

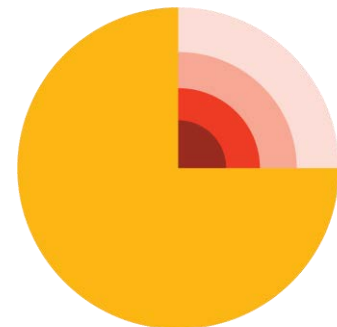
LMU	WP/T lead	2 tasks (T1.3, T6.2)
	Participates	23 tasks (T1.1, T1.2, T1.4, T1.5, T2.1 to T2.4, T3.1 to T3.3, T4.1 to T4.3, T5.1, T5.2, T6.1, T6.3, T6.4, T7.1, T7.3, T7.4), T7.6
	Main roles	SeisSol and TANDEM flagship codes, lead PD1, lead SC1.2 and SC1.3, training, EC committee, UC service enabling

LMU Munich's role in ChEESE-2P

Alice Gabriel (LMU and Scripps, UC San Diego)

Nico Schliwa, Casper Pranger, Duo Li (and more)

ChEESE KoM January 18



ChEESE



The current LMU ChEESE-2 team



Prof. Alice Gabriel



Dr. Duo Li



Dr. Casper Pranger



Nico Schliwa



SeisSol – a flagship code for earthquake and wave simulations



Researchers at Ludwig-Maximilians-Universität München and their partners at the Technical University

Earthquake shaking and noise disturbance

Earthquakes not only generate shaking or trembling of the Earth, but also audible noise. While the shaking aspect is typically of bigger concern, audible noise has developed into a real issue for geothermal power engineering. While earthquakes generated by geothermal engineering processes are in most cases not directly damaging, noise can irritate residents and thus often impedes substantially the acceptance of geothermal activities in the general public. In this article, we report on a joint endeavour of LMU, TU/M and the University of Helsinki to simulate such seismic-acoustic nuisance patterns.

21 SCIENTIFIC CODES SELECTED FOR NEW HIGH-PERFORMANCE SOFTWARE IMPROVEMENT PROGRAM

"Characteristic Science Applications" program to improve scientific software, generate benchmarks for Leadership-Class Computing Facility, and demonstrate societal impact of HPC

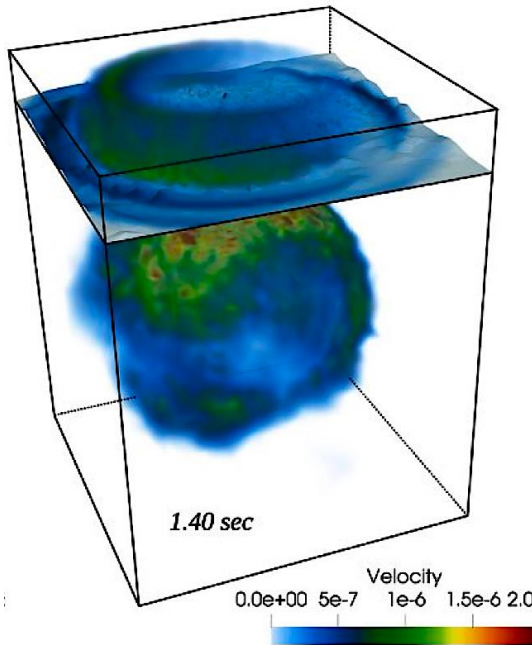
Þyrfti jarðskjálftamæla á hafsbotni við Norðurland

© 2000 Blackwell Science Ltd *Journal of Internal Medicine* 247: 105–111



el koma lyti þráttáttarmarkur á höfðinu og lyti
 einn þiggetti megi koma með nokkum áttarmarkum þar
 sem stótar af þar með stótarum einn þráttáttarmarkur.

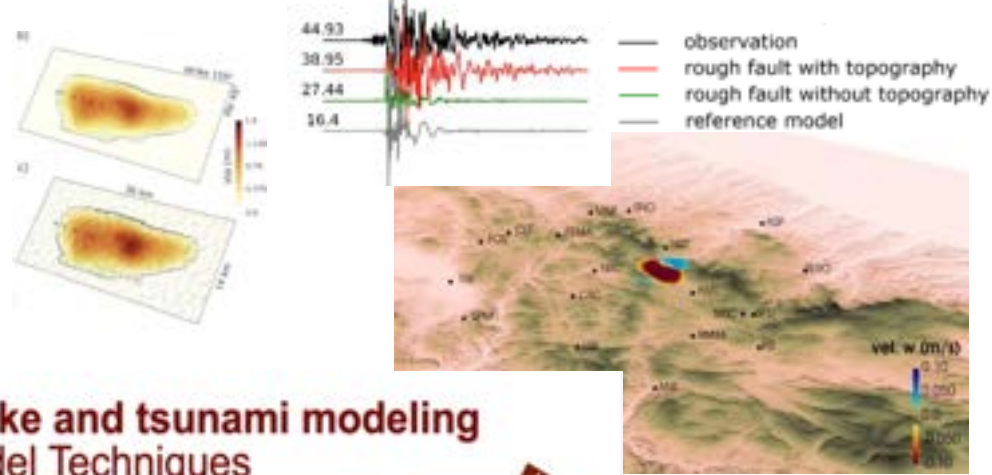
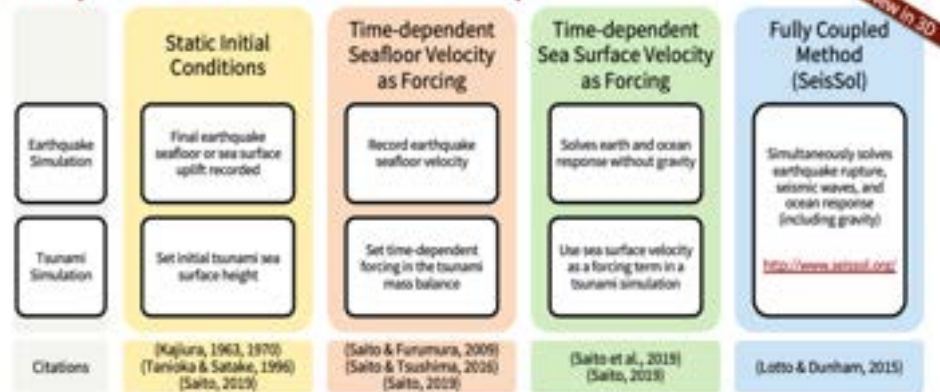
SeisSol – a flagship code for earthquake and wave simulations



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

Lauren Abrahams et al.,
EarthArxiv

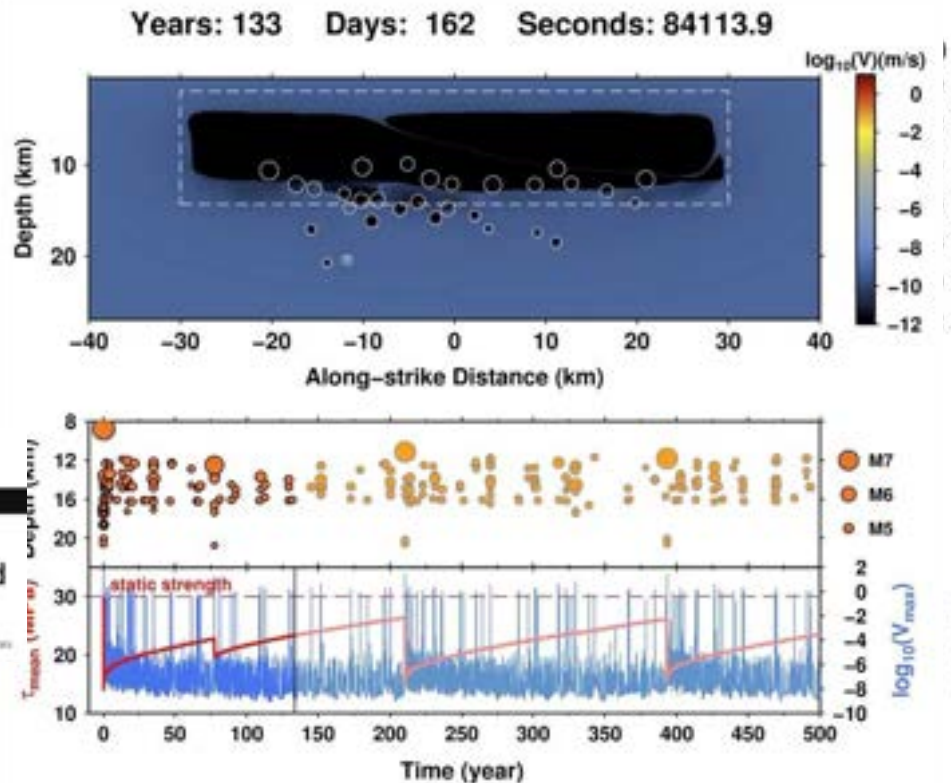
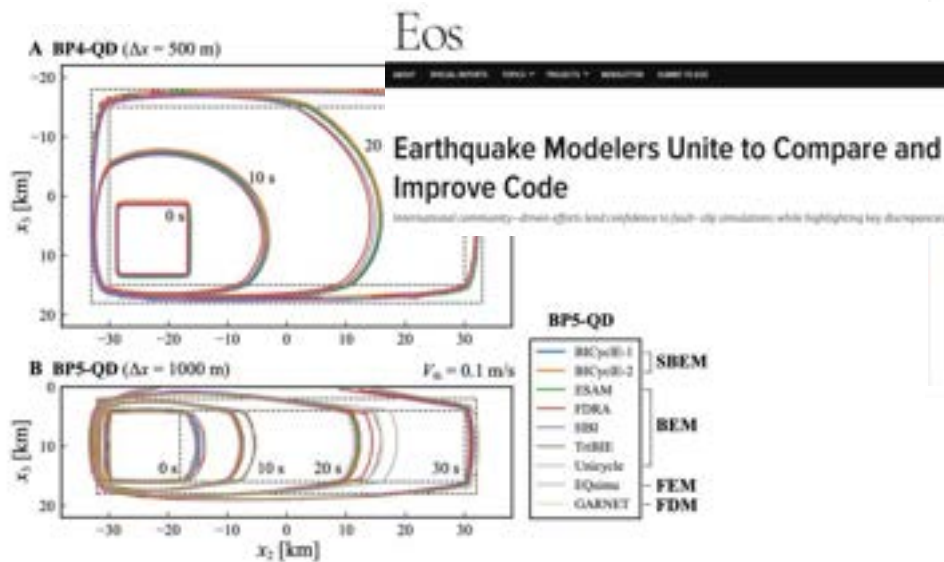
Coupled earthquake and tsunami modeling Comparison of Model Techniques



Taufiqurrahman et al., GRL'22

A new 'world' for ChEESE - Seismic cycle (SEAS) modeling

- In sequences of earthquakes and aseismic slip (SEAS) models, predefined fault surfaces obey a rate- and state-dependent friction law
- Successful benchmarking efforts, But: lack for open-source community methods and utilisation of HPC!



Jiang and Lapusta, 2016. using BEM to model the deeper penetration of large earthquakes on seismically quiescent faults

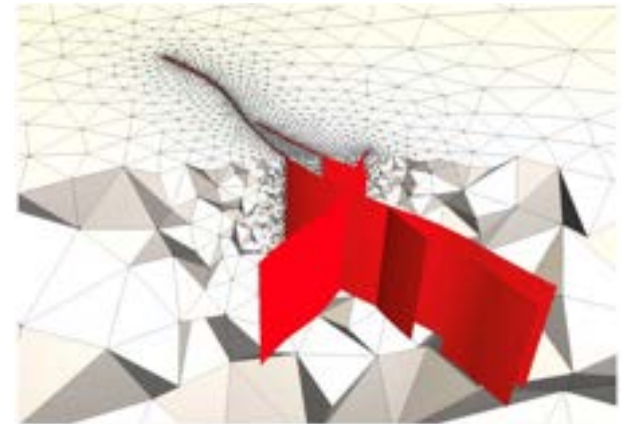
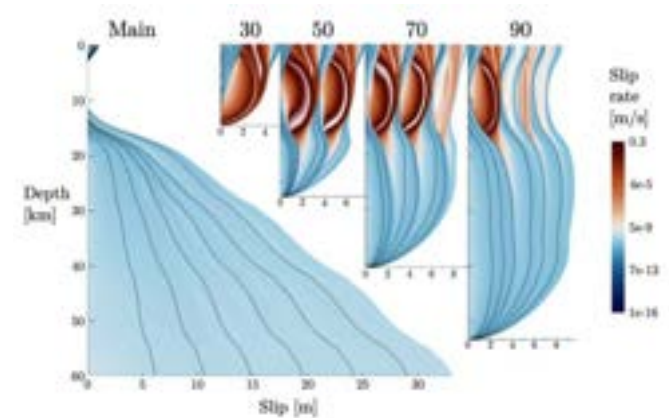
Tandem – a new flagship code for seismic cycle simulations

Tandem is an open-source **PETSc** SIPG-DG solver for elliptic seismic cycling problems, that allows for

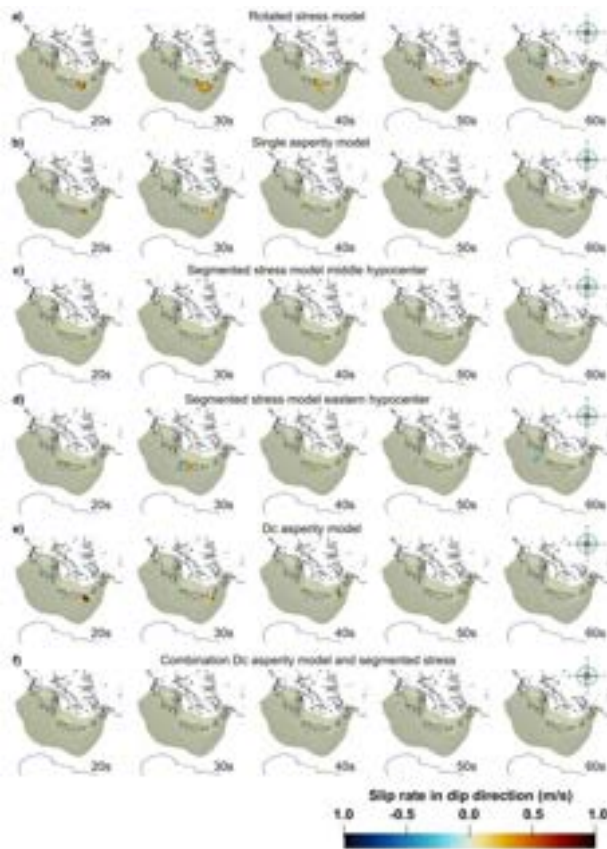
- geometric flexibility: enables unstructured, curvilinear, triangular/tetrahedral grids (future seamless linking to hyperbolic dynamic rupture solvers such as SeisSol)
- natural handling of discontinuities: using a double-valued numerical flux there is no need to split nodes or to introduce Lagrange multipliers at the fault
- we show that SIPG achieves arbitrary high-order accuracy for analytic, manufactured, and SEAS applications
- well suited to complex large-scale simulations (tested on ~5000 MPI ranks on SuperMUC-NG)

Uphoff et al., GJI 2023

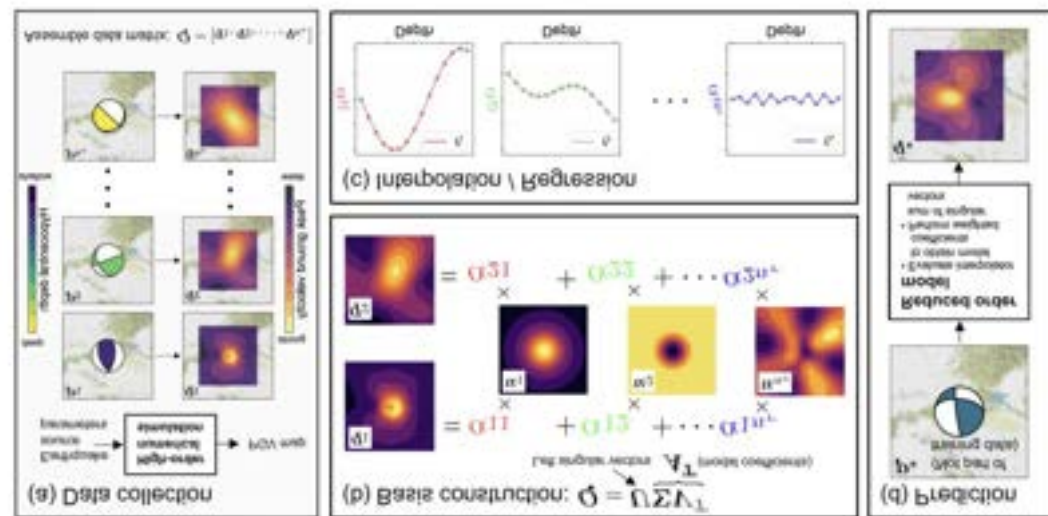
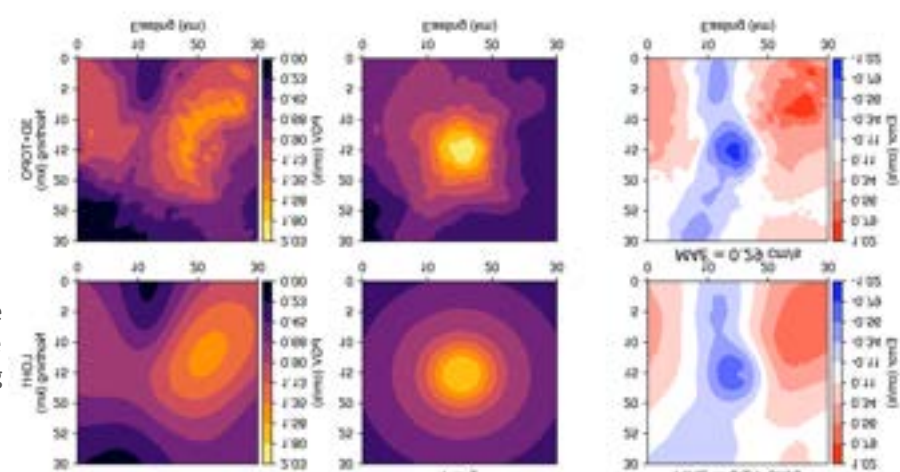
JOURNAL ARTICLE ACCEPTED MANUSCRIPT
A discontinuous Galerkin method for sequences of earthquakes and aseismic slip on multiple faults using unstructured curvilinear grids 
Carsten Uphoff, Dave A May, Alice-Agnes Gabriel
Geophysical Journal International, ggac467, <https://doi.org/10.1093/gj/ggac467>
Published: 25 November 2022



SC1.2	Next generation of earthquake simulators for the Hellenic arc and Iceland				
SC leader	LMU	Partners	TUM, CNRS, UM	Type	Basic research, hazard assessment
Description: This capacity SC will perform dynamic rupture, earthquake and slip simulations across many cycles of earthquake sequences at two relevant natural laboratories for which interdisciplinary geo- and hazard-data was acquired and unified for HPC applications in ChEESE-1P: the Hellenic Arc and the Southwest Iceland transform zone. While historical and geological records (extending over several thousands of years) have been used to construct catalogs of major earthquakes on known natural fault systems, constructing seismic hazard maps and estimating probabilities of aftershocks in the aftermath of large earthquakes are challenged by the lack of space-time complete, quantitative data on fundamental observables of the seismic cycle (e.g. magnitude and recurrence interval of large earthquakes). Also, the mechanics and feedback of earthquake fault networks throughout the seismic cycle remains poorly understood. The Hellenic Arc case will integrate novel high-resolution 3D structures developed using SPECFEM3D in PD2 (SC2.2) with earthquake-tsunami modeling capabilities of SeisSol to the developments in complex multi-source tsunami modeling of PD4. The model region is large and complex; the Hellenic Arc subduction zone itself extends over an area of 860km x 625km x 90km, including a complex slab geometry. Tsunami generating earthquakes may involve secondary splay fault activation. Time scales under consideration span from 35 Ma (starting point of SC8.2's geodynamic modeling of the evolution of the tectonic structure of the upper plate) to the seconds of seismic wave propagation. The modeling of the seismic cycle of the Southwest Iceland transform zone (~130x50 km), that poses the largest threat to the majority of the population, will be constrained in the long-term by the historical earthquake catalog (~1000 years) and in the short-term by the deformation measurements and earthquake hypocentral locations of recent decades, including the high-resolution measurements of the ongoing volcano-tectonic episode (since 2019). The modeling results will directly feed into SC1.3 where earthquake scenarios consistent with seismic cycle modeling will be simulated using physics-based approaches leading to non-ergodic hazard assessment and urgent shaking scenarios. The SC's physics-based results for aftershock sequences and short-term seismic hazard will be verified by independent, Southwest Iceland regional-specific ETAS statistical modeling.					



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



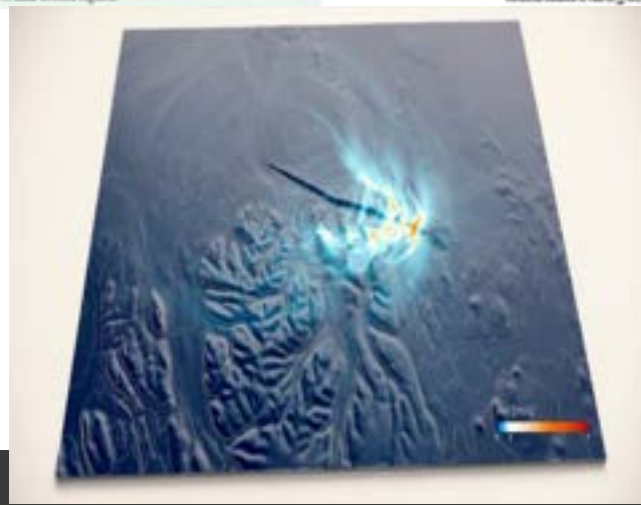
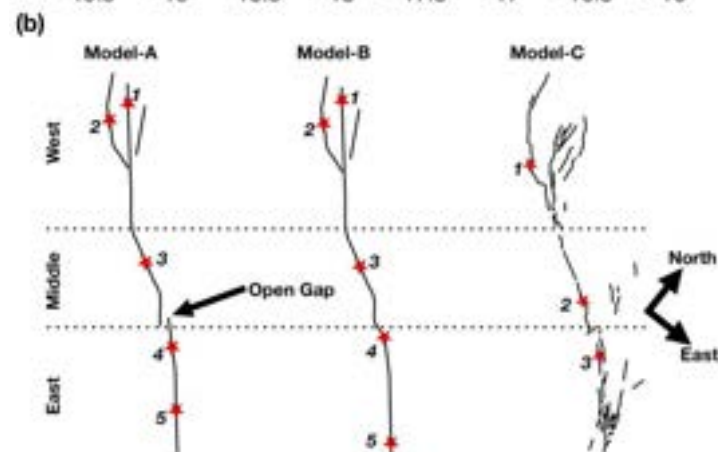
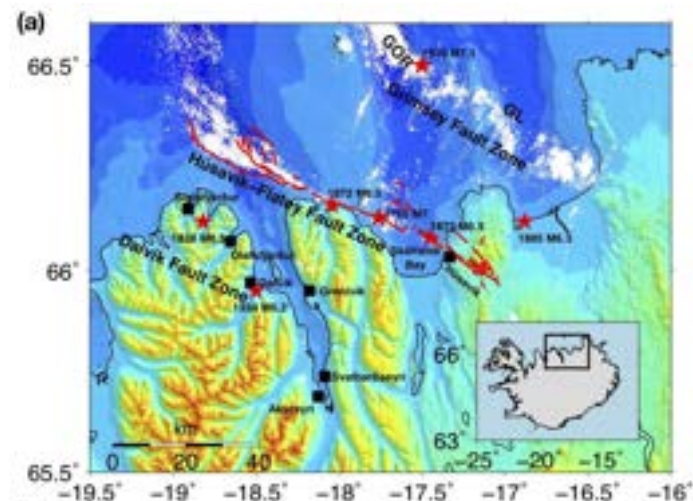
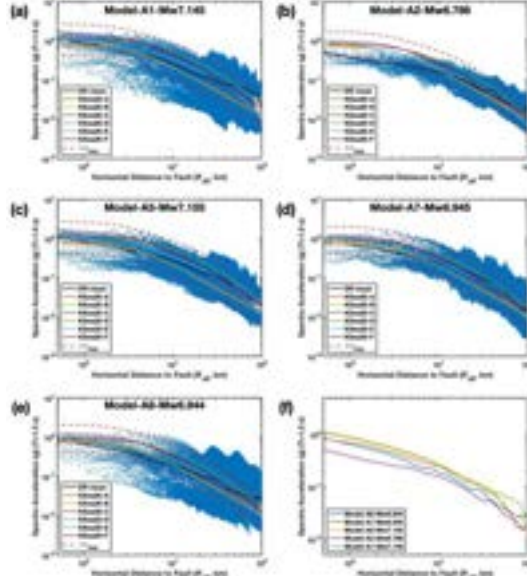
Constraining dynamic rupture simulations for tsunami hazard assessment - the Hellenic Arc (Wirp et al., AGU 22)

SC1.3	Physics-based PSHA and urgent UQ for Iceland: next generation hazard map				
SC leader	LMU	Partners	IMO, BSC, TUM	Type	Hazard assessment, urgent computing
Description: This capacity SC brings together state-of-the-art physics-based probabilistic seismic hazard analysis (PB-PSHA) with physics-based earthquake scenario forecasting (SC1.2) and strong ground shaking simulations that shall be launched immediately after seismic and/or deformation events in the Southwest Iceland transform zone to more accurately predict which areas are affected, and to what extent (UC service). In ChEESE-1P, the first PB-PSHA was carried out using time-independent finite-fault earthquake catalogs simulated on the basis of the 3D fault system model, for which earthquake rupture modeling and ground motion simulations were carried out using the fully probabilistic Southern California Earthquake Center (SCEC) CyberShake framework. Here, the seismic cycle modeling (SC1.2) is expected to directly inform on the likely hot-spots of tectonic loading along the zone in the short-term. It will thus serve as the gateway to the seamless migration from time-independent PB-PSHA to urgent and short-term earthquake scenario modeling and ground motion simulations for time-dependent forecasting, with important implications for expected impact and risk for those modern society's systems that are vulnerable to strong seismic motions. To this end, SC1.3 will unify the range of physics-based forward and ensemble simulations constrained by regional observations to which a seismic cycle model is calibrated for Southwest Iceland (SC1.2), thus ensuring consistency of all required geophysical information to enable modeling based hazard assessment.					



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Benjamin Mullerstein

We present 3-D isostatic dynamic rupture earthquake scenarios for the Hsueh-Faury Fault zone (HFFZ) in Northern Taiwan. We construct three fault system models consisting of up to 52 segments of varying geometric complexity. By varying hypocenter locations, we analyze rupture dynamics, fault interactions and their associated ground motions and observational uncertainties in 79 scenarios. We use regional observations to constrain 3-D subsurface velocities and viscoelastic attenuation as well as fault stress and strength. Our models account for wave birefringence, off-fault plasticity and we explore the effect of fault roughness. Our isostatic dynamic rupture scenarios can match historic magnitudes. We show that the fault system segmentation and geometry, hypocenter locations, initial stress conditions and fault roughness have strong effects on multi-fault rupture dynamics across the HFFZ. Breaking of different portions of the same fault system leads to varying rupture dynamics, slip distributions and magnitudes. All dynamic rupture scenarios yield highly heterogeneous near-field ground motions. We observe amplification from rupture directivity, geometric complexities, and amplification and shielding due to topography. We recover a magnitude-consistent attenuation relationship in good agreement with new regional empirical ground motion models. Physics-based ground motion variability changes with distance and increases for unilateral vs. bilateral rupture. Our study illustrates important ingredients for fully physics-based, regional earthquake scenarios, their respective importance for rupture dynamics and ground motion modeling and how they can be observationally constrained and verified. We extend that dynamic rupture scenarios can be useful for non-ergodic probabilistic seismic hazard assessment, specifically in data-limited regions.



On the Validation of CyberShake for Southwest Iceland Transform Zone Earthquakes

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Claudia Abril³, Benedikt Halldórsson^{4,5}, Milad Kowsari⁵, Farnaz Bayat⁵, Kim Olsen⁶,
Alice Agnes-Gabriel^{7,8}, Josep de la Puente¹

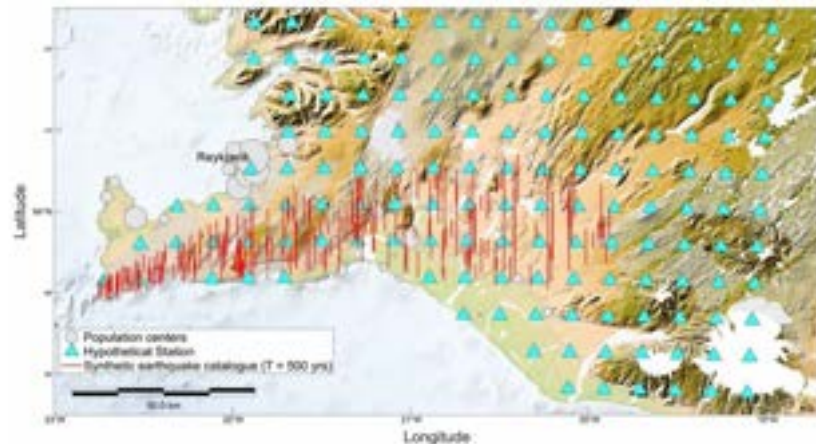


Figure 1. One realization of the synthetic fault system model (red lines) for an earthquake catalogue of 500 years, comprising 223 dextral transform faults in SISZ-RPDR and the hypothetical recording stations with 10 km grid spacing (triangles). The nearby population centers are shown in gray circles, their relative diameters indicating population size differences.

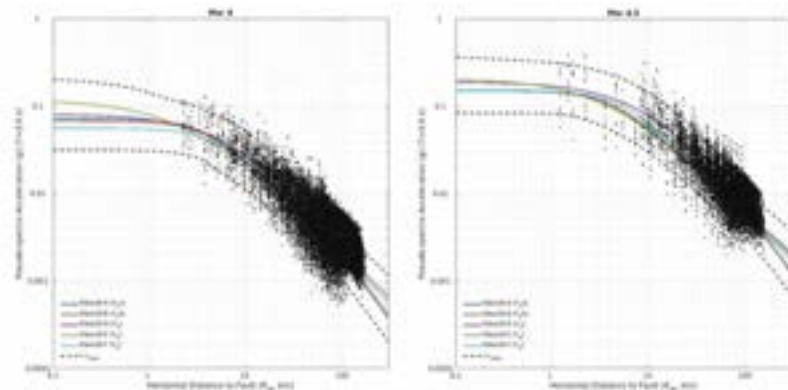


Figure 3. CyberShake PSA at 3s for events of M_w 6.0 and 6.5 are compared to a reference GMPE.

PD1	Extreme-scale modeling of seismic hazards				
PD leader	LMU	Partners	IMO, TUM, CNRS, BSC	Derived SCs	SC1.1, SC1.2, SC1.3
Problem description: This PD combines high-fidelity earthquake and seismic wave simulations performed with 4 ChEESE-2P flagship codes in order to catapult seismic simulations to bridge spatial and temporal scales by enabling the efficiency, versatility and flexibility required to allow the integration of multiphysics simulations, physics-based probabilistic hazard assessment, rapid response urgent earthquake and shaking simulations and modeling the highly complex seismic wavefield at high-frequencies, such as ubiquitous anthropogenic “noise”. PD1 will allow combining simulations that are well validated with available data with probabilistic frameworks and uncertainty quantification towards next generation physics-based hazard assessment. Using a physics-based description of earthquakes, modern numerical methods as well as hardware-specific optimisation will shed light on the dynamics, severity and cascading hazards of earthquake behavior and enable an unparalleled degree of realism exploiting high-performance computing. As a complement to forward HPC modeling, PD1 will also explore ML-based solutions that can obtain fast analogs to seismic simulations, fundamental for parameter exploration and early assessment of hazard. Objective: The objective of this PD is to improve the scalability and time-to-solution of the earthquake modeling and seismic wave propagation codes SeisSol, ExaHyPE, SPECFEM3D and Tandem. These flagship codes will be enhanced with respect to new features in model physics (such as viscoelasticity), IO including capabilities for importing and exporting 3D volume data for one-way or two-way multiphysics coupling, and mesh generation. The developed multiphysics, probabilistic and data-integration capabilities will be tailored towards future DestinE integration in digital twin components, such as those developed in DT-GEO, and specific models and data will be prepared to be shared via EPOS, utilizing synergies with Geo-INQUIRE, and inform rapid response simulations.					

