# On the use of Discrete Fault Network Simulations for Time-dependent Seismic Hazard Assessment, Application to the Sagaing fault

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## Abstract

Despite considerable advancements in our understanding of earthquake dynamics, earthquake forecasting remains a daunting challenge. The 2025 Myanmar Mandalay earthquake is a notable case, as it ruptured a 'seismic gap' on the Sagaing Fault, where a large earthquake was anticipated due to the relatively large deficit of slip that had accumulated there. In this study, we conduct long-term simulations of earthquake sequences accounting for the non-planar geometry of the Sagaing Fault system and assess the predictability of earthquakes in these simulations based on the slip-deficit rationale. The simulations demonstrate the influence of geometrical features, such as fault bends and branches, on the rupture sequence and produce sequences that resemble the historical record, including the 2025 event. While the fault geometry remains invariant, the simulation produces successive ruptures with variable extents and slip distributions that occur irregularly. We find that, despite this variability, the ruptures can be reasonably well predicted based on slip-deficit provided that the slip deficit is integrated over a period of time exceeding the return period of the maximum event (~200 yr in this case). However, the simulations also suggest that the forecast performance may be significantly lower for natural fault systems that exhibit a more chaotic behavior than observed in our simulations. Our work highlights the potential of using earthquake simulators for time-dependent seismic hazard assessment.

## Observation: 2025 Mandalay, Myanmar Earthquake

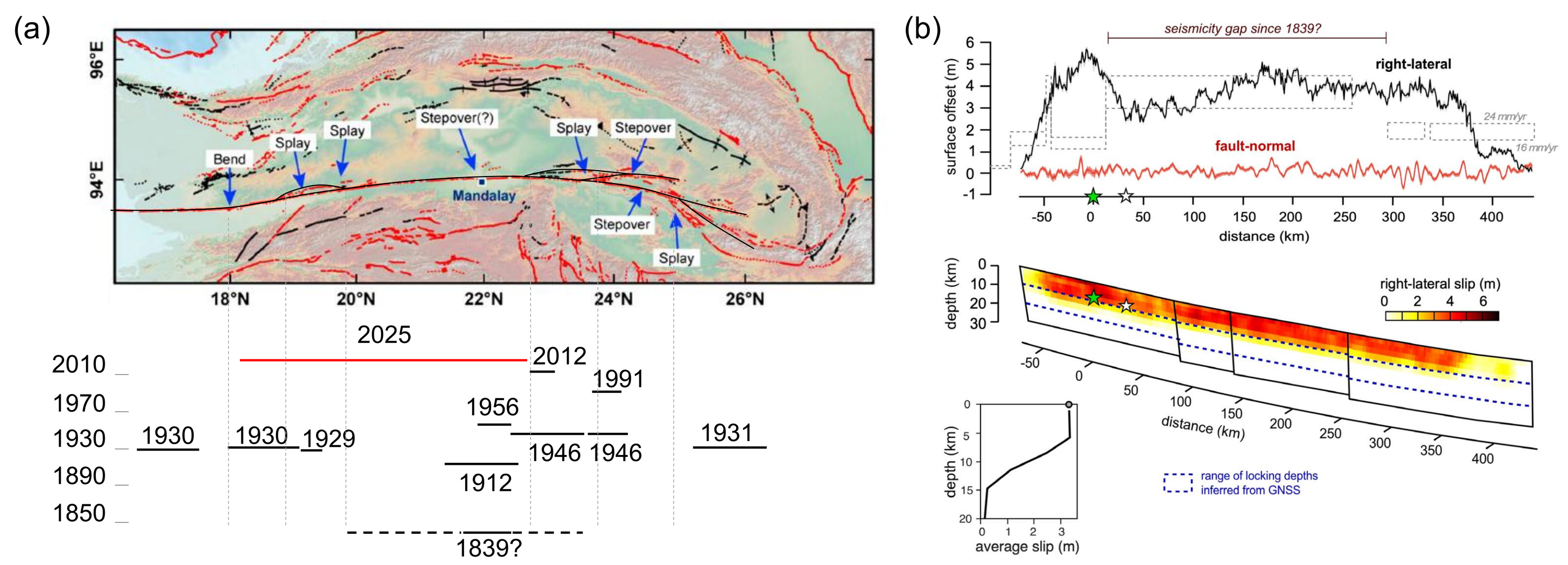



**Figure 1. Fault geometry and historical earthquakes.** (a) Sagaing fault geometry and earthquake history adopted from Wang et al. (2014). The fault geometry is traced (black line) and is utilized to construct the simulation geometry. The lower panel in (a) represents the historical seismicity identified by Wang et al. (2014). (b): 2025 Mandalay, Myanmar Earthquake: fault-parallel (black) and fault-perpendicular(red) surface offsets (upper panel) and Finite-fault slip mode (lower panel). Figure from Solane et al. (2025).

## Simulation Method

The simulation is performed using Quake-DFN, a quasi-dynamic earthquake simulator specifically designed for complex fault geometries (Im and Avouac, 2024). We utilized the surface fault map of the Sagaing fault (Wang et al., 2014) to construct the fault geometry.

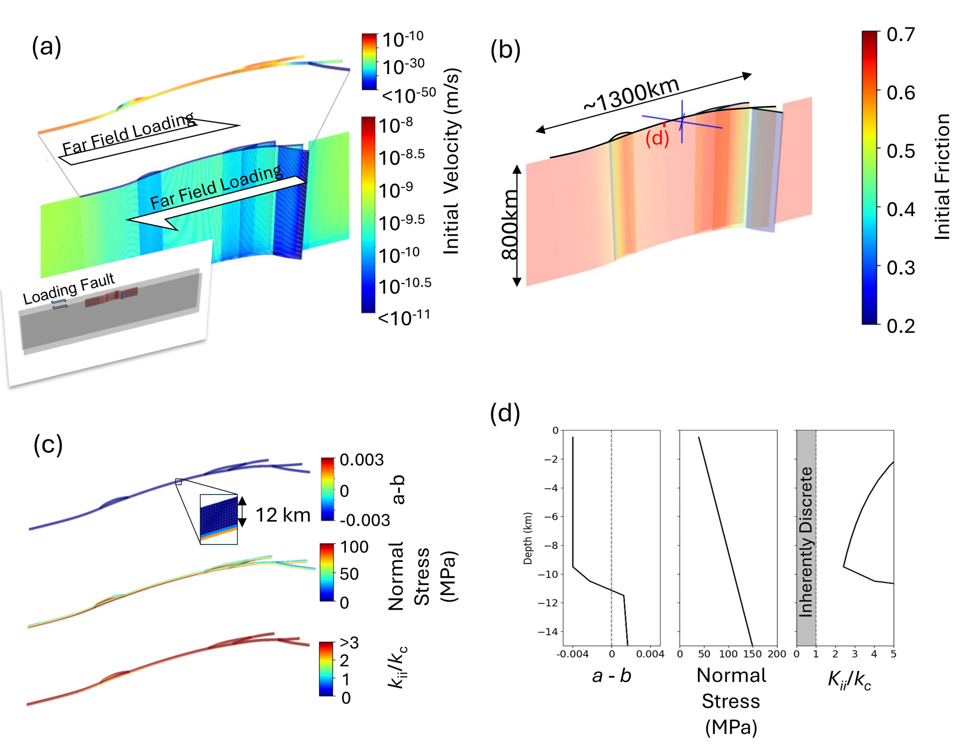



**Figure 2.** (a): Initial velocity. The arrows indicate the direction of far-field loading, while the colors represent initial velocities. These initial velocities are assigned separately for velocity-strengthening (upper) and velocity-weakening (lower) elements. (b) initial friction (color) calculated from stress tensor. Blue lines denote the relative magnitude of the stress tensor. (c,d) Friction parameters at the shallow, finely discretized elements. The normal stress is depth-dependent. 70MPa at the surface and increases with the stress gradient of 15kPa/m at the maximum stress orientation.

**Table 1**. Friction parameters used for simulation.

| No. | a | b | $D_c$ (cm) | Geometry |
|---|---|---|---|---|
| 1 | 0.003 | 0.007 | 3 | Planar |
| 2 | 0.003 | 0.007 | 3 | Main fault only (No Branch) |
| 3 | 0.003 | 0.007 | 3 | Main fault + Branch Fault |
| 4 | 0.003 | 0.007 | 4 | |
| 5 | 0.003 | 0.007 | 5 | |
| 6 | 0.003 | 0.007 | 2.5 | |
| 7 | 0.004 | 0.008 | 3 | |
| 8 | 0.004 | 0.008 | 2 | |
| 9 | 0.004 | 0.008 | 2.5 | |
| 10 | 0.005 | 0.01 | 3 | |

## Simulation Results

- The sequence of earthquake ruptures becomes significantly more complex as fault complexity increases
- With complex geometry, the ruptures appear segmented at the point of bending and the boundary of the branch structure
- The relatively planar section of the Sagaing fault, encompassing the region affected by the 2025 Myanmar earthquake, exhibits a fairly periodic sequence
- Rupture sequences similar to the paleoseismicity observed along the Sagaing fault
- We observe a notable nucleation phase. However, we note that the friction parameters we employed, which were selected for computational efficiency, result in a relatively large nucleation length.

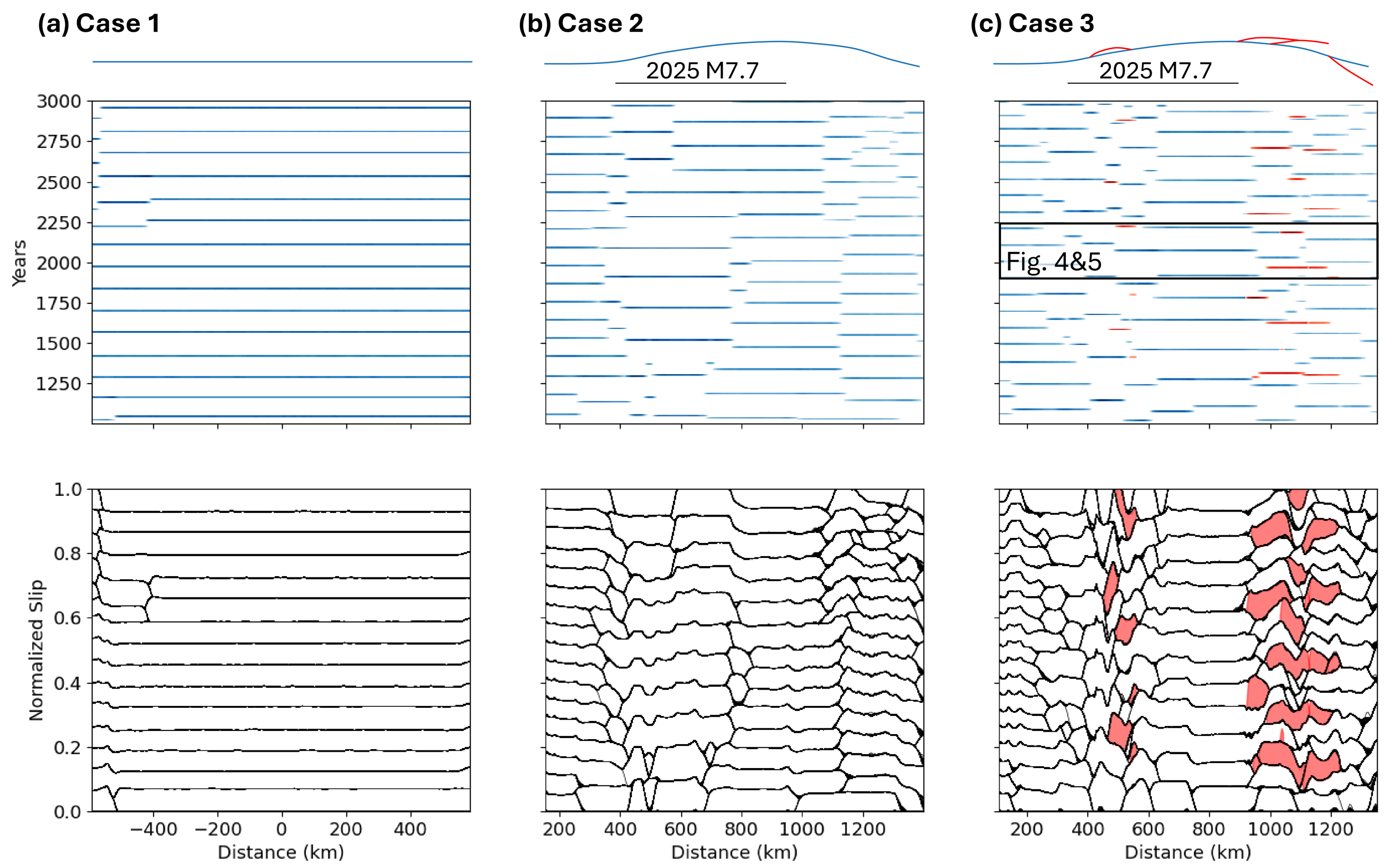



**Figure 3. Simulated earthquake rupture sequence.** The figure presents three scenarios out of a total of ten simulations: (a) planar fault geometry, (b) main fault only, and (c) main fault with branch fault. The cases a, b, and c correspond to cases 1, 2, and 3 as outlined in Table 1, respectively. The friction parameters are identical across all scenarios. In the upper panels, we display the timing of earthquake ruptures as a function of distance, with blue lines representing main fault ruptures and red lines indicating branch fault ruptures. The lower panels illustrate normalized slip versus distance, with slip values normalized to the slip recorded in the year 3000.

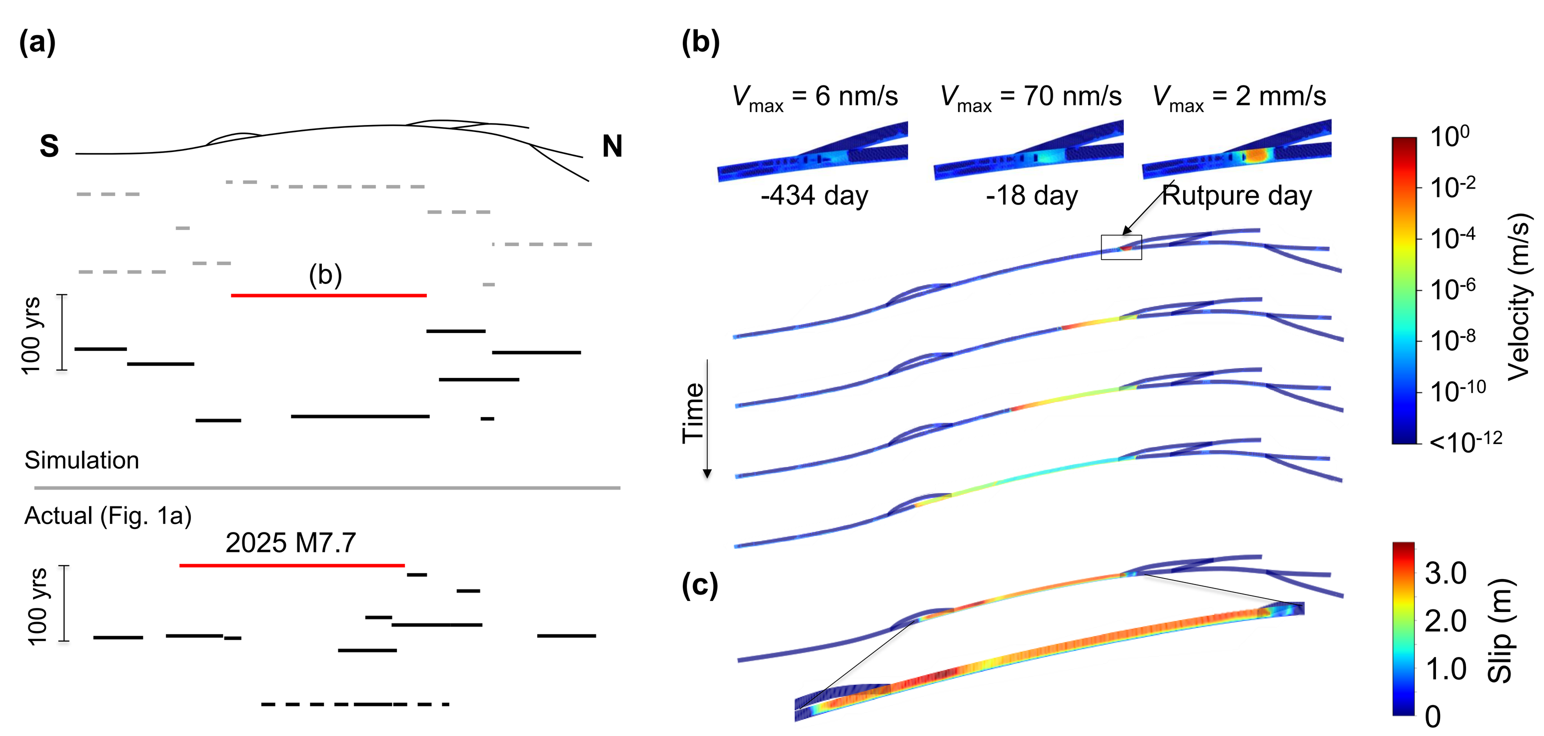
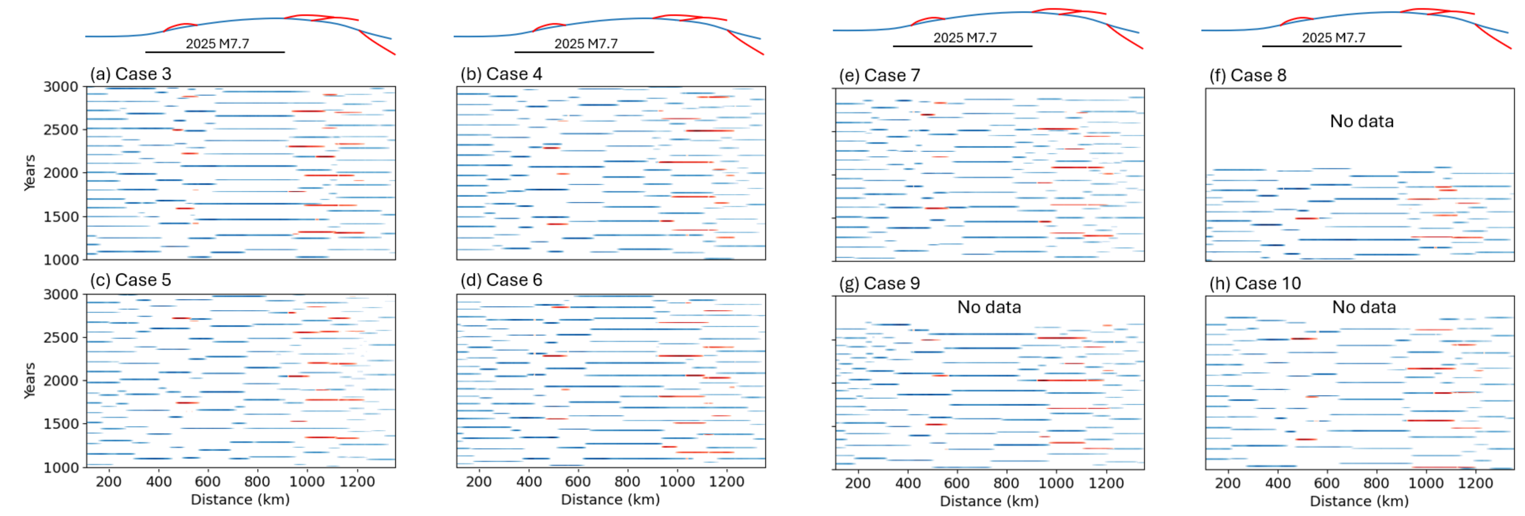



**Figure 4. An example of an analogous event in the 2025 Myanmar earthquake sequence.** (a) A comparison of the simulated (upper) and actual (lower) earthquake rupture sequences. The historical earthquake is denoted in black, while the 2025 Myanmar earthquake and its resemblance are shown in red. Simulated earthquake event extending beyond the event is represented by a gray dashed line. (b) A snapshot of the rupture sequence for the Myanmar earthquake analogy. The three upper snapshots provide a zoomed-in view of the earthquake nucleation phase, highlighting maximum velocity and timing in text. (c) The slip distribution associated with the event.

## All Results




## Can Simulated Rupture be Predicted from Slip Deficit?

### Method

- We assume that we only have access to a specific duration of geodetic data (surface slip and deep creep), ranging from 10 to 500 years before the time of predicting earthquakes.
- The slip deficit is defined as the long-term slip minus the surface slip
- If the extrapolated slip deficit falls below the lower bound, it is classified as a potential earthquake rupture.

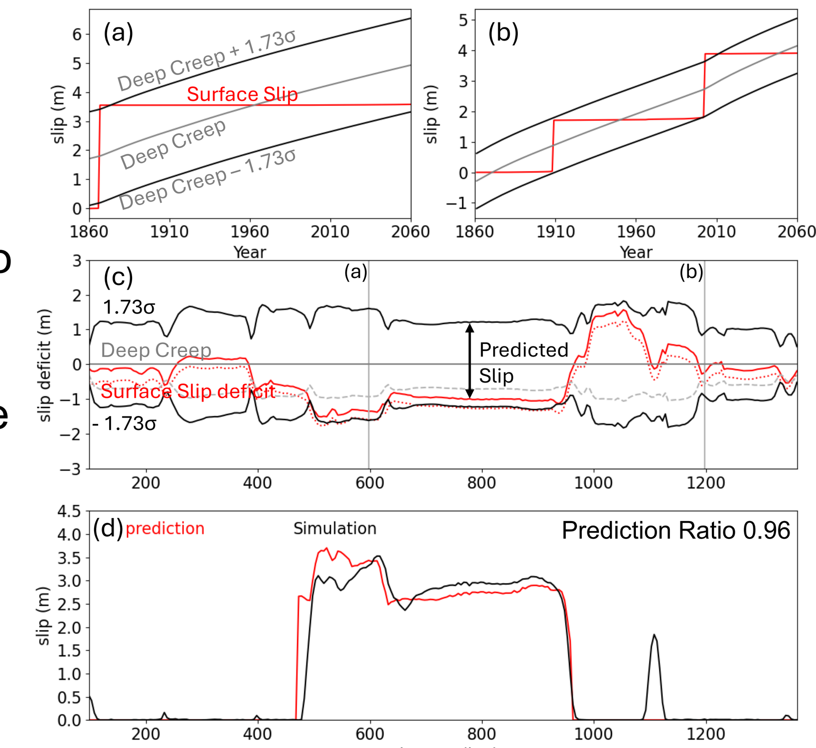



**Figure 5. Earthquake prediction method** (a,b) Surface slip (red), long-term slip (gray), and upper and lower bounds (black lines; ±1.73 times standard deviation)

### Prediction Result

- Timing and magnitude of future earthquakes can often be accurately predicted when a sufficiently large dataset is available. (Figure 6a) Prediction accuracy is significantly influenced by fault complexity
- Natural earthquakes may be more difficult as fault complexity increases, and the rupture sequence becomes increasingly chaotic

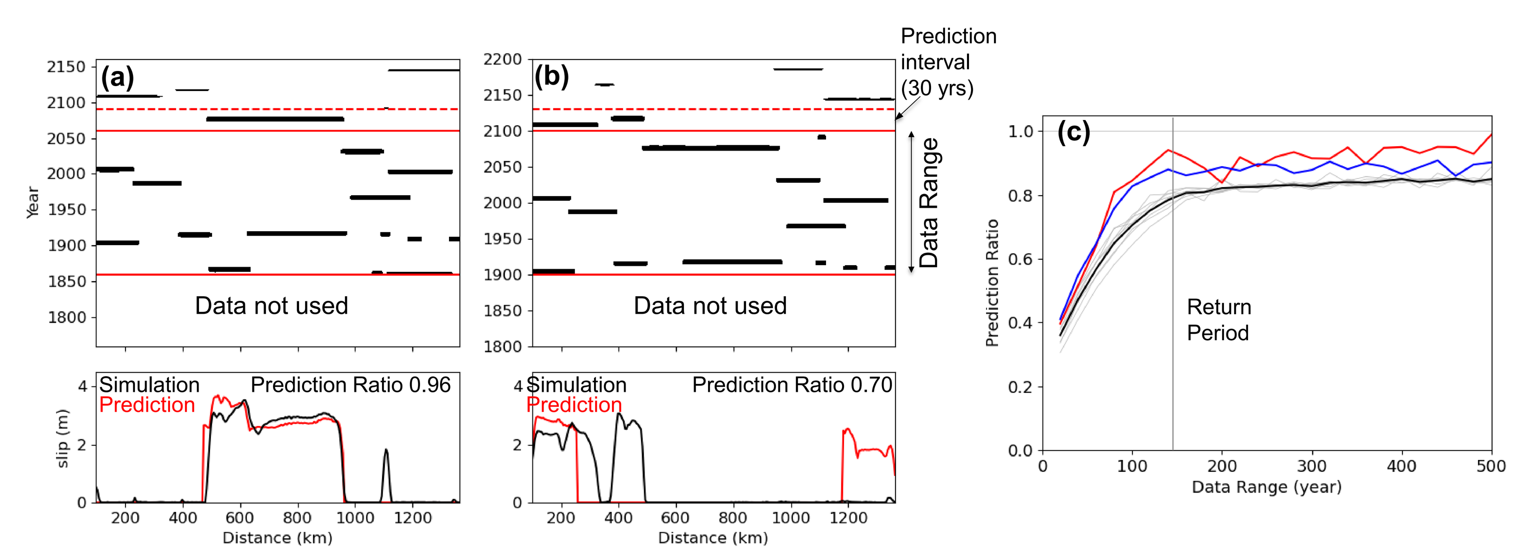



**Figure 6. Earthquake Prediction.** Panels (a) and (b) illustrate the earthquake prediction outcomes obtained prior to and following the 2025 Myanmar earthquake analogy, respectively. We utilized 200 years of data (marked by the red solid lines; a covering the period from 1860 to 2060, and from 1900 to 2100) to forecast earthquakes for the subsequent 30 years (up to the red dashed line). The prediction results are represented by the red line in the lower panel, while the black line shows the simulation results during the 30-year prediction period. Panel (c) displays all prediction results across a broad data range (10 to 500 years) with varying geometries: Red indicates planar fault geometry, Blue denotes the main fault-only geometry, Gray represents the main plus branch faults, and Black illustrates the average of the gray cases.

## References

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