Developing the next generation of 3D ground motion simulations of full and partial margin ruptures along the Cascadia Subduction Zone

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Motivation and Background

- The Cascadia Subduction Zone (CSZ) has the potential to host a large ~M8.7- 9.2 megathrust earthquake and associated tsunami but the lack of seismicity along the megathrust in instrumented history makes seismic hazard estimation difficult.
- Here, we present the workflow for developing 3D ground motion simulations for scenario earthquakes along the Cascadia megathrust to quantify hazards from infrastructure, tsunamis, and landslides, specifically focusing on coastal communities.
- This work is a part of the **Cascadia Coastlines and Peoples Hazards (CoPes) Hub**, a group of researchers across institutions in the Pacific Northwest with the aim of increasing the resiliance of coastal communities to natural hazards and climate change risks (**Figure 1**).

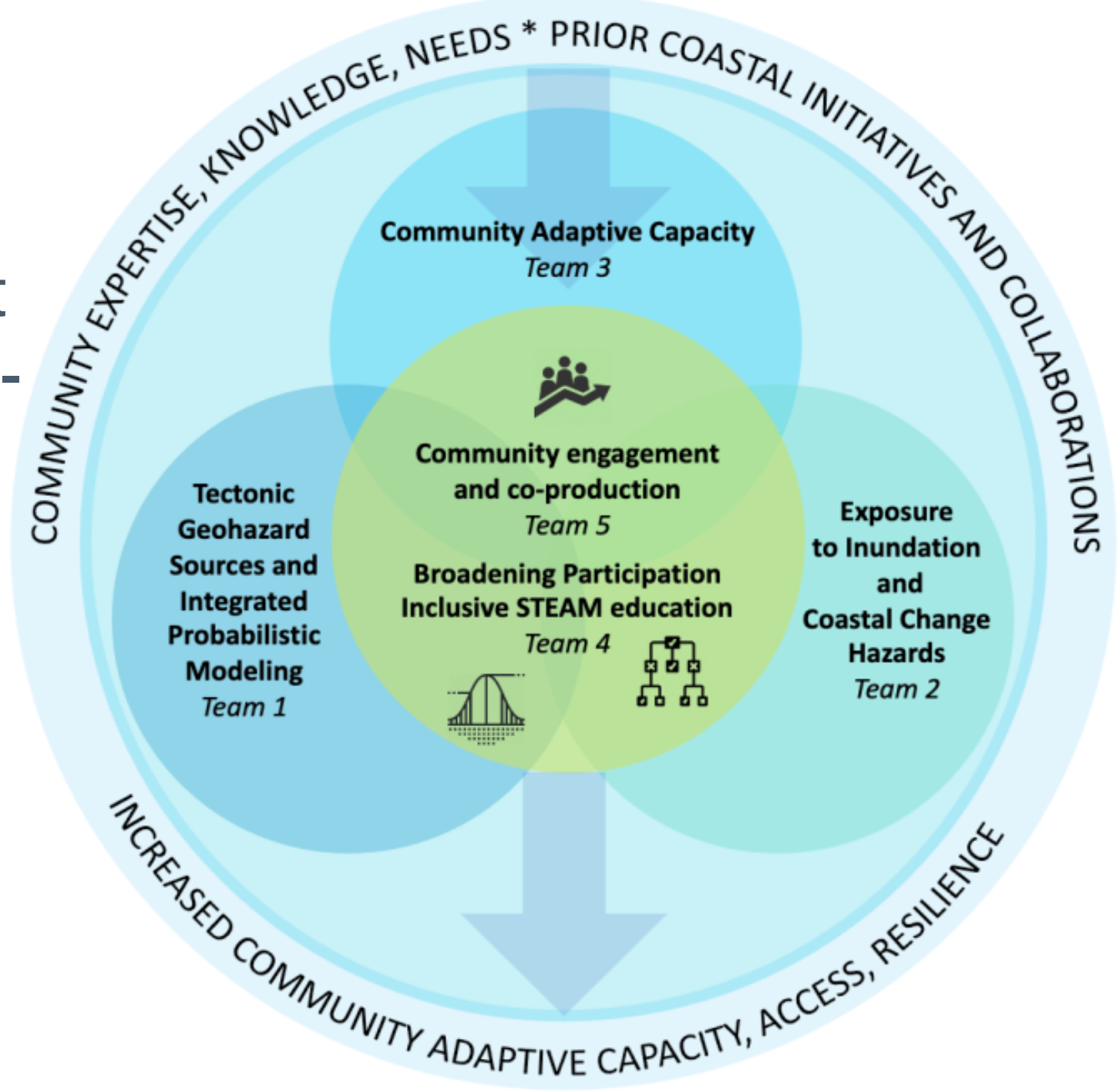


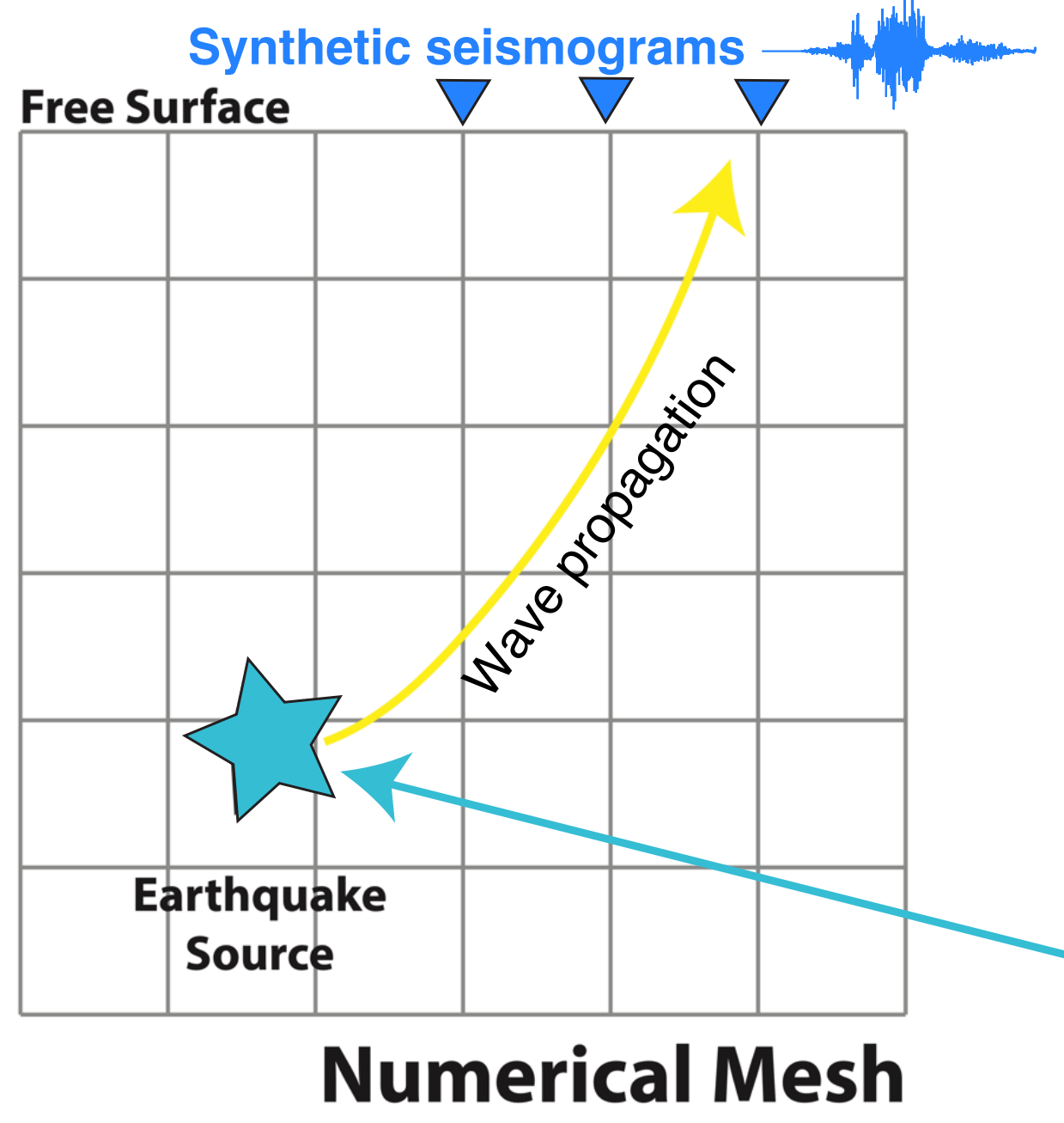
Figure 1: Venn diagram showing the 5 different teams of CoPes Hub researchers. The Hub is focused on the co-production of research among different teams and community leaders to increase communitiy resiliance in the face of natural disasters and climate change. This work is being done across the Pacific Northwest but primarily in 5 designated colaboratories. The transdisciplinary approach of the Hub is key to transforming our understanding of coastal hazards, risk, and how to communicate effectively to stakeholders and communities.

Driving research Questions:

1. *How will seismic hazard (particularly basin response) change with varying source properties?*
2. *Will splay faulting impact ground shaking on land or primarily tsunami generation.*
3. *How do ground shaking and tsunami generation interact in space and time?*

Modeling Workflow

The expected outcome of this work is a 1x1km grid of broadband synthetic ground motions for a range of potential CSZ earthquakes. The approach we use, outlined below, combines 0-1Hz deterministic seismograms modeled using a realistic 3D earth model in SPECFEM3D[1,2] and 1-10Hz stochastic seismograms to get broadband motions that can be used for a range of applications from engineering to tsunami modeling.



Low frequency (<1 Hz) synthetic seismograms are calculated deterministically in a numerical mesh (cartoon shown above) encompassing the entire CSZ with a flat free surface and elastic properties defined by a 3D velocity model (Stephenson et al., 2017)[3]. The velocity model includes basin sediment down to 600 m/s. An example source used for these models is shown in **Figure 2.**

Earthquake Source

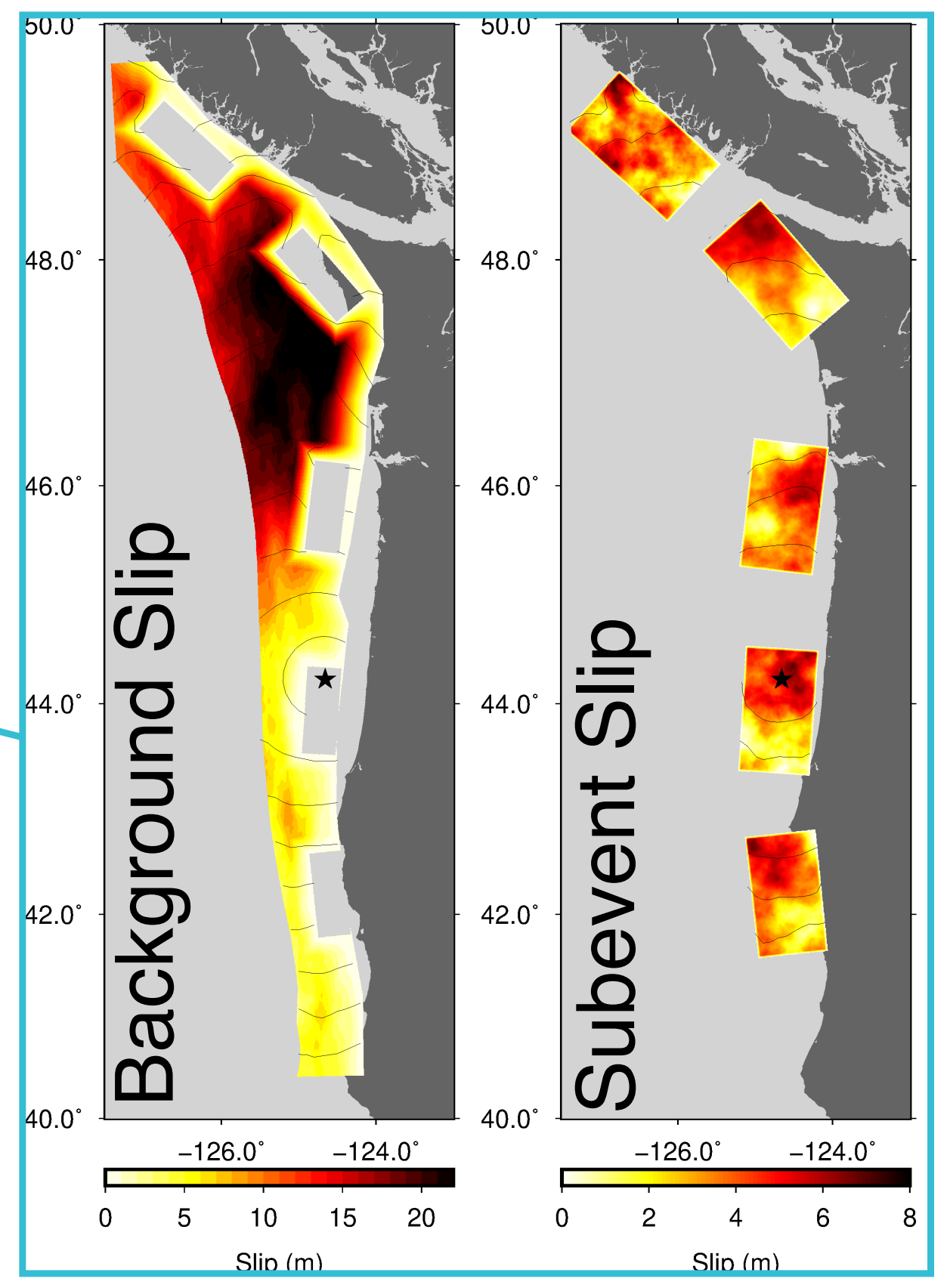


Figure 2: Example of a source model from the M9 project[4,5]. We represent the source as a kinematic rupture with seismic moment, a slip pulse, and a slip rate at each location along the rupture. This is a ***compound rupture model*** which has a region with background slip that releases the majority of the seismic moment and 5 high stress drop subevents. These subevents are equivalent to M8 earthquakes and release the majority of the high frequency energy. The location and magnitude of the subevents are based on observations from large megathrust earthquakes at other subduction zones[6,7,8,9].

To get broadband synthetics, following the method of Frankel 2017[8], we calculate stochastic waveforms from 1-10 Hz using a 1D velocity profile and site information at each station. We then combine these with the low frequency waveforms (<1 Hz) using a matched filter technique, generating synthetics from 0-10 Hz.

Broadband Synthetics

Low frequency deterministic seismograms (<1 Hz)
3D structure + compound source

\+ *Matched Filter*

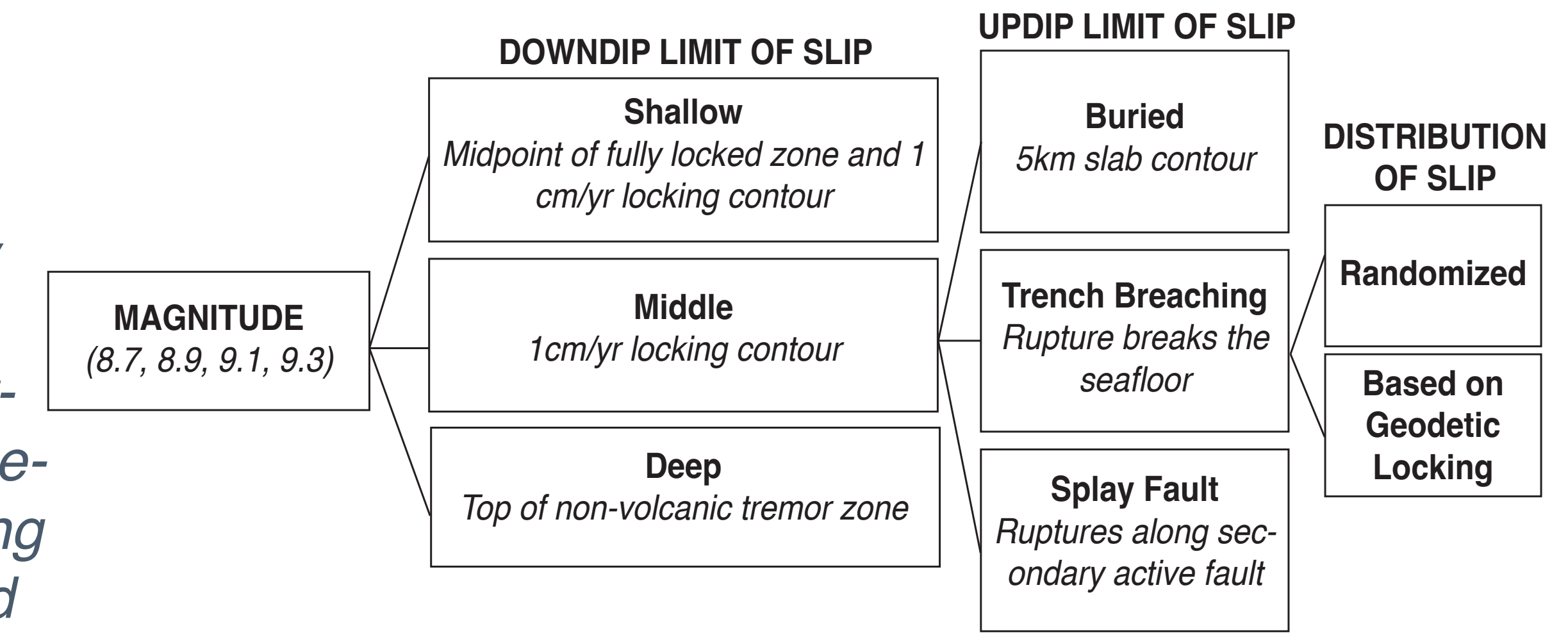
High frequency stochastic seismograms (1-10 Hz)
1D structure + site effects + subevents

=

Broadband synthetic seismograms (0-10 Hz)

Proposed Logic Tree

*We have limited information on the rupture parameters of past Cascadia megathrust earthquakes to use to predict future shaking. Therefore, we construct a logic tree to systematically vary parameters of interest to **(1)** explore their influence on modeling outcomes and **(2)** generate shaking from many possible earthquake scenarios to get a range of potential ground shaking that can be used in probabilistic seismic hazard analysis.*



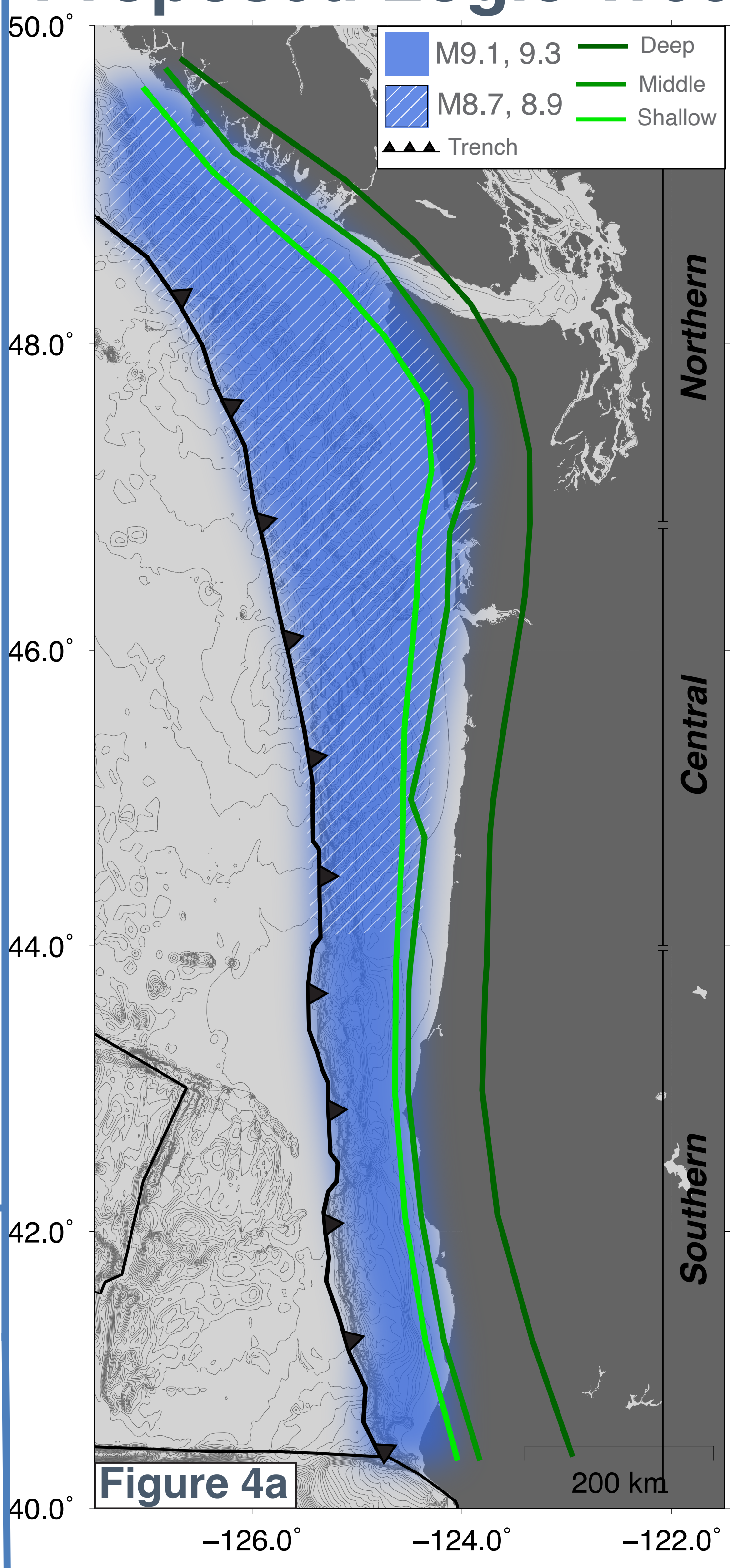
MAGNITUDE
(8.7, 8.9, 9.1, 9.3)

DOWNDIP LIMIT OF SLIP
- **Shallow** — *Midpoint of fully locked zone and 1 cm/yr locking contour*
- **Middle** — *1cm/yr locking contour*
- **Deep** — *Top of non-volcanic tremor zone*

UPDIP LIMIT OF SLIP
- **Buried** — *5km slab contour*
- **Trench Breaching** — *Rupture breaks the seafloor*
- **Splay Fault** — *Ruptures along secondary active fault*

DISTRIBUTION OF SLIP
- **Randomized**
- **Based on Geodetic Locking**

Figure 3: A logic tree for the 72 different earthquake source scenarios that will be modeled.



Updip Limits of Slip

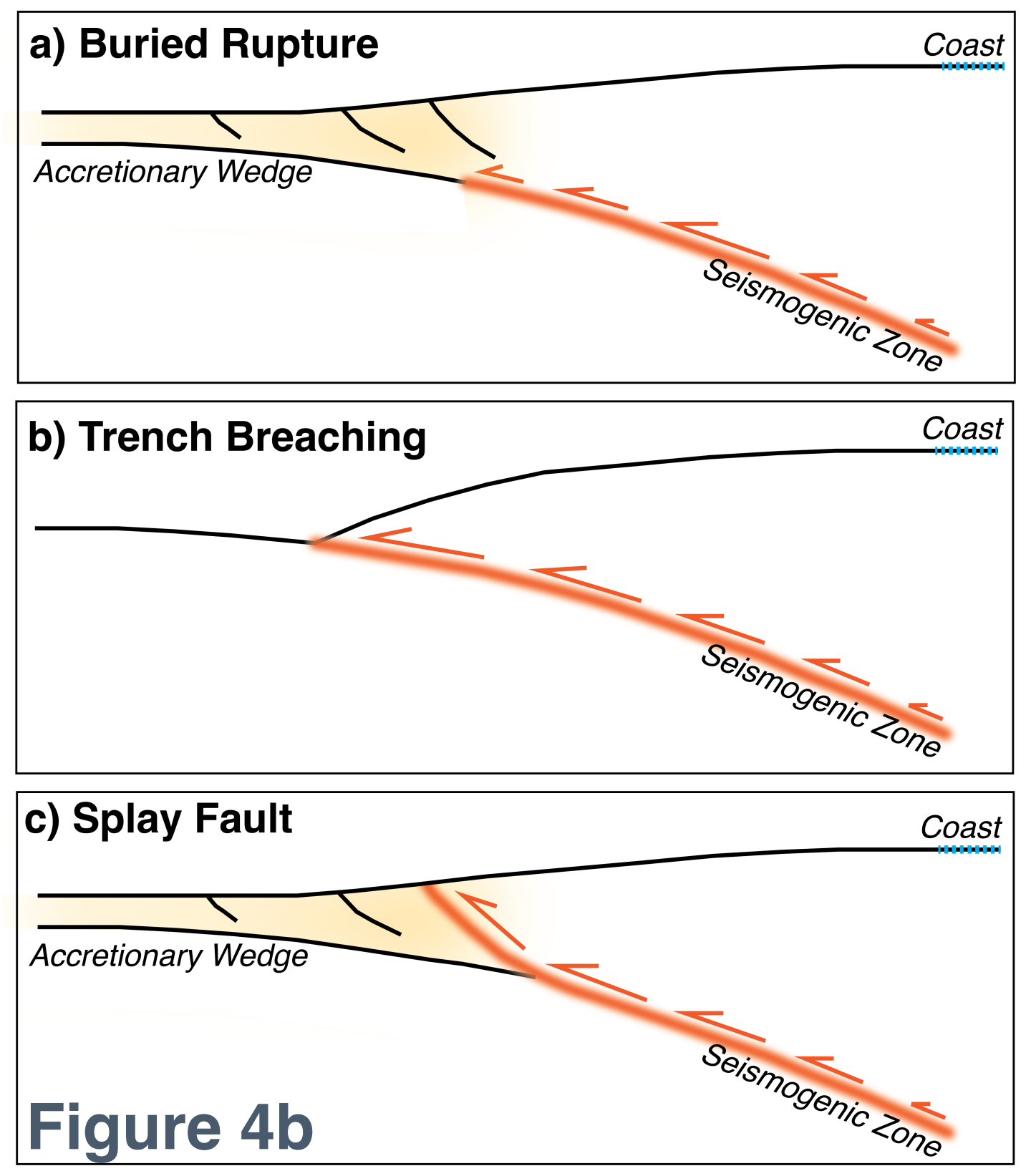


Figure 4b: Cross sections of the different updip limits of slip. We will explore 3 different scenarios, **(a)** a buried rupture, where the slip will only rupture to the 5 km depth contour of the slab, **(b)** a trench breaching rupture where the slip will propagate to the trench, and **(c)** a splay faulting rupture where the slip will rupture onto a splay fault mapped using 3D seismic reflection data.

Figure 4a: Map of the Cascadia Subduction Zone showing different variations of the source based on the logic tree. Blue and hatched blue regions represent full (M9.1-9.3) and partial margin (M8.9-8.7) ruptures, respectively. Previous work focused on only M9 ruptures[4,5]. Green gradient lines show the downdip limits of slip. Hypocenter locations will be randomly varied within the Northern, Central, and Southern zones. Updip limits are shown in cross section in **Figure 4b**.

Distribution of Slip

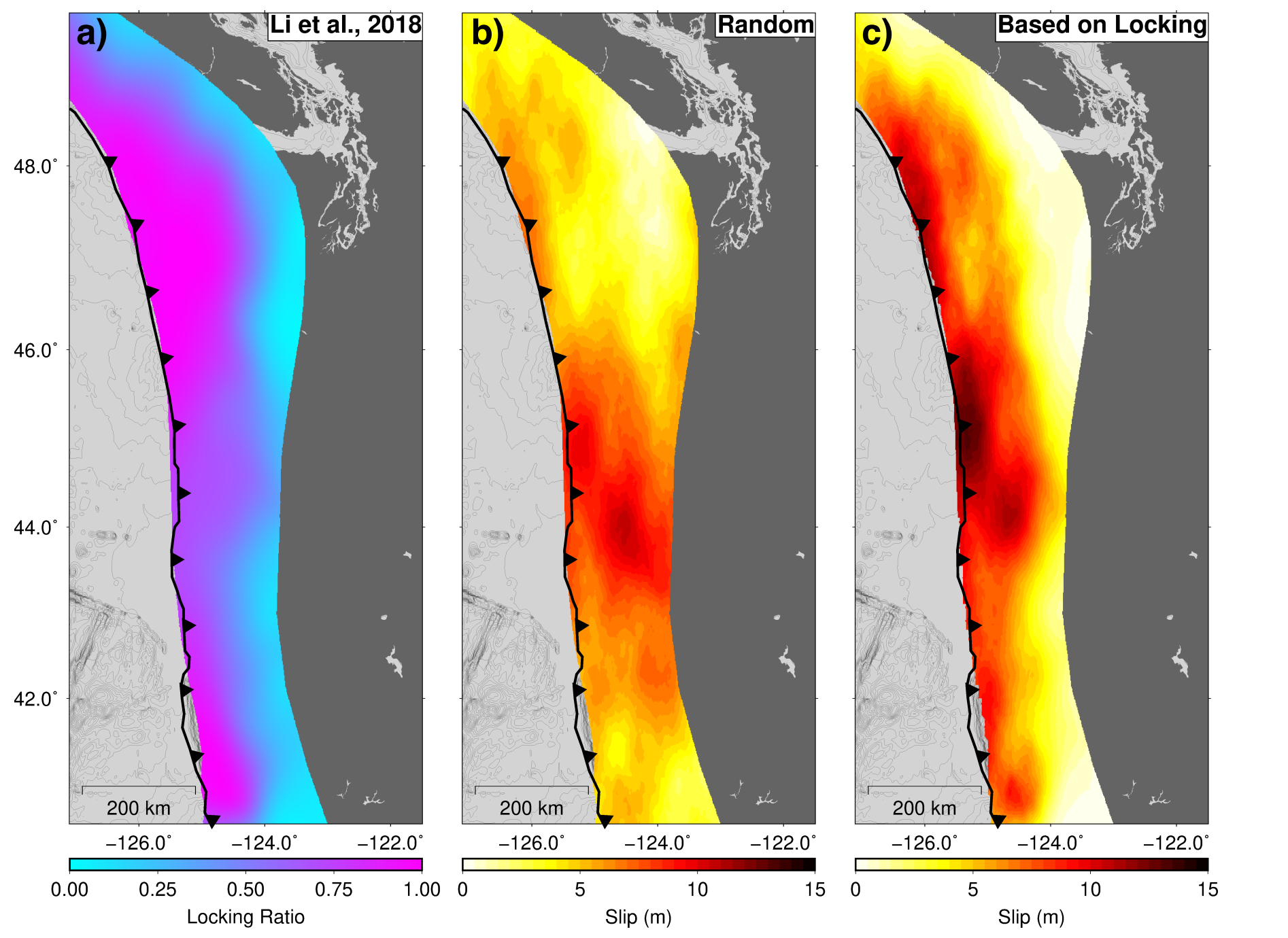
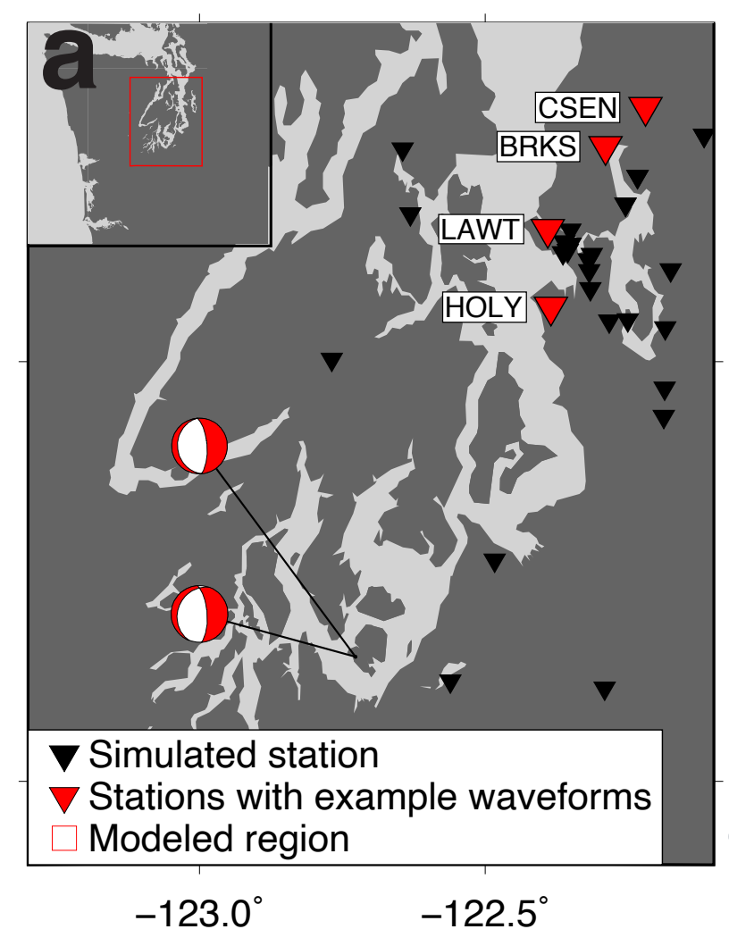


Figure 5: (a) Geodetic coupling model from Li et al., 2018[10]. **(b)** example rupture model with slip distributed randomly using a Von Karman correlation function with a k^{-2} spectral fall off and a correlation length of 500 x 200 km. **(c)** slip distribution produced with the same random seed as (b) but weighted by the locking ratio from (a) to generate a slip model that is based on what we know about the interseismic locking along the megathrust. Method based off of work from Small and Melgar 2022[11].

Validation

To validate the use of a new waveform modeling code, we compare simulations of 1) the 2001 M6.8 Nisqually earthquake and 2) a M9 project Cascadia full margin rupture modeled in SPECFEM3D and previously used codes.

1) Nisqually Earthquake



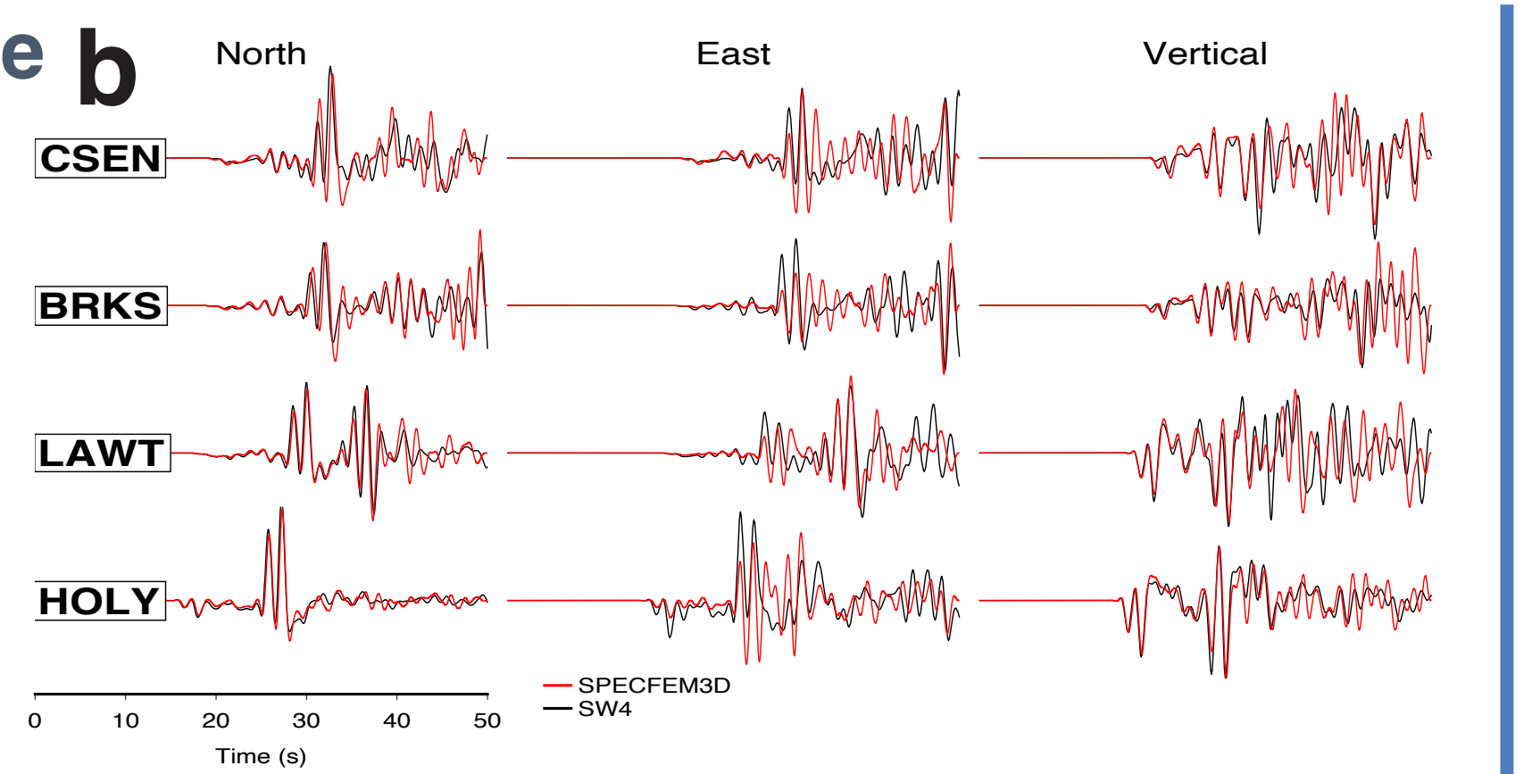
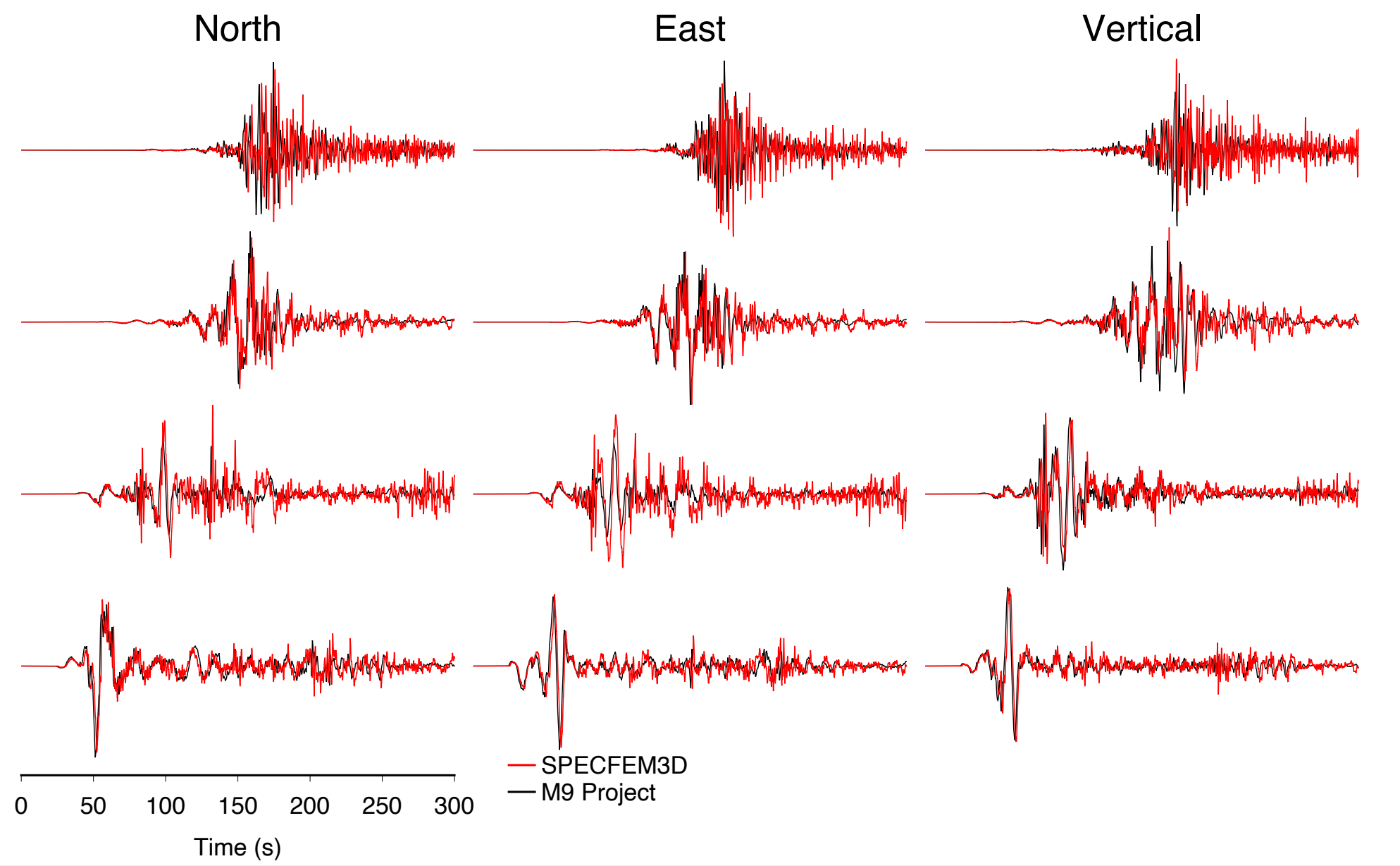


Figure 6 (a) Map of region, stations, and earthquake source description (red focal mechanism). **(b)** Waveform comparison at select stations between SPECFEM3D (red) and SW4 (black) for velocity (<1Hz).

2) M9 Cascadia Earthquake Scenario

Figure 7: Example determinstic (<1 Hz) synthetic velocity seismograms simulated from the source in **Figure 2** using a finite difference waveform propagation code (M9 Project) and SPECFEM3D (this study). Comparison shows very similar waveforms, with deviations in the basin station (top) due to the lack of attenuation currently in the SPECFEM3D runs.



Expected outcomes and applications to CoPes Hub

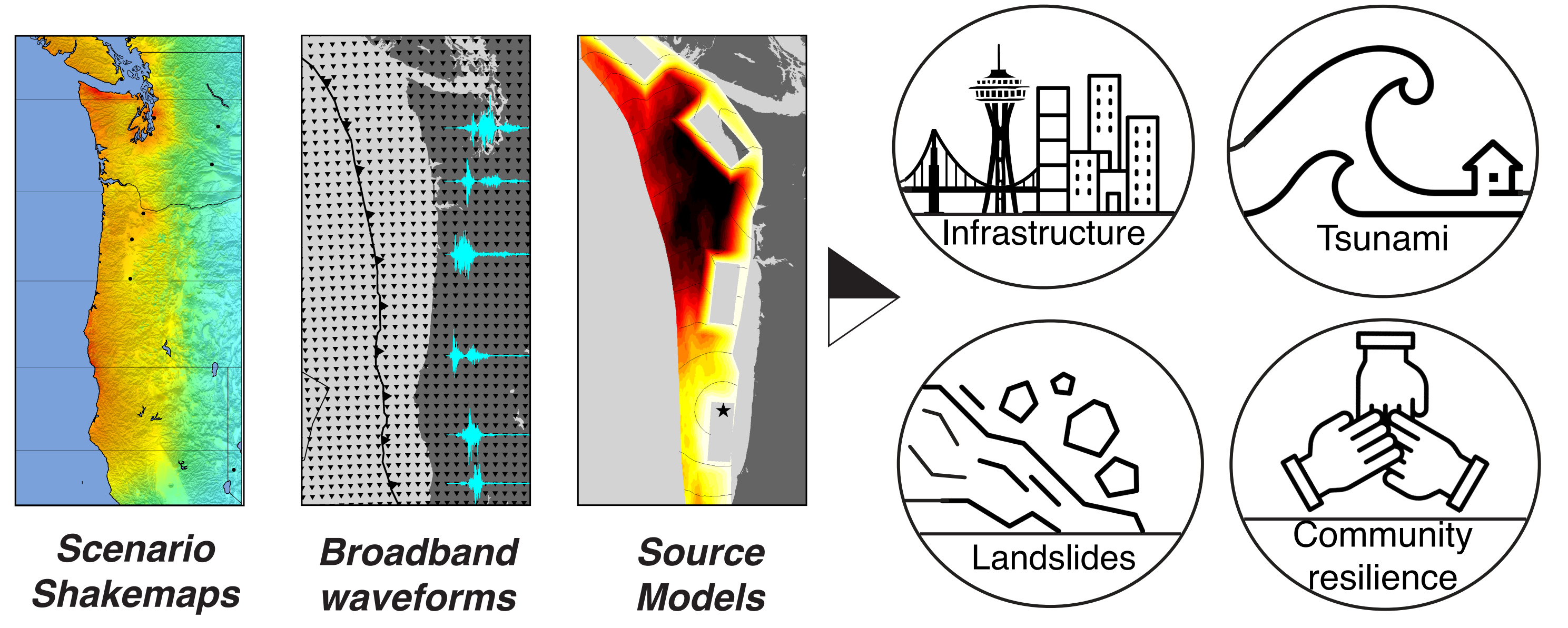


Figure 8: The outcomes of this research will be used by other members of Team 1 and the Hub to increase community resiliance and adaptability to a megathrust earthquake. Future work will include coupled simulations of earthquake sources and tsunami inundation as well as crustal fault simulations in the Puget Sound.

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