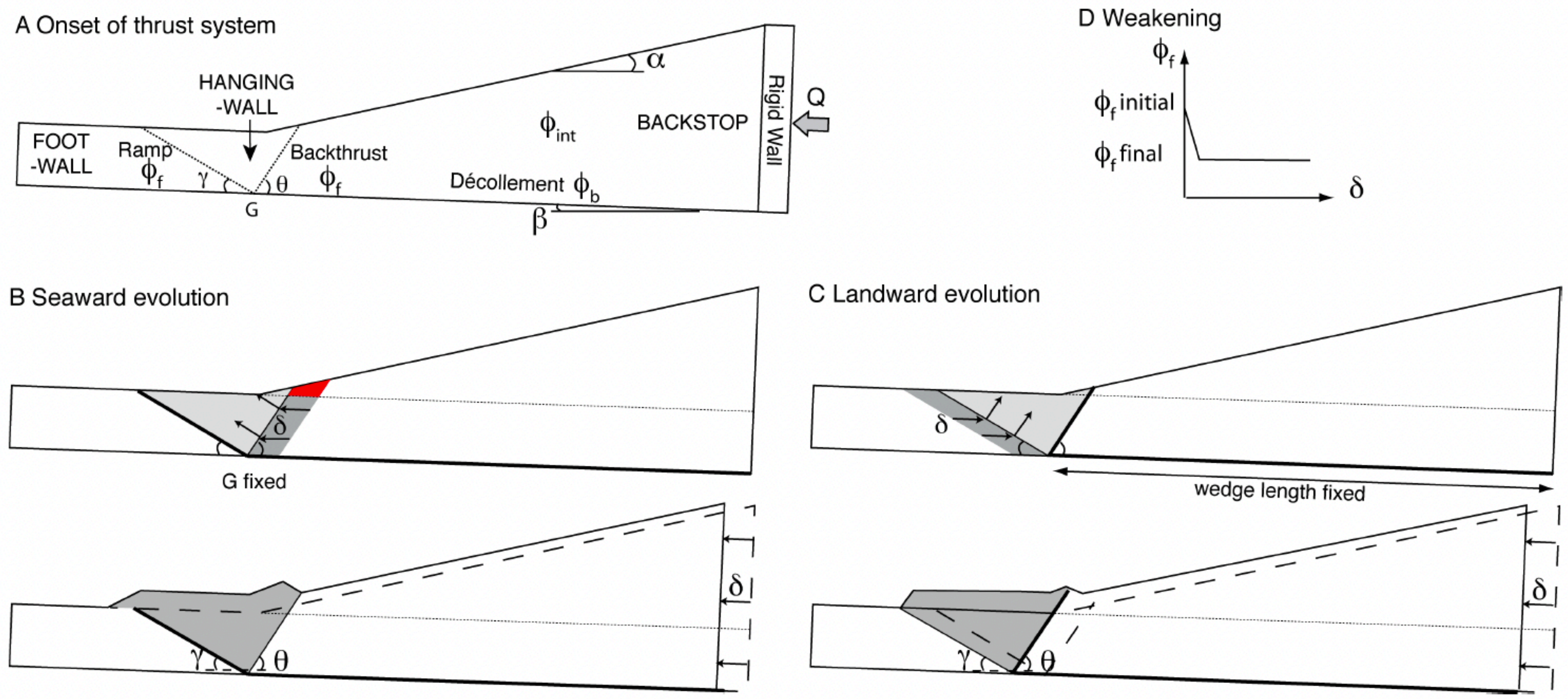
Development of landward vergent thrusts in Coulomb wedge requires <u>extremely</u> low coefficient of friction.

Representative values for the LVZ from CASIE21 lines:

surface slope $\alpha = 1.0^\circ$

megathrust dip $\beta = 2.0^\circ$

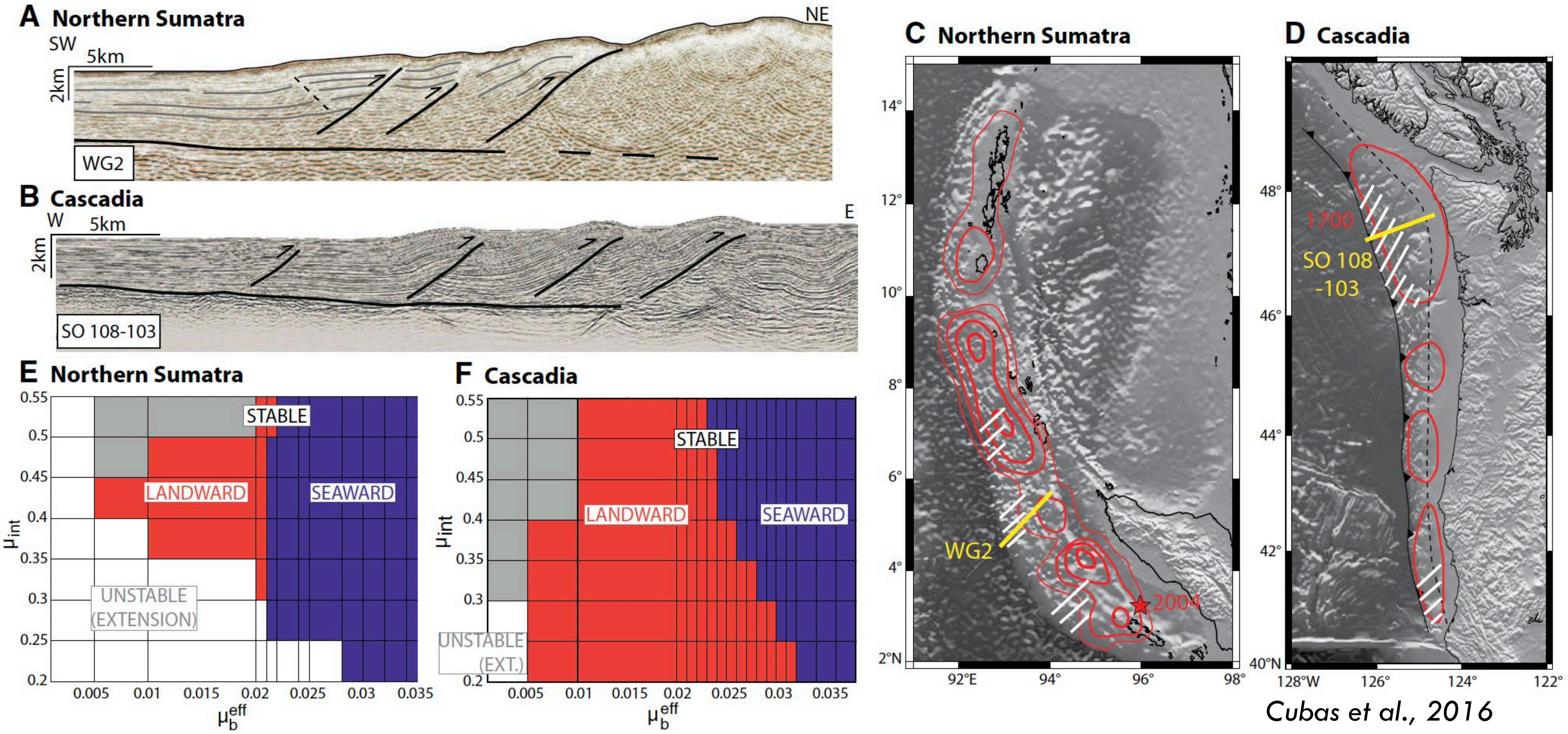
LV fault dip $\theta = 40^\circ$



Mechanical analysis by Cubas et al. (2016 in *Geology*)

Cascadia case: μ_{int} = 0.57 → LV only permitted when when μ_b -= 0.01 to 0.03

For α = ~2˚ and β = 1.1˚

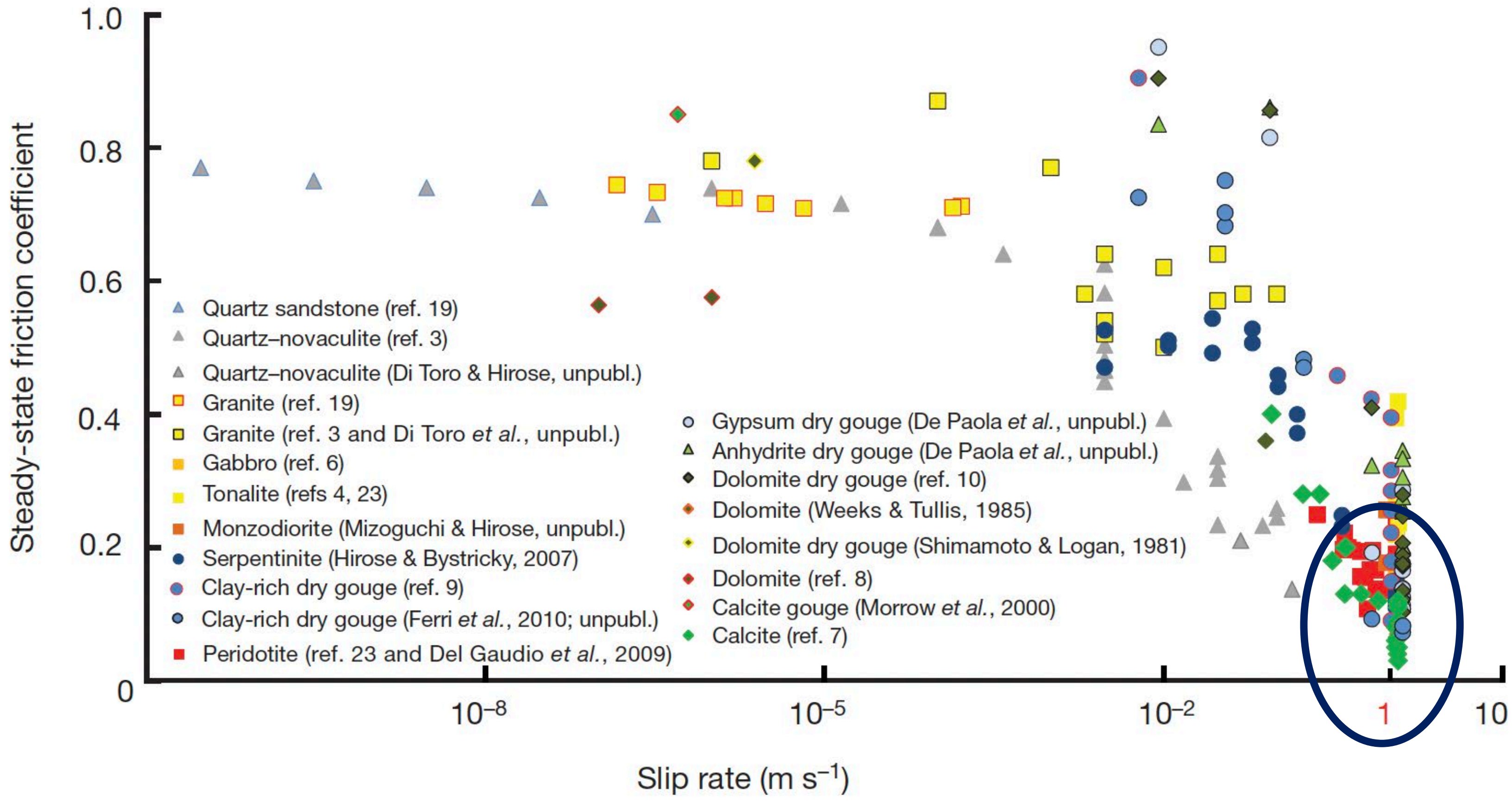


Cubas et al., 2016

Nothing has intrinsic friction that low

- No intrinsically low-friction viable candidate materials
- No evidence for extant high pore pressure … and that promotes aseismic creep, not locking
- → *Dynamic weakening is the only viable mechanism*

For the landward vergent zone to form, locking and dynamic weakening is not only permitte but <u>required</u>.



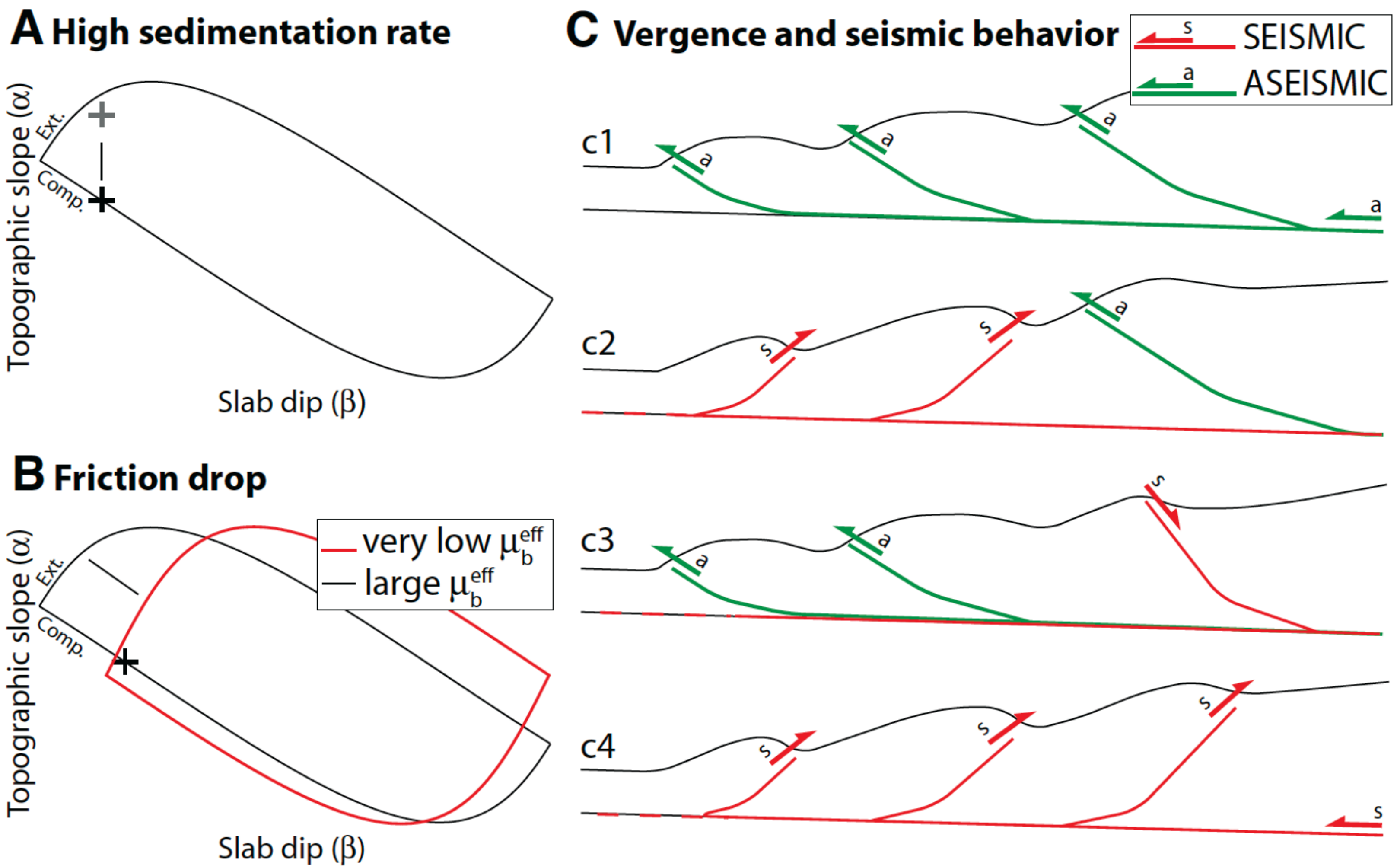
DiToro et al., 2011

Landward vergent zone is statically strong but dynamically weak

- slip on landward vergent thrusts (backthrusts) is favored *only* for basal friction $\mu^{eff} \leq 0.03$

- requires a strong wedge internal friction of ~0.5

- likely develops only via <u>dynamic weakening mechanisms</u> because materials with such low μ_b (e.g., talc) are not present

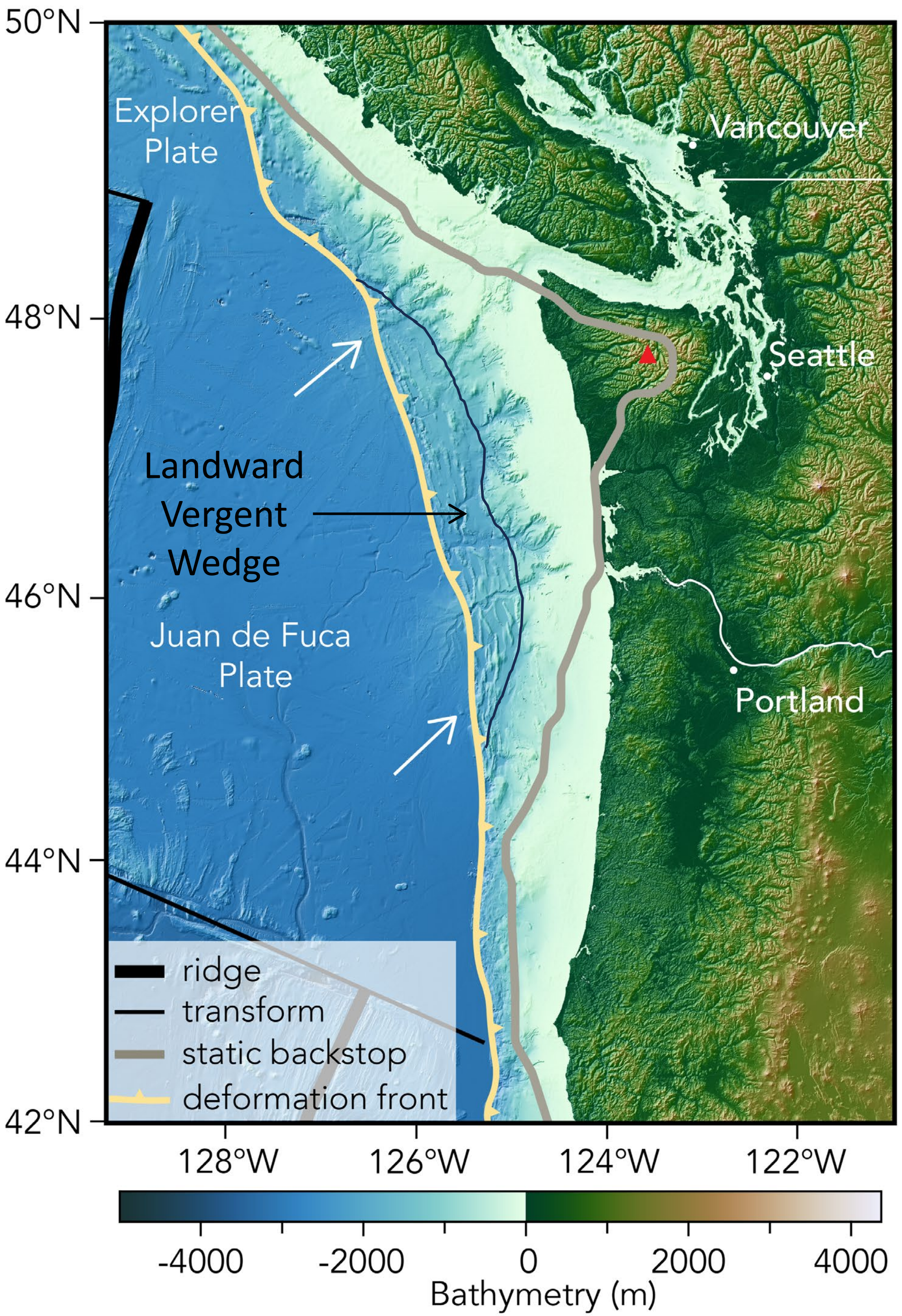


Cubas et al., 2016

Macro-scale geologic structure is a *seismic indicator*: Dynamic friction is a necessary condition for LVZ to form.

The megathrust (and outer splay faults) are capable of locking and contributing to slip deficit to the deformation front.

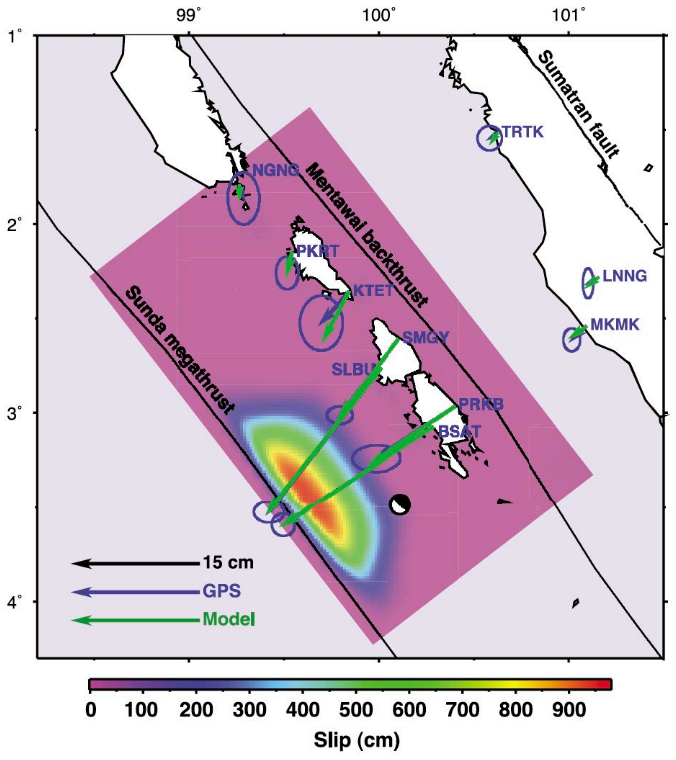
Potentially tsunamigenic surface displacements over a ~30-km wide and 400 km long must be evaluated.

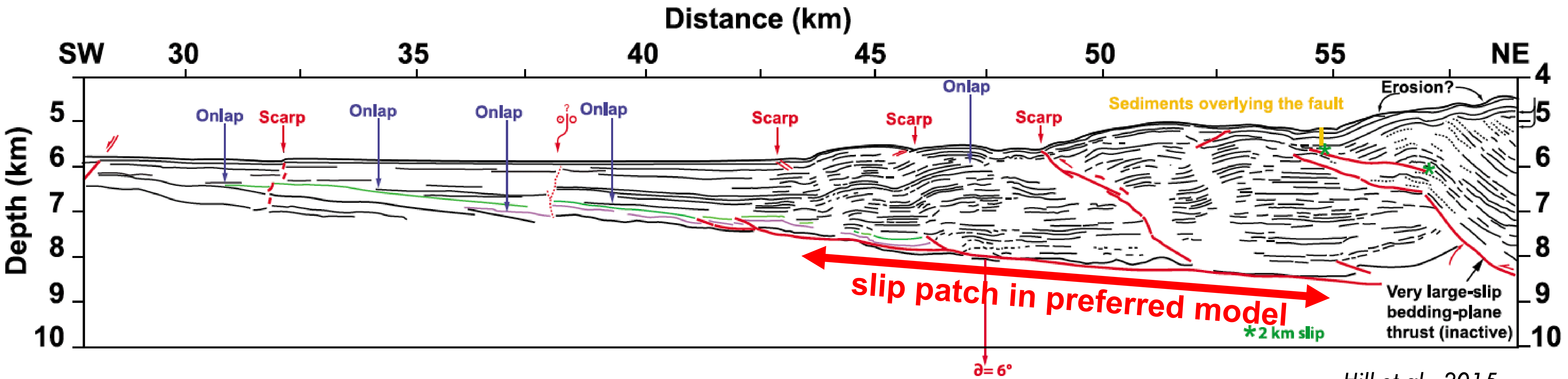


2010 Mentawai M_w 7.8 tsunami earthquake

Near-field GNSS and tsunami inundation runup inverted for rupture patch

- Tsunami runups in excess of 16 meters documented
- GNSS sites on the forearc Mentawai Islands
- Seismic reflection line in agreement with model, showing the rupture was confined to the outermost wedge, hypocenter only 6 km depth
- Peak slip in the model of ~10 meters

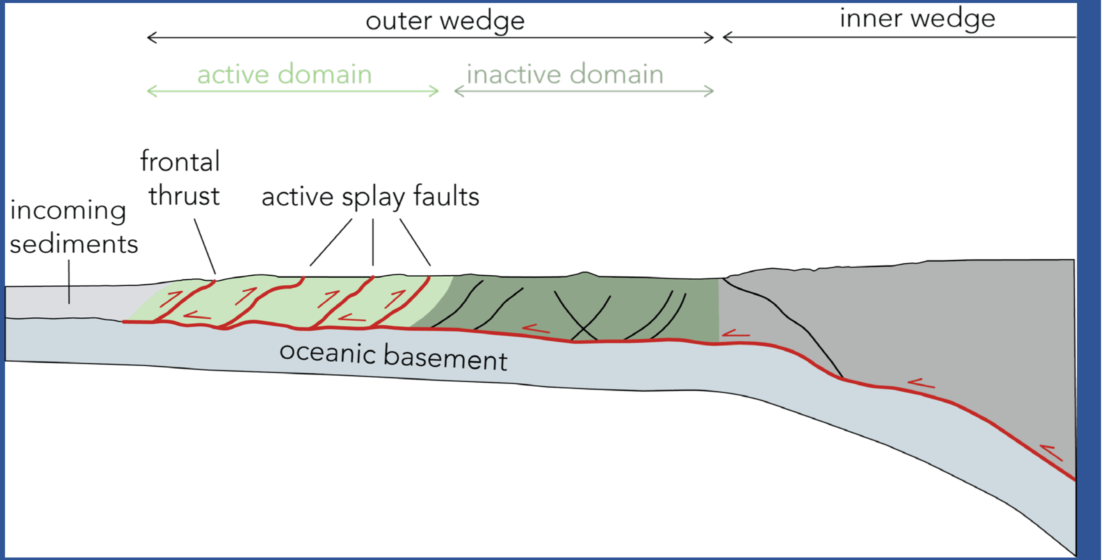


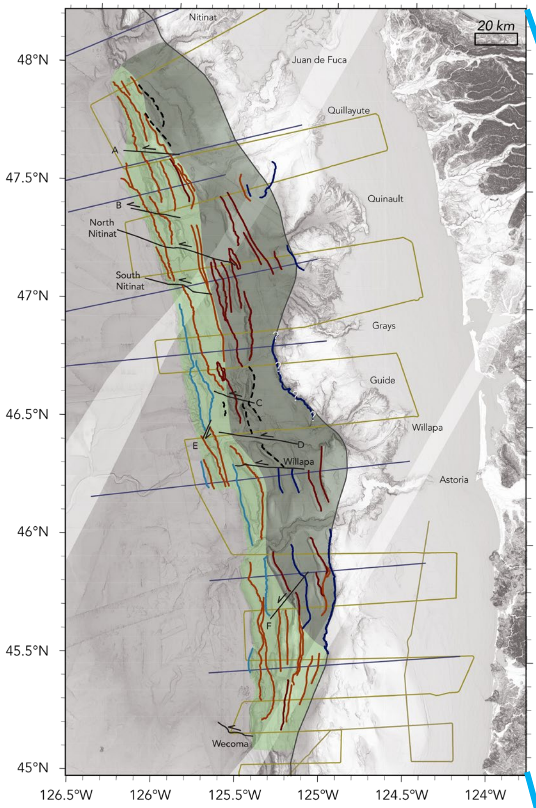


Hill et al., 2015

Take Home Message

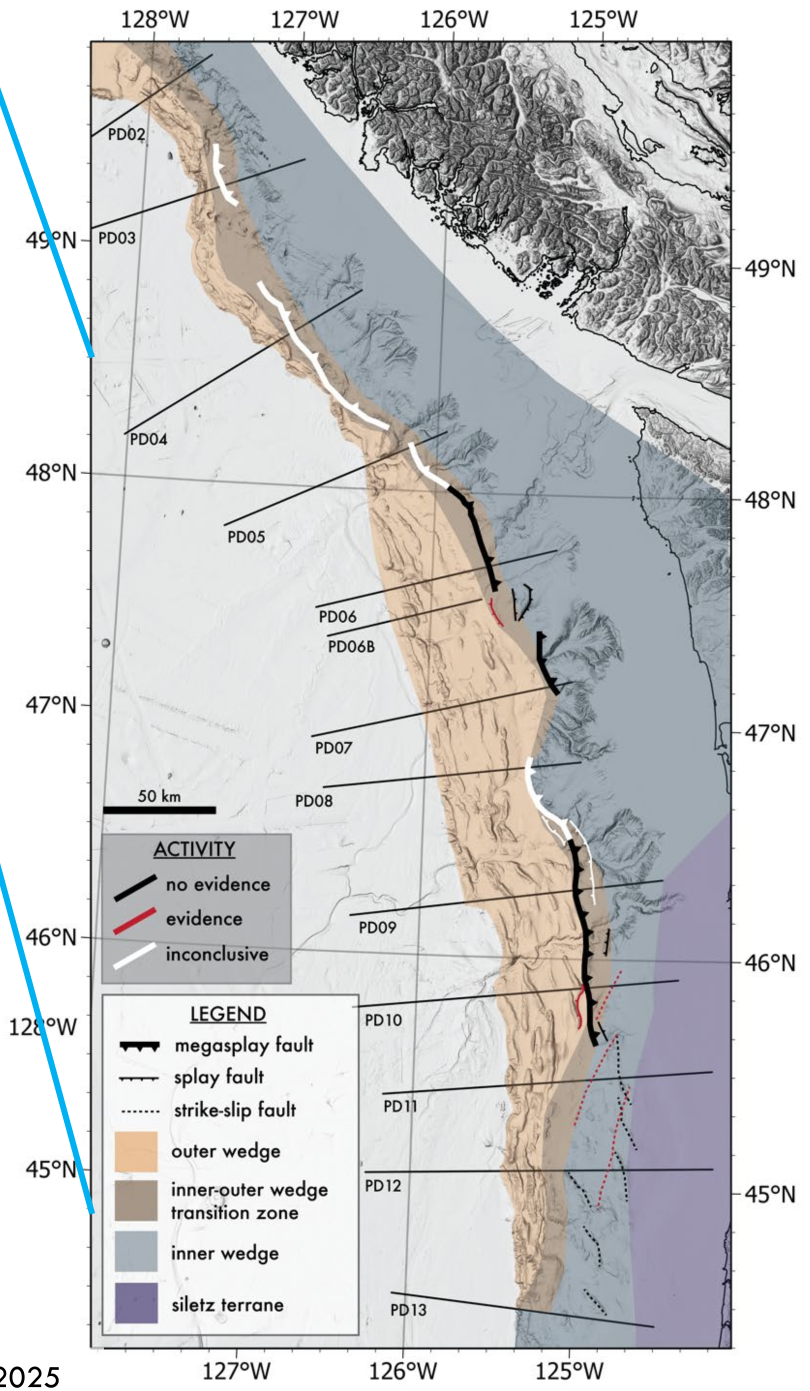
- North-central Cascadia is statically strong but dynamically weak
- Surface displacement may be enhanced by slip up splay faults in the <u>outermost</u> outer wedge
- This locked region is capable of M9 class rupture <u>by itself</u> – full margin rupture is possible but not required.





Ledeczi et al., 2024

Many recently-active faults in outermost region (light green)



"Megasplay" fault is discontinuous to absent

Lucas et al., 2025