Dynamic Rupture Behavior Across Asymmetric Fault Intersections in the Hayward-Calaveras System

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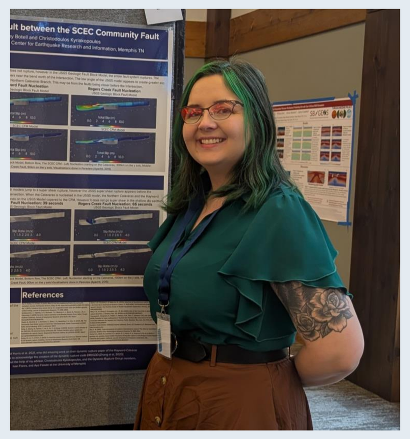

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Abstract

The Hayward–Calaveras fault system poses a major hazard in the San Francisco Bay Area, with more than seven million people living atop a network of active faults capable of producing M7-type earthquakes. Prior dynamic rupture modeling incorporated a generalized representation of the Calaveras-Hayward junction, where the two faults merge “symmetrically” at depth (see inset in Figure 1; Harris et al., 2021). This representation did not include the southernmost Central Calaveras–Hayward junction, ~11 km north of Morgan Hill, where the fault transitions abruptly into a shallow-dipping Hayward strand beneath East San Jose (see Figure 1 inset top and bottom panels). Here we want to quantify how rupture behavior differs when major junctions and intersections are implemented and evaluate the dynamic effects of the shallow-dipping Hayward strand. By comparing rupture outcomes across two independent structural models (CFM and USGS Bay Geologic Model), this project aims to identify which intersections act as mechanical barriers, viable rupture pathways, or sites of dynamic rupture partitioning. The results will refine the range of plausible large-earthquake scenarios for the East Bay and improve regional seismic hazard assessment.

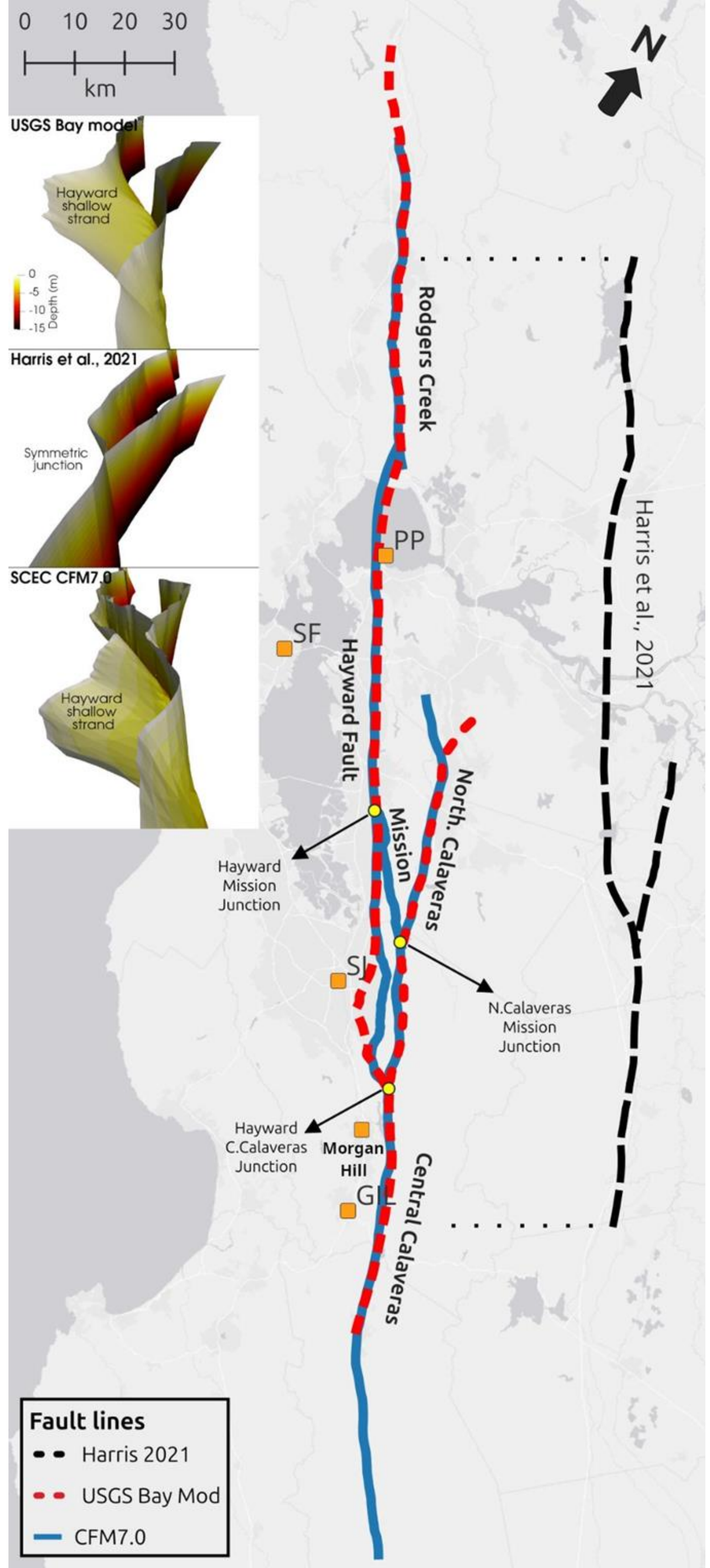
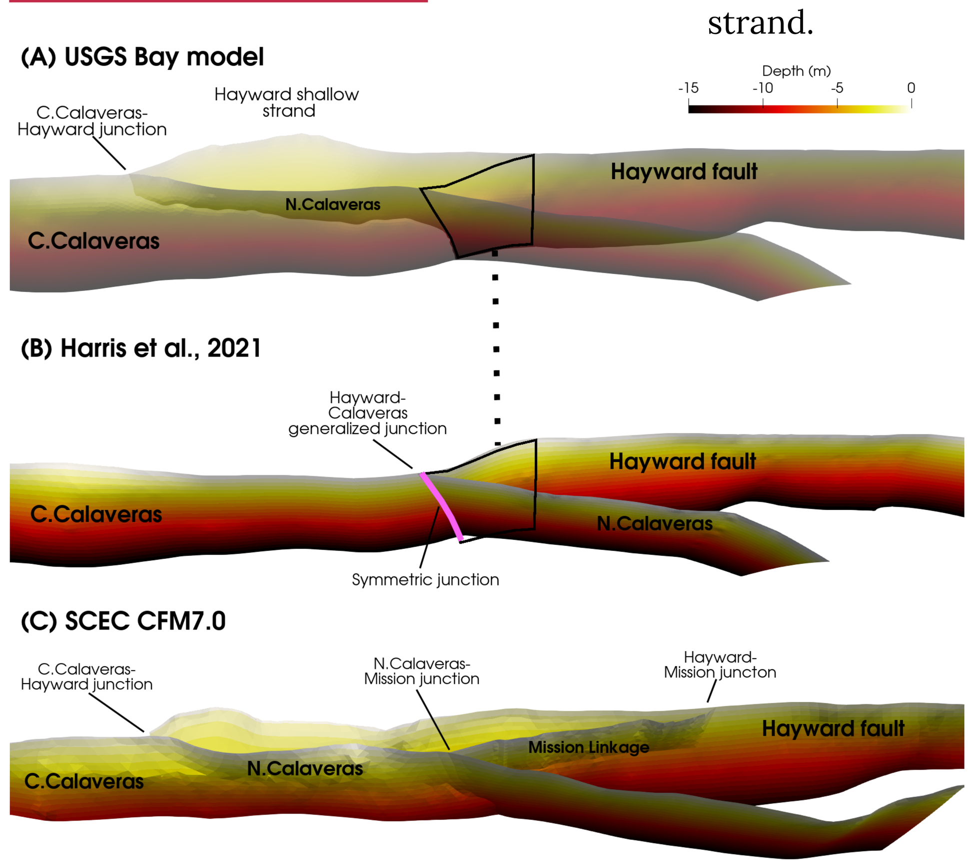


Figure 1. Map of the Hayward, Calaveras, Mission Connector, and Rodgers Creek faults. The USGS Bay Area model (red dashed line), the SCEC CFM model (blue cont. line), and the Harris et al. 2021 model (black dashed line) are shown; the Harris model is laterally offset for clarity. The upper-left inset illustrates the 3D geometry of the Hayward–Calaveras junction as represented in these models with emphasis on shallow-dipping strand.

3D Fault Geometry



USGS Bay Area Geologic Fault Block Model (USGS Earthquake Hazard Program, 2020)

Symmetric generalized junction model used in Harris et al., 2021

The California Community Fault Model (CFM) 7.0 by the Statewide California Earthquake Center (Plesch, Marshall & Shaw; 2024)

Figure 2. Fault geometries considered in this study

Model and Method

To run our dynamic rupture simulations, we use the mix-flux-based 3D discontinuous-Galerkin FEM code DRDG3D (Zhang et al., 2023; see Figure 3), which handles fault bifurcations without requiring a pre-selected continuous strand, allowing rupture paths to emerge solely from geometry and stress conditions. DRDG3D has been tested using criteria from the community driven SCEC dynamic rupture exercise (Harris et al., 2018). Starting from an original tetrahedral mesh the tets are transformed into 10-node non-linear tetrahedral elements in the dynamic rupture code, effectively increasing the node density.

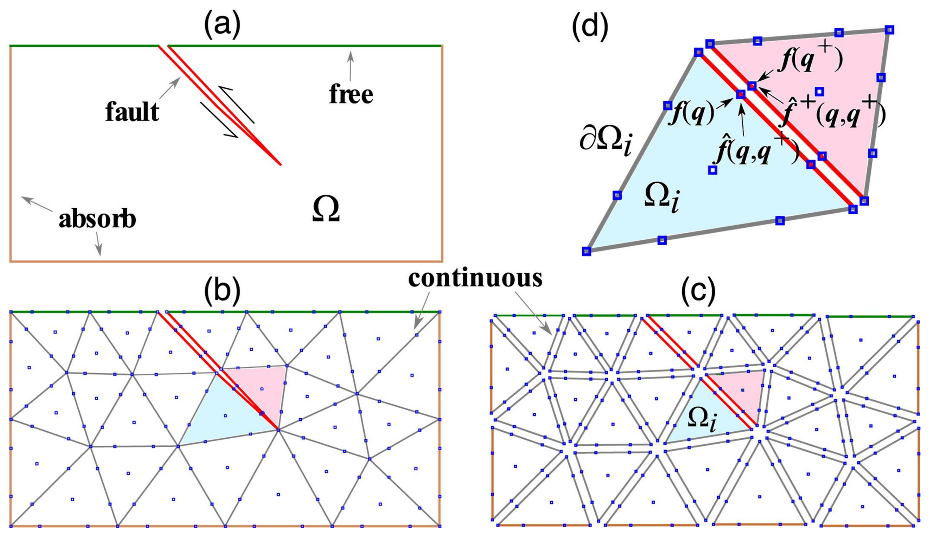


Figure 3. Fault implementation (a) using the Discontinuous Galerkin Method (DGM; (c)) vs the more traditional continuous FEM represnetation (b). In DGM both fault discontinuites and continuous boundaries are represented using “split nodes” (c); Panel (d) shows details of the discontinuous element configuration and “numerical” flux vectors; (*Figure extracted from Zhang et al., 2023*)

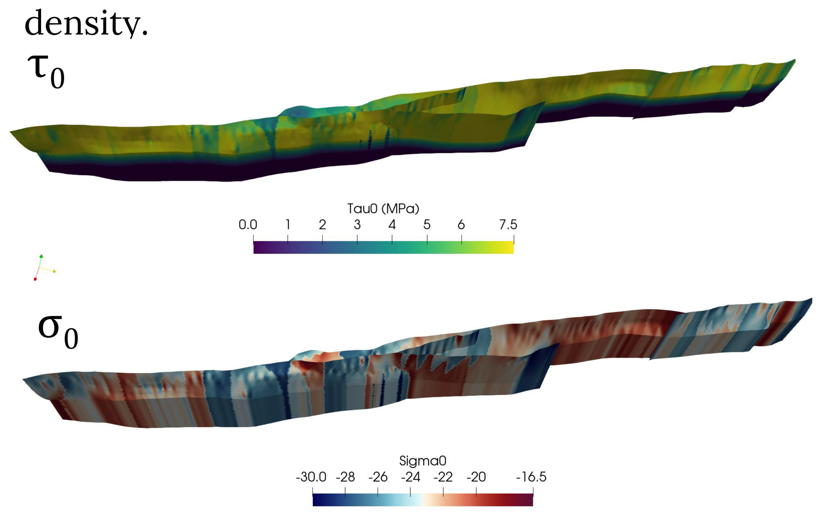


Figure 4. Fault Initial Shear and Normal Stresses

- **Initial Stresses** (Figure 4)

We set our initial stresses using the SCEC Community Stress Model (CSM). We used “PH03_NorCal” (Provost and Houston) which includes values for direction of SHmax and Aphi. Aphi combines the shape parameter ratio (σ_2 - σ_3 / σ_1 - σ_3) with the expected faulting regime based on which principal stress is most vertical. The principal stress tensor is created by inputting values for σ_1 and σ_2 and then, using Aphi to calculate σ_3. We then rotate the principal stresses so that σ_1 points in the SHmax direction. We assume strike slip faulting.

- **Friction Law** (Figure 5)

We use linear slip-weakening (Andrews, 1976; Day, 1982) with a static coefficient of friction of 0.6 and a dynamic coefficient of friction of 0.1. The slip weakening distance is 0.3 m. To avoid unrealistic high slip concentrations around the nucleation patch we nucleate our models using time-dependent slip-weakening, an expanded version of the linear slip weakening.

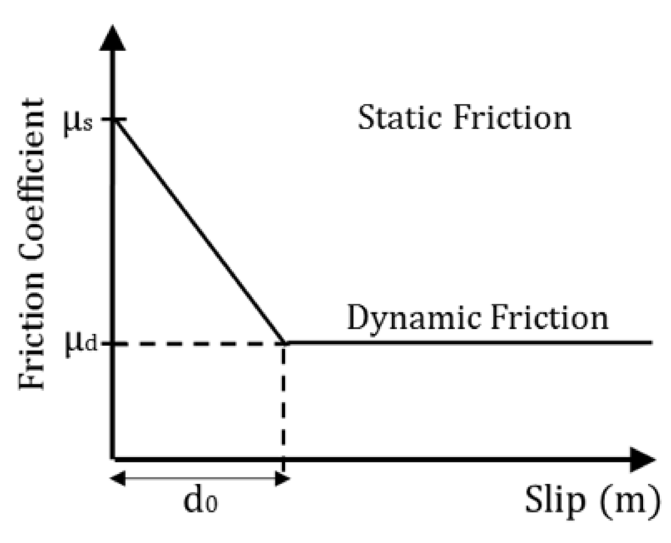


Figure 5. Linear Slip Weakeing Friction Law

- **Velocity Model** (Figure 6)

The model total dimensions are 473 km × 200 km × 60 km. We use the USGS Bay Area Seismic Velocity Model (Aagaard & Hirakawa, 2021) which honors the fault geometry and exists as a query-able option within the SCEC Unified Community Velocity Model (Small et al., 2017). The mesh is generated using Coreform cubit. We use 10-node non-linear tetrahedral elements. The mesh density is 500m near the faults and becomes larger closer to the boundaries.

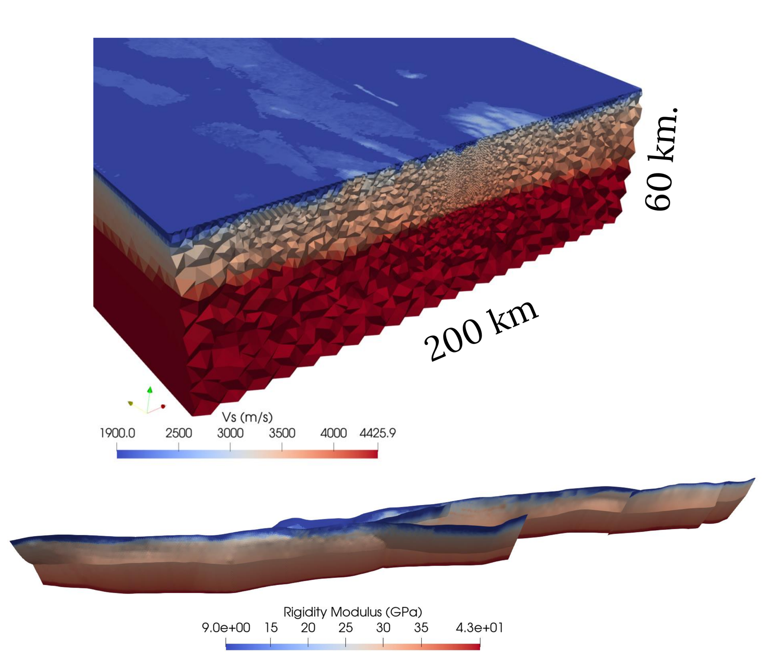
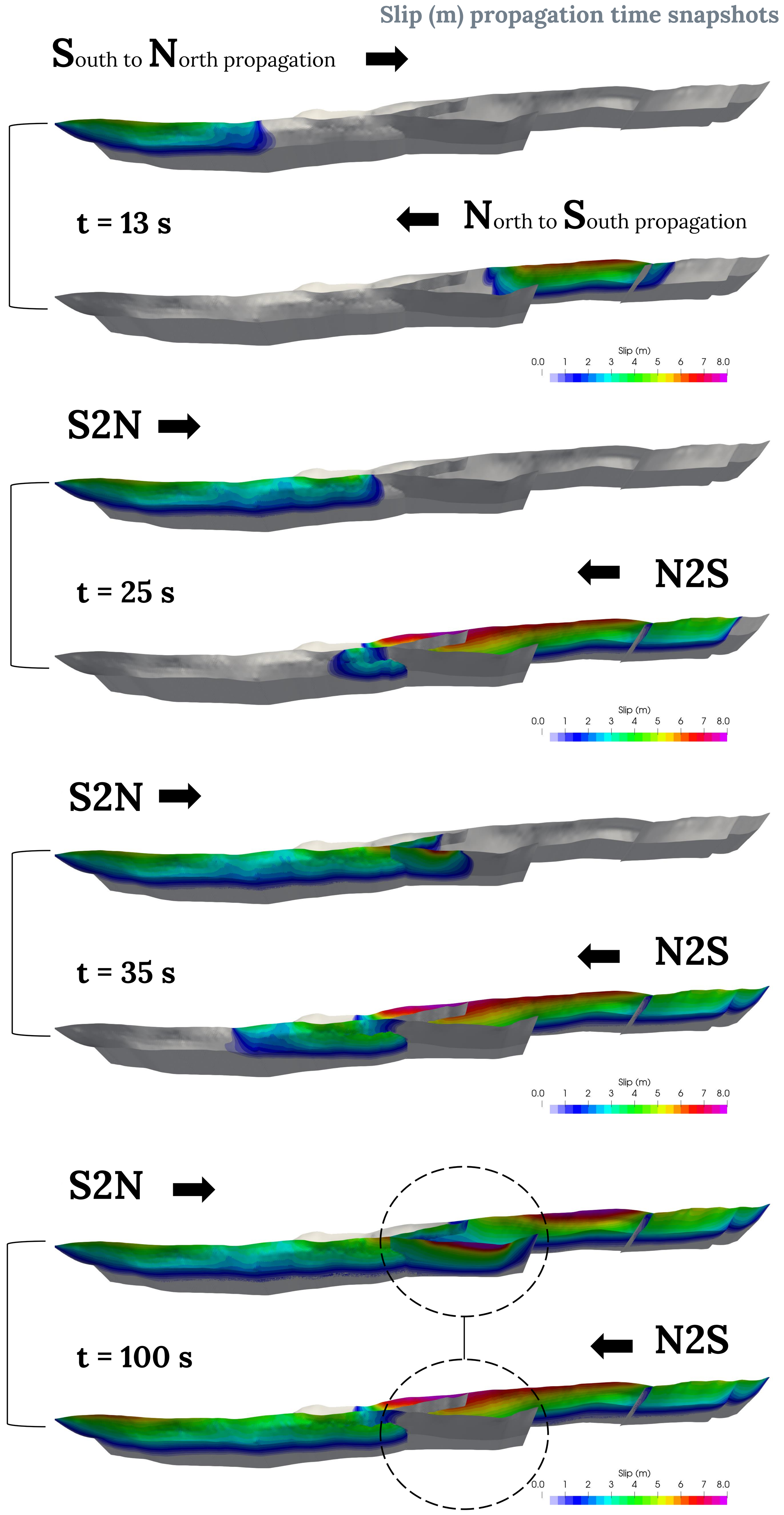


Figure 6. Example of FEM mesh grid and USGS velocity model for the Hayward-Calaveras system.

Preliminary Simulations (only for CFM case)

Slip (m) propagation time snapshots



Conclusion

Our preliminary results emphasize the impact of fault geometry on rupture path, slip rate and total slip. Accurate fault models are fundamental to estimate the extent of future earthquake rupture and the associated earthquake hazard. Additional work is required to properly assess the differences between the CFM and USGS BGM models and the effect of the shallow Hayward strand. We plan to input geodetically infered creeping/locked patches into the next iteration of our simulations to further test the difference between these models.

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