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

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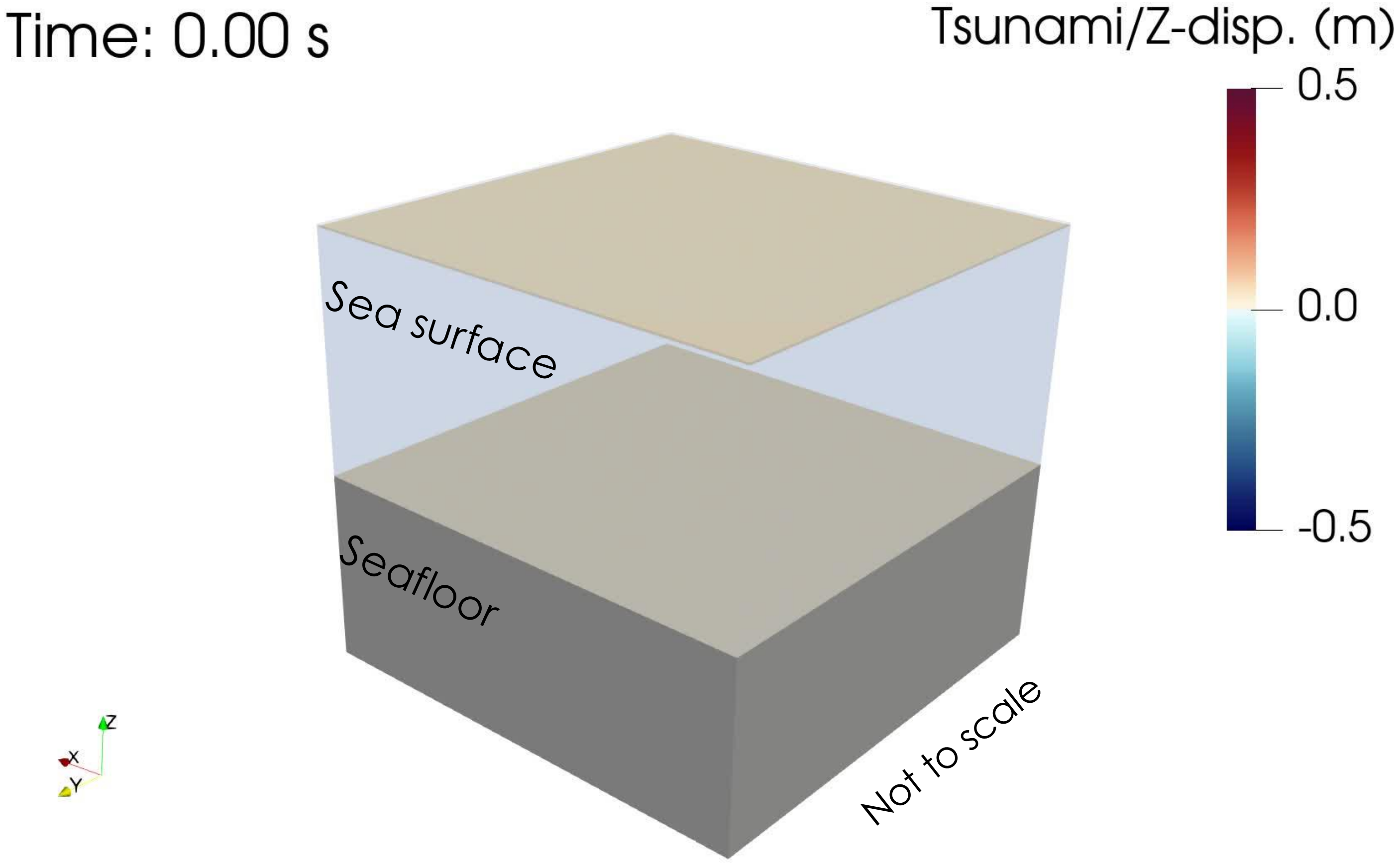
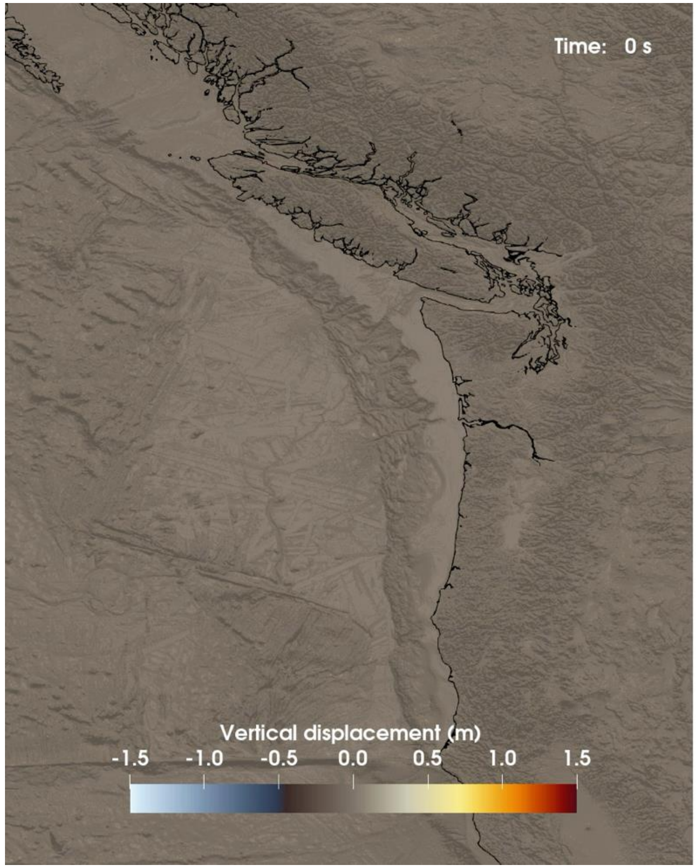
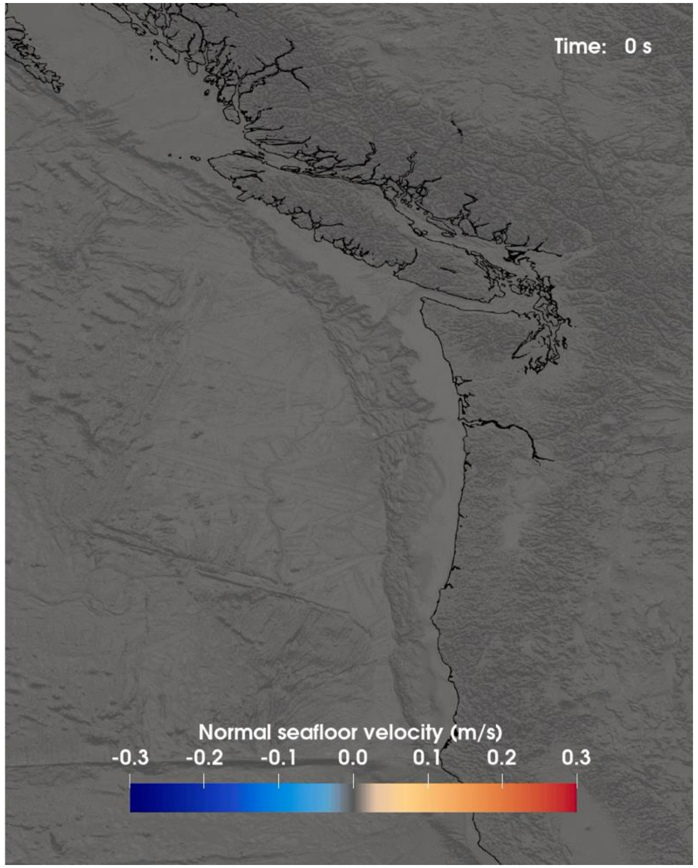


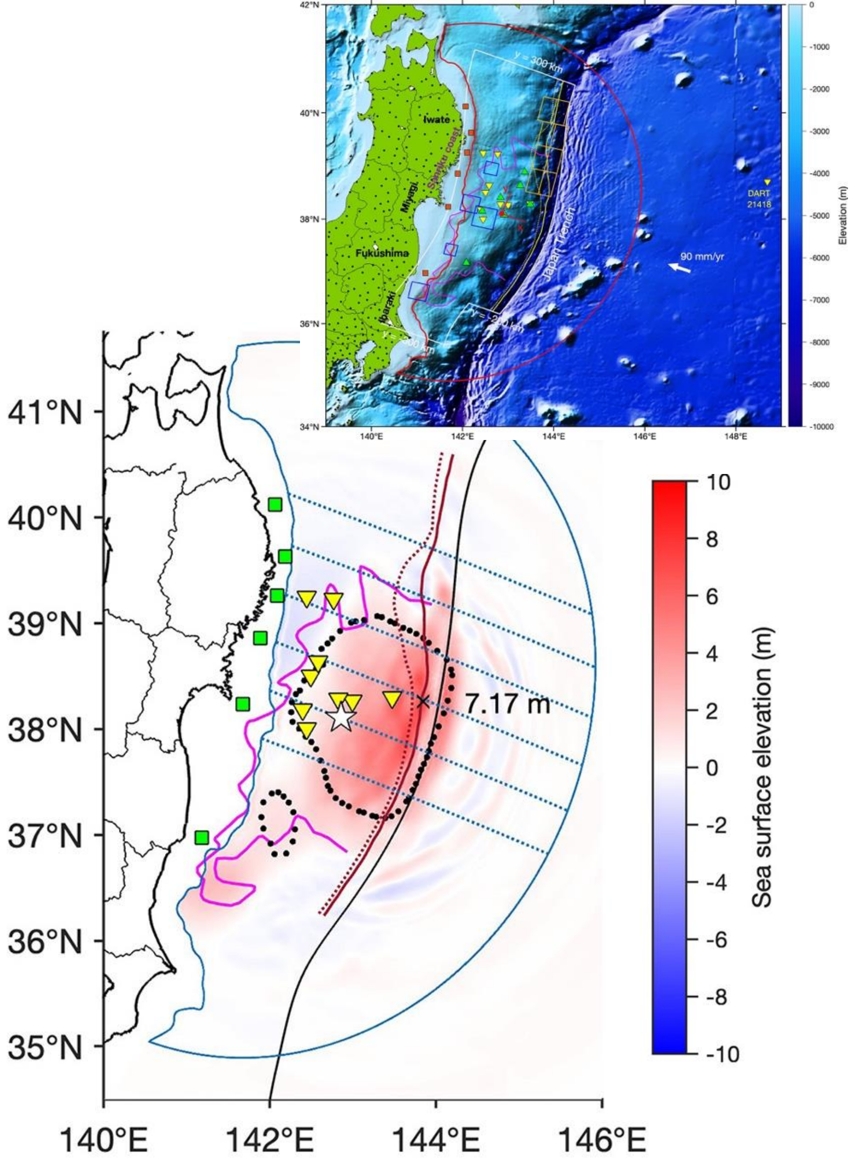
The Tsunami Problem Version 1 (TTPV1)

Realistic earthquake-tsunami scenarios help to constrain the tsunami hazard



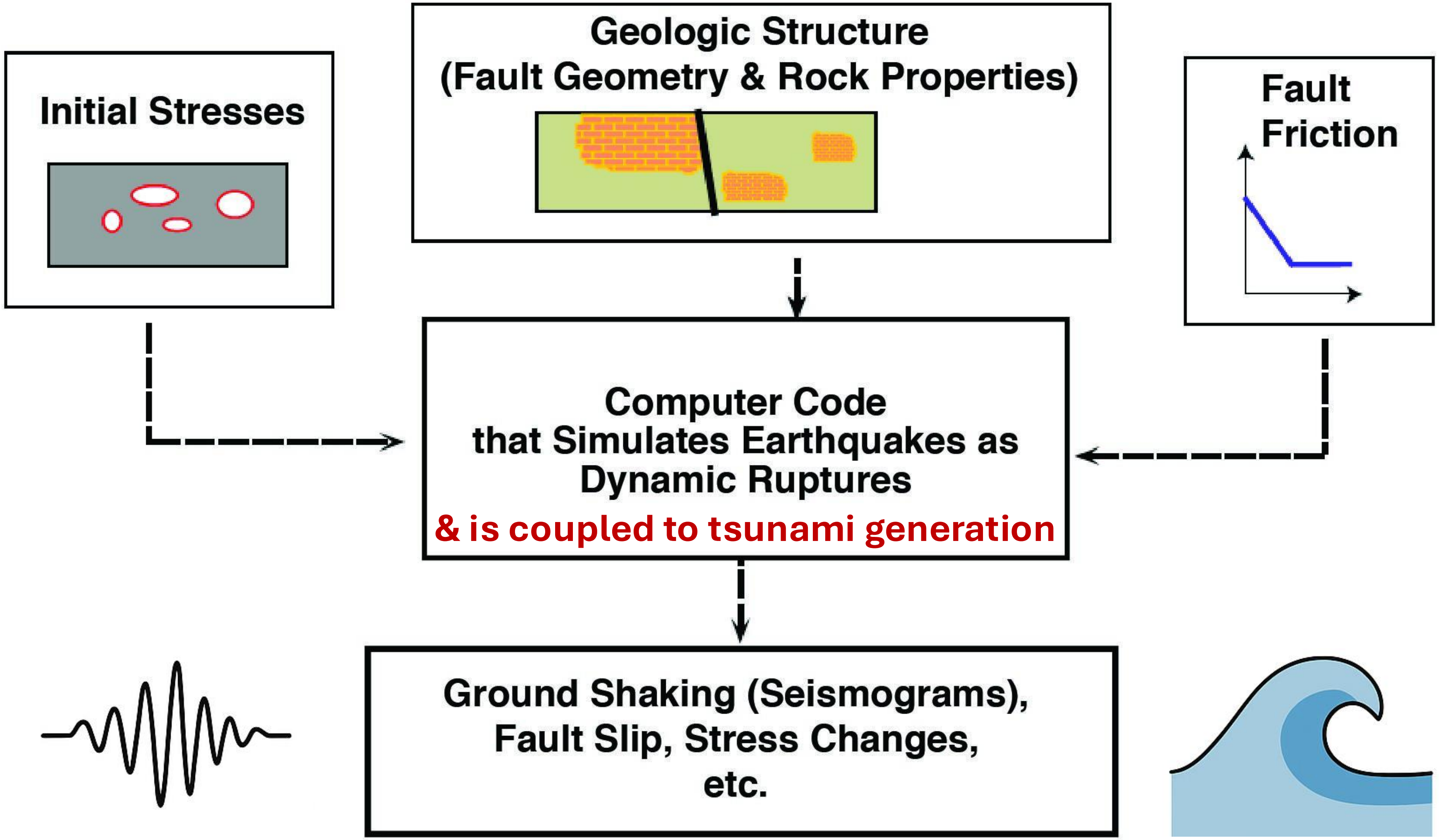


Bayesian inversion-based digital twin that employs acoustic pressure data from seafloor sensors, along with 3D coupled acoustic–gravity wave equations, to **infer earthquake-induced spatiotemporal seafloor motion** in real time and forecast tsunami propagation (Henneking et al., 2025; Glehman et al., 2025)



Extended **fully coupled earthquake-tsunami model** for the 2011 Mw 9.1 Tohoku-Oki earthquake with wedge inelasticity (Ma & Du, 2025)

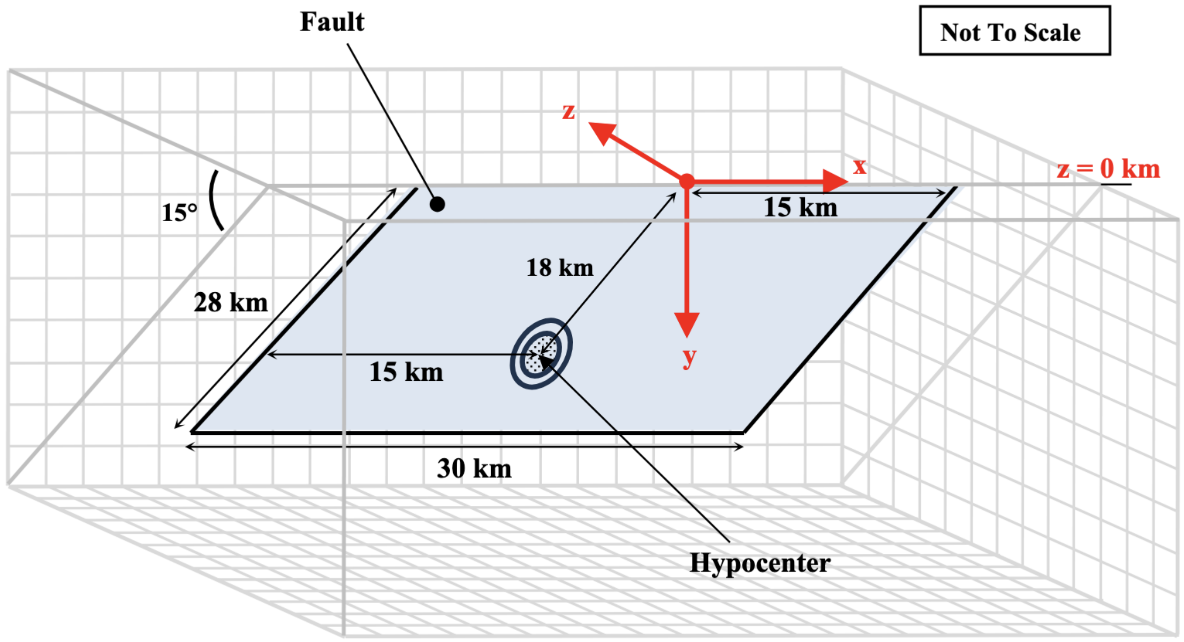
Combined dynamic rupture and tsunami ingredients



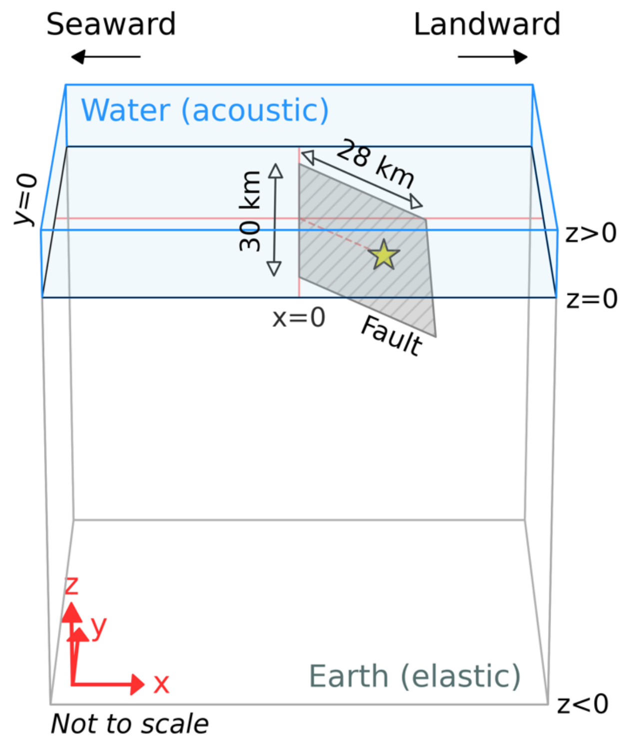
Harris & Archuleta (2004); Harris et al. (2018)

Extending an existing benchmark to tsunami generation

The Problem Version 36 (TPV36; Harris et al., in prep.)



The Tsunami Problem Version 1 (TTPV1)

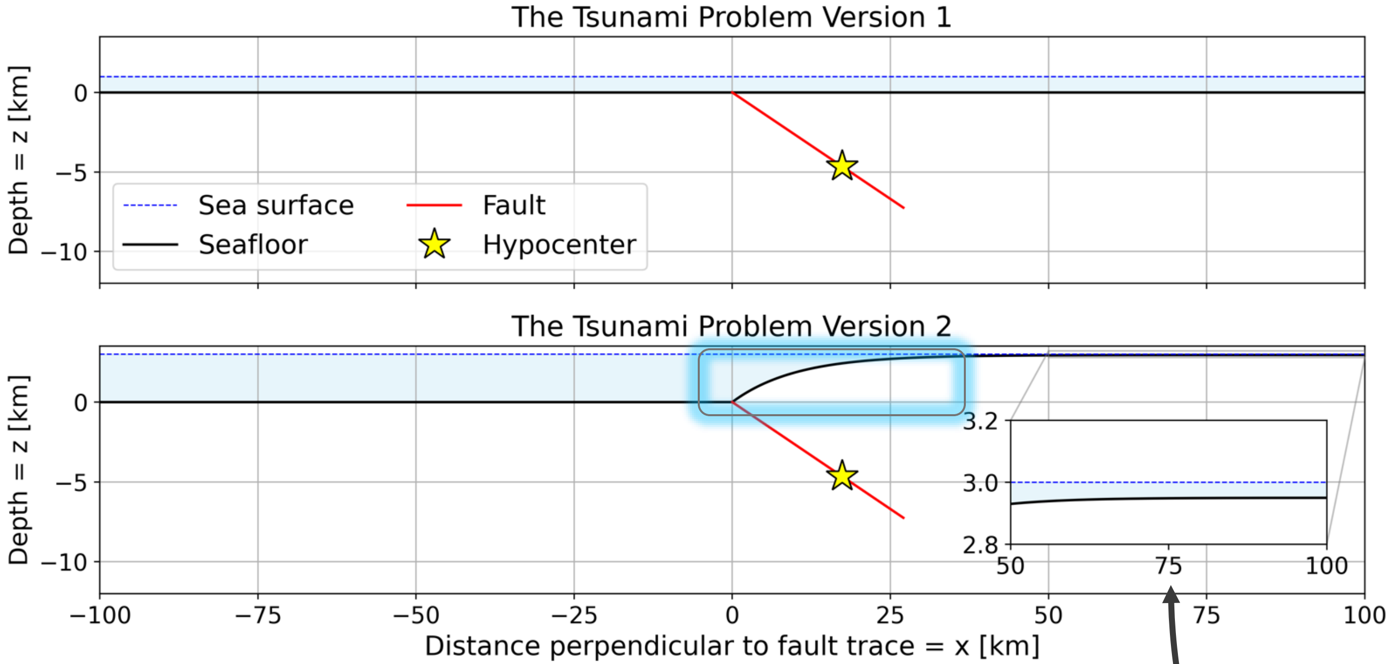


- Spontaneous 3D earthquake **dynamic rupture** on a 15° dipping thrust fault reaching the Earth's surface
- Rectangular planar fault measures 30 km along-strike and 28 km down-dip

- The **fully coupled** method combines earthquake dynamic rupture and tsunami generation into a **single simulation**
- We can capture 3D elastic, acoustic, and tsunami waves, including dispersion effects, **simultaneously** (e.g., Maeda & Furumura, 2013)

Extending an existing benchmark to tsunami generation

Side view:



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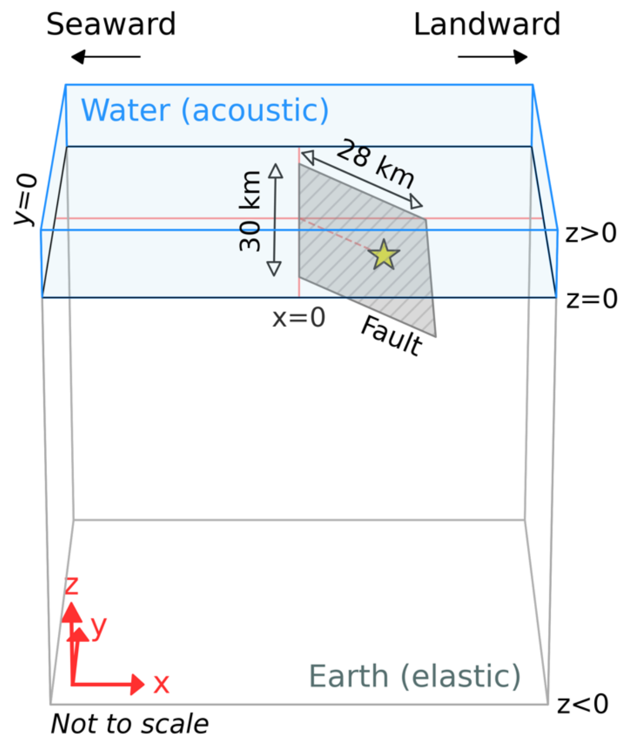

- In TTPV1, a **1 km thick uniform** water layer is added atop the elastic medium
- A water layer with **variable depth** is atop the elastic Earth, with 3 km water depth on the seaward side, sloping to shallow depth (~50 m) landwards

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Continuum problem

The **fully coupled** method combines the elastic wave equation in the **solid Earth** with the linearized equations of motion governing small perturbations of a **compressible ocean** about a rest state in hydrostatic equilibrium (Lotto and Dunham 2015; Wilson and Ma, 2021; Krenz et al., 2021)

Earth

- Velocity-stress formulation of the elastodynamic equations

$$\frac{\partial \sigma_{ij}}{\partial t} - \lambda \delta_{ij} \frac{\partial v_k}{\partial x_k} - \mu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) = 0$$

$$\rho \frac{\partial v_i}{\partial t} - \frac{\partial \sigma_{ij}}{\partial x_j} = 0 \,.$$

- six stress components of stress:

$$\sigma_{xx}, \sigma_{xy}, \sigma_{xz}, \sigma_{yy}, \sigma_{yz}, \sigma_{zz}$$

- three velocity components:

$$v_x, v_y, v_z$$

- solid Earth density ρ and Lamé parameters λ, μ

Ocean

- Combine conservation of mass with a linearized equation of state
- Conservation of momentum
- Linearized free surface boundary condition at the sea surface

$$p'(x, y, H, t) = \rho_w g \eta \,.$$

- Linearized kinematic condition for the sea surface

$$\frac{\partial \eta}{\partial t} = v_z(x, y, H, t) \,.$$

p': pressure perturbation
ρ_w: water density
$H = z - \eta(x, y, t)$: height of ocean at rest
η: vertical displacement of the sea surface

Interface conditions

Which conditions have to hold at the **material interfaces**, which can generally be elastic-elastic, acoustic-acoustic, elastic-acoustic, or acoustic-elastic?
→ Unit normal n_i points from lower side (–) of interface to the upper side (+)

Elastic-Vacuum

- "Stress-free" surface

$$\sigma_{ij}^- n_i = 0$$

→ Rayleigh waves

Acoustic-Acoustic

- Continuity of normal velocity and of pressure p

$$v_i^+ n_i = v_i^- n_i$$

$$p^+ = p^-$$

Elastic-Elastic

- Continuity of velocity and traction

$$v_i^+ = v_i^-$$

$$\sigma_{ij}^+ n_i = \sigma_{ij}^- n_i$$

→ Stoneley waves

Elastic-Acoustic & Acoustic-Elastic

- Continuity of normal velocity and traction components of stress

(Sochacki et al., 1991; Wilcox et al., 2010)

$$v_i^+ n_i = v_i^- n_i$$

$$-p' \, n_j = \sigma_{ij}^+ n_i = \sigma_{ij}^- n_i$$

→ Scholte waves

Code overview:

How to deal with the "trench" at the elastic-acoustic interface?

MAFE: velocity-stress-based finite element method with linear tetrahedral elements (Ma and Nie, 2019)	**drdg3d**: nodal mixed-flux-based discontinuous Galerkin finite element method (Zhang et al., 2023)	**SeisSol**: modal arbitrary high-order derivatives discontinuous Galerkin finite element method (Gabriel et al., 2025)

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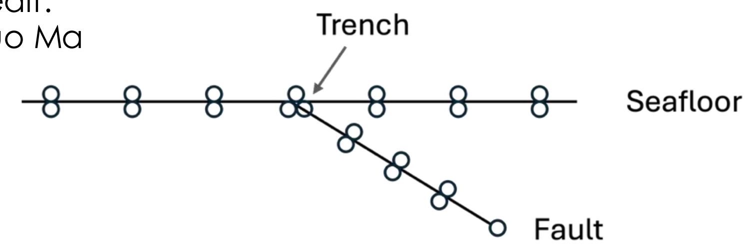
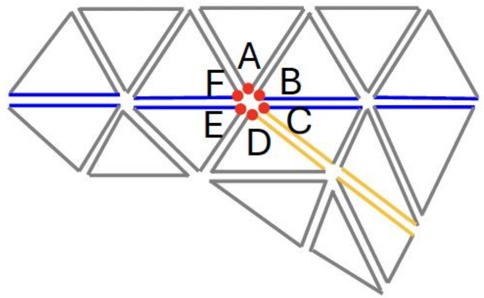
Credit: Shuo Ma



- Split-node scheme
- Introduction of fictitious node ("center of mass")

Credit: Wenqiang Zhang



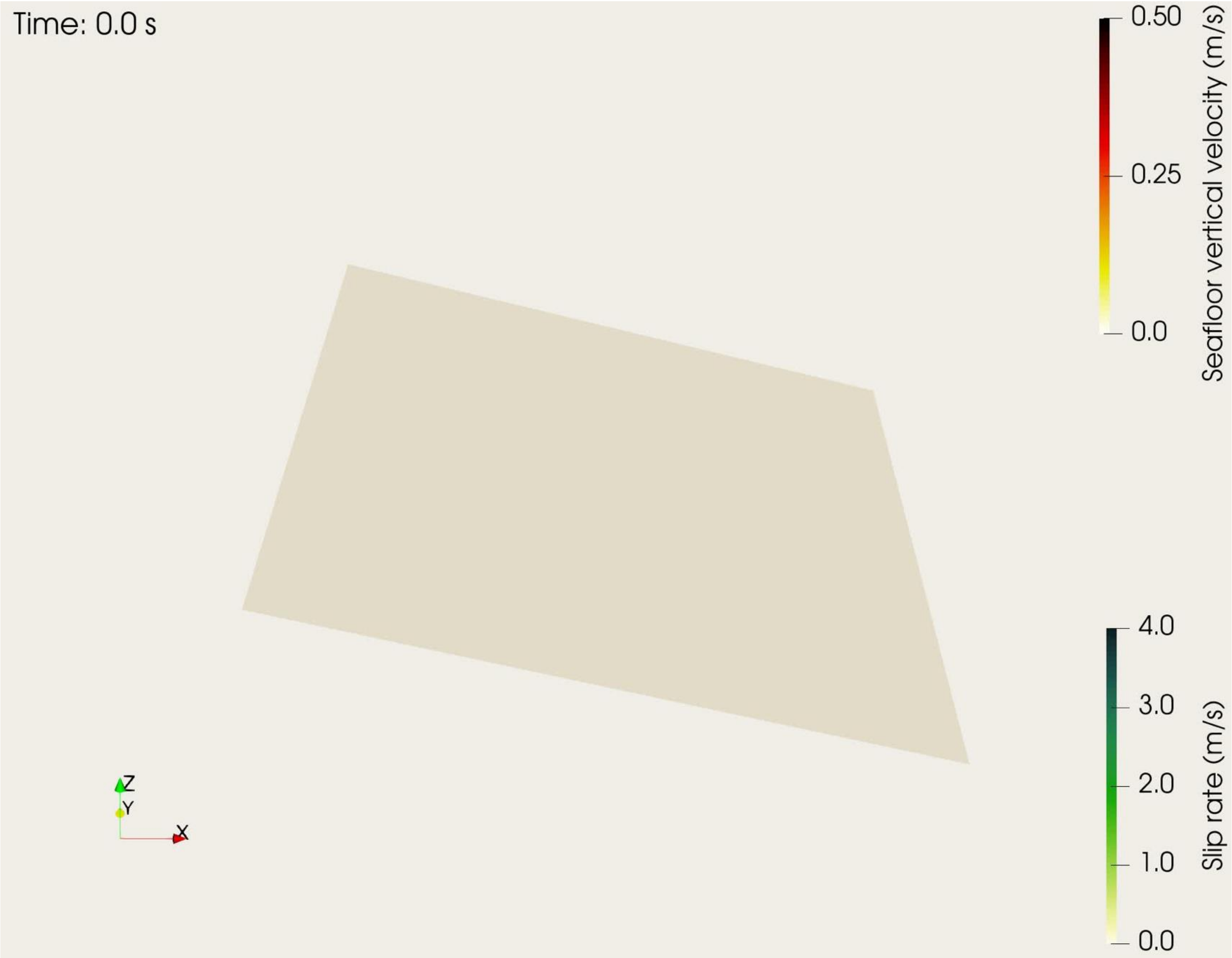
- Acoustic-acoustic: AB,AF
- Acoustic-elastic: BC,EF
- Elastic-elastic: CD,DE
- Fault: CD

→ All boundary conditions need to be explicitly implemented (via numerical fluxes)

→ SeisSol:

- **Godunov**: solves a Riemann problem at each cell interface exactly
- **Rusanov**: approximate Riemann solver, with the averaging of fluxes from both sides of an interface

Spontaneous earthquake dynamic rupture



- Simulation of a M_W 7.1 earthquake with a peak fault slip of 3.4 m to test modeling capabilities
- Linear slip-weakening friction law with (on-fault) cohesion
- Initial normal stress and the initial shear stress are proportional to distance down-dip
- Simulation time of 4 minutes

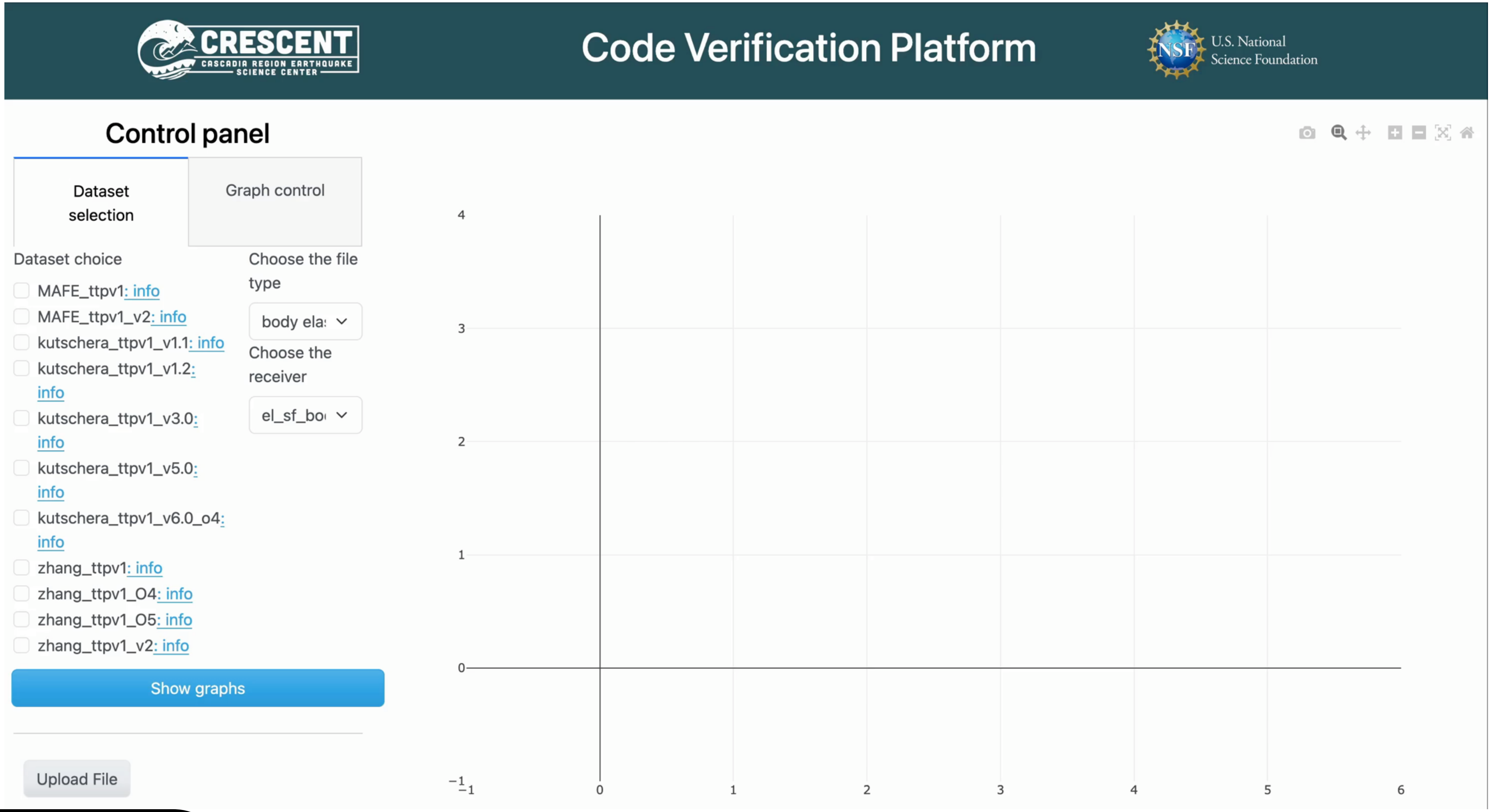
Movie: First 30 s of spontaneous dynamic rupture for SeisSol with the seafloor vertical velocity for TTPV1

TTPV1: Comparison of the final seafloor displacement

TTPV1 & 2 BENCHMARK DESCRIPTION

UPLOAD YOUR RESULTS | TTPV1 RESULTS | TTPV2 RESULTS

- Visualization based on the new code verification platform (https://cascadiaquakes.org/det)



Loïc Bachelot

Amanda Thomas

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TTPV1: Comparison of the final seafloor displacement

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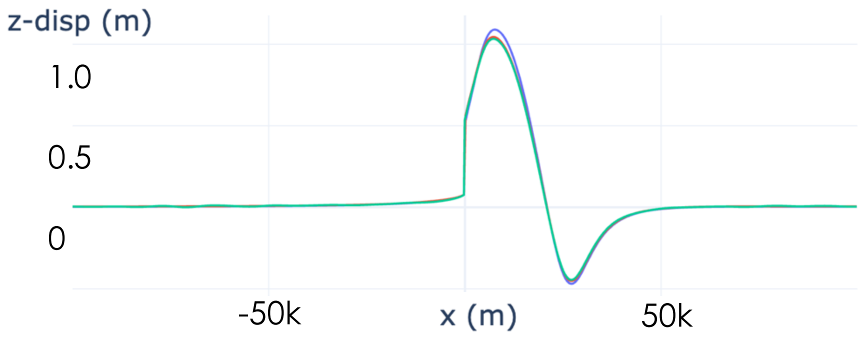
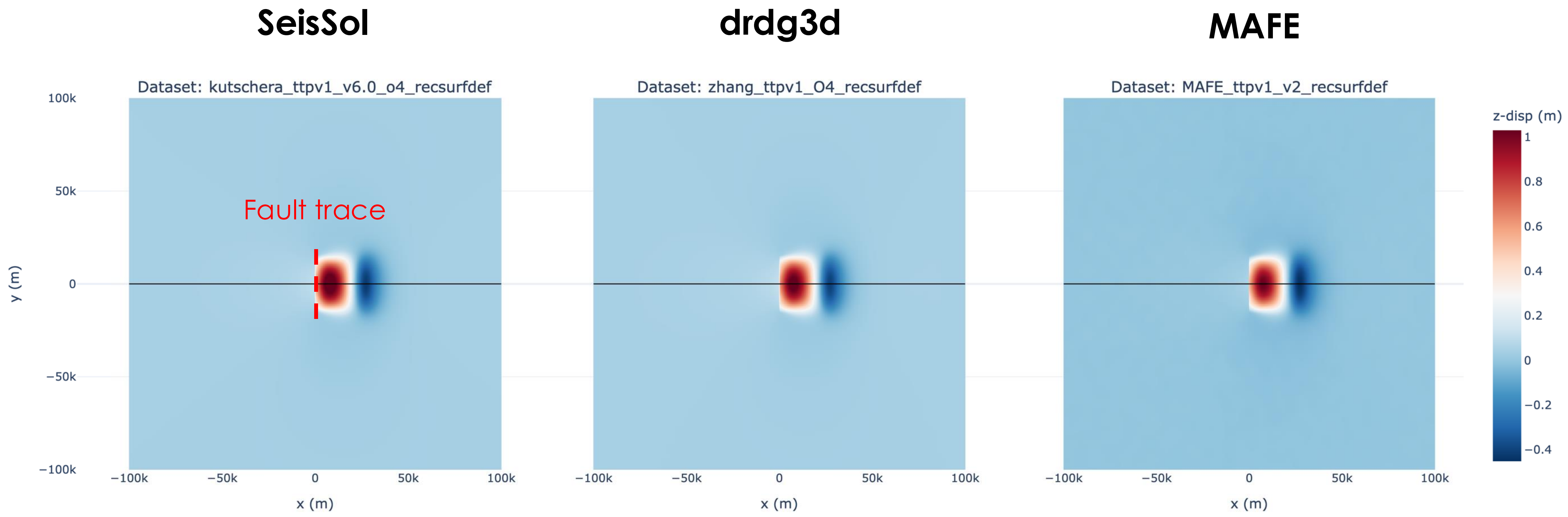
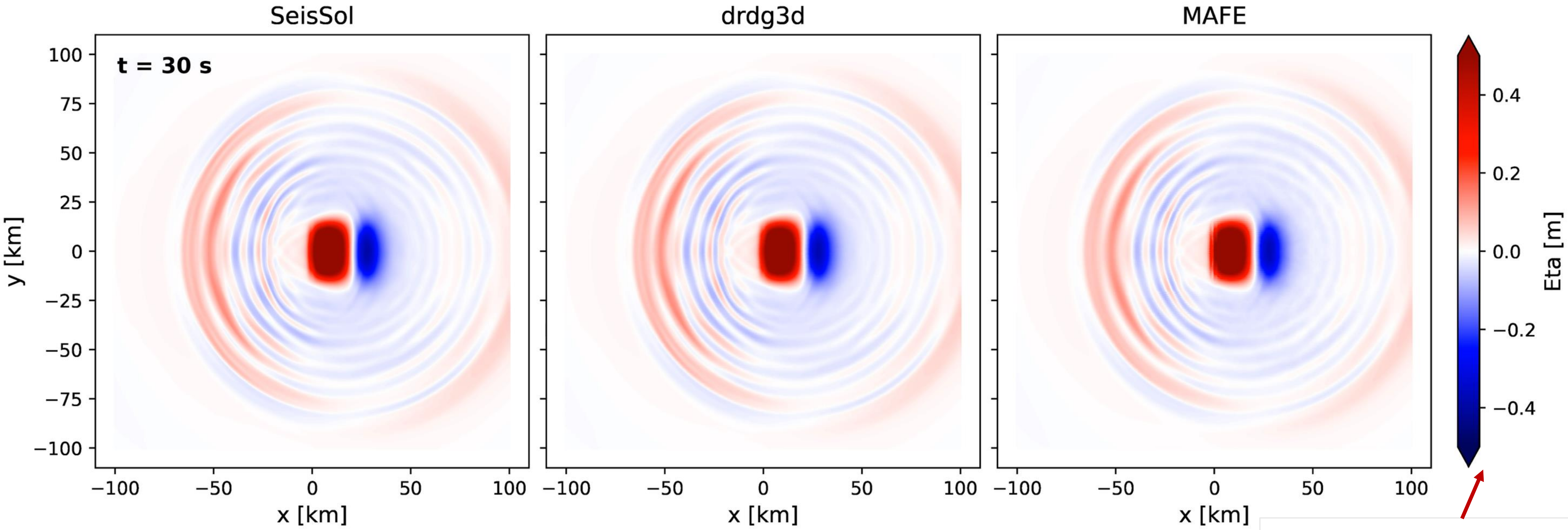




- Distribution of spatial seafloor displacement in good agreement, with peak uplift of 1.05 ± 0.02 m, and peak subsidence of -0.45 ± 0.01 m

TTPV1: Comparison of the time-dependent tsunami generation on the sea surface

- All simulations include transient seismo-acoustic waves (visible at 30 s)

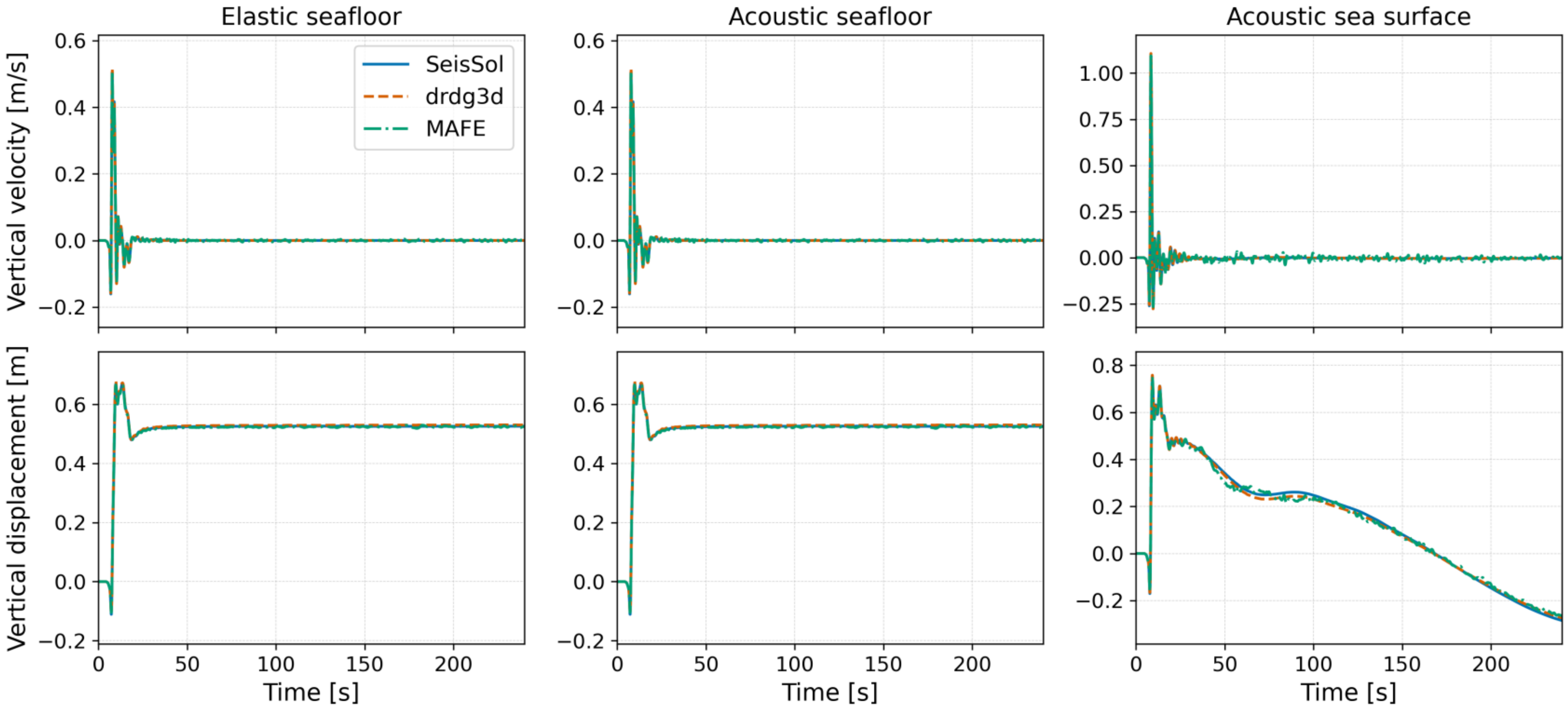


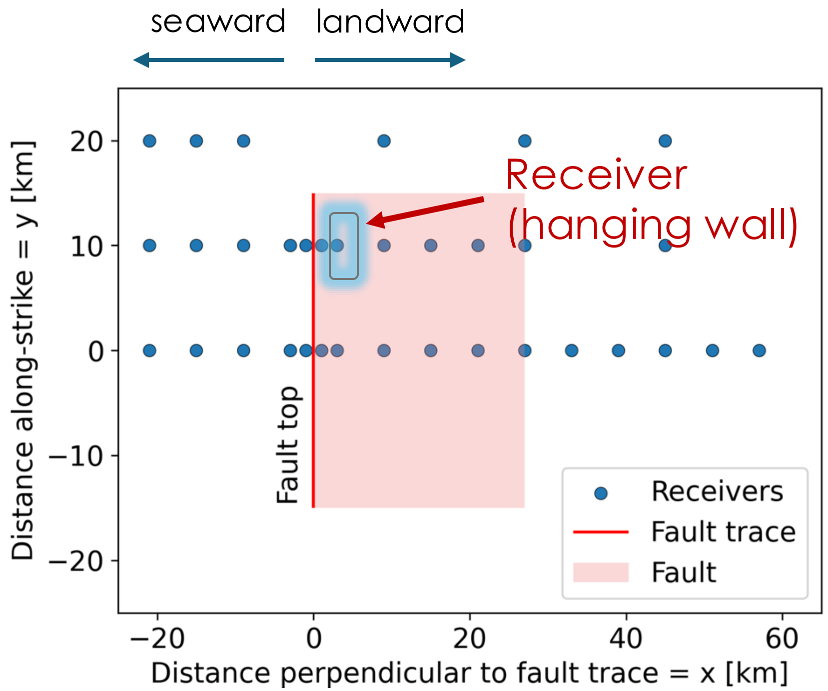
Eta = vertical displacement of the **sea surface** (tsunami + seismo-acoustic waves)

- Key features of the tsunami generation are in good agreement

TTPV1: Comparison of the receiver time-series

- Three-component velocities and displacements over time (elastic & acoustic)





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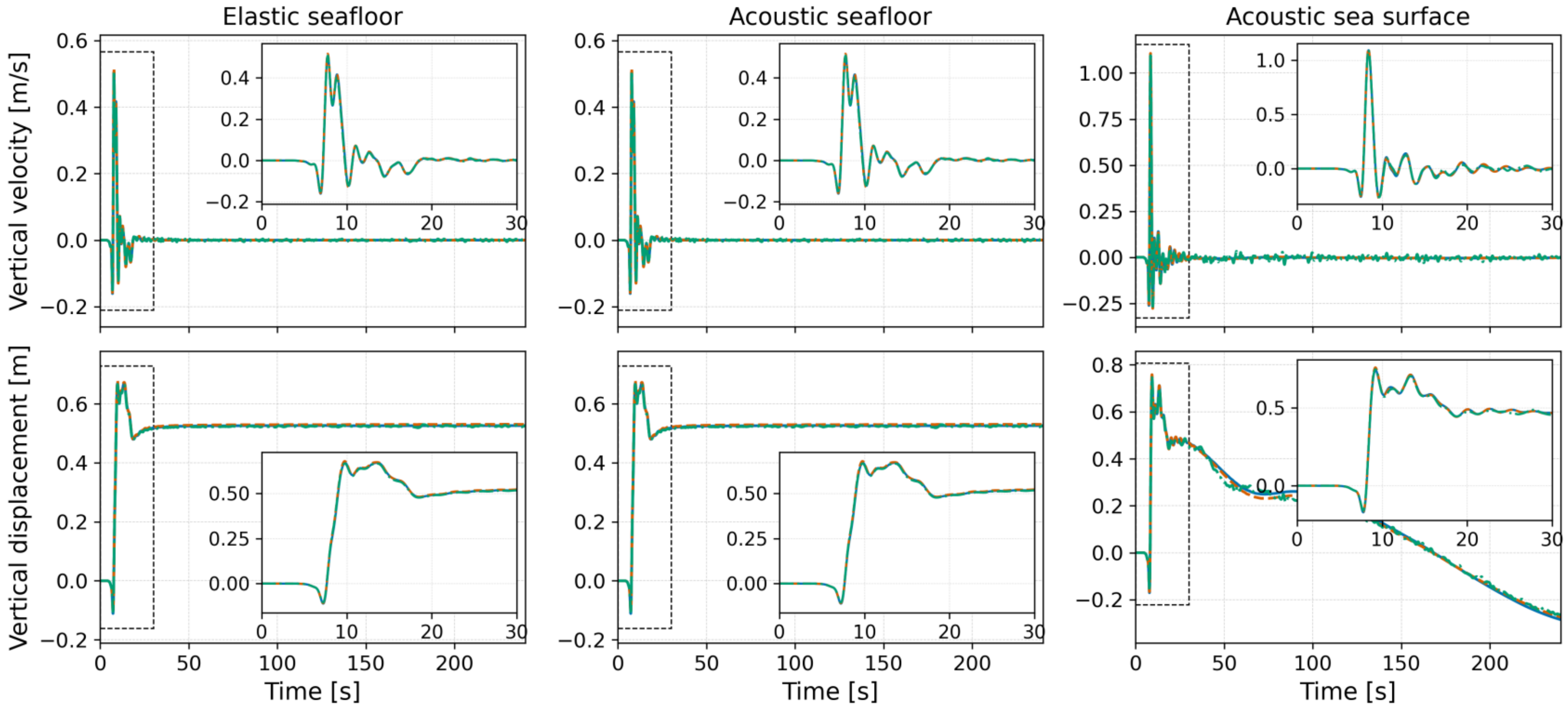
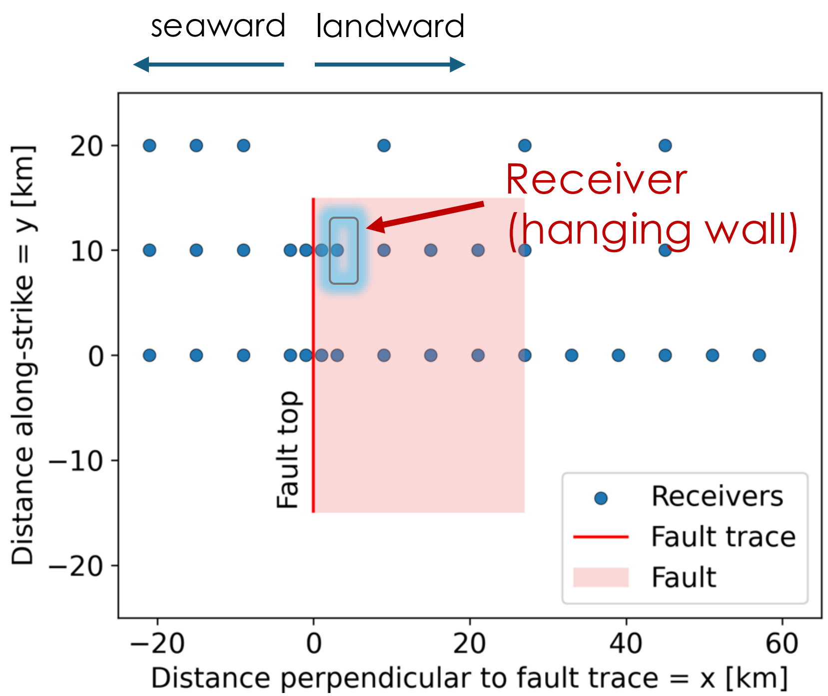
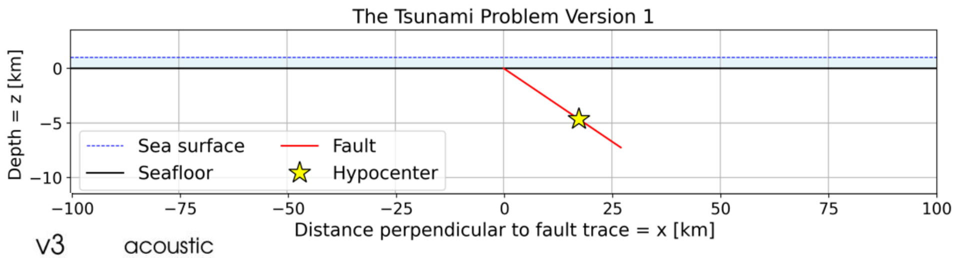




- Great agreement of the initial generation phase (first 30 s), clean of any numerical noise

Seafloor continuity requirement in TTPV1

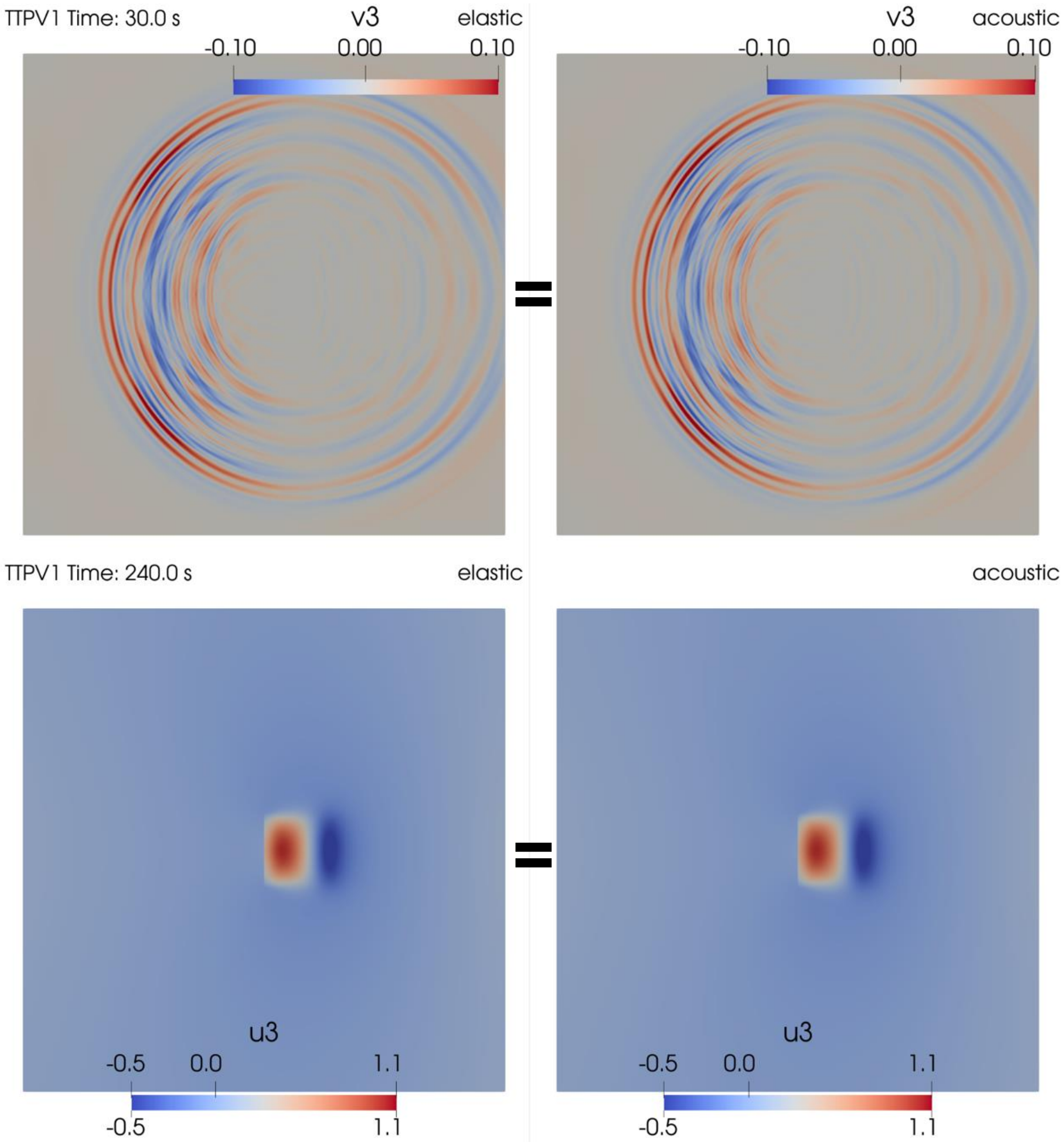


Recall continuity of normal velocity at elastic-acoustic interface :

$$v_i^+ n_i = v_i^- n_i$$

Since TTPV1 has a flat bathymetry:

$$v_z = v_i^+ n_i$$



SeisSol

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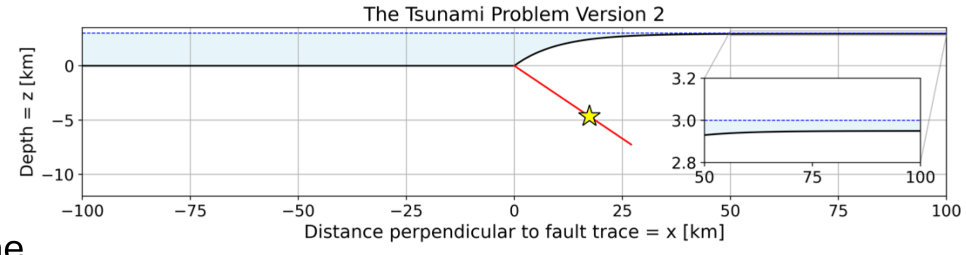
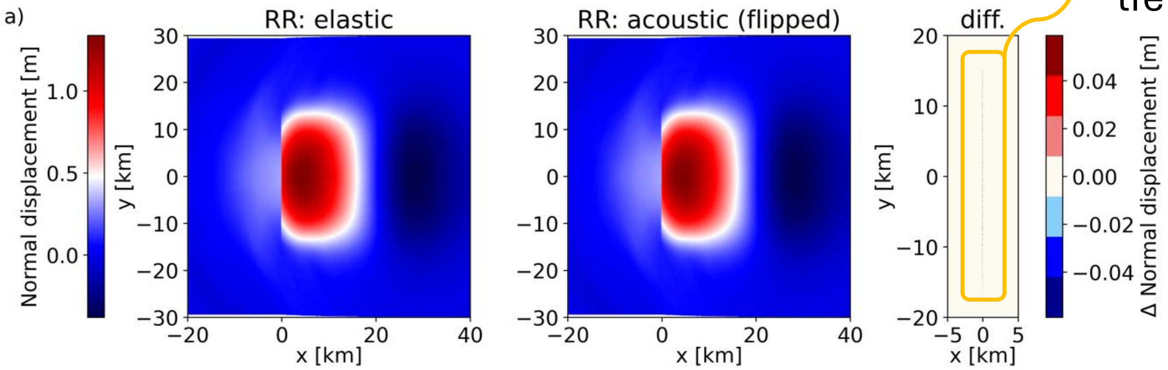
Accuracy of interface condition enforcement is affected by choice of numerical fluxes



SeisSol

Can we do better and reduce the "trench artifacts"?



- We can use different numerical fluxes, **Rusanov (R)** and **Godunov (G)**, for solving wave propagation (i) in the volume and (ii) for faces of cells adjacent to the fault

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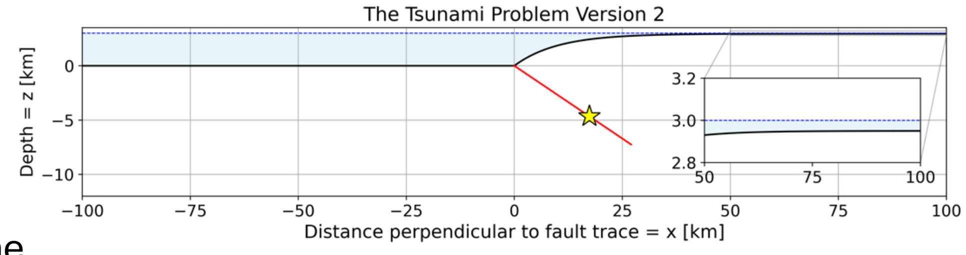

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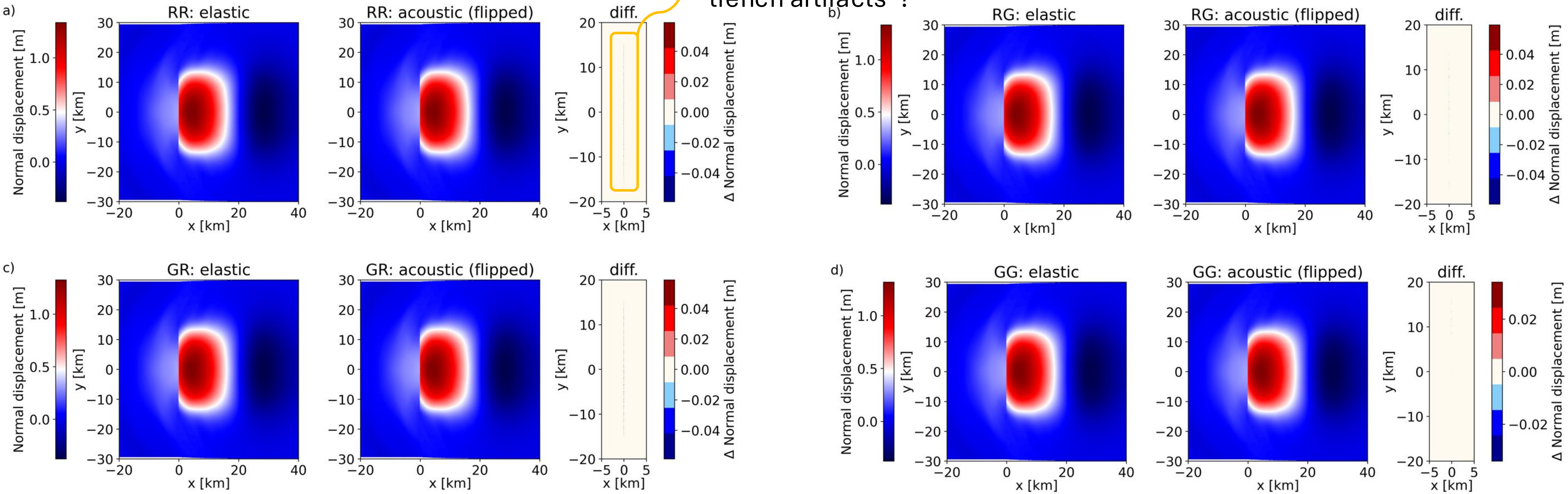
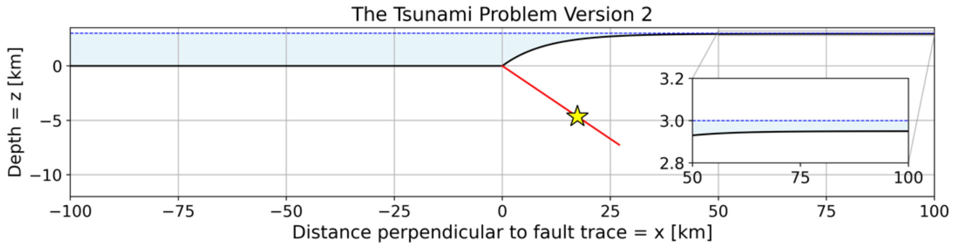


- We can use different numerical fluxes, **Rusanov (R)** and **Godunov (G)**, for solving wave propagation (i) in the volume and (ii) for faces of cells adjacent to the fault
- When using GG, the peak absolute amplitude of trench artifacts is reduced by 42.2%, 42.8%, and 42.2% when compared against GR, RG, and RR fluxes, respectively

TTPV2: Comparison of the time-dependent tsunami generation on the sea surface



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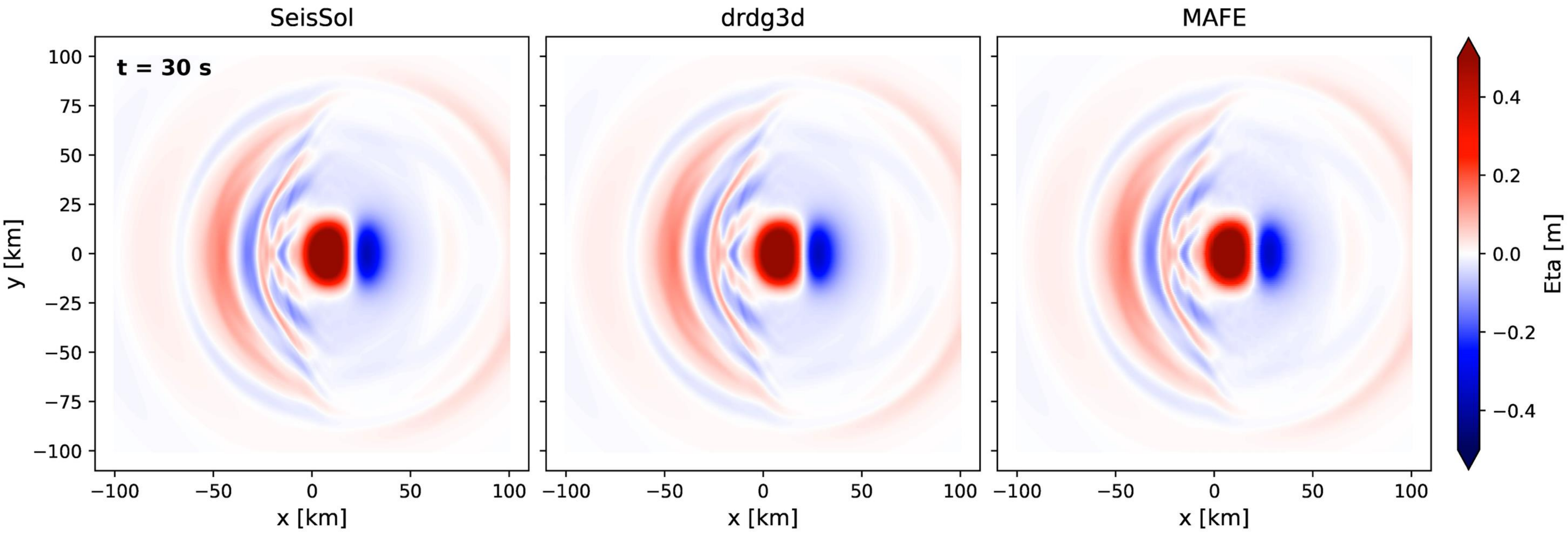

- Key features of the tsunami generation are in good agreement

Conclusions and outlook

Benchmark description: https://doi.org/10.5281/zenodo.15389414

- **3 codes were verified in 2 benchmarks** to model 3D fully coupled earthquake dynamic rupture and tsunami generation
- Good agreement of key features in the initial tsunami generation for both TTPV1 & TTPV2
- Numerical fluxes affect the accuracy of enforcing elastic–acoustic interface conditions at complex geometries
- Size matters → sufficiently large domain size is required for the benchmarks
- What's next for the SCEC-USGS Dynamic Rupture Verification Group?
  - o Explore other, more complex/realistic topography?
  - o Should we include off-fault plasticity again?