Seismic-acoustic-gravity signals in fully coupled simulations

Fabian Kutschera

June 11th, 2026

User Workshop, Training and Hackathon

10 years of ExaHyPE · 20 years of SeisSol

11./12. June 2026 - Garching (Munich)

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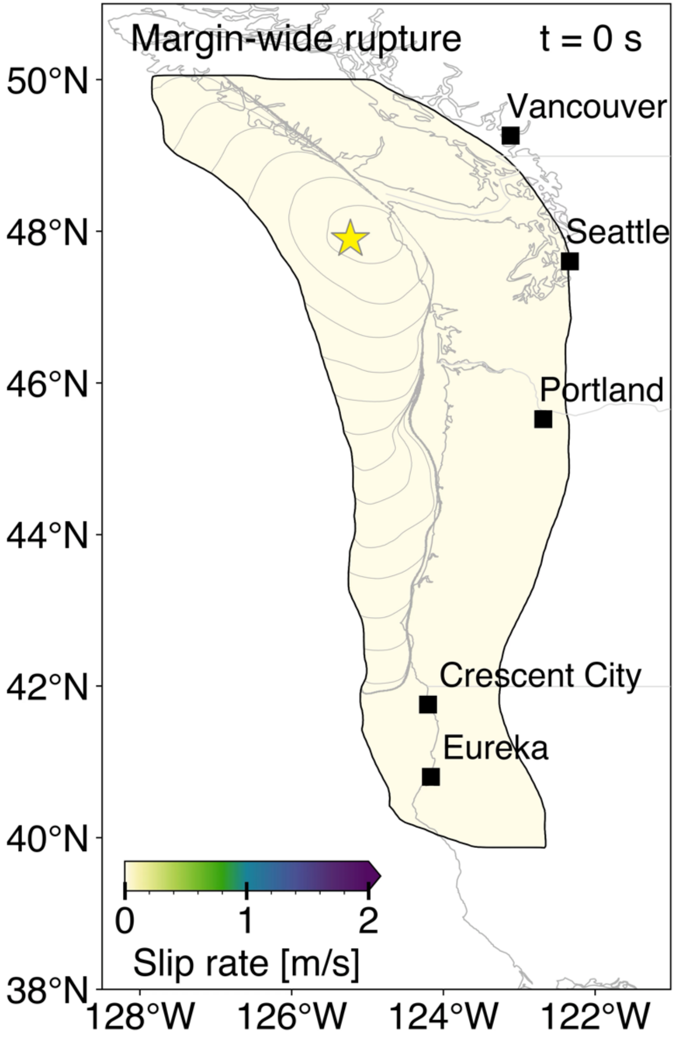
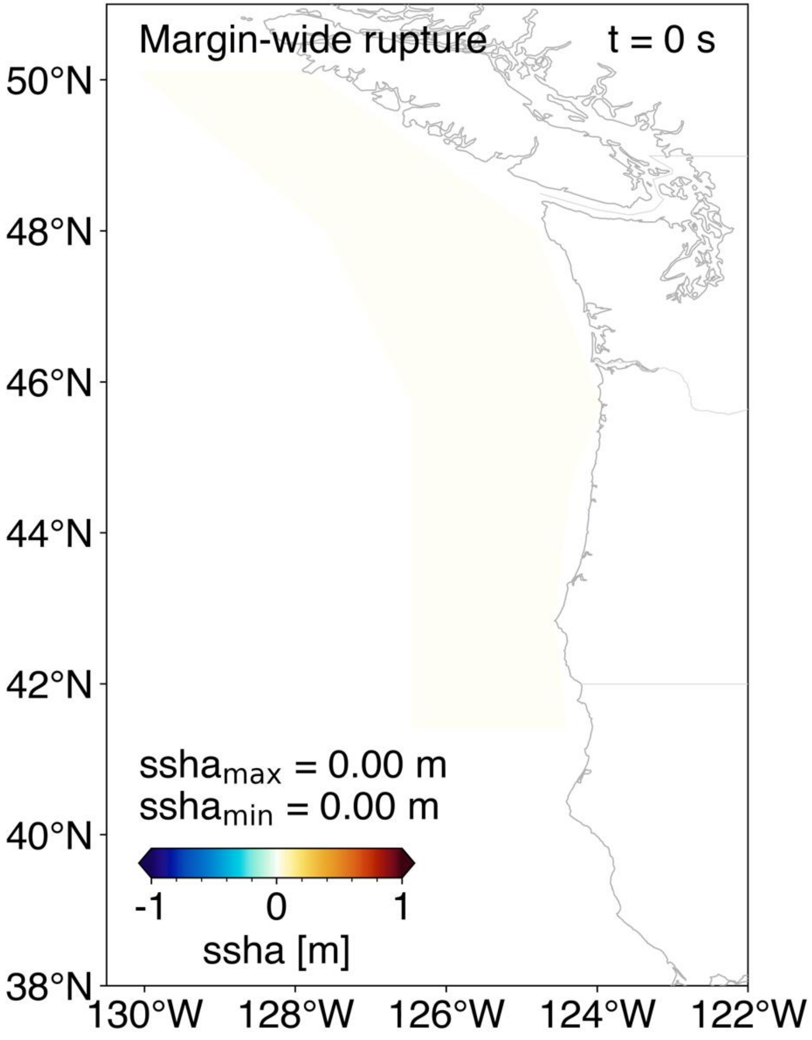
UC San Diego

U.S. National Science Foundation



Based on Glehman et al. (2025)



Henneking, Kutschera, ..., et al. (preprint, 2026)

Destructive tsunamis

- **Since 1900, 58 tsunamis have claimed more than 260,000 lives,** averaging ~4,600 deaths per event, more than any other natural hazard

- 2004 Sumatra / Indian Ocean (M_W 9.2-9.3): **~230,000 deaths across 14 countries**

- 2011 Tōhoku-Oki, Japan (M_W 9.1): **~18,000 deaths, ~$240B in damage**

The 2011 Tohoku tsunami breaching a seawall and engulfing a street in Miyako City, Iwate Prefecture, Japan. (Mainichi Shimbun / Reuters file)

Slide courtesy of Alice-Agnes Gabriel

How can we mitigate the impact of a potential destructive, future tsunami?

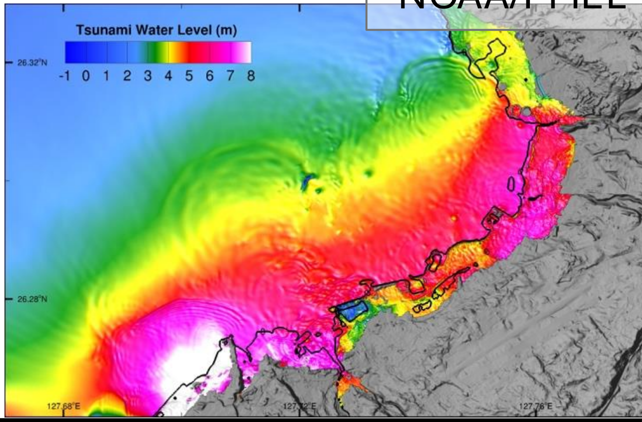
1) Awareness & Preparedness & Infrastructure

2) Early detection and real-time reporting of tsunamis in the open ocean
   - Offshore pressure observations (e.g., DART® system)

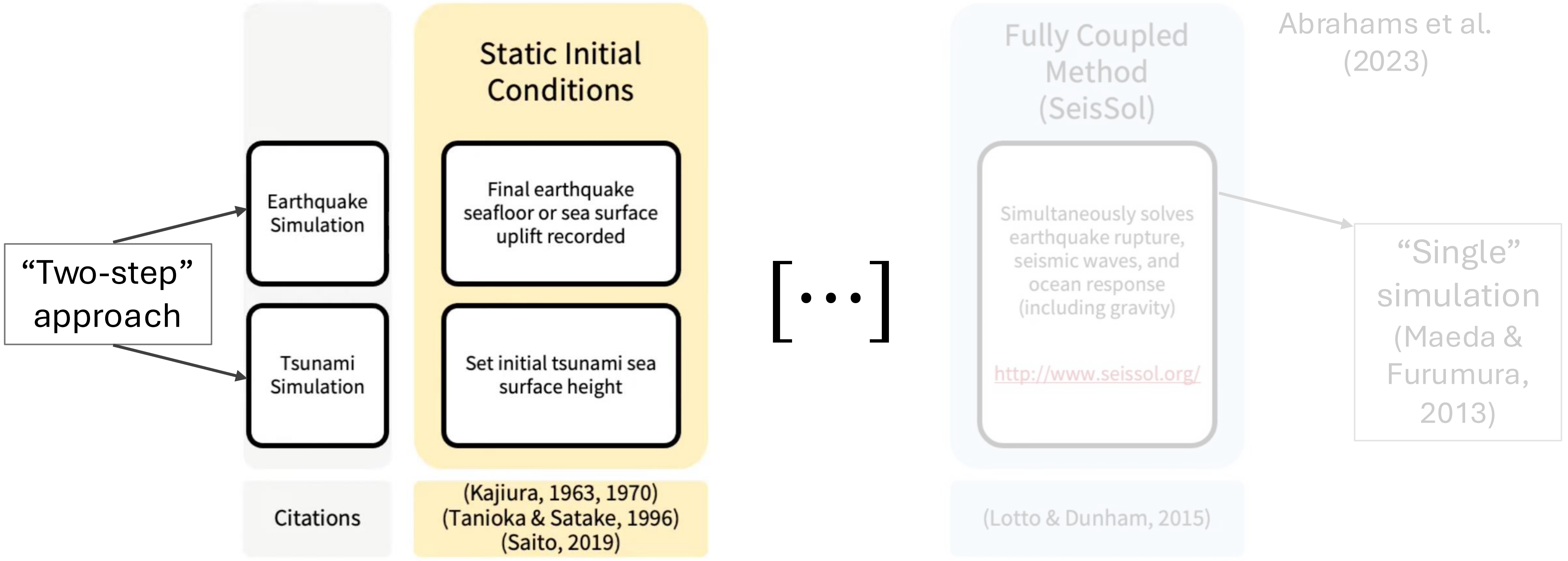
3) **Numerical modeling**
   - What governs the tsunami generation?
   - How does earthquake rupture modify the amplitude, timing, and spatial pattern of seafloor displacement?
   - Do different earthquake ruptures produce distinct seismo-acoustic signals in the water column that help to distinguish scenarios?

Fox 5, San Diego

NOAA/PMEL

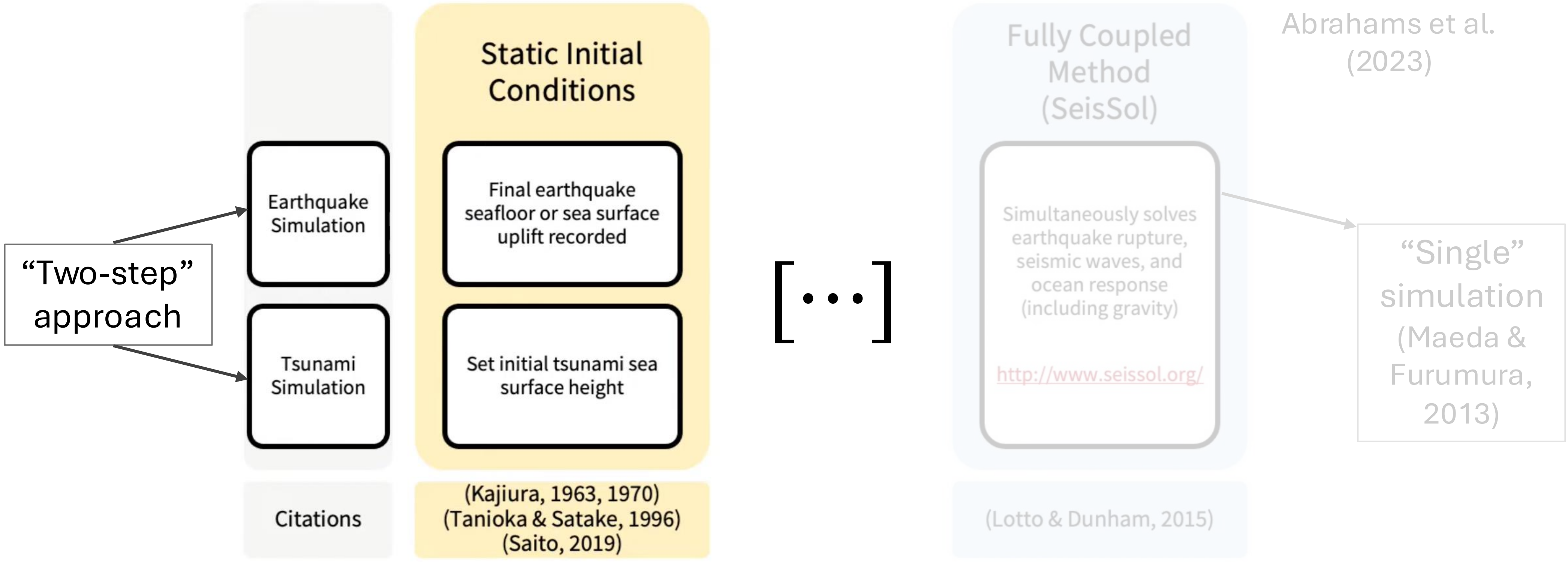


Overview of earthquake-tsunami modeling techniques

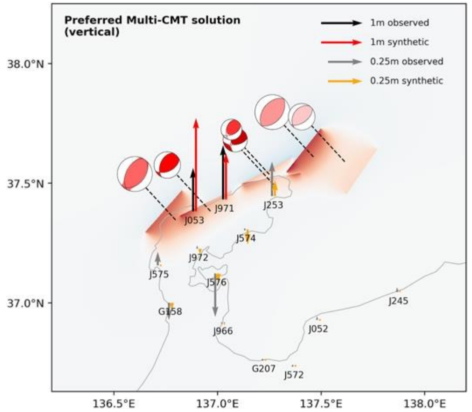


- **Conventional tsunami modeling:** two-step approach and often assumes instantaneous sourcing based on elastic dislocation theory (Okada, 1985)

Overview of earthquake-tsunami modeling techniques

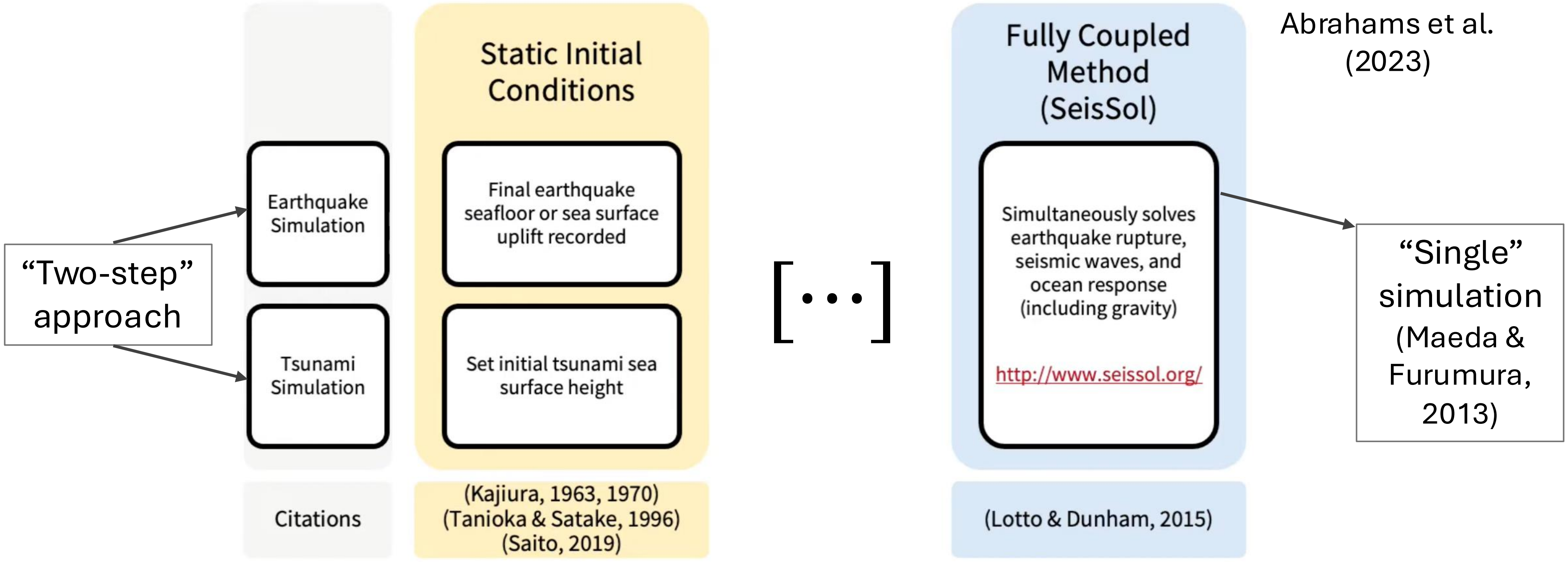


- **Conventional tsunami modeling:** two-step approach and often assumes instantaneous sourcing based on elastic dislocation theory (Okada, 1985) → The multi-segment complexity of the 2024 M_W 7.5 Noto Peninsula earthquake governs tsunami generation



Kutschera et al. (2024)

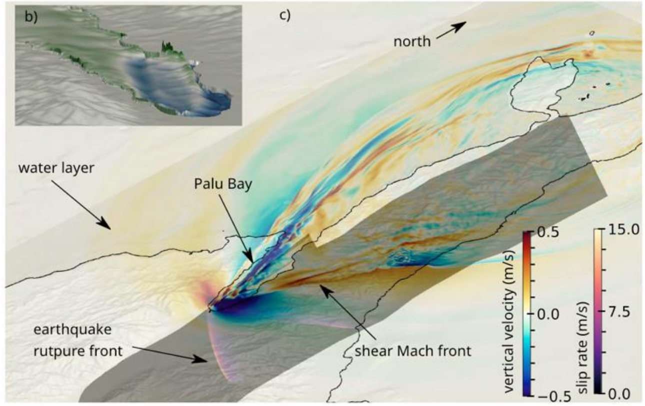
Overview of earthquake-tsunami modeling techniques



Abrahams et al. (2023)

- **Conventional tsunami modeling:** two-step approach and often assumes instantaneous sourcing based on elastic dislocation theory (Okada, 1985)

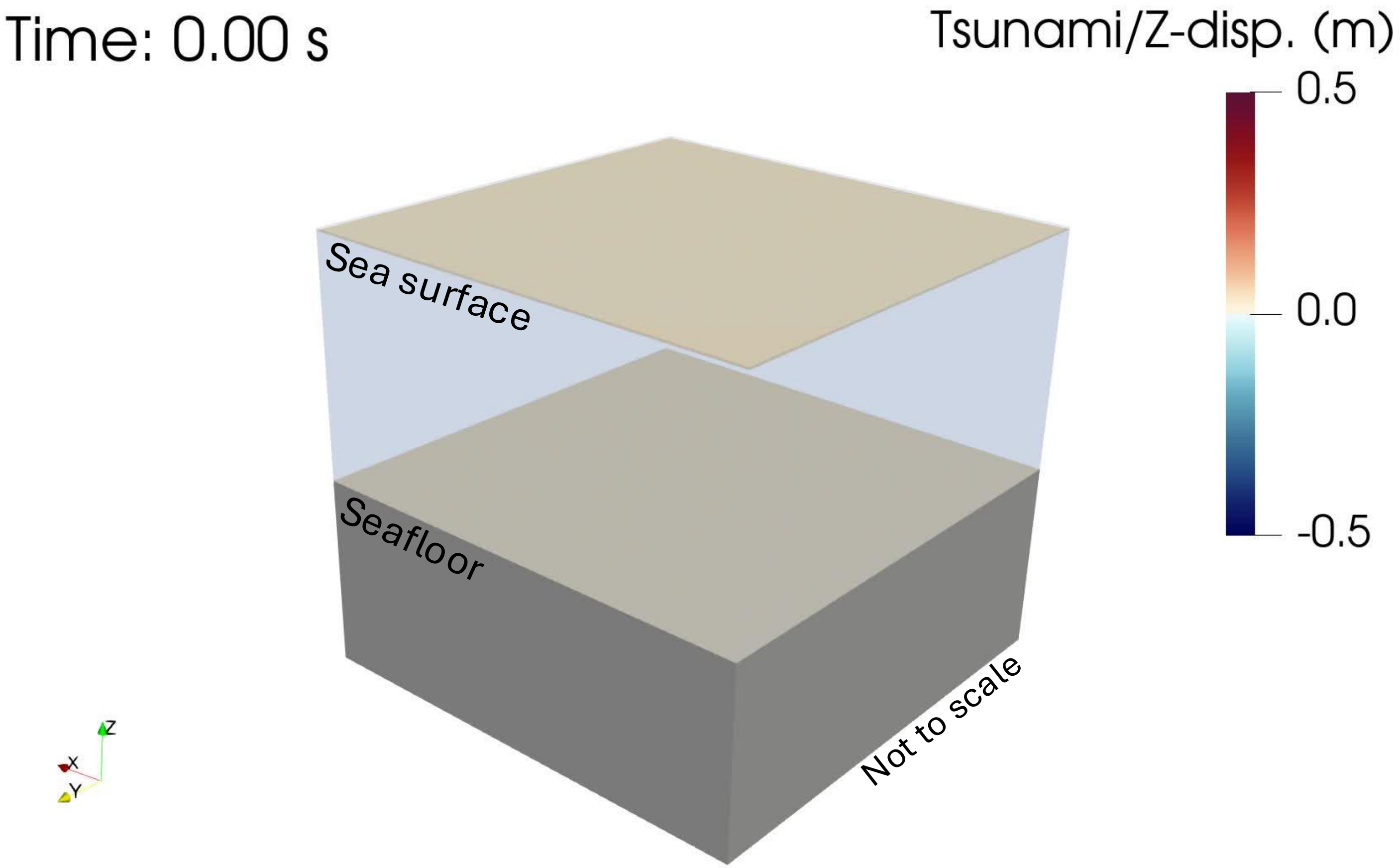
- **Fully coupled:** full seismic, oceanic acoustic, and surface gravity wavefield all at once (in 3D)



Krenz et al. (2021)

3D fully coupled earthquake dynamic rupture and tsunami benchmarks with varying bathymetric complexity

The Tsunami Problem Version 1 (TTPV1)



→ Capture 3D elastic, acoustic, and tsunami waves, including dispersion effects, **simultaneously**

In collaboration with Alice-Agnes Gabriel, Eric M Dunham, Ruth Harris, Michael Barall, Loïc Bachelot, Shuo Ma, David Schneller, Wenqiang Zhang

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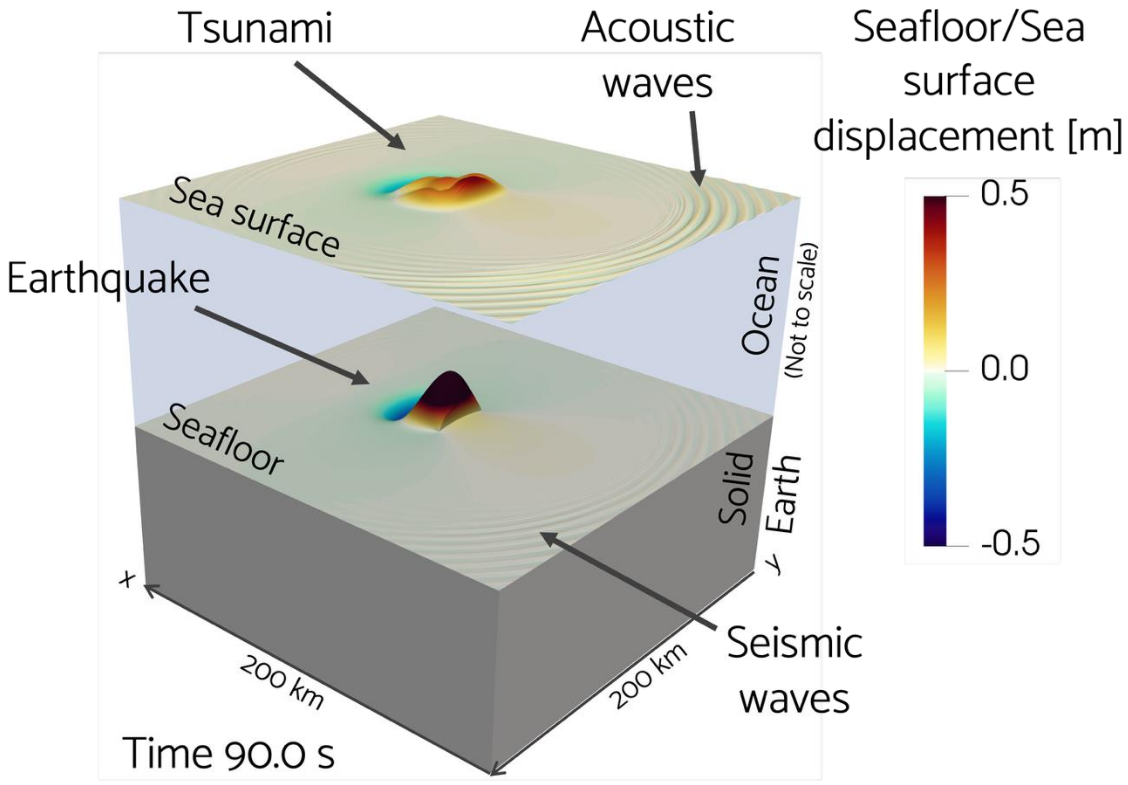

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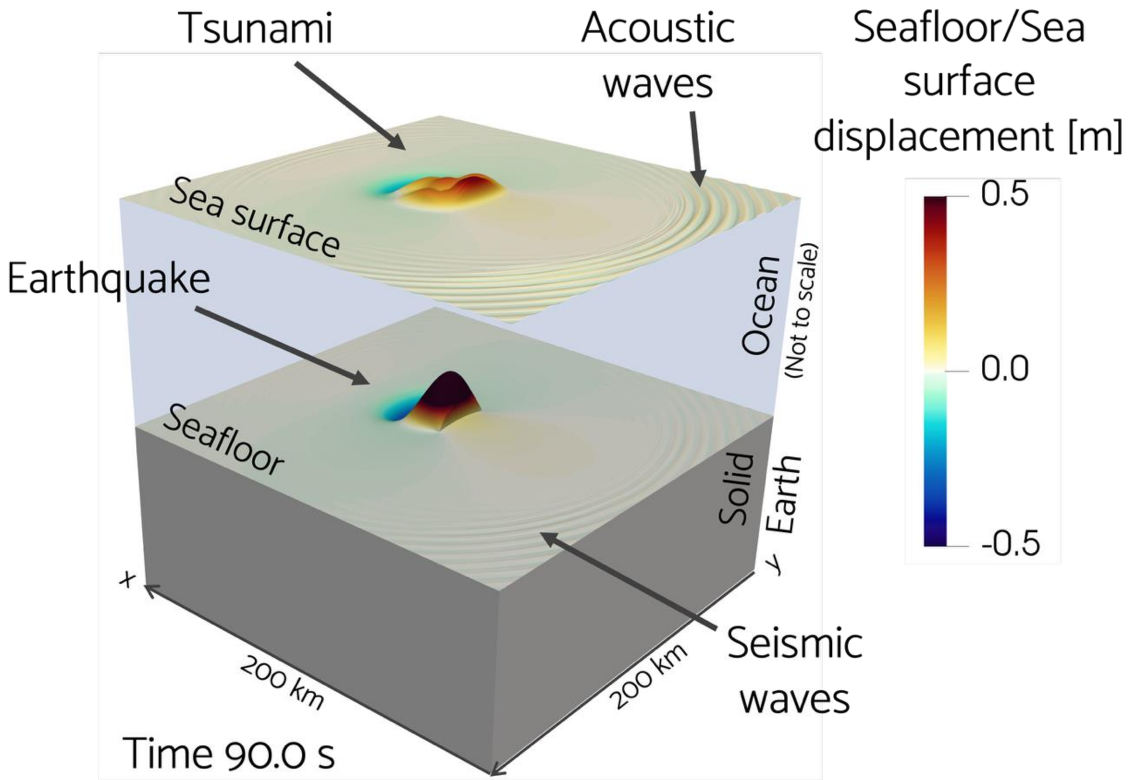

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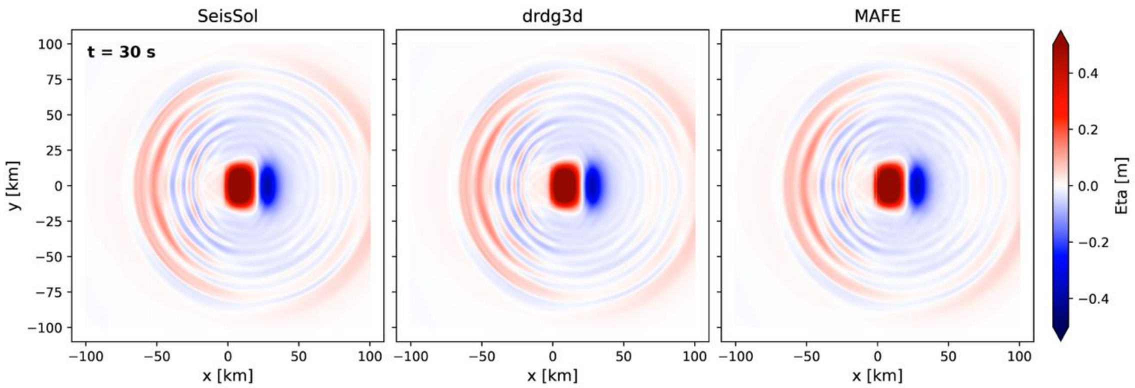
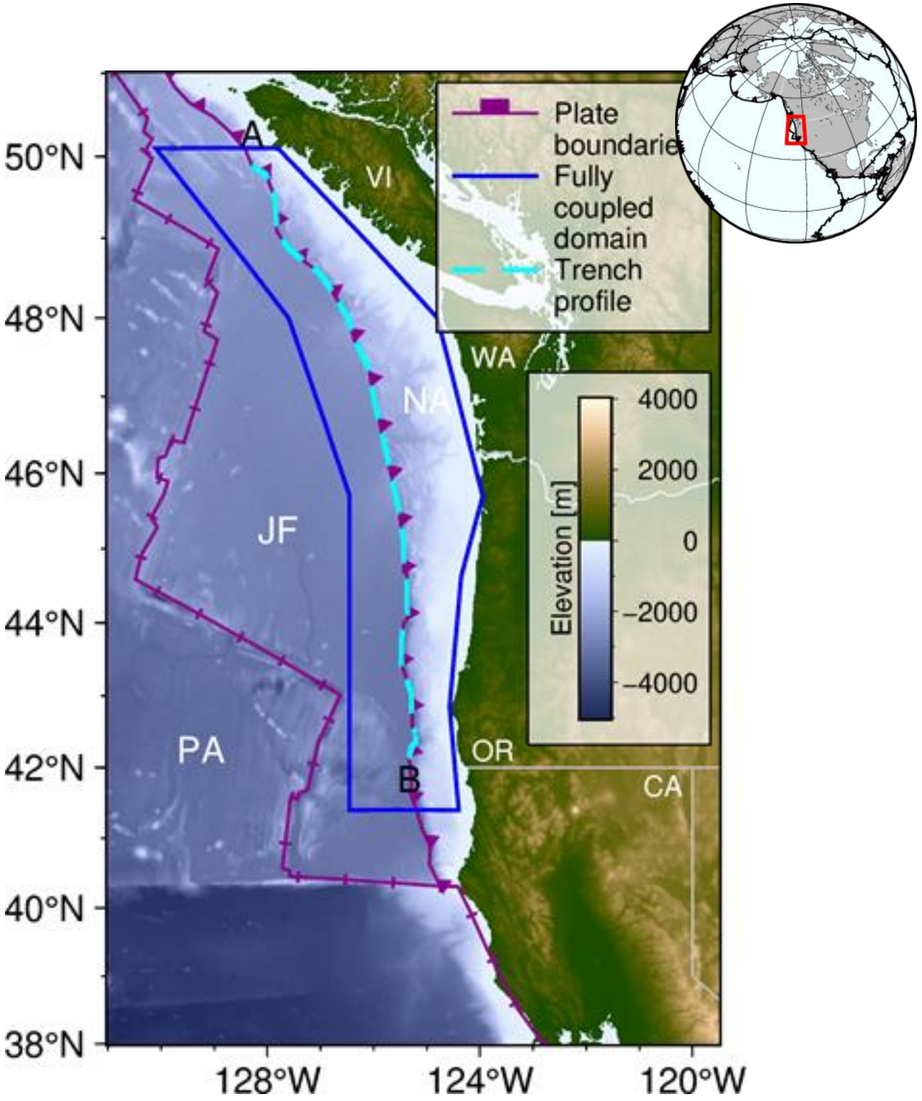


→ **3 codes were verified in 2 benchmarks** to model 3D fully coupled earthquake dynamic rupture and tsunami generation

In collaboration with Alice-Agnes Gabriel, Eric M Dunham, Ruth Harris, Michael Barall, Loïc Bachelot, Shuo Ma, David Schneller, Wenqiang Zhang

Fully coupled Cascadia Subduction Zone (CSZ) dynamic rupture-tsunami models

In collaboration with Stefan Henneking, Sreeram Venkat, Alice-Agnes Gabriel, Omar Ghattas

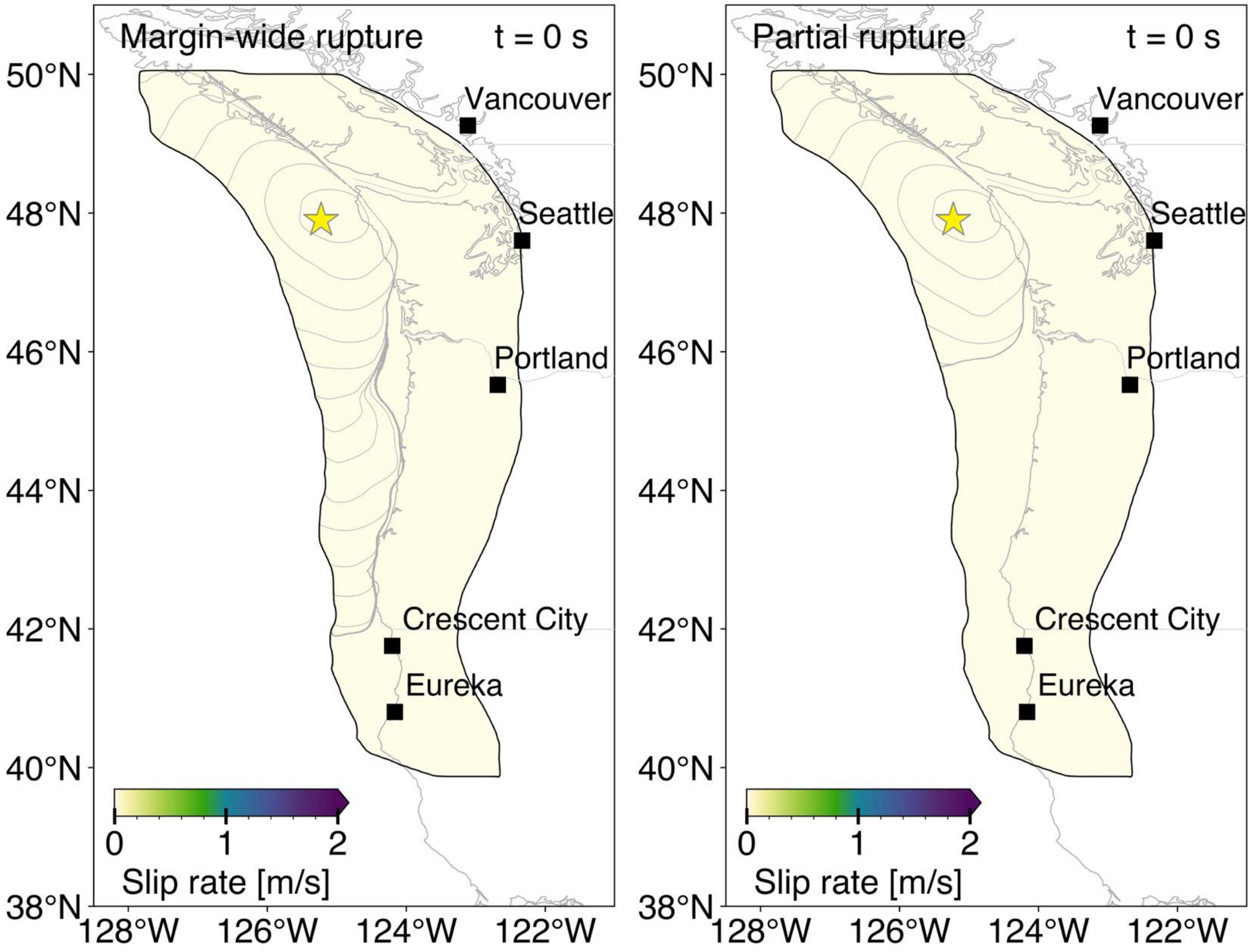


Coastal ghost forest due to subsidence of the 1700 Cascadia earthquake

- Rupture extent of past and future Cascadia earthquakes remains uncertain (Walton et al., 2021; Melgar, 2021; Ramos et al., 2021; Small et al., 2025; Goldfinger et al., 2025; DeSanto et al., 2025)

- Using a fully-coupled earthquake–tsunami model, we simulate two realistic earthquake scenarios based on Glehman et al. (2025):
  - A smaller, **partial rupture** and a larger, **margin-wide rupture**

Nucleation as crack-like ruptures that evolve into bilateral, sub-Rayleigh, pulse-like ruptures



- Similar rupture dynamics until the respective southward rupture front reaches the central CSZ (near 46°N)
- The northward rupture fronts in both scenarios terminate abruptly at the northern end of the megathrust

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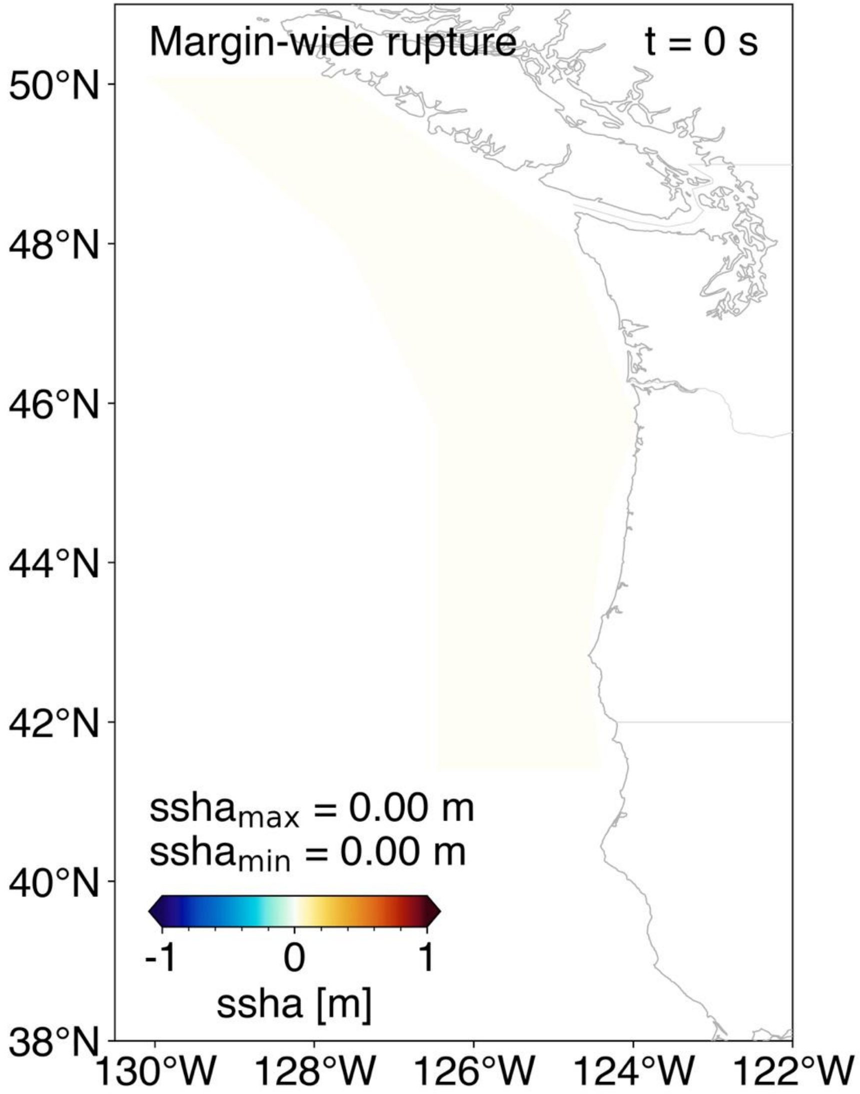
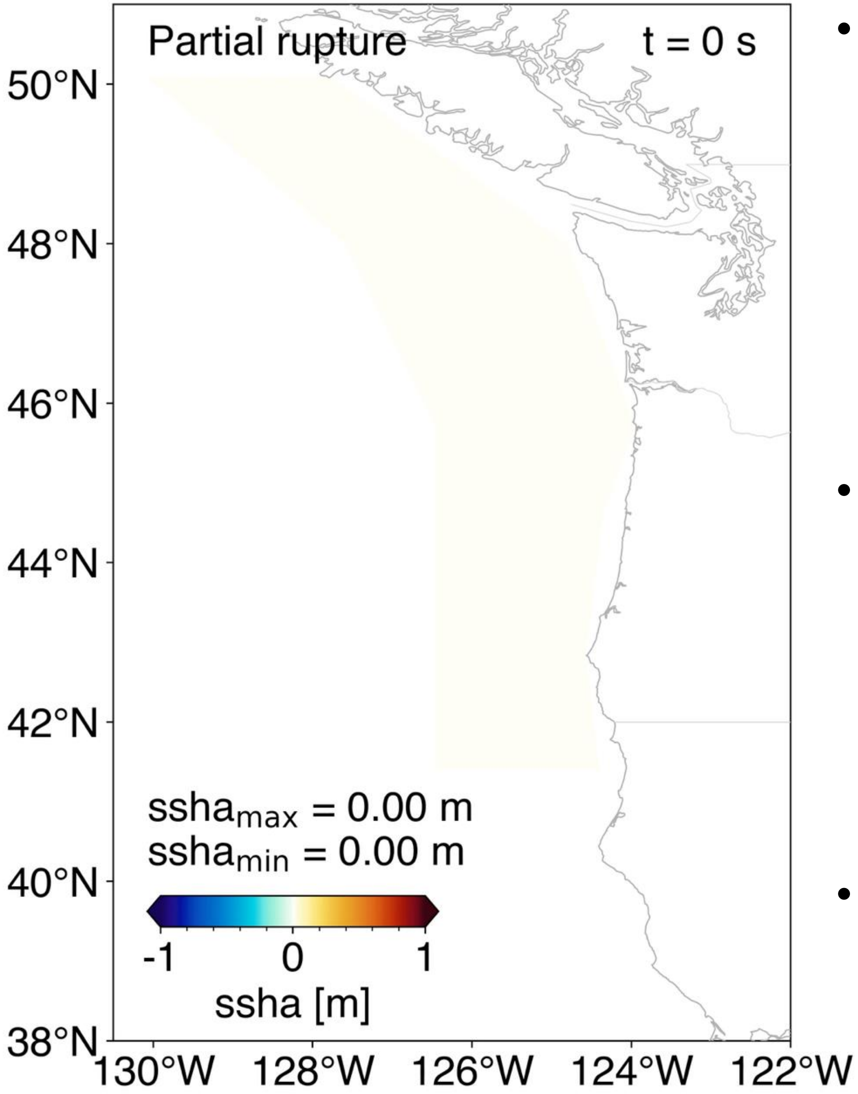
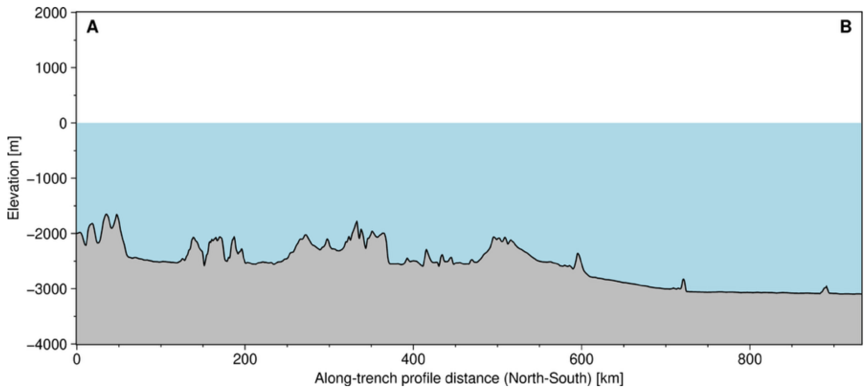
Early acoustic and tsunami response mirrors the initially similar dynamic rupture evolution

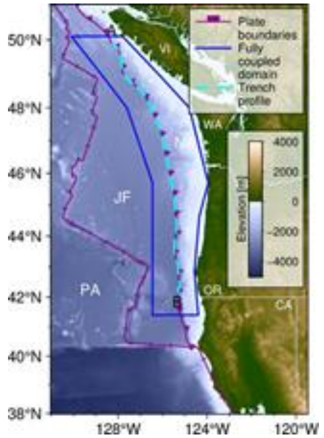




- Physically consistent representation of the evolving seafloor motion during rupture and the energy transfer to the water column
- Peak tsunami amplitudes reach ~4 m and ~2.9 m for the margin-wide and partial rupture scenario
- Wavefields diverge once the partial rupture arrests

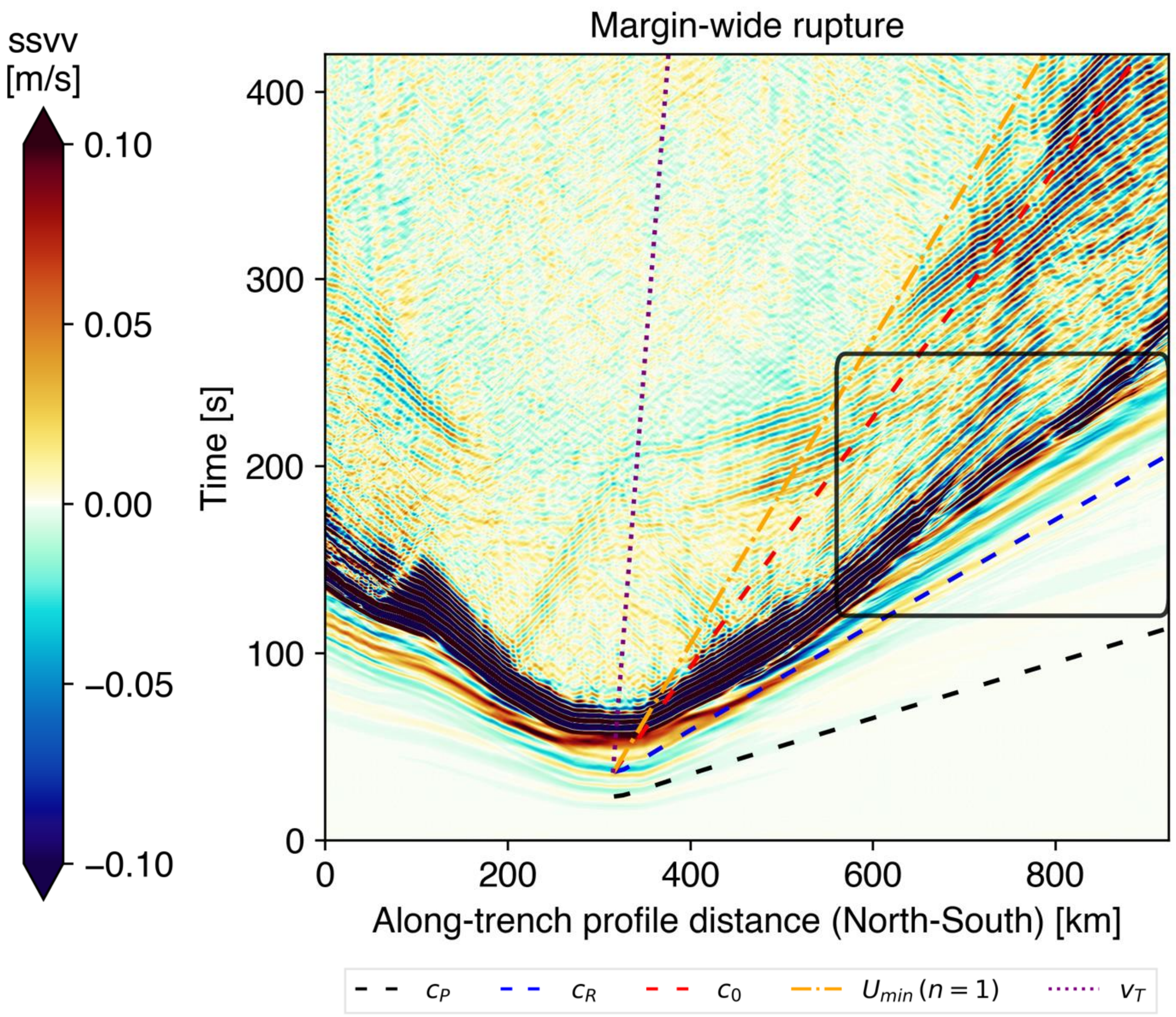
Modeled ocean wavefield contains multiple seismo-acoustic phases in addition to long period, dispersive tsunami signal

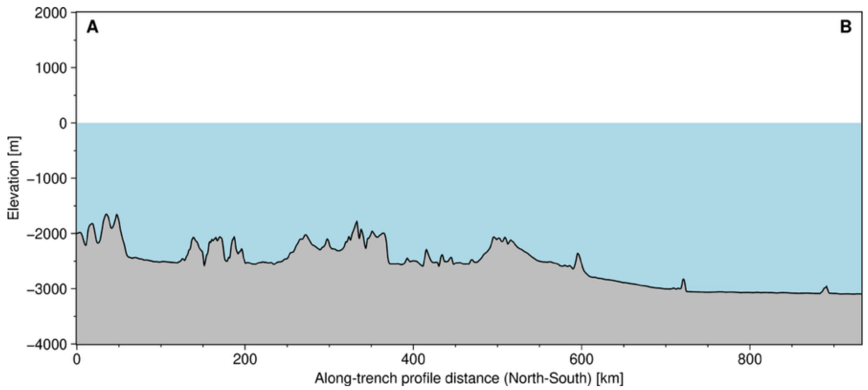


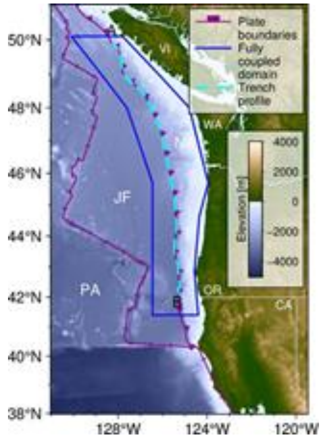


- Synthetic line of receivers at the sea surface to compare the space-time evolution of sea surface vertical velocities (ssvv)

Modeled ocean wavefield contains multiple seismo-acoustic phases in addition to long period, dispersive tsunami signal

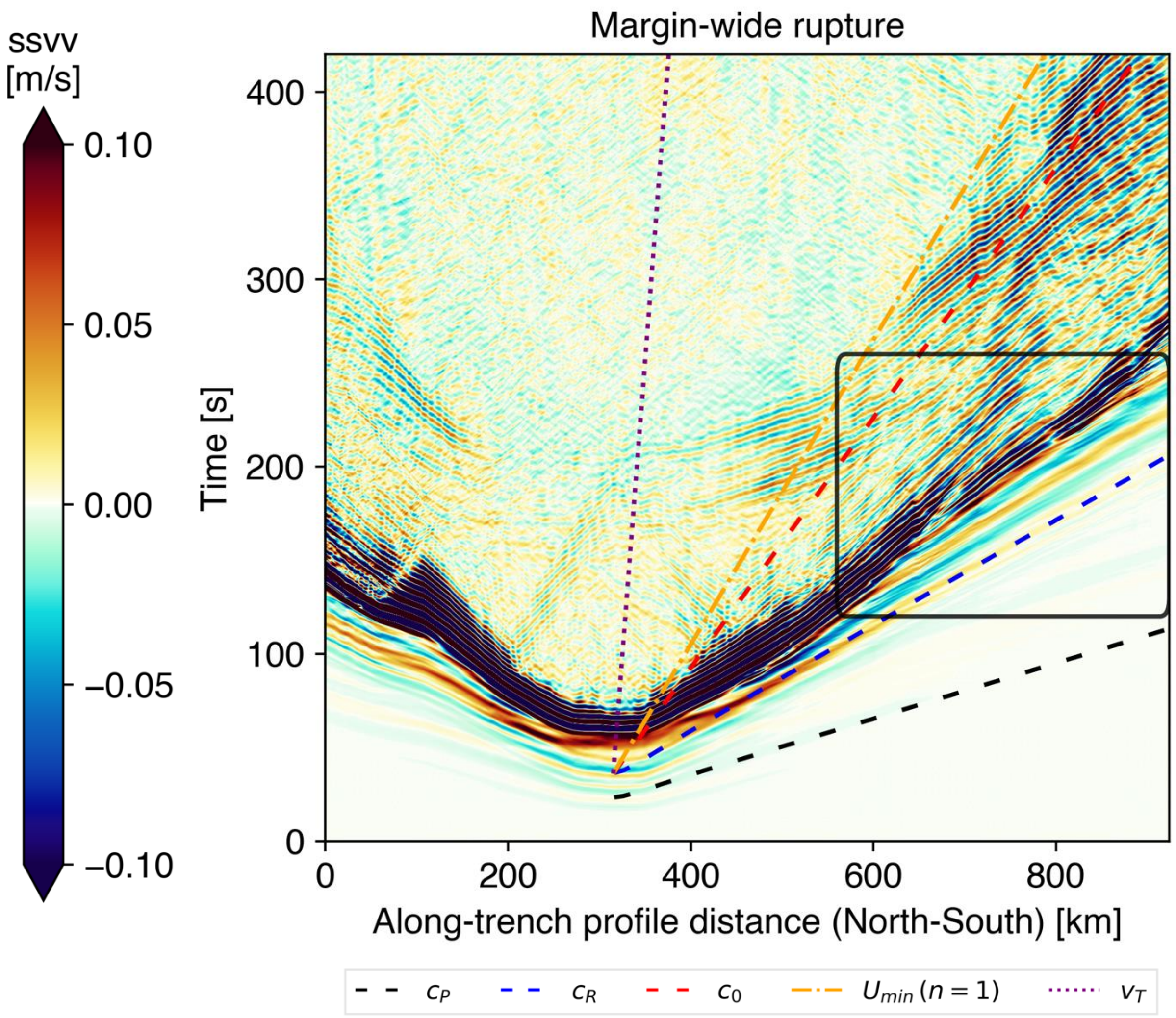


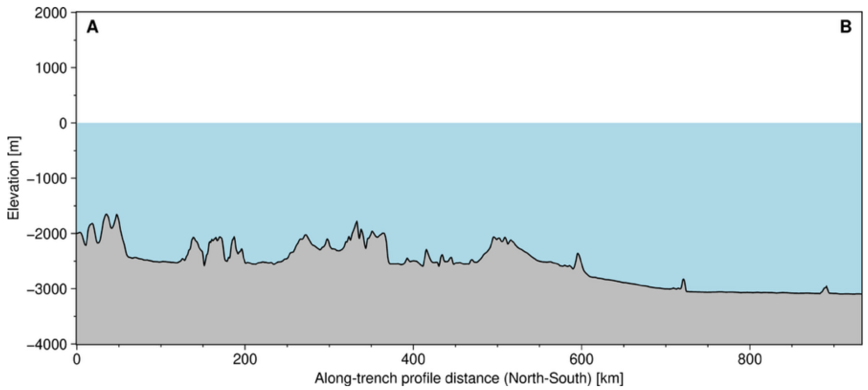


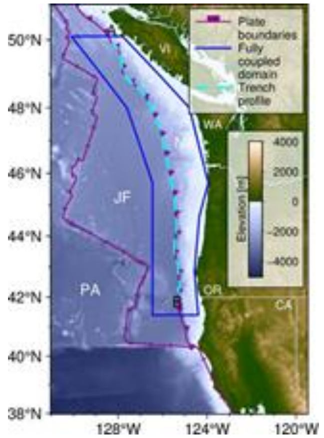


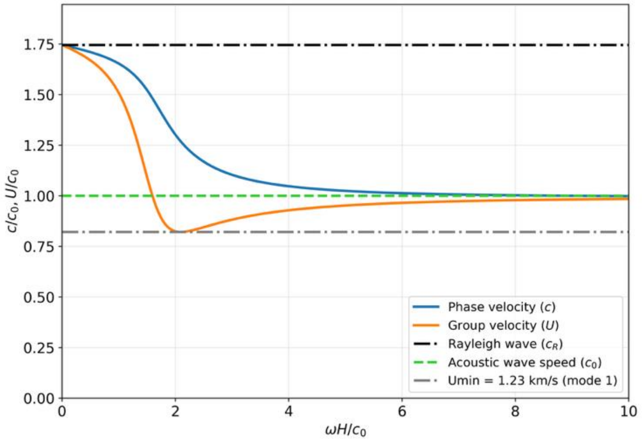
- Synthetic line of receivers at the sea surface to compare the space-time evolution of sea surface vertical velocities (ssvv)
- Seismic waves dynamically perturb the seafloor and overlying water column and thereby produce sea-surface motion preceding the developing tsunami signal

Modeled ocean wavefield contains multiple seismo-acoustic phases in addition to long period, dispersive tsunami signal





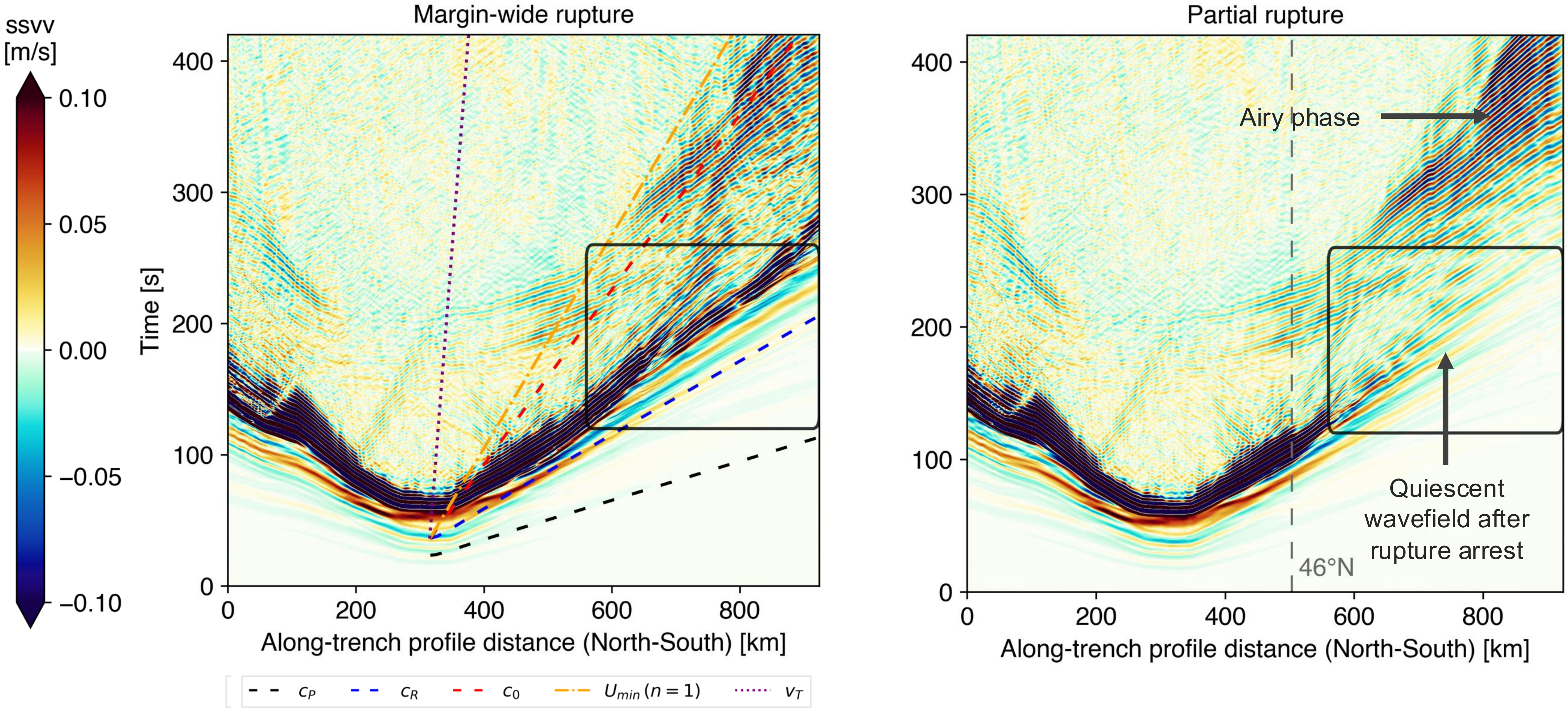




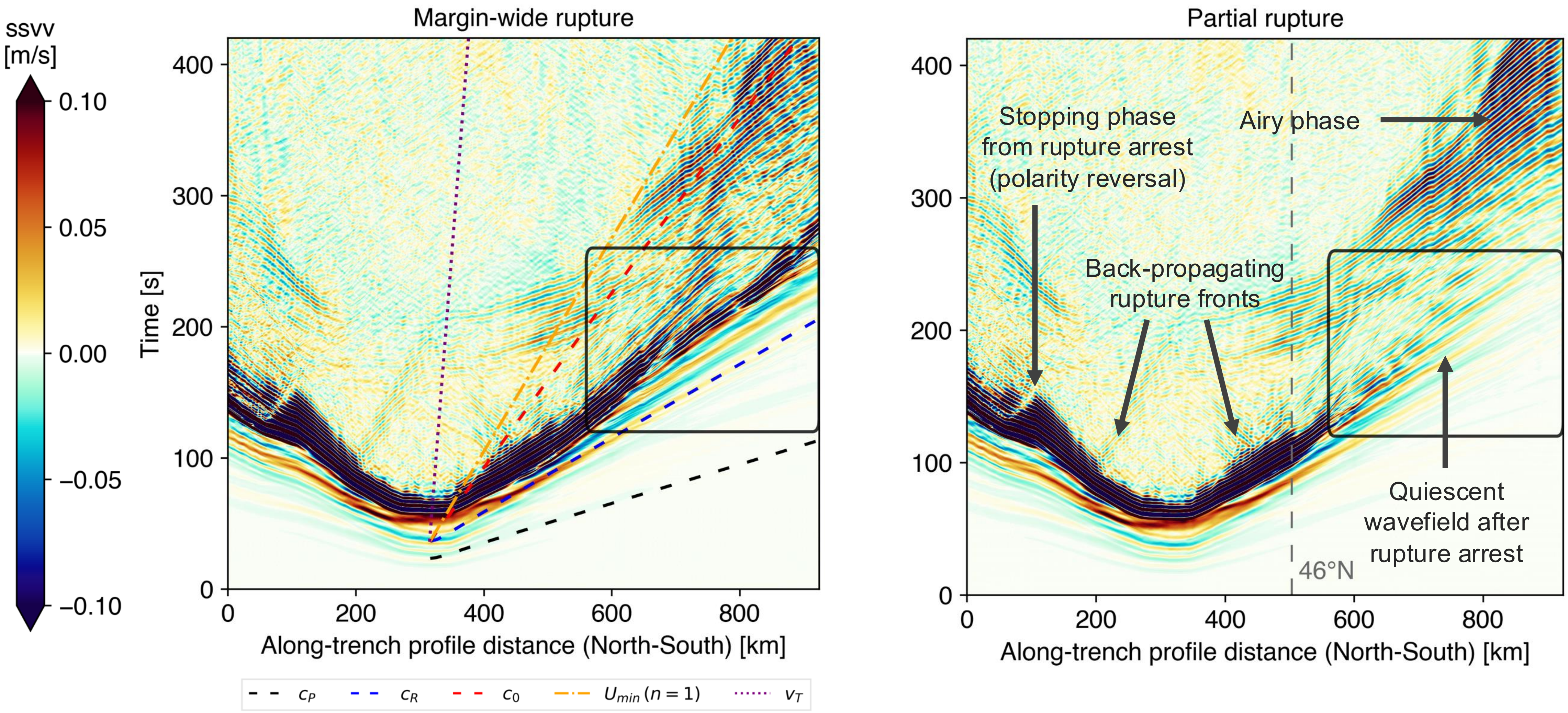
Following Abrahams et al. (2023)

- Oceanic Rayleigh waves propagate slower than solid-Earth Rayleigh waves (e.g., Noguchi et al., 2016)

Vertical sea surface velocity signals as proxy for the along-strike extent of active rupture



Dynamic rupture translates to signals observable at the sea surface



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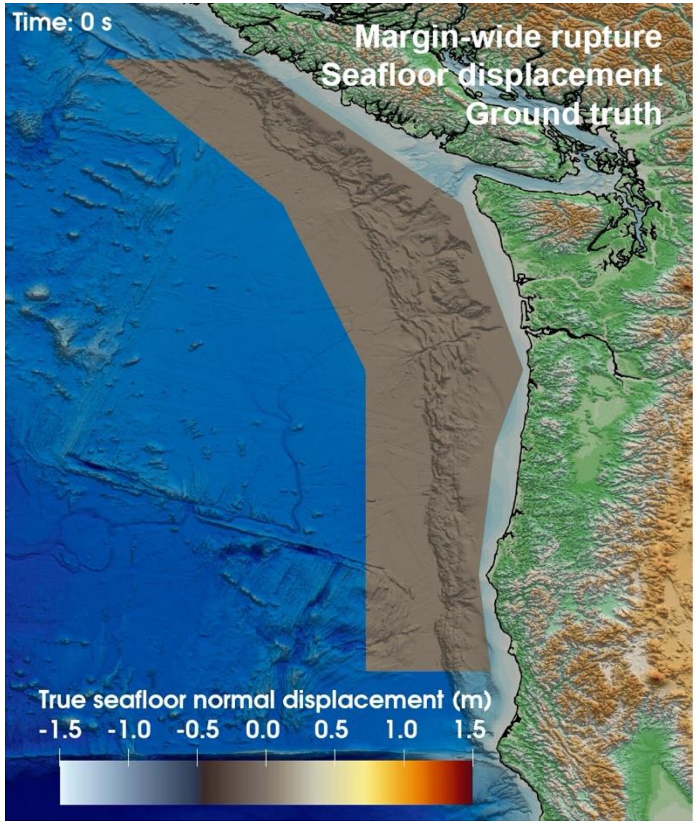
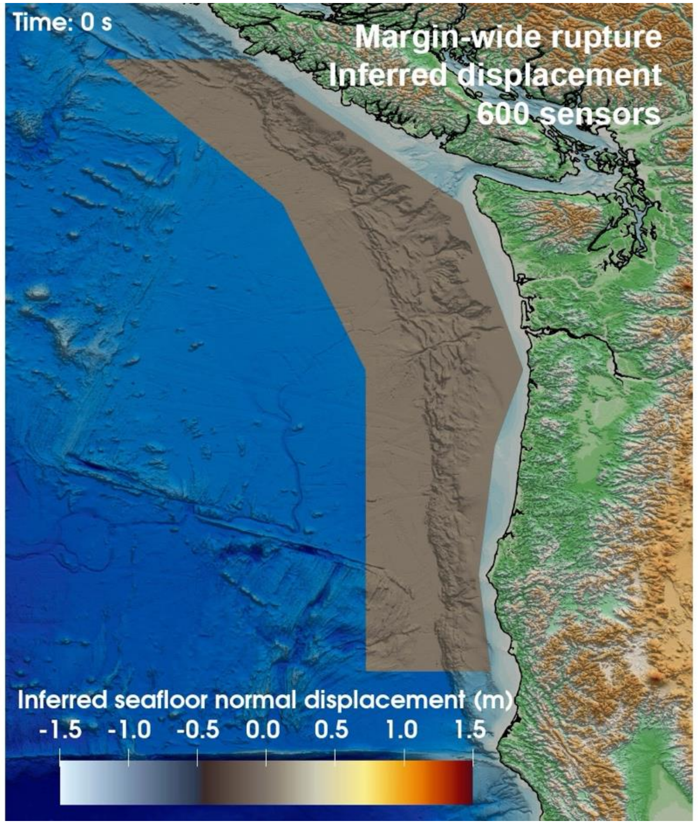
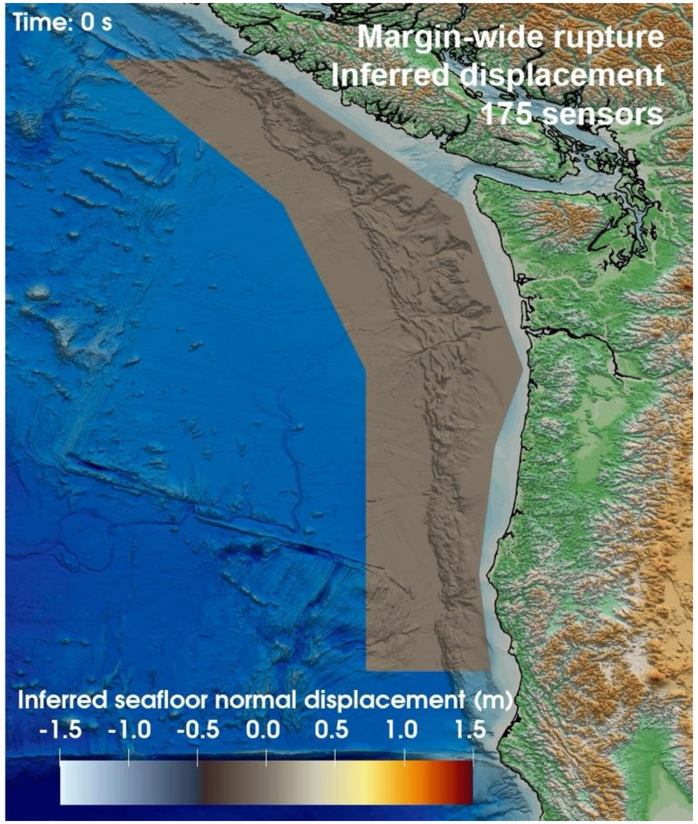
Real-time probabilistic tsunami forecasting in Cascadia from sparse offshore pressure observations

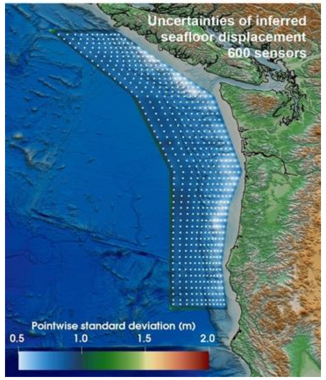
- Using an acoustic–gravity inversion with assimilation of pressure data, tsunami wave height forecasts are obtained in less than a second
- Forecast errors for sparse 175 sensor network remain low at 22.1% for the margin-wide and 19.6% for the partial rupture



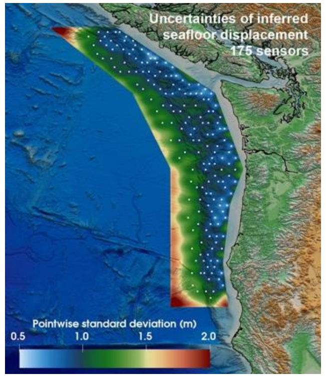




600 sensors



175 sensors



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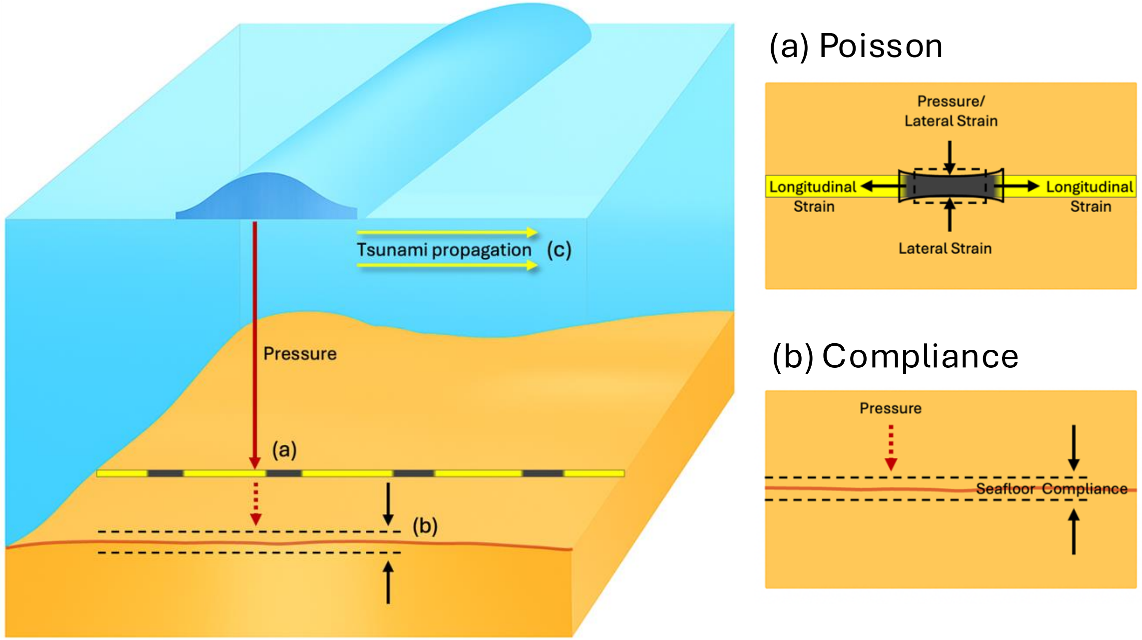
(Henneking et al., 2025, 2026)

Outlook: Submerged acoustic and gravity wave detection using DAS*

*Distributed Acoustic Sensing

Adapted from Becerril, ..., Kutschera, ..., et al., (2026)



Hydrostatic pressure:

- Poisson & compliance effect

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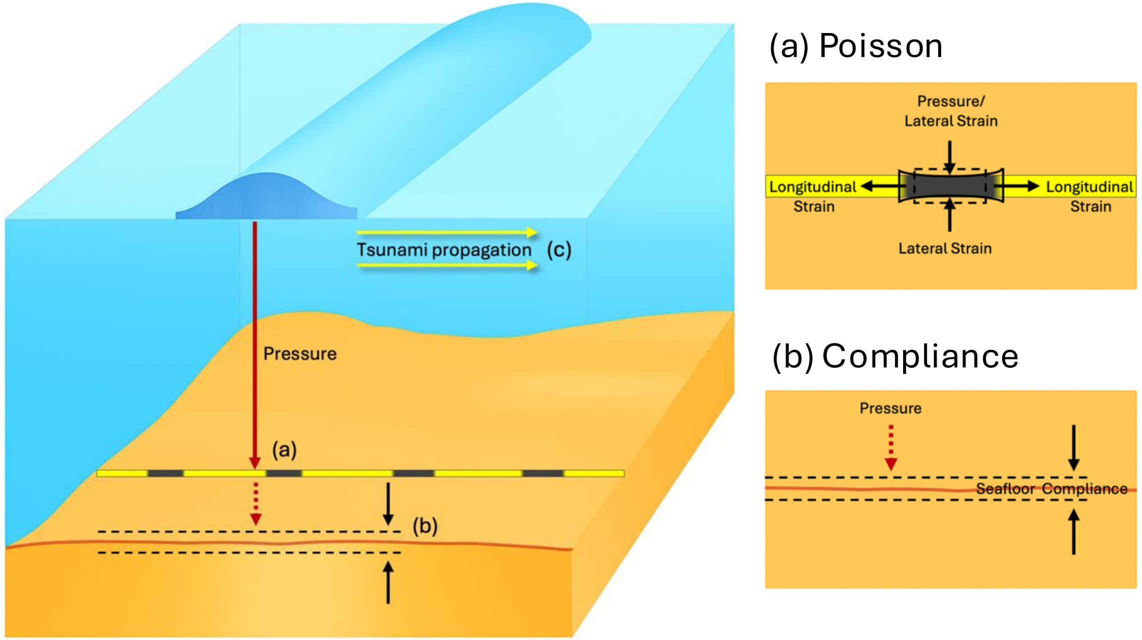
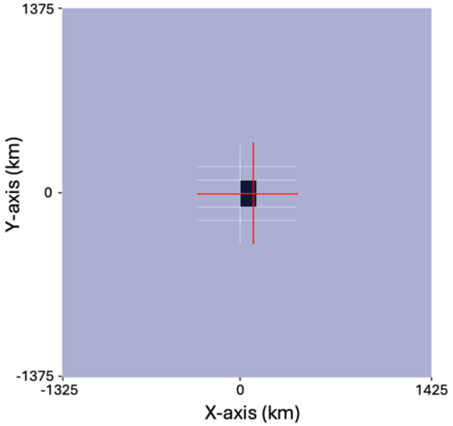
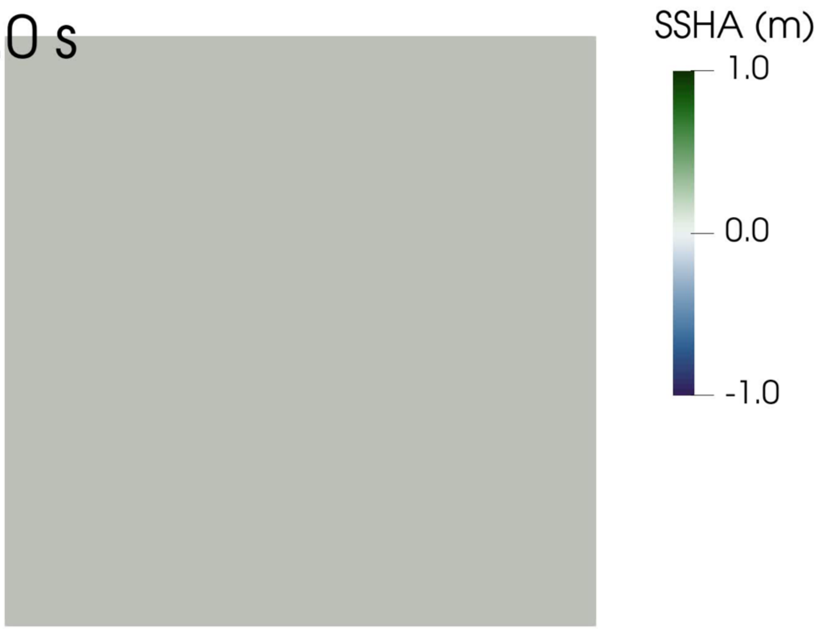




Time: 0.0 s



Hydrostatic pressure:

- Poisson & compliance effect

- Near-source DAS tsunami observation possible within a few minutes of the earthquake onset
- Successful real-world tsunami detection (e.g., Xiao et al., 2024; Tonegawa & Araki, 2024; Mazur et al., 2025)

Conclusions

Mapview

Complex dynamic rupture source effects imprint distinct signals on the sea surface wavefield.

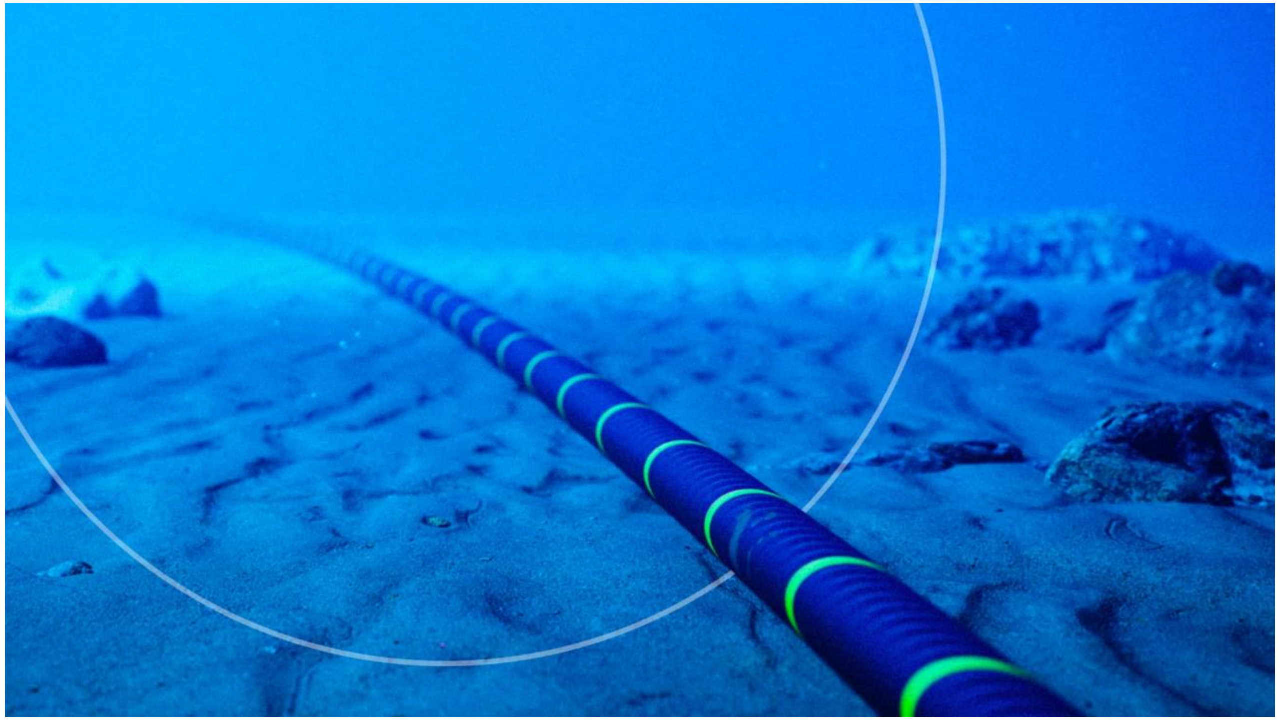
Divergence of near-field seismo-acoustic wavefields after two minutes helps distinguish partial from margin-wide Cascadia ruptures.

Real-time acoustic-gravity inversion accurately infers tsunamigenic seafloor motion from fully-coupled Cascadia dynamic rupture scenarios.

Distributed acoustic sensing (DAS) is expanding offshore observational coverage and may improve our ability to resolve tsunami characteristics.

Henneking, Kutschera, ..., et al. (preprint, 2026)

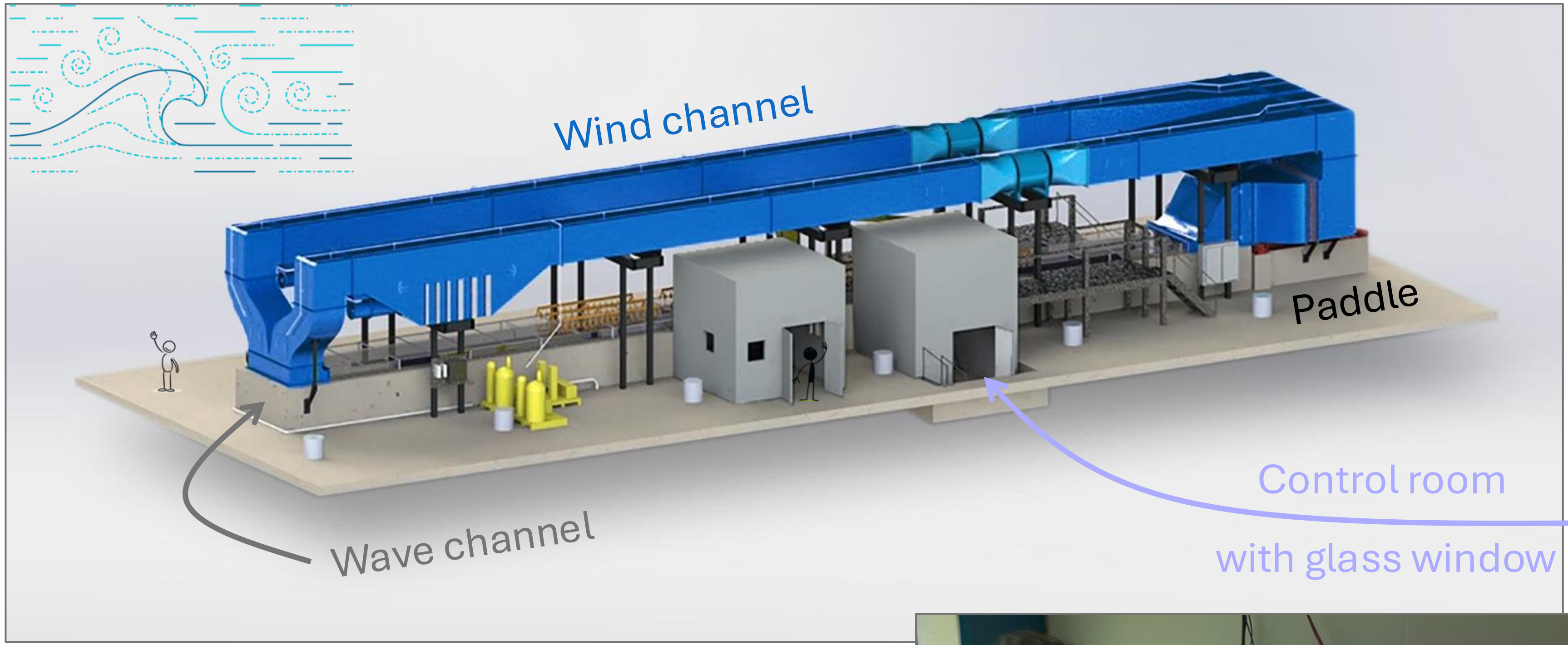
Outlook and Backup



DAS experiments in large 120 ft wave channel

with Baoning Wu, Yan Yang, Chih-Chieh Chien, Ryan Craft, Steven Constable, Mark A Zumberge, Alice-Agnes Gabriel

SOARS = Scripps Ocean-Atmosphere Research Simulator (Moore et al., 2025)

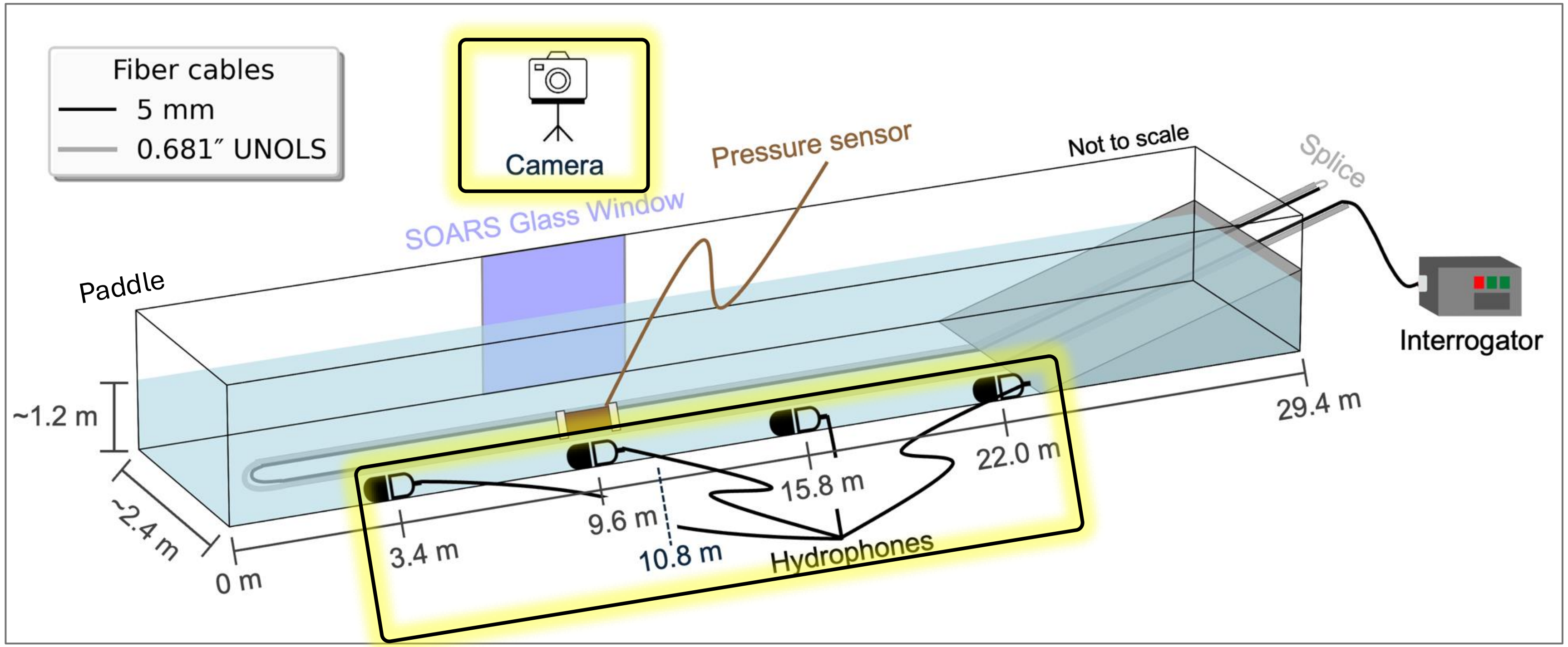


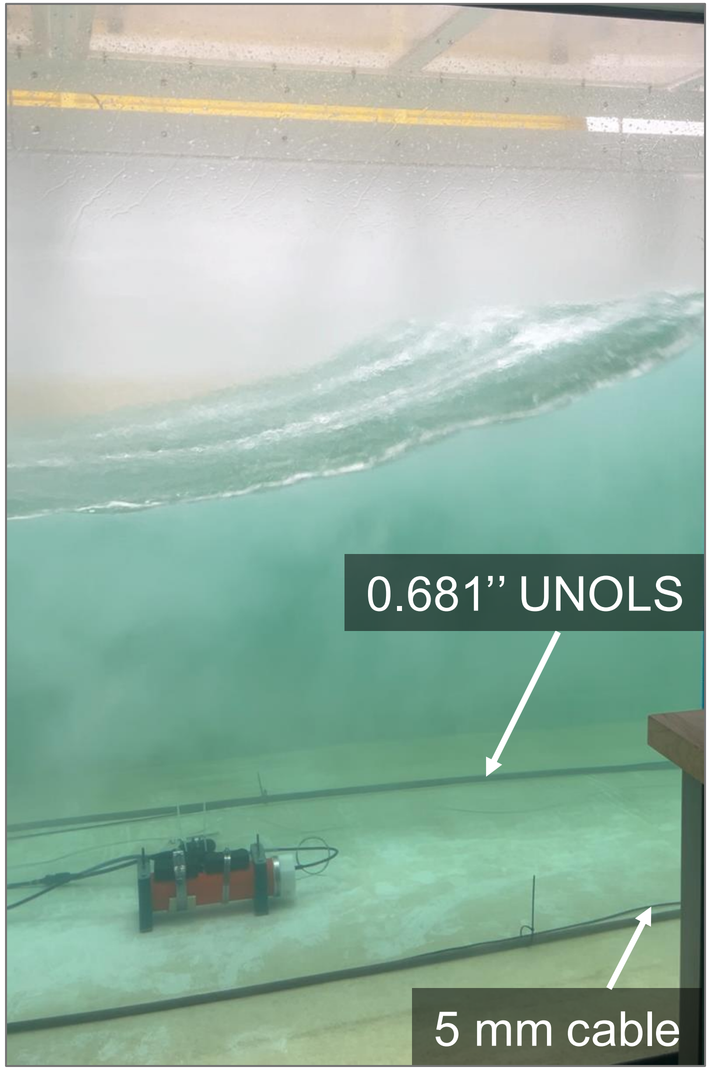
$2,500 proposal from Shepard Foundation at SIO written by Kutschera and Chien

From the control room, we can vary
1) Wave amplitude
2) Wave shape (sine vs breaking waves)
3) Absence or presence of wind

DAS experiments in large 120 ft wave channel

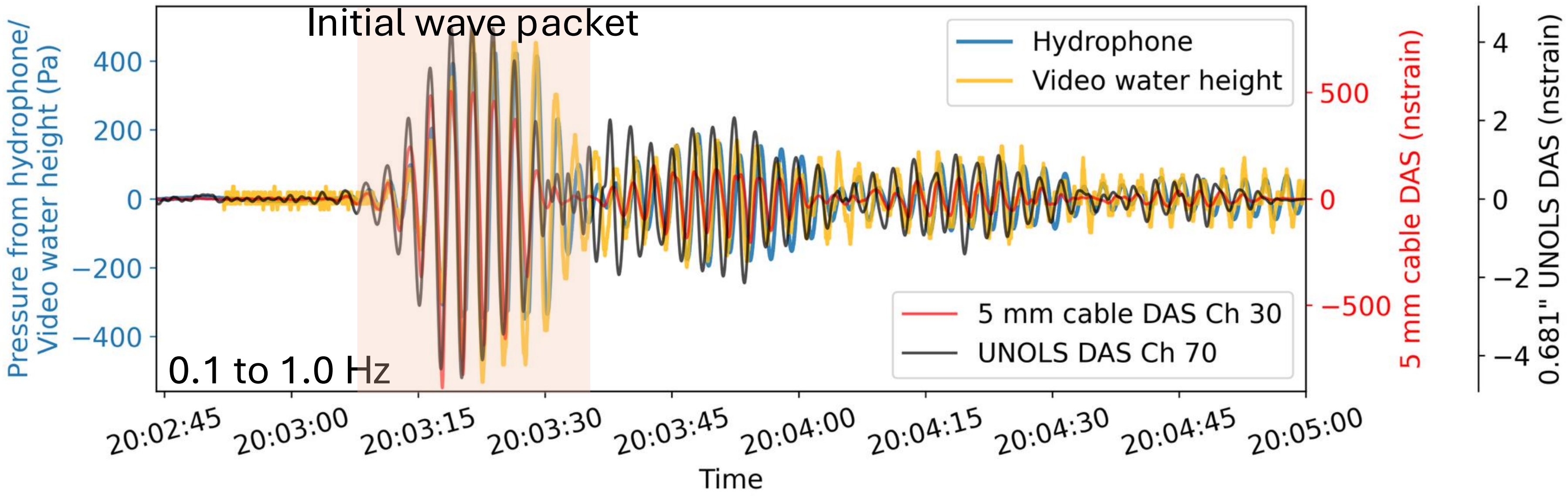
View of cable placement in **SOARS** from control room opposing side:



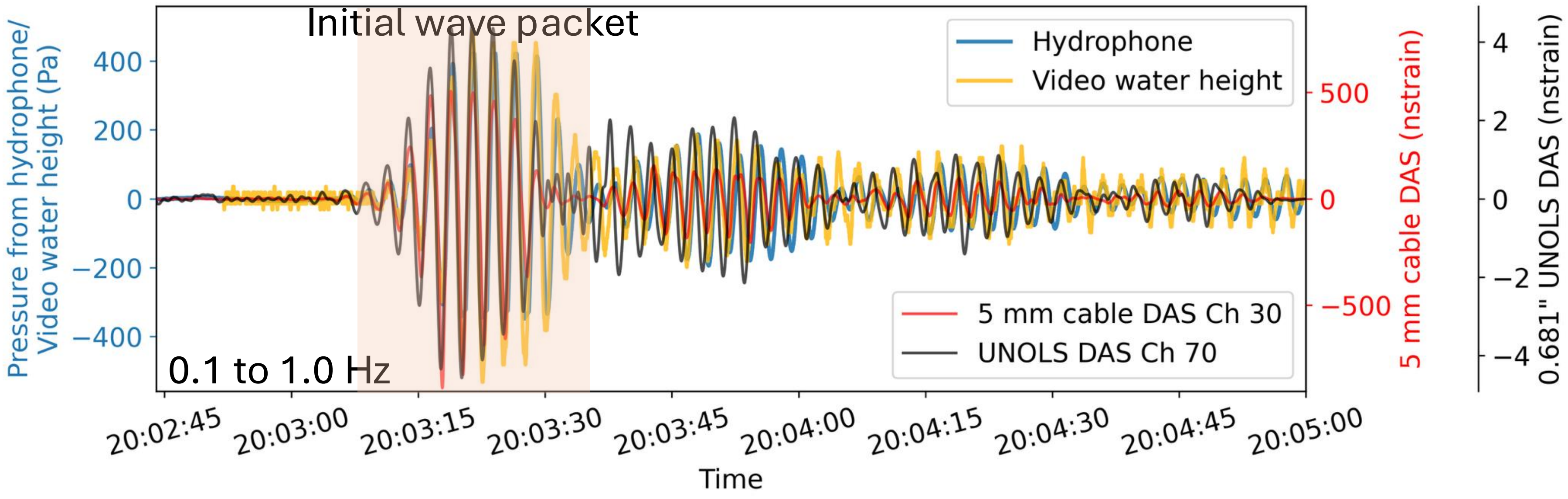


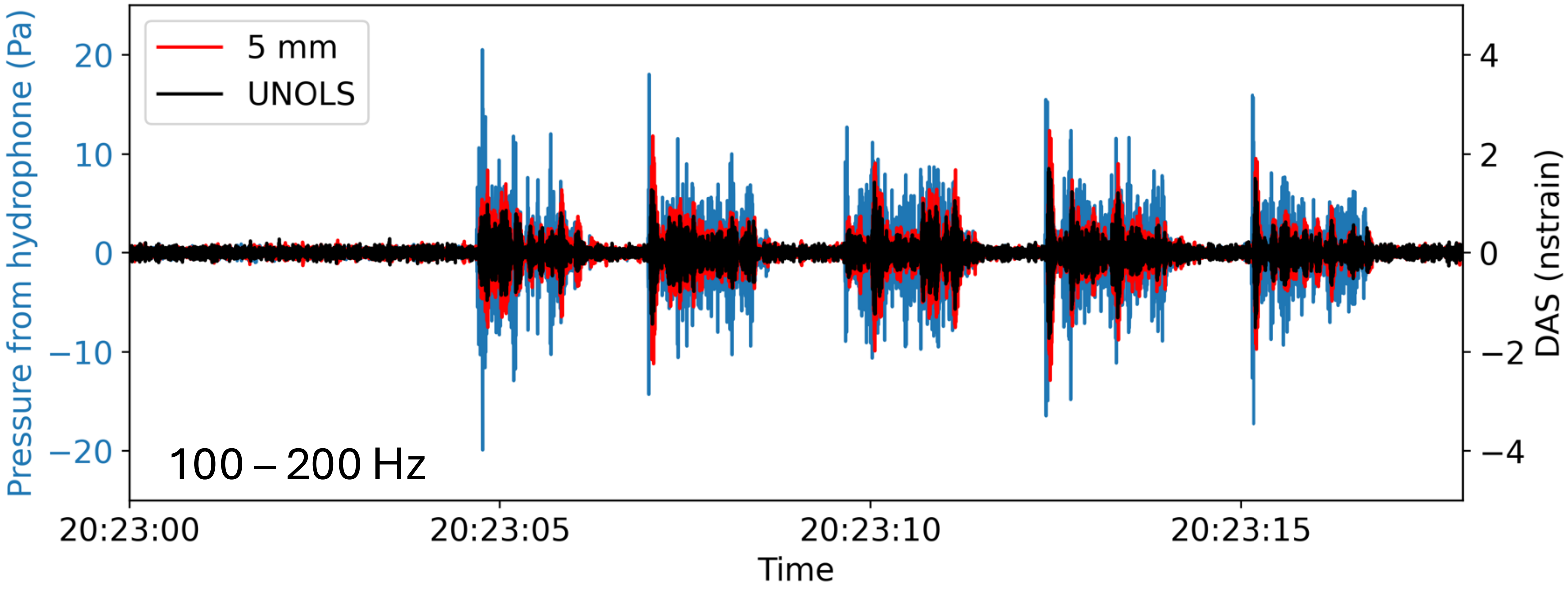
- Single-mode optical-fibers in **5 mm** & **0.681"** (1.729 cm) electro-optical-mechanical armored **marine UNOLS cable** are probed using channel spacing of 1.6 m and varying gauge lengths (1.6 m, 3.2 m, 4.8 m)
- Four co-located **hydrophones** and video-digitized wave height time series (**stationary camera**) allow validation of DAS measurements

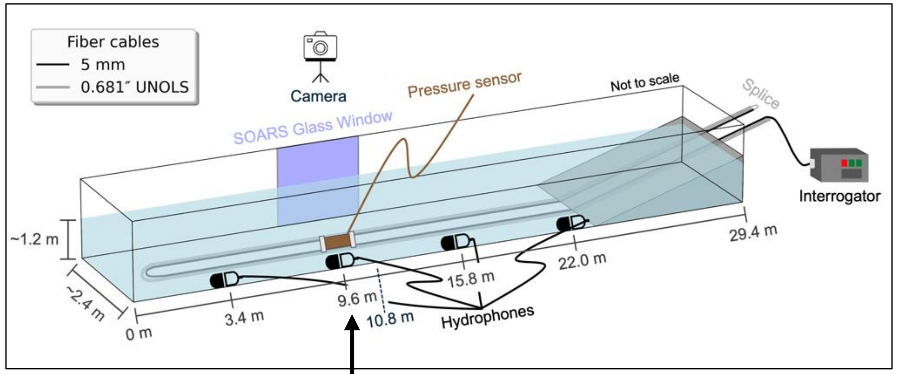
Consistent recorded waveforms: gravity



Consistent recorded waveforms: gravity & acoustic







Emitting **5 acoustic bursts** near 2nd hydrophone

Conclusions

with Baoning Wu, Yan Yang, Chih-Chieh Chien, Ryan Craft, Steven Constable, Mark A Zumberge, Alice-Agnes Gabriel

- Validation of DAS recordings in **controlled laboratory wave tank experiments**
- Pressure effects alone, without bottom compliance, can induce detectable strain
- Consistent recorded waveforms
- **Different scaling factors** for low-, and high-frequency signals
- **Framework** to quantify and understand how fiber-optic sensing detects acoustic and gravity waves in **submarine settings**

We thank Glenn Sasagawa, Jessica Hallisey, the Hydraulics Lab at SIO, the Shepard Foundation at SIO, and Shaun Diplock & David Hill from Sintela