From Research to Operations: Preparing for the Next Big Tsunami

Amy Williamson

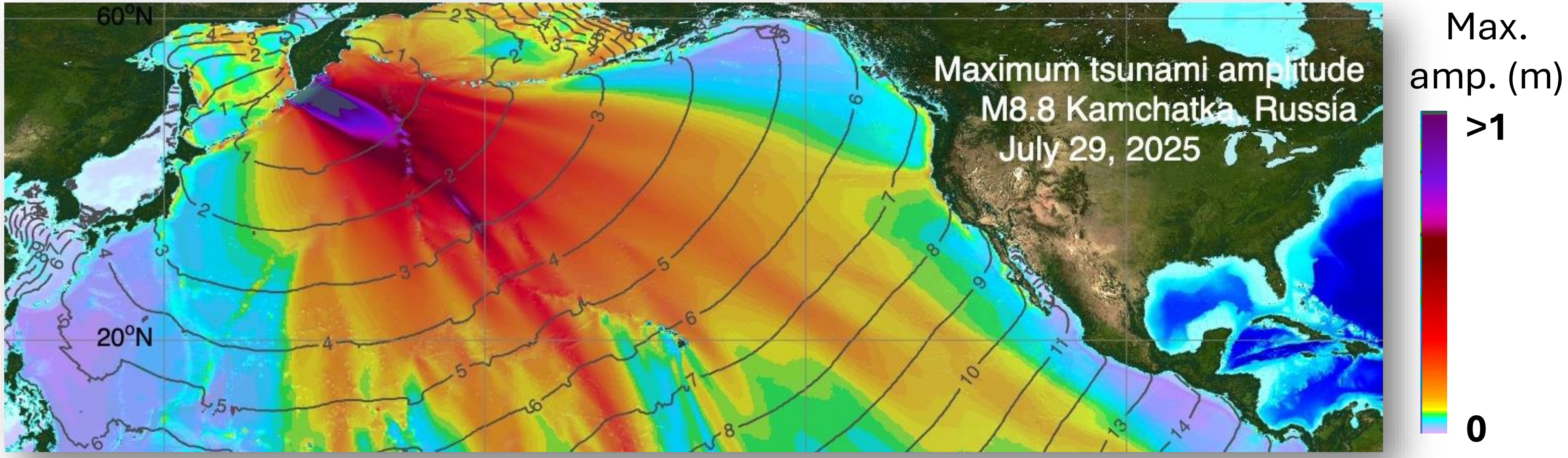
With contributions and discussions from: Diego Melgar (UO), Donsub Rim (WUSTL), Randy LeVeque (UW), Brendan Crowell (OSU), Richard Allen (UCB), & Fernando Salazar-Monroy

CRESCENT annual meeting

October 29, 2025

Berkeley Seismology Lab

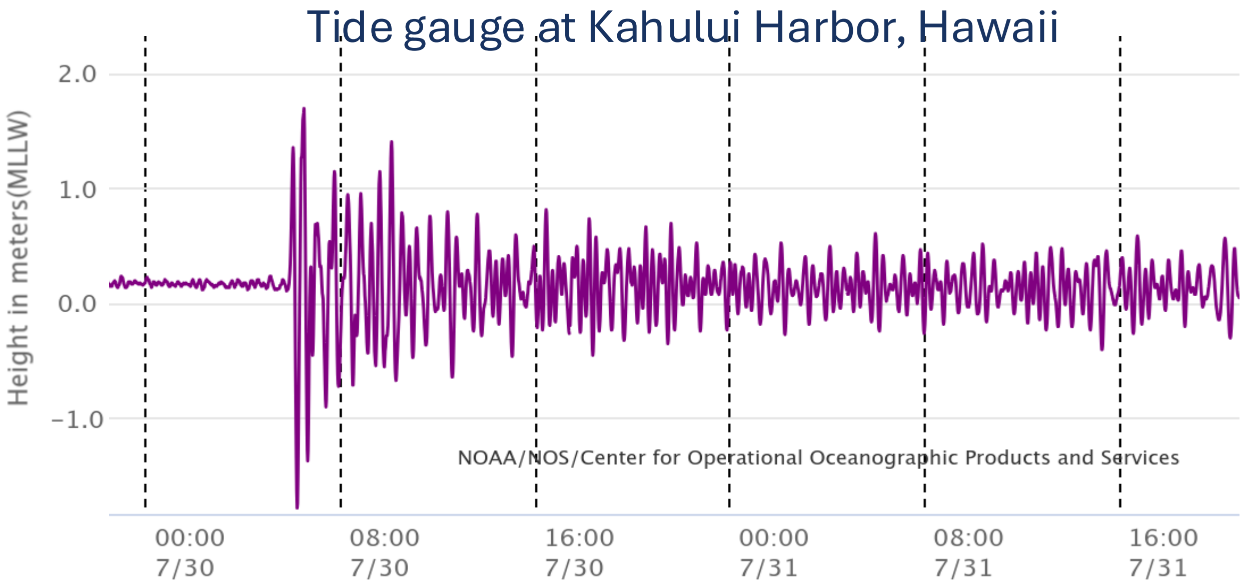
Introduction



Modified from NOAA Center for Tsunami Research

On July 29th, 2025 a M8.8 earthquake ruptured along the Kamchatka Peninsula, generating a transoceanic tsunami

Both US Tsunami Warning Centers issued warnings and advisories to affected coastlines, monitoring the tsunami as it progressed across the Pacific

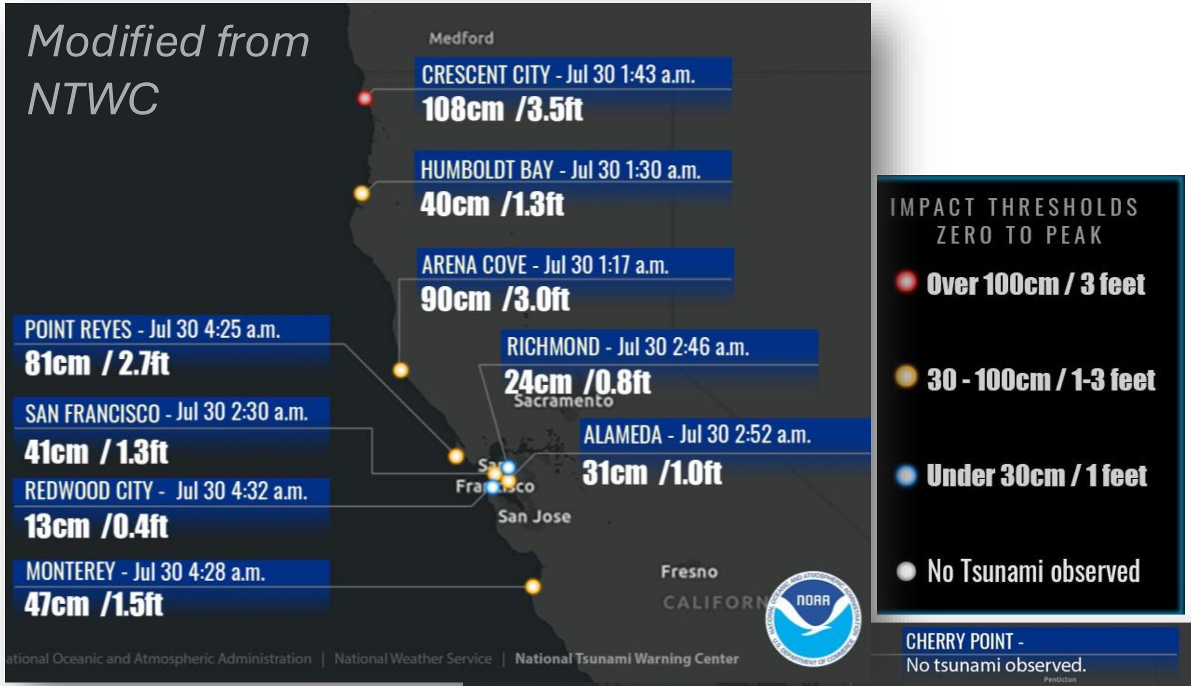


Introduction

From Shaking to Warning: A Tsunami Roadmap

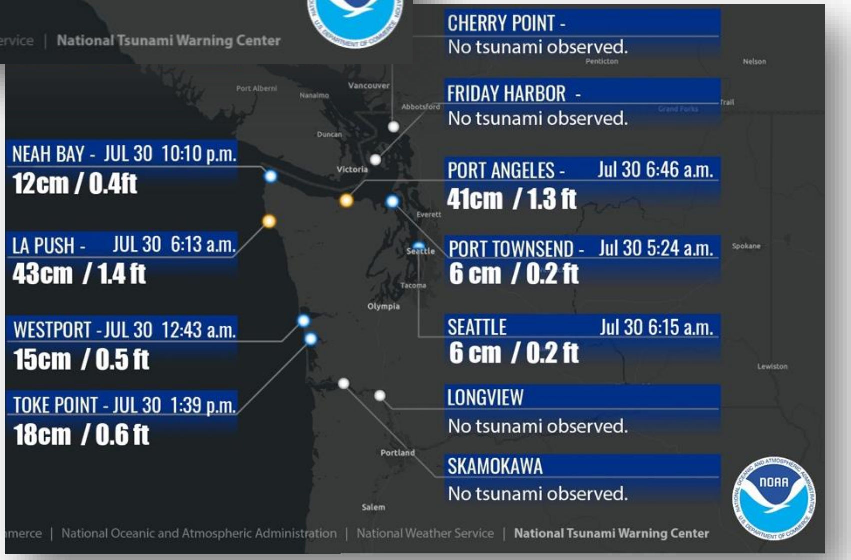
T = 5 minutes

- First information available is the earthquake's location and magnitude. This is used to determine the extent of initial warnings/advisories
- Forecast coastal heights are based on a best match from a directory of pre-computed models



T = 2-3 hours

- As tsunami passes over offshore gauges, the forecast is coarsely refined. The extent of the warning/advisory zone may be updated



T = 1 – 24+ hours

- Wave amplitudes at local tide gauges are monitored. Tsunami alerts may be cancelled as the wave heights fall below set amplitude thresholds

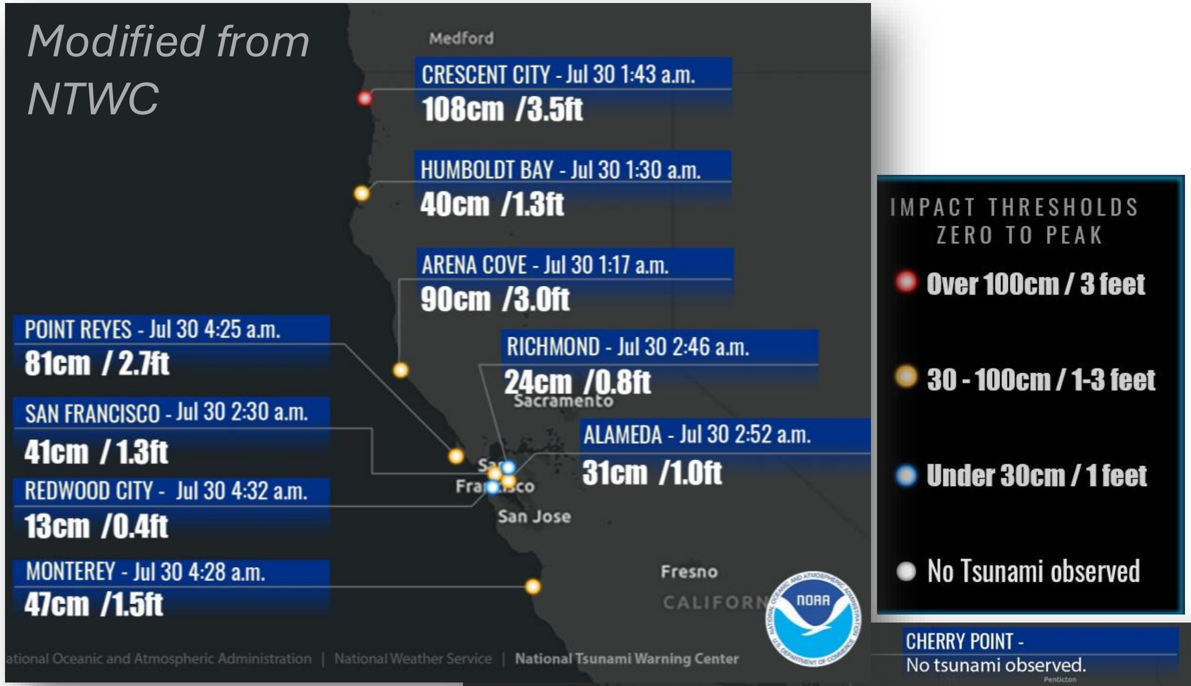
Introduction

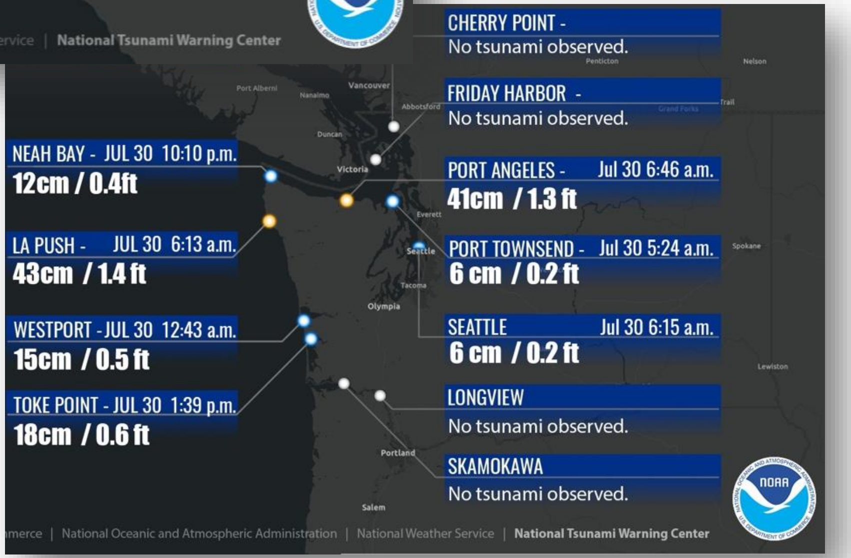
The tsunami's progress across the Pacific was well documented thanks to a network of open-ocean DART pressure gauges and coastal tide gauges

This event was in contrast to the 1952 Kamchatka earthquake & tsunami with an estimated 10,000 casualties, mostly due to the tsunami

The success of the 2025 Kamchatka tsunami was due to a long-term investment in data, resources, and tsunami related research.

Through additional research to operations investment, we can build on current operational models, including new datasets and more real time information about the earthquake rupture





Tsunami Response & Preparedness Matters

NEWS | BAY AREA & STATE

Rescues needed as hundreds went to San Francisco's Ocean Beach despite tsunami advisory

By **Amanda Bartlett**, *Assistant Local Editor*
Updated Jan 16, 2022 5:07 p.m.

SFGATE

Tsunami monitoring is important not just for the really *really* big ones

Even small tsunami waves from far-field events can be dangerous.

What are some areas where research can aid tsunami operations?

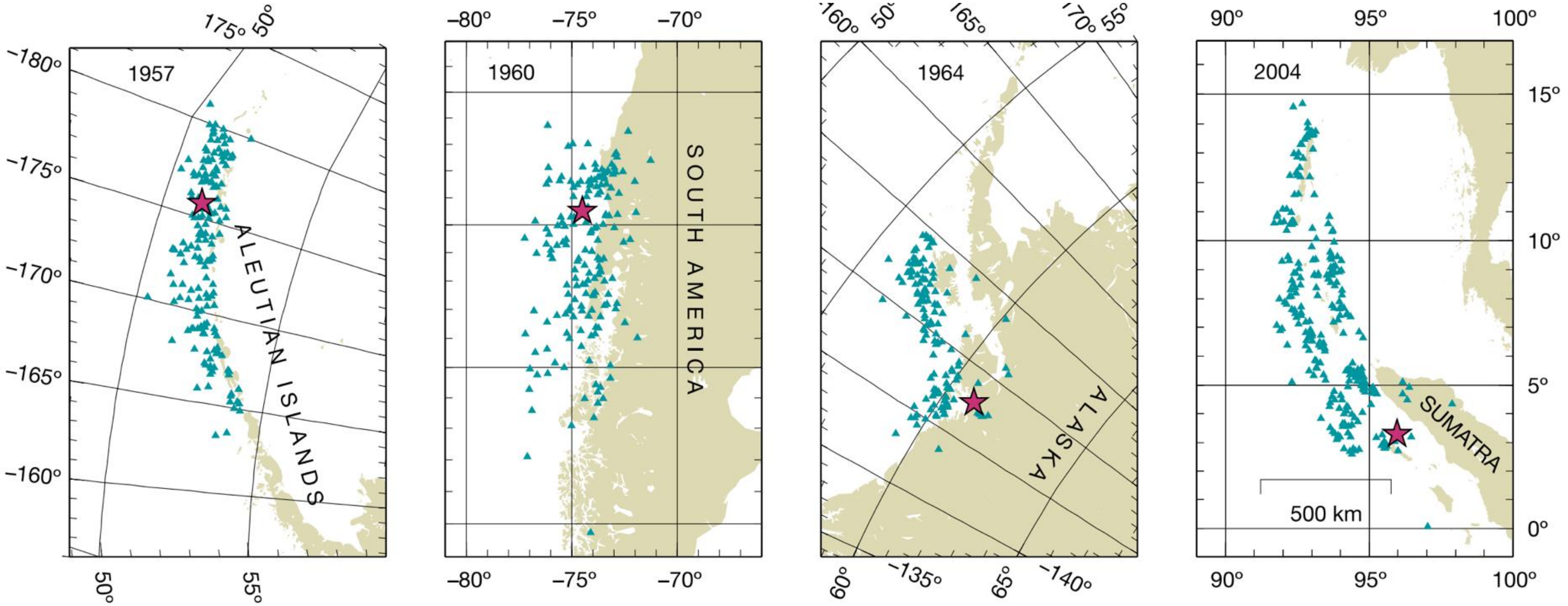
- What factors about the earthquake source matter for tsunami generation
- What matters at local coastlines and what matters in the far-field?
- Can we data-share across multiple agencies to produce faster/more refined alerts?

Q. Does the rupture duration matter?

Tsunami propagation is relatively slow compared to earthquake rupture velocities

Tsunami models often assume an instantaneous rupture (velocity → infinity)

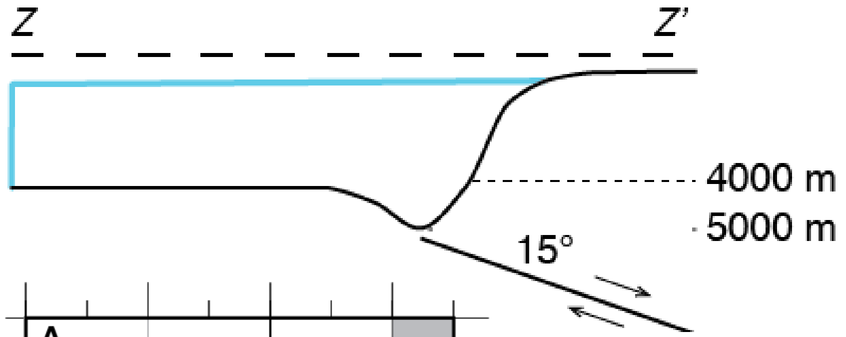
Large earthquakes may rupture over minutes time scales, especially if ruptures propagate unilaterally



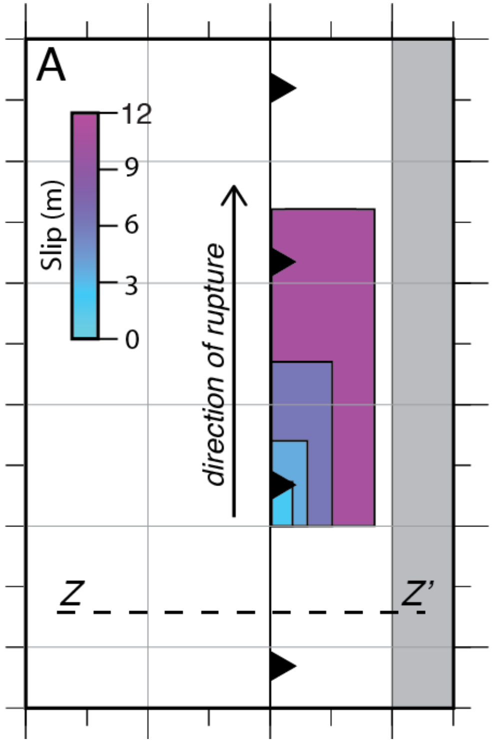
Aftershock as proxy for rupture extent from *Ishii et al., 2005*

Q. Does the rupture duration matter?

We can test this first using simple models and then scale upwards

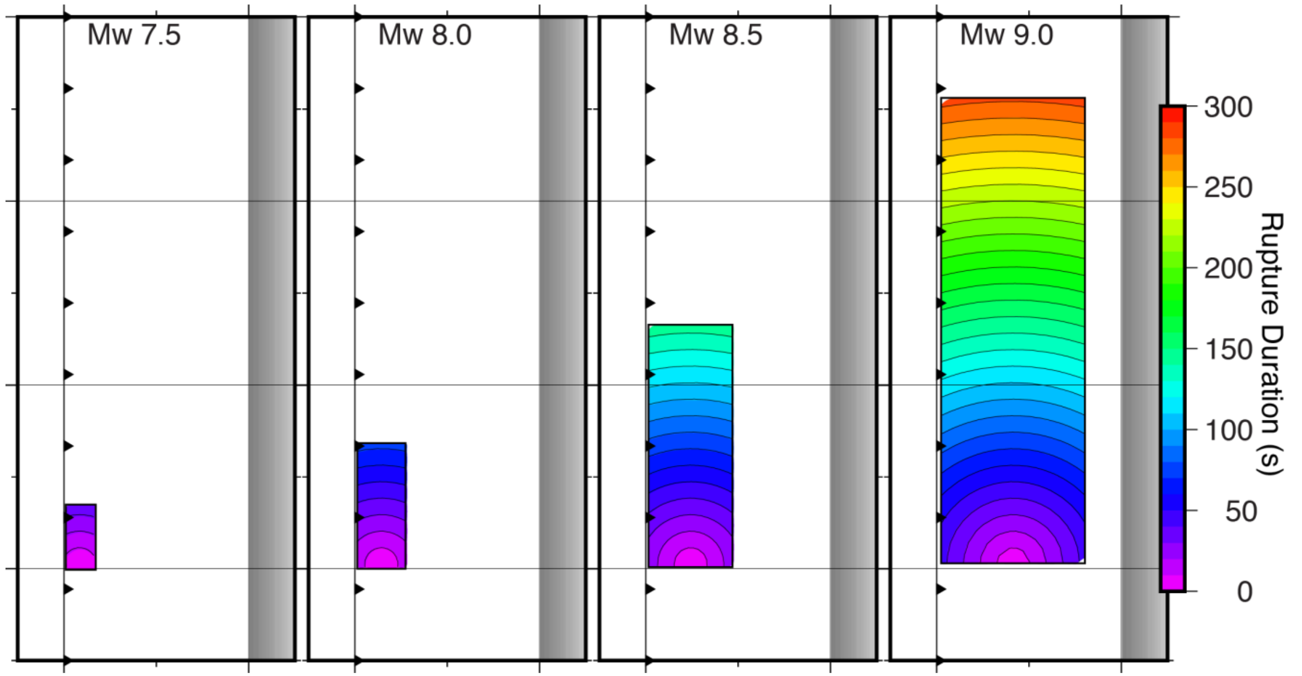


Take a simple subduction zone profile with smooth bathymetry, an infinite coastline, and a shallow dipping planar fault



Build simple scaled ruptures with increasing rupture areas

Assign a set rupture direction and velocity (2.0 km/s)



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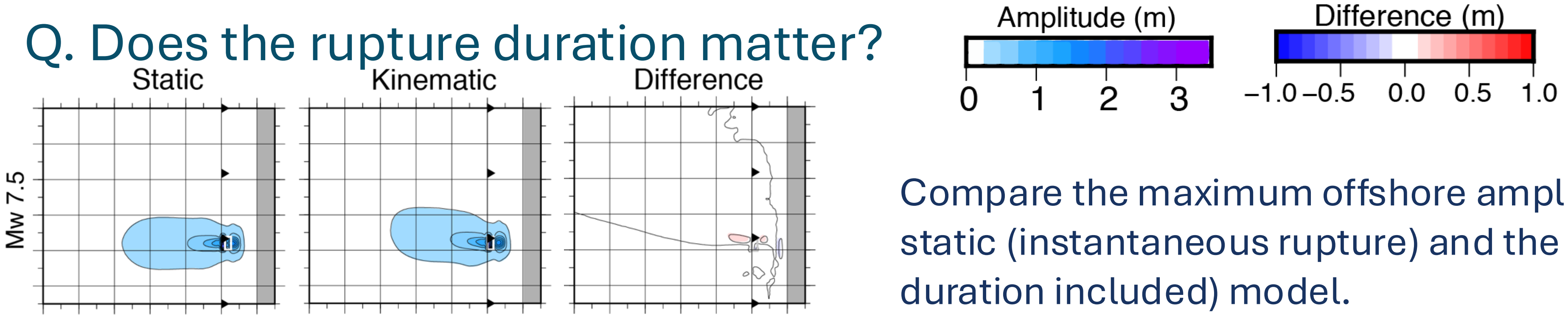

Compare the maximum offshore amplitude between a static (instantaneous rupture) and the kinematic (rupture duration included) model.

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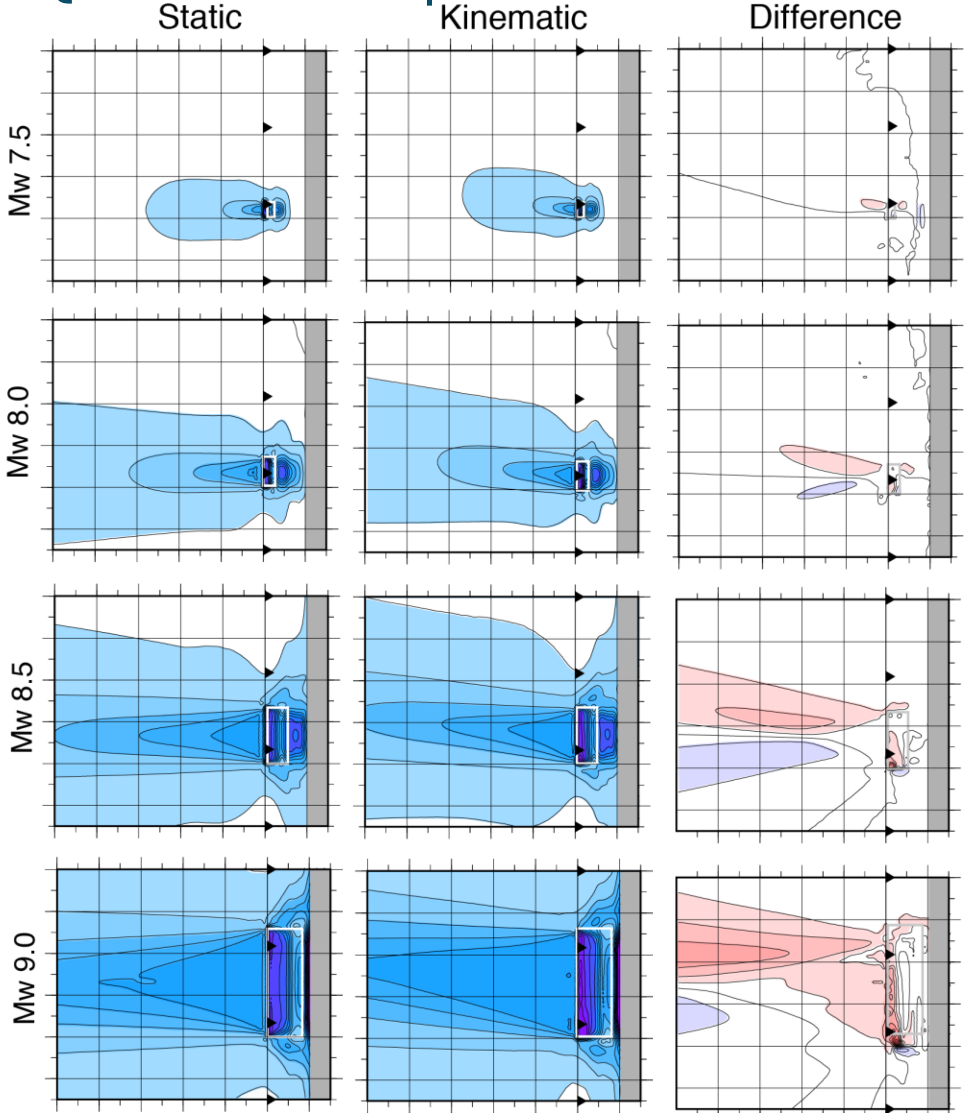
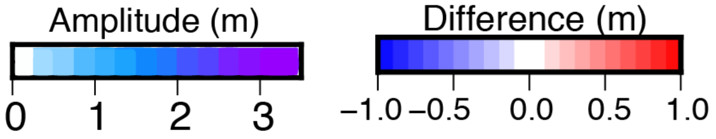
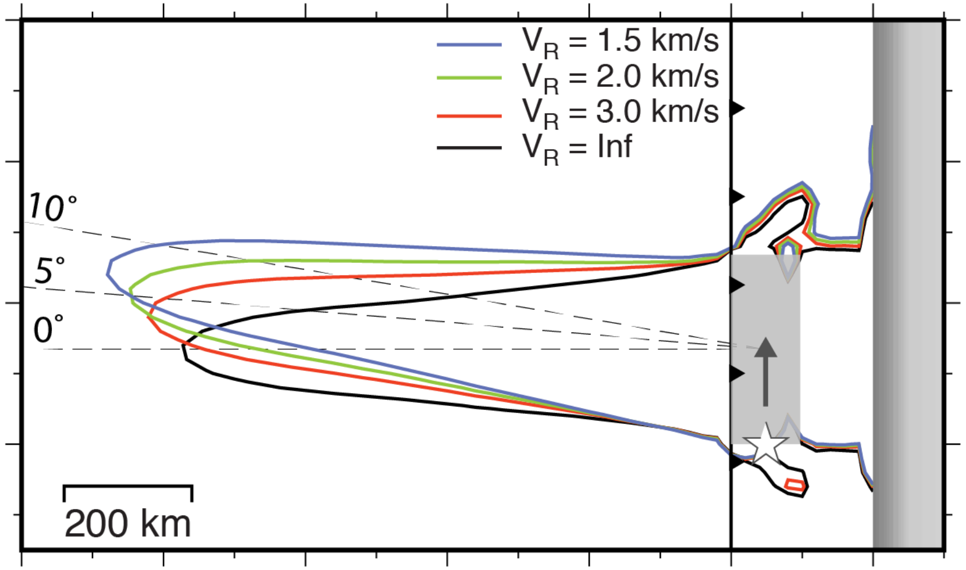




Compare the maximum offshore amplitude between a static (instantaneous rupture) and the kinematic (rupture duration included) model.

… and extend comparison across larger and larger ruptures



Williamson et al. 2019

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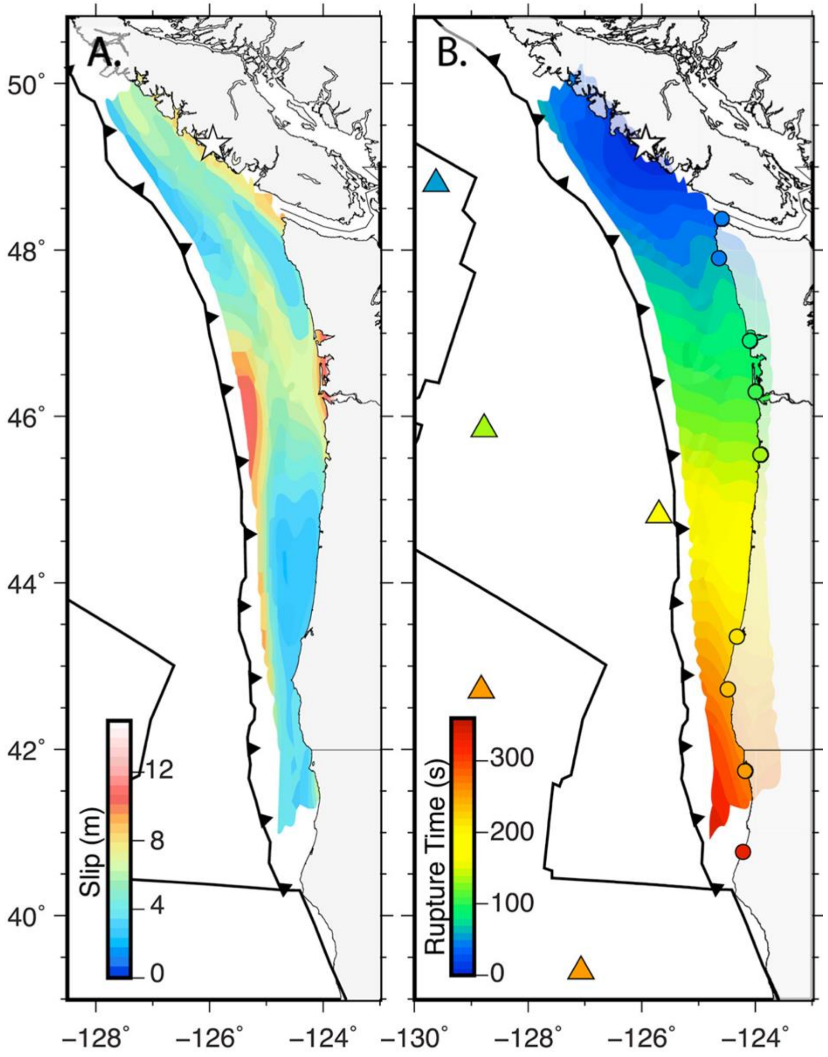

Add more complexity:

Use a non-planar fault with complex patterns of slip and a non-uniform coastline

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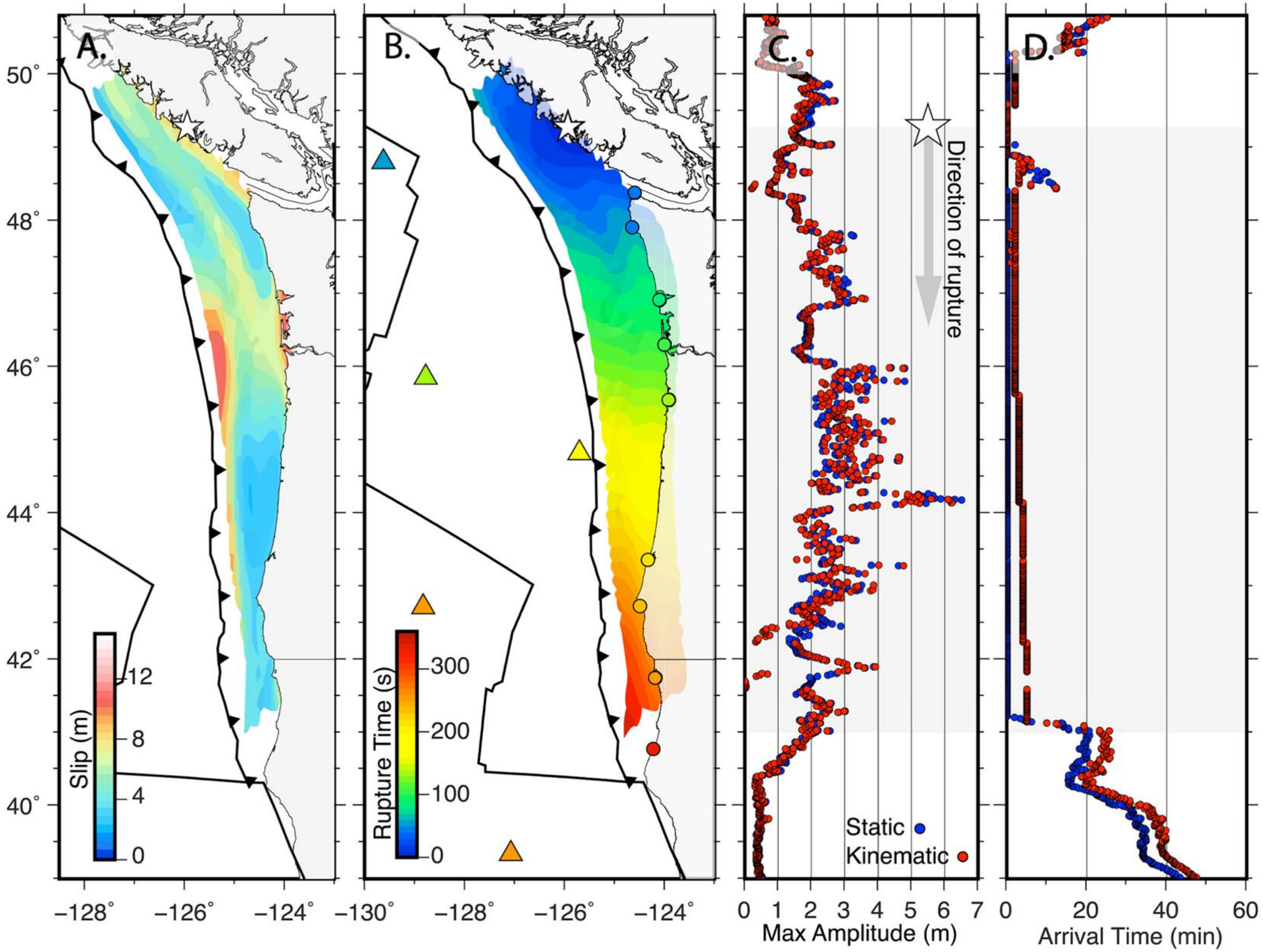

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Use a non-planar fault with complex patterns of slip and a non-uniform coastline

At local coastlines, the difference is minimal: small shift in arrival times and very little change in maximum onshore amplitudes

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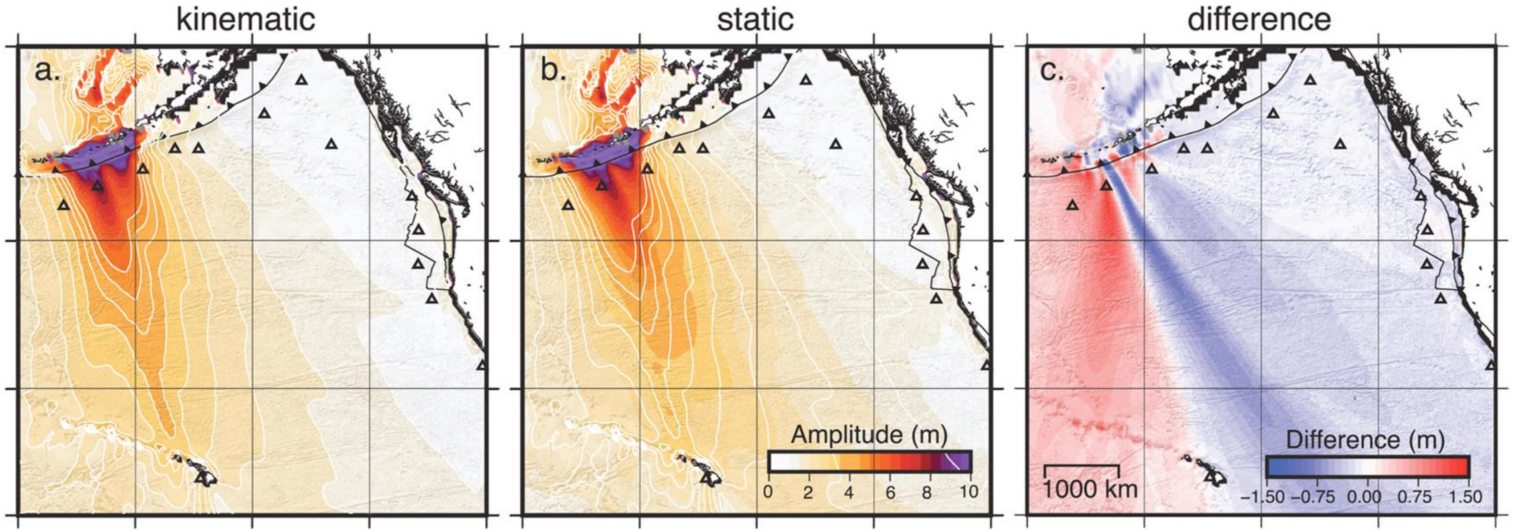

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Use a non-planar fault with complex patterns of slip and a non-uniform coastline

At local coastlines, the difference is minimal: small shift in arrival times and very little change in maximum onshore amplitudes

In the far-field, the rupture velocity can matter a lot

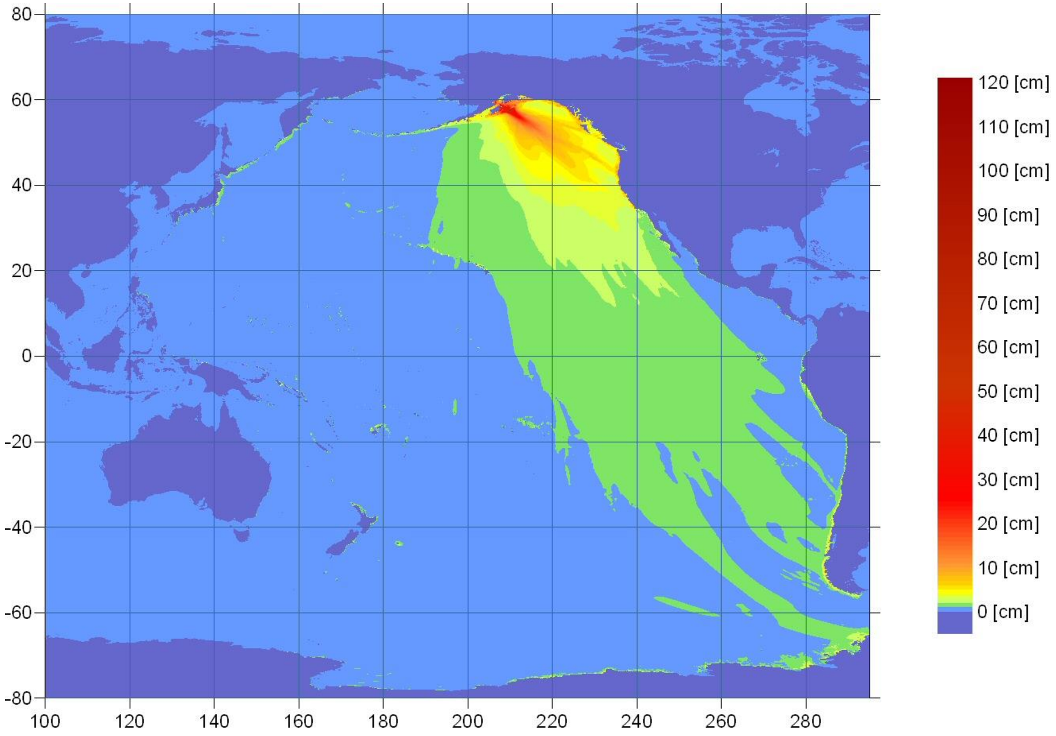
The directionality of the rupture can substantially alter the tsunami amplitude and therefore hazard at far distances.

Example above shows a case where the potential tsunami warning to Hawaii is greatly affected by the input model.

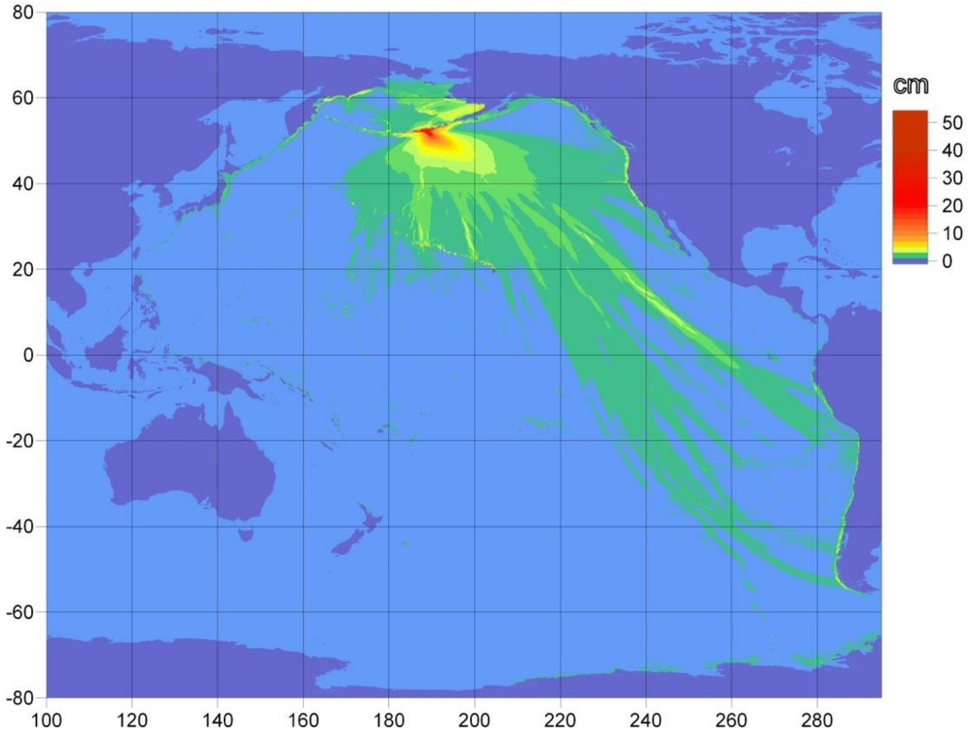
Q. Does the slip distribution matter?

The simplest (and most common) assumption is uniform slip

Uniform slip models are used in operational forecasts and in long term hazard assessments



ATFM models for the 2018 M7.8 Gulf of Alaska tsunami (left) and the 2011 M7.2 Amukta Pass tsunami (right)



Earthquake Rupture to Tsunami Generation

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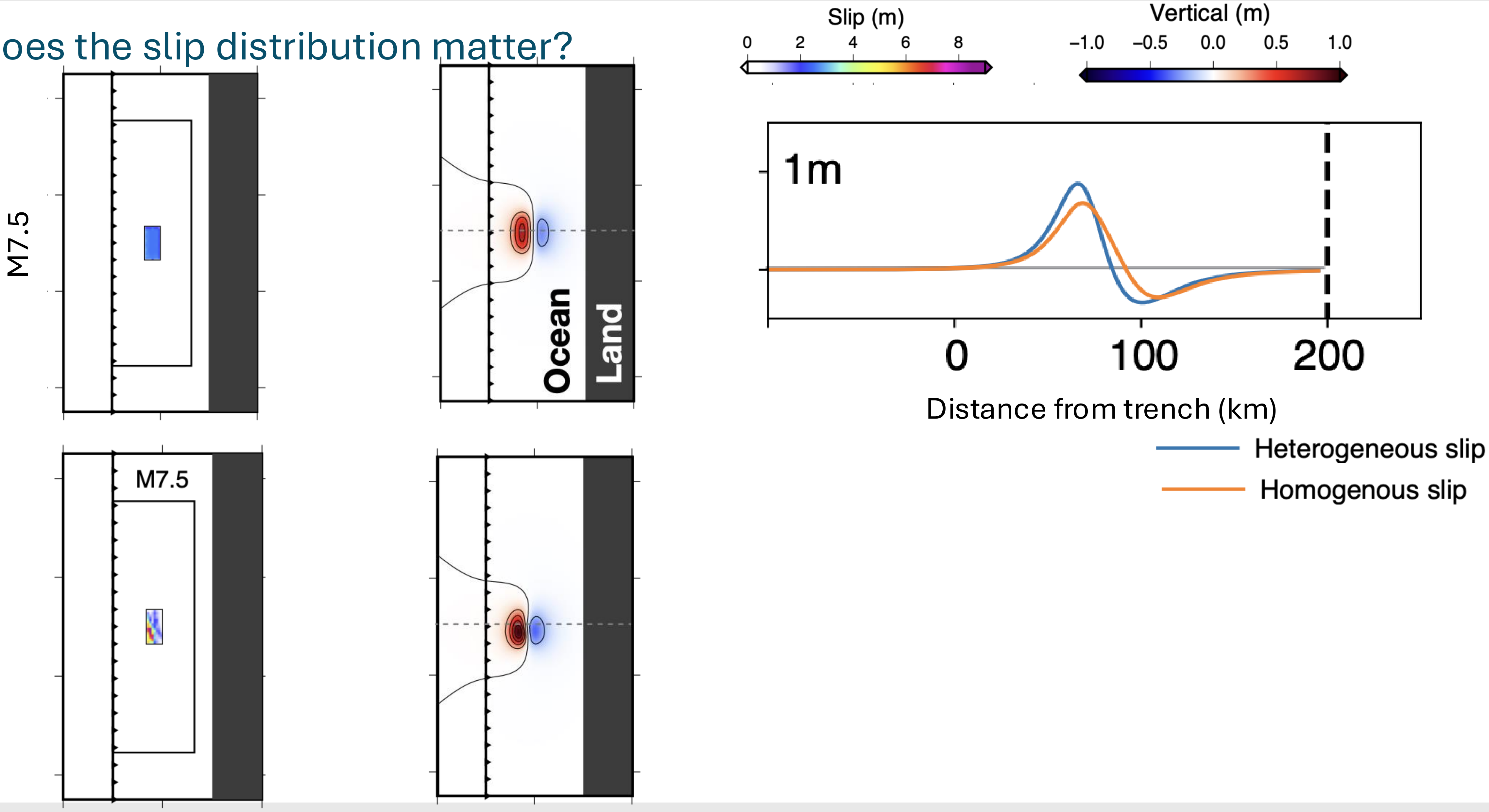

Melgar, Williamson, Salazar (2019)

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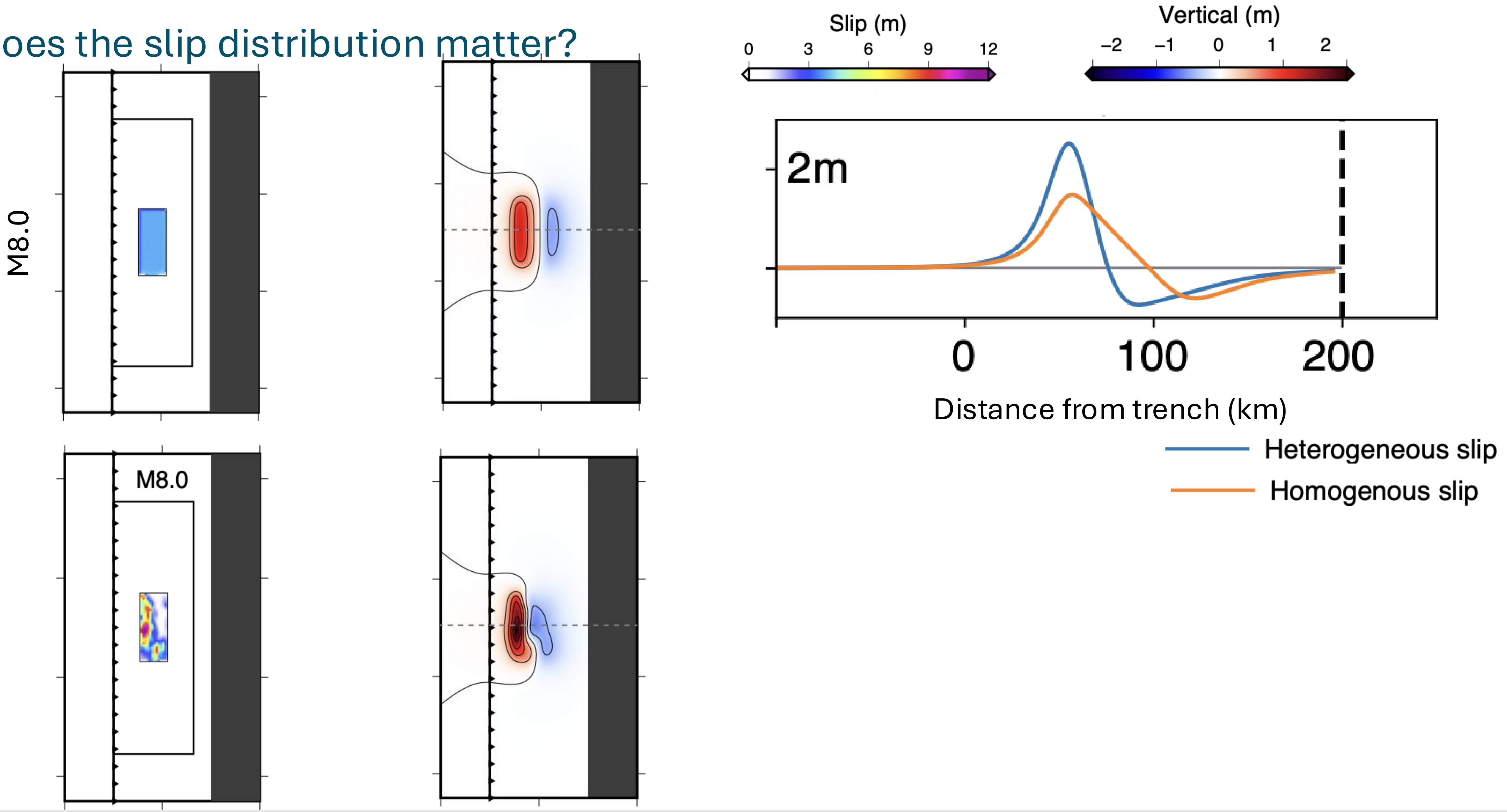

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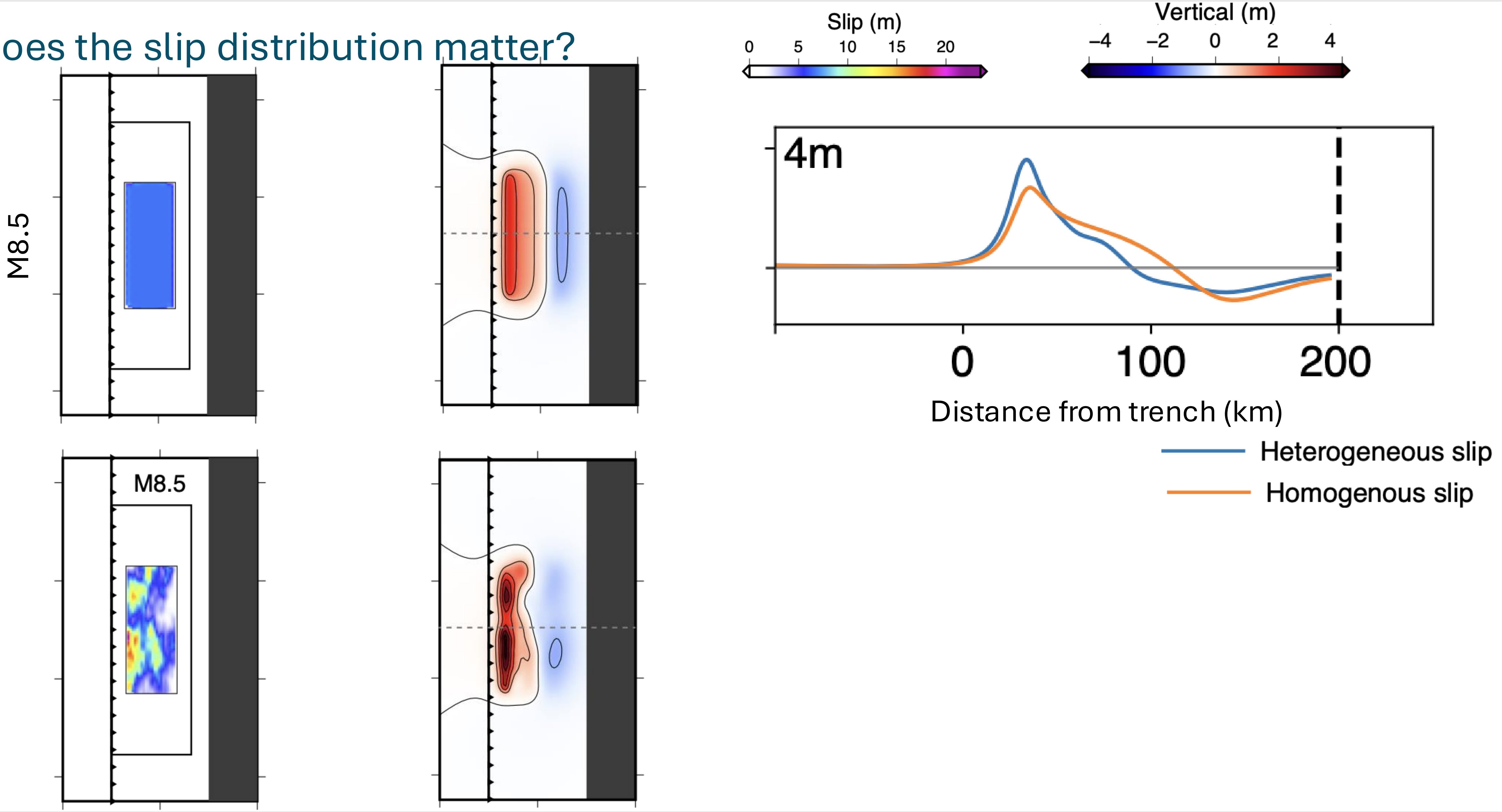

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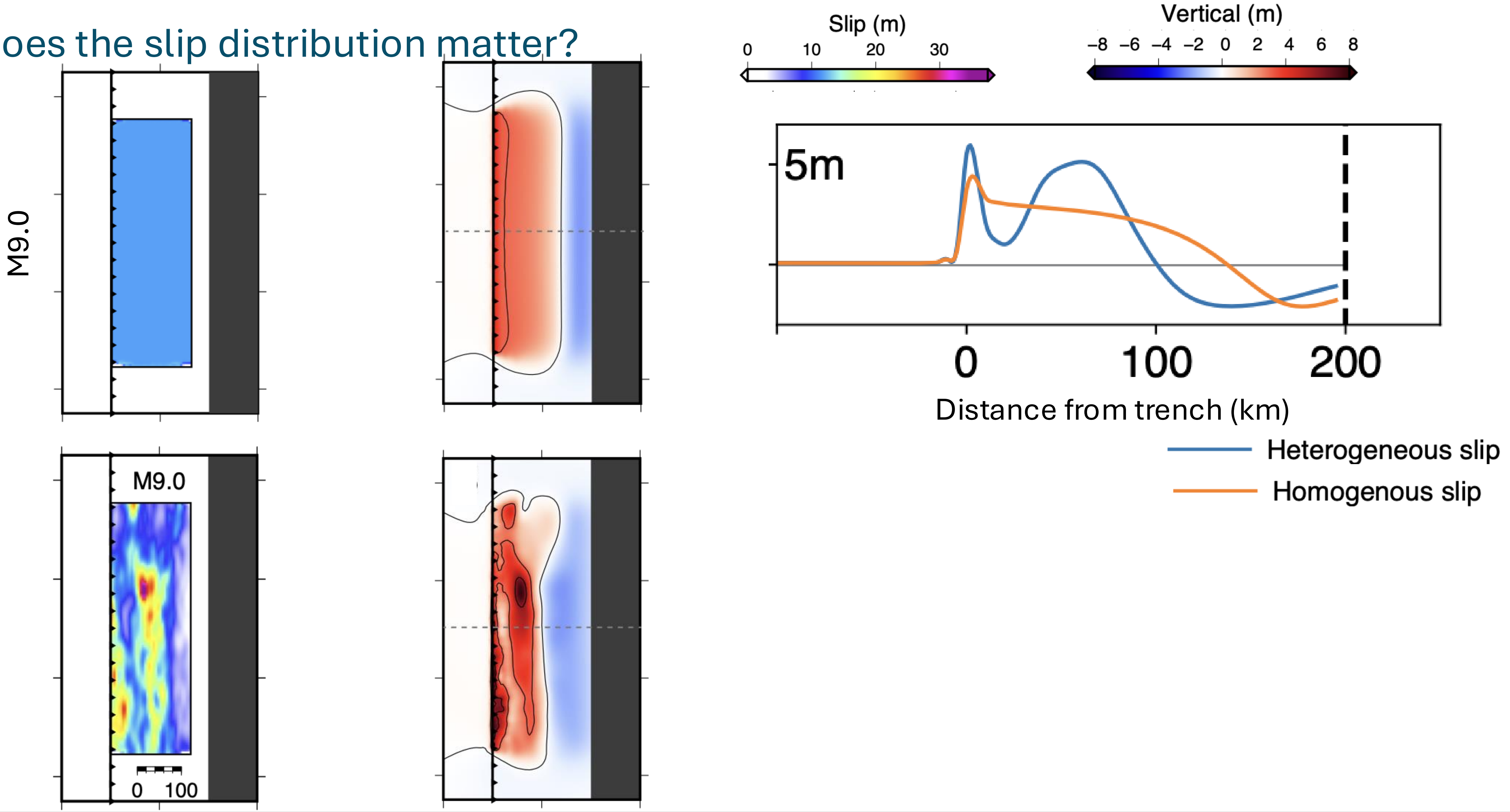

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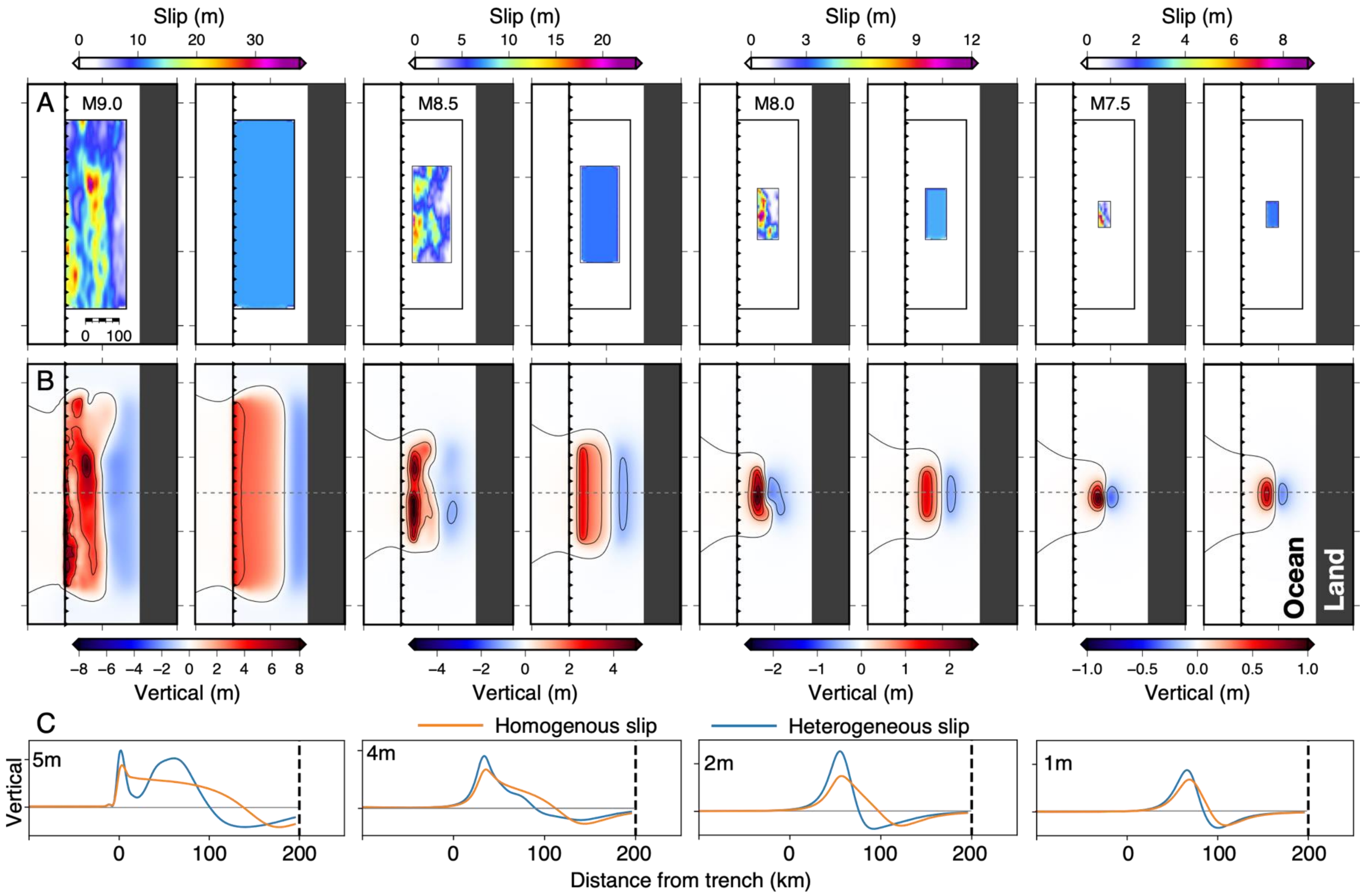


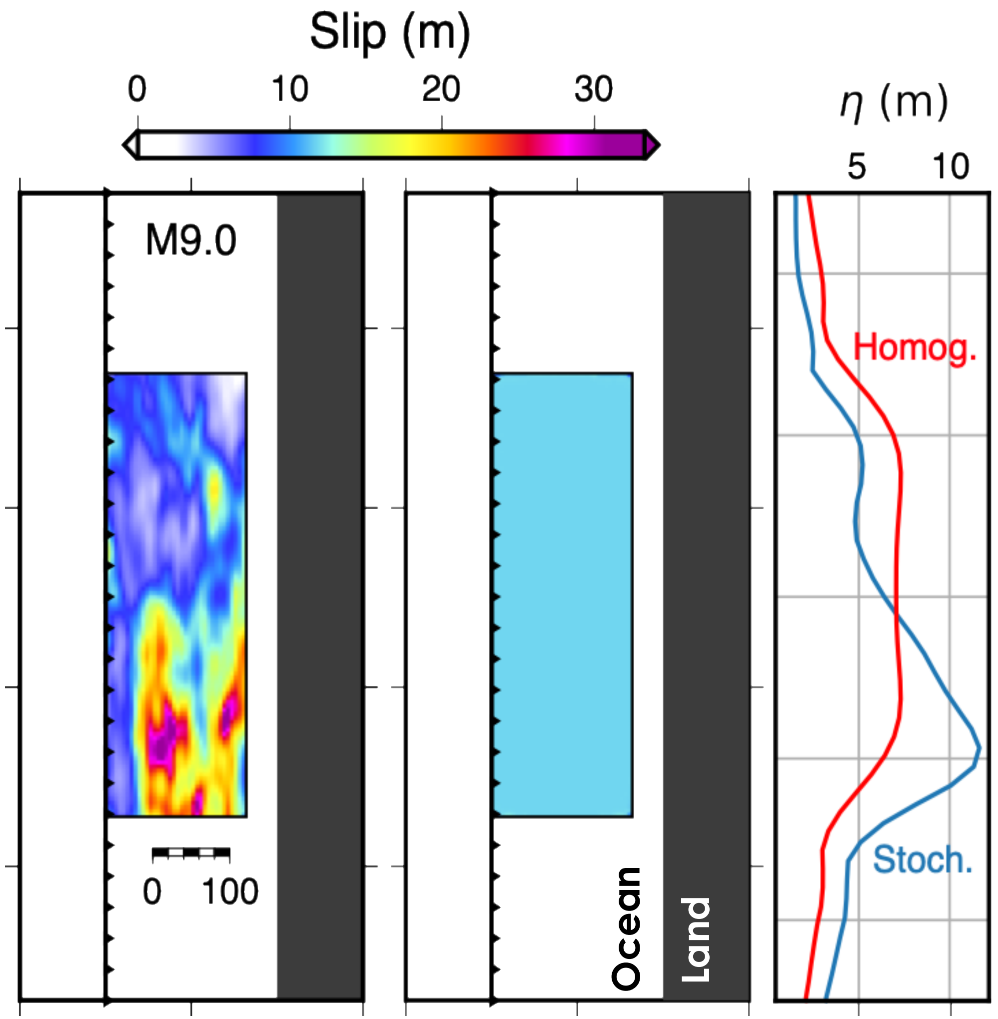
Stochastic slip causes a wider range of surface deformations

The larger the magnitude, the greater the variation

How does that range in seafloor deformation affect the tsunami at a coastline?

Melgar, Williamson, Salazar (2019)

Q. Does the slip distribution matter?



Tsunami amplitude at the coast is affected by where we see slip.

Because there are near infinite combinations of complex slip, this test needs to be repeated many times to properly sample all possible slip combinations!

Model 4200 ruptures between M7.0 and M9.0

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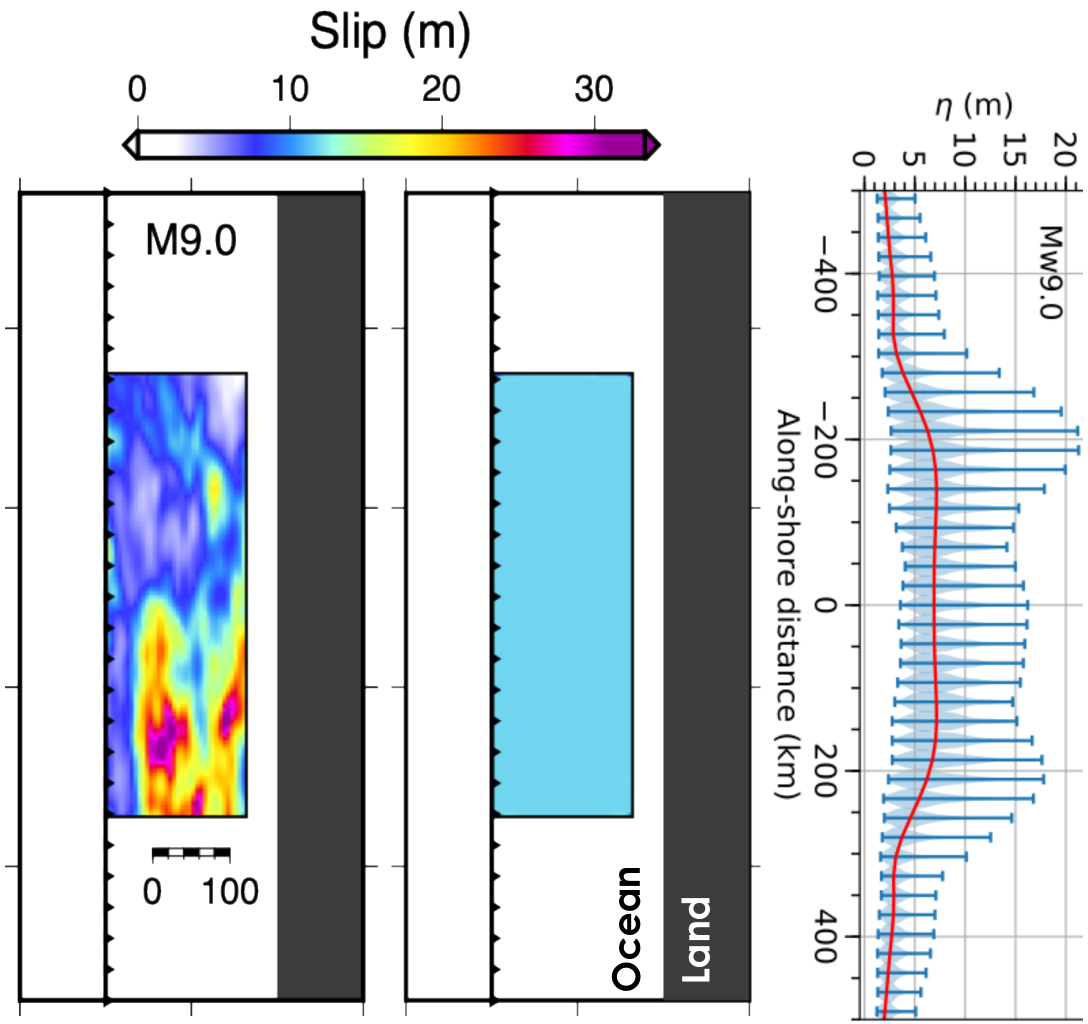

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Model 4200 ruptures between M7.0 and M9.0

Uniform slip case approximates the median of the suite of complex slip models

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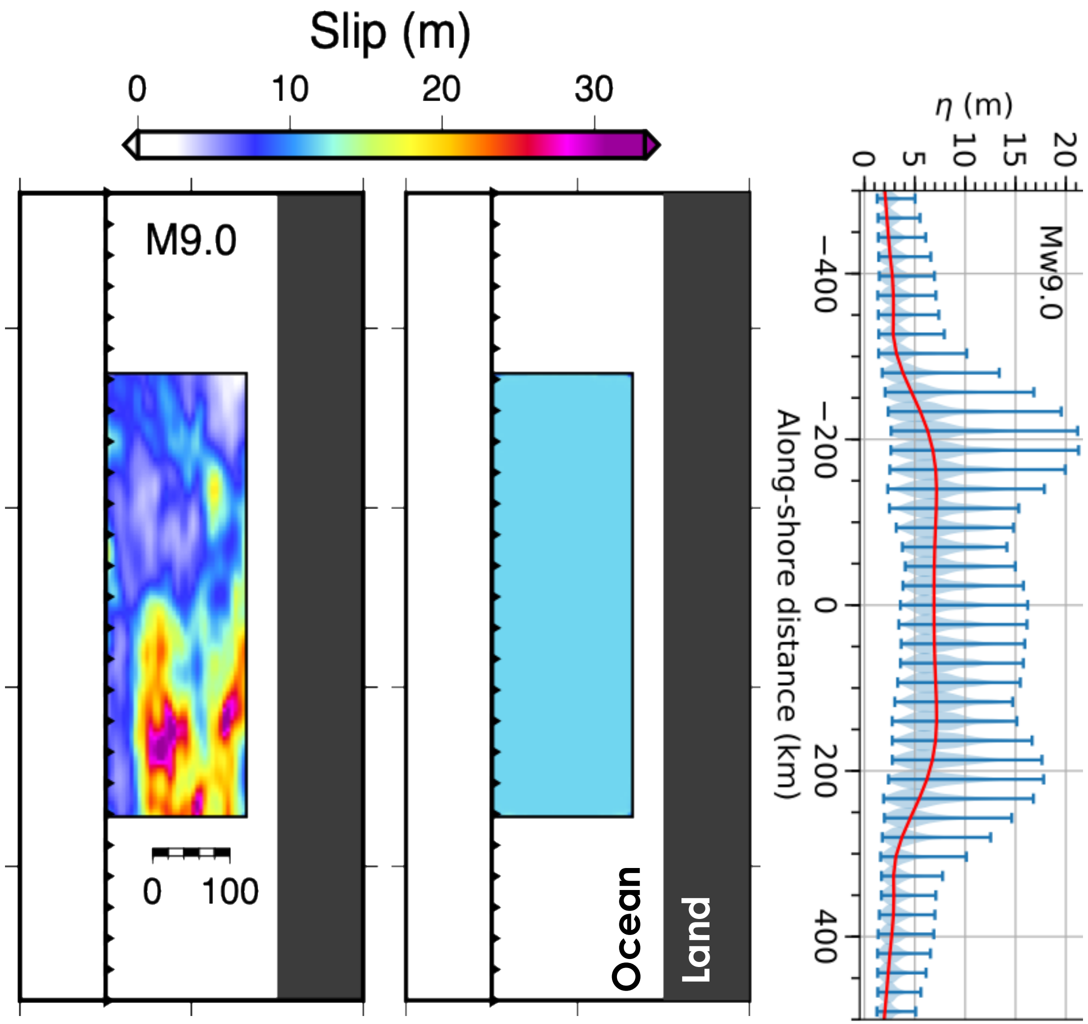
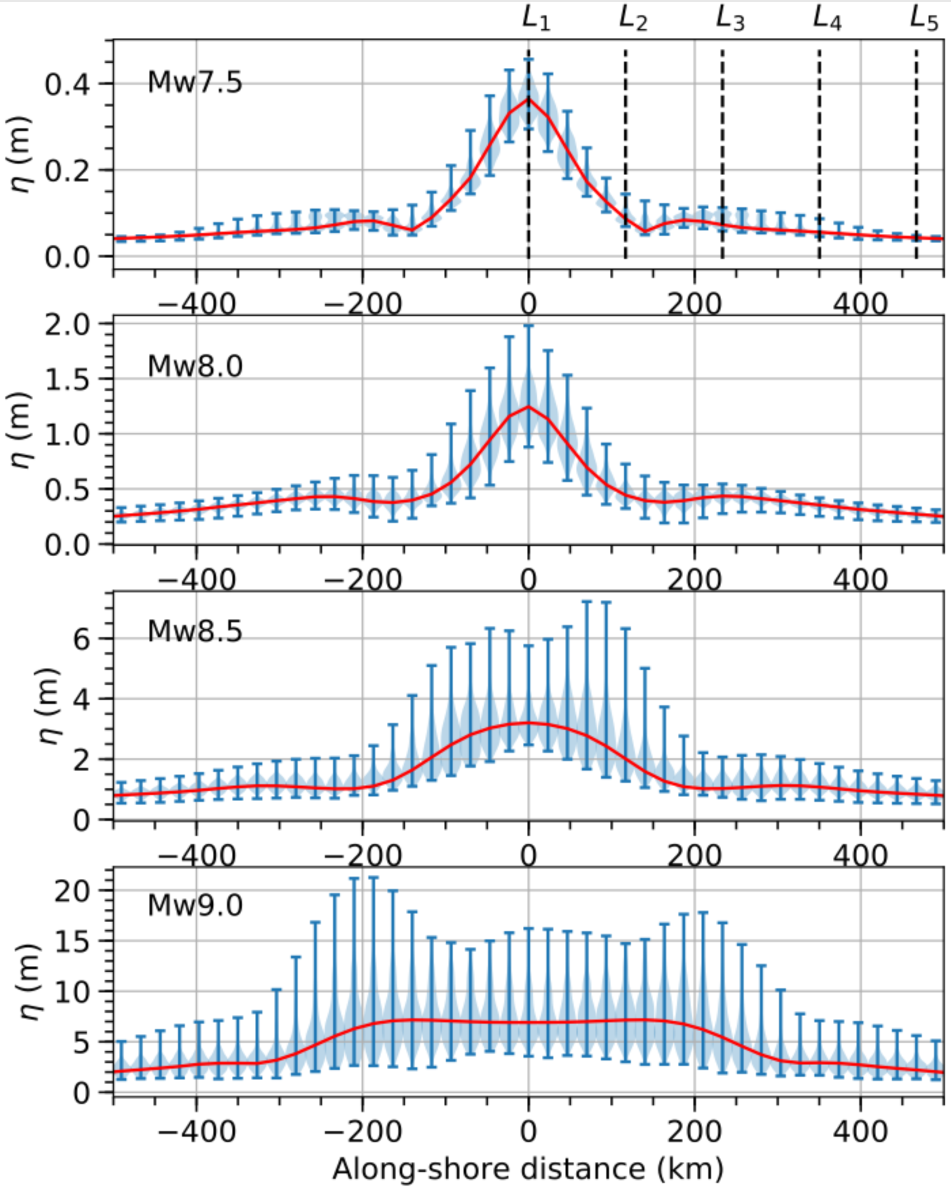
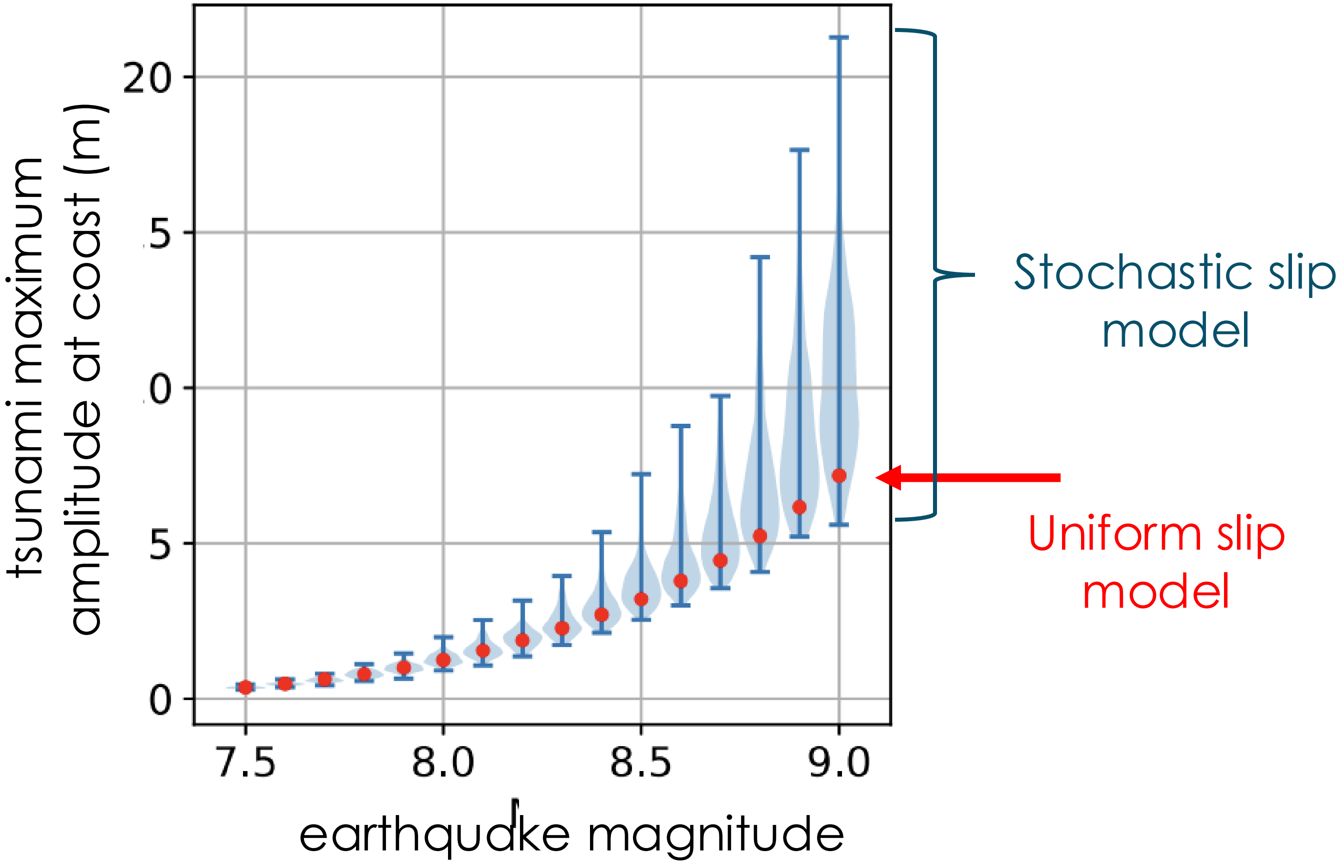




Q. Does the slip distribution matter?

Uniform (and simplified) slip models do not capture the full range of possible earthquake behaviors



As a result, they systematically underestimate the resulting near-field tsunami hazards

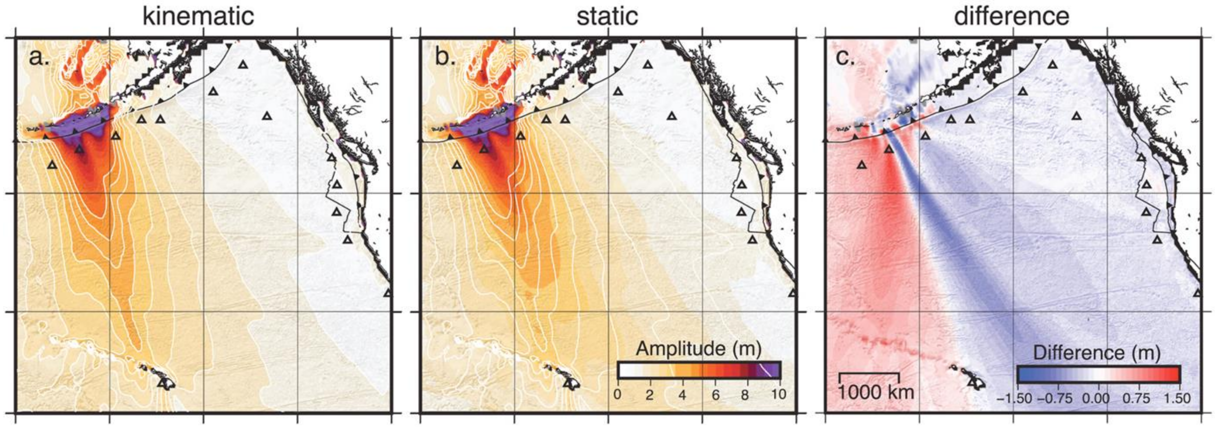
The issue is exacerbated as magnitude increases

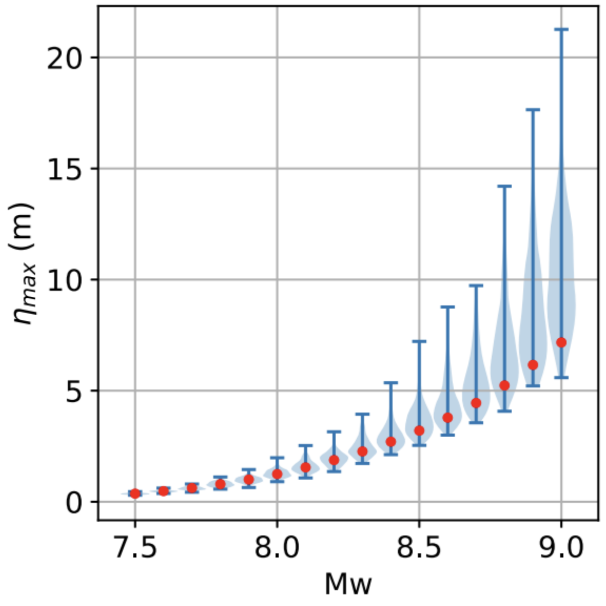
Tsunami Generation to Real Time Alerts

Features of the earthquake rupture can affect tsunami generation through the spatial and temporal evolution of surface deformation.

In the near-field, details of slip distribution can have an outsize effect on local maximum tsunami amplitudes.

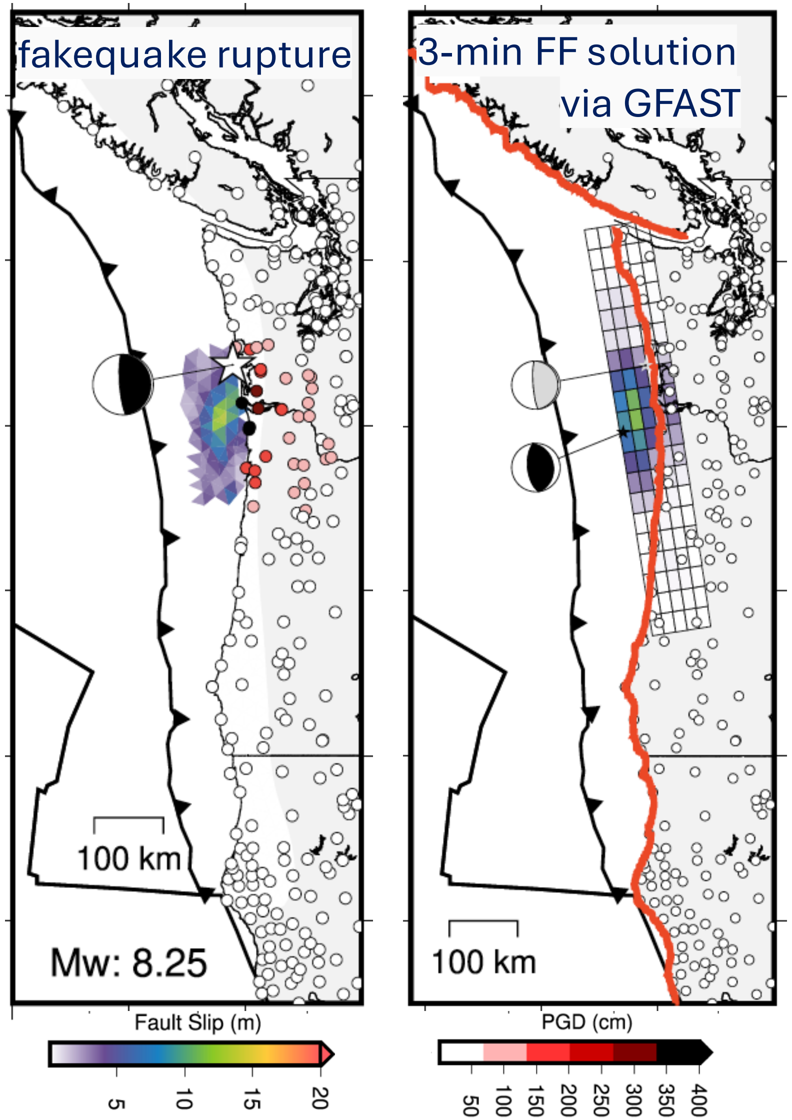
Rupture duration can affect tsunami wave heights in the mid- and far-field.





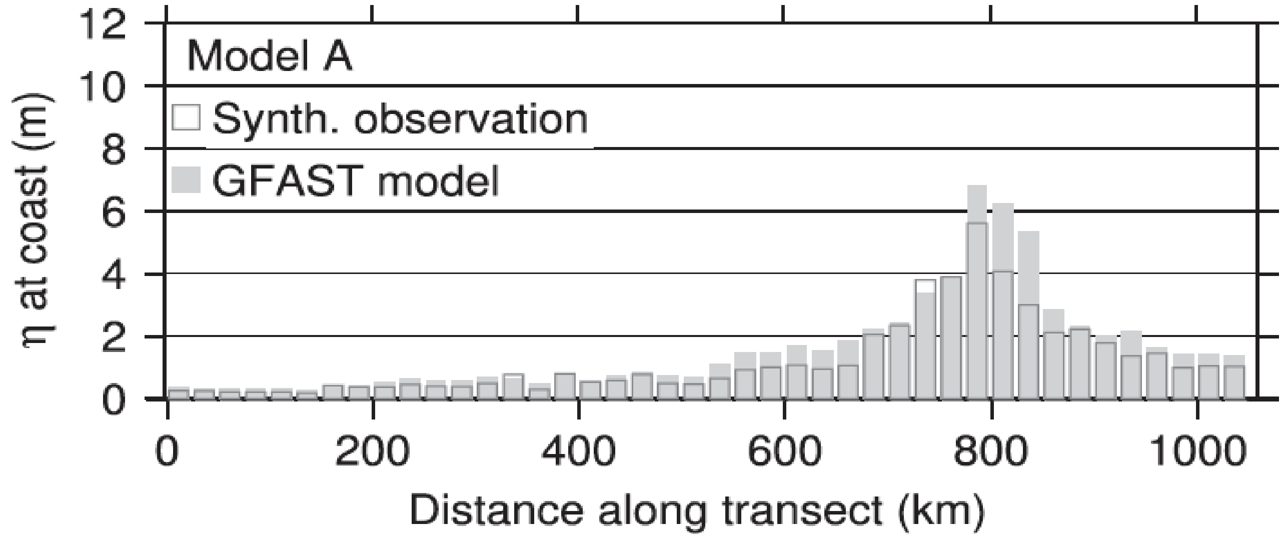
What tools to we have to include rupture details into operational tsunami forecasts?

The groundwork for tsunami early warning is here



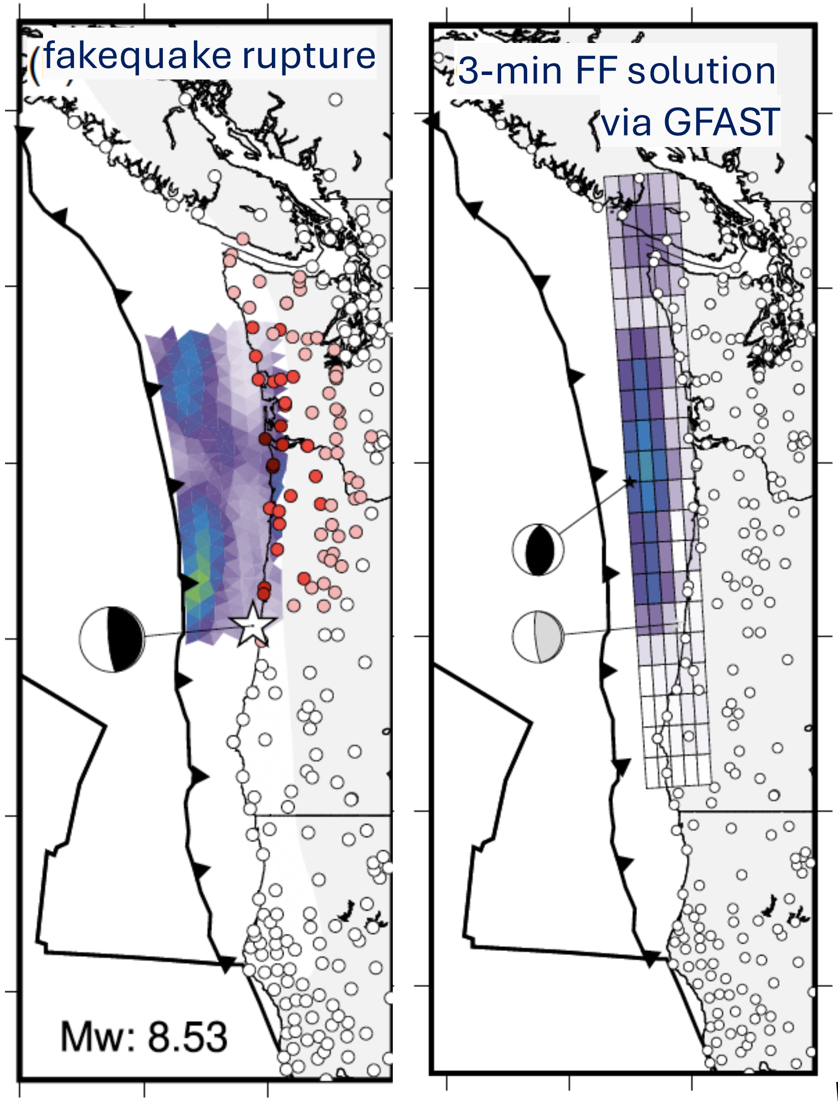
Real time GNSS data is available on the west coast through regional networks into programs like ShakeAlert

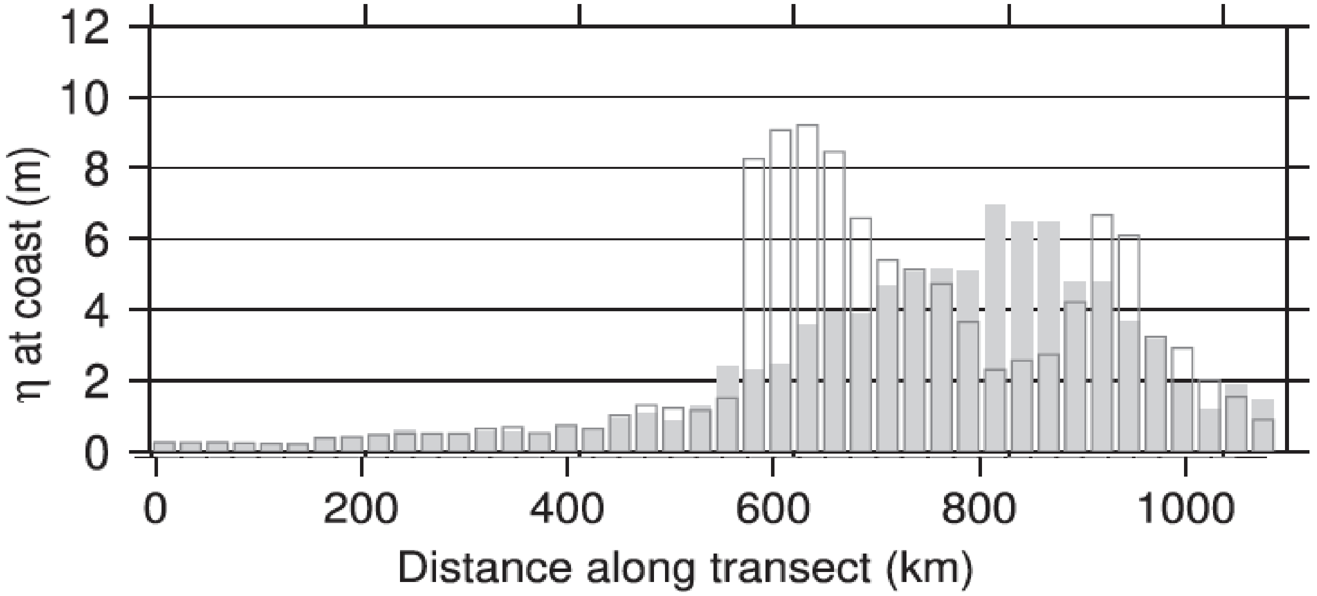
Rapid models can be produced within minutes providing estimates of fault plane and slip.



These models combined with high performance computing can be leveraged to produce rapid coastal tsunami forecasts

The groundwork for tsunami early warning is here





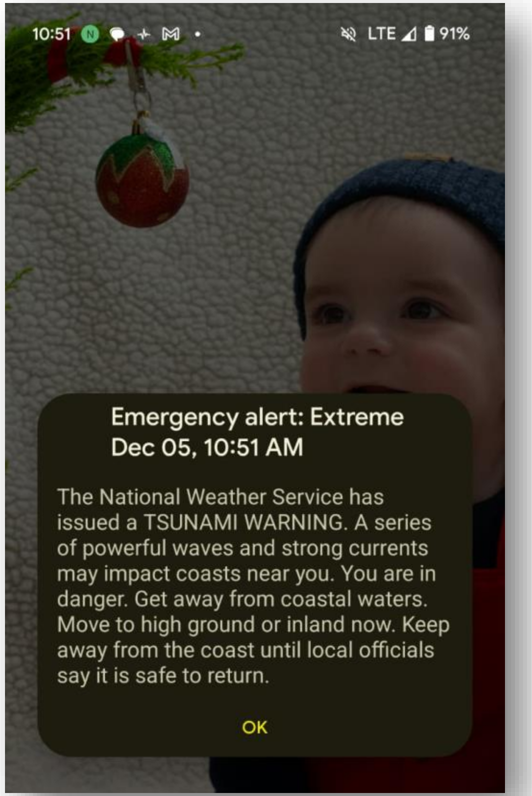
Even in cases where we miss some features, we still largely recover where the tsunami is- and is not- above warning thresholds and at a finer spatial scale than current alerts

Williamson et al., 2020

Tsunami Generation to Real Time Alerts

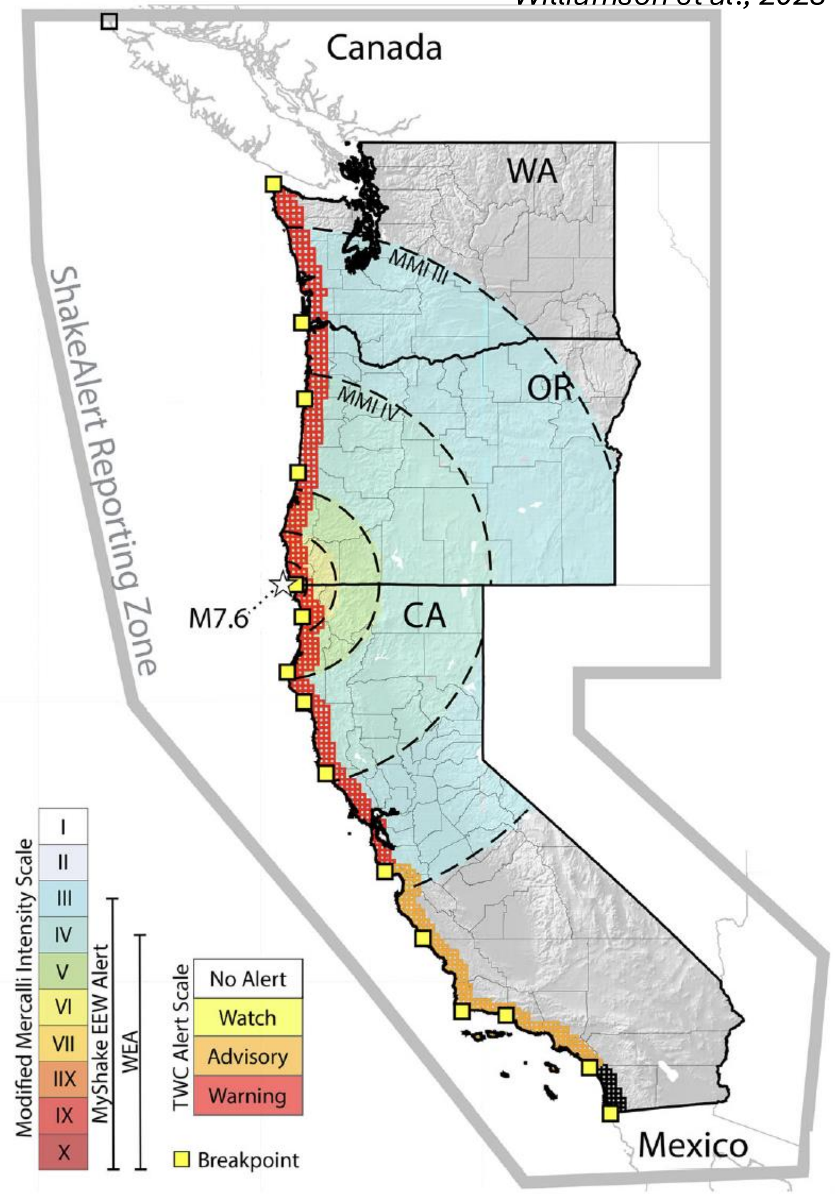
With high-resolution tsunami forecasts, affected communities can be alerted over a finer scale than the current breakpoint/segment system

For Pacific NW earthquakes, multiple agencies monitor and provide alerts to affected communities, but through multiple platforms over different messaging schedules

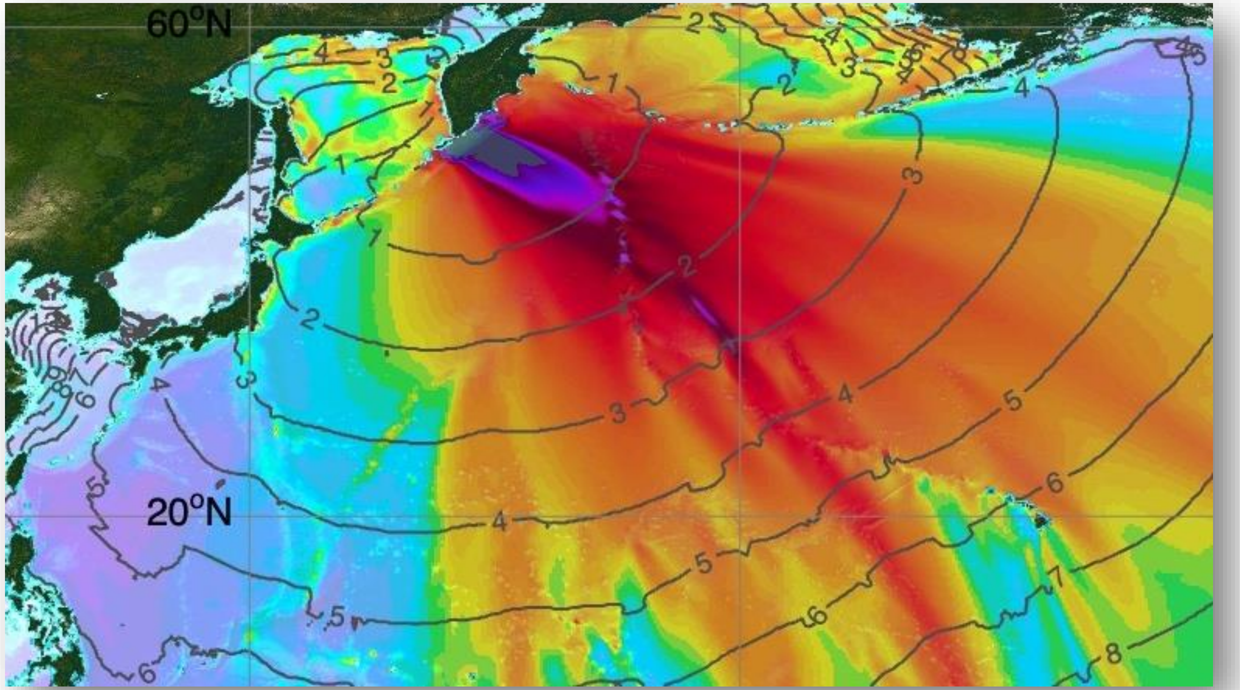


Left: alerts from the Dec, 2024 M7.0 Mendocino event

Williamson et al., 2023



Outlook



2025 Kamchatka tsunami highlights the data, model, and expertise needed to generate a successful alert.

We can continue to improve warnings for both near and far-field communities by transitioning tsunami research into operations, leveraging advances in computational power and data availability

In the first few minutes, we can generate distributed slip estimates using data already available via EEW programs. These can refine which coastlines do and do not need alerting.

In the following hours, additional features, like rupture direction and duration can be modeled against tide and offshore gauges, further refining warnings for mid- to far-field coastlines.

Working across agencies during local events can also help to streamline and refine tsunami and earthquake alerts into a single messaging system