Report of Transnational Access Projects

(Note: the information here will be publicly disclosed in the Geo-INQUIRE website, do not include sensitive information)

Project ID: C3-TA2-541-11_3

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Project title: Towards physics-based seismic hazard assessment: validating finite-fault models of the 2011 Tohoku-Oki earthquake with ensembles of dynamic rupture simulations

Project acronym: FFM-Tohoku

Hosting installation: LMU, Germany

Hosting team: Vikas Kurapati (TUM), Zihua Niu (LMU), Iris Christadler (LMU), David Schneller (TUM), Giorgio Amati (CINECA), Piero Lanucara (CINECA)

Period of access: 30. June- 11. July 2025, remote access continued

Report of activities:

Subduction zones host the largest earthquakes on Earth. These large events rupture hundreds of kilometers in minutes, generating strong, potentially damaging ground motion and posing potential tsunami hazards to coastal cities. Understanding the fundamental processes and faulting conditions governing these types of ruptures is essential for evaluating megathrust seismic hazard. Imagining the spatiotemporal slip evolution is key to studying the physics of earthquake rupture. However, imaging rupture evolution based on observations remains challenging due to the non-uniqueness of inversion results and uncertainties in faulting conditions. These challenges are exemplified by the 2011 Tohoku-Oki, Japan, earthquake, one of the largest and most well-recorded events in history. Distinctive slip models have been proposed for this event using different types of data and inversion methods, yet the physical processes underlying megathrust earthquake ruptures remain unresolved.

Here, we utilize CINECA's Leonardo high-performance computing platform to conduct 3D dynamic rupture simulations to evaluate the dynamic viability of finite-fault slip models. During the PI's visit to LMU in summer 2025, the TA team set up the SeisSol GPU version and implemented the new Ensemble Kalman Inversion framework in the CINECA Leonardo HPC system.

Applying this new approach to 32 models of the 2011 Tohoku-Oki earthquake, we identify 26 dynamically viable 3D rupture scenarios using 285 total forward simulations. Across the ensemble, both smooth and highly heterogeneous finite-fault slip models can be reproduced dynamically. Yet these models converge to three dynamic rupture families, characterized by crack-like, single-reactivation, or multiple-reactivation rupture styles. This convergence suggests that apparent finite-fault diversity may reflect a smaller set of dominant controls on rupture dynamics, including the level of prestress heterogeneity. Multiple-reactivation dynamic rupture models best reproduce the observed depth-dependent rupture behavior and moment-rate complexity. By contrast, large tsunamigenic slip near the trench and comparable partitioning of released strain energy between breakdown and radiated energy persist across dynamically viable models, despite differences in initial shear stress conditions and rupture style. These results show that finite-fault slip model heterogeneity can map onto a smaller set of dynamically viable rupture styles, preserving robust first-order features. Our EKI framework provides an efficient pathway for integrating observations with physics-based simulations and identifying dynamically consistent earthquake source models. We utilize the new Geo-INQUIRE Simulation Data Lake (SDL), which provides not only capacity to store terabytes of synthetic data, but also allows open and FAIR (Findable, Accessible, Interoperable, Reusable) sharing of the results through Digital Object Identifiers (DOIs) for each dataset and the accompanying model files. The results are presented at the SCEC Annual Meeting in September 2025, AGU Annual Meeting in December 2025, and at the CRESENT topical workshop in May 2026. The manuscript of the main project is in process and is expected to be submitted before the summer. A complementary paper is accepted and will be published soon.

Project outcomes:

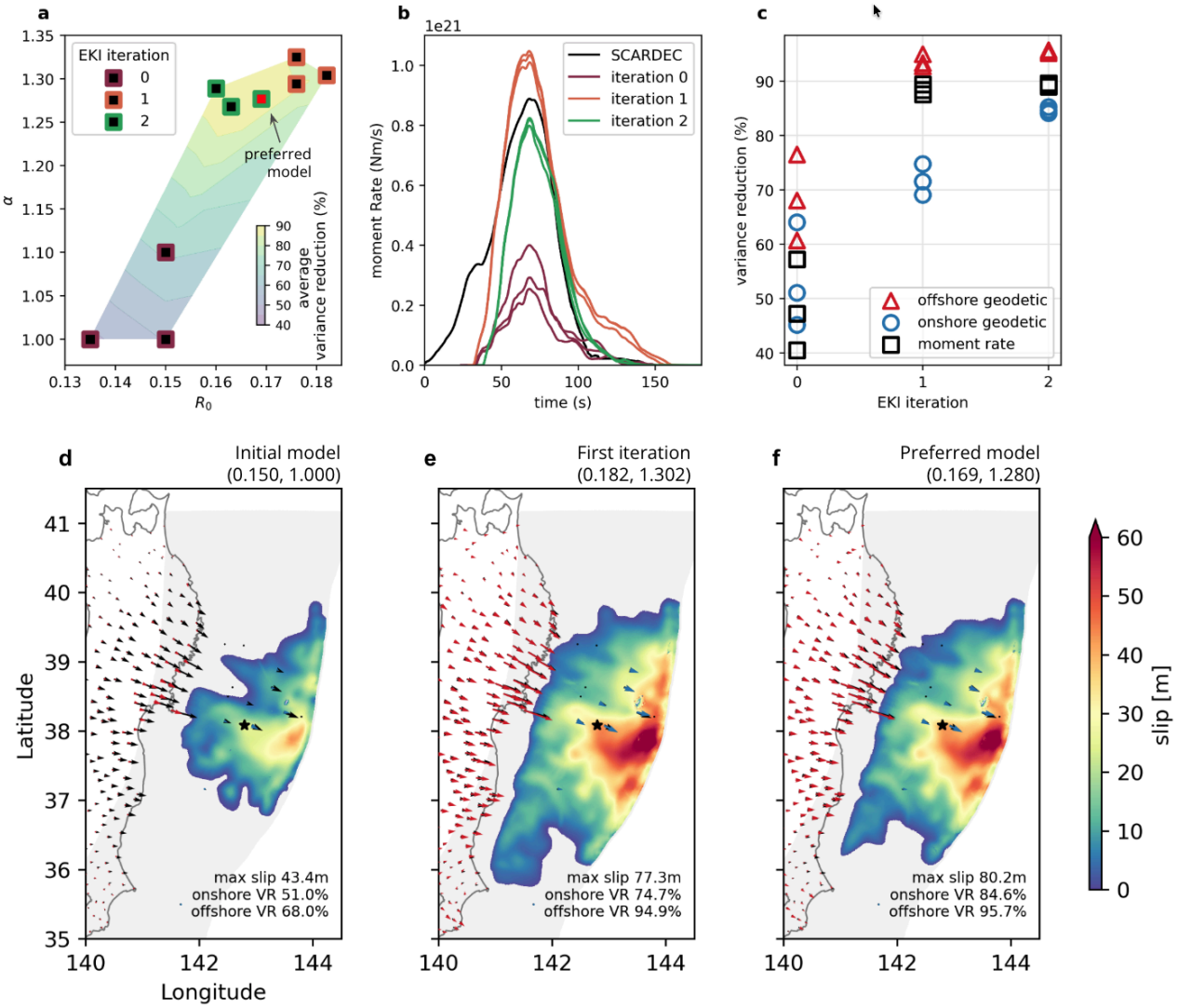
Conference presentation/ poster:

SCEC Annual meeting 2025: https://central.scec.org/publication/14509

AGU poster: *https://agu.confex.com/agu/agu25/meetingapp.cgi/Paper/1942108*

Publication:

Wong, J. W. C., Gabriel, A. A., & Fan, W. (2026, Nature Communications). Dynamic restrengthening and stress heterogeneity explain megathrust earthquake complexity.



Geo-INQUIRE is funded by the European Commission under project number 101058518 within the HORIZON-INFRA-2021-SERV-01 call