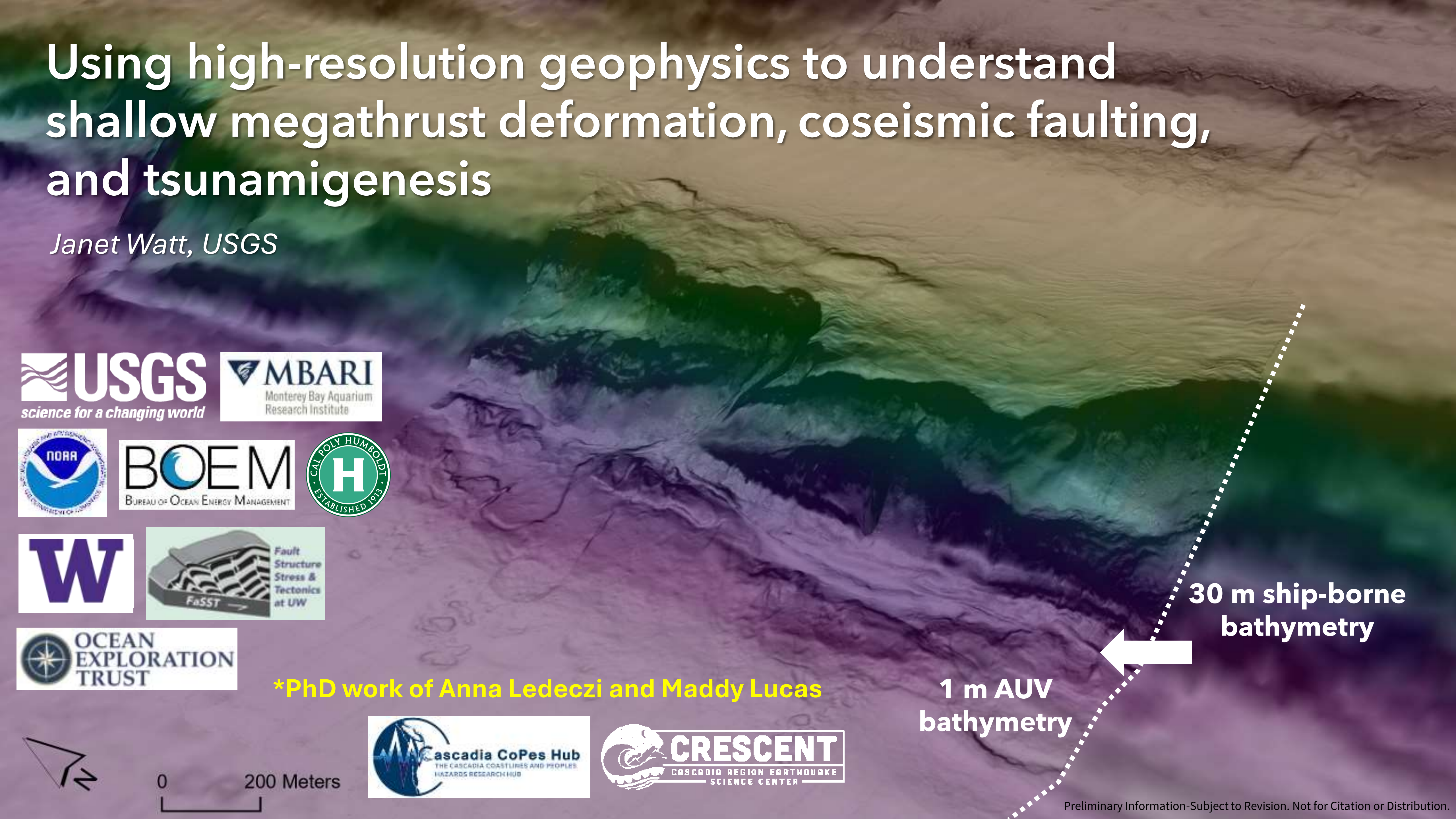
Using high-resolution geophysics to understand shallow megathrust deformation, coseismic faulting, and tsunamigenesis

Janet Watt, USGS



***PhD work of Anna Ledeczi and Maddy Lucas**

How will the seafloor deform in the next megathrust earthquake?

SCIENCE ADVANCES | RESEARCH ARTICLE

GEOPHYSICS

Megathrust locking encoded in subduction landscapes

Bar Oryan[1,2*], Jean-Arthur Olive[1], Romain Jolivet[1,3], Luca C. Malatesta[4], Boris Gailleton[5], Lucile Bruhat[6]

Shallow megathrust slip patterns encoded in outer wedge inelastic (permanent) deformation

How can these deformation patterns inform earthquake/tsunami models (simulations) in Cascadia?

seascape landscape

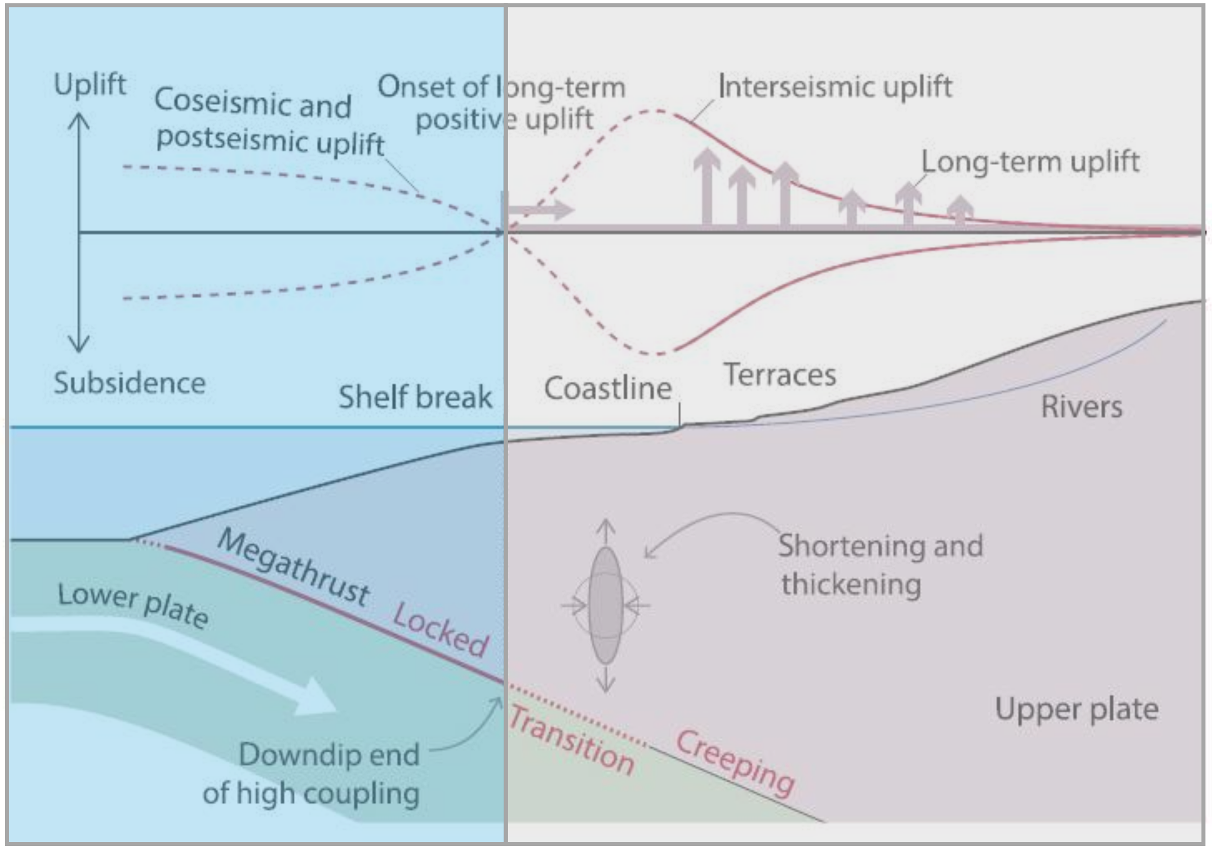
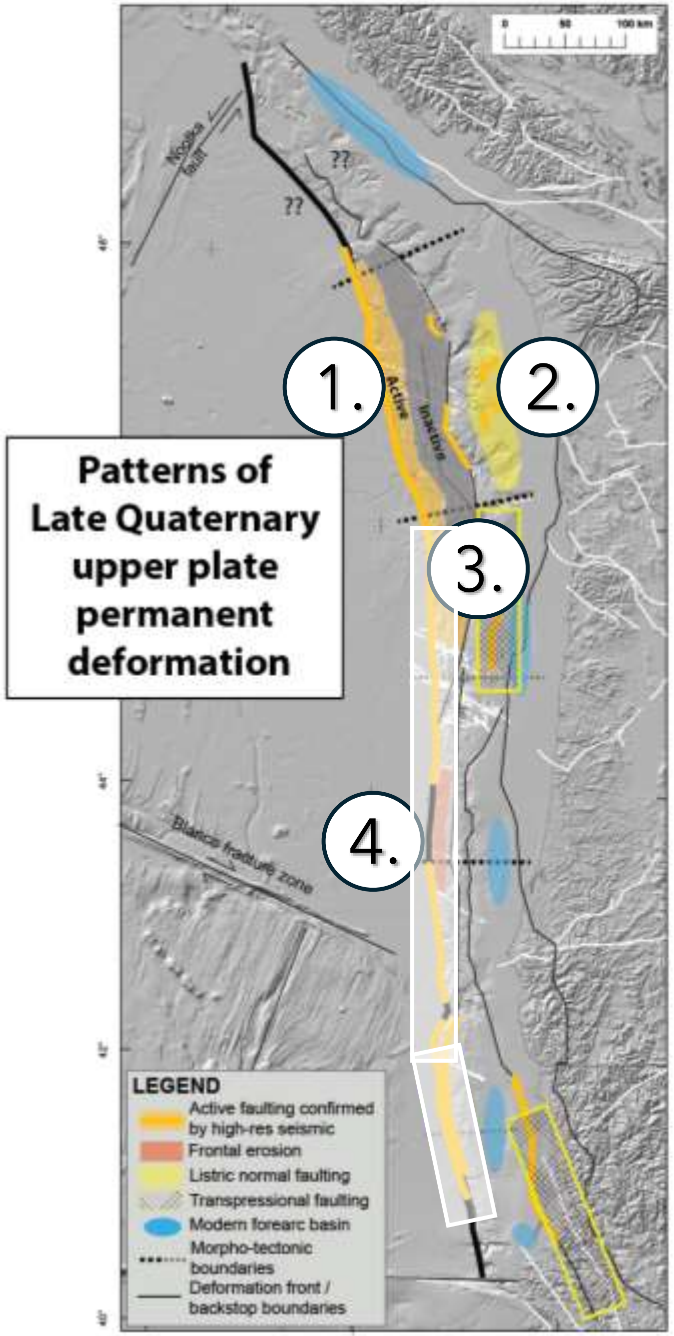


Fig. 1. Signatures of the short-term megathrust cycle in long-term forearc morphology. Elastic surface displacement during the interseismic, postseismic, and coseismic periods is denoted by red curves. Evidence for permanent surface deformation recorded by rivers, terraces, and shelf breaks is marked by pink arrows.

Recent offshore multi-scale geophysical observations that inform our understanding of long-term, likely coseismic, shallow megathrust slip patterns:



Patterns of Late Quaternary upper plate permanent deformation

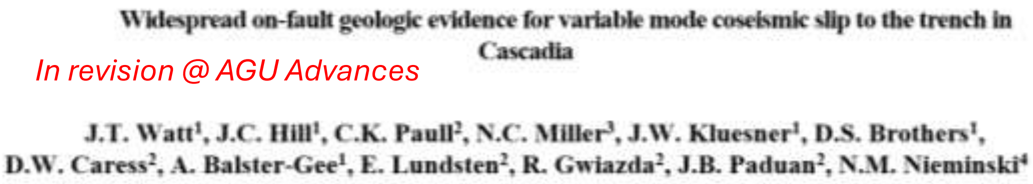
1. ~30km-wide zone of late Quaternary splay fault activity above shallow megathrust offshore WA and northern OR (Ledeczi et al., 2024)

2. Possible coseismic activation of listric normal faults along the shelf edge offshore WA
*Jenna Hill talk NEXT!!!

3. No evidence for late Quaternary active margin-spanning ***megasplay*** fault offshore OR and WA (Lucas et al., 2025)

4. Widespread evidence for variable mode slip to-the-trench in central and southern Cascadia (Watt et al., *in review* @ AGU Advances)

What is the updip limit and mode of shallow megathrust coseismic slip in central and southern Cascadia?

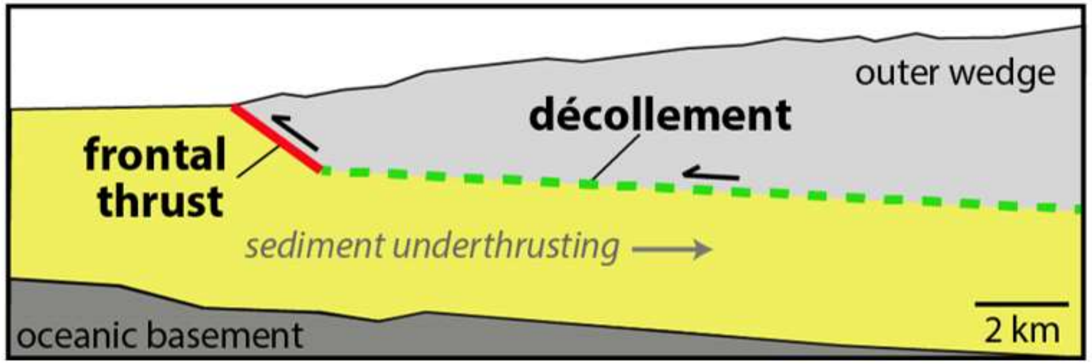


Widespread on-fault geologic evidence for variable mode coseismic slip to the trench in Cascadia

J.T. Watt[1], J.C. Hill[1], C.K. Paull[2], N.C. Miller[3], J.W. Kluesner[1], D.S. Brothers[1], D.W. Caress[2], A. Balster-Gee[1], E. Lundsten[2], R. Gwiazda[2], J.B. Paduan[2], N.M. Nieminski[4]

In revision @ AGU Advances

Shallow megathrust =
décollement + frontal thrust faults



Multi-scale Approach:

Integrate 30 m ship-borne multibeam bathymetry and sparker seismic with targeted autonomous underwater vehicle (AUV) 1 m bathymetry and chirp data

1. Characterize Holocene active structure and morphology along the frontal thrust fault zone (FTFZ)
2. Document and evaluate geomorphic and stratigraphic evidence for coseismic frontal thrust rupture

Joint interpretation with depth-migrated crustal-scale seismic data (CASIE21)

3. Link shallow morpho-tectonics to deeper décollement structure and behavior

Why we should expect coseismic slip to the *sediment-filled* trench in Cascadia

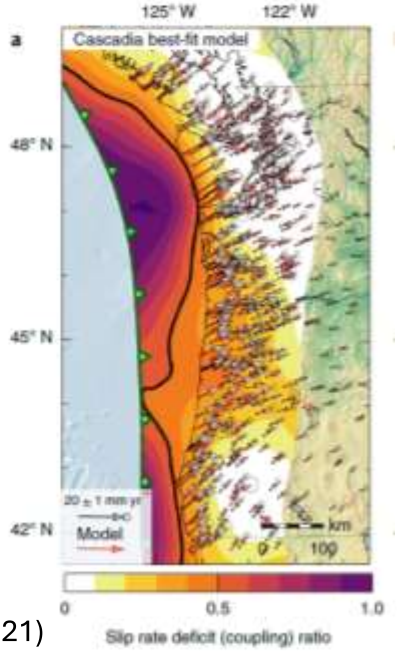
- Temperatures as high as 170°C and thick incoming sediment place the thermally-defined updip limit of the seismogenic zone at the deformation front (Hyndman and Wang, 1993; 1995; Hüpers et al., 2017; Salmi et al., 2017; Carbotte et al., 2024).

- Geodetic observations and modeling indicate the shallow megathrust fault along the deformation front is moderately to fully locked and accumulating strain (Lindsey et al., 2021; DeSanto et al., 2025).

- Strong (consolidated) wedge in northern Cascadia likely promotes shallow slip (Han et al., 2017)

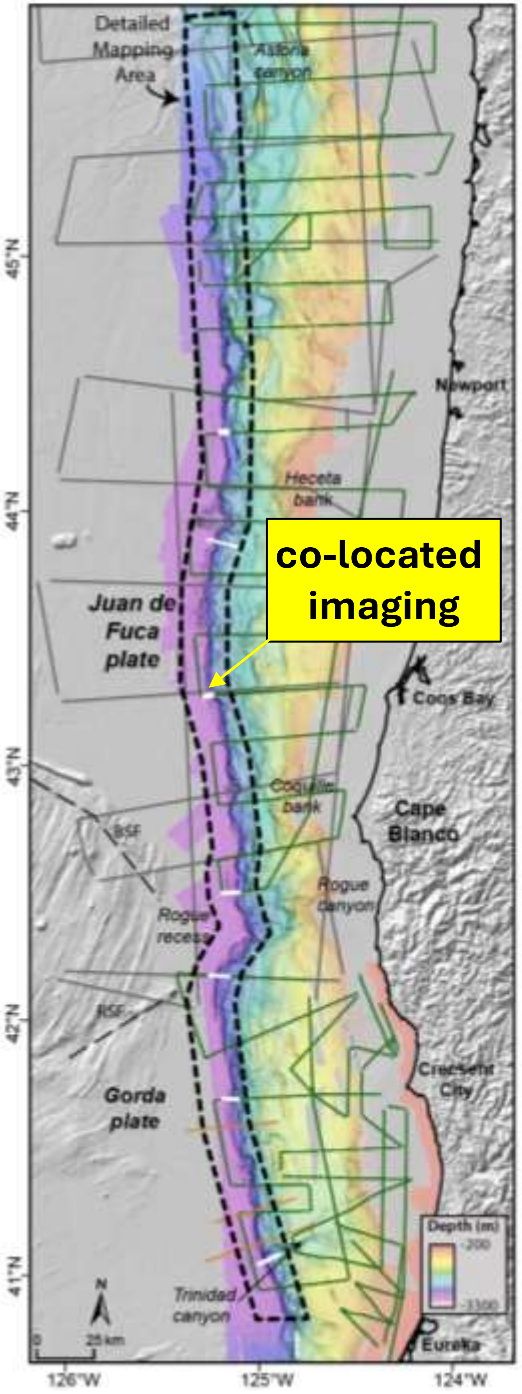
- Pervasive and punctuated mass wasting events along the deformation front in Cascadia that appear to coincide (*in time*) with ruptures of the megathrust suggest coseismic deformation of frontal thrust structures (Hill et al., 2026)

Hyndman and Wang (1995)



Lindsey et al. (2021)

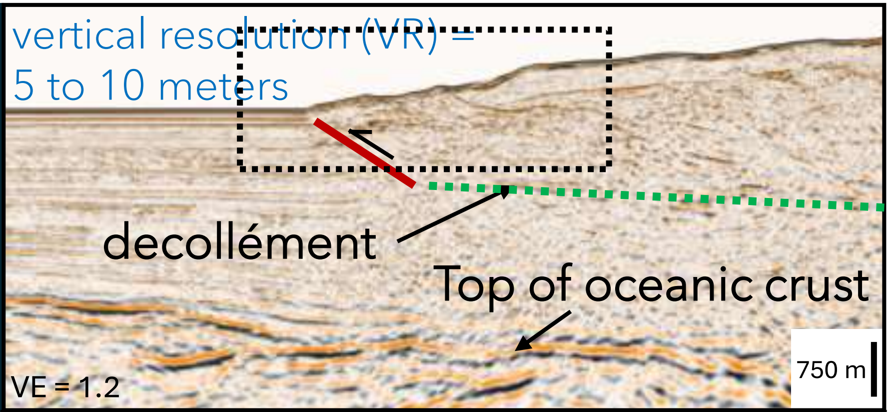
Seismic Imaging Resolution → Deformation timescale



Long-offset airgun (CASIE 21)

Depth-migrated = fault geometry

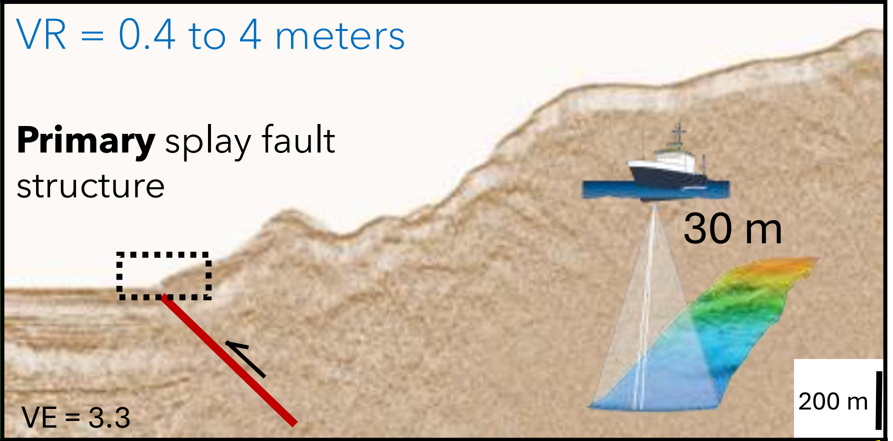
crustal-scale



Undifferentiated Quaternary (<1.6 Ma)

Multi-channel Sparker

shallow



Late Quaternary (<130,000 yrs)

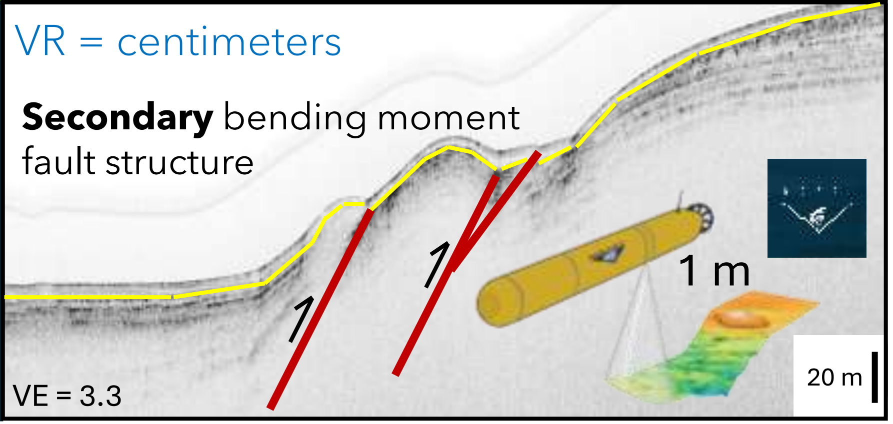
Long-term deformation patterns

Game changer!

AUV chirp

near-surface

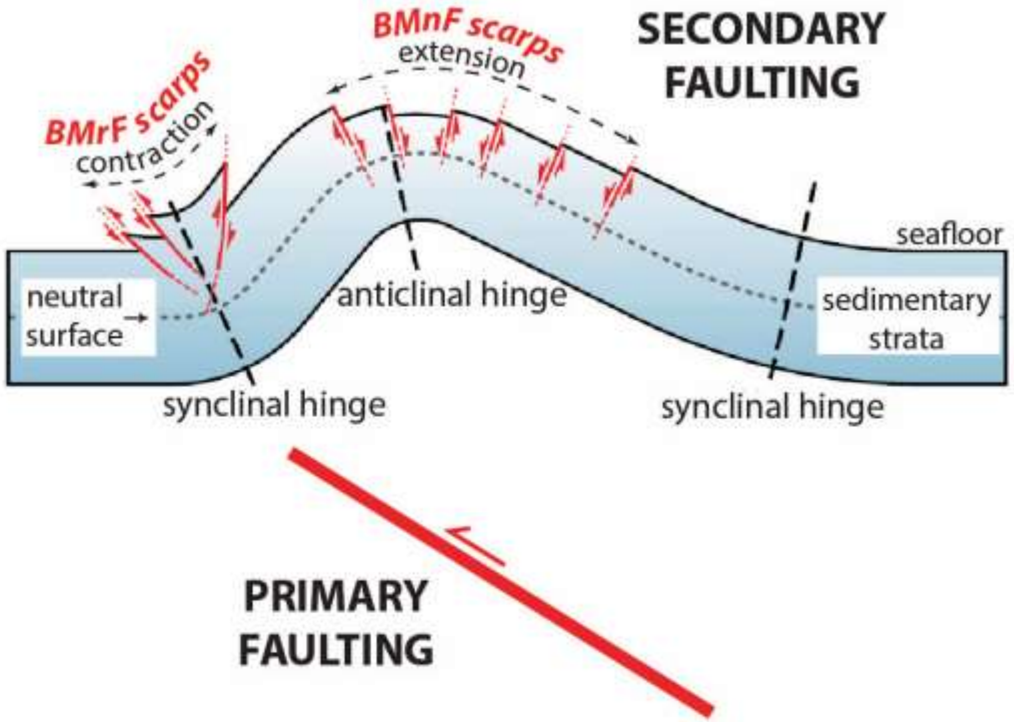
Inferred Holocene strata



Holocene (<11,700 yrs)

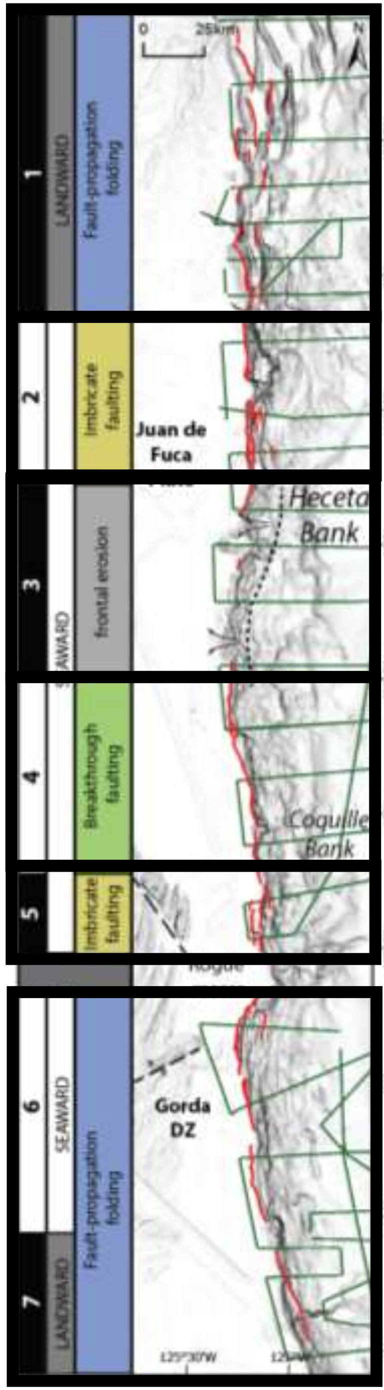
event-scale stratigraphy

Primary and secondary fault structure



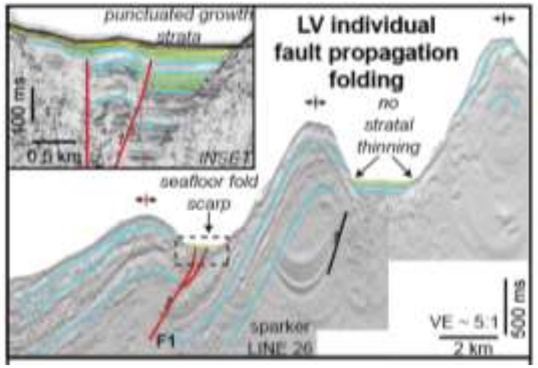
Modified from Li et al. (2018)

Fault Characterization:

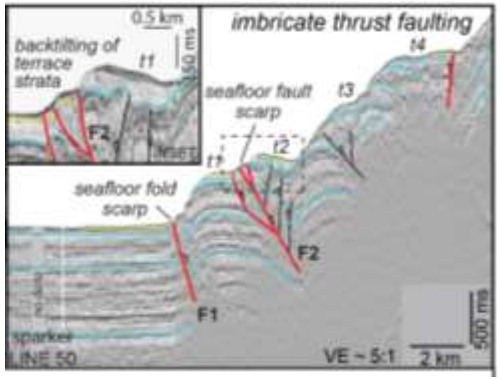


- \- **extensive evidence for Holocene active faulting along the FTFZ**, except for an (~65-km-long) section offshore Heceta bank in central Oregon
- **7 sections:** along-strike variations in primary fault vergence, Holocene deformation style, and seafloor morphology
- \- **four primary frontal thrust deformation styles:** individual fault propagation folding, imbricate thrust faulting, pervasive mass wasting and frontal erosion, and breakthrough thrust faulting.

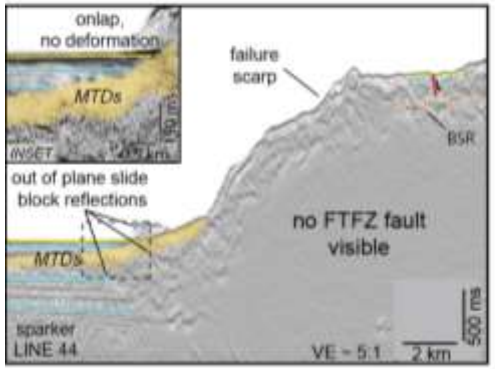
Individual fault-propagation folding



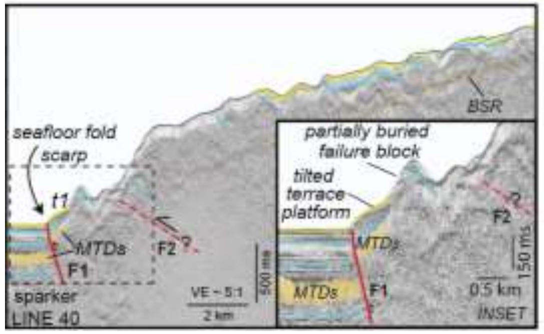
Imbricate thrust faulting



Pervasive mass wasting / frontal erosion



Breakthrough thrust faulting



Distinguishing creep and coseismic slip in the offshore geologic record

Observed Holocene active faulting along the FTFZ is the result of:

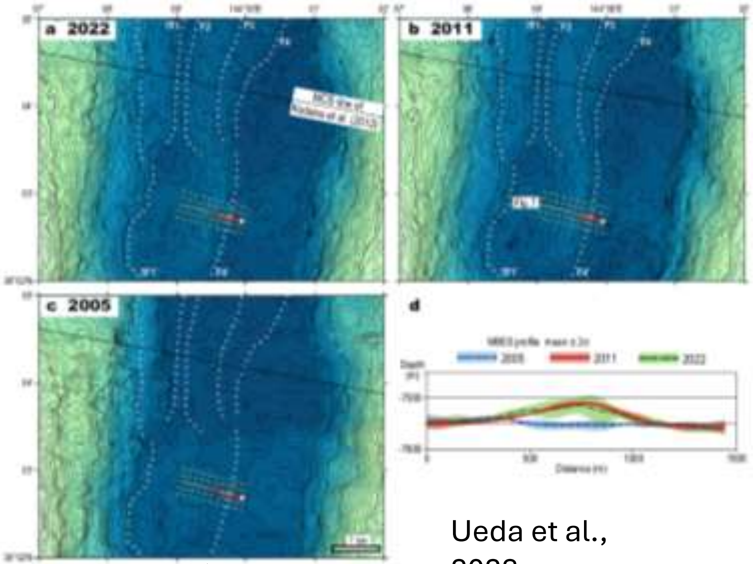
1. *Continuous steady creep*
2. *Rapid coseismic slip*
3. *Afterslip*
4. *Some combination of the above*

Extra tricky!

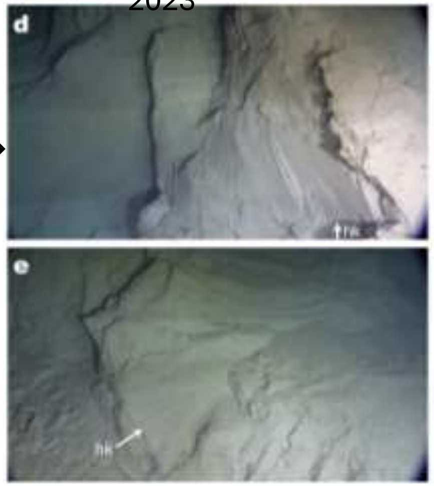
We cannot definitively distinguish between these 3 slip modes without
- a recorded earthquake!
- repeat bathymetry
- continuous cross-fault geodetic monitoring (cabled seafloor arrays)

BUT, we can follow the lead of paleoseismologists on land and look for geomorphic and stratigraphic clues…

Repeat Bathymetry



Ueda et al., 2023



Surface expression of the F4 fault trace = 26m scarp

On-fault geologic evidence for coseismic slip

Geomorphic

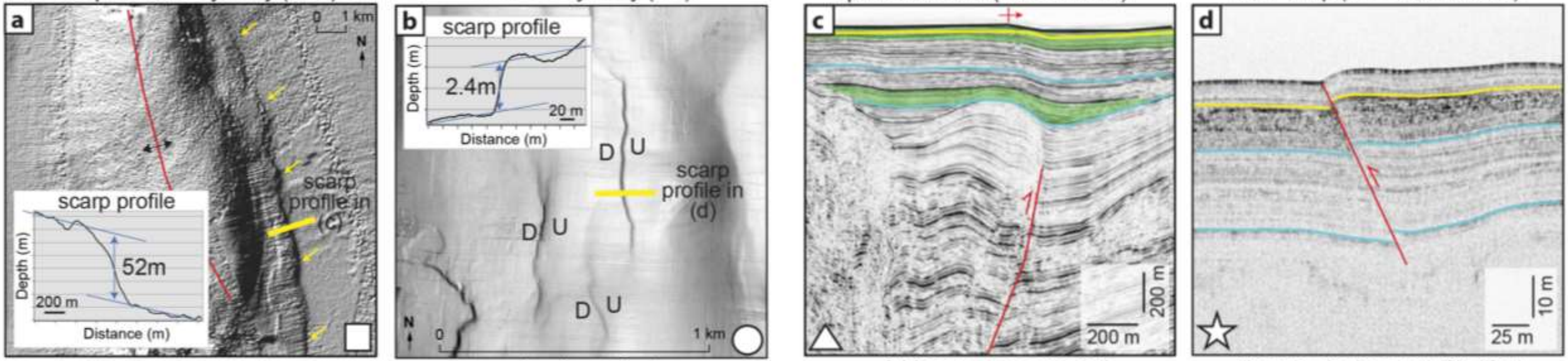
Stratigraphic

Shipborne bathymetry (30m)

AUV bathymetry (1m)

Shipborne
Sparker seismic (VR = meters)

AUV chirp (VR = centimeters)



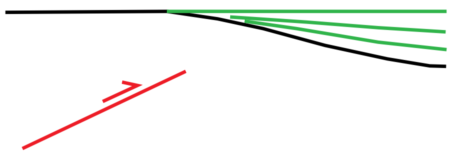
primary thrust fault scarp

secondary thrust fault scarp

fold scarp + punctuated
growth strata

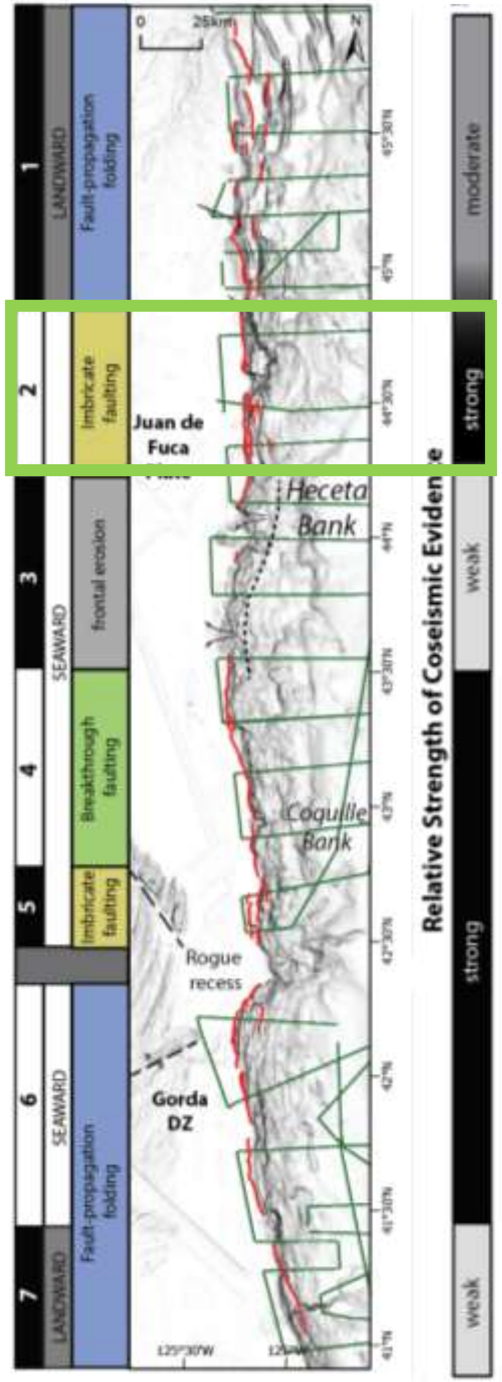
discrete single event (?) offset
no growth strata

Continuous stratal thinning



Active fault
(continuous steady creep)

On-fault geologic evidence for coseismic slip



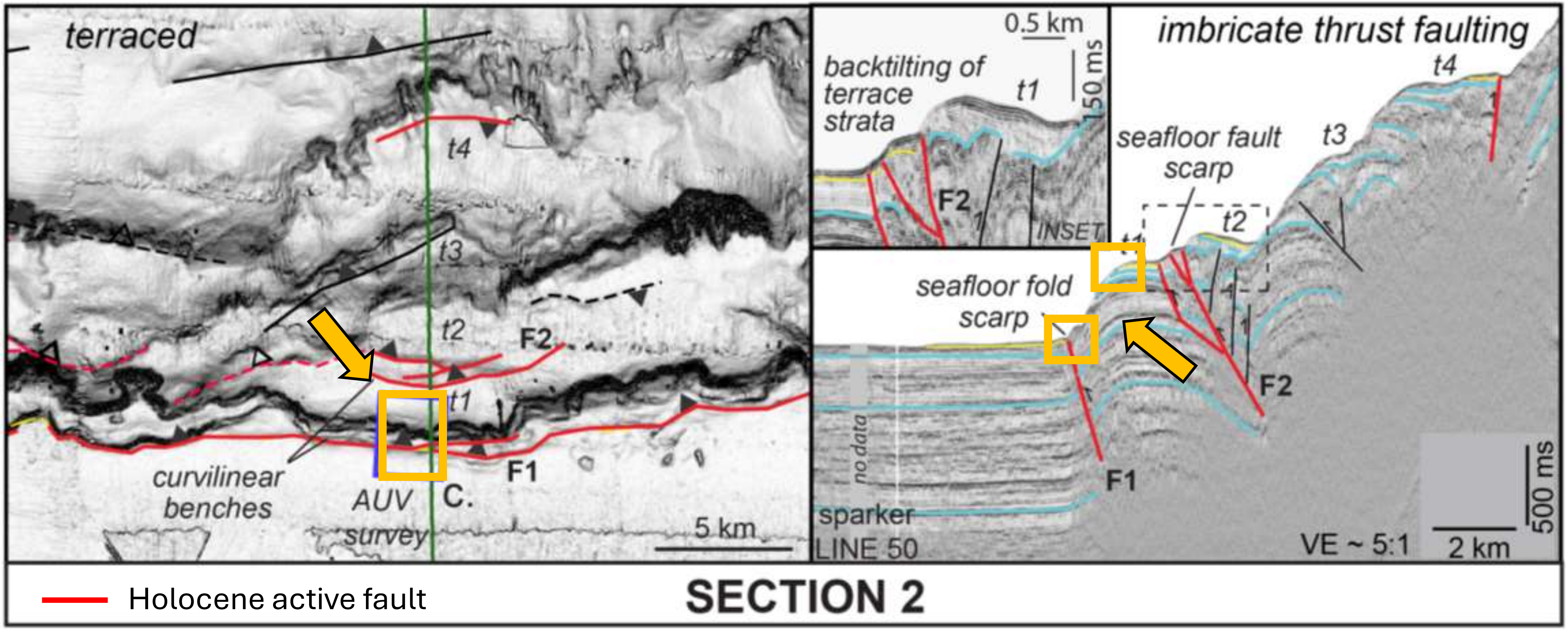
- Widespread geomorphic and stratigraphic evidence for Holocene active, likely coseismic deformation along the frontal thrust splay fault system *(*strength of evidence varies by section)*
- The type of on-fault geologic evidence for coseismic slip along the FTFZ varies among fault sections, with no clear relationship to primary FTFZ deformation style.
- The relative strength of geomorphic or stratigraphic evidence for coseismic slip varies along-strike and depends on both the resolution of available data and whether geomorphic evidence is combined with stratigraphic evidence in a particular location

Morphology and Primary fault structure:

Shallow sparker + ship-based bathymetry

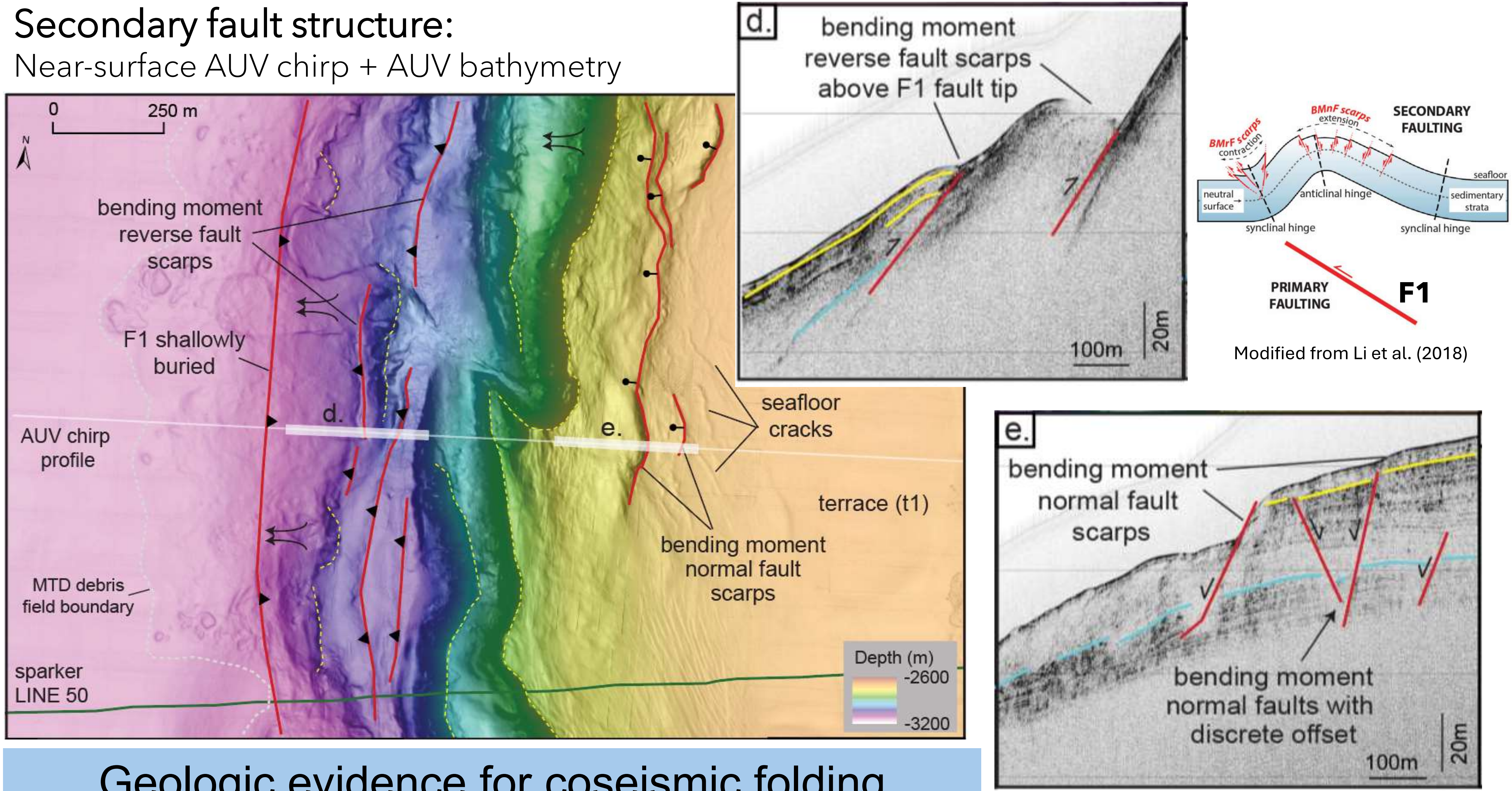
Imbricate faulting

(terraced lower slope)



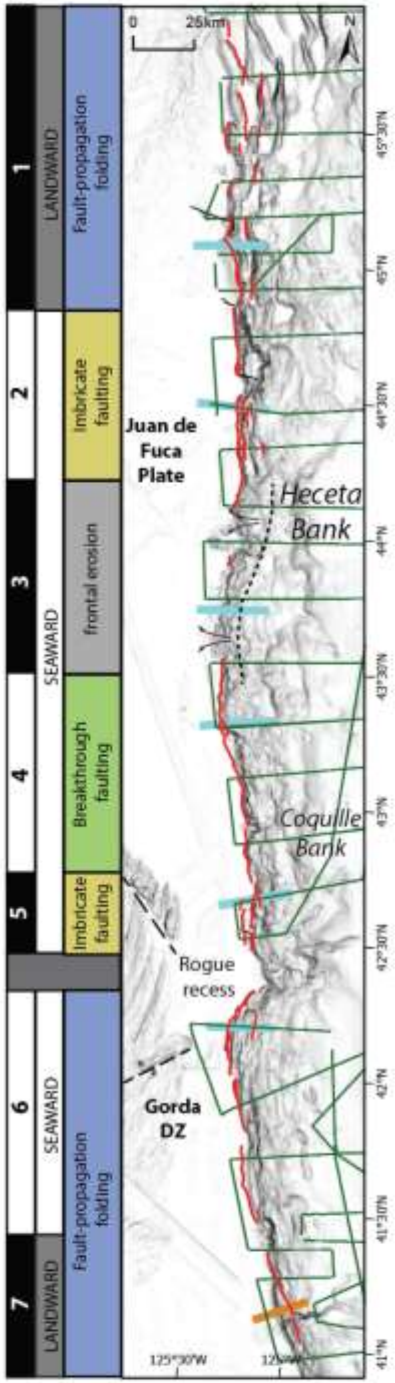
Secondary fault structure:

Near-surface AUV chirp + AUV bathymetry



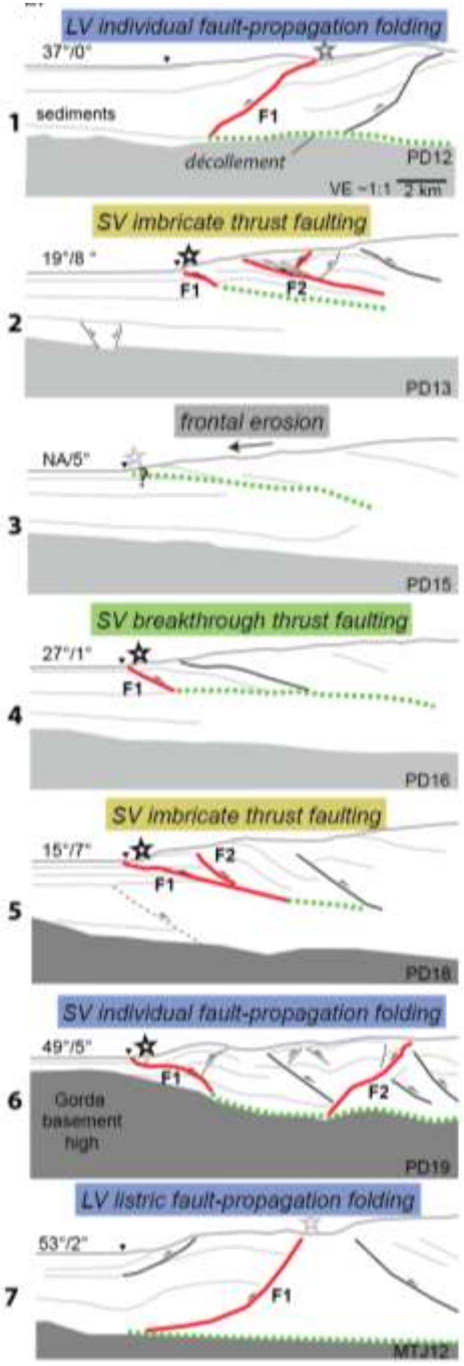
Modified from Li et al. (2018)

Geologic evidence for coseismic folding



Joint interpretation with crustal-scale seismic

- Fault geometry
- Rupture mode



Shallow megathrust geometry and rupture mode varies along-strike

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Fault Dip:

- FTFZ dips 11° to 53 °
- Decollement dips 0 ° to 8 °

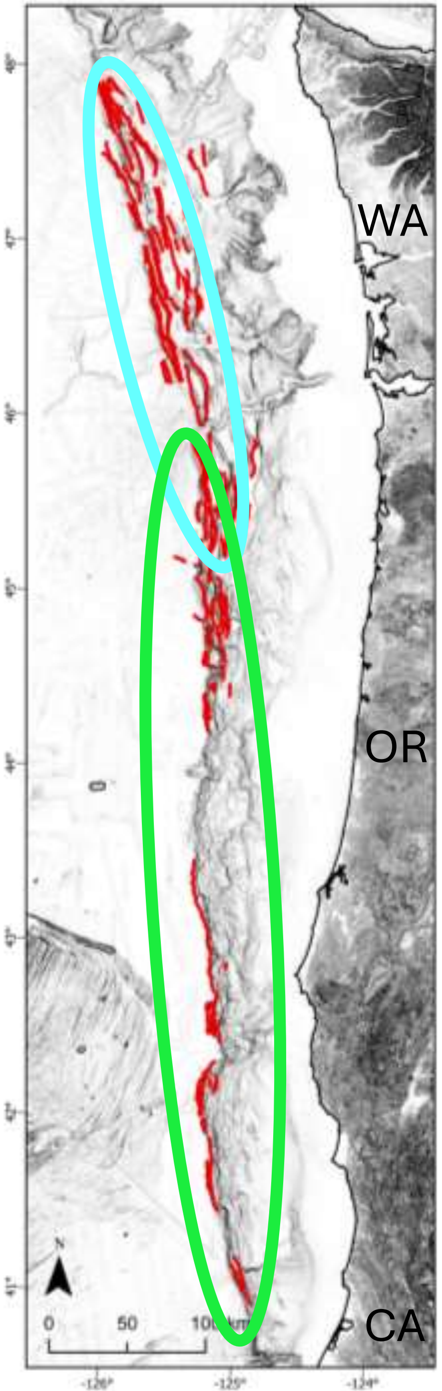
Decollement depth (below seafloor)**:**

- 0.8 to 3.3 km

— active frontal thrust splay faults

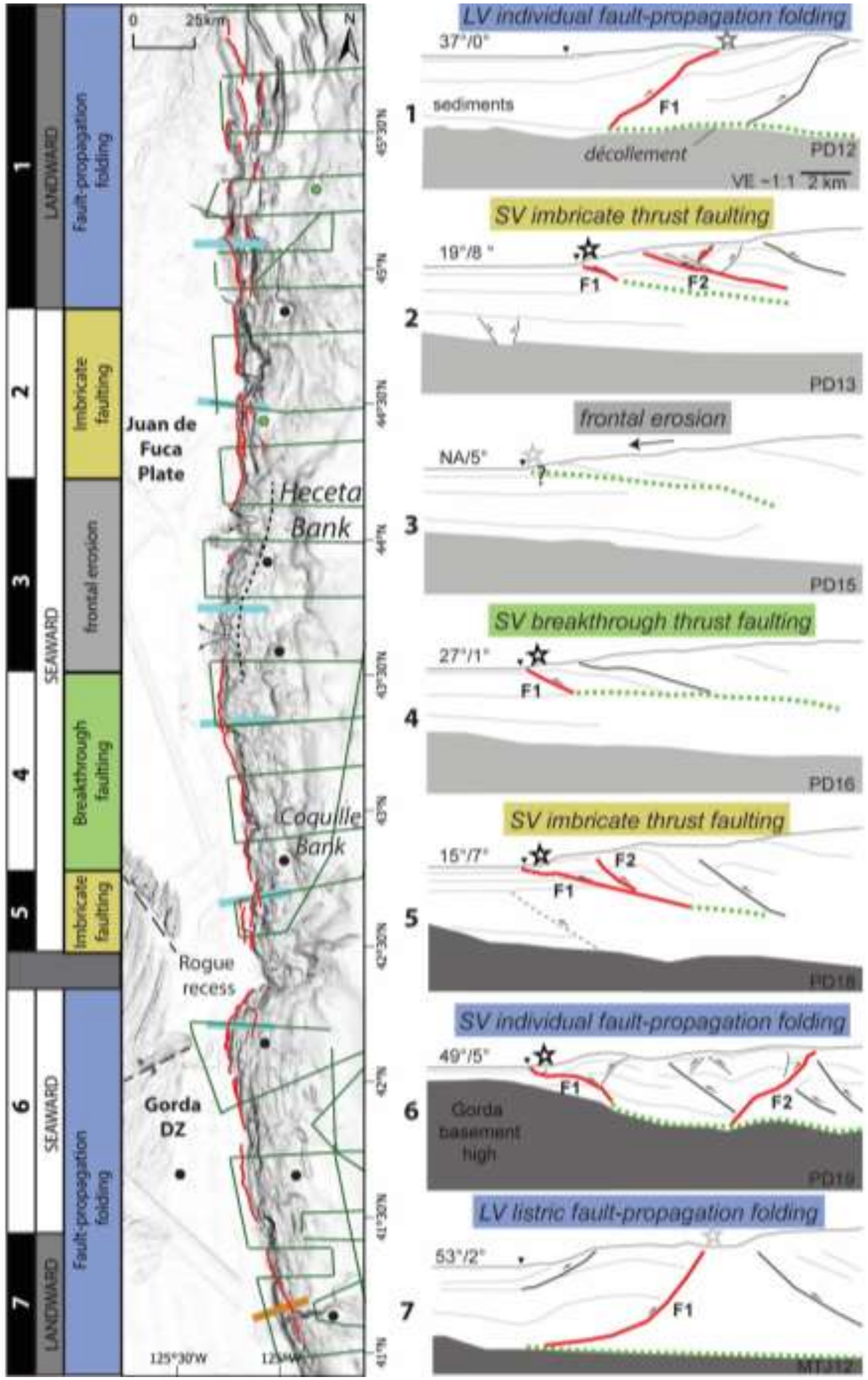
┈ megathrust décollement

Updip limit and mode of shallow megathrust coseismic slip in Cascadia



Widespread distribution of on-fault geologic evidence for coseismic slip along the FTFZ presented here, combined with similar results offshore WA *(Ledeczi et al., 2024; Beeson et al., 2017)* suggests **slip to the trench is a common rupture mode along the U.S. Cascadia margin**

Results presented here offer a comprehensive and detailed view of the along-strike changes in frontal thrust deformation style, geometry, and connectivity to the décollement that highlights the **heterogeneity in near-trench permanent seafloor deformation that can be expected in future Cascadia megathrust earthquakes**

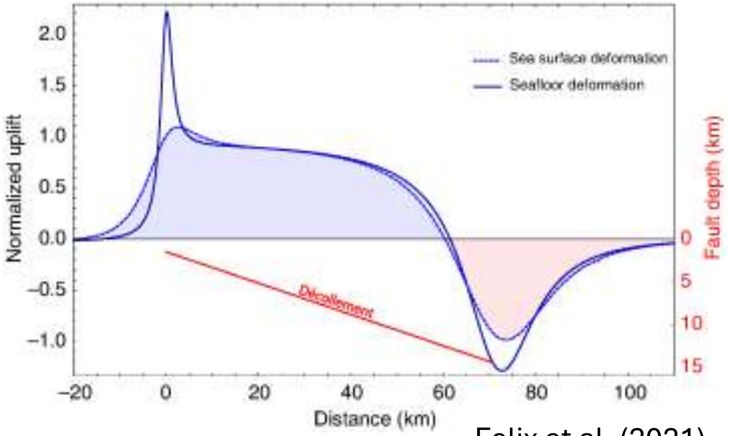


Implications for tsunamigenesis

This heterogeneity argues for variability in cumulative (décollement + FTFZ) shallow megathrust fault slip and **latitudinal differences in tsunamigenesis along the margin that should be examined in future tsunami models**.

Besides coseismic slip magnitude, shallow megathrust fault source parameters that are thought to contribute most to tsunamigenesis include:

1. **fault and seafloor geometry**
2. **water depth**
3. **décollement depth**



*Damping effect of water column

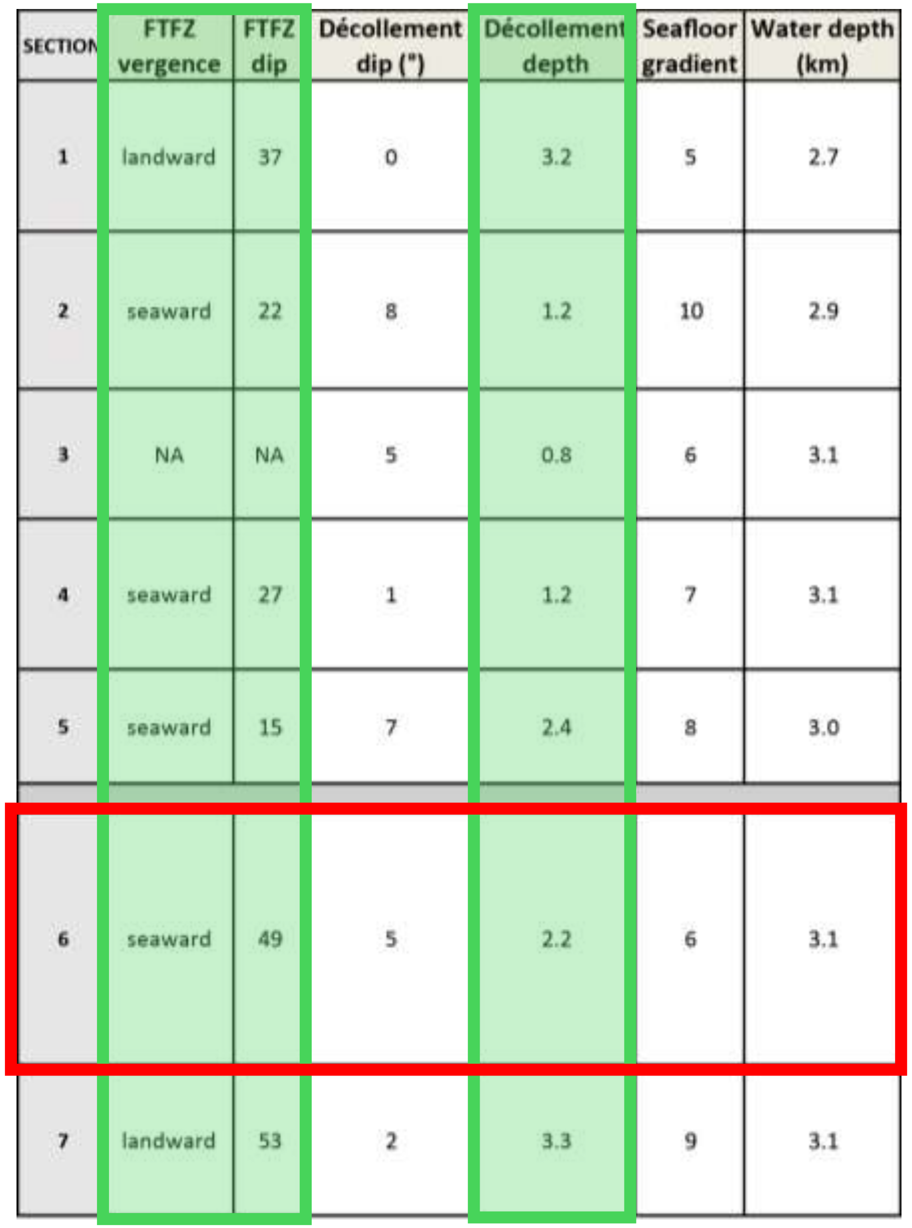
Felix et al. (2021)

Shallow megathrust tsunami source parameters

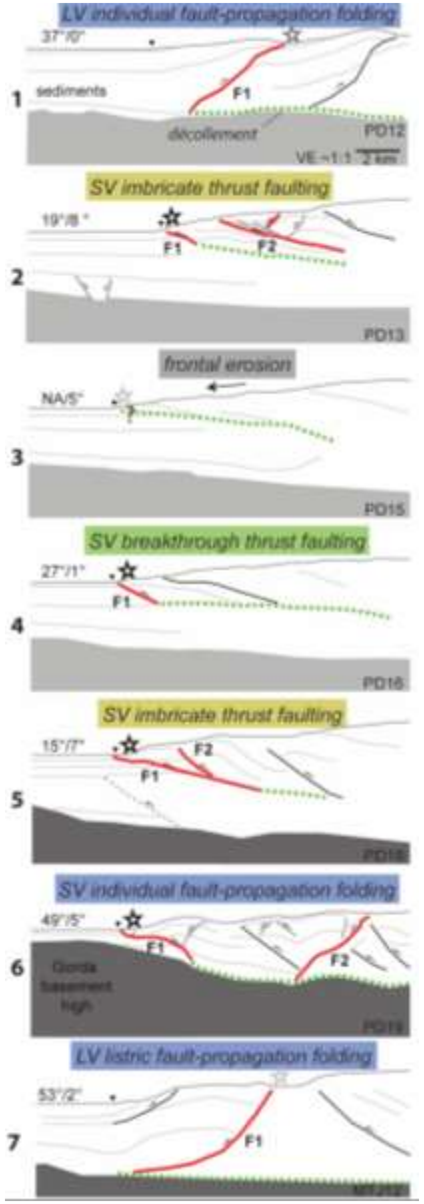
Greatest differences in FTFZ geometry and décollement depth

- Greater decollement depths generate larger tsunami energy due to the greater width of the uplift patch relative to water depth (Felix et al., 2021)
- 2D and 3D dynamic rupture simulations show that seaward vergent splay faults host greater slip, seafloor uplift, and tsunami heights than landward vergent splays (Aslam et al., 2021; Biemiller et al., 2025)

*Section 6 may have greatest tsunami potential (moderate decollement depth + steeply-dipping, seaward vergent frontal thrust)

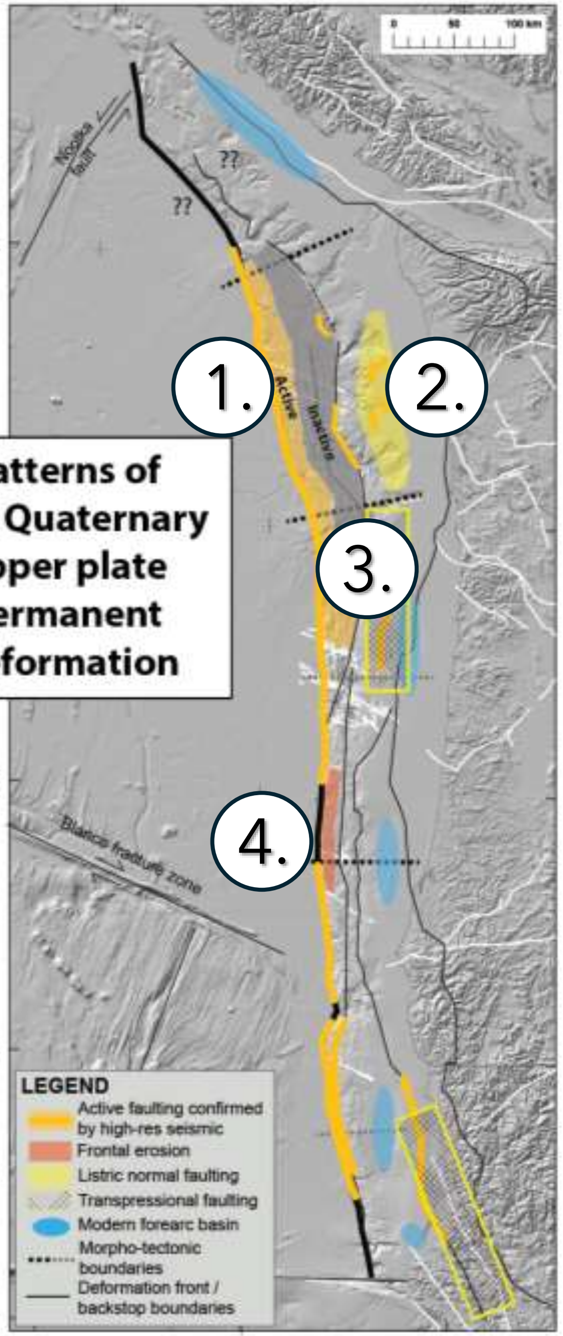


SECTION	FTFZ vergence	FTFZ dip	Décollement dip (°)	Décollement depth	Seafloor gradient	Water depth (km)
1	landward	37	0	3.2	5	2.7
2	seaward	22	8	1.2	10	2.9
3	NA	NA	5	0.8	6	3.1
4	seaward	27	1	1.2	7	3.1
5	seaward	15	7	2.4	8	3.0
6	seaward	49	5	2.2	6	3.1
7	landward	53	2	3.3	9	3.1

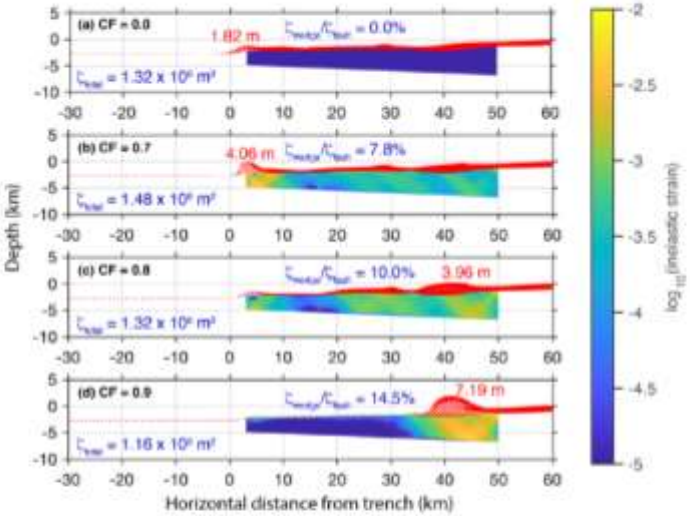


Improving earthquake/tsunami models (simulations) in Cascadia

Together, these studies provides geologic constraints on the extent and mode of inelastic, permanent coseismic deformation along the shallow megathrust in Cascadia that can be used to inform models of tsunami generation and tsunami hazard assessment in Cascadia



Patterns of Late Quaternary upper plate permanent deformation

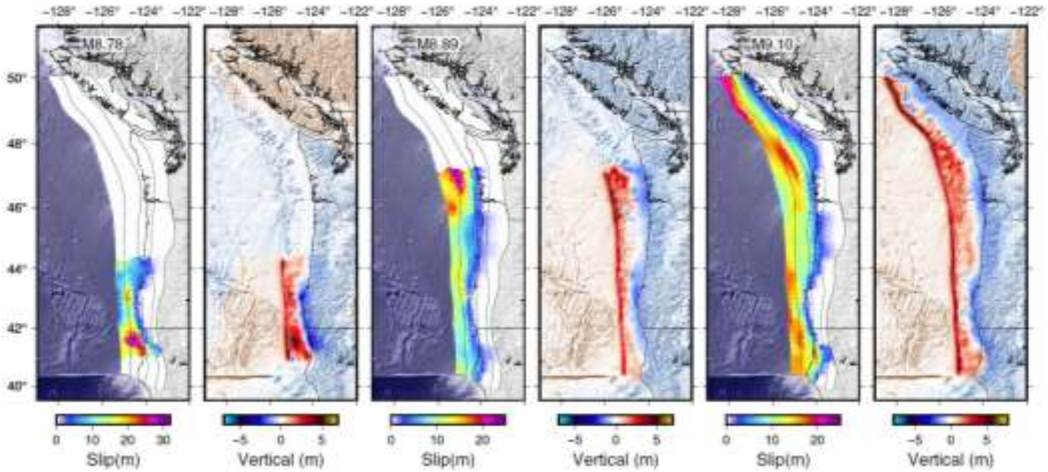


Modeled seafloor deformation from fully coupled dynamic rupture and tsunami simulations (*considering inelastic deformation)

Wilson & Ma, 2021

Modeled seafloor deformation from kinematic rupture models

Melgar, 2021



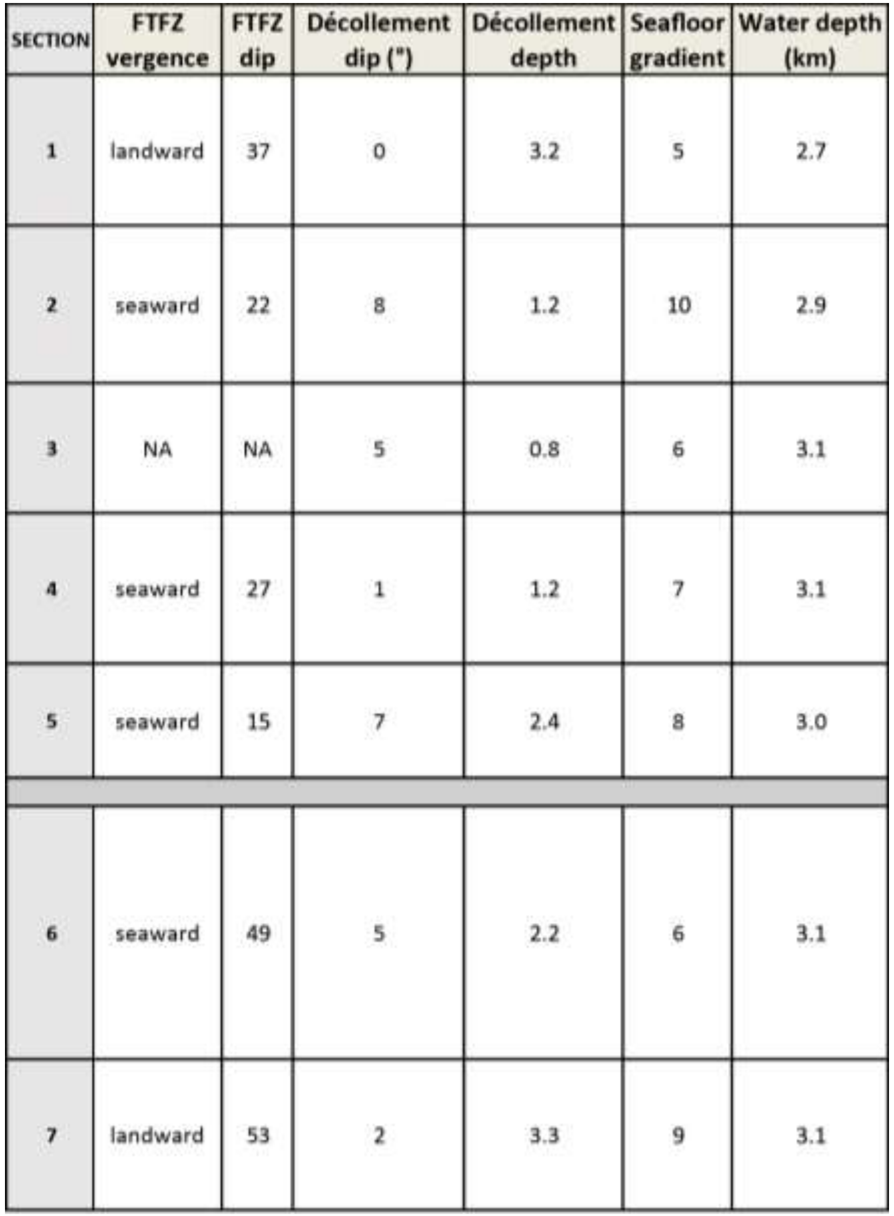
Remaining questions…

1. How do differences in shallow megathrust geometry impact tsunamigenesis and hazard along the margin? Need to consider elastic and inelastic behavior

2. Can we use dynamic rupture models incorporating realistic megathrust/splay fault geometries and wedge properties to place bounds on shallow megathrust slip magnitude?

3. How are variations in elastic wedge properties (consolidation state, Vp, density) expressed in patterns of inelastic wedge deformation and how do these properties influence tsunamigenesis?

4. How does the shape/geometry of the plate interface control earthquake size and recurrence? Are there quantifiable differences between various slab/interface models?



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