Linking geodynamic subduction models to self-consistent 3D dynamic earthquake rupture and tsunami simulations

Sara Aniko Wirp[1], Alice-Agnes Gabriel[1], Elizabeth H. Madden[2], Iris van Zelst[3], Lukas Krenz[4], and Ylona van Dinther[5]

Motivation

3D dynamic rupture models of subduction zone earthquakes can account for complex structural variations of both fault and oceanic or continental crust. Due to the in-situ inaccessibility and strong variations of material properties, fault strength and loading stresses along arc and depth, it is difficult to assign initial conditions to dynamic rupture models. A newly developed workflow bridges the spatial and temporal scales from tectonics to dynamic rupture and links the outcome of geodynamic subduction and seismic cycling models to dynamic rupture (van Zelst et al., 2019; Madden et al., 2019).We use this approach to investigate how increasing complexity in terms of fault stress and strength, off-fault material and rupture dynamics impacts seafloor uplift and tsunami propagation and generation.

First, we use the 2D geodynamic and seismic cycling model as input for a 3D dynamic rupture model by extending heterogeneous along-dip material properties and stresses into the third dimension. Second, we show results of a 2D geodynamic model linked to a 2D dynamic rupture model including off-fault plasticity. Third, we show a newly developed fully-coupled 3D dynamic rupture-tsunami model in which acoustic and gravity wave propagation are directly coupled to seismic wave propagation and dynamic rupture.

Earthquake rupture modeling and the fully-coupled tsunami modeling utilize SeisSol (www.seissol.org), a flagship code of the ChEESE project (www.cheese-coe.eu). SeisSol is an open source software package using unstructured tetrahedral meshes that are optimally suited for the complex geometries of subduction zones.

ChEESE - Center of Excellence for Exascale in Solid Earth

13 Partners

→ includes academic and industrial institutions in 10 countries across Europe that are in charge of e.g. geophysical monitoring networks, hardware development, civil protection

10 Community flagship codes for the upcoming pre-Exascale (2020) and Exascale (2022) supercomputers

- 4 in the field of computational seismology (EXAHYPE, SALVUS, SEISSOL, SPECFEM3D)
- 2 in tsunami modelling (T_HYSEA, H_HYSEA)

12 Pilot Demonstrators (PD)

- enable services on hazard assessment, urgent computing and early warning forecast

PD4 - Physics-based tsunami-earthquake interaction:

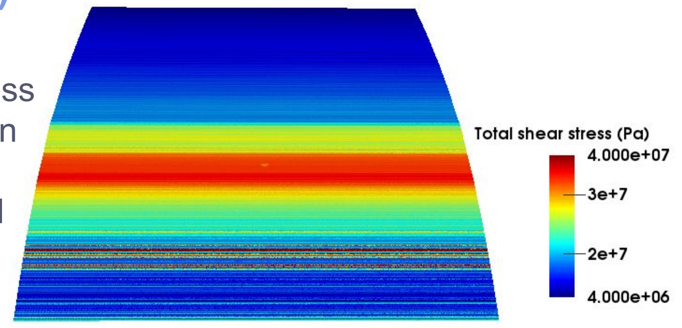
- tsunami early warning should incorporate a science-based alarm for damaging events and include enough accuracy and reliability to justify measures such as evacuation
- hydrostatic 2D models are not capable of representing seismic or acoustic waves sufficiently
  - early warning system should be based on signals of seismic surface waves and acoustic waves that propagate faster than tsunami wave signals

ChEESE
Center of Excellence for Exascale in Solid Earth

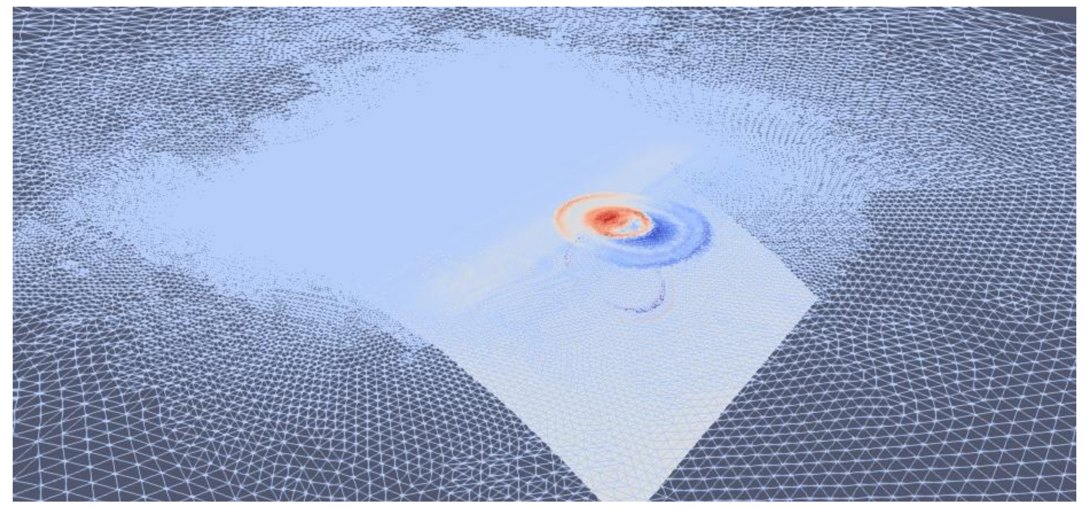
Linked models

1) 3D Geodynamic - Dynamic Rupture linking (linear elasticity)

Initial total shear stress in dip direction taken from the 2D geodynamic model

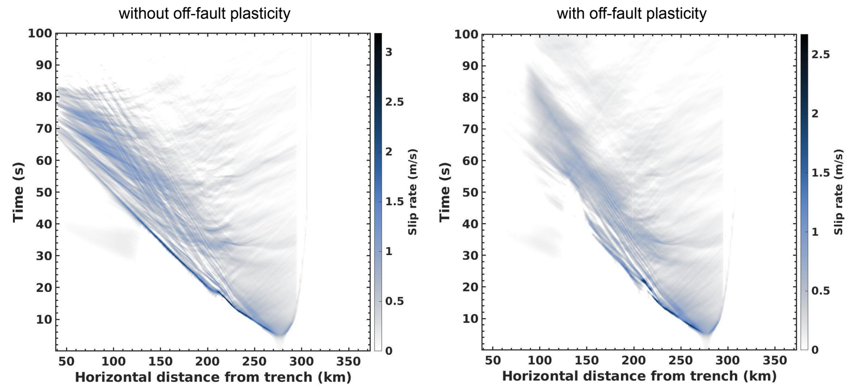


- The complex geodynamic seismic cycling model of van Zelst et al., 2019 is extended to constrain 3D megathrust dynamic rupture modeling
- We use an unstructured tetrahedral mesh



We observe:

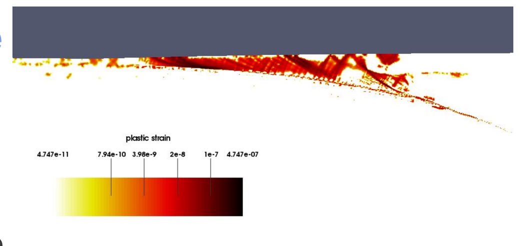
- High sensitivity of earthquake dynamics to the dimensions of the nucleating weak region
- Higher slip rate and more complex waveforms updip than downdip
- Seafloor uplift strongly depends on fault geometry as well as along arc material and stress variations



2) 2D Geodynamic - Dynamic Rupture linking (linear elasticity & off-fault plasticity)

Off-fault plasticity results in

- **Suppression of surface rupture** and rupture pulses
- **Increased seafloor uplift** (up to 70%)
- Co-seismic **splay-like strain accumulation**



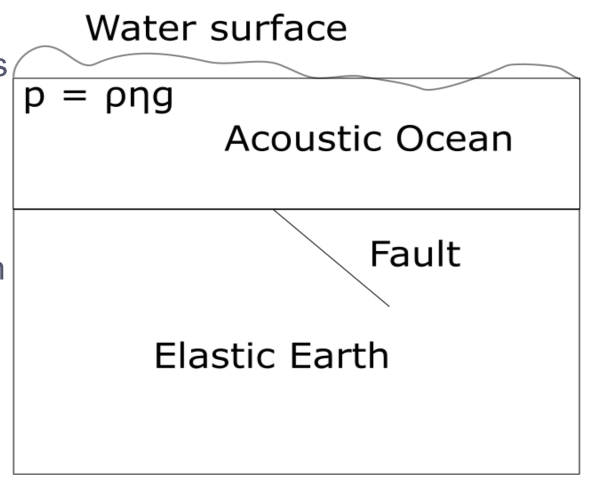
above: Off-fault damage for 2D dynamic rupture scenario - complex structures evolve during the simulation

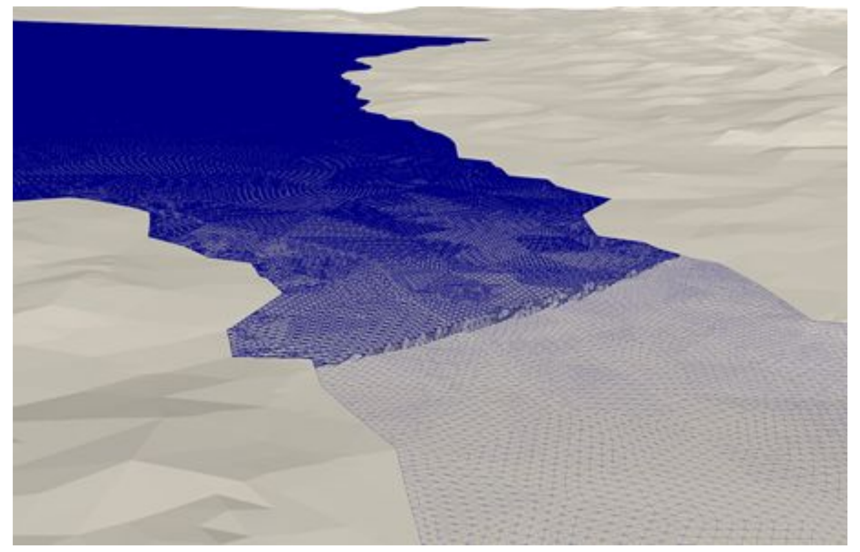
Complex subduction zone structures - such as splay faults - **affect the tsunami evolution and propagation, height, wavelength as well as inundation pattern at the coast** (Van Zelst et al., EGU 2020, https://doi.org/10.1029/2019JB017539).

3) Fully coupled 3D dynamic rupture-tsunami model (Krenz et al., AGU 2019; Abrahams et al., AGU 2019)

- Direct coupling of wave propagation in water (acoustic wave propagation) with seismic wave propagation (elastic wave equation in velocity-stress formulation)
- **Modified free-surface boundary condition** is implemented to include gravity effects in the water layer (Lotto and Dunham et al., 2015)
  p= ρηg (pressure, ρ:density, η: horizontal displacement of water height, g: gravity)
- Convergence tests successfully performed

Linearized gravitational effects in the water layer implemented by adding a modified free-surface boundary condition (Krenz et al., AGU 2019)





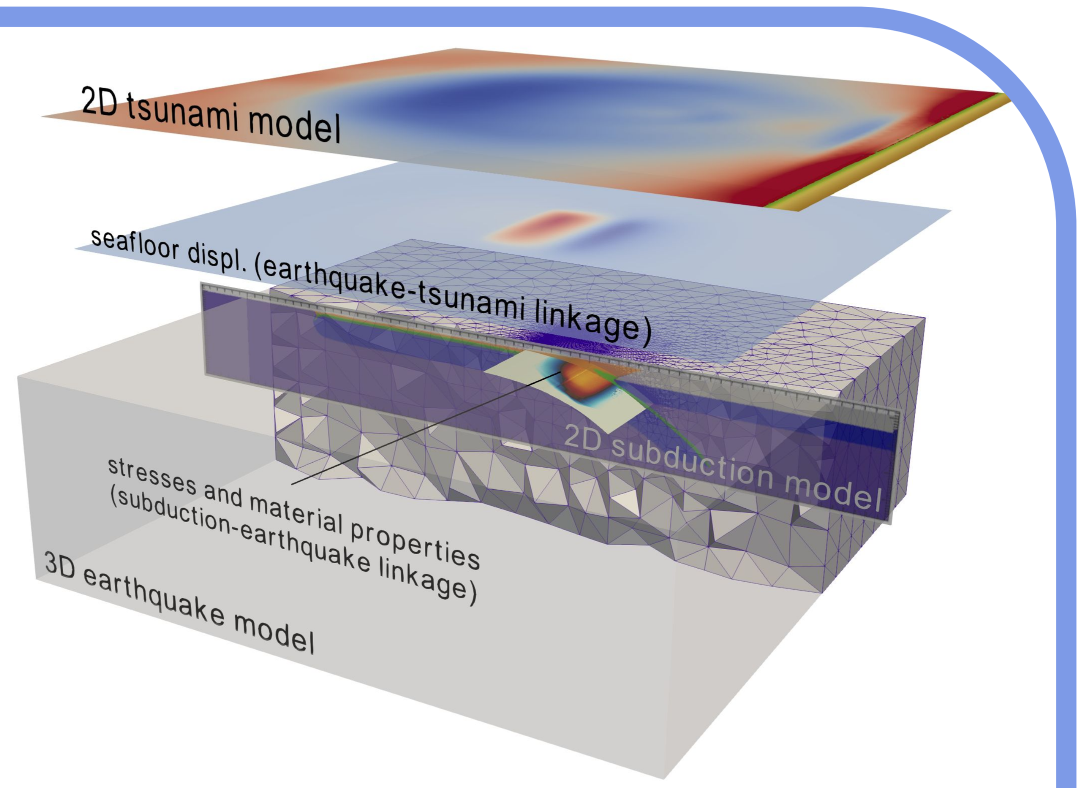
Showcase of adding a water layer to the earthquake model of the 2018 Palu Sulawesi event that triggered a tsunami (Ulrich et al., 2019, *Pure Appl. Geophys.*)

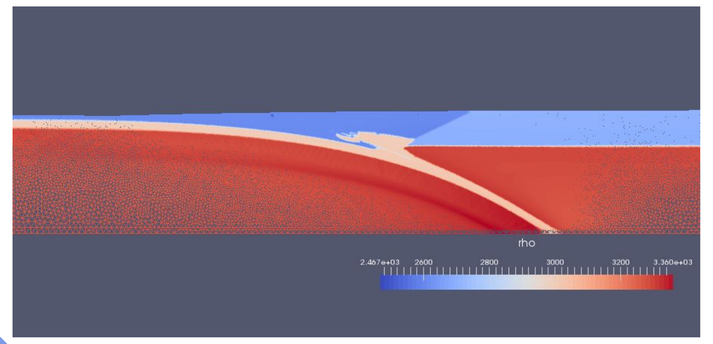
Methods

1-way coupling of subduction dynamics, seismic cycling, earthquake dynamic rupture and tsunami models

(following the workflow of Madden et al., 2019)

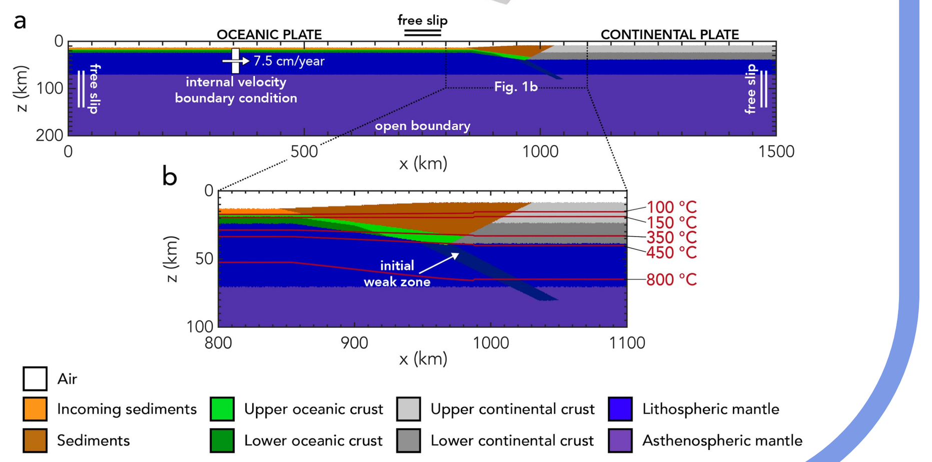
- Earthquake rupture highly depends on initial conditions, some are poorly constrained in subduction zones
- **Model geometry** and **rheology** as well as **material properties** and **fault strength** arise self-consistently from thermo-mechanical modeling of subduction evolution over millions of years (e.g. van Dinther et al. 2013b, van Zelst et al., 2019)
- Capture physical complexity of subduction evolution in dynamic rupture by taking **initial conditions** of one 'slip event' during the seismic cycling phase of the geodynamic model (provides all material properties)
- 3D dynamic rupture **seafloor displacement linked to tsunami model** → tsunami sourced over entire simulation time
- Next step: Link **tsunami model** (sam(oa)^2, Meister et al., 2016) which uses depth-integrated hydrostatic shallow water equation → efficiently models large scale horizontal flows as well as wave propagation and inundation





left: 2D density evolved during the subduction evolution in the geodynamic models - used as one of the inputs for dynamic rupture modeling

right: Structure of Seismic cycle model indicating different crustal parts and materials (van Zelst et al., 2019)



Outlook

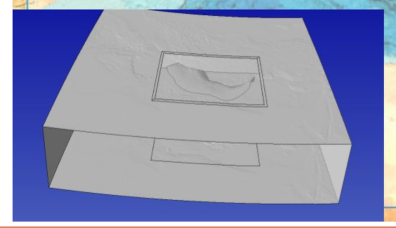
- Evaluate effects of along-arc variations of megathrust curvature, sediment content, and closeness to failure of the wedge on earthquake dynamics
- Add off-fault plasticity in 3D dynamic rupture models constrained by geodynamics
- Change friction law from linear slip weakening to fast velocity weakening rate-and-state friction

Dynamic earthquake rupture and Tsunami simulation for the Hellenic Arc

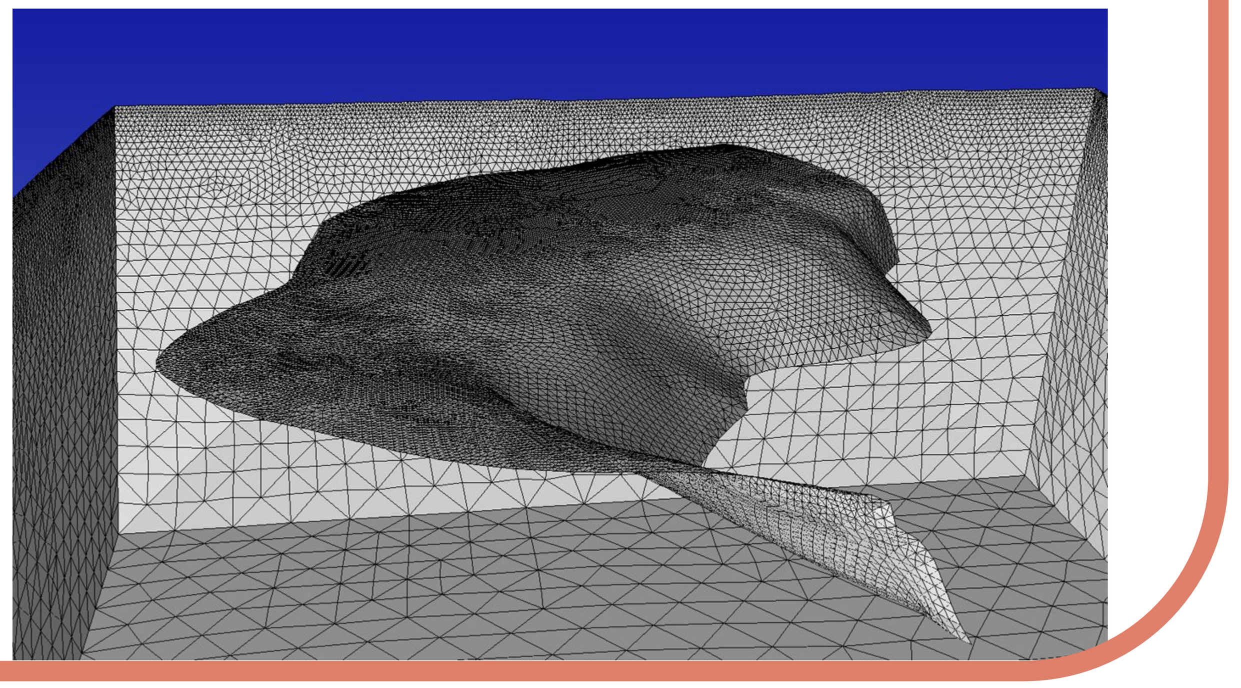
- Knowledge on tsunami genesis and propagation essential for hazard forecasting and potential warning in case of the risk
- Apply the method on realistic area in the Mediterranean Sea (2400km x 1800km)
- Topography and bathymetry data of area is highly resolved

1) Model region for a dynamic rupture - tsunami simulation of the Hellenic Arc

2) Mesh of the subducting Hellenic Arc



- Detailed knowledge of geological structure of Mediterranean and Hellenic Arc (includes seismic velocity structure, stresses and strengths)
- Model several multi-physics DR EQ scenarios and vary hypocentral location at subducting slab, rupt speed and resulting magnitude
- Present plausible tsunamigenic EQ scenarios and evaluate associated tsunami hazard
- Compare slip distributions, geodetic and possible seismic effects and tsunami waveforms generated all around eastern Mediterranean
- Calculate and analyze non-linear inundation process



(1) LMU
(2) Universidade de Brasília
(3) University of Leeds
(4) Technische Universität München
(5) Universiteit Utrecht

References:

Abrahams, L. S., Krenz, L., Dunham, E. M., Gabriel, A.-A. (2019). Verification of a 3D Fully-Coupled Earthquake and Tsunami Model, *AGU.*

Lotto, G. C., **and Dunham**, E. M. (2015). High-order finite difference modeling of tsunami generation in a compressible ocean from offshore earthquakes, *Comput Geosci.*, 19:327–340

van Dinther, Y., Gerya, T. V., Dalguer, L. A., Mai, P. M., Morra, G., & Giardini, D. (2013b). The seismic cycle at subduction thrusts: Insights from seismo-thermo-mechanical models, *Journal of Geophysical Research: Solid Earth.*

Krenz, L., Uphoff, C., Abrahams, L. S., Gabriel, A.-A., Dunham, E. M., Bader, M. (2019). Elastic-Acoustic Coupling for 3D Tsunamigenic Earthquake Simulations with ADER-DG on Unstructured Tetrahedral Meshes, *AGU.*

Madden, E., Bader, M., Behrens, J., van Dinther, Y., Gabriel, A.-A., Rannabauer, L., Ulrich, T., Uphoff, C., Vater, S., Wollherr, S., van Zelst, I. (2019). Methods and Test Cases for Linking Physics-Based Earthquake and Tsunami Models, *EarthArXiv Preprints*.

Meister, O., Rahnema, K., & Bader, M., (2016). Parallel, memory efficient adaptive mesh refinement on structured triangular meshes with billions of grid cells, *ACM Transactions on Mathematical Software*, 43(3), 19:1–19:27.

Ulrich, T., Vater, S., Madden, E.H. et al. Coupled, 2019. Physics-Based Modeling Reveals Earthquake Displacements are Critical to the 2018 Palu, Sulawesi Tsunami. *Pure Appl. Geophys*. 176, 4069–4109.

van Zelst, I., Wollherr, S., Madden, E. H. , Gabriel, A.-A., and Van Dinther, Y. (2019). Modeling megathrust earthquakes across scales: one-way coupling from geodynamics and seismic cycles to dynamic rupture, *Journal of Geophysical Research: Solid Earth*, 124.

van Zelst, I., Rannabauer, L., Gabriel, A.-A., van Dinther, Y. (2020). The effect of multiple splay fault rupture on tsunamis, *EGU.*

This work was funded by the European Union's Horizon 2020 research and innovation programme under the grant agreement N° 823844 (ChEESE centre of excellence, www.cheese-coe.eu).