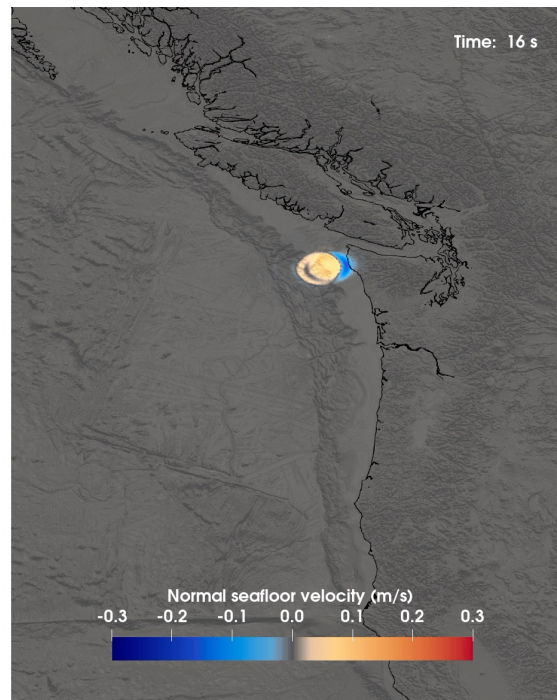
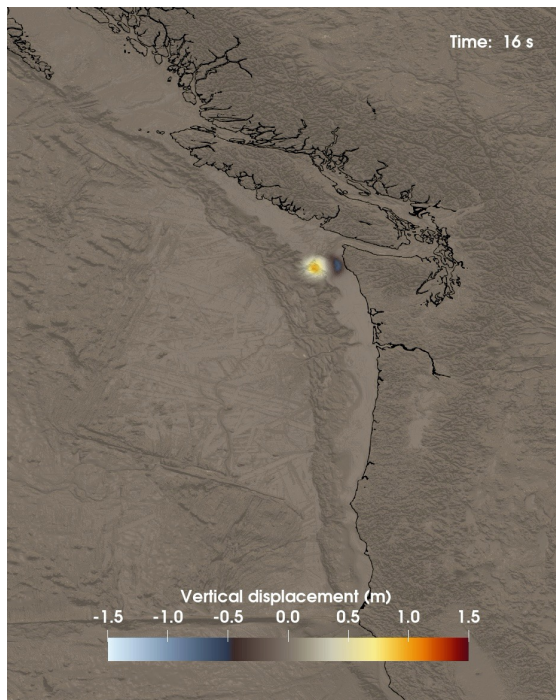


Alice-Agnes Gabriel

(and many others as referenced throughout the talk)

Rupture Rhapsody: Splay and Partial Rupture Dynamics in Cascadia



Henneking et al.,
SC'25 & Glehman et
al., Seismica 2025

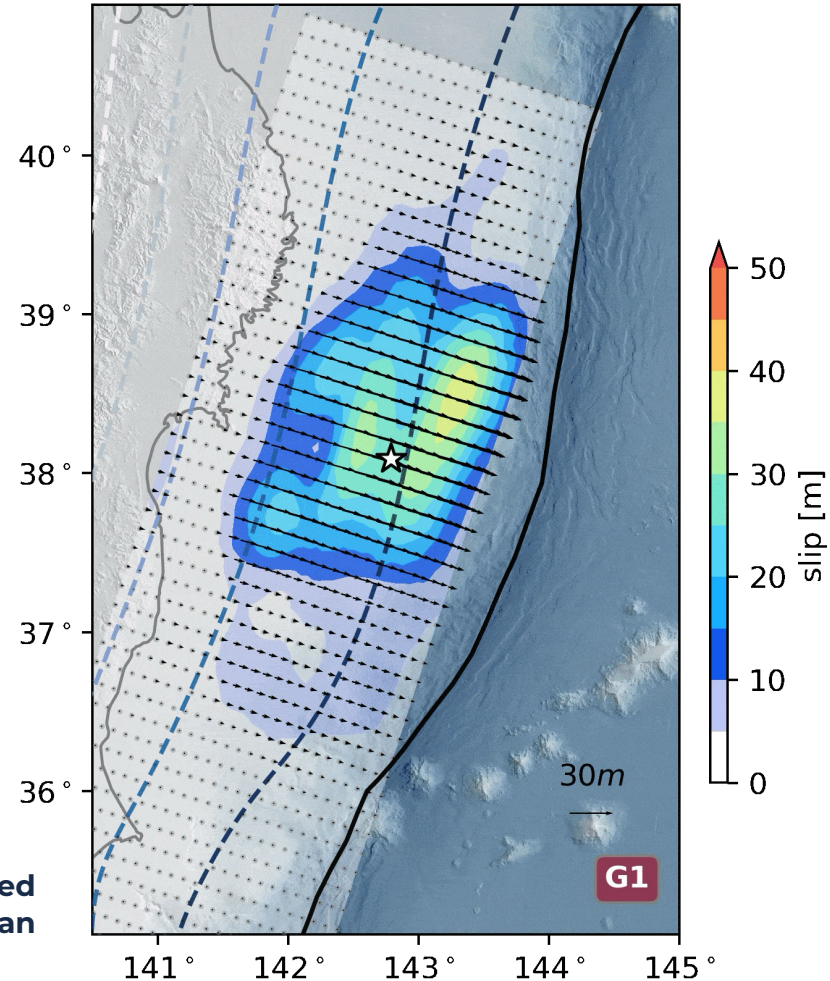


Integrating interdisciplinary observations remains difficult

- Without **physics-based models**, integrating interdisciplinary observations remains difficult, can lead to **non-unique results, opposing hypothesis** and **datasets studied in isolation**

32 finite fault models of the same well-recorded earthquake: the 2011 Tohoku-Oki earthquake in Japan

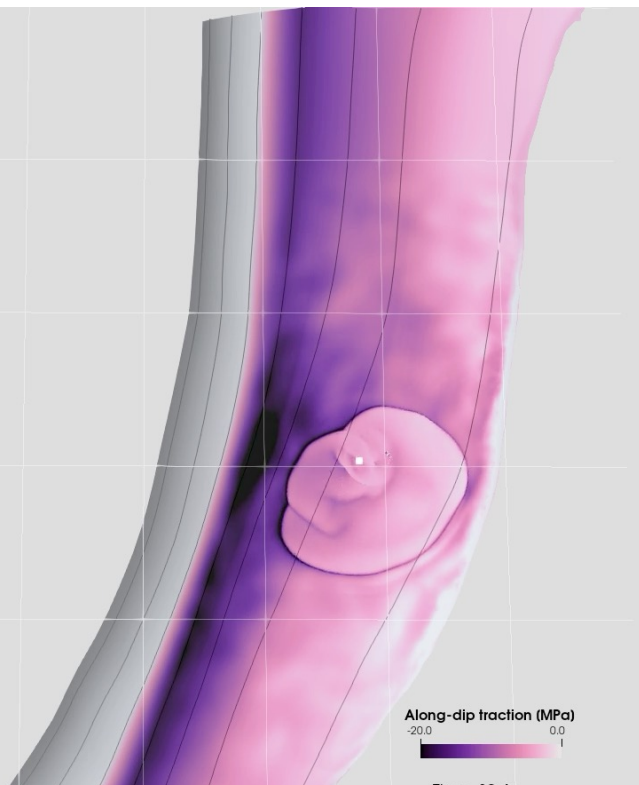
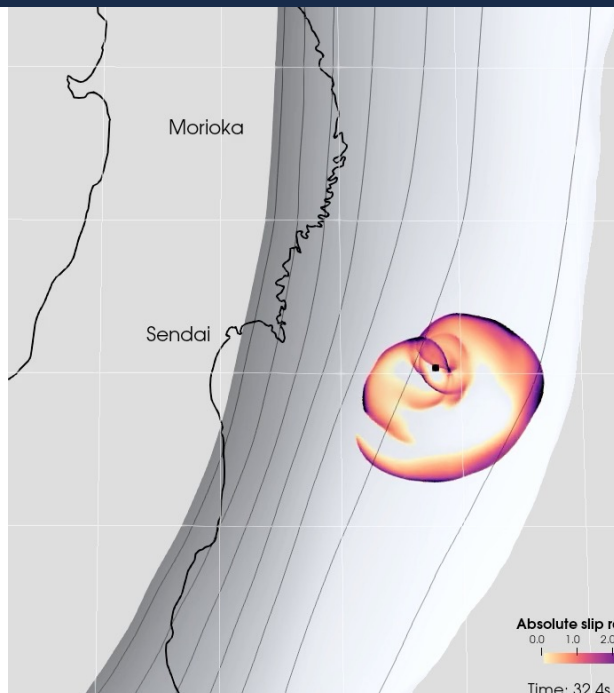
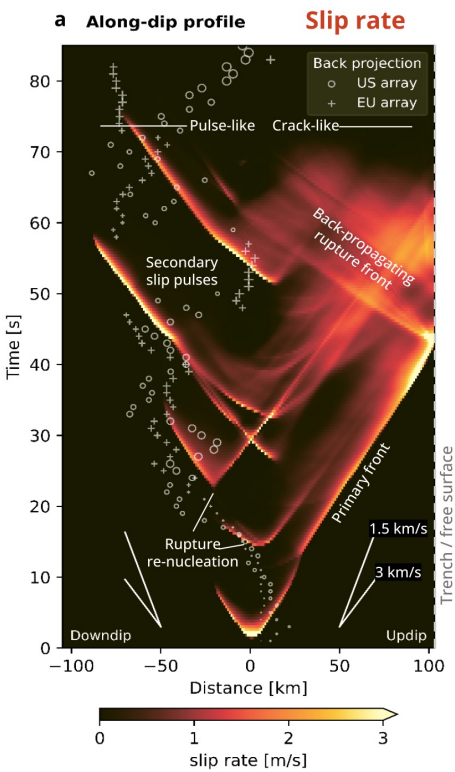
Wong, Fan & Gabriel, *JGR-Solid Earth*, 2024



Dynamic rupture modeling at the megathrust scale

Physics-based models bridge gaps in observational data, unravel space-time dynamics of earthquakes, and provide insights that transcend regional statistical approaches

Wong, Gabriel & Fan, *EarthArXiv*,
under review at *Nat. Comms.*, 2025

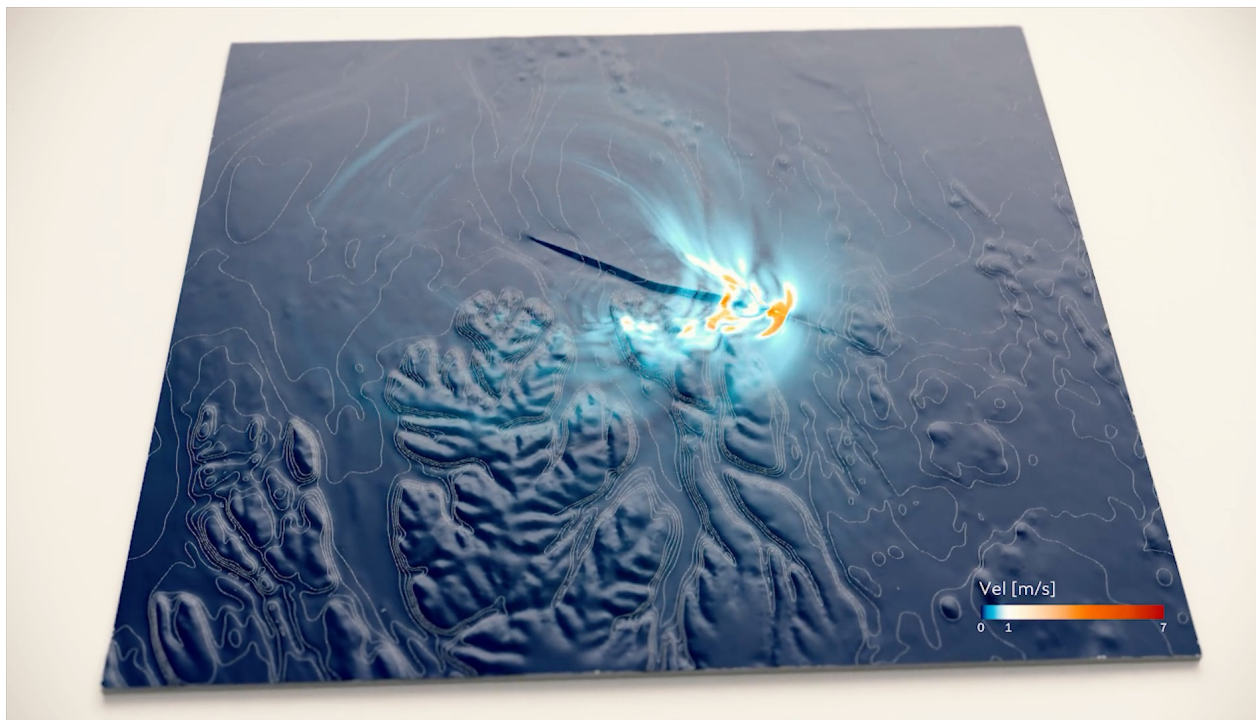


Dynamic weakening and restrengthening and fault heterogeneity explain megathrust earthquake complexity in 3D dynamic rupture simulations of the 2011 Tohoku-Oki event

Dynamic rupture simulations*

*earthquake dynamics are not predetermined in these models but evolve due to the model's initial conditions and the way the fault yields and slides controlled by an assigned friction law relating shear and normal traction on frictional interfaces and the non-linear coupling with seismic wave propagation

- **Earthquakes:** frictional shear failure of brittle solids under compression along preexisting weak interfaces
- **Dynamic rupture modelling:** Seismic wave propagation coupled to dynamically running shear fracture on a frictional interface embedded in a rheological continuum (elastic, visco-plastic, poroelastic, ...)
- Efficiently utilizing the largest **supercomputers** world-wide since decades (**and still today!**) building upon decade-long developments in computational seismology

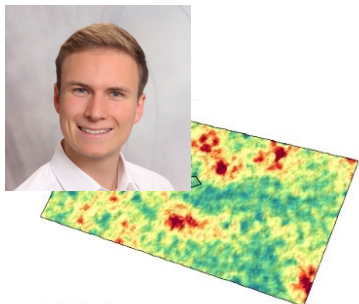


One of a suite of dynamic rupture simulations informing physics-based PSHA in North Iceland, Bo Li et al., JGR 2023

Initial conditions

- Data-driven: **constrained and validated** by the full breath of earthquake observations

See talk by Fabian Kutschera

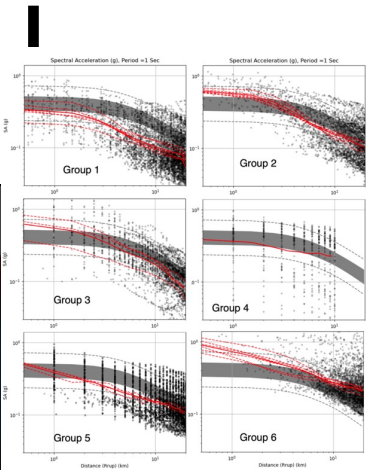


Initial fault loading

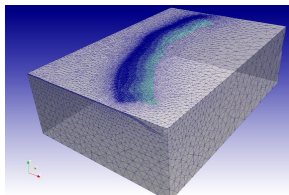
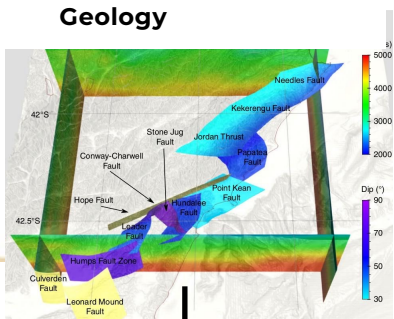
Interdisciplinary links, e.g., tsunami, ground motions, ..

Physics-Based Simulation of Near-Source Ground Motions: A Group Modeling Approach towards Advancing Seismic Hazard Characterization using Dynamic Ruptures

Kyle Withers¹, Yongfei Wang^{*2}, Thomas Ulrich³, Danyu Liu⁴, Ben Duan⁵, Alice-Agnes Gabriel^{**6,3}, Elif Oral^{7,8}, Shuo Ma⁹, Jean-Paul Ampuero¹⁰, Luis Dalguer¹¹, Domniki Asimaki⁷, František Gallovič¹², Lubica Valentova¹², and Christine Goulet^{***2}



Geology



Mesh generation

"Input"

SOLVER

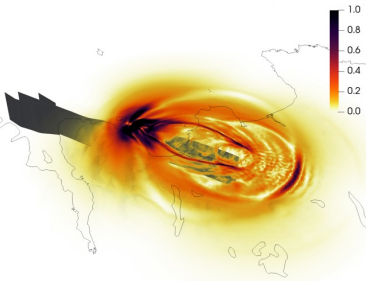
"Output"



Friction experiments

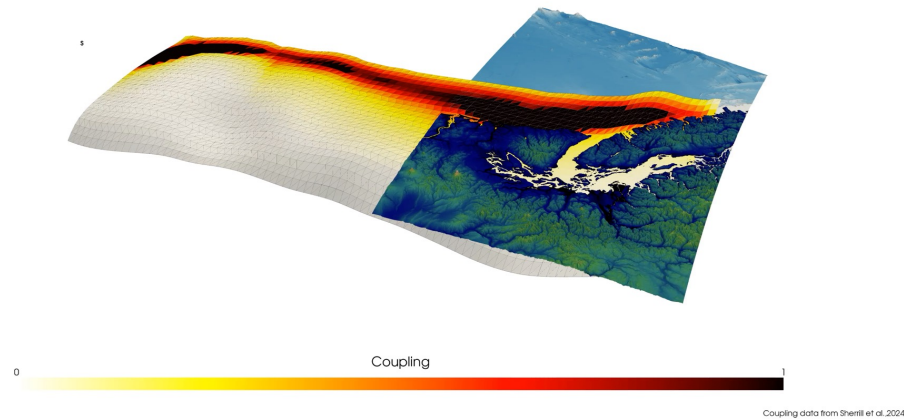
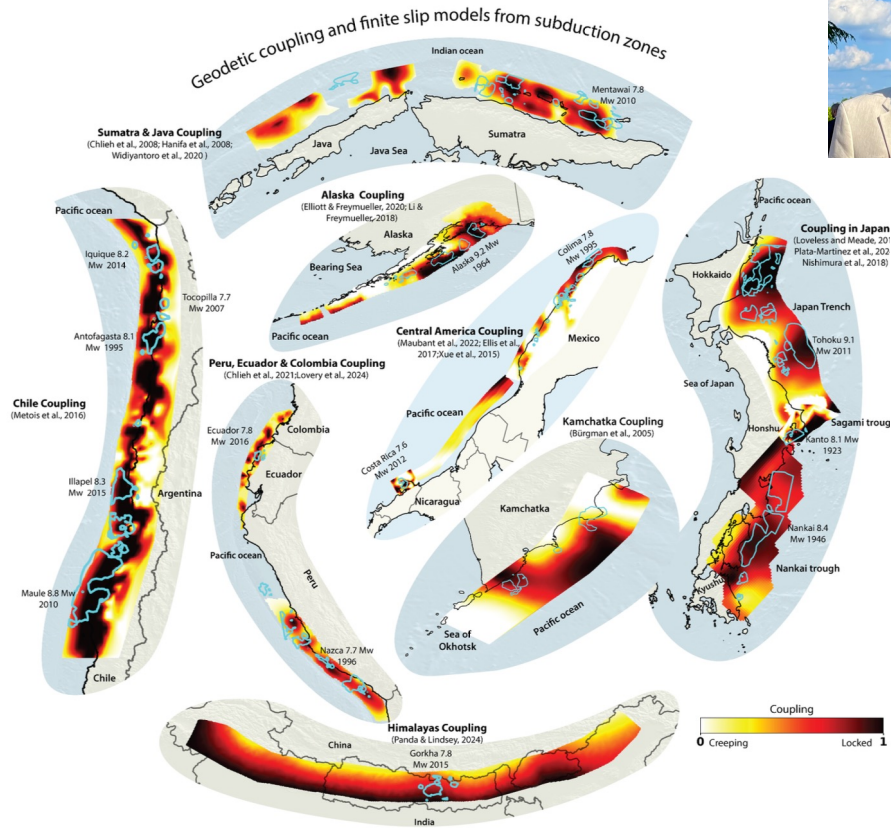
Fundamental Physics

Synthetic observables



From geodetic slip deficit models to Cascadia dynamic rupture simulations

Do coupled megathrusts rupture? See poster by Bar Oryan

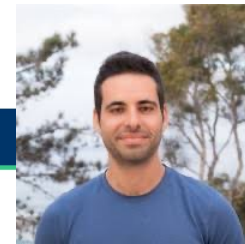


From geodetic slip deficit models to Cascadia dynamic rupture simulations

Do coupled megathrusts rupture? See poster by Bar Oryan

doi:10.26443/seismica.v2i4.1427

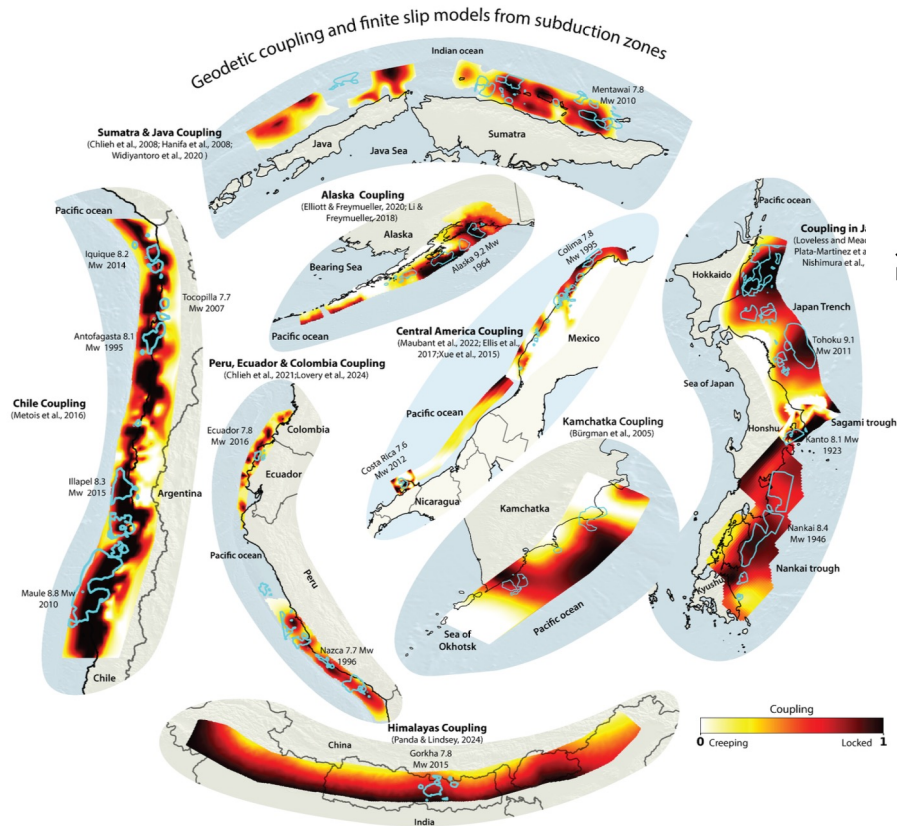
SEISMICA



Partial ruptures governed by the complex interplay between geodetic slip deficit, rigidity, and pore fluid pressure in 3D Cascadia dynamic rupture simulations

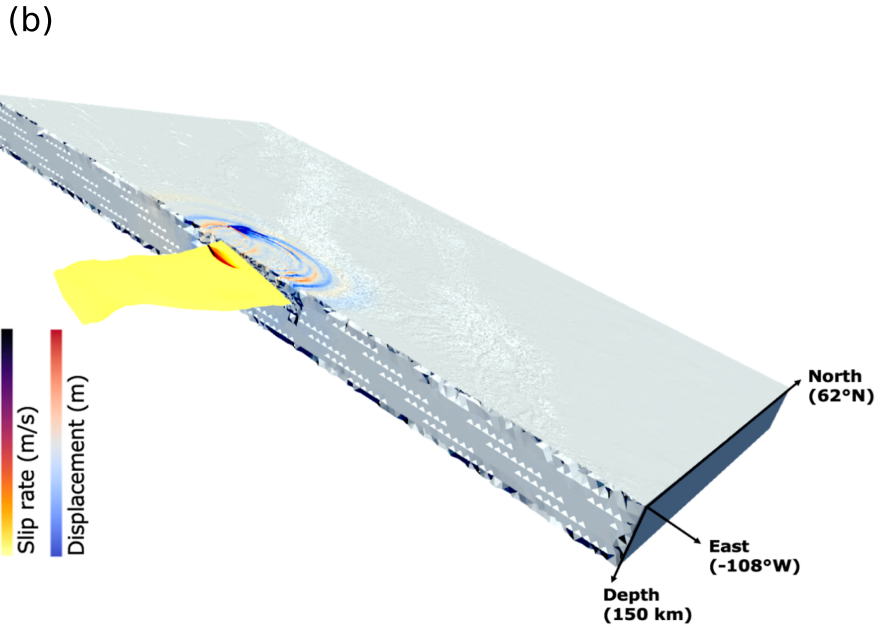
Jonatan Glehman ¹, Alice-Agnes Gabriel ^{1,2}, Thomas Ulrich ², Marlon D. Ramos ³, Yihe Huang ⁴, Eric O. Lindsey ^{5,6}

- Geodetic models imply $\sim O(10 \text{ m})$ accumulated slip deficit, **but the translation of those rates into dynamic rupture initial stresses is non-unique**, e.g., depends on material properties
- We link geodetically inferred slip deficit models to 3-D dynamic rupture simulations varying shallow rigidity structure and pore-fluid pressure (effective normal stresses)

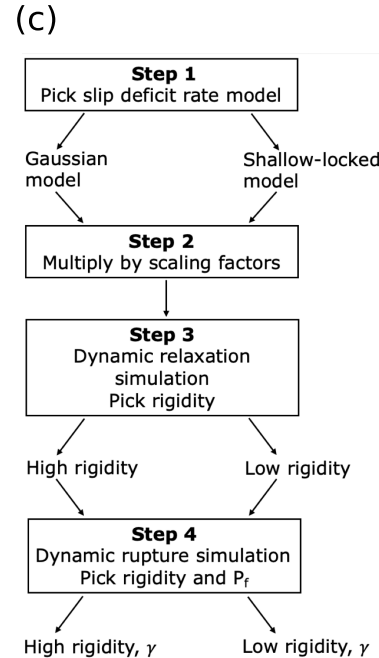


Workflow: from geodesy to self-consistent initial stresses to dynamic rupture

Glehman et al., *Seismica*, 2025



Unstructured tetrahedral mesh for SeisSol (Gabriel et al., 2025) simulation, accounting for the megathrust, and topo-bathymetry, 6,5 million elements. Modeling 400 seconds of rupture and waves requires 6000 CPUh (2 hours on 3k cores)



- Select a **slip-deficit model (SDM)**, assign along-strike recurrence-time scaling factors
- Compute stress changes with an **in-code dynamic relaxation simulation** using the same mesh and geometry and accounting for off-fault **rigidity**
- Sum the SDM-derived stress changes with **depth-dependent normal stress** to obtain the total initial shear and normal stress on the megathrust
- This **links shear and normal stresses consistently** and allows exploration of sensitivities, e.g., to depth-variable pore-pressure gradients

Workflow: from geodesy to self-consistent initial stresses to dynamic rupture

Glehman et al., *Seismica*, 2025

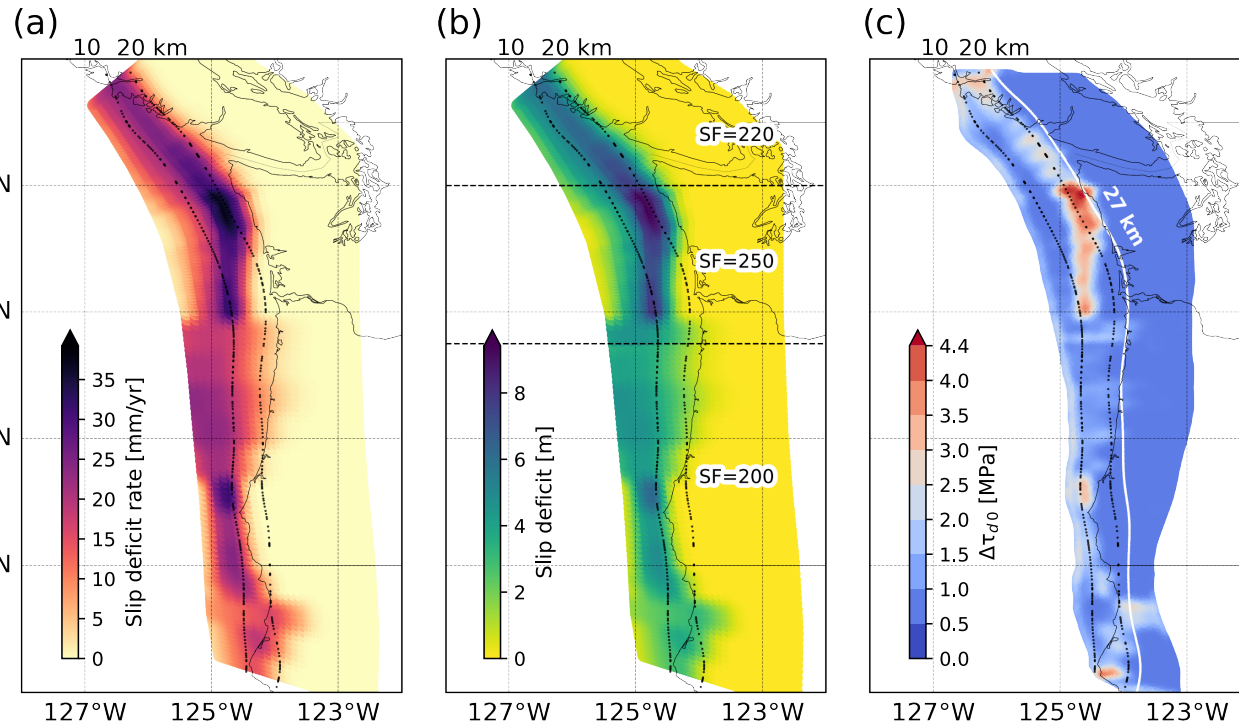
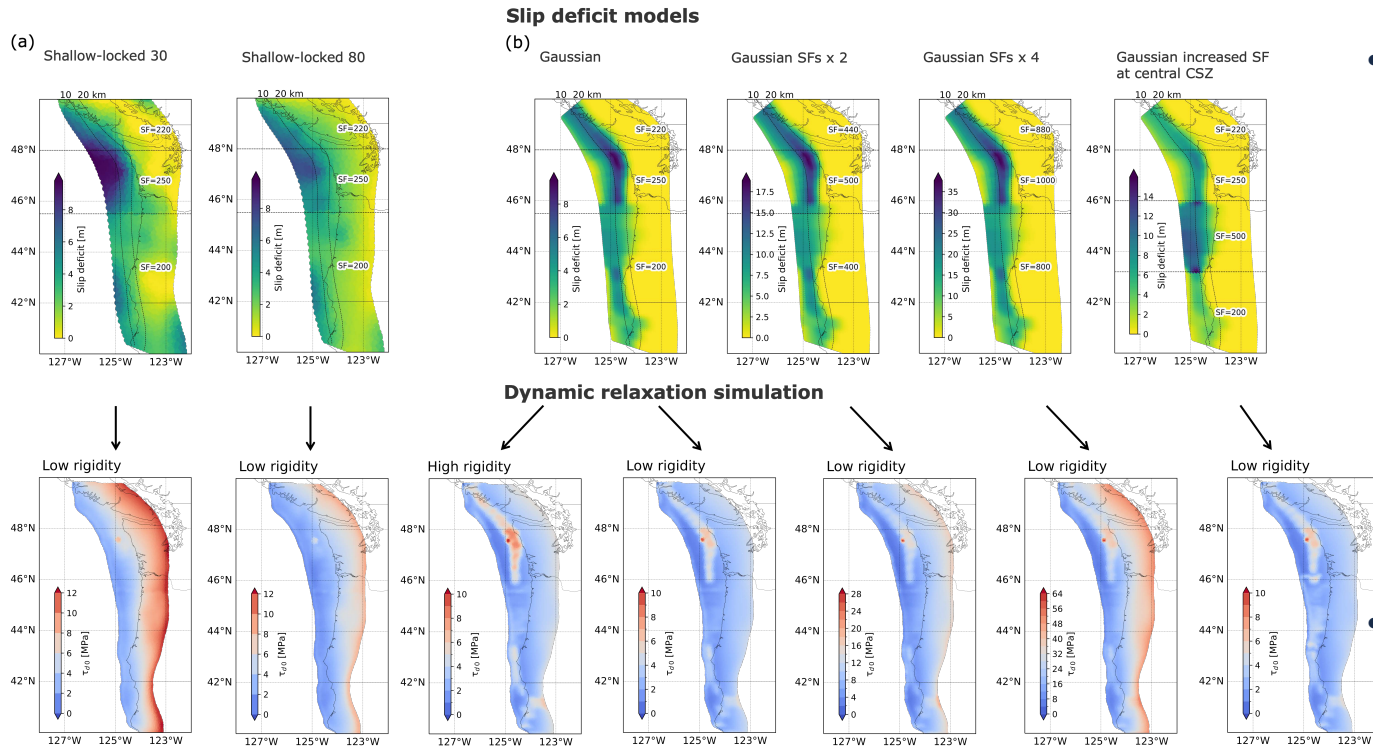


Illustration of the workflow to derive initial stresses from a given slip deficit model

- Select a **slip-deficit model (SDM)**, assign along-strike recurrence-time scaling factors
- Compute stress changes with an **in-code dynamic relaxation simulation** using the same mesh and geometry and accounting for off-fault **rigidity**
- Sum the SDM-derived stress changes with **depth-dependent normal stress** to obtain the total initial shear and normal stress on the megathrust
- This **links shear and normal stresses consistently** and allows exploration of sensitivities, e.g., to depth-variable pore-pressure gradients

Model inputs: slip-deficit models

Glehman et al., *Seismica*, 2025

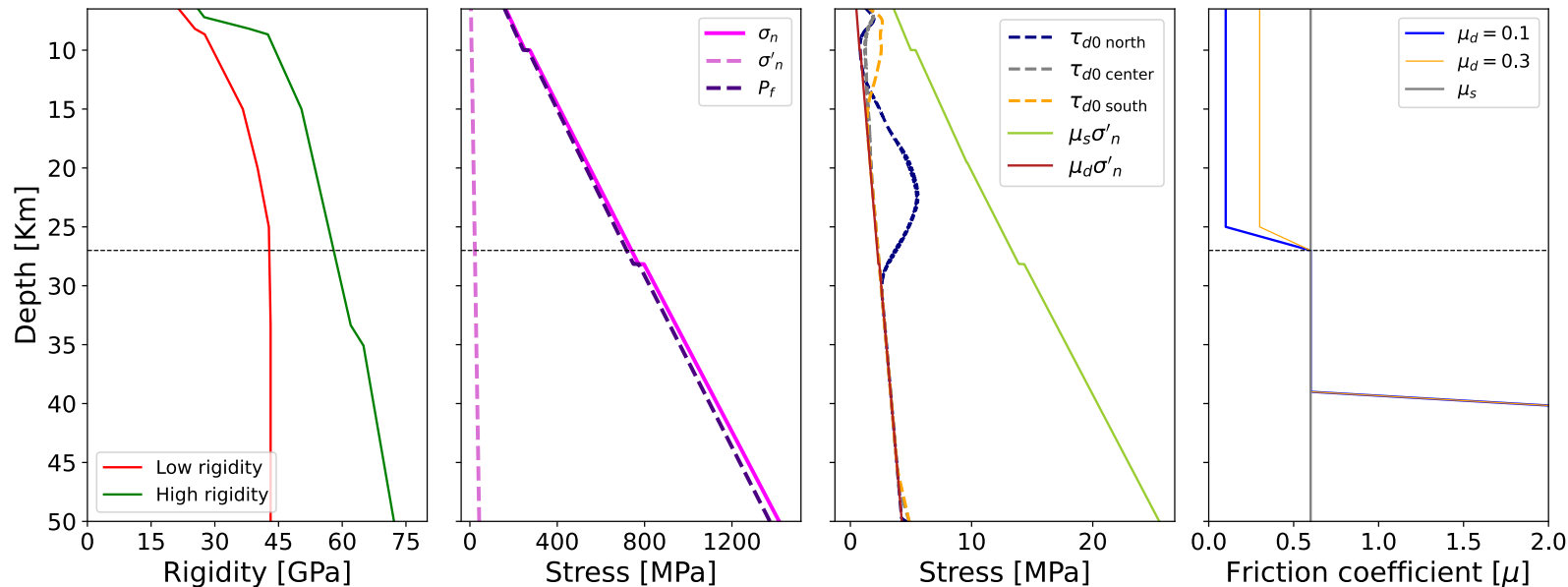


- **3 SDMs tested: Gaussian** distribution (Schmalzle et al., 2014) and two **shallow-coupled** SDMs based on Lindsey et al. (2021) that taper the shear-stress rate to be non-negative down to either 30 km or 80 km depth

- Markedly **different initial stress fields**, especially near the trench

Model inputs: rigidity, friction, pore fluid pressure

Glehman et al., *Seismica*, 2025



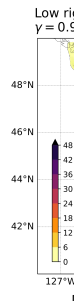
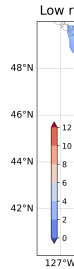
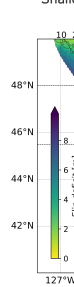
- These choices are intentionally simple to isolate key trade-offs. E.g., rigidity changes alter both rupture dynamics and the SDM-derived initial stresses,
- and pore fluid pressure controls the effective normal stress and thus dynamic fault strength.
- Future work: include off-fault plasticity.

- Pore fluid pressure is varied from moderate-high ($\gamma = 0.95-0.97$), high ($\gamma = 0.95-0.97$), to very high ($\gamma = 0.96-0.97$) with depth

22 dynamic rupture scenarios

- Under self-consistent initial stresses derived from SDMs, **partial ruptures are favored dynamically**
- Higher-rigidity** profile raises potential co-seismic slip yet reduces initial shear stress because the SDM-derived stress change depends on the elastic model; near-trench behavior is especially sensitive
- Rigidity and initial stresses must be specified **jointly to avoid unphysical initial conditions** when moving from geodesy to dynamics
- Pore fluid pressure** strongly modulates viability of large rupture and speed (see also *Madden et al., JGR, 2022*)

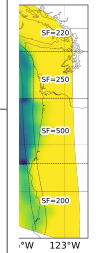
(a)



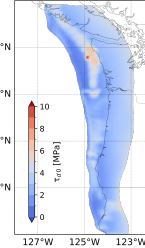
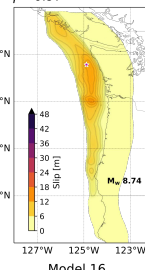
Slip deficit models

(b)

Models and parameters								
Model	Description	R_{crit} [m]	D_c [m]	μ_d	γ	Rigidity (dynamic relaxation simulation)	Rigidity (Dynamic rupture)	
Gaussian SDM								
1	Low rigidity model with negative shear stresses and very high P_f	3400	1.0	0.1	0.97	low	low	
2	low rigidity model with non-negative shear stress changes and very high P_f	3400	1.0	0.1	0.97	low	low	
3	Same setting as model 2 with slip-neutral friction zone replaced by slip-weakening friction	3400	1.0	0.1	0.97	low	low	
4	Same setting as model 2 with slip-neutral and slip-strengthening friction zones replaced by slip-weakening friction	3400	1.0	0.1	0.97	low	low	
5	High rigidity model and very high P_f	3400	1.0	0.1	0.97	high	high	
6	Constant rigidity model and very high P_f	3400	1.0	0.1	0.97	constant	low	
7	Model to assess the dynamic effect of the low rigidity	3400	1.0	0.1	0.97	high	low	
8	Mixed P_f ; $\gamma = 0.62$ when $z < 10$ km and $\gamma = 0.97$ when $z > 10$ km	3400	1.0	0.1	mixed	low	low	
9	Low rigidity model with very high but slightly lower P_f	3400	1.0	0.1	0.96	low	low	
10	Reference SFs x 2 and high P_f	1400	1.0	0.1	0.91	low	low	
11	Reference SFs x 2 and high P_f	1400	1.0	0.1	0.88	low	low	
12	Reference SFs x 2 and high P_f	1400	1.0	0.1	0.85	low	low	
13	Reference SFs x 4 and moderate-high P_f	1200	1.0	0.1	0.71	low	low	
14	Reference SFs x 4 and moderate-high P_f	1200	1.0	0.1	0.68	low	low	
15	Reference SFs x 4 and moderate-high P_f	1200	1.0	0.1	0.65	low	low	
16	Margin-wide rupture with higher scaling factor at center Oregon and very high P_f	4400	1.0	0.1	0.97	low	low	
17	Southern epicenter and very high P_f	3400	1.0	0.1	0.97	low	low	
18	Shallower coupling depth of 22 km and very high P_f	3400	1.0	0.1	0.97	low	low	
shallow-coupled SDMs								
19	Negative shear stress rate tapered up to 30 km and very high P_f	7600	1.0	0.3	0.97	low	low	
20	Negative shear stress rate tapered up to 30 km with smaller D_c and very high P_f	5400	0.7	0.3	0.97	low	low	
21	Negative shear stress rate tapered up to 30 km with constant rigidity and very high P_f	5400	0.7	0.3	0.97	constant	low	
22	Negative shear stress rate tapered up to 80 km and very high P_f	6200	0.7	0.3	0.98	low	low	

Increased SF
SZ

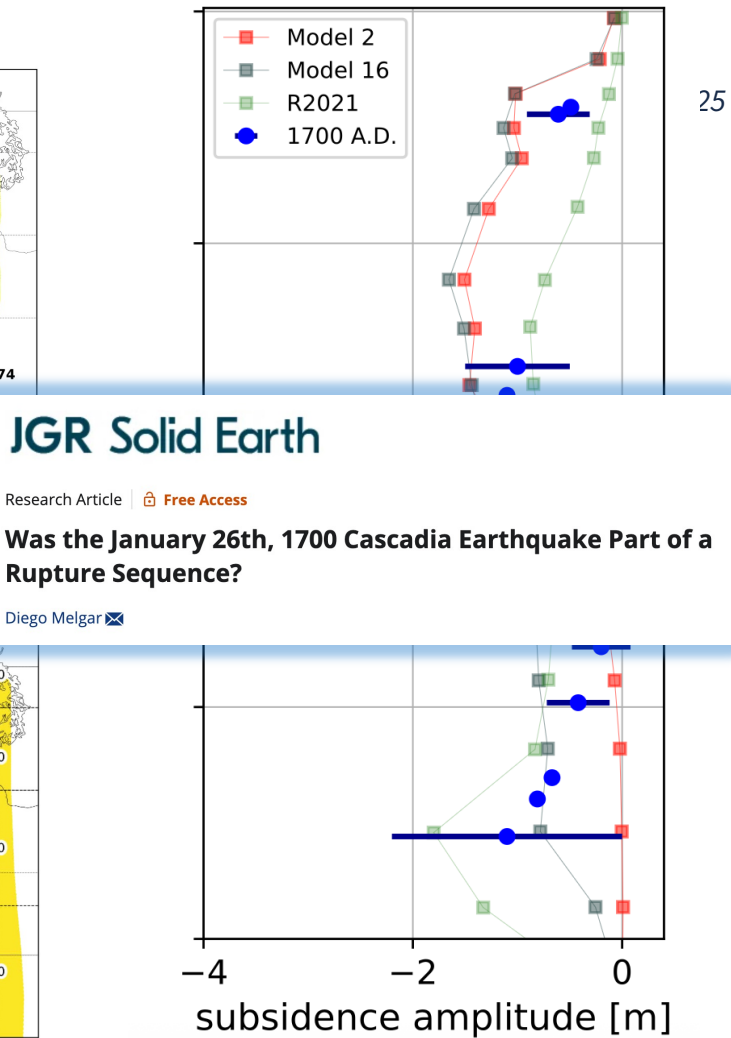
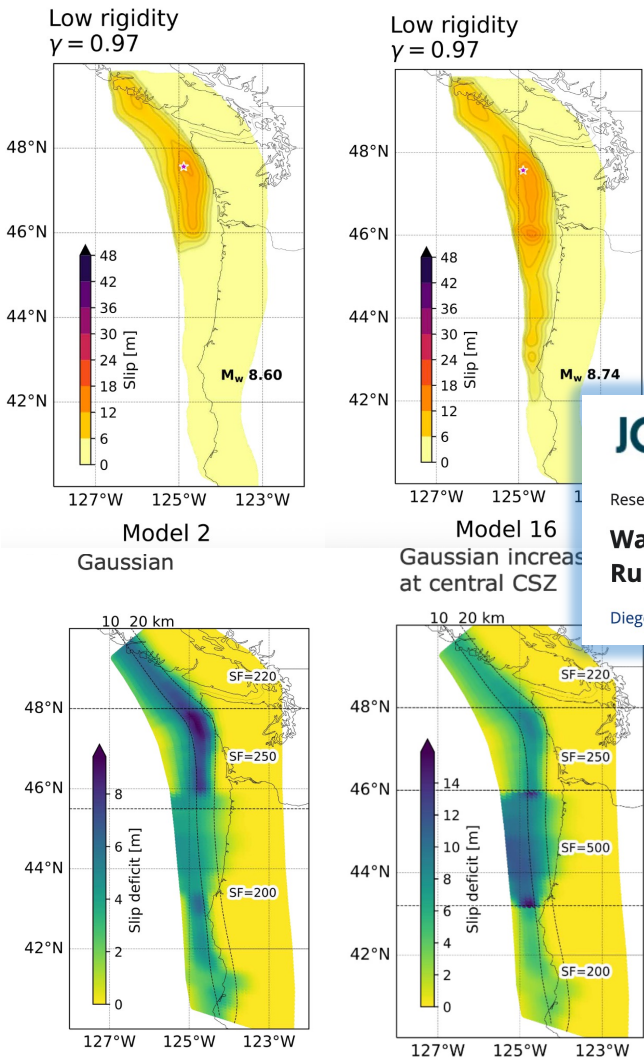
Low rigidity

Low rigidity
 $\gamma = 0.97$ 

Model 16

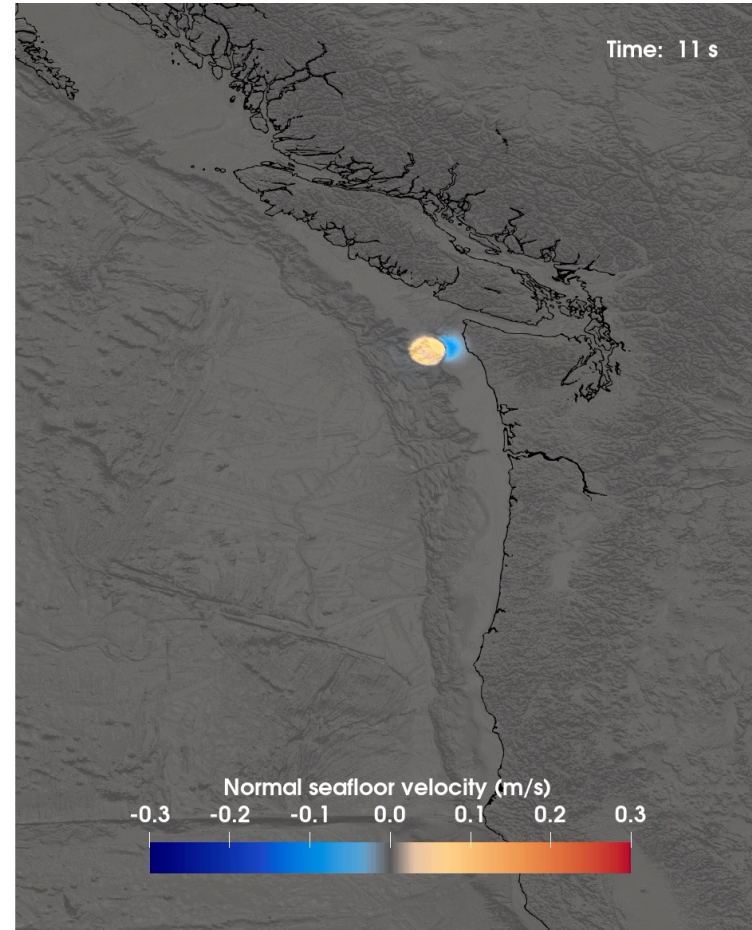
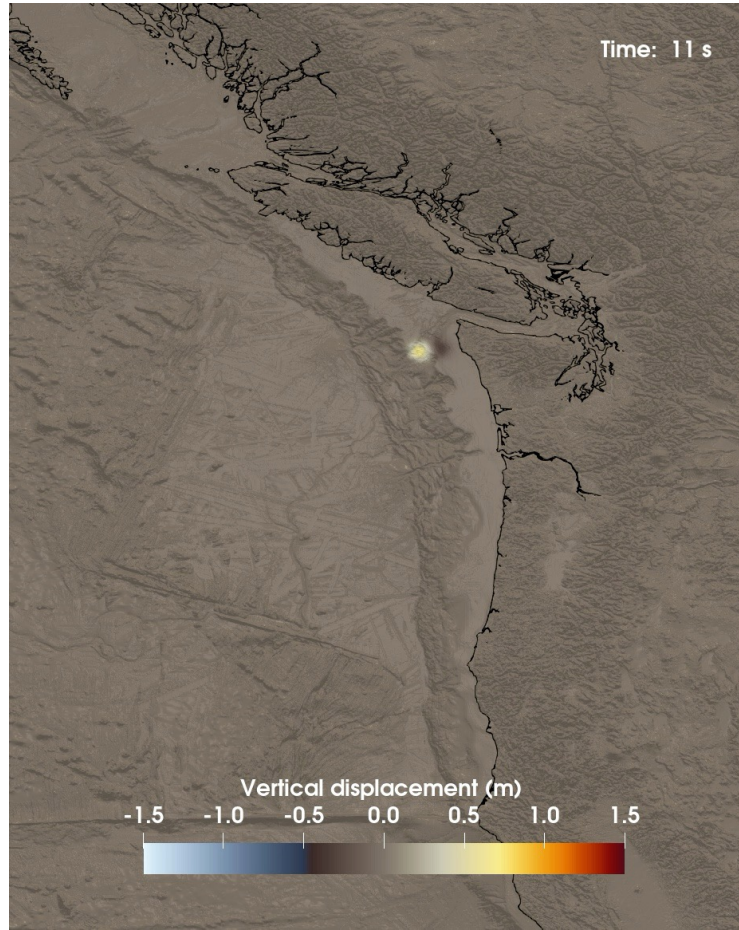
One margin-wide rupture scenario

- **Margin-wide rupture** requires a **large central Cascadia slip deficit** (>10m)
- The central CSZ acts as the **key control on through-going rupture**
- Without additional central loading, dynamics ruptures tend to arrest, consistent with a **tendency toward partial ruptures**
- **Reproducible workflow and open framework** to feed downstream ground-motion and tsunami simulations



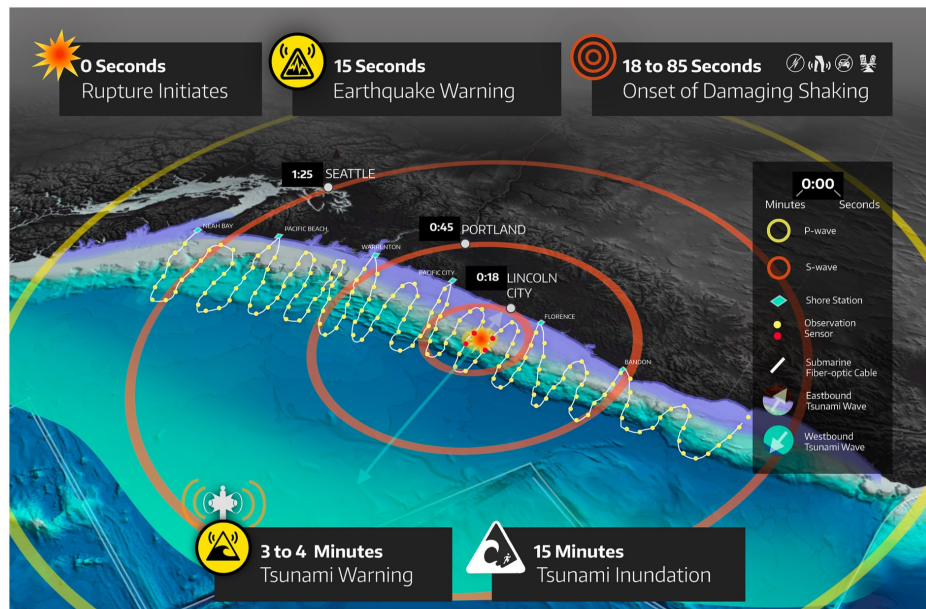
One margin-wide rupture scenario

Henneking et al., *SC'25*
Glehman et al., *Seismica*, 2025



A Tsunami Digital Twin for Cascadia Using the World's Largest Computer

- Conventional early-warning systems rely on simplified source models and struggle to resolve **near-field tsunamis that reach shore within minutes**
- New approach that couples seafloor acoustic-pressure data with 3-D acoustic-gravity wave simulations to infer earthquake-driven seafloor motion and **predict tsunami propagation with quantified uncertainty**



A Tsunami Digital Twin for Cascadia Using the World's Largest Computer

- **Billion-parameter inverse problem governed by billions DOF forward model, requires current #1 supercomputer**
- **Synthetic tests based on a Mw 8.7 dynamic-rupture scenario show that 600 seafloor pressure sensors suffice to reconstruct the spatiotemporal seafloor motion and forecast surface-wave heights at 21 locations with 95 % credible intervals**

Inverse problem:

Henneking et al., SC'25

Given pressure recordings from sensors on the seafloor, infer the spatiotemporal seafloor motion in the subduction zone

Forecasting problem:

Given inferred spatiotemporal seafloor motion, forward predict tsunami wave heights at specified coastal locations

See poster by Stefan Henneking



Real-time Bayesian inference at extreme scale:
A digital twin for tsunami early warning applied to the Cascadia subduction zone

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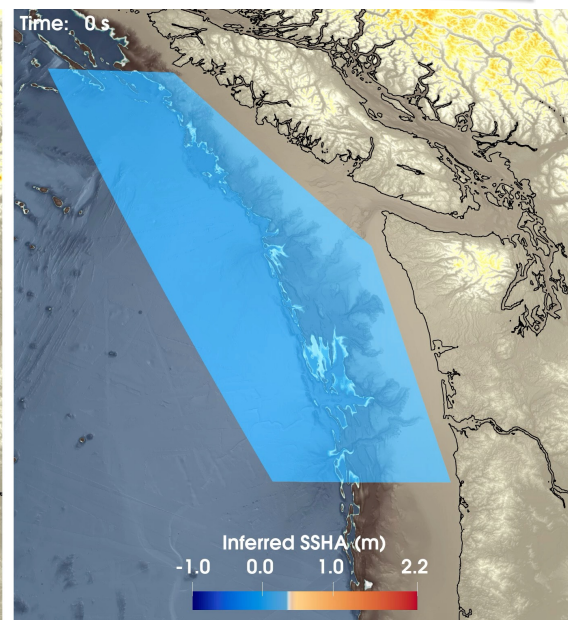
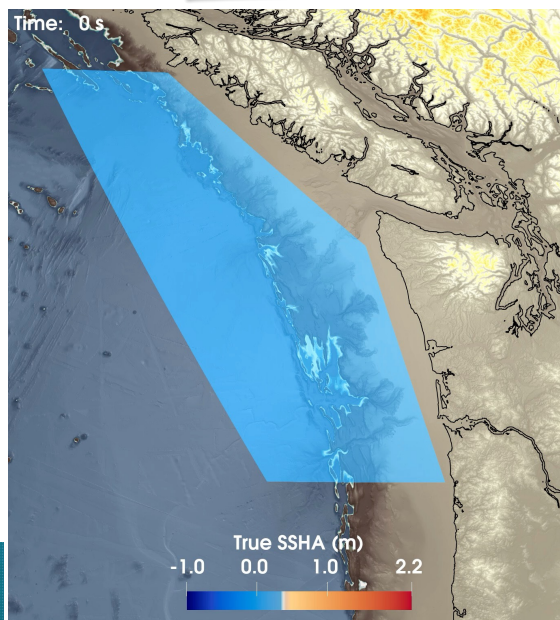
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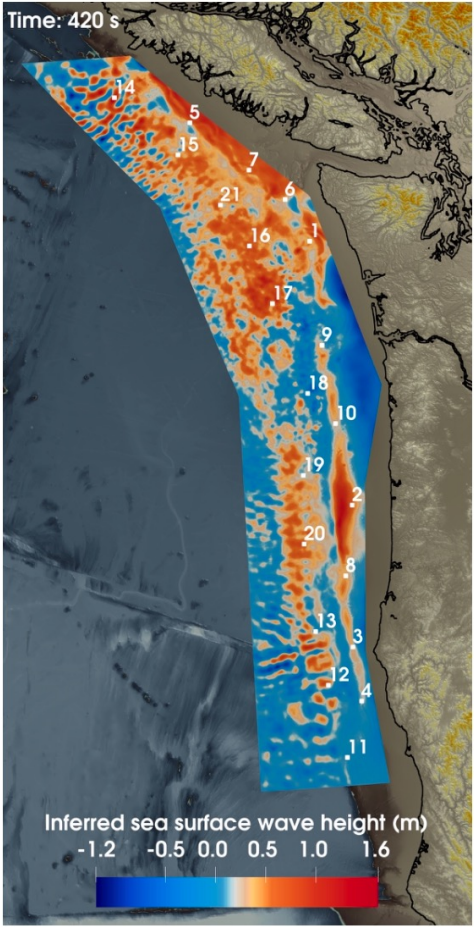


ACM Gordon Bell Prize

Innovations in applying high-performance computing to science, engineering, and large-scale data analytics

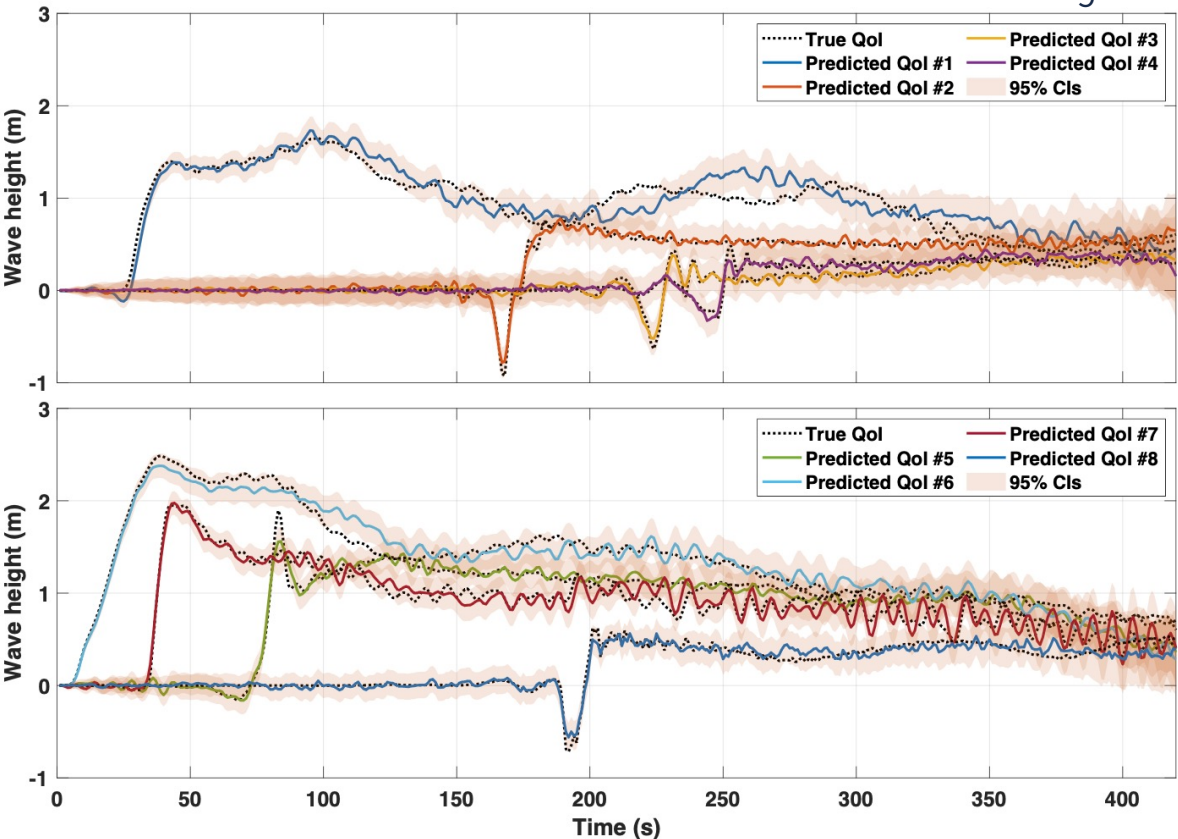
A Tsunami Digital Twin for Cascadia Using the World's Largest Computer

Qol forecasting locations



Real-time Qol predictions with uncertainties illustrated as 95% credible intervals (CIs) inferred from noisy, synthetic data of 600 hypothesized seafloor acoustic pressure sensors for a margin-wide rupture in the CSZ

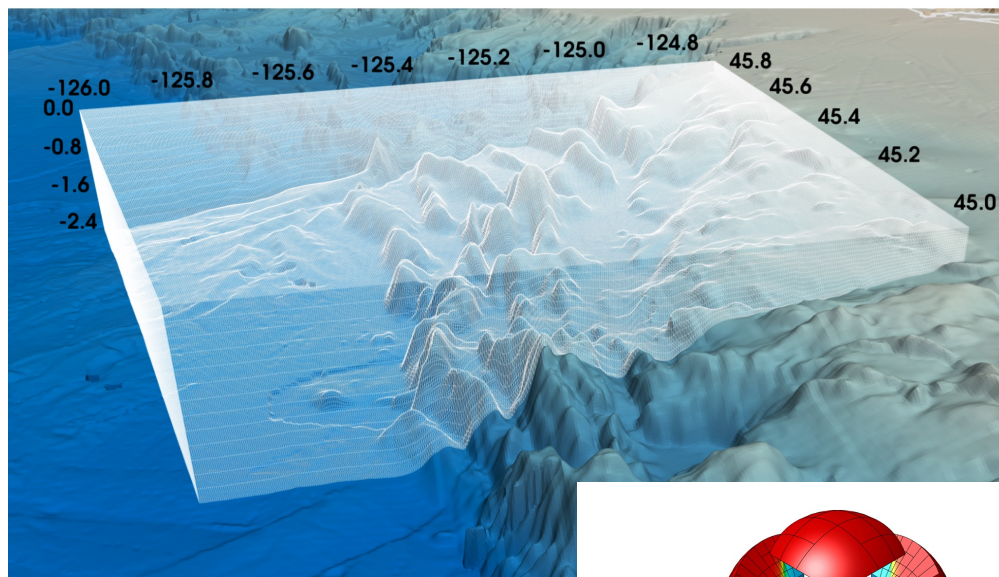
Henneking et al., SC'25



A Tsunami Digital Twin for Cascadia Using the World's Largest Computer

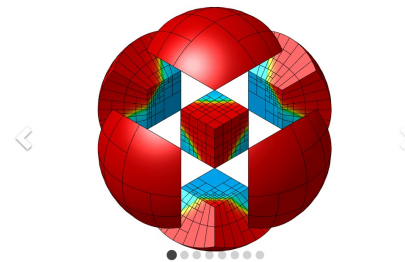
Henneking et al., SC'25

- The method exploits the autonomous (time-invariant) nature of the acoustic-gravity equations to reformulate the **inversion in the data space** rather than parameter space
- A block-Toeplitz representation of the parameter-to-observable map enables FFT-based Hessian matrix-vector products and a complete offline-online decomposition
- Offline: one adjoint wave solve per sensor and forecast site; scaled to **43,520 GPUs on El Capitan** (55.5 trillion DOF, 92 % weak and 79 % strong scaling efficiency)
- Online: exact Bayesian inversion and tsunami prediction in < 0.2 s on 512 GPUs — a 10^{10} -fold speedup over conventional conjugate-gradient solvers
- **Wave heights at critical locations and their uncertainties computed in a fraction of a second**



Next:

- Port to Japan & S-net
- Optimal experimental design for optimal placement of seafloor sensors (e.g, DAS)



MFEM is a free, lightweight, scalable C++ library for finite element methods.

Features

- Arbitrary high-order finite element **meshes** and **spaces**.
- **Wide variety** of finite element discretization approaches.
- Conforming and nonconforming **adaptive mesh refinement**.
- Scalable from laptops to **GPU-accelerated** supercomputers.
- ... and **many more**.

Structural controls on splay fault rupture dynamics in Cascadia megathrust earthquakes

Biemiller et al., AGU Advances, in press

AGU Advances

RESEARCH ARTICLE

10.1029/2025AV001812

Peer Review The peer review history for this article is available as a PDF in the Supporting Information.

Key Points:

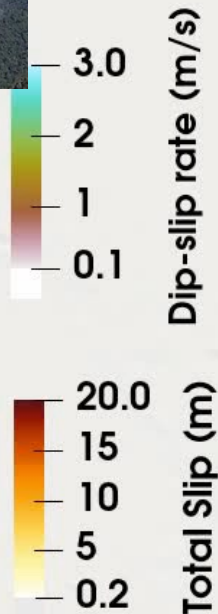
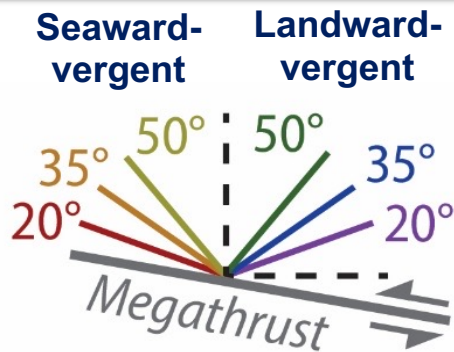
- 3D dynamic rupture models of Cascadia subduction zone earthquakes reveal coseismic competition between megathrust and splay fault rupture
- Fault geometry modulates shallow slip partitioning: gently dipping seaward-vergent splays slip more than steeper, landward-vergent splays
- Distinct static and dynamic mechanisms result in dip- and vergence-dependent splay fault slip during megathrust earthquake ruptures

Structural Controls on Splay Fault Rupture Dynamics During Cascadia Megathrust Earthquakes

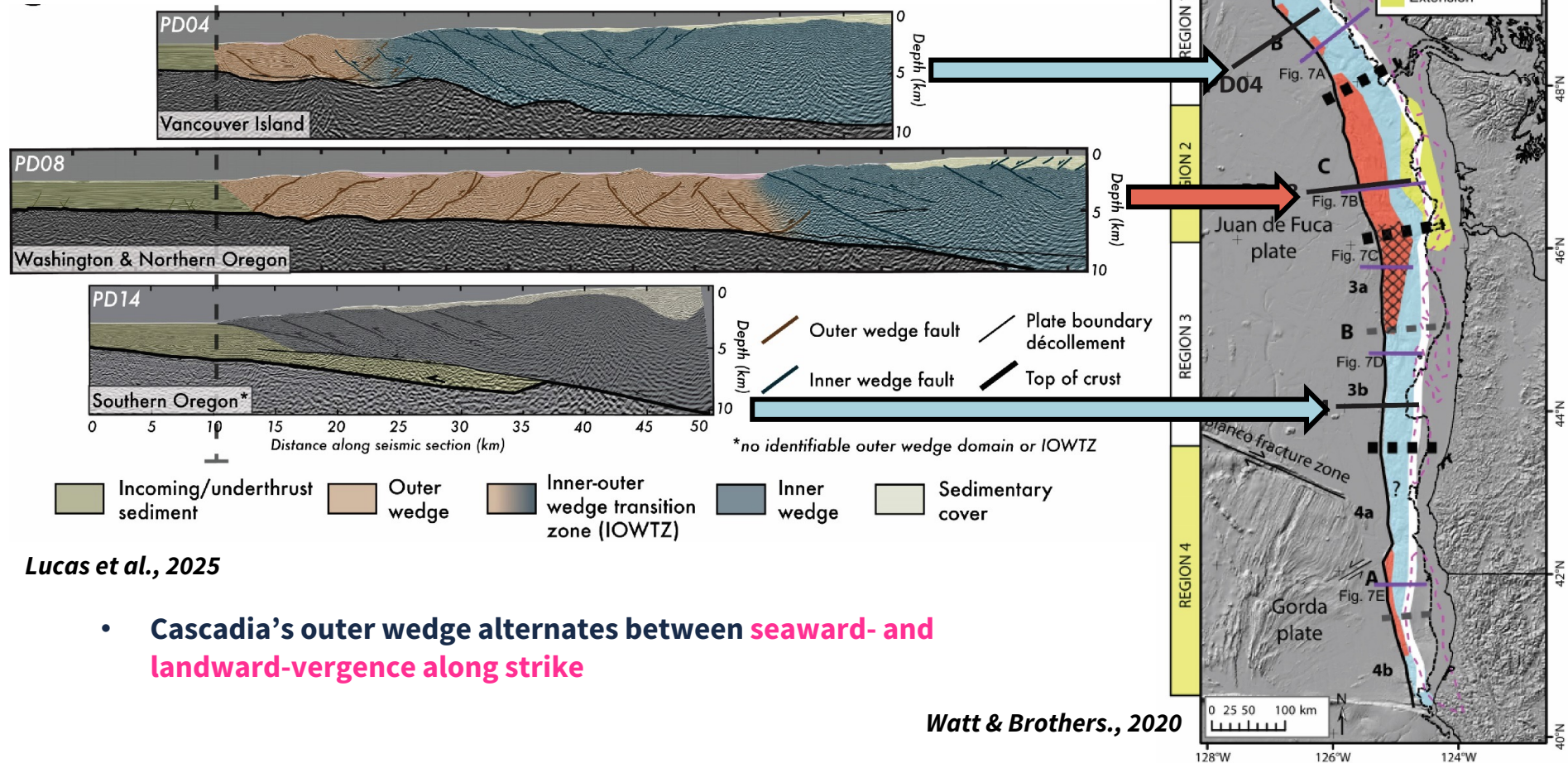
J. Biemiller¹ , A.-A. Gabriel^{2,3} , L. Staisch¹ , T. Ulrich³ , A. Dunham⁴, E. Wirth⁴ , J. Watt⁵ , M. C. Lucas⁶ , and A. Ledeczi⁶ 

¹U. S. Geological Survey, Geology, Minerals, Energy and Geophysics Science Center, Portland, OR, USA, ²Ins. Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA, ³Department of Earth and Environmental Sciences, Ludwig Maximilian University of Munich, Munich, Germany, ⁴U. S. Geological Survey, Earthquake Science Center, Seattle, WA, USA, ⁵U. S. Geological Survey, Pacific Coastal and Marine Science Center, Santa Cruz, CA, USA, ⁶Department of Earth & Space Sciences, University of Washington, Seattle, WA, USA

Abstract Great subduction earthquakes ($M_w \geq 8.0$) can generate devastating tsunamis by rapidly displacing the seafloor and overlying water column. These potentially tsunamigenic seafloor offsets result from coseismic fault slip and deformation beneath or within the accretionary wedge. The mechanics of these shallow rupture phenomena and their dependence on subduction zone properties remain unresolved, partly due to the sparsity of offshore observations of shallow megathrust earthquake deformation. Here, we analyze how offshore structure



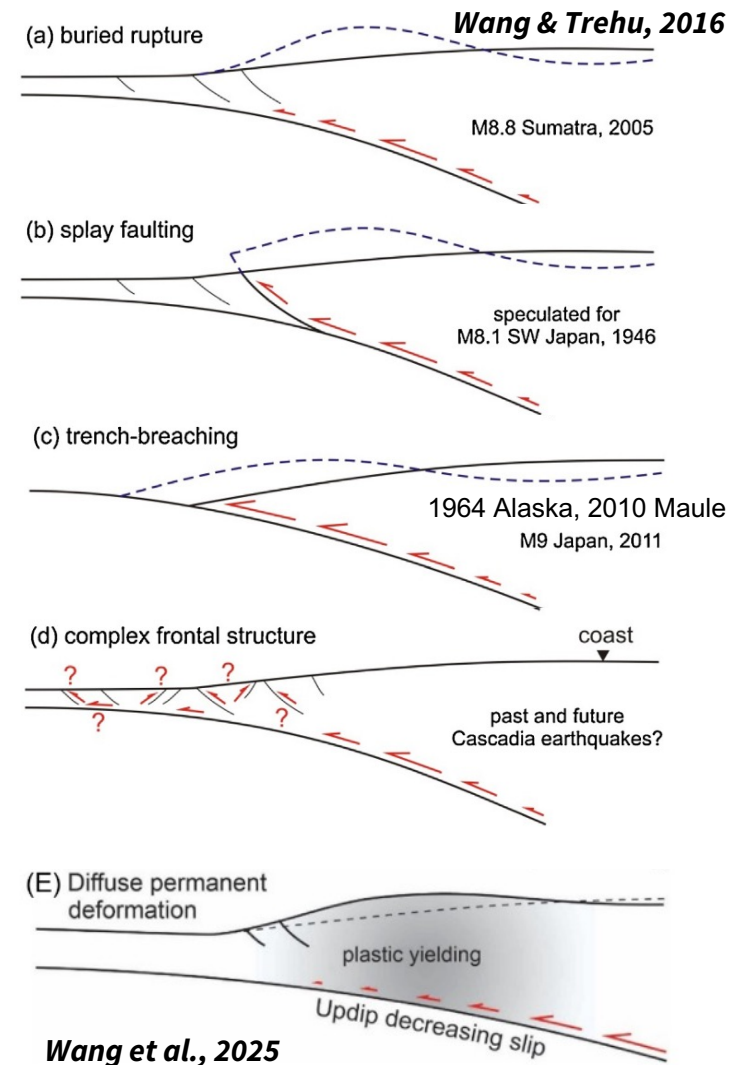
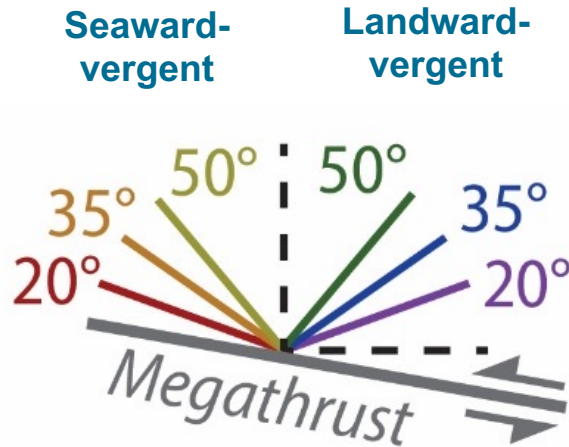
Cascadia splay faults: along-strike structural variability



- Cascadia's outer wedge alternates between **seaward-** and **landward-vergence** along strike

Splay fault dynamic rupture

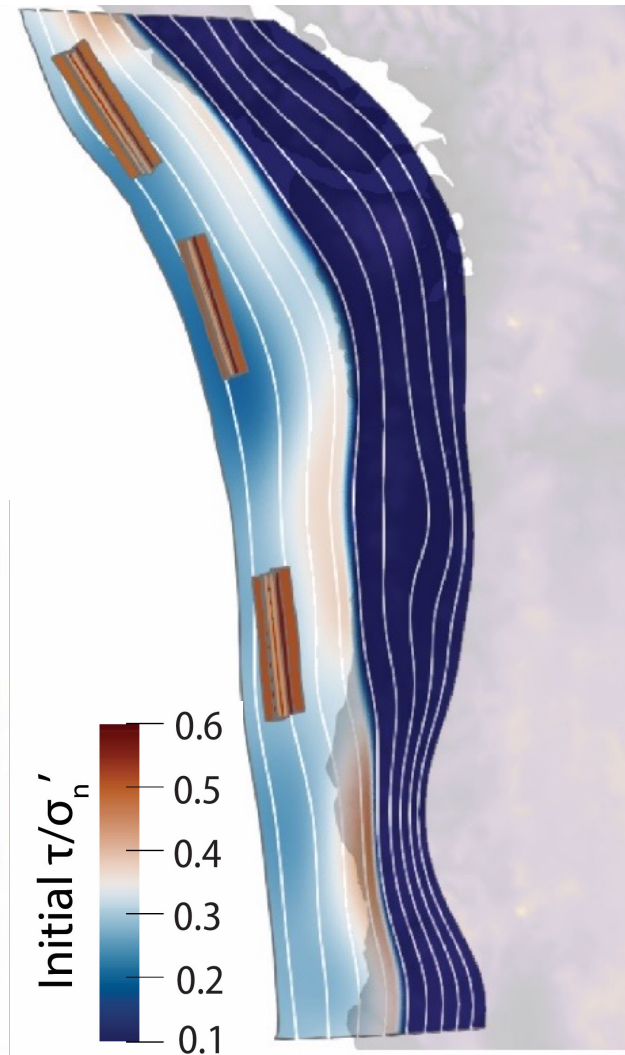
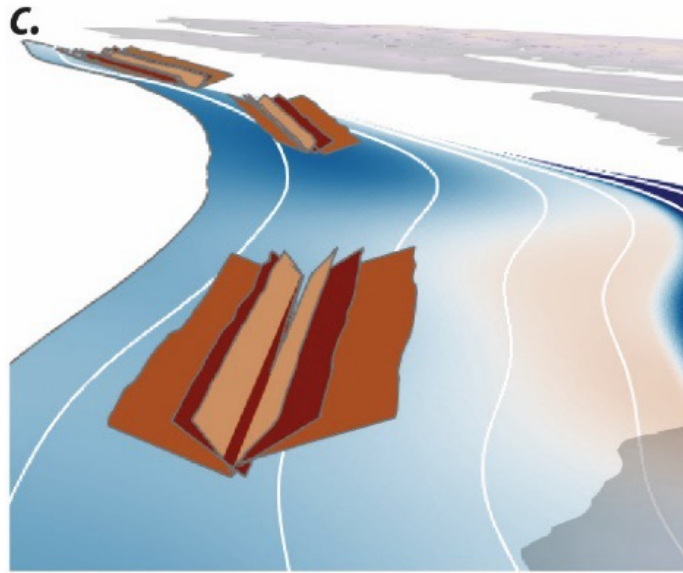
- **Different dynamic rupture pathways and tsunami sources:**
How do different splay faults modulate coseismic slip partitioning, shallow deformation and eventually tsunami hazard when a megathrust earthquake reaches the shallow wedge?



Structural controls on **splay faulting** in Cascadia subduction zone earthquakes

Biemiller et al., AGU Advances, in press

- Large (margin-wide) dynamic rupture models of Cascadia subduction zone earthquakes to study **coseismic competition** between megathrust and splay fault rupture
- Fault geometry modulates shallow slip partitioning: **gently dipping seaward-vergent splays slip more** than steeper, landward-vergent splays
- Distinct **static and dynamic rupture mechanics** result in dip- and vergence-dependent splay fault slip during megathrust earthquake ruptures

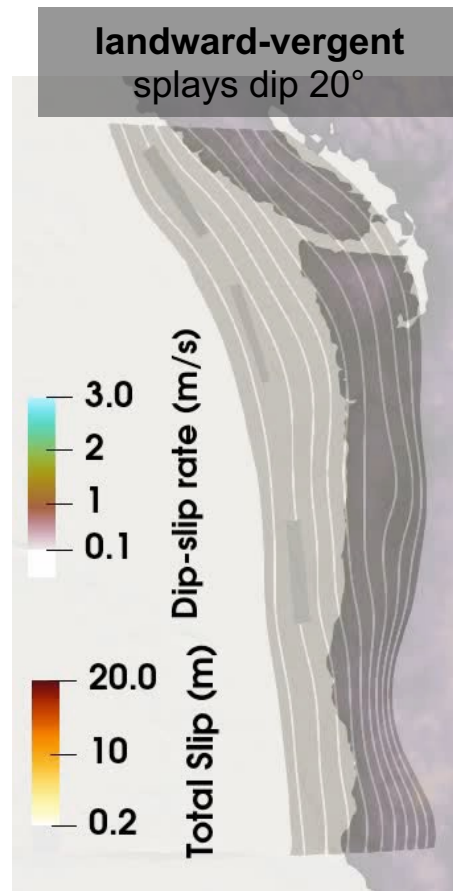
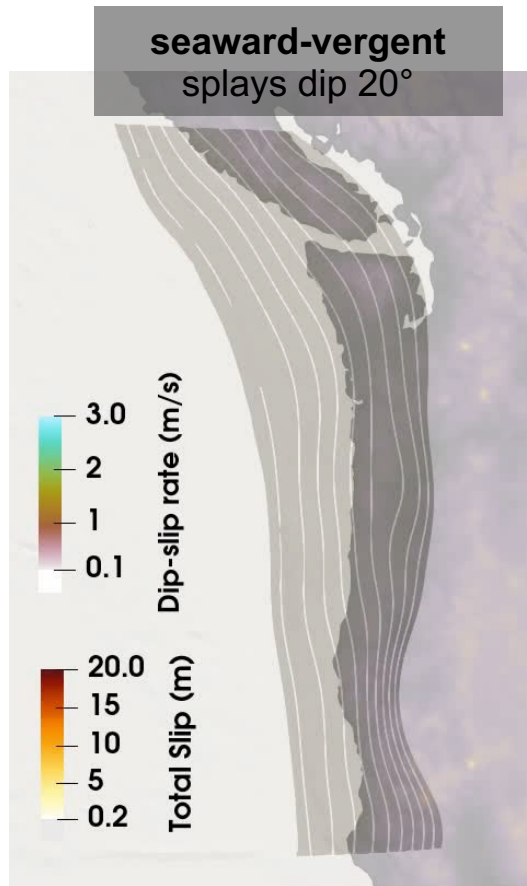
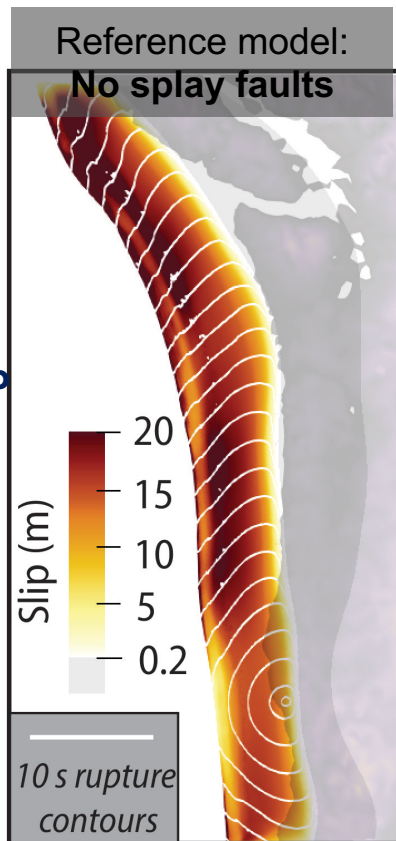


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Biemiller et al., AGU Advances, in press

Shallow rupture partitions between the megathrust and splays; **more splay slip means less updip interface slip**

Shallow-dipping and seaward-vergent splays are more dynamic rupture-viable and take more slip

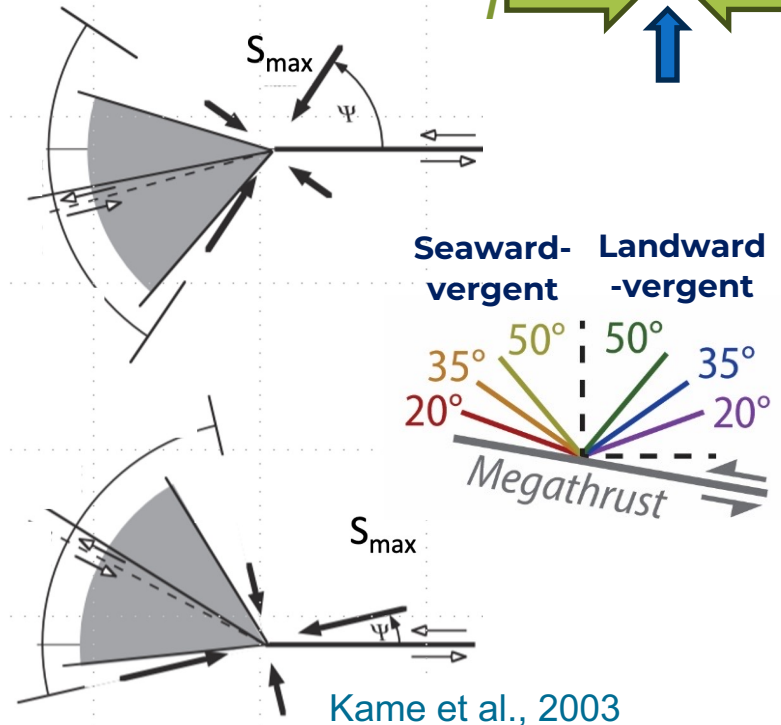
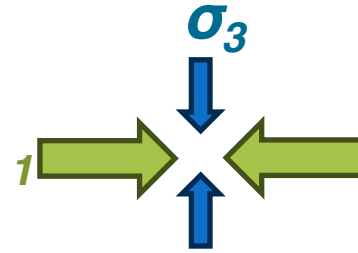


Structural controls on **splay faulting** in Cascadia subduction zone earthquakes

Biemiller et al., AGU Advances, in press

- **Shallowly dipping splays better-oriented** in the classic, quasistatic sense
- **Seaward-vergent splays** better-oriented for positive **dynamic stressing** ahead of updip-propagating rupture **forward-branching** is dynamically favorable
- Applied to Cascadia, we expect **stronger localization of coseismic uplift over splays** offshore Vancouver Island and in southern Oregon **where sea-award vergence dominates**, and **more distributed uplift** involving both splays and the deformation front offshore Washington where **landward-vergence** dominates

Andersonian thrust-faulting:



Kame et al., 2003

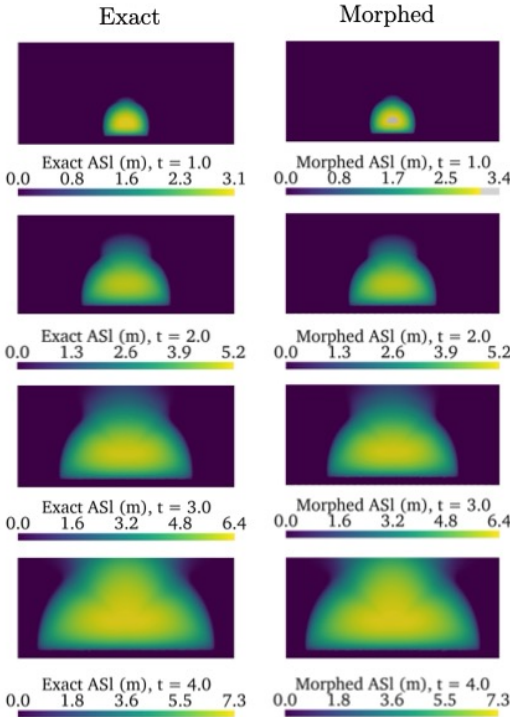
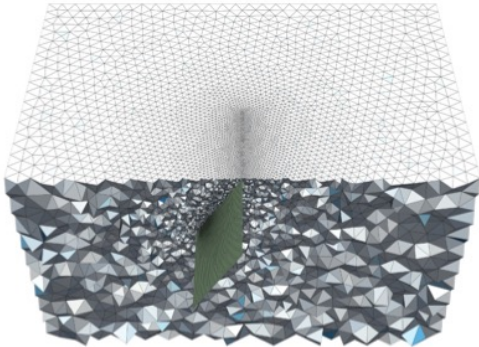
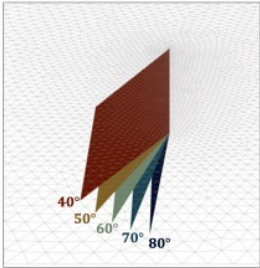
Near-Instantaneous physics-based reduced-order modeling



Surface displacement from dynamic rupture simulations

► 10^8 x faster !

Hobson et al., 2025



arXiv > physics > arXiv:2506.15892

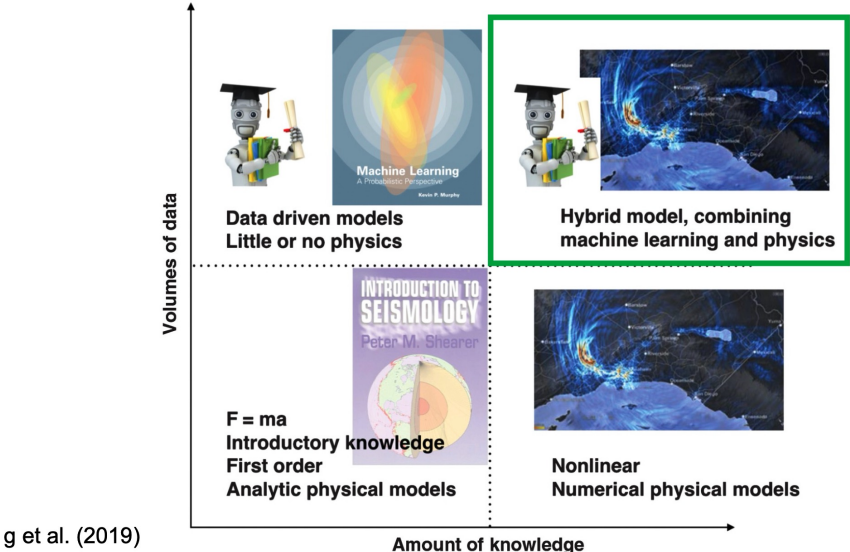
Physics > Geophysics

[Submitted on 18 Jun 2025]

Quantifying the influence of fault geometry via mesh morphing with applications to earthquake dynamic rupture and thermal models of subduction

Gabrielle M. Hobson, Dave A. May, Alice-Agnes Gabriel

... just accepted in G3

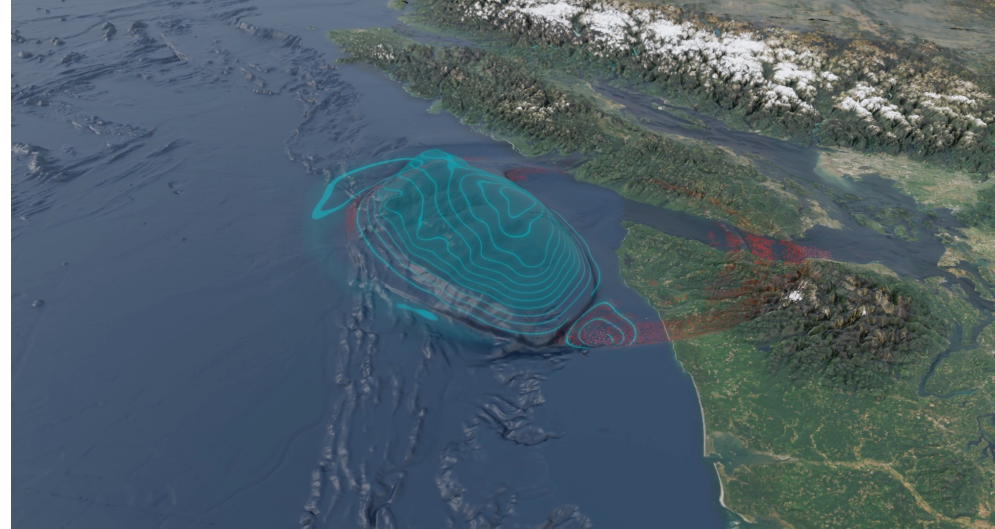


g et al. (2019)

Summary

www.alicegabriel.com

Art in HPC Submission SC'25



- In our 3D dynamic rupture simulations, with (1D) depth-dependent rigidity and pore fluid pressure, informed from geodetic slip-deficit models, tend to favor **partial ruptures**; margin-wide rupture is only possible when elevating central Cascadia's slip deficit
- Splay faults and the megathrust **compete for co-seismic slip**, gently dipping **seaward-vergent splays slip more** than steeper landward-vergent ones, and the underlying drivers are a combination of static alignment with the tectonic stress field and dynamic forward-branching as rupture nears the free surface
- A new digital-twin framework enables **real-time probabilistic tsunami forecasting for near-field Cascadia dynamic rupture-tsunami scenarios**, demonstrating the feasibility of Bayesian data assimilation at exascale for Earth-system hazard

Henneking et al., SC'25

Glehman et al., Seismica, 2025

Biemiller et al., AGU Advances, in press

Thank you! Questions?

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