What Did the 1700 AD Cascadia Earthquake Look Like?

Correlating Deformation and Tsunami Inundation Modeling with Paleoseismic Proxies

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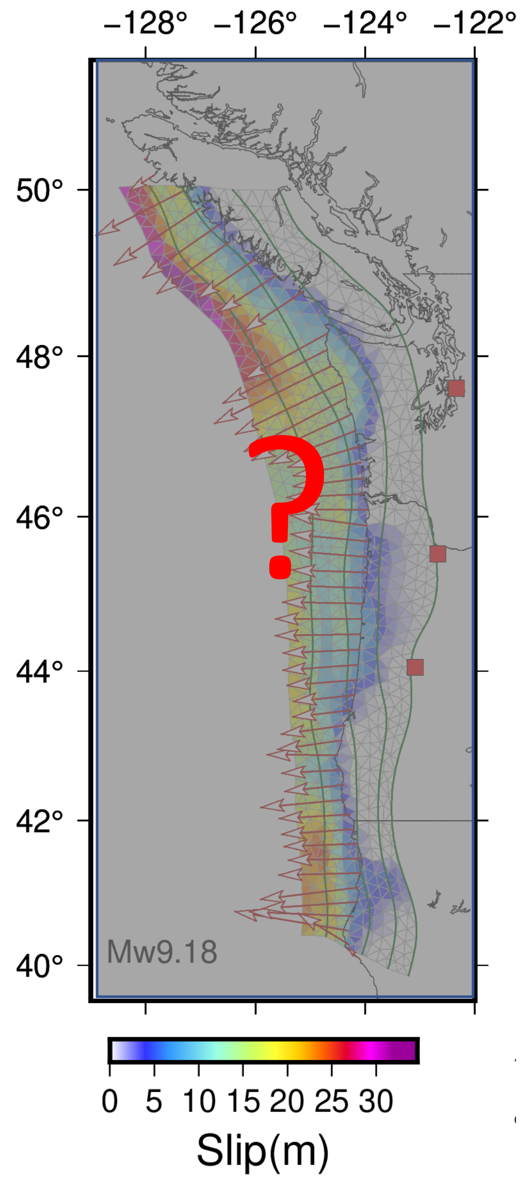
Goals/Focuses of this work:

1. Utilize paleoseismic proxies to study the 1700 Cascadia event

2. Devise a method for testing synthetic rupture models using regional paleotsunami data
   - Test the sensitivity of inundation models to tide levels

3. Constrain potential slip patterns of the 1700 CE event… kinda.



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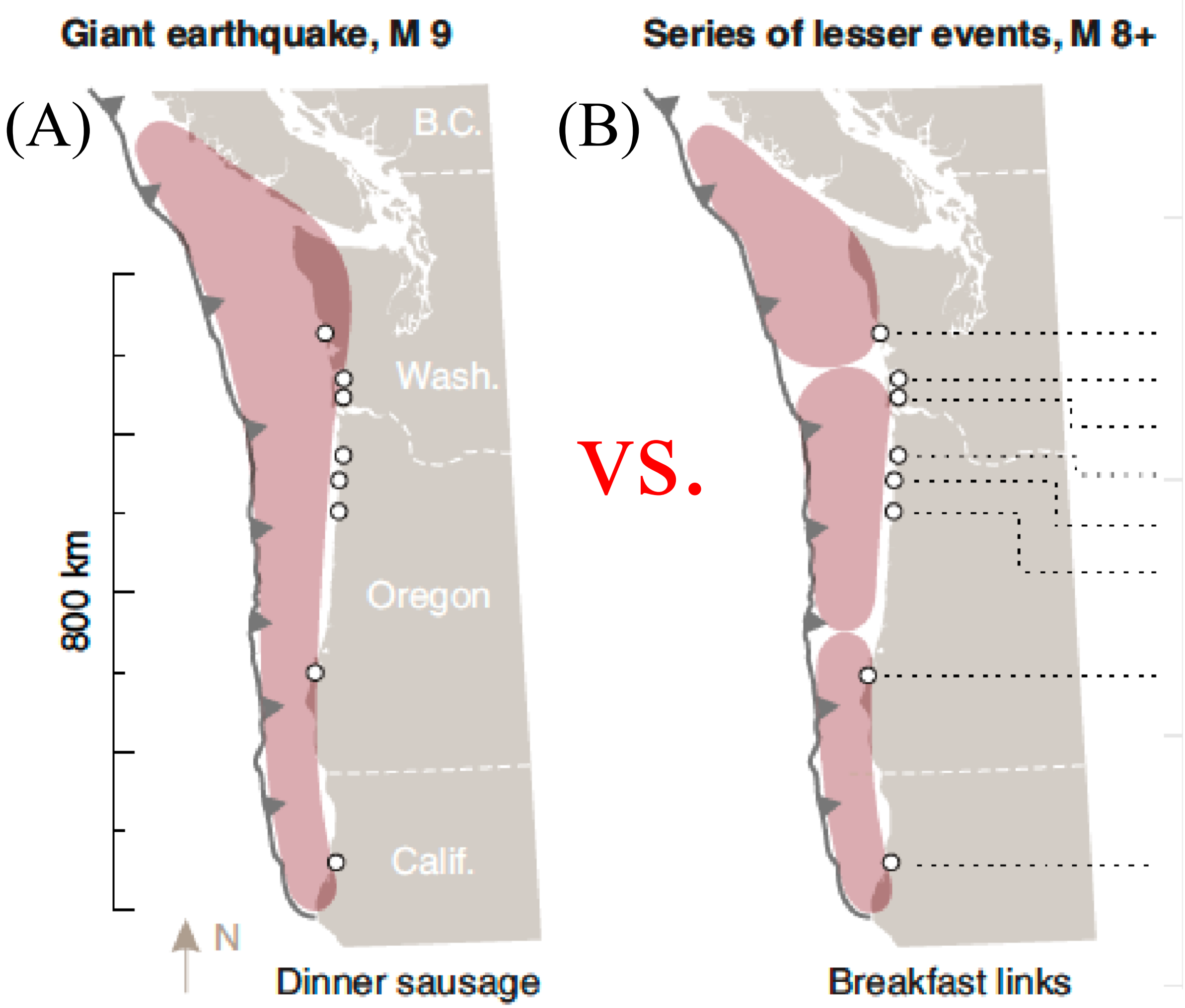
Why do we care? – implications for the future



Atwater et al., 2005

1. Understanding the earthquake cycle of the past helps our understanding for the future

2. Are full margin ruptures possible or likely?

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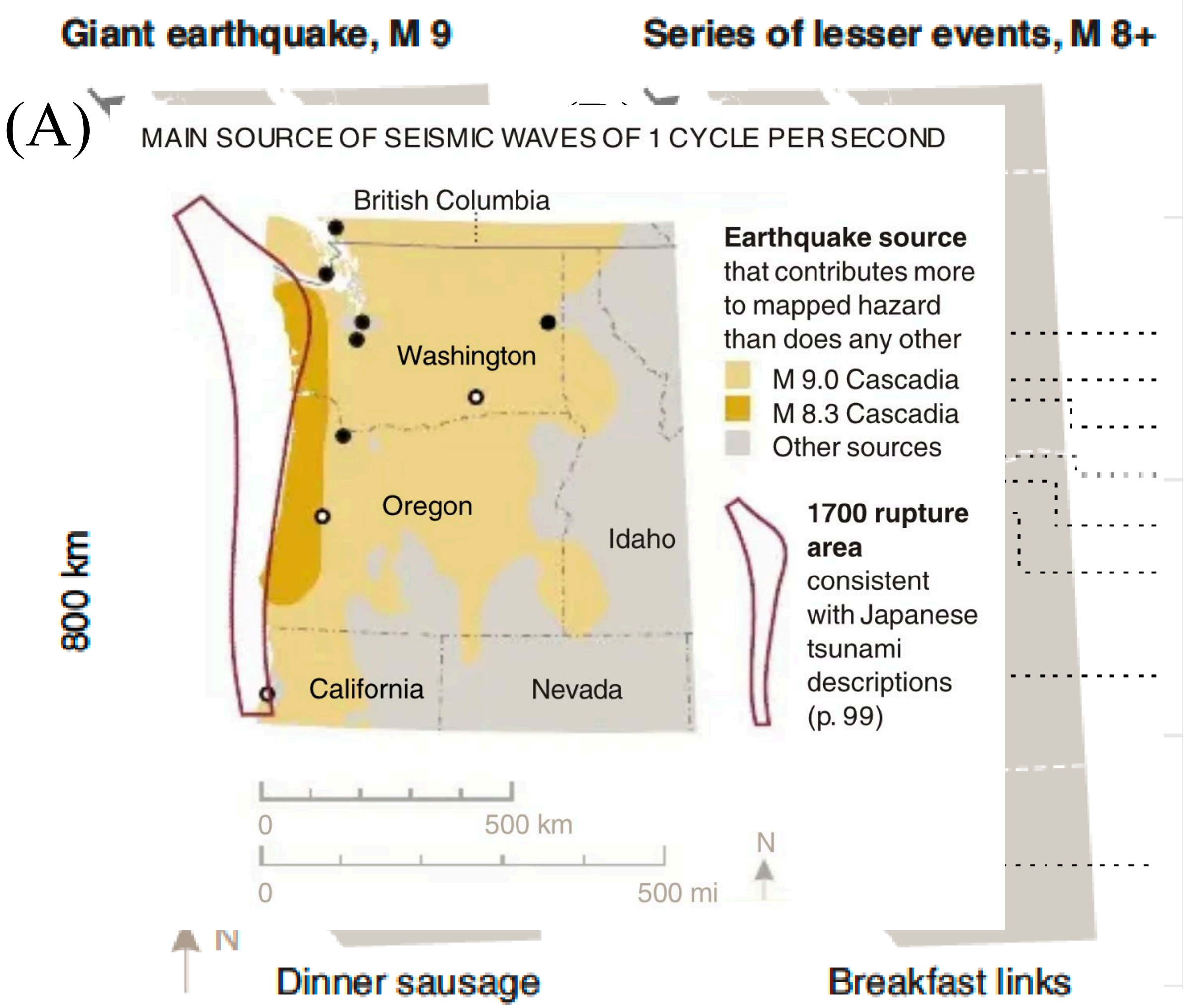


Atwater et al., 2005

1. Understanding the earthquake cycle of the past helps our understanding for the future
2. Are full margin ruptures possible or likely?

- Model A produces wider regions of seismic hazard potentials than Model B

How can we test likelihood of one model over the other?

What is a **paleoseismic proxy?**

A paleoseismic proxy is a **geological clue** that can be attributed to a past earthquake. It is the **effect** of a rupture recorded as **indirect evidence** of the event

Atwater et al., 2005

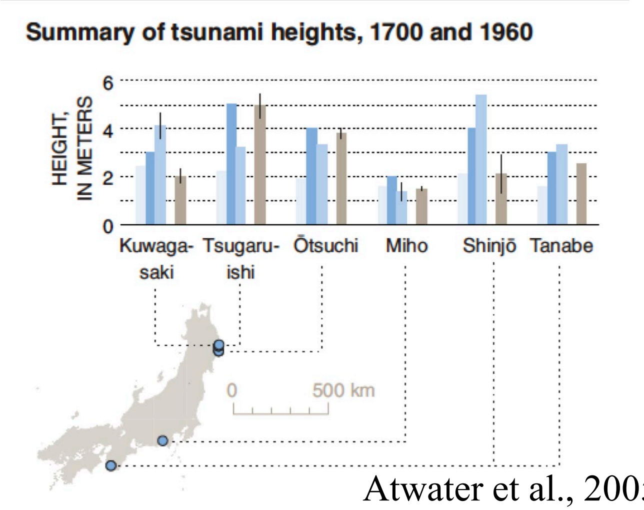
Melgar, 2021

"Ghost forest"

Jamie Hale/The Oregonian

Paleoseismic proxies:

- Japanese orphan tsunami (26th January 1700 CE)
- Coastal subsidence records (100-400 yrs BP)
- Deep sea turbidites (260 yrs BP +- 120 yrs)
- Ghost forest tree rings (1699 CE)
- Coastal tsunami deposits



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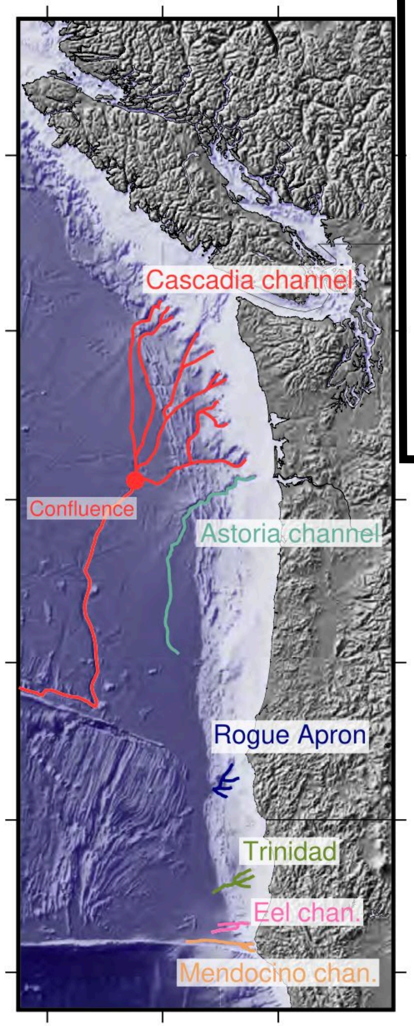

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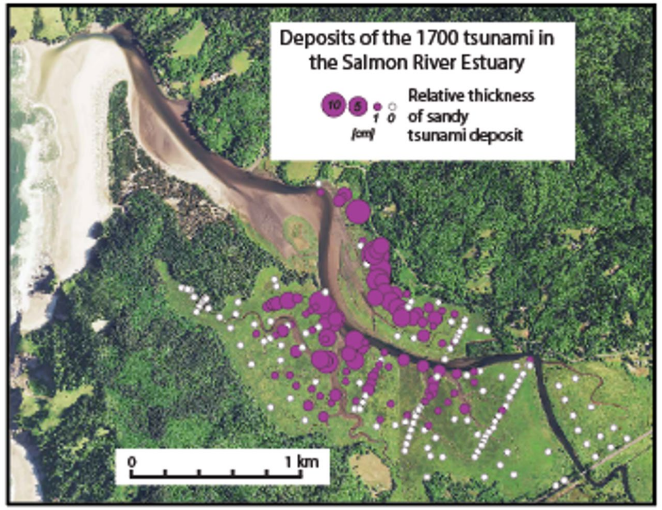
Things we don't to know:

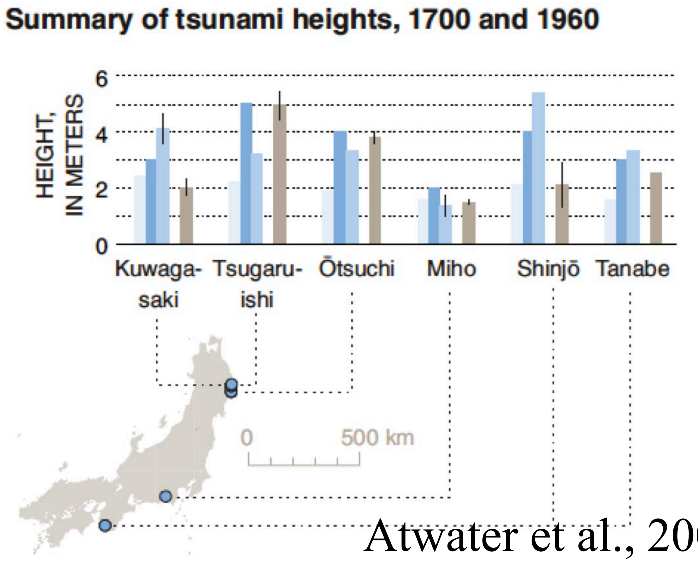
- What did the 1700 event slip distribution look like?
- Single event or sequence?

Stochastic slip rupture modeling

- Computationally fast kinematic models based on general statistical parameters
- 37,500 ruptures of Mw 7.8 - 9.5
- Varying rupture area (full and partial margin ruptures permitted)
- Stochastic ruptures are tested based on 3 proxies:
    1. Does the rupture produce coastal subsidence that matches the record?
    2. Does the rupture produce noticeable tsunami heights at Japan sites?
    3. Does the rupture produce inundation that matches coastal deposit records?



LeSelle et al., 2022



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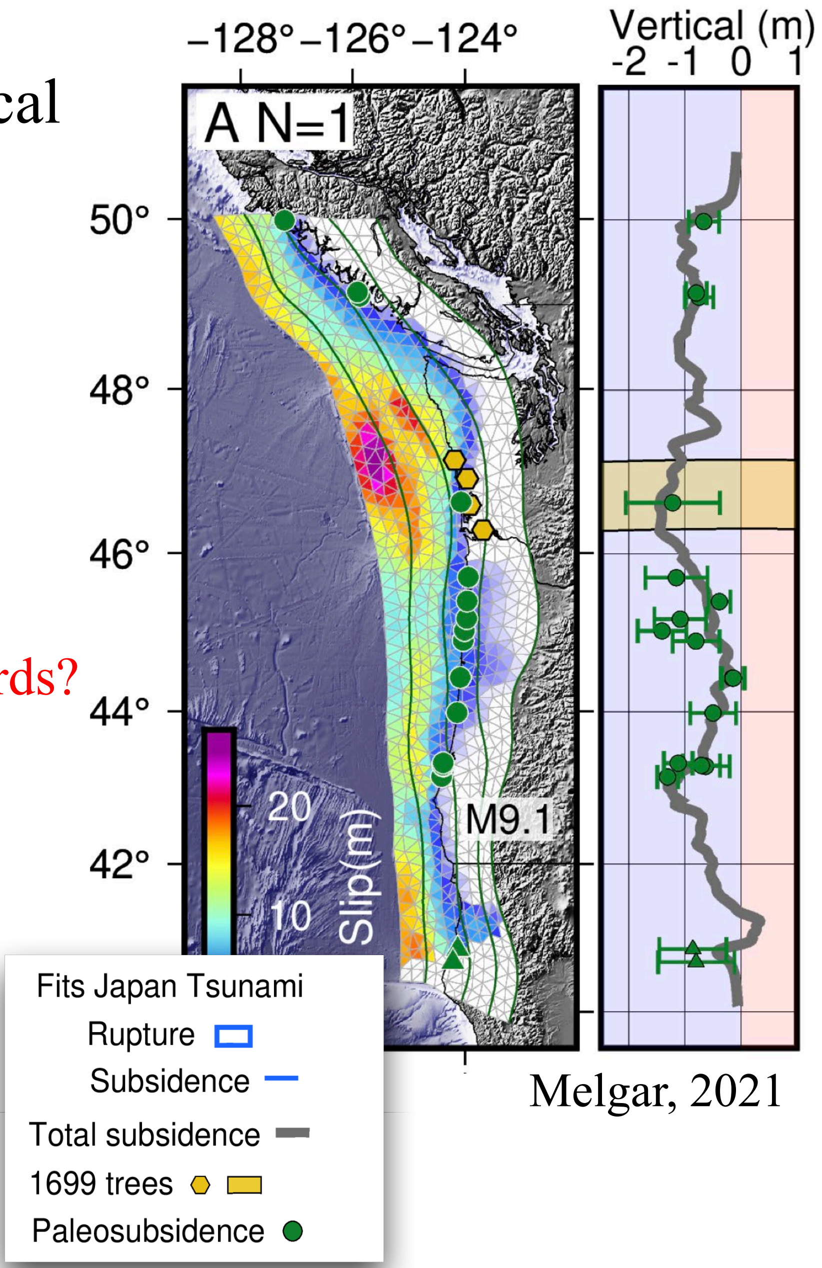

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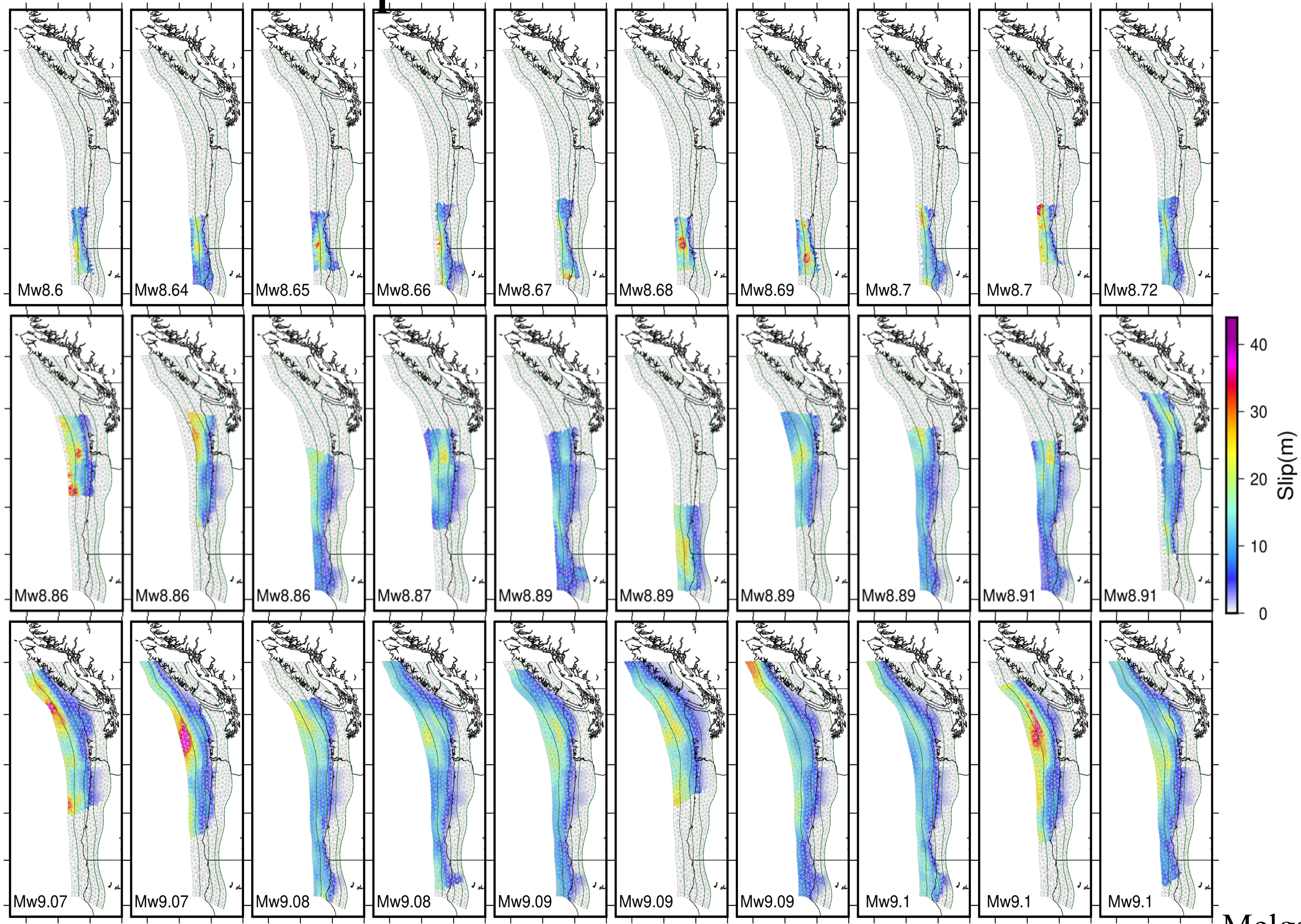
Example stochastic rupture models



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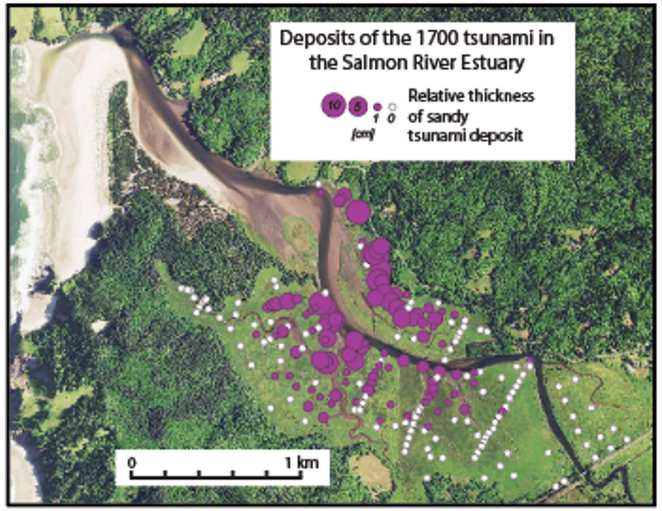
Inundation modeling

- Fine resolution inundation modeling using Geoclaw (https://www.clawpack.org/geoclaw.html)
- Two sites of focus: Salmon River and Alsea Bay, OR
  - Pro: high resolution core data (tsunami deposit thickness estimates)
  - Con: close to one another (70km)
- Include different tide stages to test sensitivity of inundation potentials
  - Highest/Lowest tides (+/- 2m), 50th percentile tides (+/- 0.8m), and zero tide
  - Projected tide level at the time of the January 26th event is ~ -0.8m!



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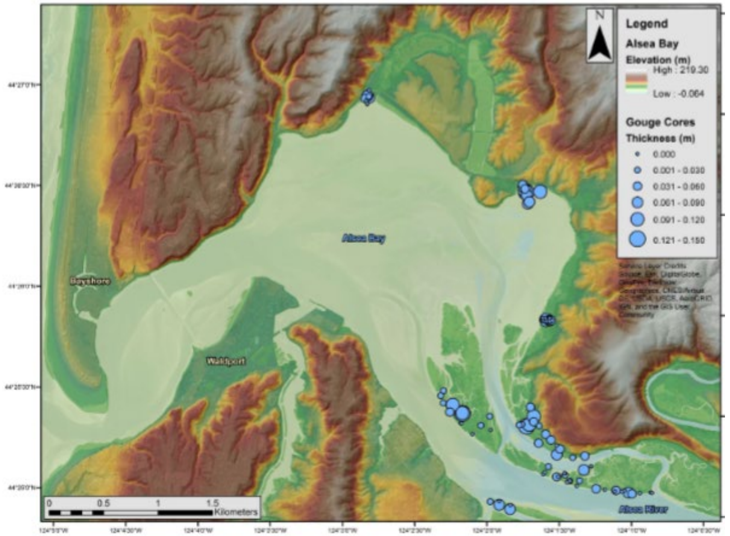
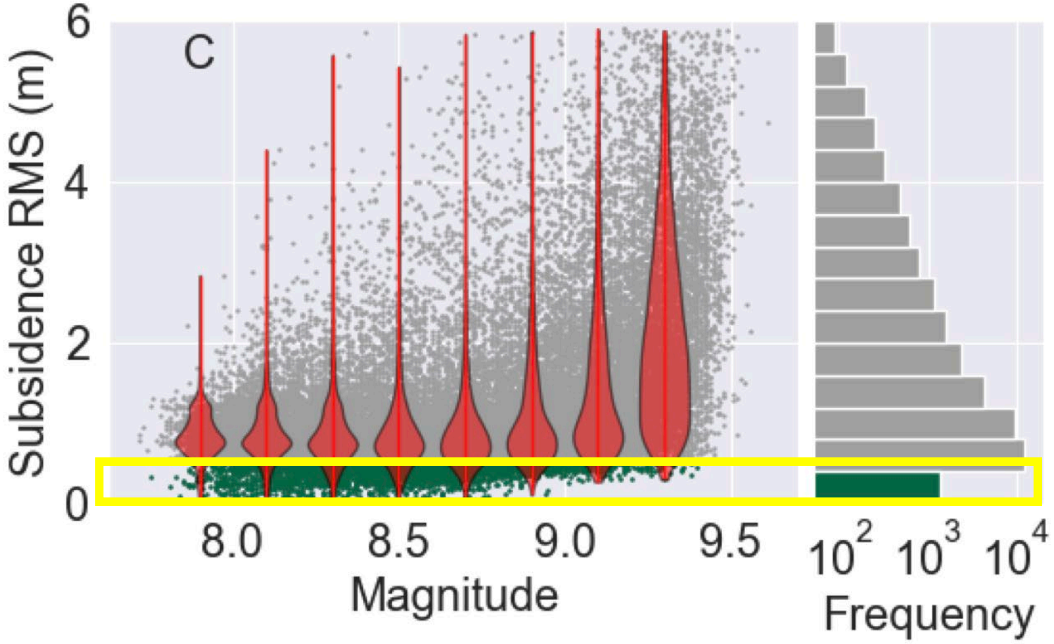


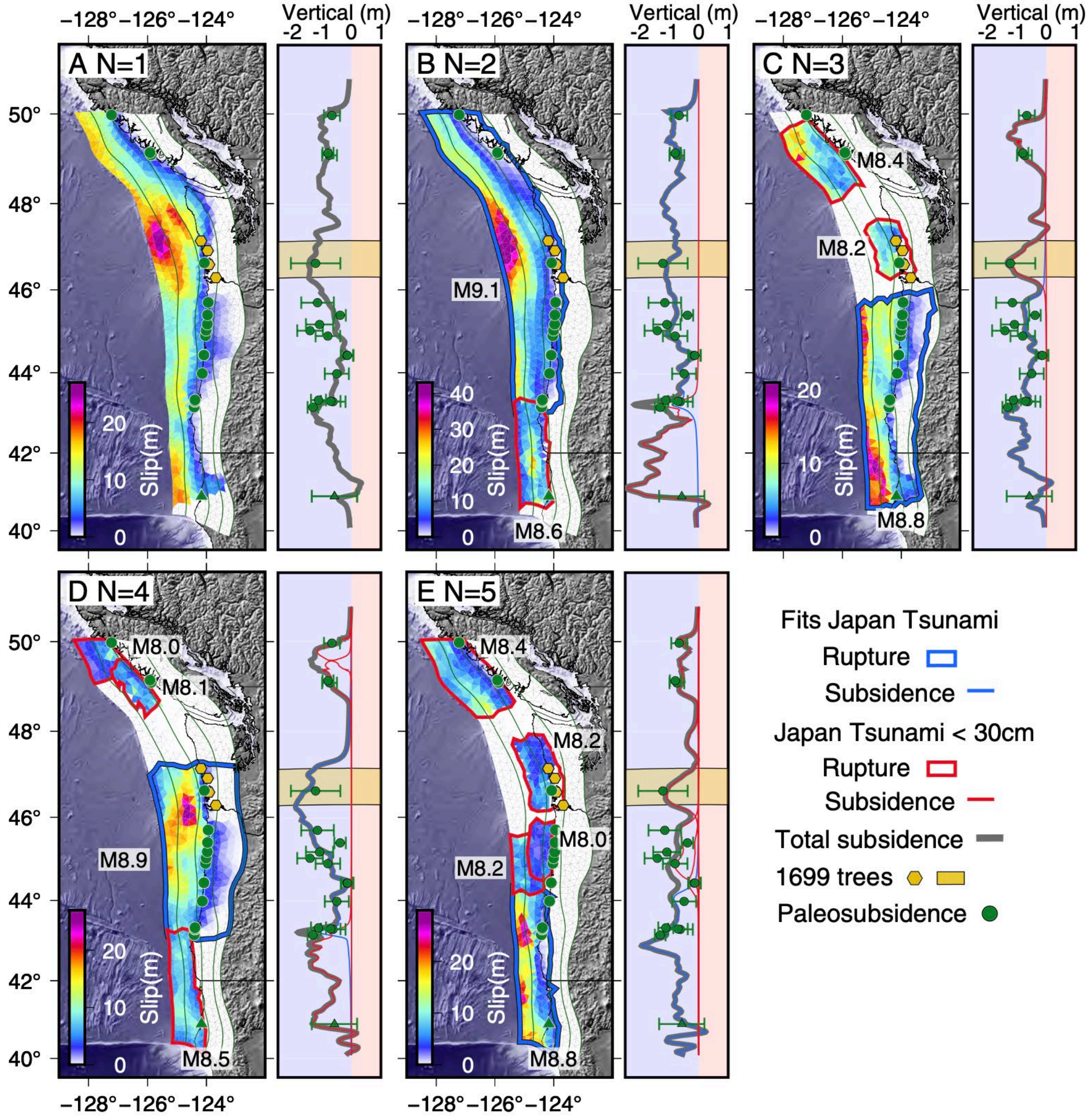
Courtesy of Andrew Meigs, OSU

Comparing coseismic subsidence

- Qualification for matching subsidence:
    1. Match coastal subsidence sites located < 50km away from rupture area with RMS < 0.4m.
- Since we are relaxing the assumption of full margin rupture, a single partial rupture does not need to produce all necessary subsidence!

- 1,635/37,500 match local coseismic subsidence to RMS<0.4m





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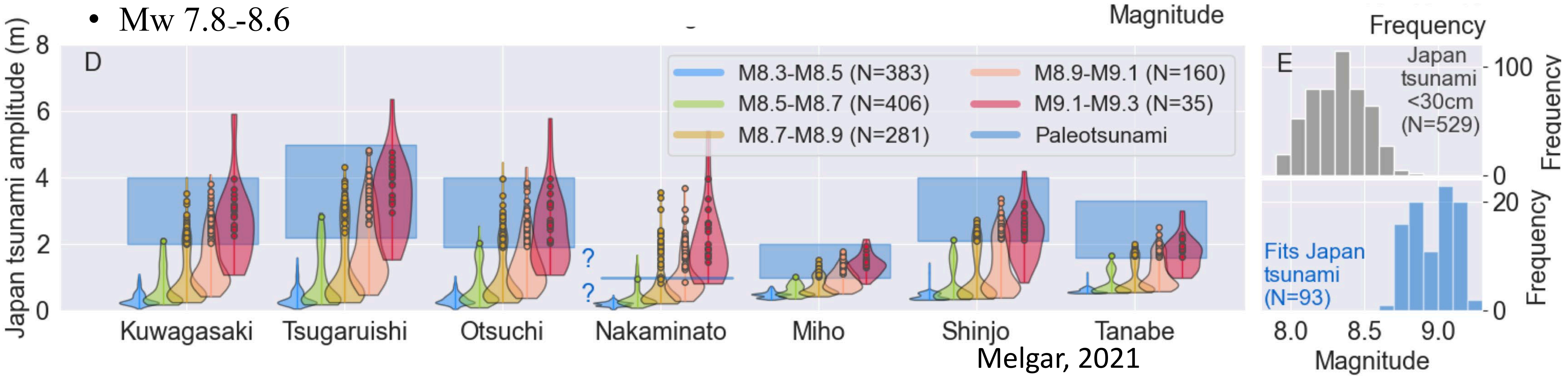
Comparing Japan tsunami

- Qualification for matching tsunami:
    1. Produce tsunami that matches records in Japan
    2. Or does not produce tsunami > 30cm
- Since we are allowing partial ruptures to occur, a rupture does not need to produce a noticeable tsunami in Japan to be considered a potential
- 93/1,635 events fit subsidence & tsunami
    - > Mw 8.6
- 529/1,635 events fit subsidence but tsunami < 30cm
    - Mw 7.8-8.6

For the next phase we subset ruptures down to only those who produce subsidence at the two sites of interest… 230!



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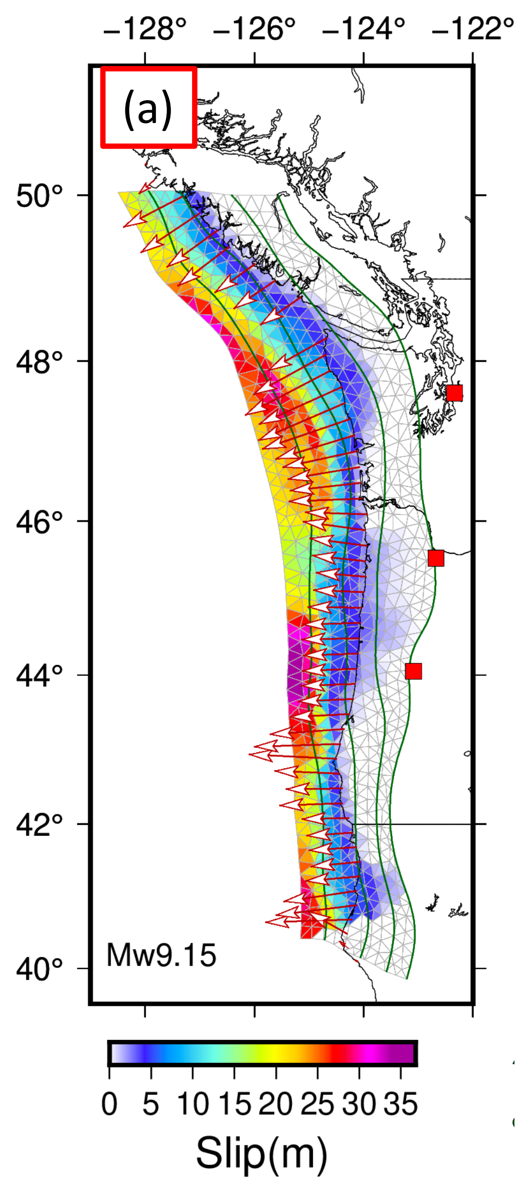
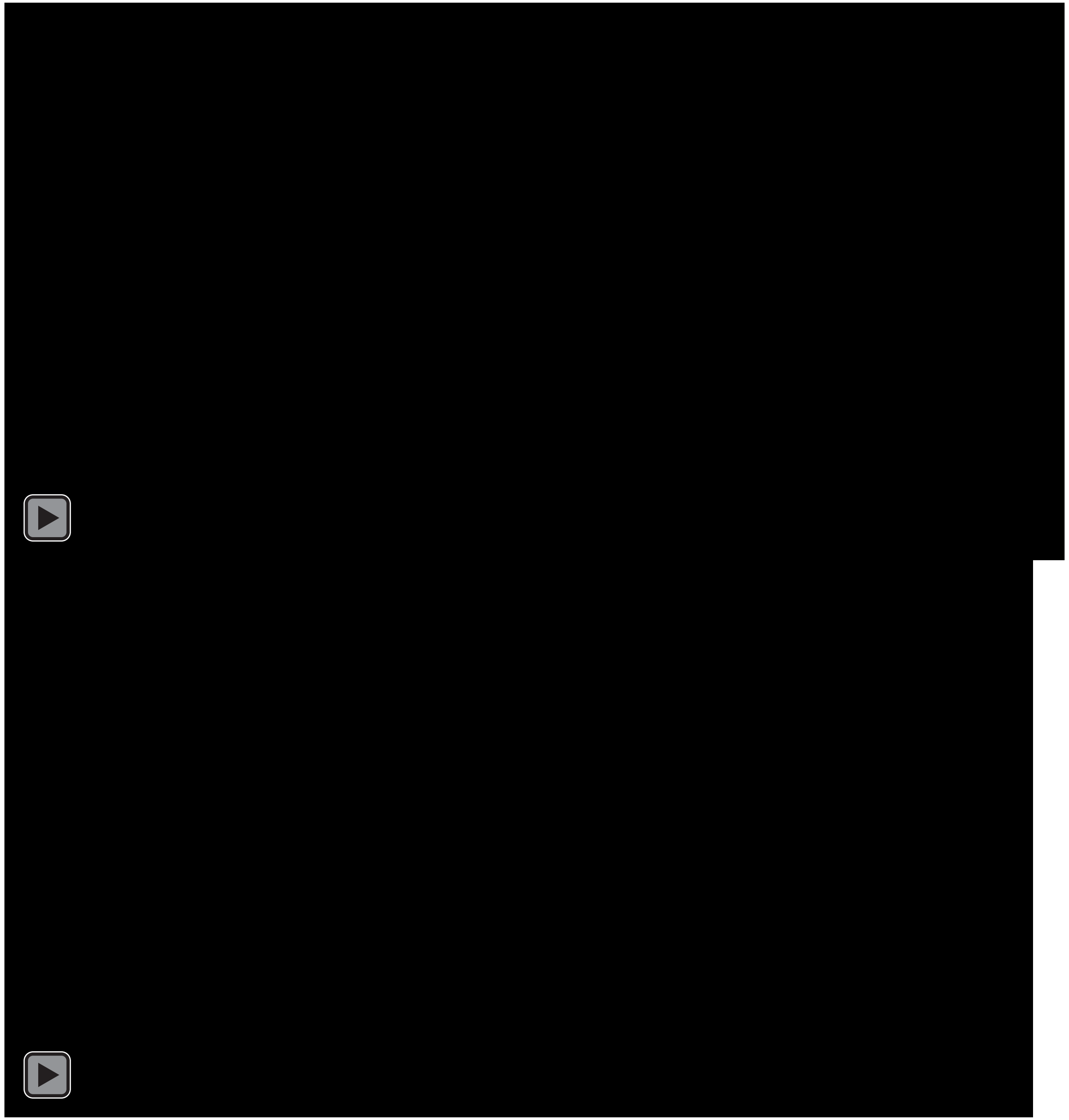
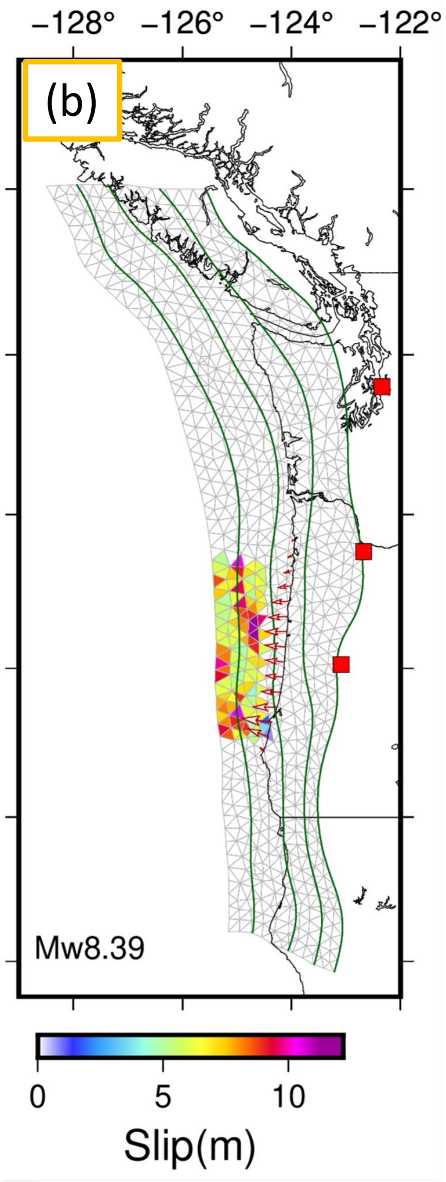
Comparing inundation

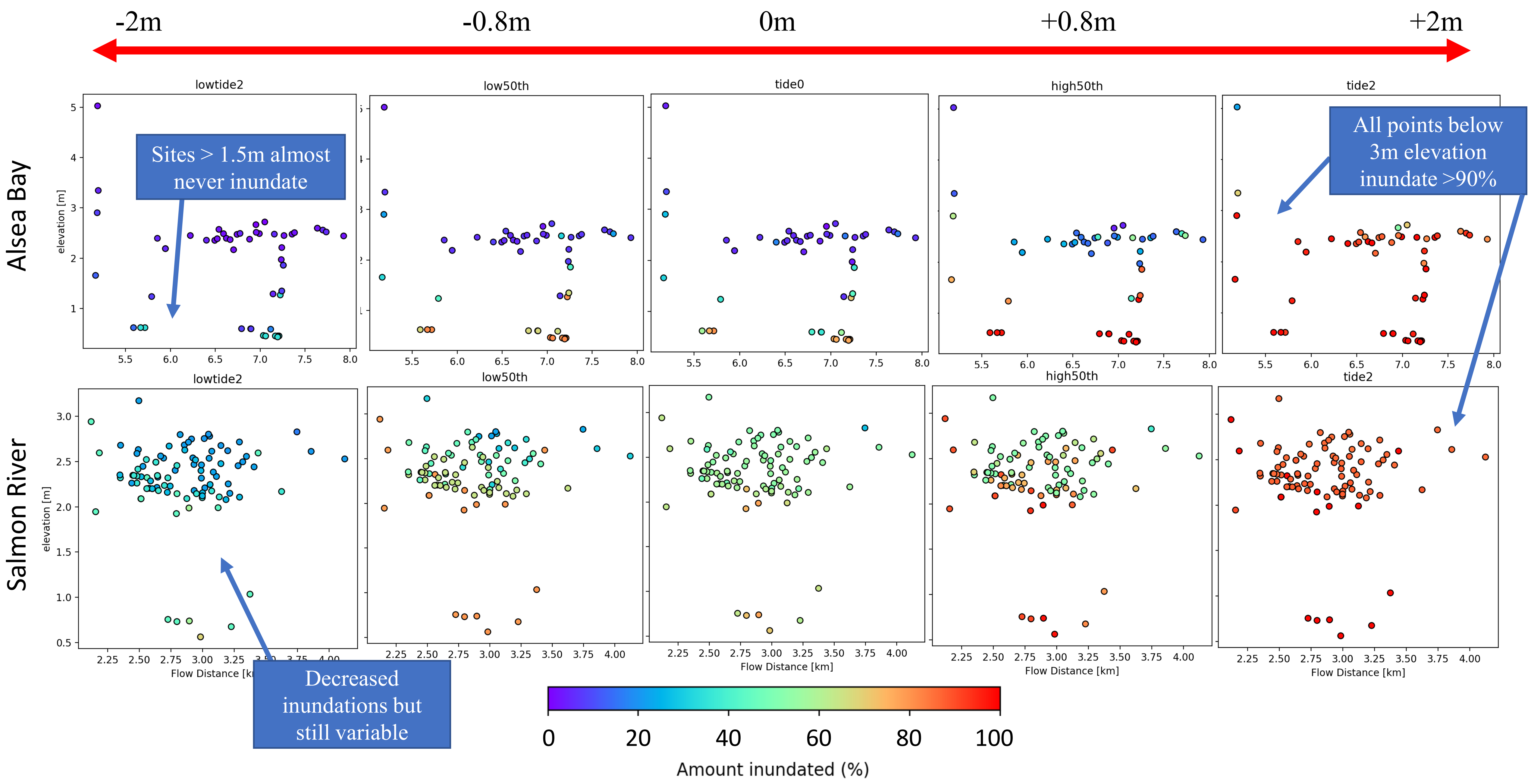




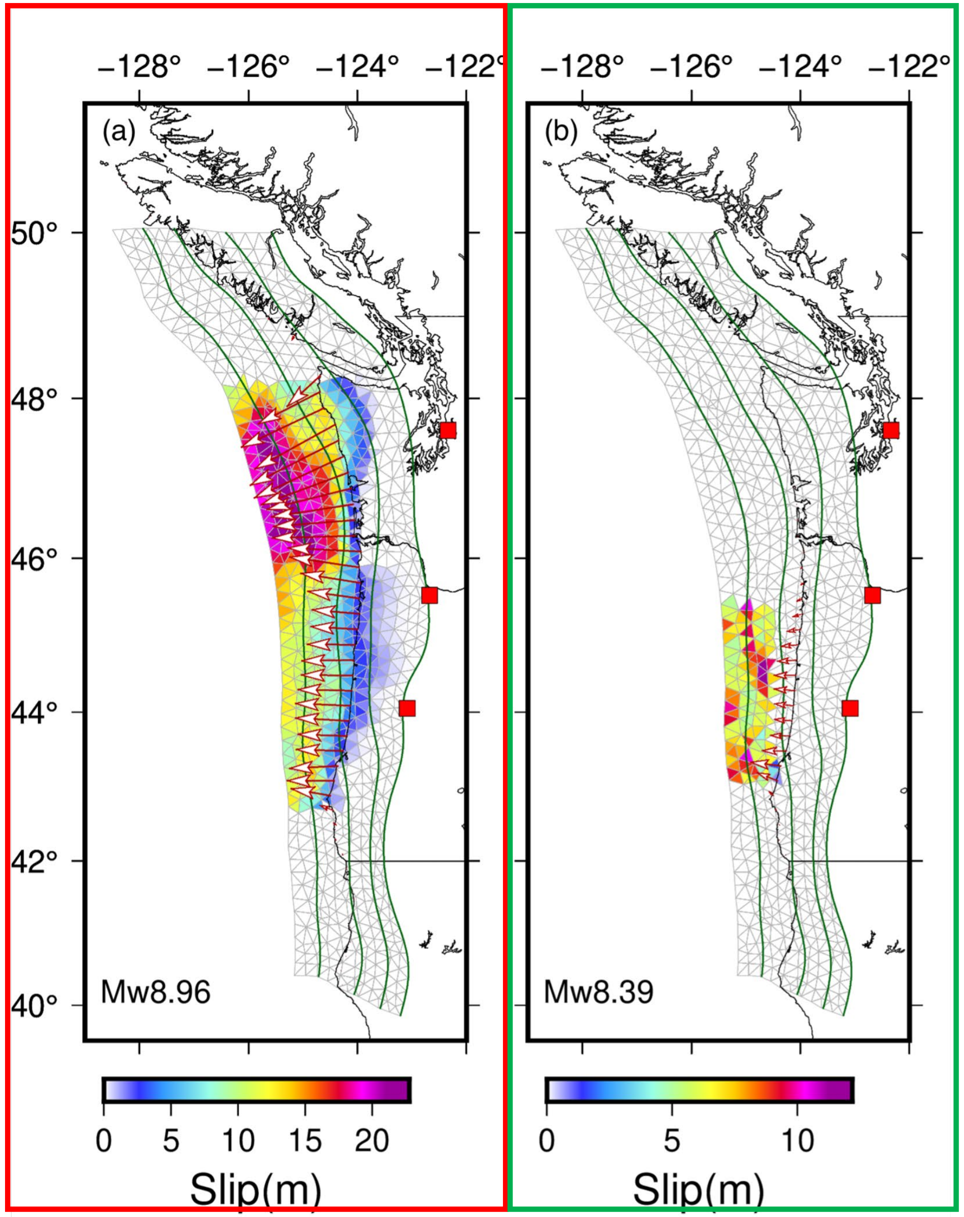


Results

Tidal influence in inundation modeling



Tidal influence in inundation modeling



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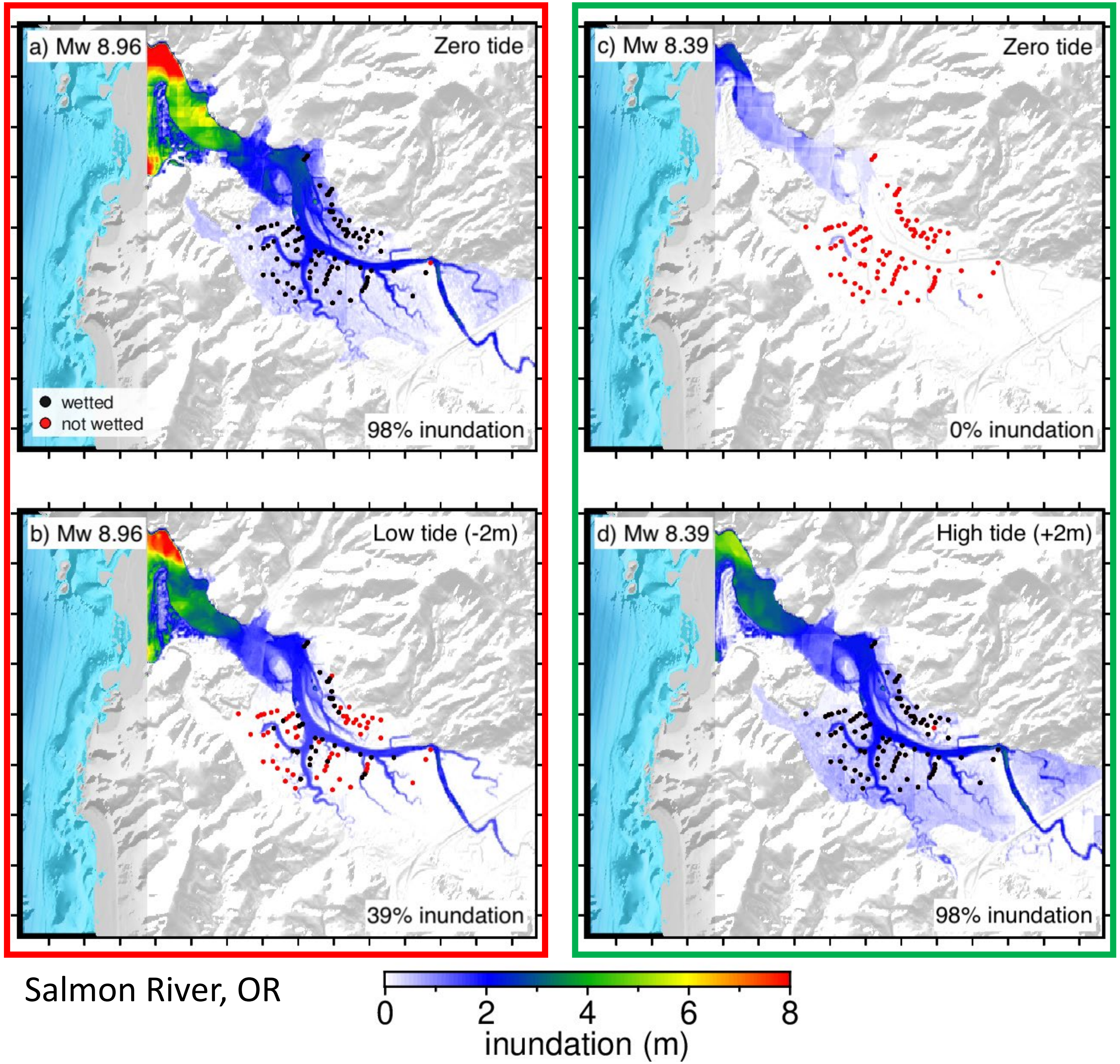
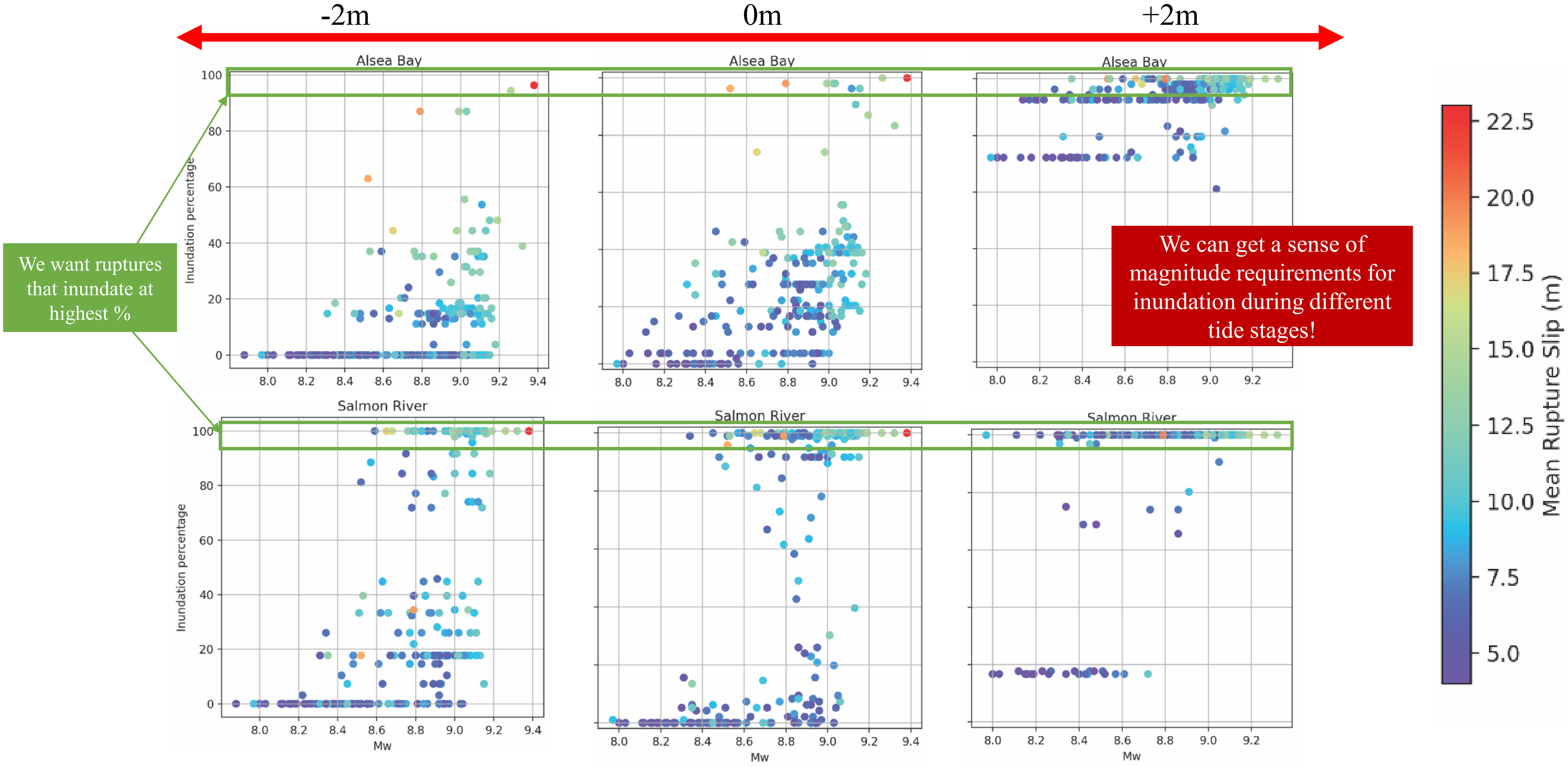


Salmon River, OR

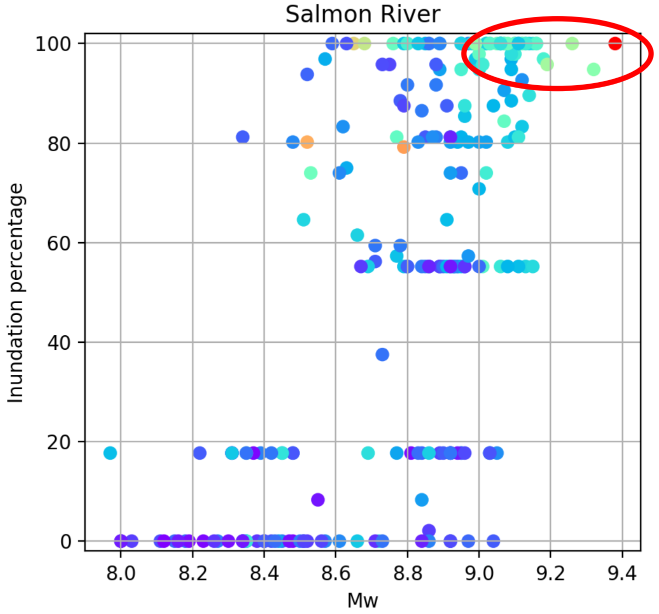
Comparing Inundation

*technically with such close sites, we cannot rule in or rule out ruptures. But we can provide a framework for doing so later…



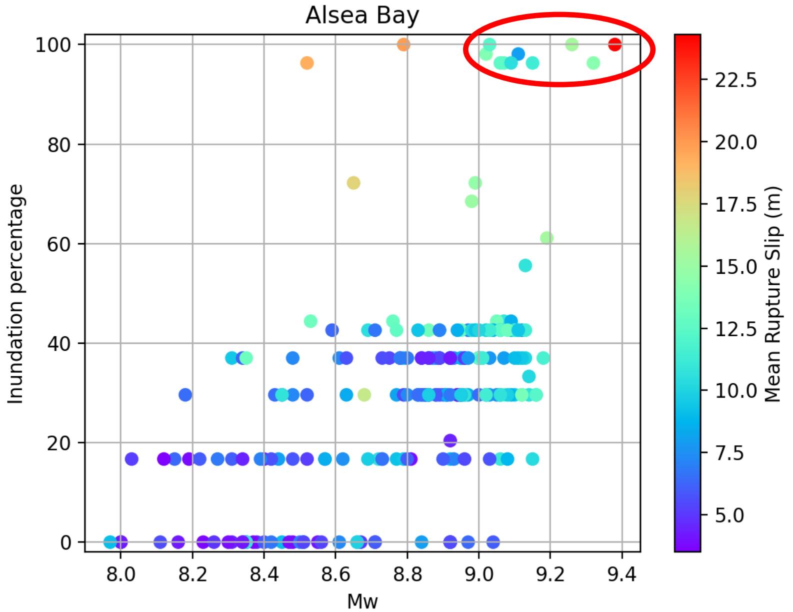
Comparing inundation on January 26th, 1700, low tide

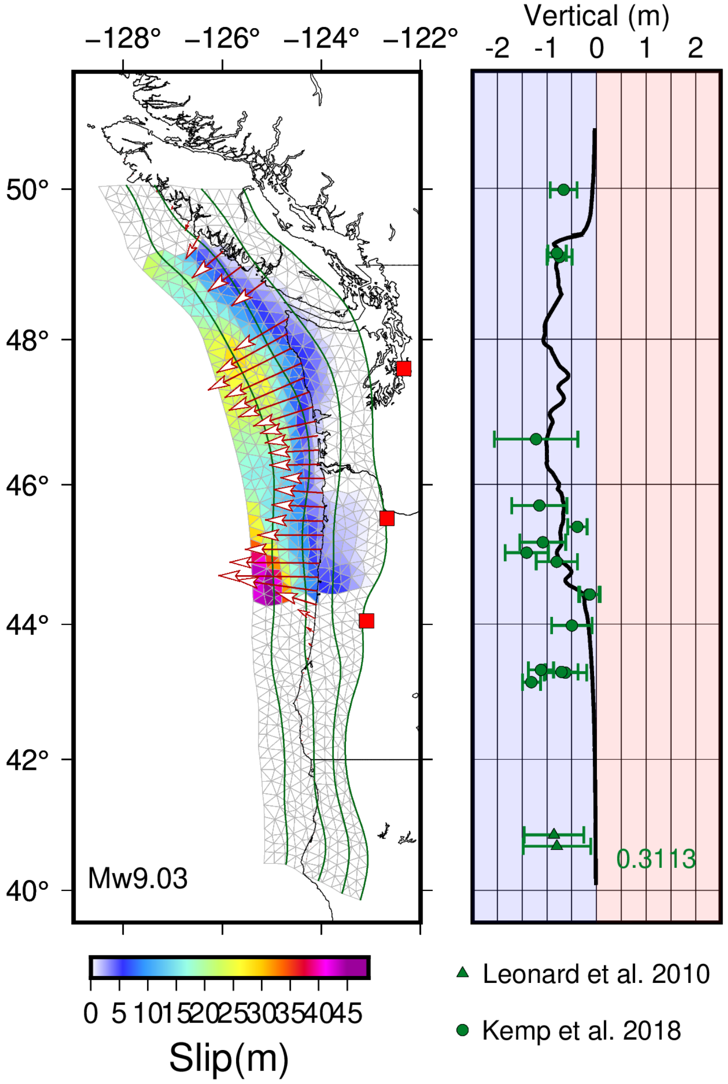
We will now assume both these sites are a result of the January 26th event:



- Full/almost full inundation percentage needed to qualify ruptures
- 7/230 ruptures with Mw > 9.0 produce inundation percentage > 95% at both sites

7/37,500 ruptures (so far) fit all three paleoseismic proxies!





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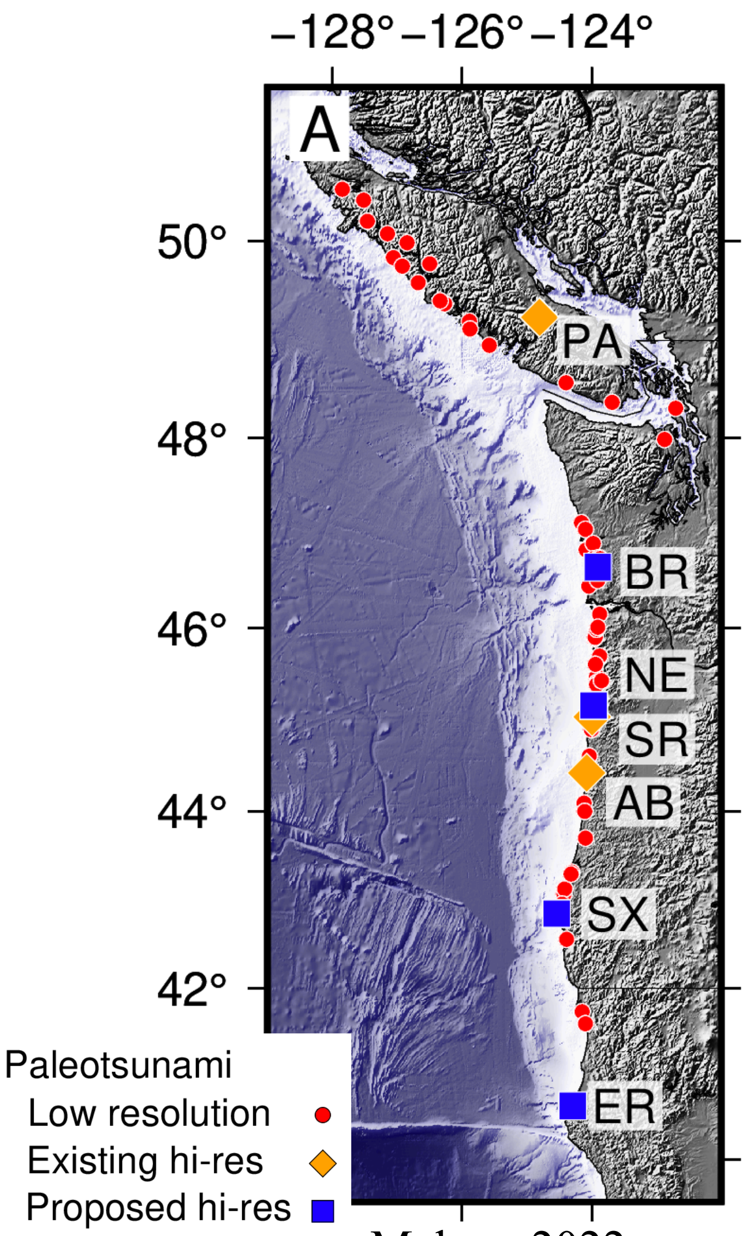
Key points

- Tidal stage plays an influential role in inundation
  - Alsea Bay much more than Salmon River
  - Highest high tide almost always inundates completely
- 7/37,500 ruptures fit all three proxies for the January 26th tide level
  - This includes both partial and full margin ruptures!
  - Mw > 9.0 needed to fit both sites fully

- What influence do other model conditions have on inundation potentials?
  - Paleotopography reconstruction
  - Bed roughness
  - Sea level rise
- More high resolution survey sites along the PNW needed to best constrain potential slip patterns!



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Thank you!

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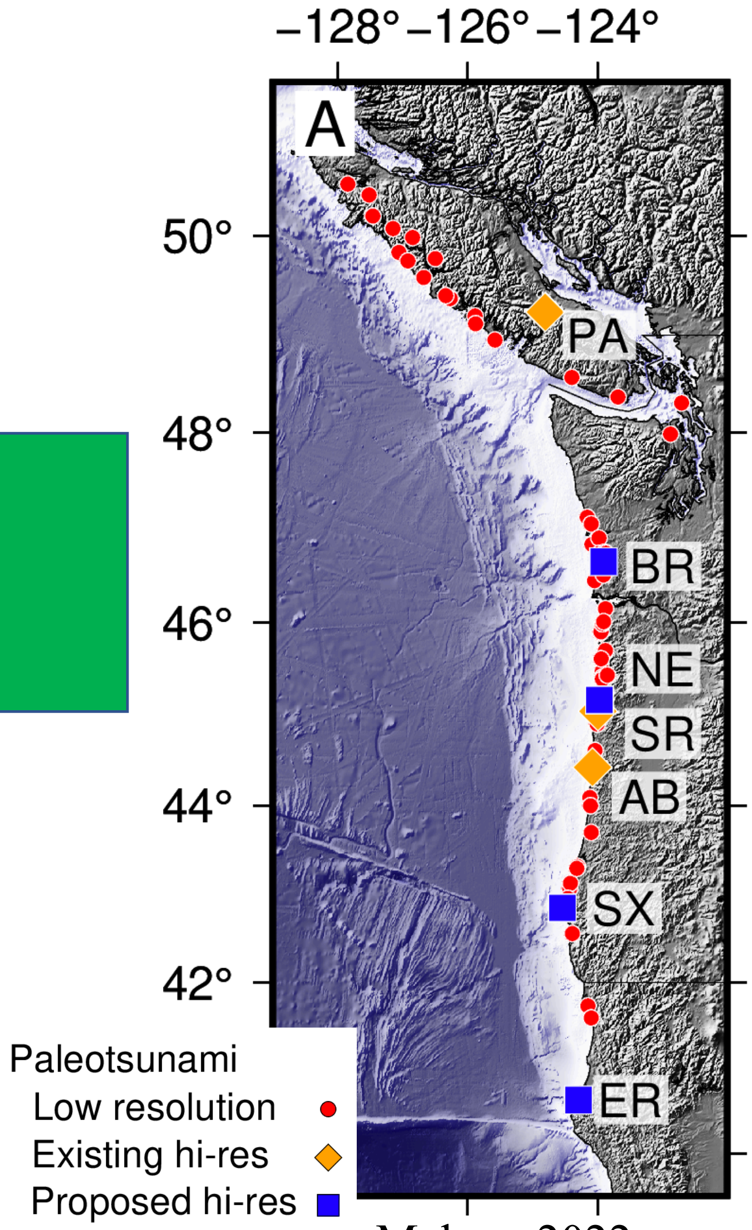

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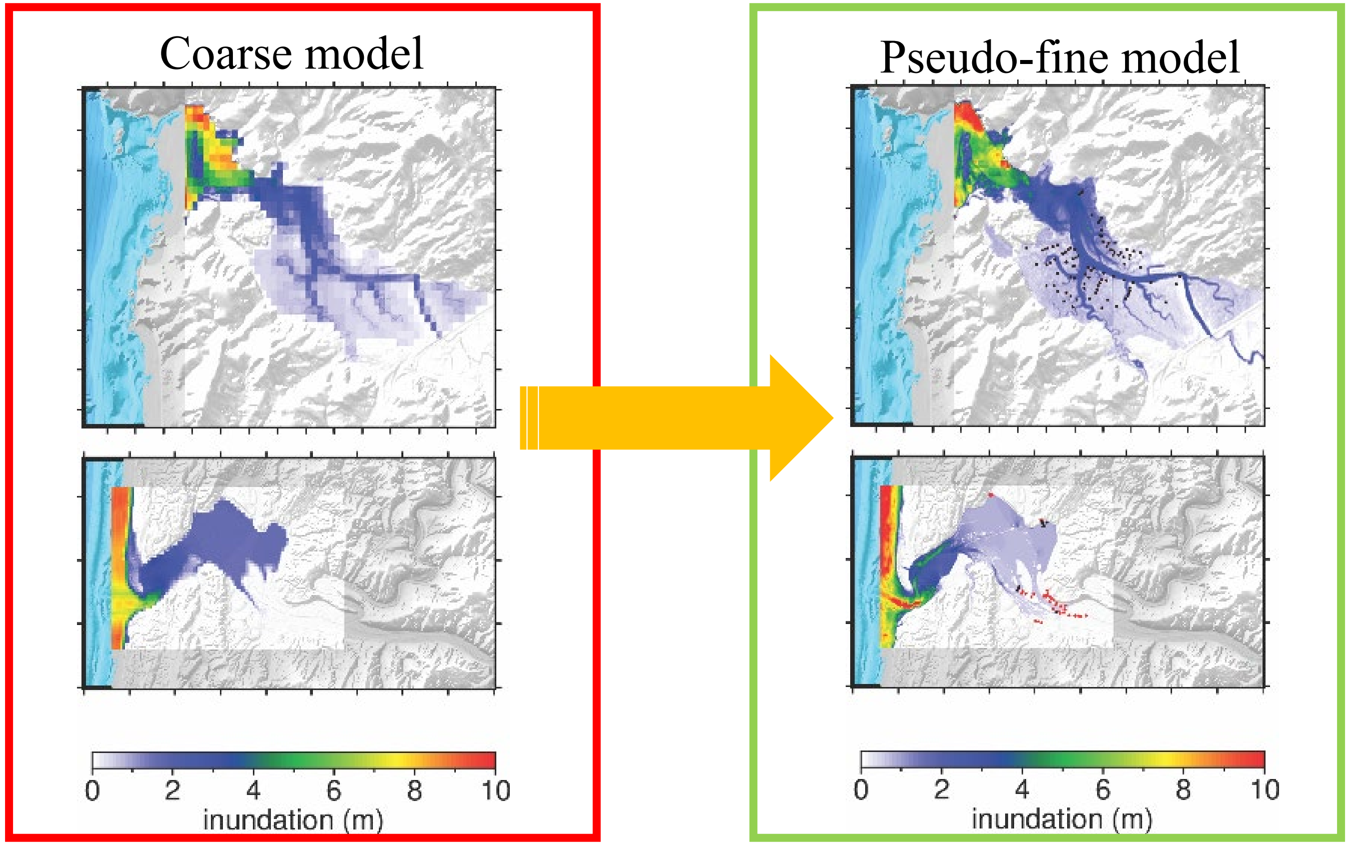
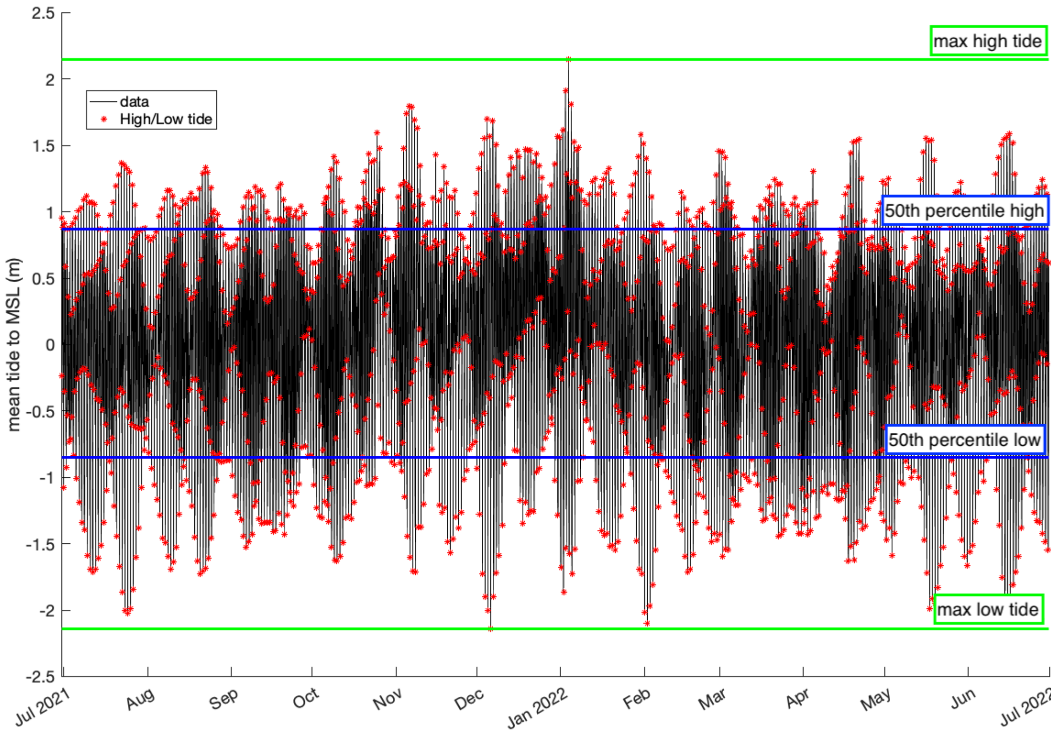
Cluster inundation modeling

- Method from Williamson et al. (2021)
- 1/3” resolution inundation modeling for a single event takes ~ 1 days
  - Running models for 200 ruptures with cluster method takes ~1 week compared to months!
- Run models at 3” and modify to create pseudo-fine model at 1/3” resolution

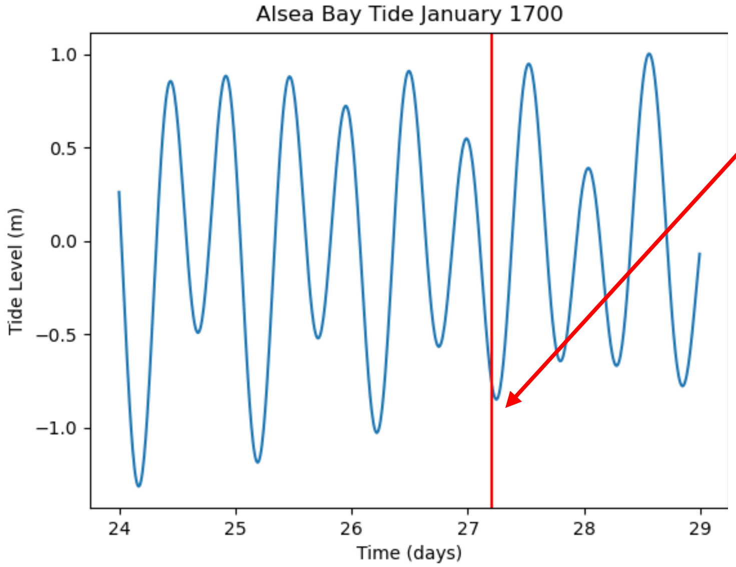


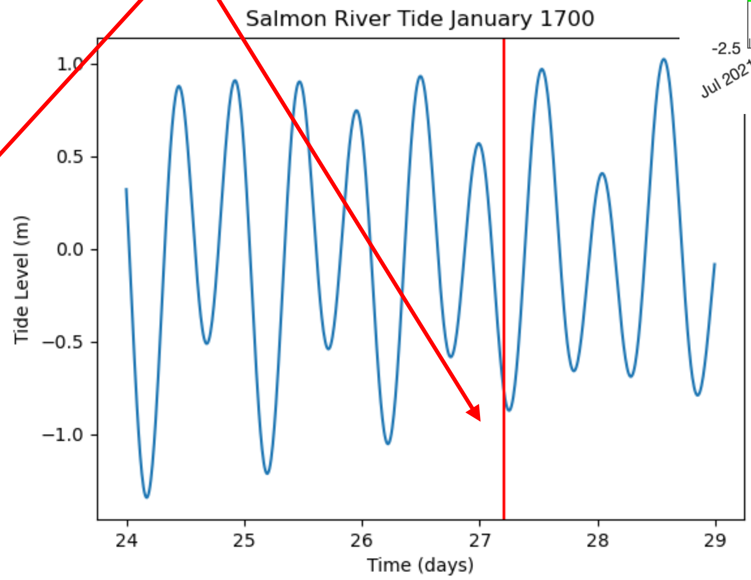
Cascadia tidal stages

- Tsunami arrived **at or shortly following low tide** in the evening of 26th January 1700 (Witter et al., 2012)



Low tide ~ -0.8m (50th percentile low tide)





** Plots shown in UTC**

Paleotide projections courtesy of Angel Ruiz-Angulo

- Run inundation models using **5 tide stages** based on tides during 1 year record

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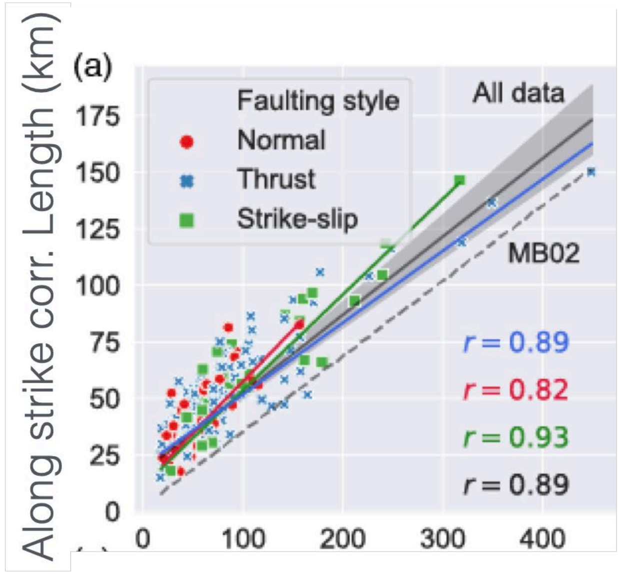
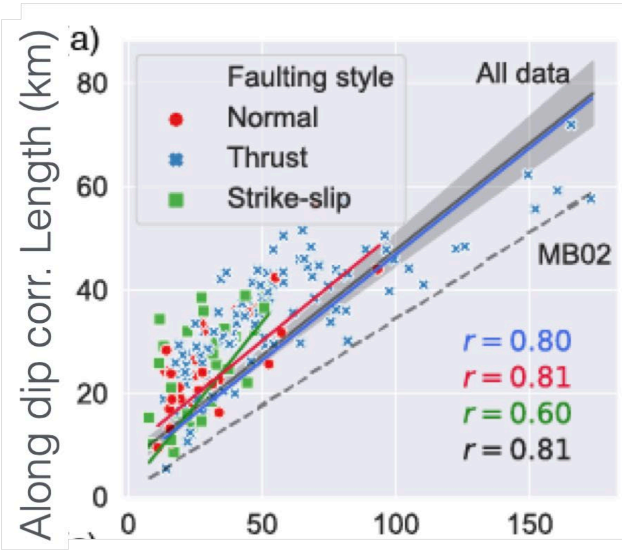
Stochastic slip rupture modeling

- Slip on a fault is a random field (Mai & Beroza, 2002)
  - von Karman autocorrelation function best describes ruptures
- 3 variables defined by simple statistical parameters
  - Correlation lengths and Hurst exponent (Melgar & Hayes, 2019)
  - Fault dimensions (scaling law from Blaser et al. 2010)





(Melgar & Hayes, 2019)

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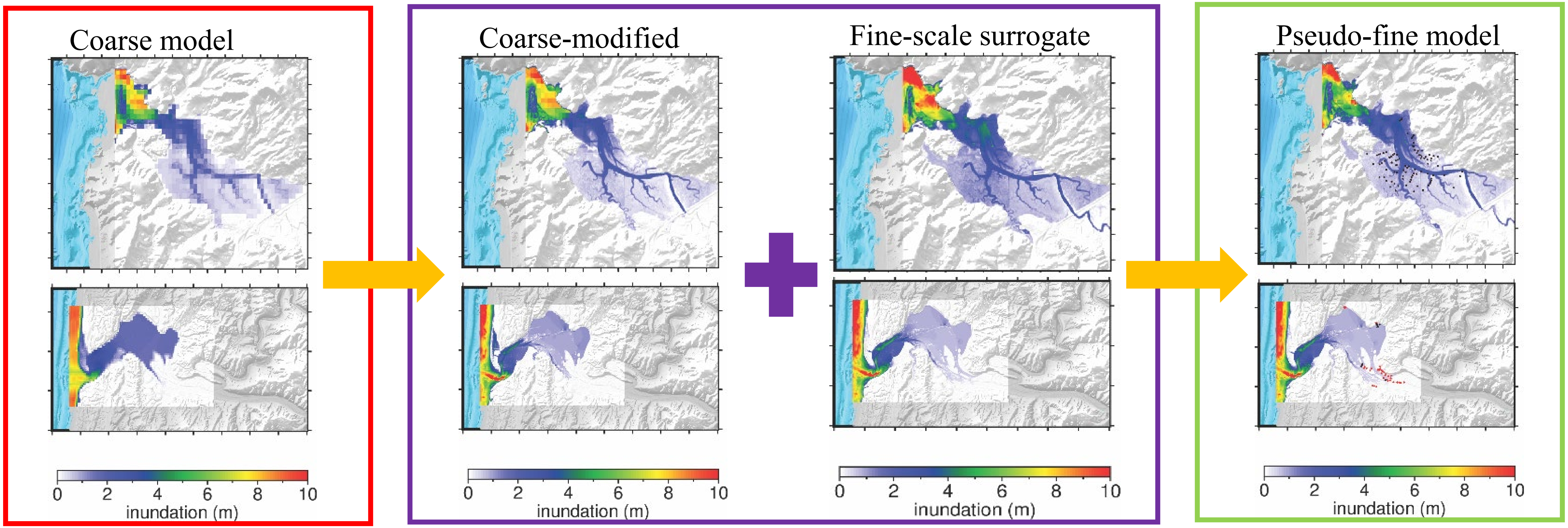
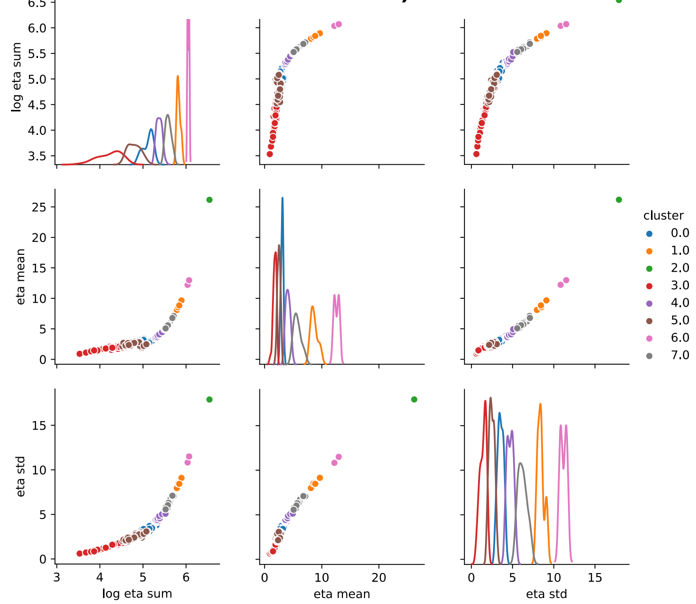


Discussion topics

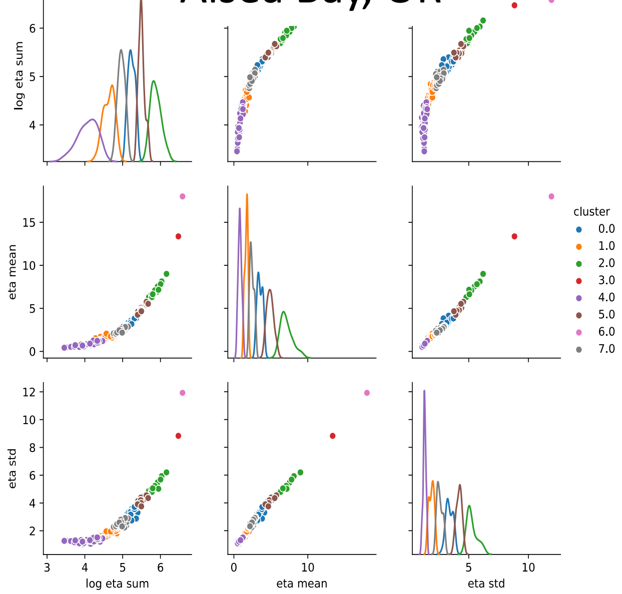
1. What makes a “good” survey site?
2. Homogeneous vs heterogeneous surface roughness?
3. Landscape reconstruction for paleo topography?
4. What can we sediment transport modeling tell us about 1700 tsunami deposits?

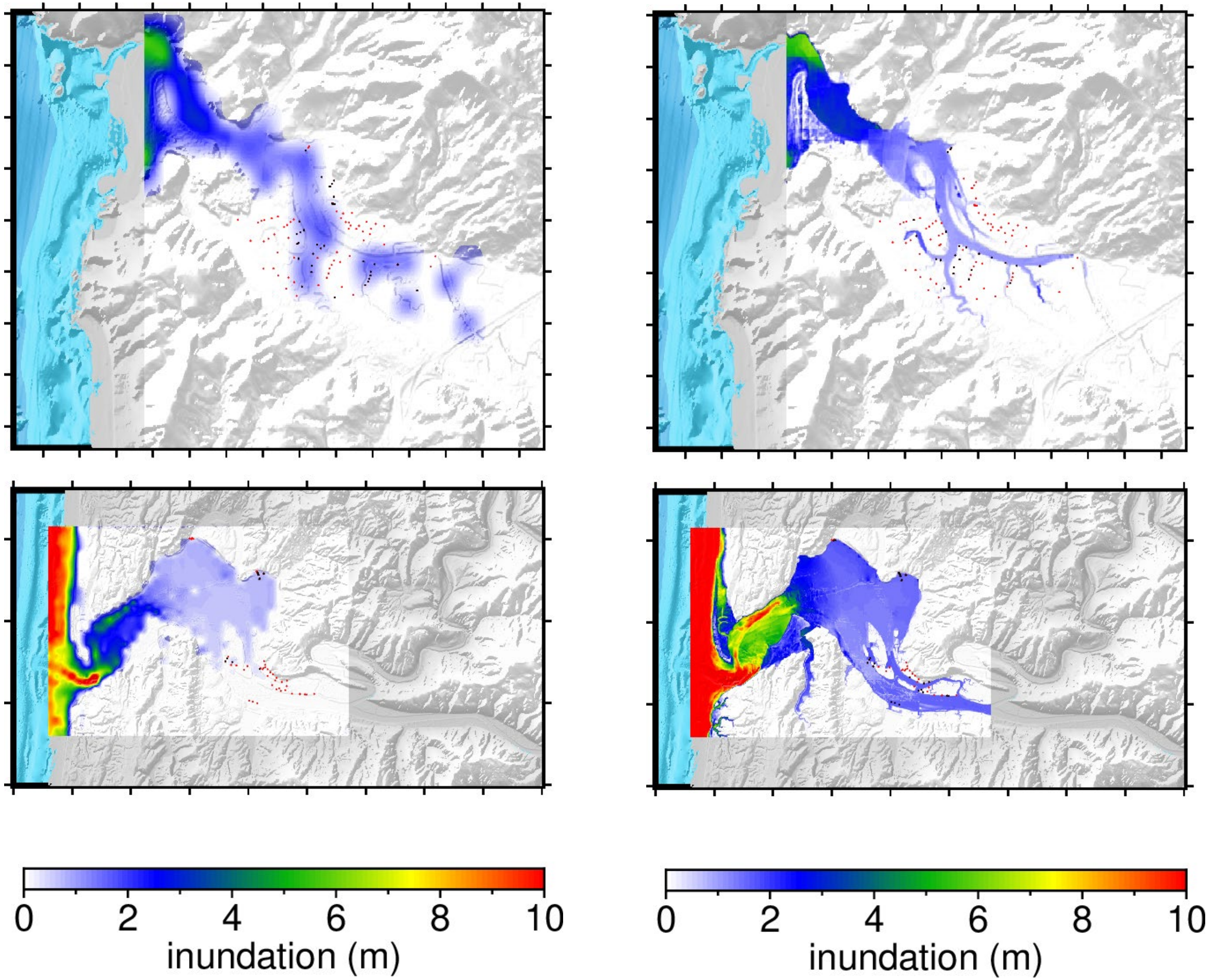
1928 T-Sheet for Alsea Bay

Salmon River, OR



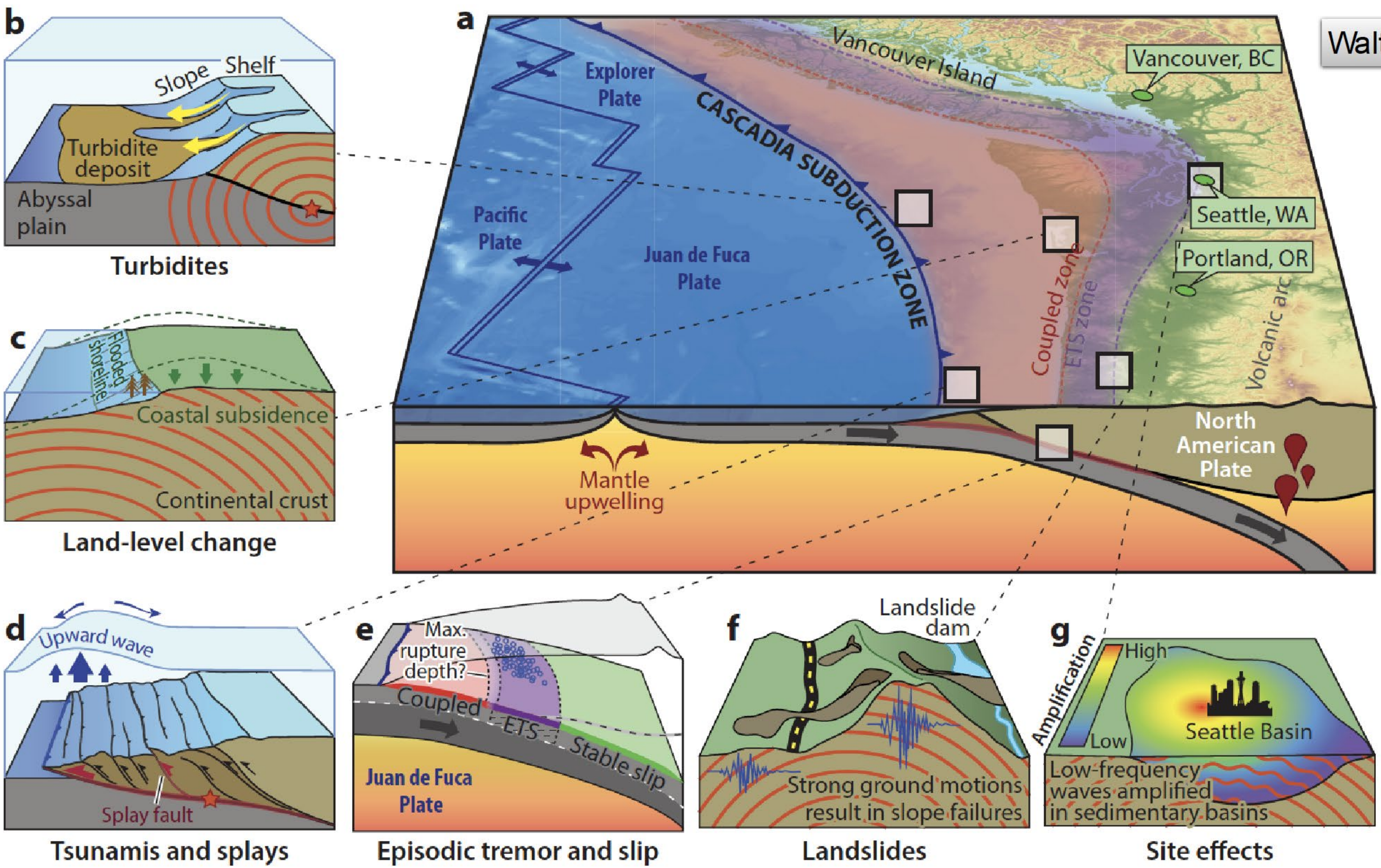
Alsea Bay, OR





Paleoseismic observations in Cascadia

Walton et al. (2021)



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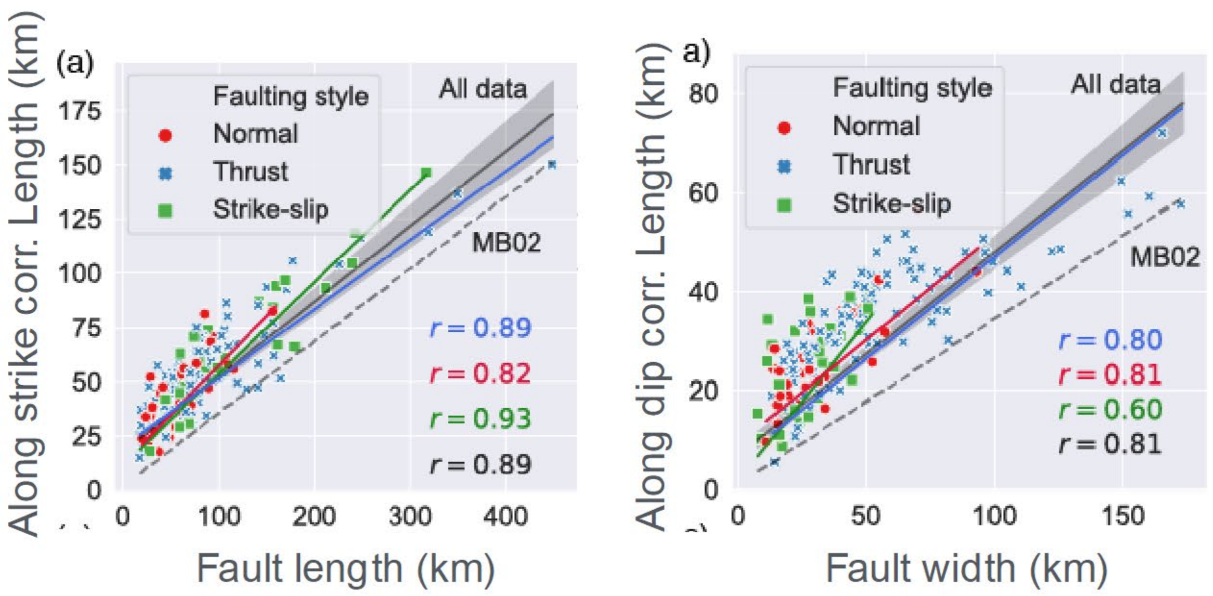
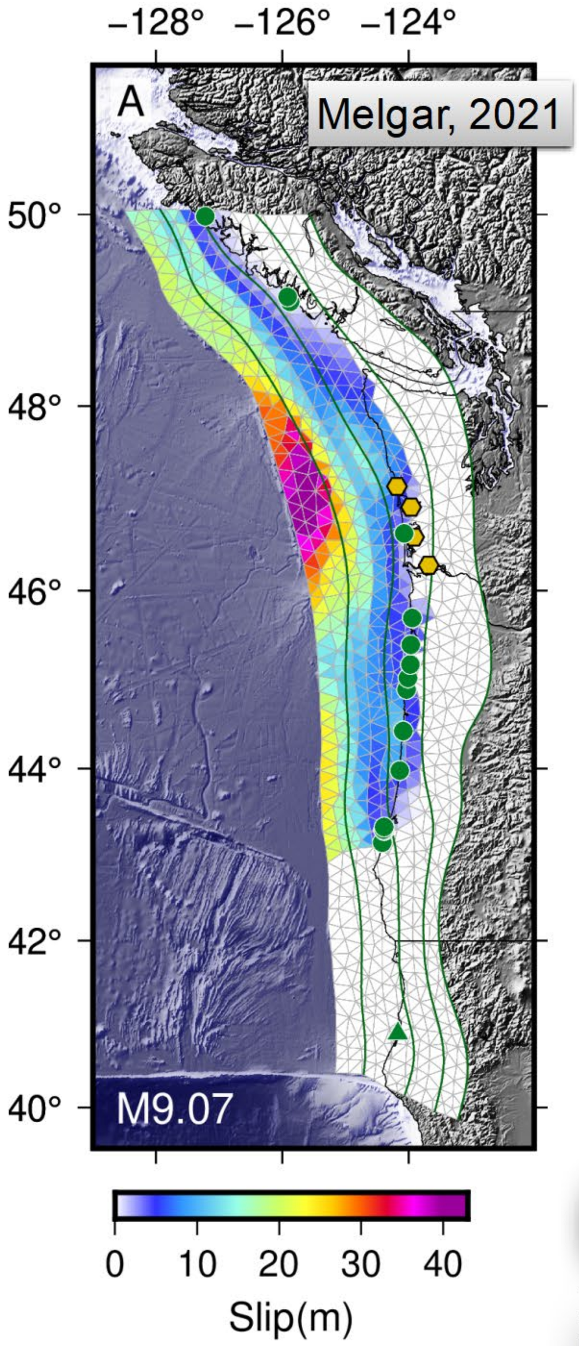
Stochastic kinematic ruptures: The slip patterns

- Analysis of historical earthquakes shows a **VonKarman correlation** function describes slip well
- We have measured correlation lengths on the USGS database of large earthquakes (Hayes, 2017). They **depend on fault dimension**

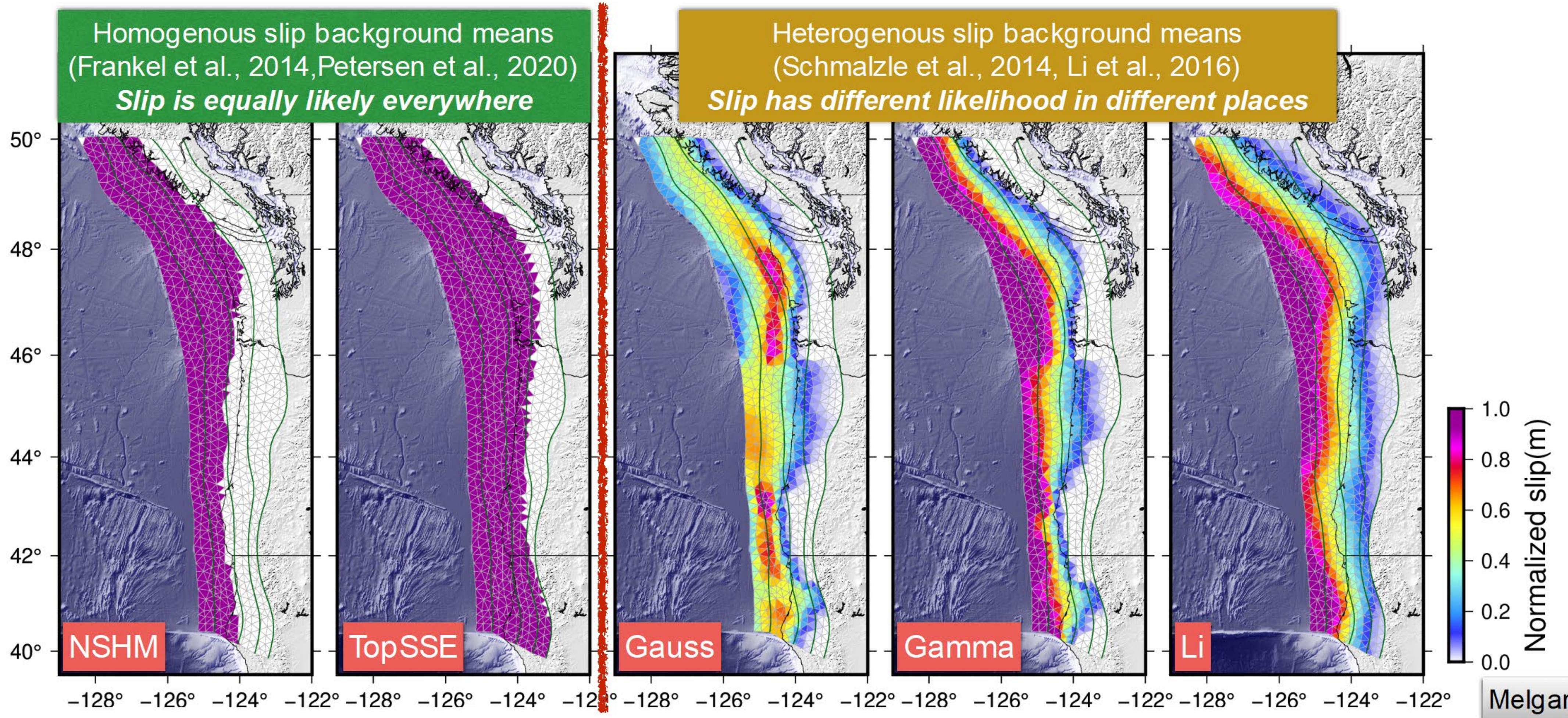


Melgar & Hayes (2019)



Stochastic kinematic ruptures: The background mean

- The correlation lengths (and the Hurst exponent) control the variability but we also have to **define the "mean" of the slip pattern**
- We can make several "**geophysically informed**" choices



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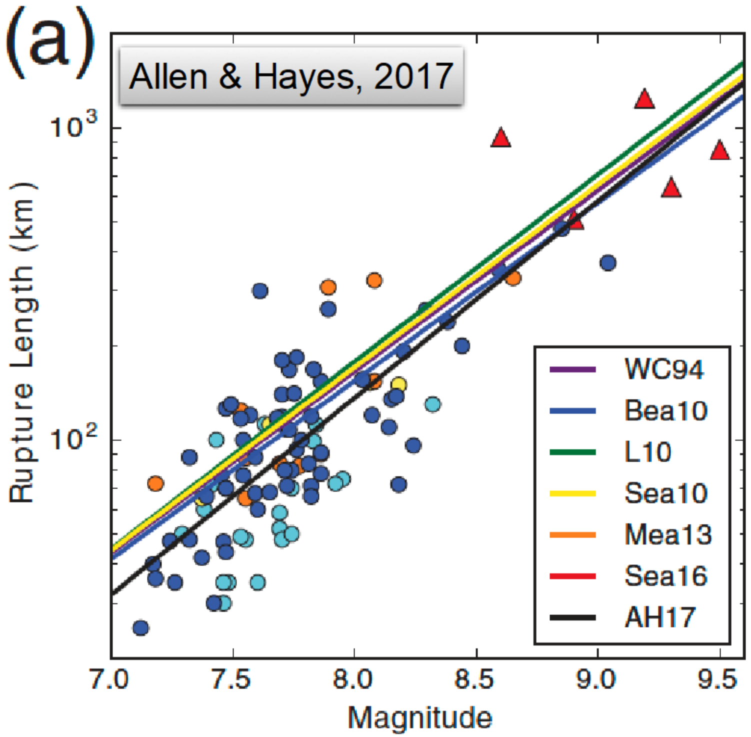
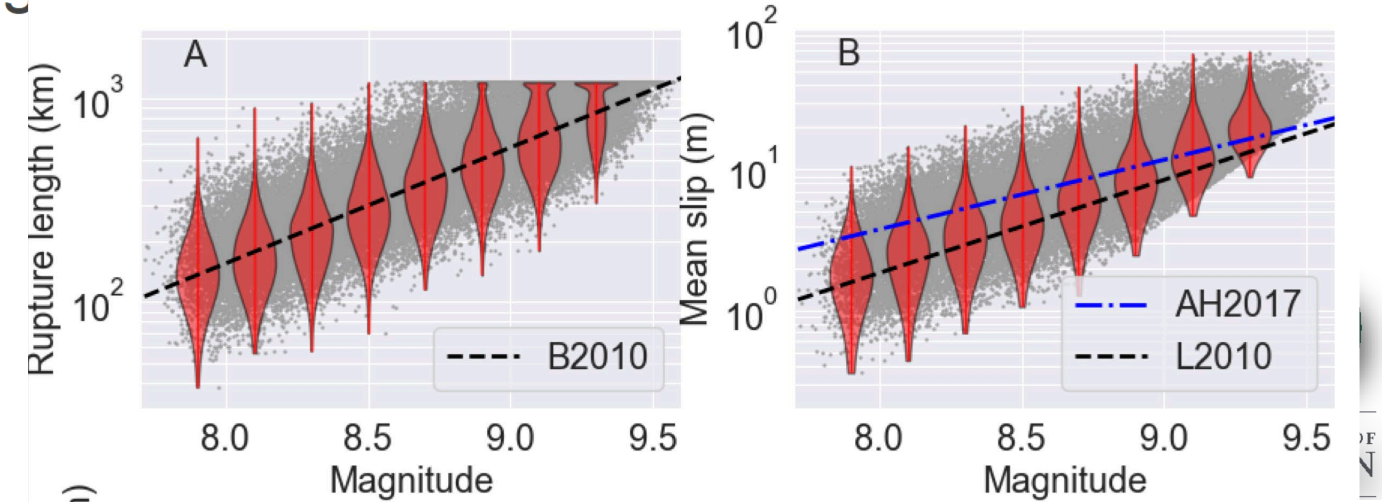
Stochastic kinematic ruptures: Fault dimensions

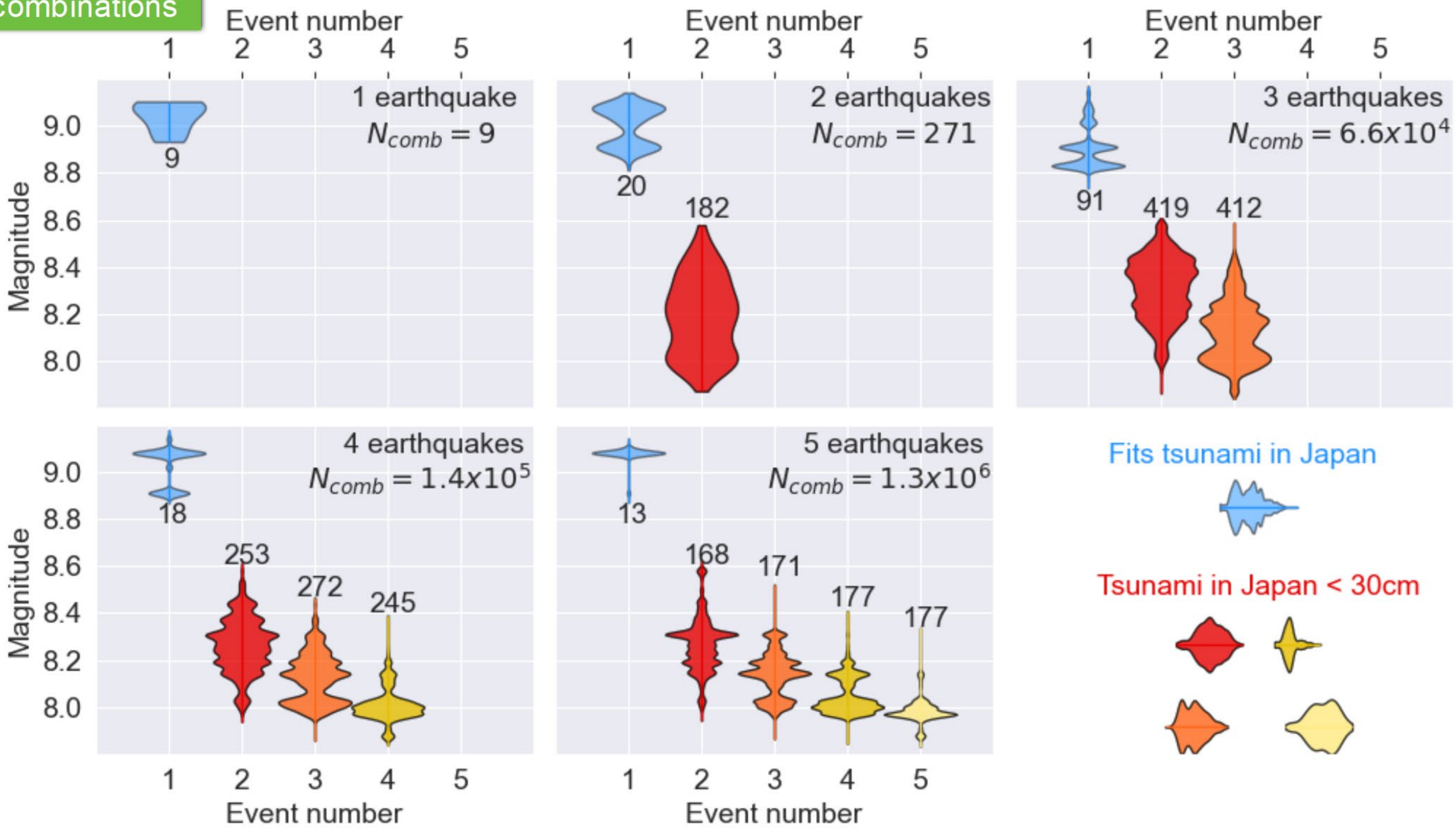
- We also know there is variability in the **rupture dimensions**
- Earthquakes of the same magnitude have varying lengths/widths. **Some times they are long, some times they are short**
- We use a **log-normal probabilistic scaling law** to replicate natural variability (e.g Blaser et al., 2010)
- We don't always select the **entire megathrust** when making a rupture





Sequences with more than one earthquake

Grid search through data sets for all possible combinations



Melgar (2021)

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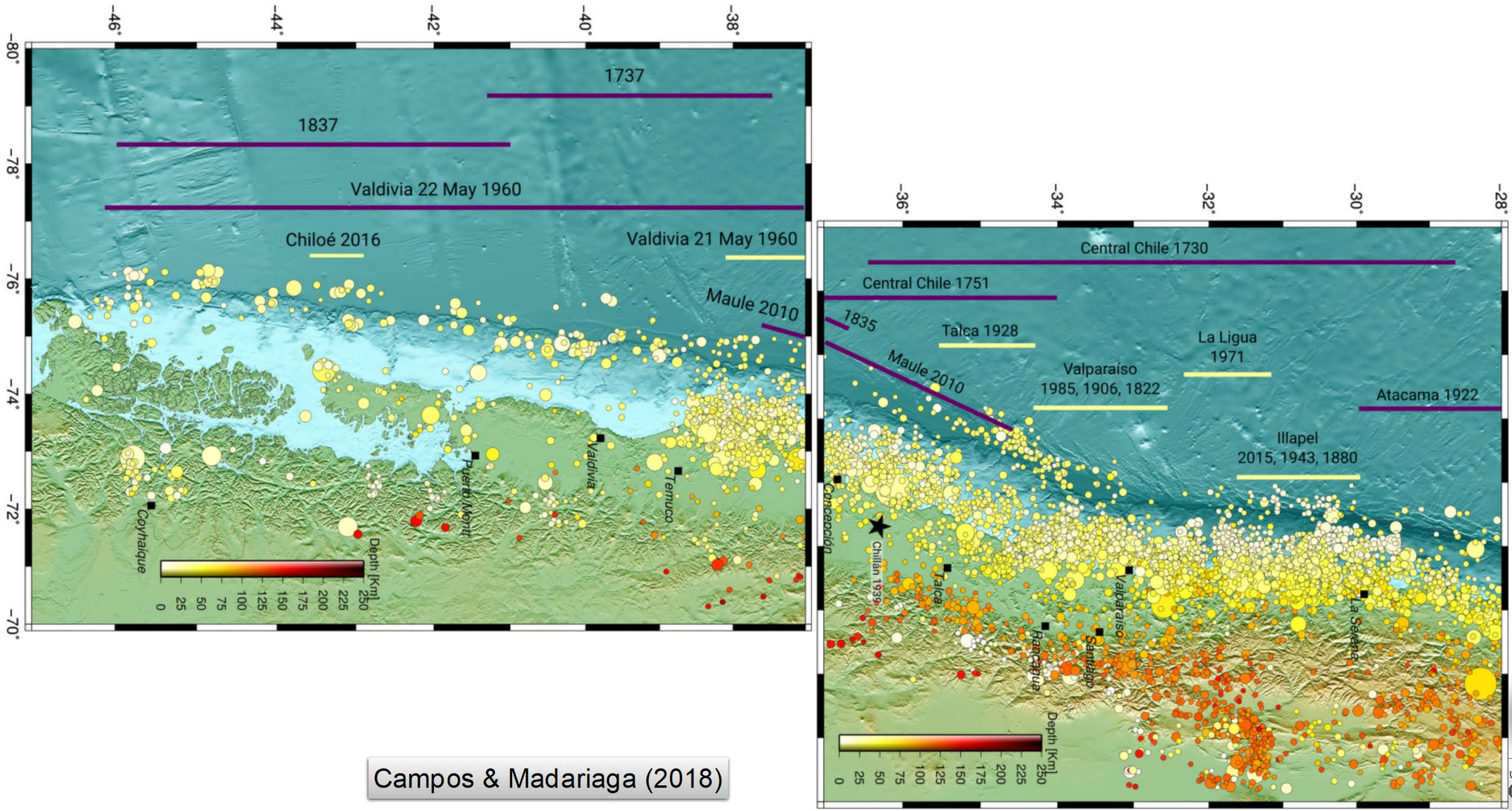

Campos & Madariaga (2018)

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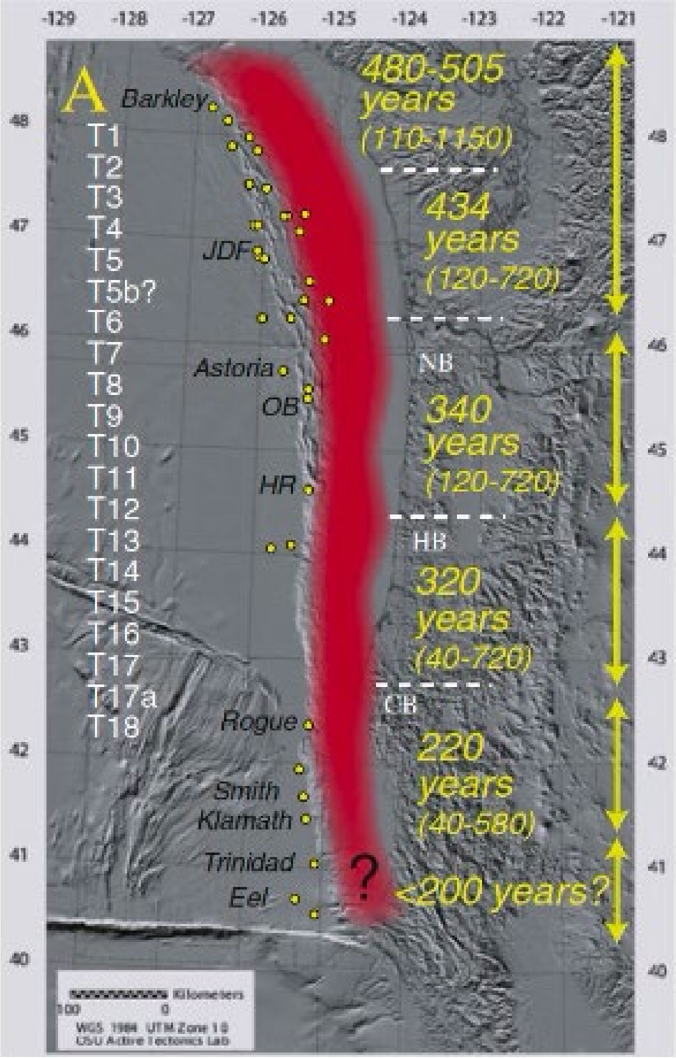

Goldfinger et al., 2017