SCRIPPS INSTITUTION OF OCEANOGRAPHY
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LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Supercomputing for rupture and tsunami dynamics throughout the seismic cycle on megathrust scales

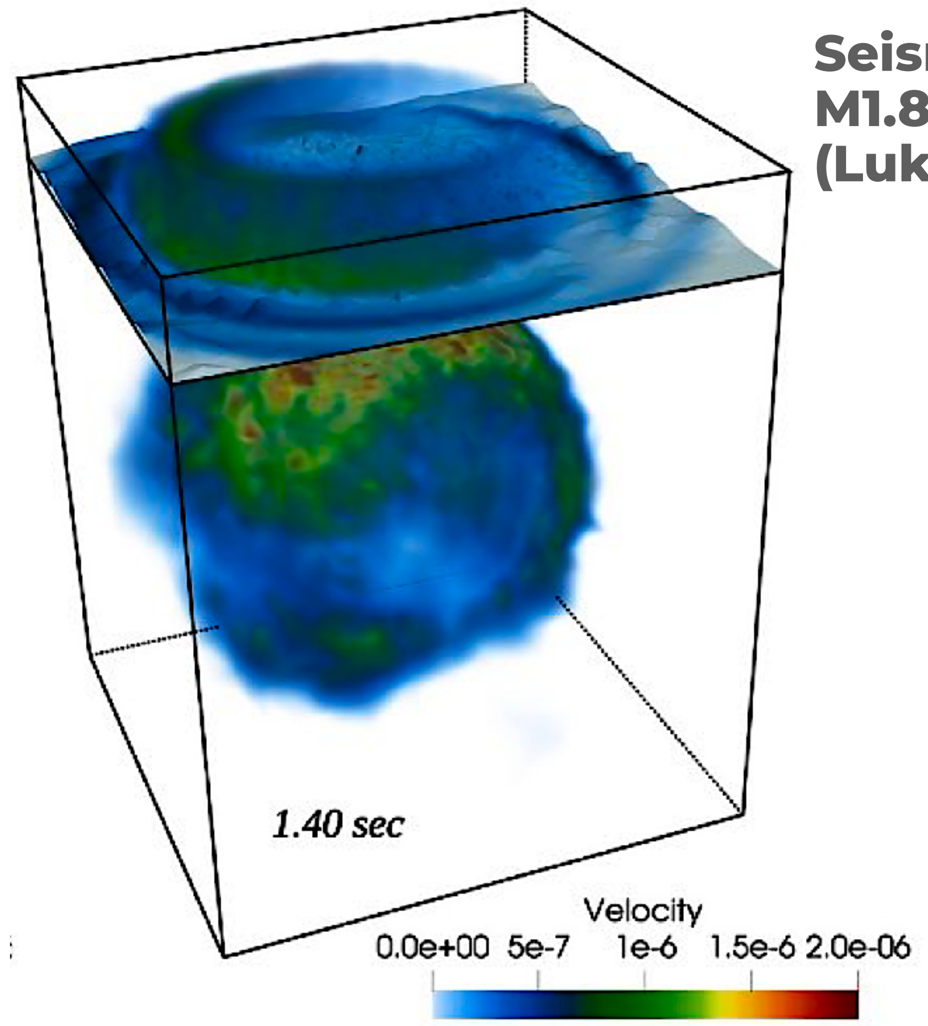
Alice-Agnes Gabriel
(and many collaborators)

Krenz et al. SC'2021

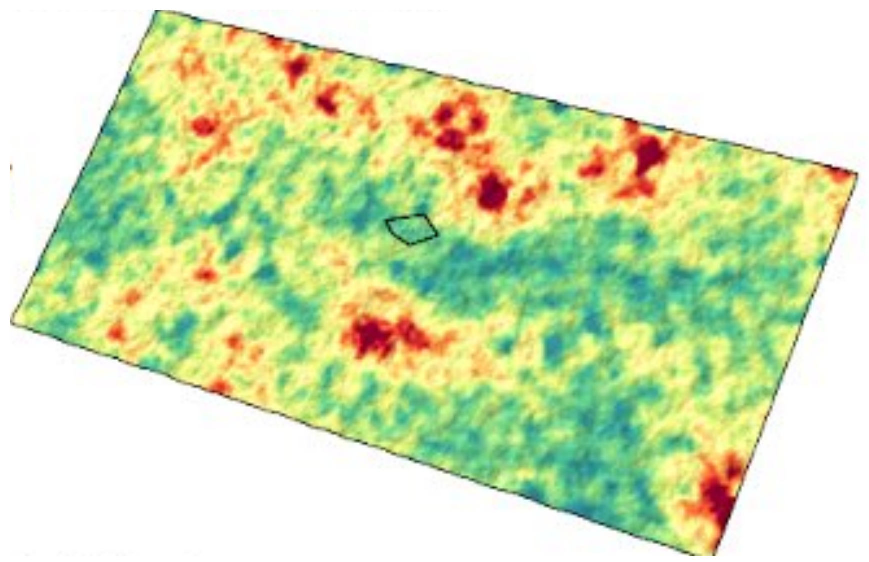
3D Rupture and tsunami dynamics modeling

Adapted from Harris et al., SRL 2011, 2018

- 3D models strive for the **integration and interpretation of the full breath of geophysical observations**

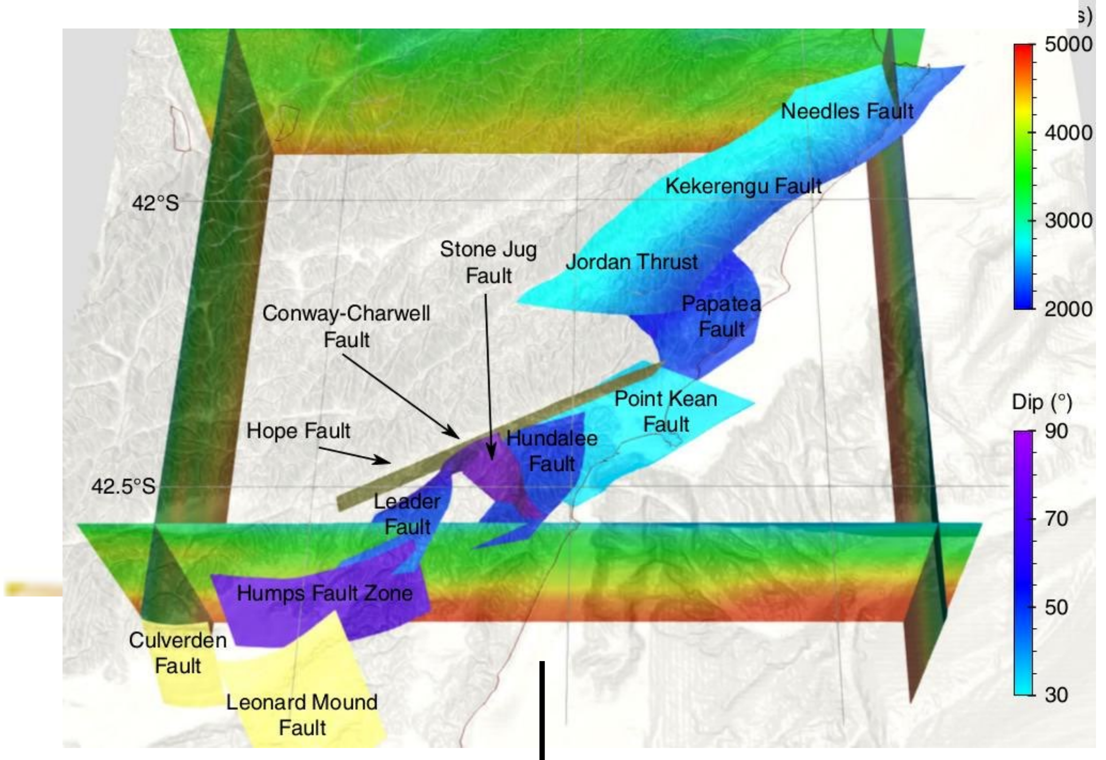


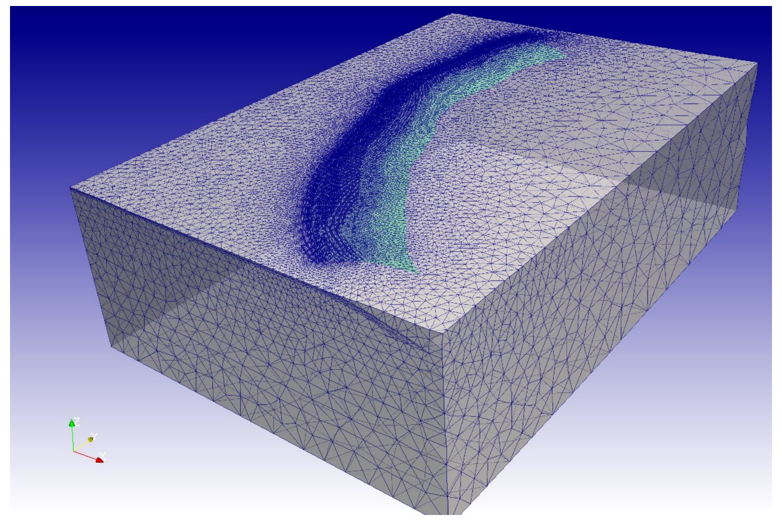
Seismic-acoustic simulation of the ‘bang’ that a M1.8 induced earthquake produces in Helsinki (Lukas Krenz et al., ArXiv)



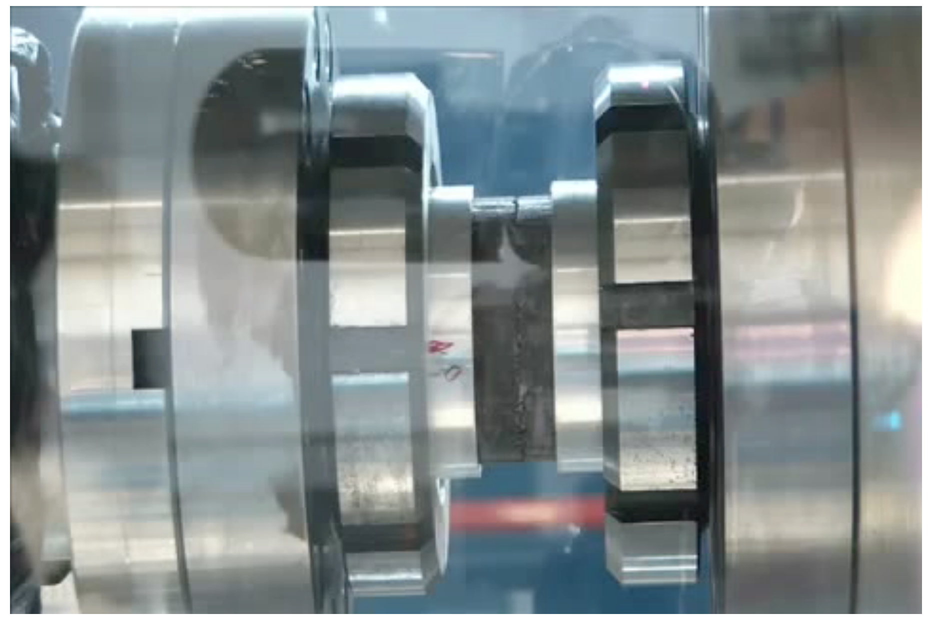
Initial fault loading

Geology





Mesh generation



Friction experiments

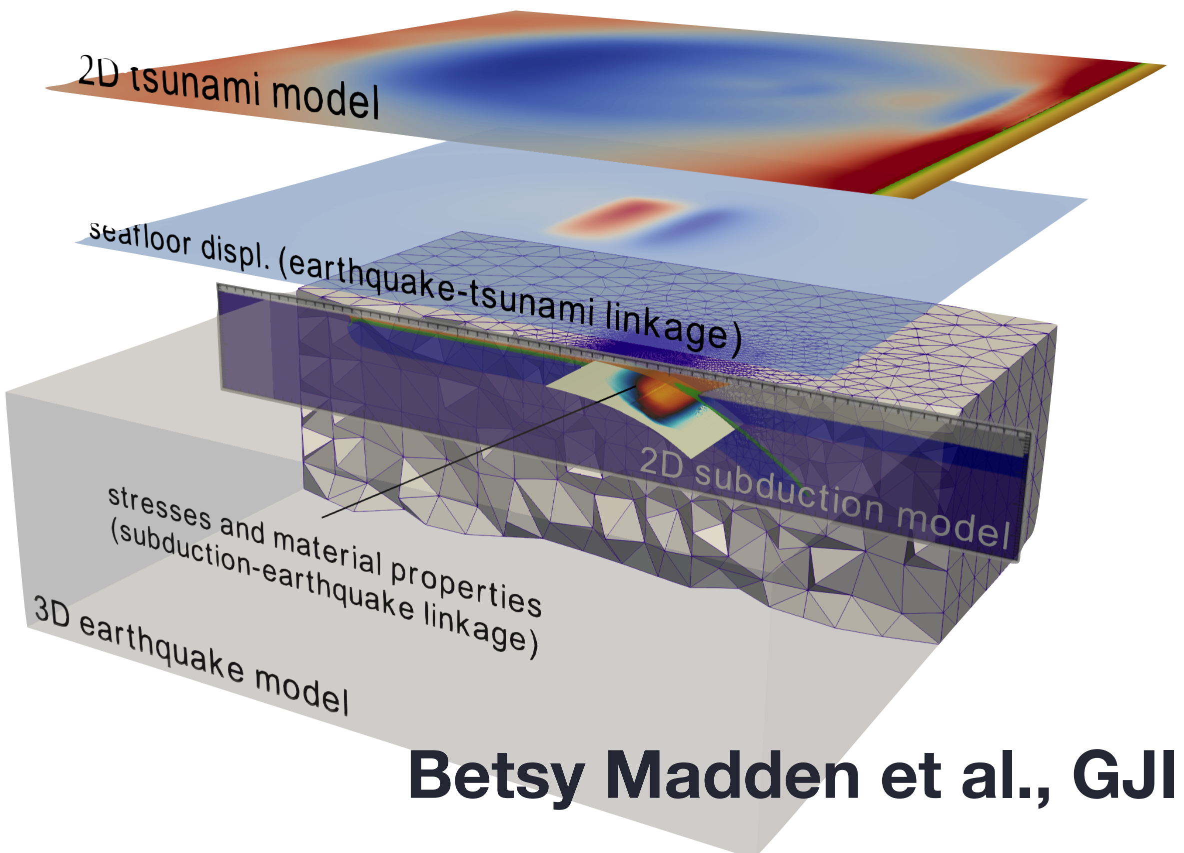
“Input”

SOLVER

“Output”

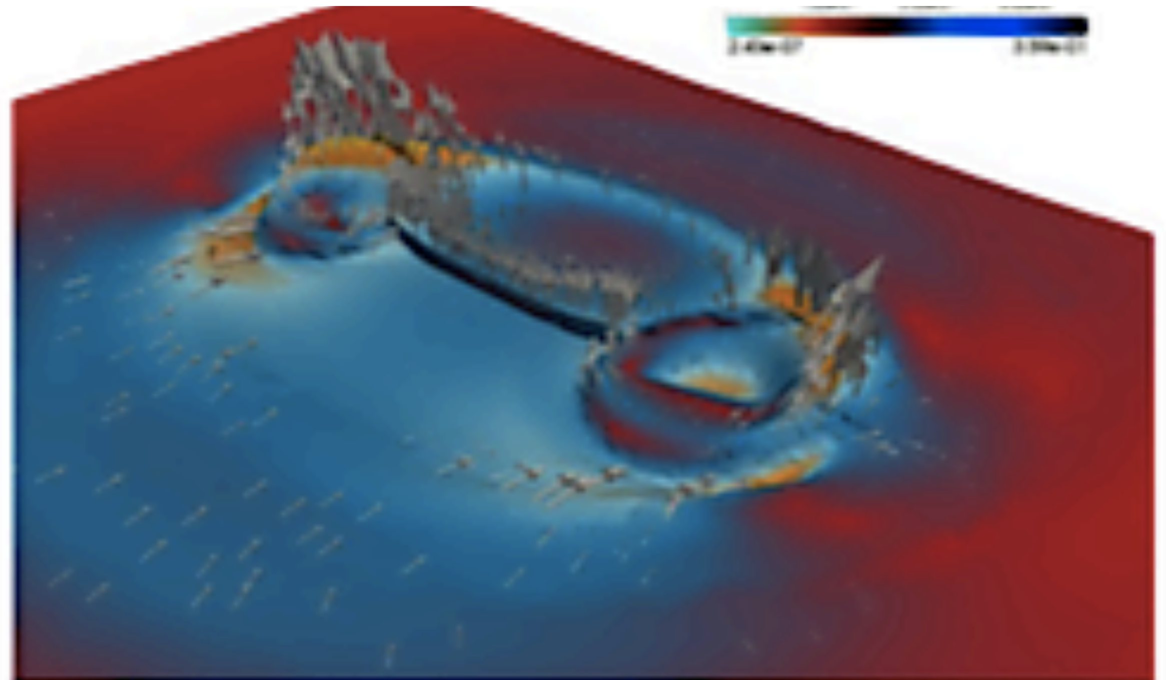
Fundamental Physics

Coupling to long-term geodynamics and acoustic & tsunami wave propagation

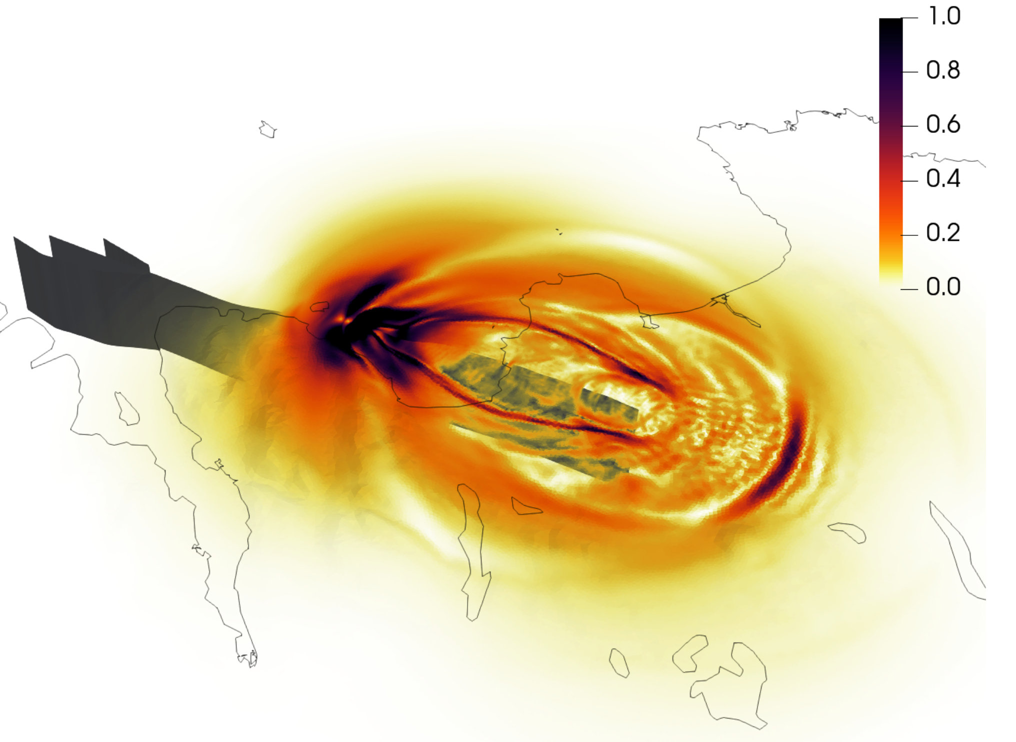


Betsy Madden et al., GJI 2020

Ground deformation



Synthetic observables

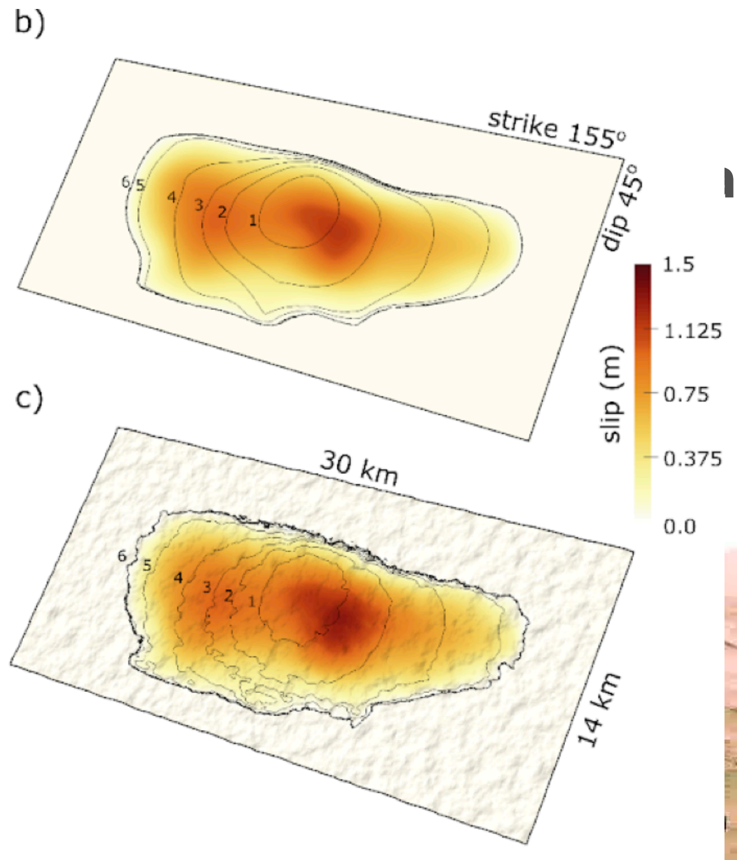


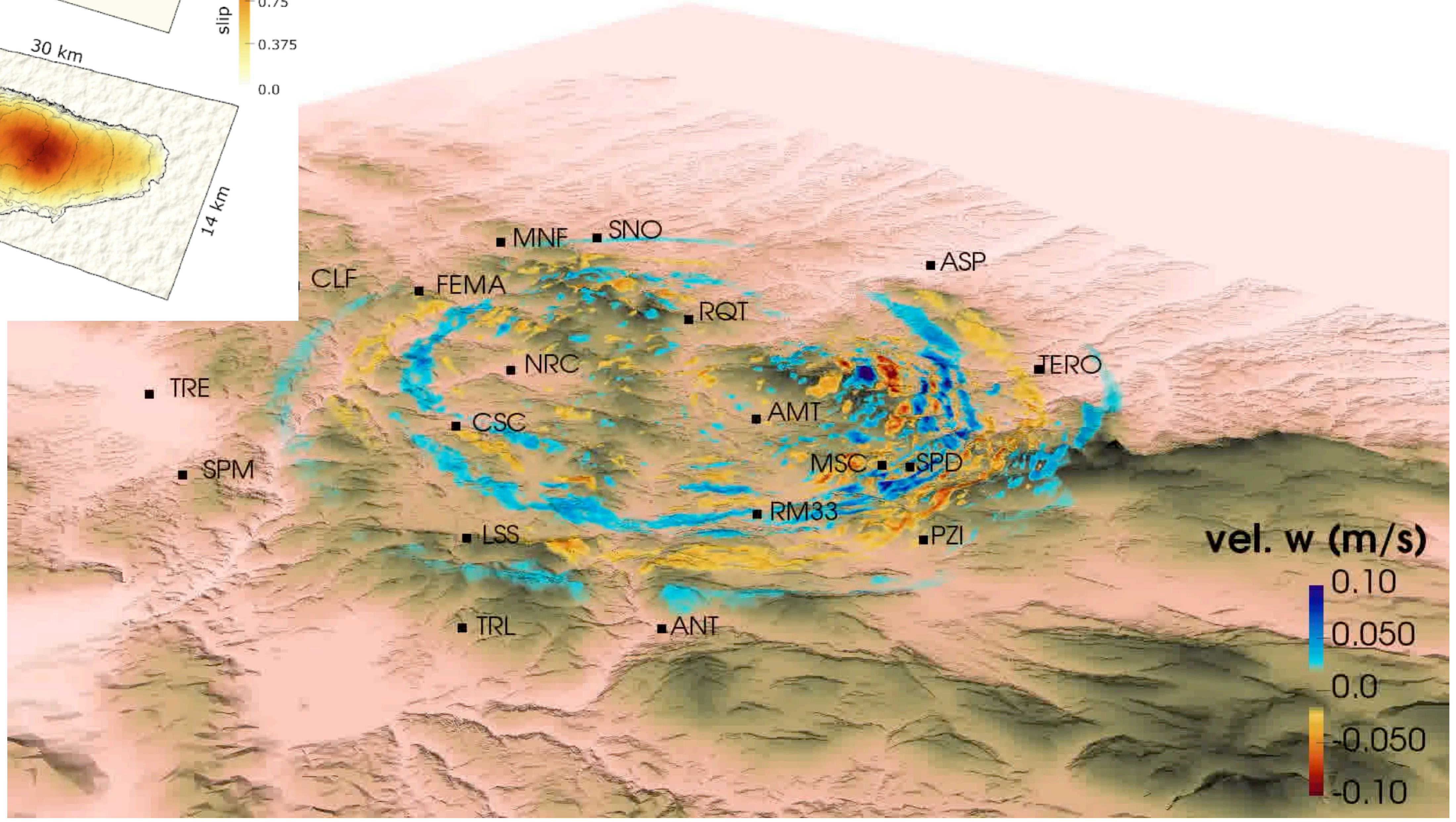
HPC enables data-driven *and* physics-based models

- Recent work demonstrating feasibility of physics-based earthquake inversion, broadband ground motion modeling, and PSHA

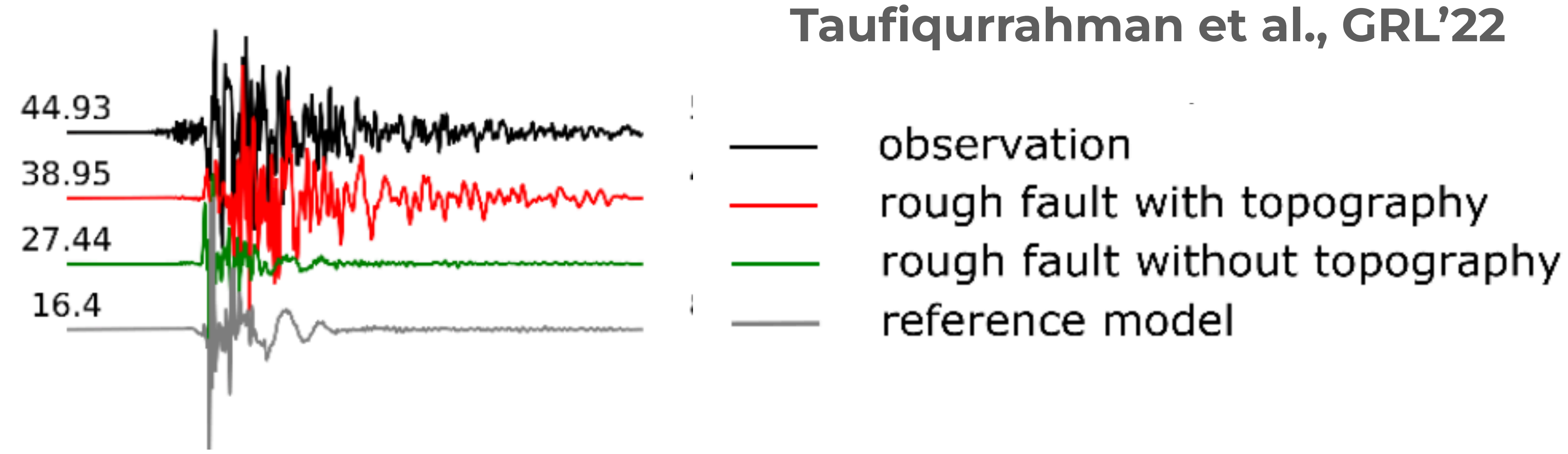
Fully Physics-based Broadband Ground motion modeling: We extend a smooth, best-fitting 2016 Amatrice earthquake dynamic rupture model from Bayesian dynamic rupture source inversion of strong-motion data (<1 Hz) with fractal fault roughness, frictional heterogeneities, viscoelastic attenuation, and topography. High-frequency ground motions are amplified early-on by fault roughness, while topography-induced scattered waves prolong their duration.

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



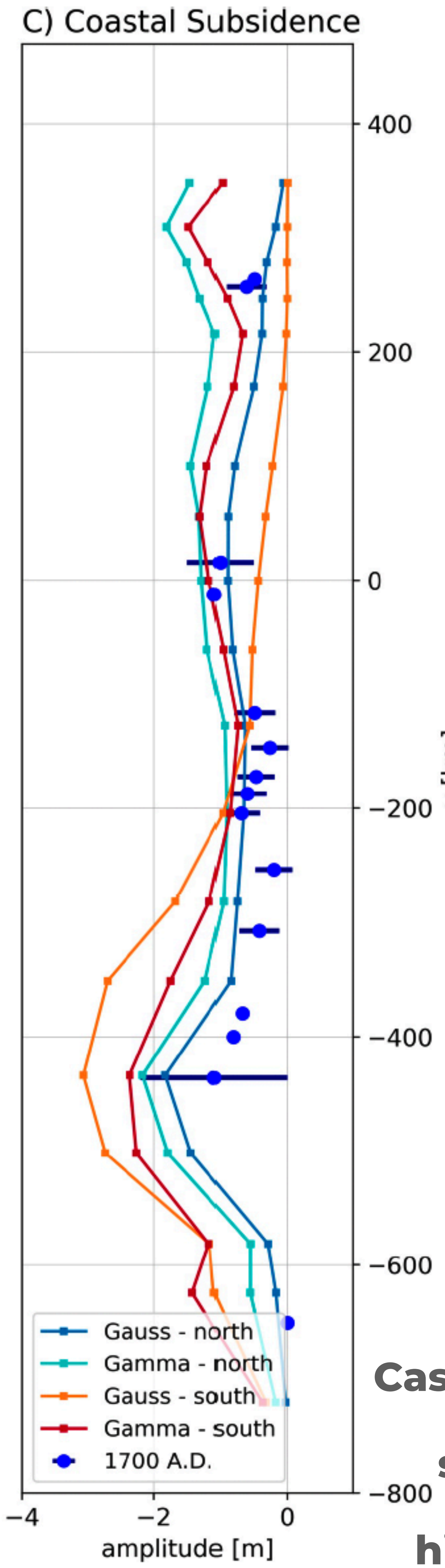


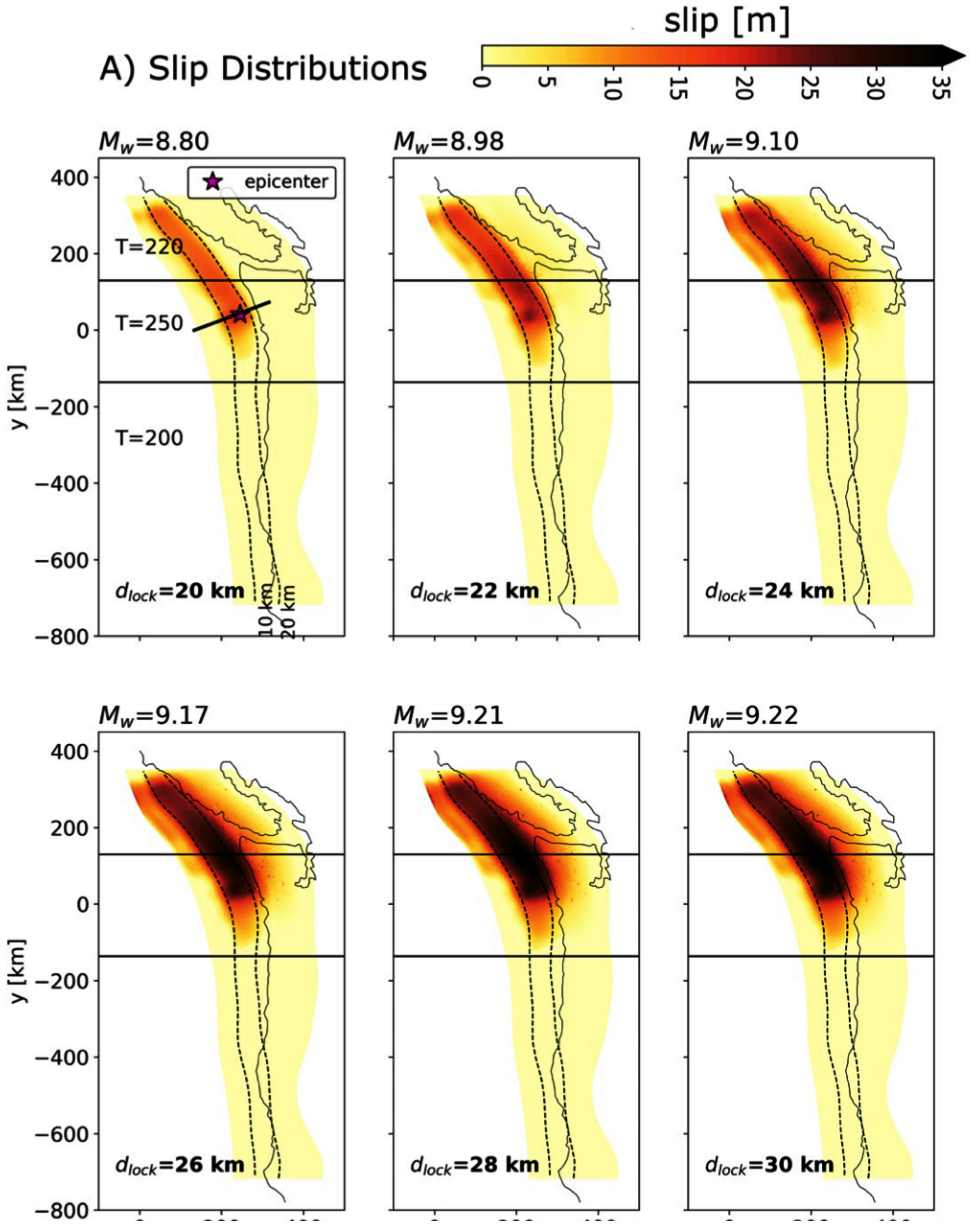
Taufiqurrahman et al., GRL'22



3D earthquake modeling on megathrust scales

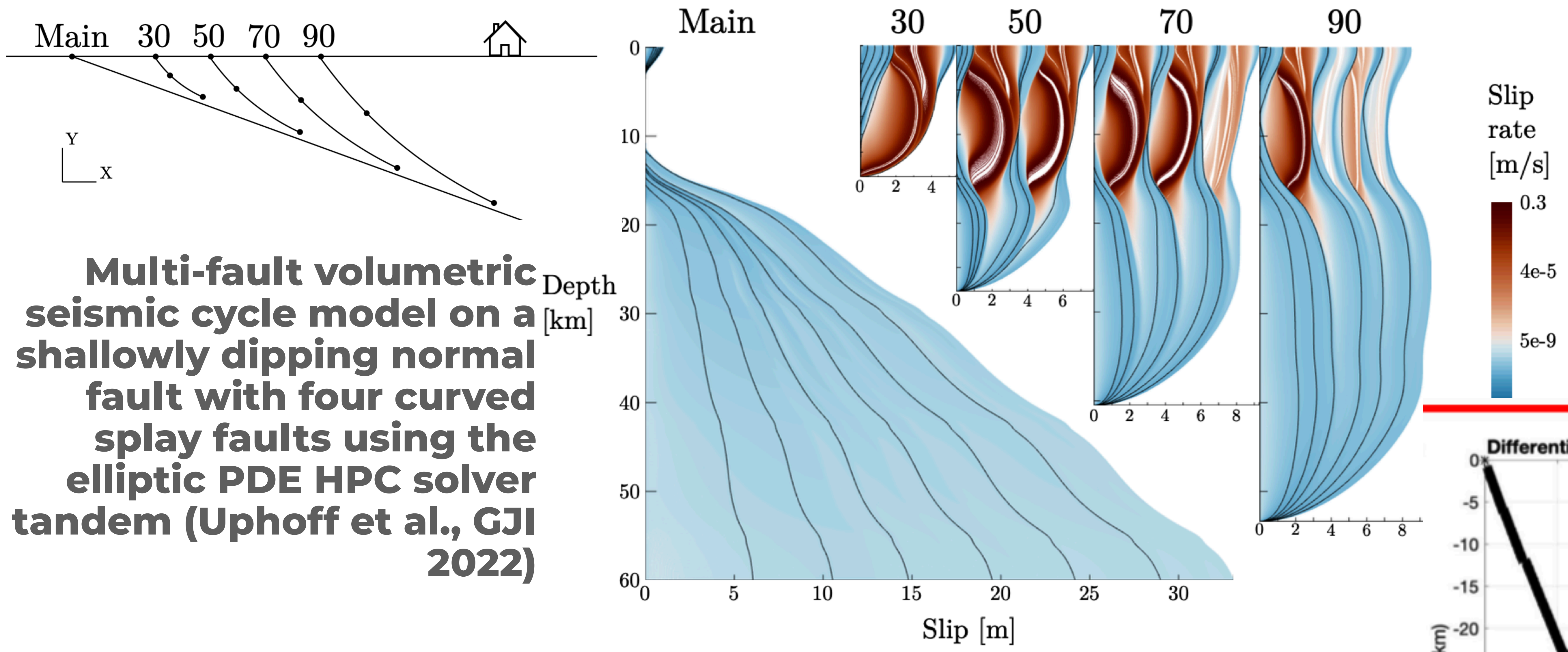
- **Requires numerical methods handling geometric complexity and highly varying resolution requirements (e.g., SeisSol for dynamic rupture + seismic wave propagation and tandem for volumetric seismic cycling, see Poster by James Biemiller)**
- **End-to-end computational optimization** including auto-generated assembler-level DG kernels, hybrid MPI/OpenMP parallelization, a geoinformation server (ASAGI) for fast and asynchronous input/output and clustered local time stepping
- **"Hero runs", e.g.** with 220 million finite elements (~111 billion degrees of freedom) and 3.3M time steps took 14h (in 2017)
- Todays typical subduction earthquake simulations (20 million elements) now require **5h30 minutes on 16 nodes** (4k CPUh)





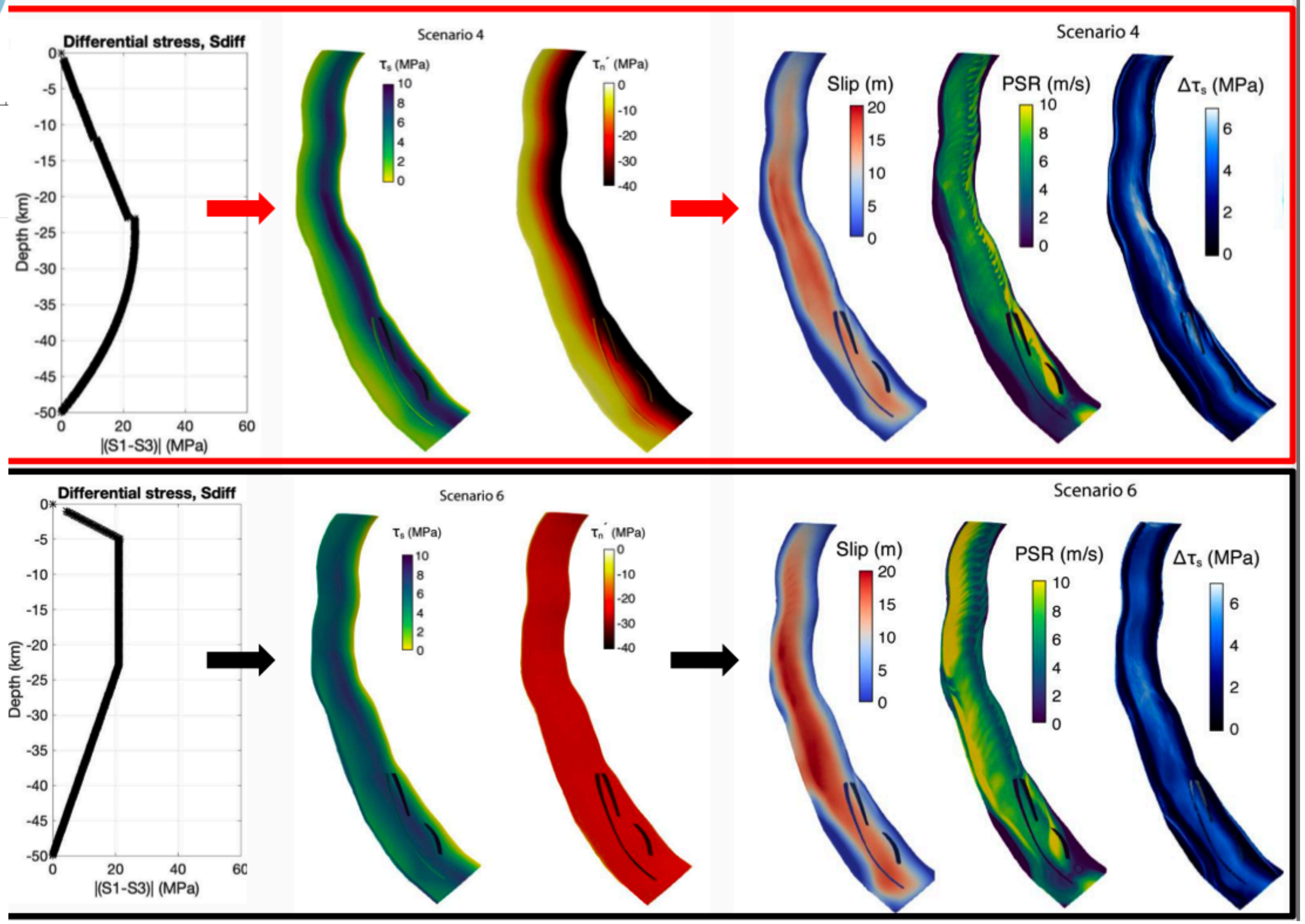
Locking depth is a key factor allowing for margin-wide Cascadia dynamic rupture earthquake simulations. A close fit to 1700 A.D. subsidence data can be achieved using shallow Gaussian or Gamma coupling distributions with locking depths of 15 or 20-km depth, without localized, high amplitude slip asperities along the down-dip region
Marlon Ramos et al., JGR 2021

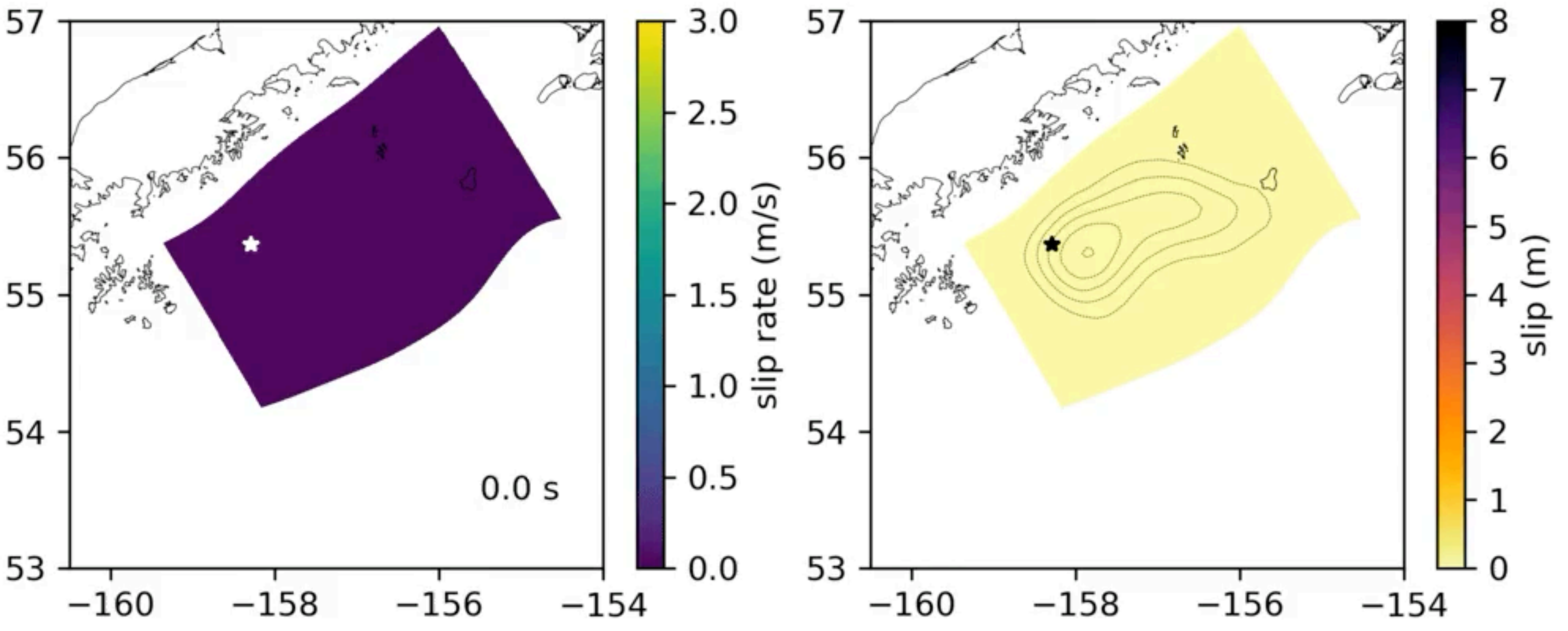
3D earthquake modeling on megathrust scales



Multi-fault volumetric seismic cycle model on a shallowly dipping normal fault with four curved splay faults using the elliptic PDE HPC solver tandem (Uphoff et al., GJI 2022)

Sub-lithostatic (above) vs lithostatic (below) pore fluid pressure on coseismic rupture dynamics: Increasing Pf decreases fault strength, Mw, cumulative slip, peak slip rate, stress drop, and rupture velocity. Betsy Madden et al., JGR 2022

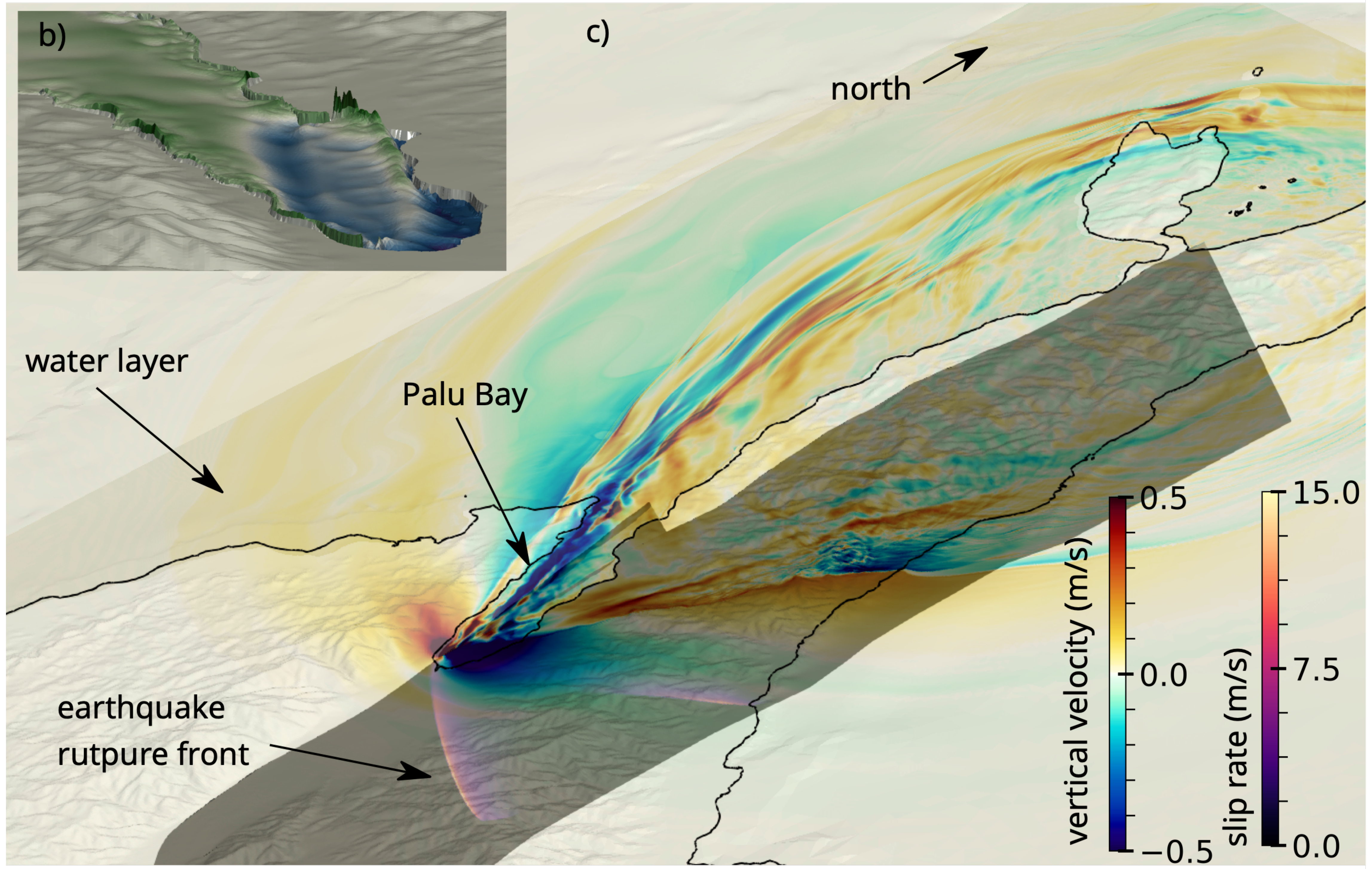




The effect of thermal pressurization at hypocentral depth drives a run-away rupture of the 2021 Chignik Alaska Earthquake (Duo Li et al., AGU 2022)

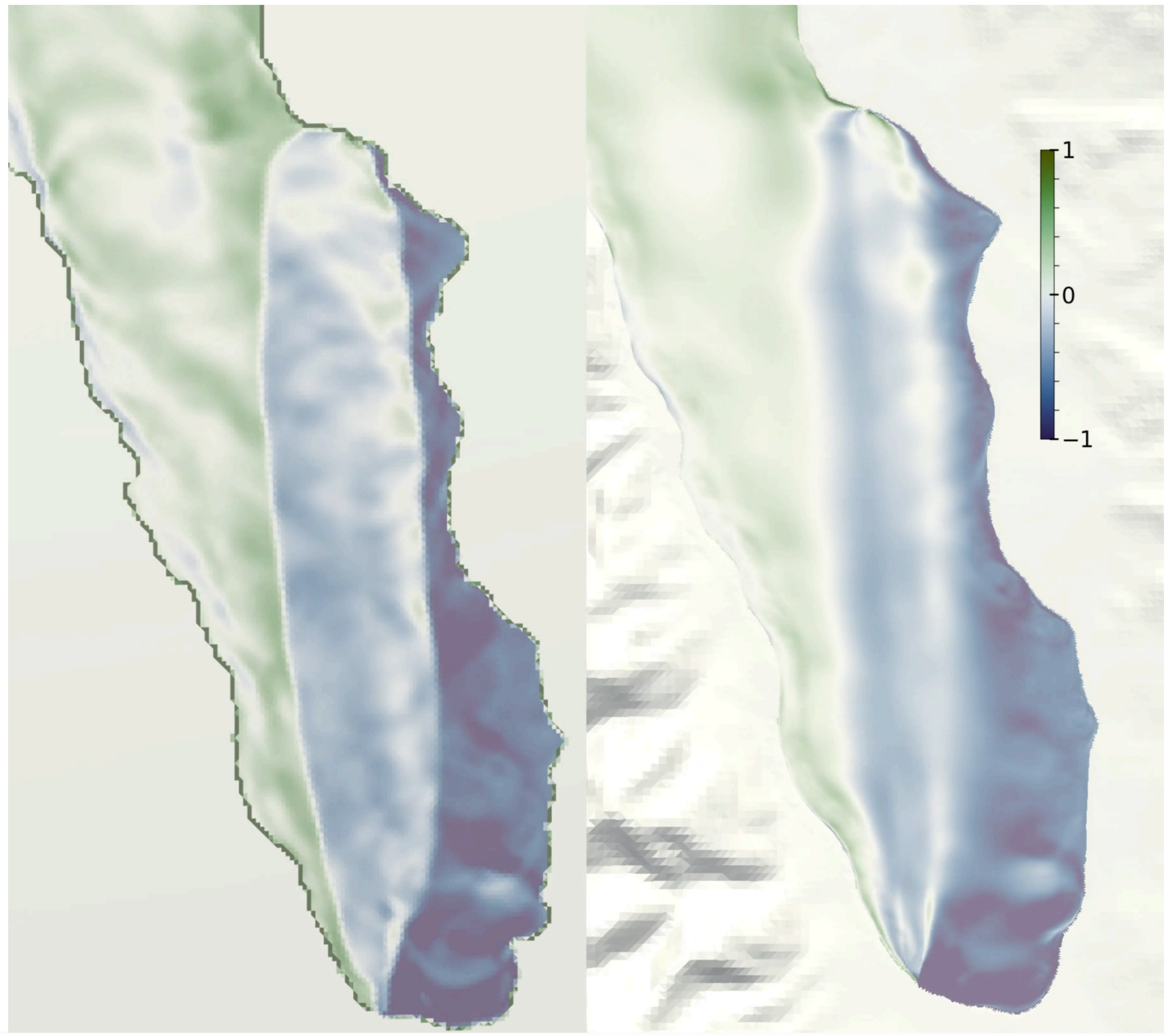
HPC enables data-driven *and* physics-based models

- **New ways how physics-based modeling bridges gaps, e.g. between currently often separate seismic / tsunami hazard assessment**



Fully-coupled earthquake, acoustic and tsunami model for the 2018 Palu events.

Lukas Krenz et al. SC'2021



- fully-coupled 3D simulations open the possibility to explore the effects of **variable depth ocean non-hydrostatic response, compressibility and acoustic wave generation across complex bathymetry**

- **seismic waves (including the sharply imprinting supershear Mach front)** result in transient motions of the sea surface and affect the ocean response **but do not appear to contribute to tsunami generation**

Coupled earthquake and tsunami modeling
Comparison of Model Techniques

New in 3D

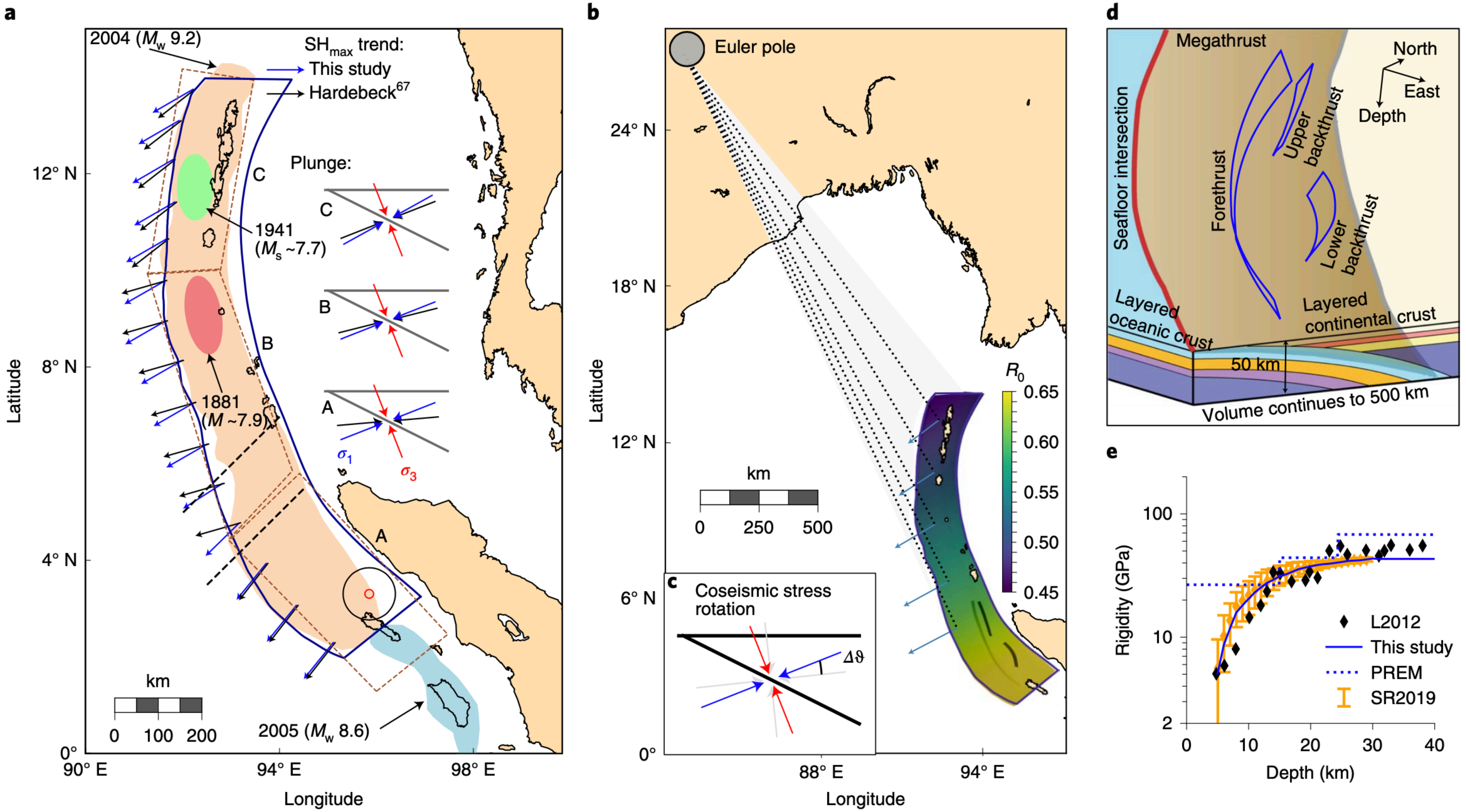
	Static Initial Conditions	Time-dependent Seafloor Velocity as Forcing	Time-dependent Sea Surface Velocity as Forcing	Fully Coupled Method (SeisSol)
Earthquake Simulation	Final earthquake seafloor or sea surface uplift recorded	Record earthquake seafloor velocity	Solves earth and ocean response without gravity	Simultaneously solves earthquake rupture, seismic waves, and ocean response (including gravity) http://www.seissol.org/
Tsunami Simulation	Set initial tsunami sea surface height	Set time-dependent forcing in the tsunami mass balance	Use sea surface velocity as a forcing term in a tsunami simulation	
Citations	(Kajiura, 1963, 1970) (Tanioka & Satake, 1996) (Saito, 2019)	(Saito & Furumura, 2009) (Saito & Tsushima, 2016) (Saito, 2019)	(Saito et al., 2019) (Saito, 2019)	(Lotto & Dunham, 2015)

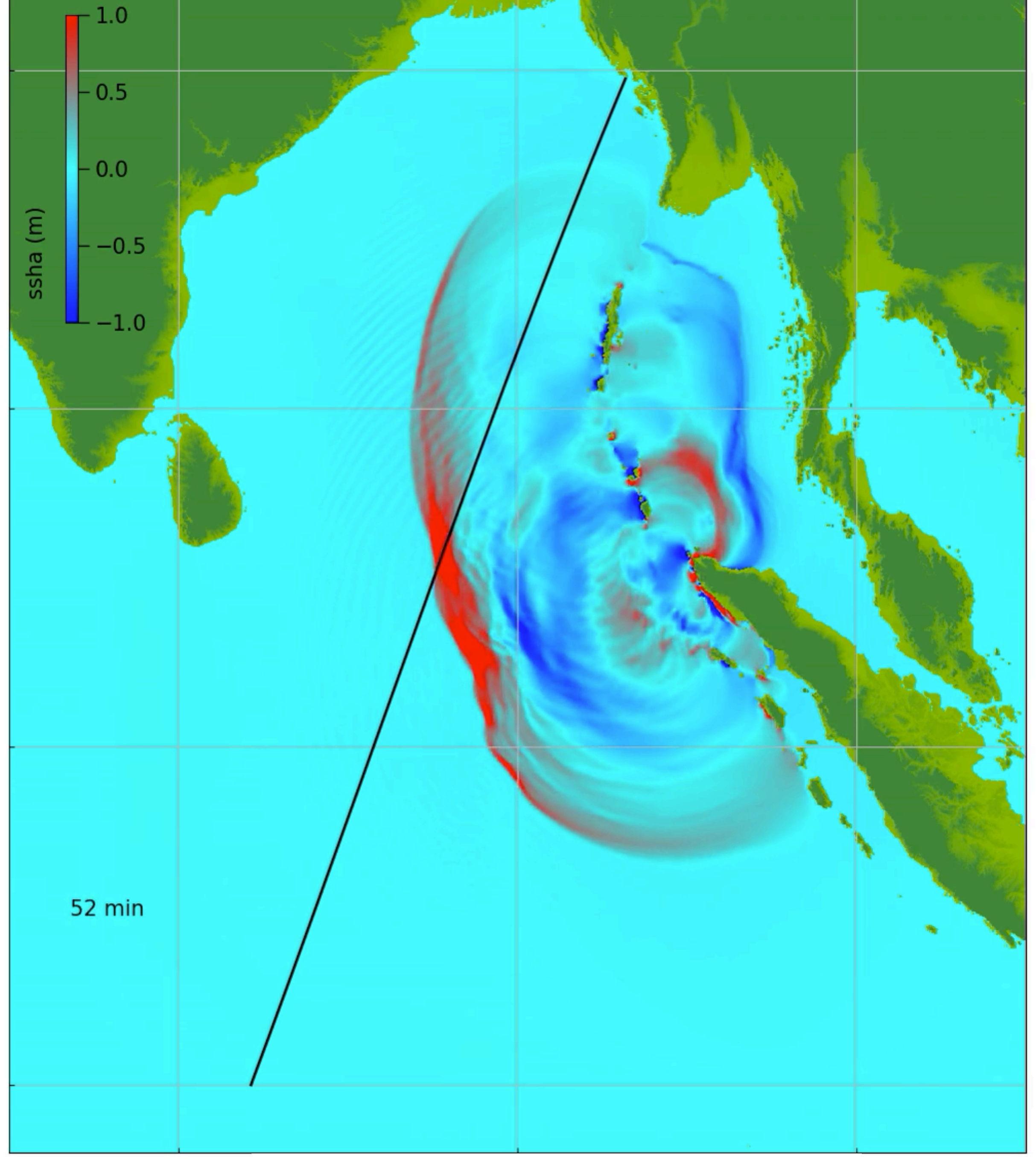
Lauren Abrahams et al., EarthArxiv

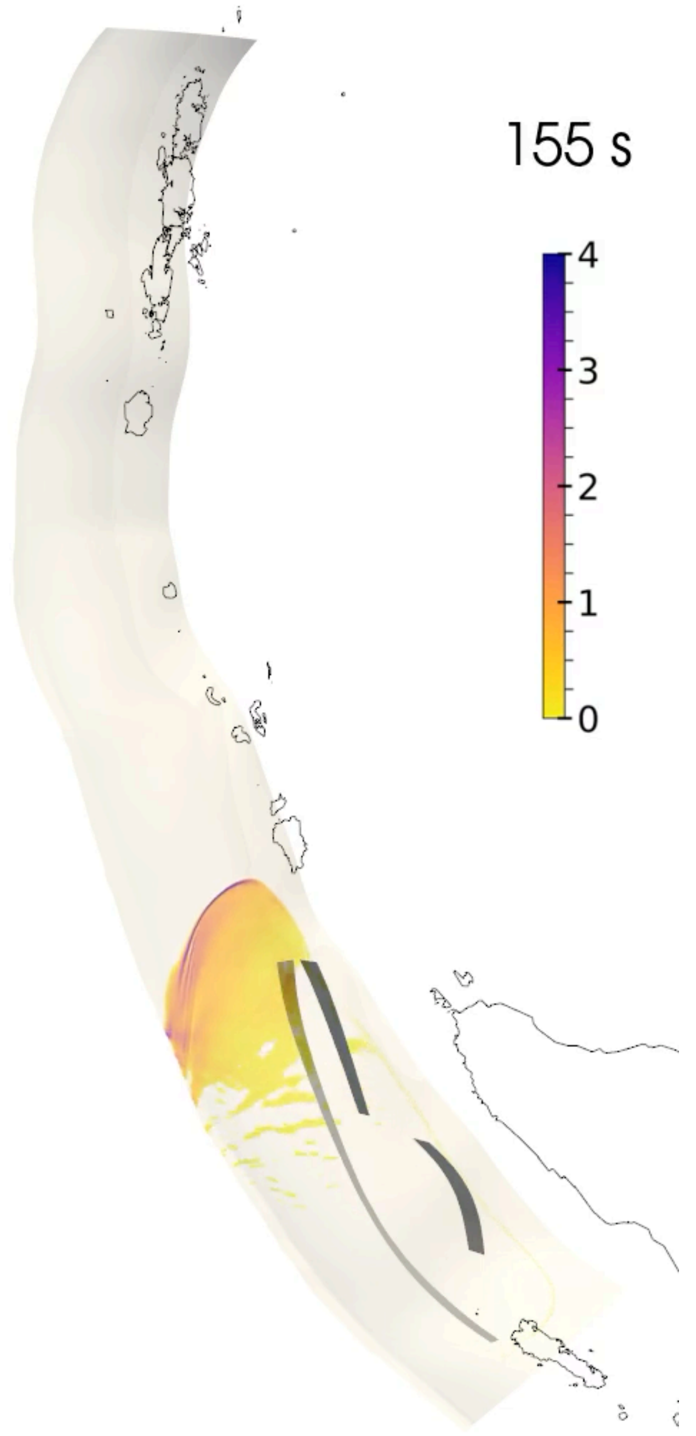
Stress, rigidity and sediment strength control megathrust earthquake and tsunami dynamics

Ulrich et al., Nature Geoscience 2022

- **reconciling near- and far-field earthquake and tsunami observations** of the 2004 Sumatra-Andaman events
- Using **regional-scale** observations of **stress, rigidity and sediment strength** to decipher megathrust hazards in a physics-based manner



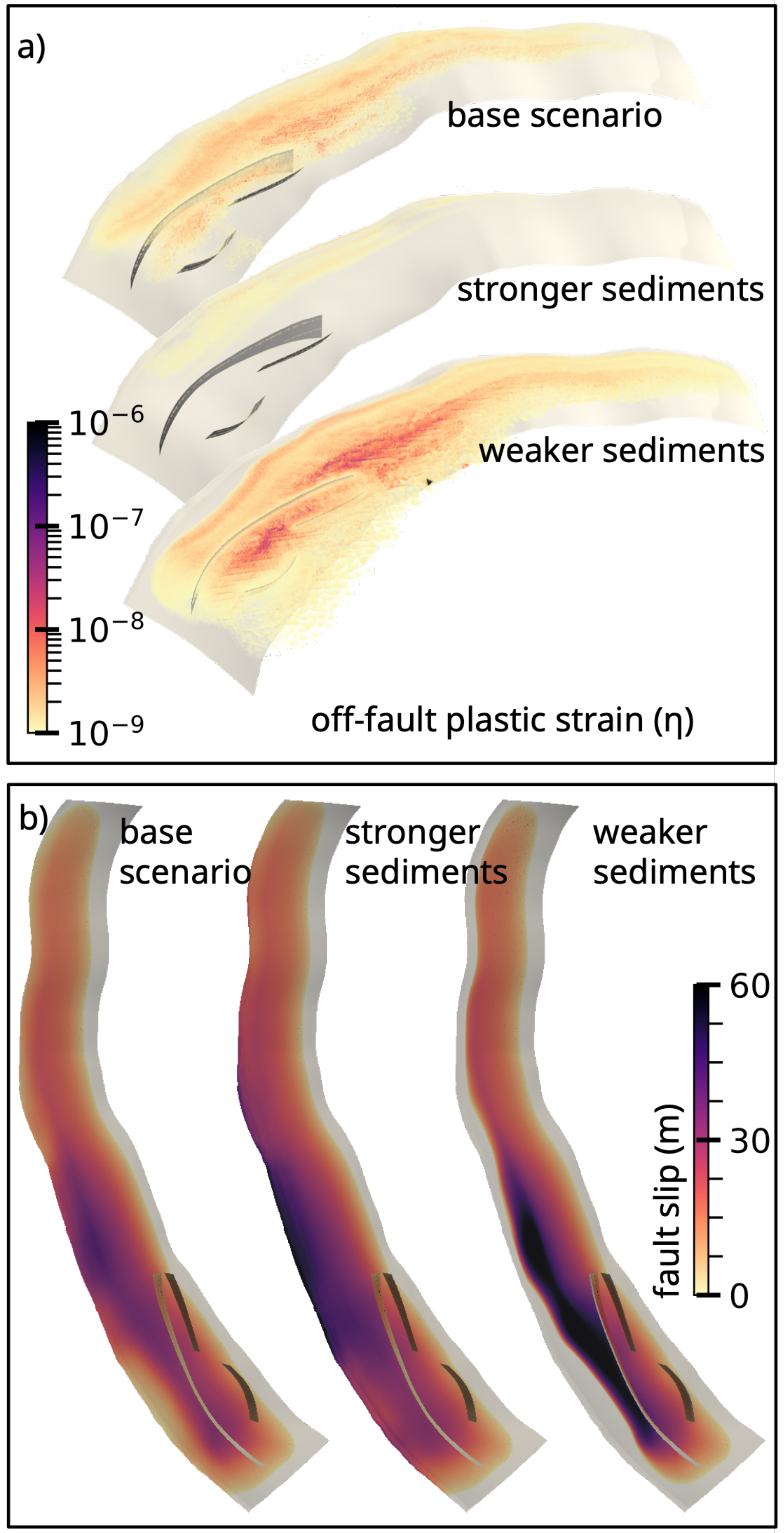


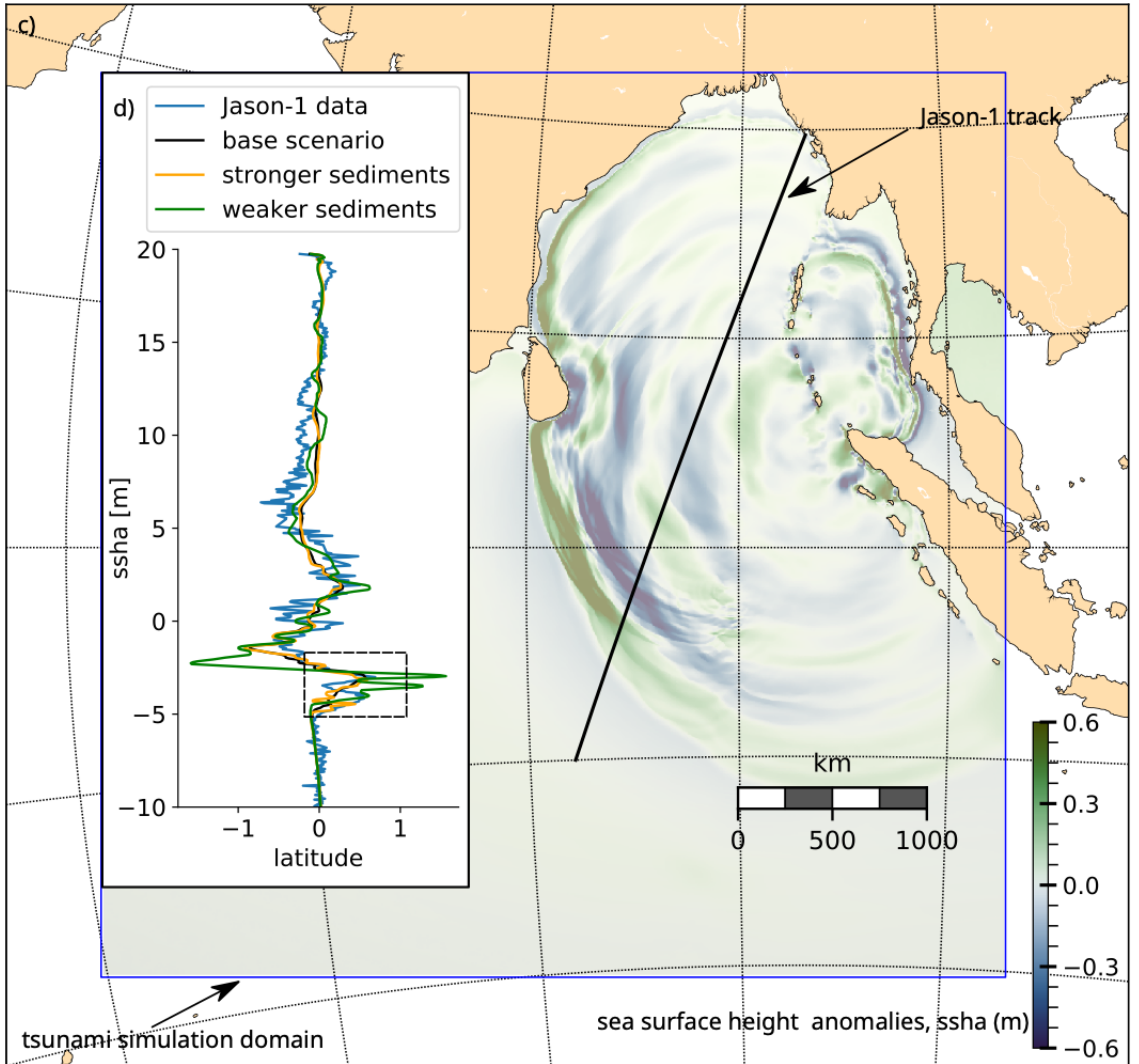


Stress, rigidity and sediment strength control megathrust earthquake and tsunami dynamics

Ulrich et al., 2022, Nature Geoscience

- trade-offs between **slip to the trench, splay faulting, and bulk yielding of the accretionary wedge**

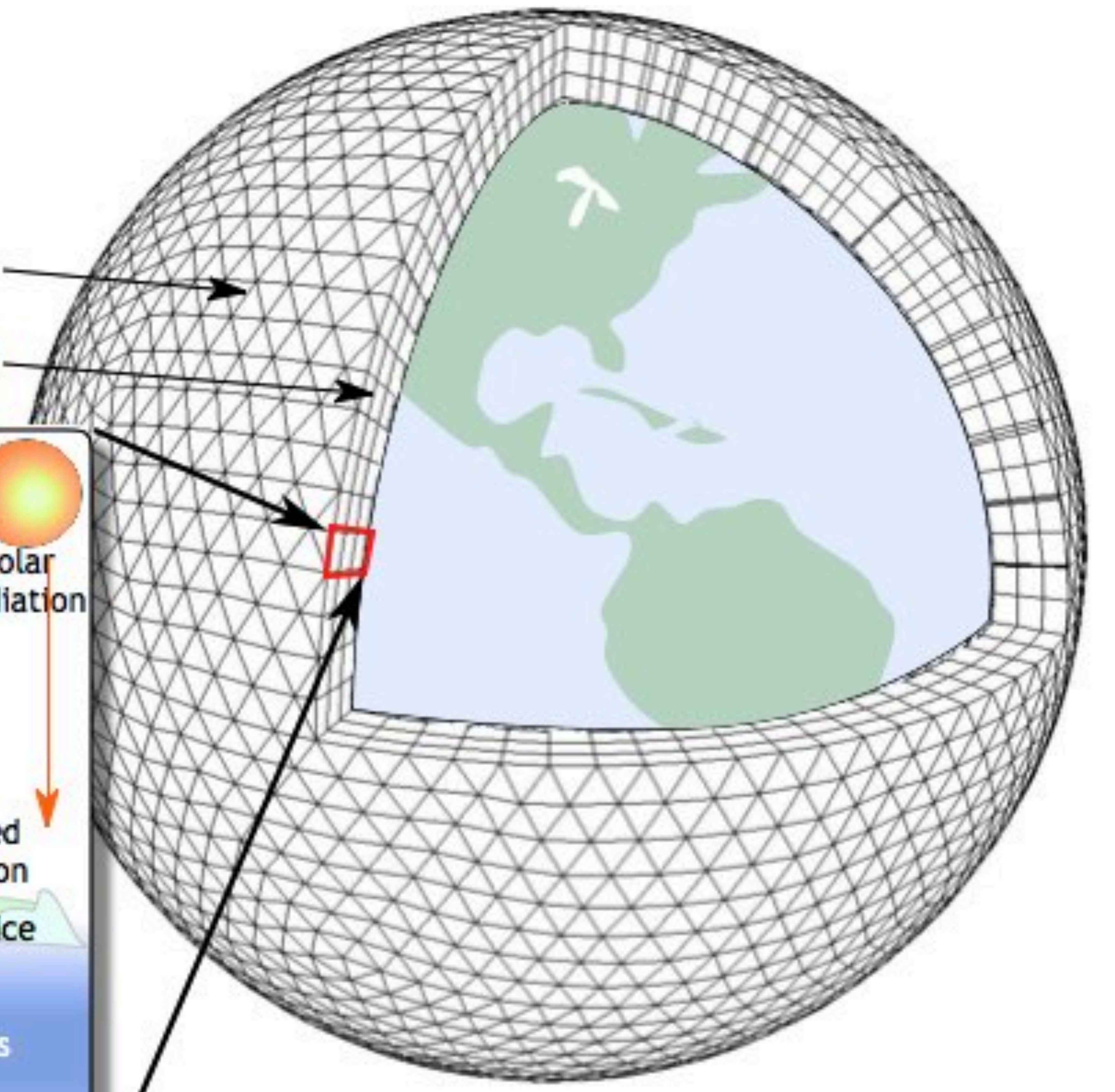


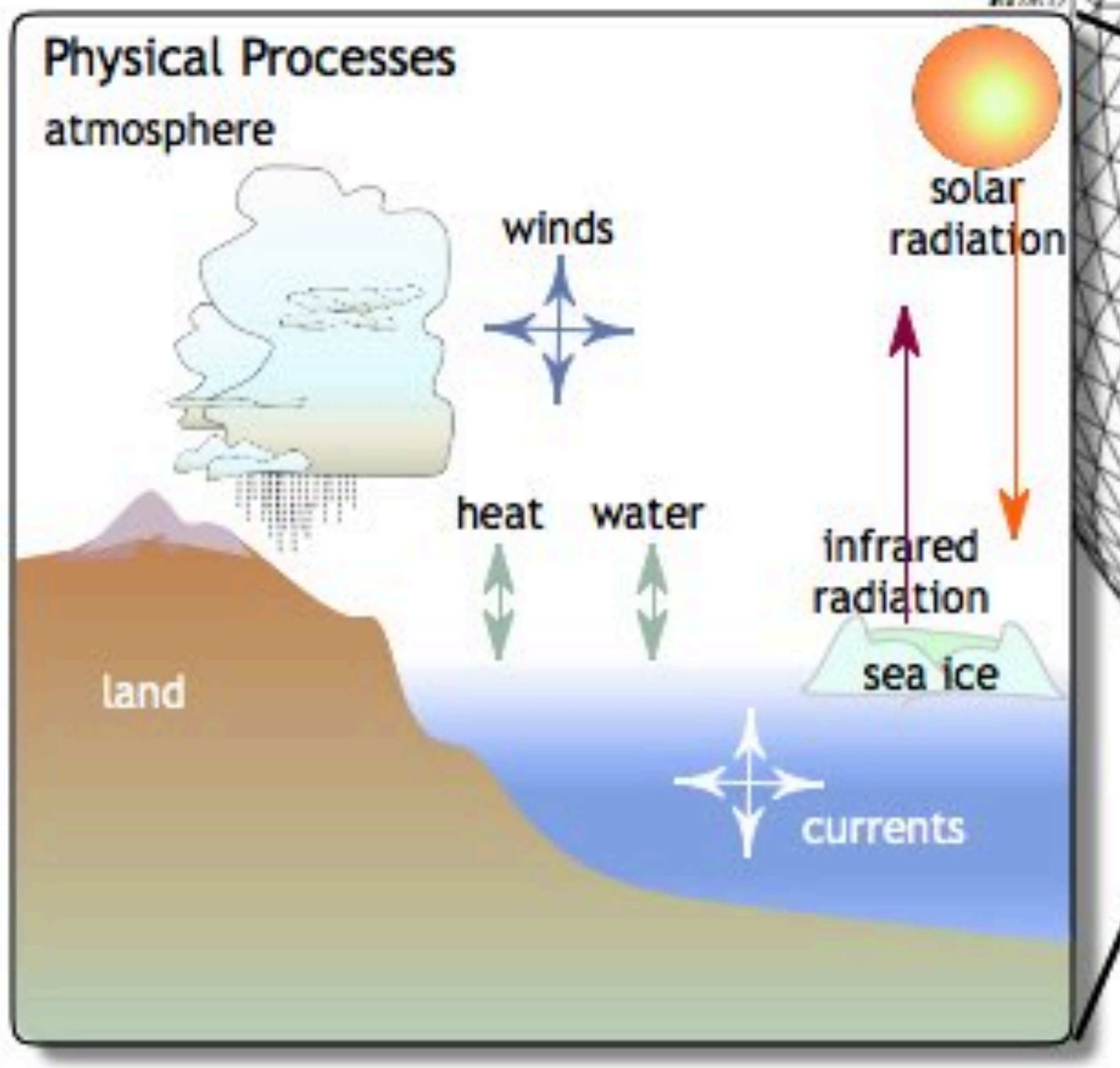


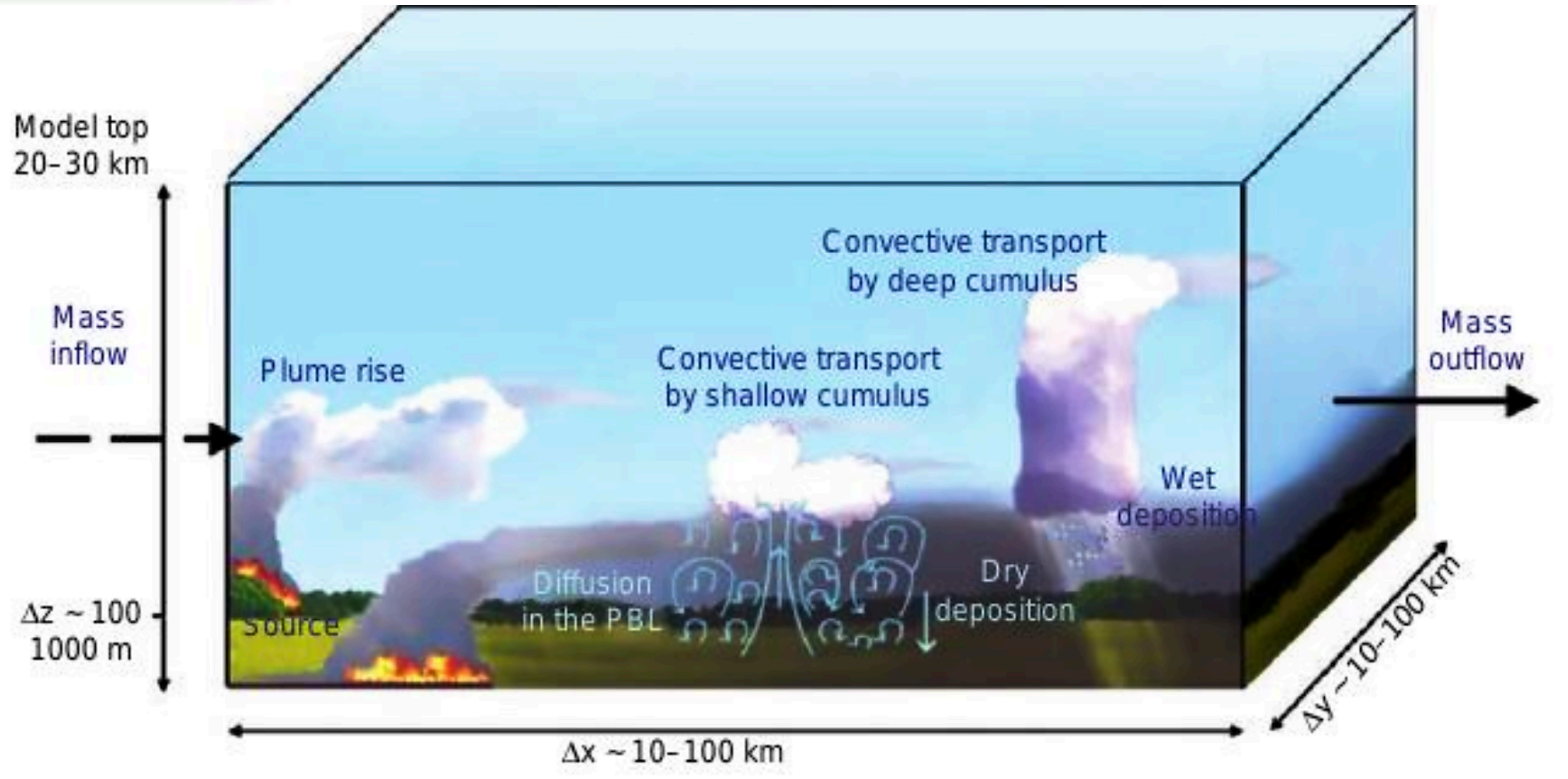
Outlook:

Are subduction zones more difficult than weather?

- **"Digital Twin" Global Atmospheric Models** are highly successful
- **Dynamic core:** PDEs (e.g., mass conversation) that the community agrees on
- "**Sub grid" physics:** (e.g., chemistry) where all dirty tricks are allowed
- **Short-term and long-term predictability** based on data assimilation, i.e. is a function of **data availability in space but even more importantly in time**







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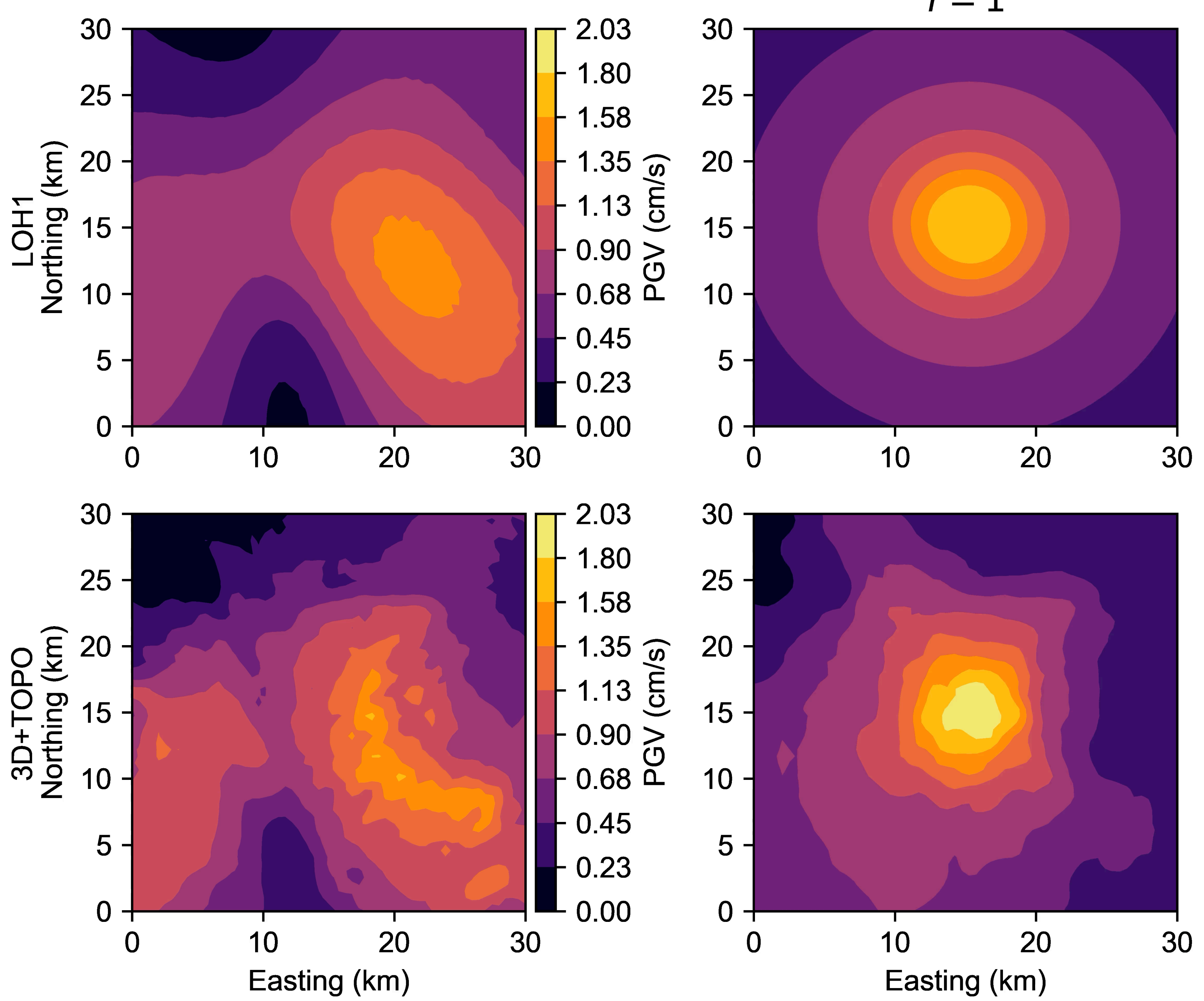
- **Short-term and long-term predictability** based on data assimilation, i.e. is a function of **data availability in space but even more importantly in time**
- **Digital Subduction Zone:** Combining rich, continuous and interdisciplinary data-sets in a core dynamic framework makes hypothesis testing is easy



Constructing reduced order surrogate models combined with machine learning for ground motion modeling (Rekoske et al., ArXiv)