Tectonic and Dynamic Controls in the 2023 Kahramanmaras and Ekinozu, Türkiye, Earthquake Sequence Illuminated by Physics-Based Simulations

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Recent progress in the dynamic rupture simulations demonstrates successful reproducibility in the processes of natural large earthquakes (e.g., Ando et al., 2017, EPS; Ando and Kaneko, 2018, GRL). In this talk, we present the analysis results for the 2023 Türkiye-Syria earthquake sequence and the 2024 Noto Peninsula, Japan earthquake as two new examples, identifying the importance of the fault geometry and stress tensor that control the dynamic rupture processes.

The balance between the energy release rate and the fracture energy governs the rupture dynamics. They are described by the functions of the shear stress drop and normal traction applied on fault surfaces. Since the regional stress field is described by the stress tensor, the shear and normal traction vector components depend on the local fault orientations. This nature underlies the mechanical roles of the fault geometry and the surrounding stress fields. Although estimating the absolute values of the stresses at the depth is difficult, the four components of the stress tensor out of the six independent components can be constrained by the inversion analysis based on the observations of the focal mechanisms of small earthquakes in targeted regions. The estimates of the other two components can be less precise, but the magnitudes of the overburden pressure and the empirical values of a few MPa for the stress drop can provide primary constraints for them. The 3-D fault geometry can be constrained based on the geometry of surface fault traces and estimated dip angles with average values of 90, 60 and 30 degrees for the strike-slip, normal and reverse faults. While the geometrical irregularity in the dip direction is difficult to estimate without subsurface surveys, the surface fault traces can provide strong constraints, particularly to model large crustal earthquakes (M>7), where the ruptures are thought to propagate along pre-existing faults in the lateral direction determining the magnitudes of the earthquakes. On this basis, we can develop minimalistic models for the initial and boundary conditions for the dynamic rupture simulations based on pre-seismic observations for targeted areas and events. Such a minimalistic model has a small number of input parameters, and the model is uniquely constrained in a robust manner to some extent.

The 2023, M7.8, Kahramanmaras earthquake (the first event) ruptured mainly the transform plate interfaces between the Anatolian and the Arabian plates, called the East Anatolia fault (EAF). The first event was nucleated on a subsidiary fault of the EAF, located on the northern extension of the Dead Sea Fault, accommodating the slip between the Arabian and African plates. In 9 hours, the M7.6 Ekinozu earthquake (the second event) occurred on the Çardak-Sürgü fault branched away from the main strand of the EAF to the Anatolian plate. This sequence shed light on the mechanism underlying the complex seismic motion of the plate interfaces. We show, by using a physics-based simulation, that the 3-dimensional fault geometry and tectonic stress conditions are the key controlling factors.

We perform the fully dynamic rupture simulations using the boundary integral equation method accelerated with the fast domain partitioning method (Ando, 2016, GJI). This method is capable of handling non-planar 3-D fault geometries at the time complexity of O(N^2M) and the memory use of O(N^2), reducing the numerical costs of the original BIEM at O(M) for the number of the time steps M.

We built models and compared the obtained simulation results (forward models) with the coseismic observations and slip inference (inverse models) in the cases of the 2023 Türkiye-Syria earthquake sequence. The simulations reproduce the primary characteristics of the observed rupture processes and slip distributions. For the mainshock (the first event) of the 2023 event, the simulation reproduces the rupture propagations through the three major segments with the branch and bends. The simulated process includes the observed time delay for the backward branching (Figure 1). We find physical conditions that lead to the triggering of the second event. Our results demonstrate the reasonable gain in the forecastability of the dynamic rupture processes with the observational constraints of the fault geometry and stress tensor field. This further suggests the importance of building these structural models beforehand to assess the possible scenarios of future large earthquakes.

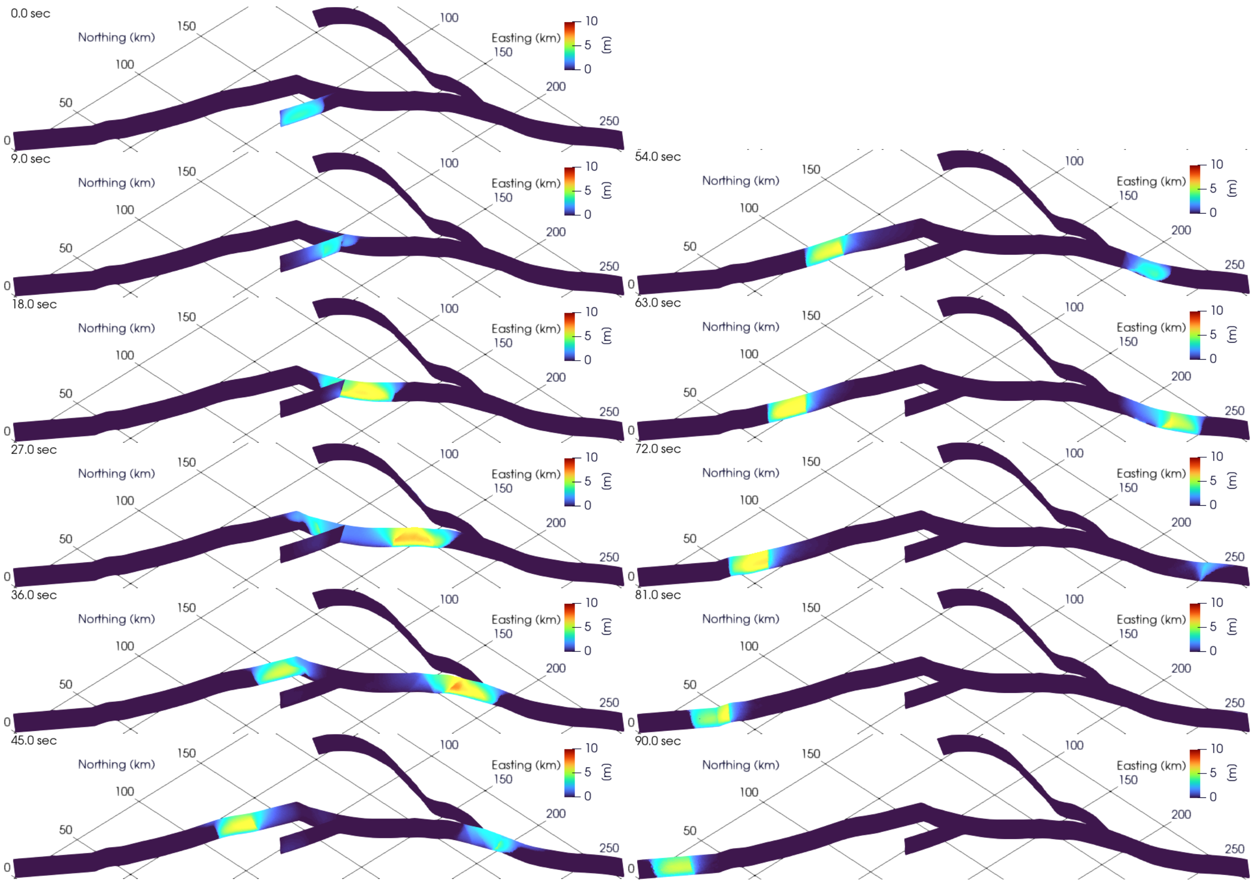

Figure 1. Snapshots of the rupture process. The slip amount within the 9-second intervals is shown. The annotated times at the top left denote the onset of the intervals. Modified after Ando et al., 2024.

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