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On the Influence of Fault Geometry on Earthquake Ruptures and Predictability

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Abstract

The geometry of faults system has a strong influence on the extent of earthquake ruptures and may also affect earthquake predictability. Here, we explore this issue based on long-term earthquake rupture sequence simulations and using a slip-deficit-based forecasting method. Our numerical simulations are tuned to the Sagaing Fault system in Myanmar. They account for the observed fault geometry, including fault bends and branches, and assume that fault slip is governed by rate and state friction. We investigated a range of friction parameters and found that certain combinations of parameters could produce sequences that resemble the historical record, including the M_w 7.7 2025 Mandalay Earthquake. The simulation produces successive ruptures with variable extents and slip distributions that occur irregularly. We find that ruptures can be reasonably well predicted based on the slip-deficit distribution, provided that the slip deficit is integrated over a period exceeding the return period of the larger events. Predictability tends to be better in simpler fault geometries, but it diminishes significantly in complex fault zones. Our research indicates that fault geometry strongly affects earthquake predictability, suggesting that effective earthquake forecasting should incorporate more comprehensive approaches that account for the complex loading and interaction driven by fault geometry.

Forecasting large natural earthquakes remains a daunting challenge in earthquake science. One well-identified factor limiting predictability is that stress redistribution within a single fault or within a fault network creates self-sustained complexity and chaotic behavior (Stein, 1999; Barbot, 2019; Cattania, 2019; Becker, 2000; Liu et al., 2022). This chaotic behavior is more likely to intensify when fault geometry is complex, since it leads to smaller, segmented earthquake ruptures (Wesnousky, 2008; King and Nabelek, 1985; Hubbard et al., 2016; Kumar et al., 2025; Wang et al., 2014; Guvercin and Barbot, 2025), which result in complex interactions among fault segments.

As a matter of fact, smaller earthquakes tend to produce less regular rupture patterns (Griffin et al., 2020). Larger earthquakes are more periodic, but the path to time-dependent forecasting of large ordinary earthquakes still remains unclear. A purely statistical approach based on past records is a possible path forward (Wang et al., 2024; Griffin et al., 2025). However, this approach is limited for two main reasons: first, the difficulty of precisely estimating the time, rupture extent, and slip associated with past events; and second, the fact that these records are often incomplete and short compared to the return period of large events, which is typically of the order of centuries to millennia. One possible solution is to assume a time passage model for the return of seismic ruptures and impose the elastic rebound model (Reid, 1911). Such an approach has been implemented in the seismic hazard model for California UCERF3 (Field et al., 2015). However, slip is generally poorly predicted from the elapsed time, and the time of the next rupture is poorly predicted from the estimated slip in a past event (Murray and Segall, 2002; Konca et al., 2008). Another issue is that, while slip might show some degree of regularity, segmentation is highly variable and difficult to assess from paleoseismic records (Weldon et al., 2004; Klinger et al., 2011). How ruptures return in time and space can't generally be derived solely from observations. It would therefore be preferable to ground time-dependent forecasting on physics-based models that account for fault geometry and yield rupture time series comparable to observations. Fault geometry clearly plays an important role in controlling the extent of earthquake ruptures (e.g., Wesnouski and Biasi, 2011; Harris et al., 1991) and fault slip distribution (Milliner et al., 2022).

Numerical simulations are capable of producing time series of ruptures comparable to observations. Recent advances in the development of earthquake simulators now allow for simulations of earthquake sequences in discrete networks of non-planar faults (Tullis et al., 2012; Zielke and Mai, 2023; Im and Avouac, 2024; Cheng et al., 2025). Such simulations can produce realistic earthquake sequences comparable to observations (Shaw et al., 2018; Liu et al., 2022; Howarth et al., 2021; Antoine et al., 2025). Numerical simulations therefore hold potential for assessing earthquake predictability in fault systems with realistic fault geometry under measurable tectonic loading.

In this study, we leverage the ability to generate long time series of earthquake sequences with an earthquake simulator to explore the influence of fault complexity on earthquake rupture sequences and predictability. To assess predictability, we developed a slip-deficit-based forecasting approach. This method builds on Reid's (1911) elastic rebound principle (McCann et al., 1979) and the hypothesis that returning large earthquakes on a

given fault are similar (Schwartz and Coppersmith, 1984), and therefore can be predicted based on the time elapsed since the last rupture. We assume faults embedded in a purely elastic medium. As a result, earthquake slip over the long term balances the slip deficit accumulated during the interseismic period. Details of the numerical simulations and the forecasting method are given in the Method section. The simulations are tuned to the example of the Sagaing fault (Supplementary Fig. 1), which has produced a M7.7 earthquake (Antoine et al., 2025) and is relatively well documented from geological, paleoseismological, and geodetic studies (Wang et al., 2014; Tin et al., 2022).

Result

Earthquake sequence simulation on the Sagaing Fault

We selected the Sagaing fault as a basis for our analysis. In 2025, a magnitude 7.7 earthquake occurred on that fault, causing significant damage in Myanmar and Thailand (USGS, 2025; Antoine et al., 2025). While the Sagaing fault zone is predominantly straight, it features several bends and branches (Fig. 1 and Supplementary Fig. 1). Our simulations use Quake-DFN, a quasi-dynamic earthquake simulator tailored for complex fault geometries (Im and Avouac, 2024). Previous research has already shown that such simulations could yield a spatio-temporal distribution of ruptures akin to the historical record of past events (Antoine et al., 2025). We conducted 11 simulations (see Supplementary Table 1). Nine of these runs employed the full fault complexity (Fig. 1c); one simulation excluded the branch faults (Fig. 1b), while another utilized a flat planar fault geometry (Fig. 1a).

The sequence of earthquake ruptures becomes significantly more complex as fault complexity increases (Fig. 1). For a planar fault geometry, the ruptures are essentially periodic M7.7 events with few occasional partial ruptures (Fig. 1a). When fault bends are introduced, the rupture pattern becomes more complex (Fig. 1b). In this scenario, the rupture tends to segment at the bends (e.g., around 400 km in Fig. 1b). As the geometry becomes increasingly more complex, the rupture sequences become more complex as well, particularly within the horsetail structure (Fig. 1c, 900–1200 km). The ruptures appear segmented at the junctions with the fault branches. This segmentation at the branch is attributed to the partitioning of slip rates at the junction, as the far-field loading is distributed among the main fault and branches (Supplementary Fig. 2a). Consequently, the rupture behavior becomes progressively more chaotic and less predictable.

In the nine simulations with varied parameters in a more realistic fault geometry (Supplementary Fig. 3), we selected one simulation (Fig. 1c) that shows a similar rupture sequence to the Sagaing fault. This case indicates a recurrence interval of approximately 150 to 200 years, similar to past ruptures along the Sagaing fault (Wang et al., 2014). The roughly uniform ~3 m slip magnitude (Fig. 2c) and extent are comparable to the 2025 M7.7 Mandalay earthquake (Antoine et al., 2025). Moreover, the rupture pattern is more complex in regions characterized by more complicated geometry, as also observed in reality, especially in the northern area, where the fault geometry is more intricate (Fig. 1c & 2a).

In our simulation, large earthquakes tend to happen on the segment adjacent to where previous ruptures have arrested. Although this pattern cannot be verified for the Sagaing fault due to the uncertain rupture extent of past events, it is a well-documented pattern on other faults, in particular the North Anatolian Fault (Stein et al., 1997). Our simulations show a notable nucleation phase for most earthquake ruptures (Fig. 2b). A pronounced increase in slip rate is observed even a year prior to the rupture event. The peak slip rate increased to 42 nm/s (~ 1.3 m/year) 28 days before the earthquake rupture. The long duration and large size of the aseismic nucleation process are due to the relatively large value of D_c adopted in our simulations, chosen for computational efficiency. As a result, our simulations predict mostly large events ($M > 6.5$). It is likely that earthquake nucleation may occur at a smaller scale and for a shorter duration in reality, as no lower limit to the magnitude of natural earthquakes has yet been observed (Abercrombie et al., 1995).

Note that the synthetic earthquakes in our simulations are neither time-predictable nor slip-predictable. These two notions, as defined by Shimazaki and Nakata (1980), assume respectively that either the time of the next event is predictable from the slip in the previous event, or that the slip in the next event is predictable from the time since the previous rupture.

Earthquake Forecasting

Our forecast is based on the local slip deficit, which is defined as the difference between the slip that would have resulted from continuous creep at the long-term slip-rate (Supplementary Fig. 4-7a, gray line) and the surface slip due to the historical earthquakes (Supplementary Fig. 4-7a, red line). We make the assumption that past ruptures are known over a chosen data period, and the tectonic loading rate has been constant. We determine the upper and lower bounds as ± 1.73 times the standard deviation of the time series of slip deficit over the data period (Fig. 3a, black lines). The determination of these bounds is explained in the Method section. We focus on forecasting large surface-rupturing strike-slip earthquakes. Such events typically exceed $M_w 6$ and rupture through the seismogenic zone (0- 15 km in the case of the Sagaing fault, a value typical of continental strike-slip faults), and have rupture lengths exceeding 10km (Lavrentiadis et al., 2025). Similarly, our simulation yields ruptures that systematically saturate the seismogenic depth and extend laterally for more than 10km. Accordingly, we assume that if the slip deficit exceeds the upper bound of the slip deficit over a contiguous segment of at least 10km, the fault is deemed unstable and a surface-rupturing event is predicted there. The predicted slip is the difference between the upper and lower values of the slip deficit estimated locally (Fig. 3). Once a surface rupture is predicted, the rupture is assumed to extend along strike to a connected extent where the slip deficit exceeds one standard deviation (Fig. 3a gray dashed line). For instance, in Fig. 3, this criterion is satisfied in the range of ~ 400 km to ~ 850 km. This analysis is conducted along the entire Sagaing fault length (Fig. 3). Fig. 3&4a show a case example where one of the larger ruptures, an event similar to the 2025 Mandalay earthquake, is correctly predicted. The slip distribution within a 30-year period (from 1590 to 1620) is determined based on the slip deficit accumulated in the previous 200 years (from 1390 to 1590). Notably, the predicted slip

compares well with the large rupture occurring in that time window in our simulation (Fig. 3b & 4a lower panel).

However, the forecast is not always successful, as a similar analysis conducted 35 years after the mainshock shows (Fig. 4b and Supplementary Fig. 6). The simulation yields one large and a few smaller earthquakes within the 30-year window, whereas none are forecasted based on the 200-year-long slip deficit distribution. We note, however, that the large earthquake is correctly predicted if the slip deficit is calculated over 500 years instead of 200 years (Supplementary Fig. 7).

When we apply our forecast to, for example, the entire simulation for case 4 (Figure 4c), we find that out of the 148 events observed in the simulation, 118 (80%) are predicted and 30 are missed (20%). The total seismic moment of the 118 predicted events is 1.1×10^{22} N·m, which yields an average M_w of 7.25 for each predicted earthquake. The forecast predicts 194 windows where events should have been observed, indicating 76 false positives. We note that all of the false positives are actually forecasts that are too early. Once a window turns red and no rupture is observed by the end of the 30-year lapse time, it remains red in the following 30-year period, and a rupture is observed in the following years until an earthquake happens in the gap.

We analyzed the performance of the forecasting method across all 11 simulation cases. We varied the duration of the data period used to calculate the slip deficit distribution from 20 to 500 years, with 30-year sampling intervals throughout the simulation. The forecast performance is evaluated using the f-score metric (Sasaki, 2007; see Method for details). We find that the forecast accuracy is significantly influenced by fault complexity and the duration of the period used to inform the forecast (Fig. 4d). In the simulation with a planar fault, the f-score can exceed 0.9 with sufficiently long data ranges. This is not surprising given the nearly periodic behavior observed in that case. With a more realistic representation of the Sagaing fault geometry, the f-score is around 0.6-0.8 when an adequate data time range is used to inform the forecast. For a time range shorter than 150 years—approximately the earthquake recurrence interval of the larger events—the accuracy is poor. While the f-score continues to improve beyond this duration, the improvement is relatively modest.

Earthquake predictability vs. geometric complexity

The predictability of earthquake recurrence heavily depends on fault complexity. As shown in Fig. 4c, simpler fault sections tend to produce more regular earthquakes, making forecasting more effective. This is evident in Fig. 5, where the COV and f-score are estimated along the fault length. Segments with a simpler fault geometry correspond to lower COV (indicating more periodic activity) and consequently a higher f-score (around 800 km). The lowest f-score (< 0.5) occurs in the most complex horsetail structures, near the area of three-fault interaction. As observed in the previous study of actual earthquake sequences (Griffin et al., 2020), the COV is also dependent on the earthquake magnitude. This is not surprising, since complex fault zones tend to generate smaller earthquakes (Fig. 6). For example, the mean magnitude of earthquakes in the simpler fault-geometry area is about M_w 7.53, while in

the horsetail structure area, it is M_w 7.12 (Supplementary Fig. 8). Since the slip-deficit-based earthquake prediction method heavily relies on the earthquake quasi-periodicity, earthquake prediction efficiency is strongly dependent on COV, and therefore, fault complexity (Fig. 6).

Discussion

Other factors that contribute to complexity

This study is focused on the influence of fault geometry on the complexity of earthquake sequences. While we demonstrated that fault geometry alone can produce realistic rupture sequences, other factors probably also play an important role in reality. One such factor is frictional heterogeneity, which can lead to segmentation because recurrence times vary from creeping to unstable patches, adding to the complexity of rupture sequences (Kaneko et al., 2010; Chen et al., 2026). Another key element is nucleation length. For this study, we used a relatively large nucleation length (large D_c) to speed up simulations, but a smaller nucleation length can introduce complexity even with uniform frictional properties, generating rupture sequences that include small earthquakes our prediction method could not capture (Cattania, 2019; Barbot, 2019). Lastly, our models did not include inelastic off-fault deformation (e.g., Miliner et al., 2025; Antoine et al., 2024), which influences earthquake characteristics and must occur in reality to dissipate elastic stress buildup at fault kinks or fault ends, leading to fault growth and variable fault geometry. Off-fault plastic deformation and fault propagation would add complexity to rupture sequence, especially for long-term earthquake sequence modeling. While the primary focus of this study is on fault geometry, these other factors can independently contribute to more complex rupture sequences.

Slip-deficit-based earthquake prediction

Our study presents an approach to time-dependent earthquake forecasting based on the slip-deficit distribution. The forecast is informed by the knowledge of past ruptures, as could be inferred from historical accounts or paleoseismic investigations. Our approach shares similarity with the forecast based on the seismic gap hypothesis (McCann et al., 1979) and the time-dependent rupture forecast study in California (Field et al., 2015), but differs in that it is based not only on the time since the previous ruptures but on the slip-deficit integrated over the entire duration of the data period, i.e., the duration of the catalog of historical or paleoseismic events. By applying the method to a synthetic catalog generated by an earthquake simulator tuned to the Sagaing fault, we find that a satisfying forecast is obtained when fault complexity is simple.

Our simulations, however, reveal limitations of slip-deficit-based earthquake prediction in the case of complex fault geometries. Even with the simplified fault geometry used in our simulations, the predictability is substantially lower in the more complex fault zones. Given that real faults are more intricate than our simulation, the effectiveness of slip-deficit predictions is probably even less in practice. This might question the applicability of this approach in reality. However, as shown in our results (Figure 6) and prior studies (Griffin

et al., 2020), larger earthquakes tend to follow more regular recurrence patterns, making slip-deficit forecasts useful for these events.

Another limiting factor, not accounted for in our forecast, is the potential influence of earthquakes that are too small to be represented in historical and paleoseismological catalogs. These limitations could be assessed using more complex synthetic sequences than those generated in this study, or by analyzing real data. The slip-deficit-based approach is indeed in principle applicable to real data, provided that constraints on past ruptures, fault slip rate, and interseismic strain are available. It would, however, require some adaptation to accommodate uncertainties and gaps in the historical and paleoseismological records. A particular difficulty is that paleoseismic records are local point measurements; they do not contain direct information about rupture length, which can only be assessed by correlating records from different trenches (e.g., Biasi and Weldon, 2006). These limitations could probably be addressed in future studies.

Using numerical simulation for earthquake forecasting

Our simulations show that the chaotic behavior of earthquake sequences intensifies as fault geometry becomes more complex, because interactions among fault segments become more complex, making prediction more difficult. Nevertheless, the chaotic nature does not mean that it is totally unpredictable. Slow slip events (SSE) in Cascadia, for example, exhibit chaotic behavior but are predictable on a timescale of a few weeks (Gualandi et al., 2020; Kaveh et al., 2026; Truttman et al., 2024). In that case, predictability is enabled by geodetic time series over a period much longer (>10 years) than the typical return period of SSEs (0.5-1 year). However, applying these findings to larger earthquakes remains challenging due to the long recurrence intervals and greater measurement errors of historical earthquakes.

Numerical simulation can be an ideal tool for earthquake forecasting because it can integrate paleoseismic and geodetic observations with the complexities of fault geometry and heterogeneous fault properties. In recent decades, the quality and quantity of geodetic measurements and paleoseismic data have significantly improved. Although simplified, our simulation shows that we can realistically reproduce the earthquake sequences if we account for actual fault geometry. We investigated a wide range of parameter spaces (Supplementary Fig. 3) and found that, in some parameter combinations, the rupture patterns (recurrence time and segmentation) resemble those observed in the paleoseismic data (Figure 2b). This shows that the simulation-based parameter inversion and potential earthquake forecasting may be possible in the future. The trade-off should be between including more physics and achieving faster simulation. Faster simulation would let us explore a larger parameter space but would oversimplify the system, missing some of the complex rupture sequence. Eventually, as demonstrated in slow slip forecasting (Kaveh et al., 2024) and as widely used in weather forecasting (Epstein 1969), simulation-based ensemble forecasting might become feasible once quick, precise simulations are accessible. This approach can account for various uncertainties, including simulation model errors and measurement inaccuracies.

Method

Numerical simulations of earthquake sequences

The rate and state friction framework (Dieterich, 1979) has provided a foundation for simulations of earthquake sequences (Harris et al., 2018; Erickson et al., 2020; Lapusta et al., 2000). Such calculations are computationally costly, but some progress in computational methods, such as the use of hierarchical matrices (Hackbusch, 1999), and simplifying assumptions, such as the quasidynamic approximation (Rice, 1993), allow us to simulate earthquakes in fault networks with realistic geometry (Howarth et al., 2021; Zielke and Mai, 2023; Im and Avouac, 2024; Cheng et al., 2025). In this study, simulations are performed using Quake-DFN, a quasi-dynamic earthquake simulator that was specifically designed for complex fault geometries (Im and Avouac, 2024).

We chose the example of the Sagaing fault to design our analysis. In 2025, a magnitude 7.7 earthquake occurred on that fault, causing significant damage in Myanmar and Thailand (USGS 2025; Antoine et al., 2025). This event was partially anticipated, as it occurred in a previously identified seismic gap (Supplementary Fig. 1a; Wang et al., 2014). The earthquake ruptured primarily along a straight segment of the Sagaing fault in Myanmar. Although the Sagaing fault zone is remarkably straight, it does exhibit bends and branches (Supplementary Fig. 1). In a previous study, it was shown that accounting for the fault geometry yields simulations with a spatio-temporal distribution of ruptures similar to the observed history of past ruptures (Antoine et al., 2025).

We use the map of the Sagaing fault system (Wang et al., 2014) to construct the fault geometry (Supplementary Fig. 1 and Supplementary Fig. 2). The total simulation domain, the colored fault within the two loading faults in Supplementary Fig 2, has dimensions of approximately 3000 km $\times$ 800 km. The seismogenic area (i.e., velocity-weakening elements, Supplementary Fig. 1b red area) spans approximately 1300 km along strike and extends 11 km in depth. The seismogenic area is discretized into relatively small elements (<1 km), while the surrounding velocity-strengthening elements are coarsely discretized to reduce computational cost. The large velocity-strengthening elements do not reflect the actual size of the Sagaing fault, but are introduced to relax stress at the edges. The total domain is discretized into ~ 55 k elements, while the shallow velocity-weakening element is discretized into ~ 26 k elements. Far-field loading is applied (e.g., Fitzenz and Miller, 2004; Zielke and Mai, 2023) by employing two constantly slipping loading faults (Supplementary Fig. 2b). The dimensions of each loading fault are 10000 km $\times$ 4000 km, and they are separated by 400 km from each other. Because the loading faults are not discretized, they have almost no influence on simulation speed. The long-term slip rate on the Sagaing fault is determined by the slip rate of these loading faults. Given the complex fault geometry, the slip rate is not uniform (Supplementary Fig. 2a) across the fault. The far-field loading is adjusted to obtain a long-term slip rate of 20 mm/year ($\sim 6.4 \times 10^{-10}$ m/s) on the fault segment ruptured in 2025, consistent with the observed geological slip rate (Wang et al., 2014).

Initial stress is determined by applying a regional stress tensor. The orientation and relative magnitudes of the principal stresses are assumed to be uniform, but the absolute

magnitudes are dependent on depth. We impose $\sigma_3 = 0.3\sigma_1$ with σ_1 trending N30°E. The maximum horizontal stress σ_1 is 70MPa at the surface and increases by 15 MPa/km with depth (Supplementary Fig 2c&d). We assumed a uniform initial frictional state $\theta_i = 100$ years with a reference friction coefficient of $\mu_0 = 0.67$. In the rate and state friction law, the initial condition should satisfy,

$$\mu_i = \mu_0 + a \log\left(\frac{V_i}{V_0}\right) + b \log\left(\frac{V_0\theta_i}{D_c}\right). \quad (1)$$

Given that the initial friction μ_i is calculated from the stress tensor and $\mu_0 = 0.67$, $V_0 = 10^{-9}$ m/s, $\theta_i = 100$ years, the initial velocities of each velocity-weakening fault patch can be calculated from equation 1. The initial velocity of the velocity-strengthening elements is determined by the long-term slip rate resulting from the applied tectonic loading. To obtain the long-term slip rate, we conducted a simulation with homogeneous velocity-strengthening faults under low normal stress (1 MPa) until near-steady velocity was achieved.

Due to the initial stress heterogeneity, the area characterized by low initial stress (or equivalently, low initial velocity) experiences delays of several hundred years before the first earthquake event (Supplementary Fig. 9). The steady state regime is reached after a few centuries, leading to a relatively constant potency increase as the loading rate is maintained at a constant level (Supplementary Fig. 9b). To avoid bias due to this spin-up phase, we exclude the first 1000 years of each simulation in our analysis. Note that the geometry of the Sagaing fault is relatively simple. Hence, we assume that the accumulation of elastic stress in the medium around the fault bends and branches can be neglected over the time scale of the simulations presented in this study. A more complex fault geometry, or simulations over a longer period of time, would require accounting for the finite strength of the medium by explicitly including off-fault yielding or stress-relaxation mechanisms (Oglesby, 2008).

We conducted 11 simulations in total. Nine simulations were conducted with full fault complexity described previously. On the other hand, one simulation was conducted without the branch faults (Fig. 1b), and the other simulation was conducted with a flat planar fault geometry (Fig. 1a). All velocity-strengthening elements in all cases were conducted with $a = 0.006$, $b = 0.003$, and $D_c = 2\text{cm}$. For the velocity-weakening elements, we used a range of a , b , and D_c of $0.003 \leq b-a \leq 0.005$ and $2\text{cm} \leq D_c \leq 5\text{cm}$ (see Supplementary Table 1).

The parameters are selected to achieve an optimal balance between numerical resolution, which requires a small cell size relative to the nucleation length scale, and computational efficiency. If the self-stiffness (k_{ii} , as defined in the stiffness matrix calculated based on Okada, 1992) of an element falls below the critical stiffness, $k_c = (b-a)\sigma/D_c$, that element is categorized as being in the “inherently discrete regime” and can lead to the emergence of non-physical self-organized complexity (Rice, 1993). In our simulations, we ensure that the ratio of k_{ii} to k_c consistently remains above 1 throughout the model (Supplementary Fig. 2).

We acknowledge that the fault network in our simulations is still a drastic simplification of natural fault systems. For instance, we employ a quasi-dynamic approximation, assume a smooth fault surface, a vertical dip angle, and uniform friction parameters across each area of

velocity weakening and strengthening. Our primary objective is to simulate realistic earthquake sequences, including ruptures similar to those of the 2025 Mandalay earthquake, while satisfying seismic moment conservation.

Earthquake forecast and performance evaluation

The forecast is based on the knowledge of the long-term slip rate and the history of surface slip over a time interval. This information is analogous to a paleoseismological catalog. We vary the data period, the duration of the 'catalog', between 20 years and 500 years. The long-term slip rate is determined by the slip rate in the deep velocity-strengthening zone at ~25 km depth, similar to the slip rate that would be determined from geodetic measurements or from the offset of geological markers. The slip deficit is defined as the long-term slip (Supplementary Fig. 4a, gray line) minus the surface slip (Supplementary Fig. 4a, red line), with the average slip deficit centered at zero (Supplementary Fig. 4b). We next determine the slip deficit that needs to be exceeded for a surface rupture to occur. This is calculated based on the simple case of periodic ruptures. In this case, the slip deficit distribution varies over one cycle between -1.73 and 1.73 times the standard deviation (σ) of the distribution. Here, we select $\pm 1.73\sigma$ because it is the upper and lower bound of a perfectly periodic earthquake (boxcar distribution). We therefore define upper and lower bounds of the slip deficit (Supplementary Fig. 4b & c, black lines) set at $\pm 1.73\sigma$ of the slip deficit in the data period.

To forecast the earthquake rupture area, we extrapolate the slip deficit over a 30-year (chosen arbitrarily) prediction interval following the end of the data period. If the extrapolated slip deficit (Supplementary Fig 4c red dashed line) becomes above the upper bound (Supplementary Fig 4c positive black solid line) for more than 10km spatial distance, it is classified as an earthquake rupture. Once a surface rupture is predicted, the rupture is assumed to extend along strike to a connected extent where the slip deficit exceeds one standard deviation, which is determined by testing a range of factors relative to the standard deviation to show good prediction. (Supplementary Fig. 4a gray dashed line). This criterion accounts in a very simplified way for the rupture propagation process: once a rupture has nucleated, the stress drop in the rupture area leads to a stress increase at the tips of the ruptured area, allowing the rupture to extend further as long as the stress level is high enough. The threshold value of one standard deviation was found to predict the simulated ruptures relatively well. For instance, in Supplementary Fig. 4c, this criterion is satisfied in the range of ~400 km to ~ 850 km. The magnitude of slip is determined by the difference between the projected slip deficit and the upper bound of the slip deficit, which represents the gap between the red dashed line and the upper-bound black line in Fig. 3c.

To evaluate prediction performance, we set a minimum value of 0.5 m to identify the ruptures for both the forecast and simulation results. If both the simulation and the prediction at a given point indicate a rupture, it is labeled a true positive (TP). Conversely, if the simulation shows a rupture but the prediction does not, it is termed a false negative (FN). Additionally, when the simulation indicates no rupture but one is forecasted, it is classified as a false positive

(FP). To evaluate prediction performance, we utilize the f-score metric (Sasaki, 2007) defined as follows:

$$f = \frac{2TP}{2TP+FN+FP}. \quad (2)$$

In this metric, TP, FN, and FP denote the lengths of the respective categories in each prediction session. The f-score matrix is used when the positive class is rare. For example, if one model predicts no earthquakes all the time, the prediction is correct most of the time because earthquakes are rare, but that does not mean it is a good predictive model. The f-score removes the contribution of true negatives (correctly predicted no earthquake). The f-score ranges from 0 to 1, with a higher f-score indicating better performance.

Coefficient of Variation

The degree of periodicity of a point process can be measured by the coefficient of variation (COV; Griffin et al., 2020).

$$COV = \sigma/\mu. \quad (3)$$

where σ is the standard deviation of the interevent time and μ is the mean interevent time. A random Poisson process has a COV close to 1, quasiperiodic processes have $0 < COV < 1$, and $COV > 1$ indicates clustering of events. We measure interevent times and magnitudes at a specific, localized point in the simulation results (Supplementary Fig. 8). Any events passing through this point, whether from main or branch faults, are considered as events at that location. The COV for each location is derived from the interevent times of all events observed there. Similarly, the f-score is evaluated locally at the specific point. In contrast, magnitude is considered as the overall magnitude of the detected event at the location. These measurements are taken at 100 m intervals between 300 m and 1200 m across all complex fault cases (cases 3–11). These data are used to plot COV versus magnitude and f-score versus COV (Fig. 6).

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Data availability

Simulation result data are available in the Caltech data repository (<https://doi.org/10.22002/D1.1455>).

Code availability

All simulation results in this article are generated by Quake-DFN. The simulator and source code are provided on GitHub (<https://github.com/limkjae/Quake-DFN>) and the GMG Center web page (<https://gmg.caltech.edu>).

Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

Author contributions

K.I. carried out the data analysis and numerical simulations. K.I. and J.-P.A. designed the study and wrote the article.

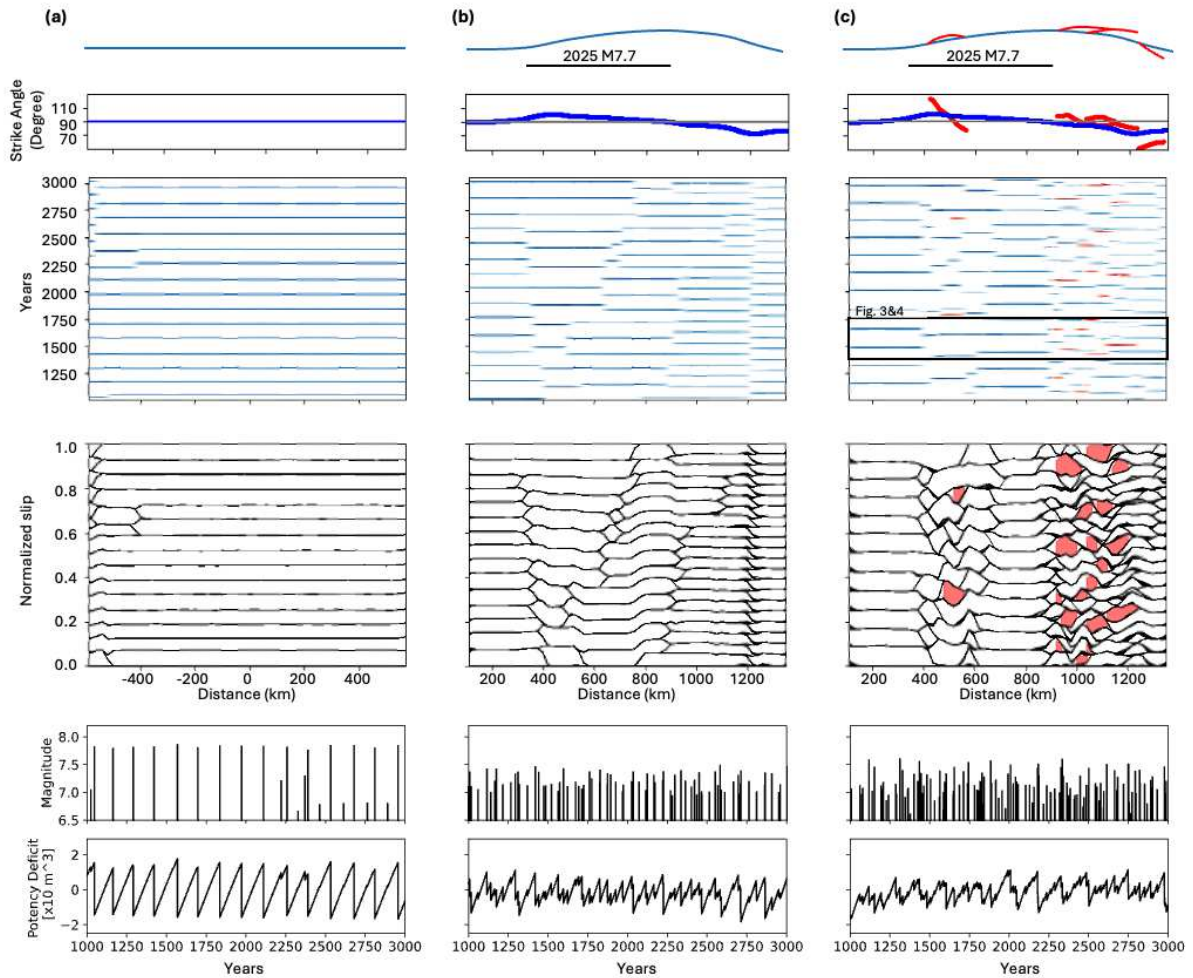


Figure 1. Simulated earthquake rupture sequence. The figure presents three scenarios out of a total of eleven simulations: (a) planar fault geometry, (b) main fault only, and (c) main fault with branch fault. The cases a, b, and c correspond to cases 1, 2, and 4 in Supplementary Table 1, respectively. On top, fault geometry and strike angle are presented (blue: main and red: branch). Then the next panels show the timing of earthquake ruptures and their extent, with blue lines representing main fault ruptures and red lines indicating branch fault ruptures. The next panels show normalized slip versus distance, with slip values normalized to the slip recorded in year 3000. Lower panels present earthquake magnitude and slip potency (slip $\times$ area) deficit vs. time. See supplementary Fig. 3 for the other case results.

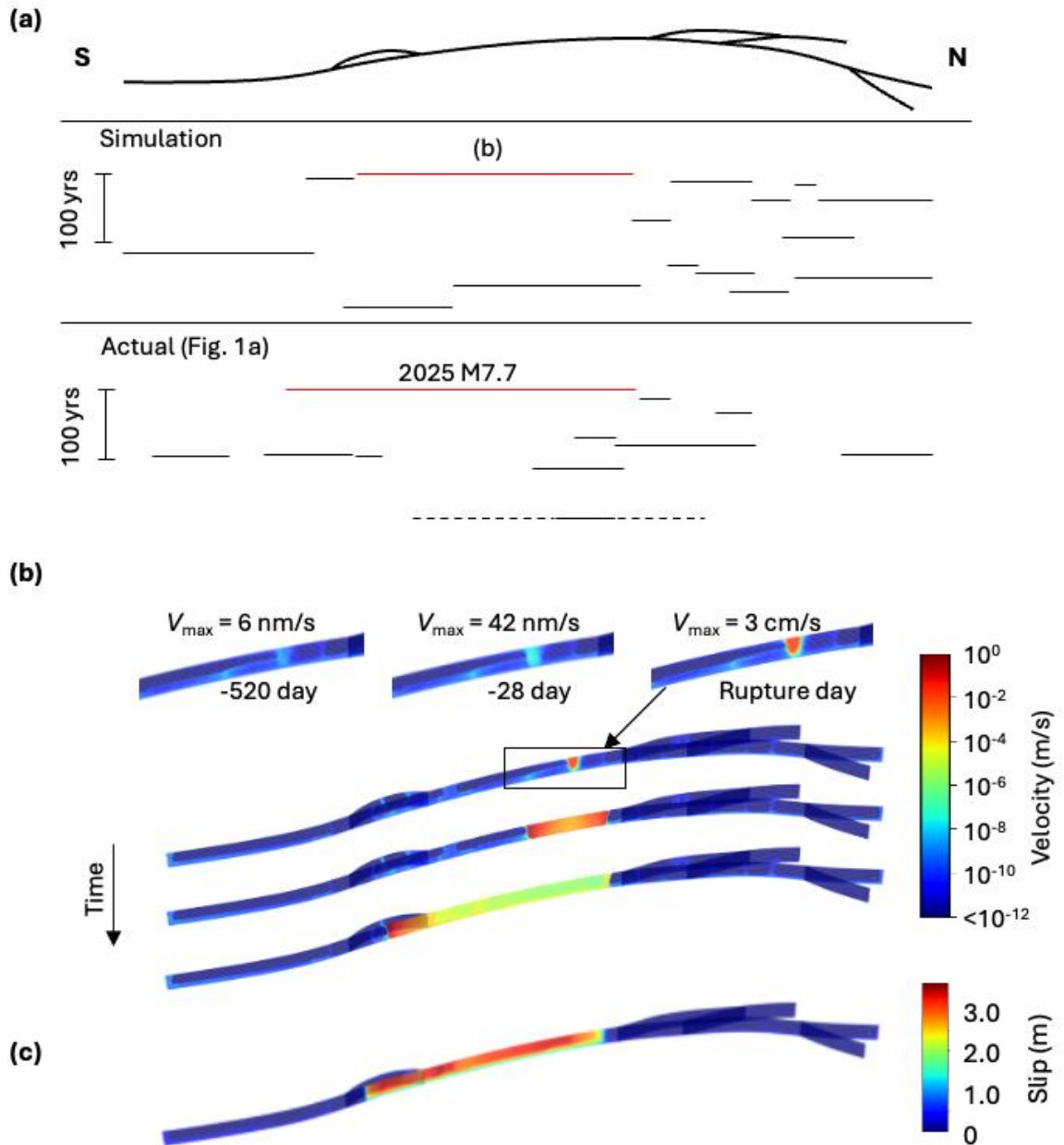


Figure 2. An example of an analogous event in the 2025 Myanmar earthquake sequence. (a): A comparison of the simulated (upper) and actual (lower; Wang et al., 2014) earthquake rupture sequences. The historical ruptures are depicted in black, while the 2025 Myanmar earthquake and its equivalent in our simulation are shown in red. (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 simulated event is similar to that of the Mandalay earthquake. The faults in panels (b) and (c) are vertically exaggerated threefold.

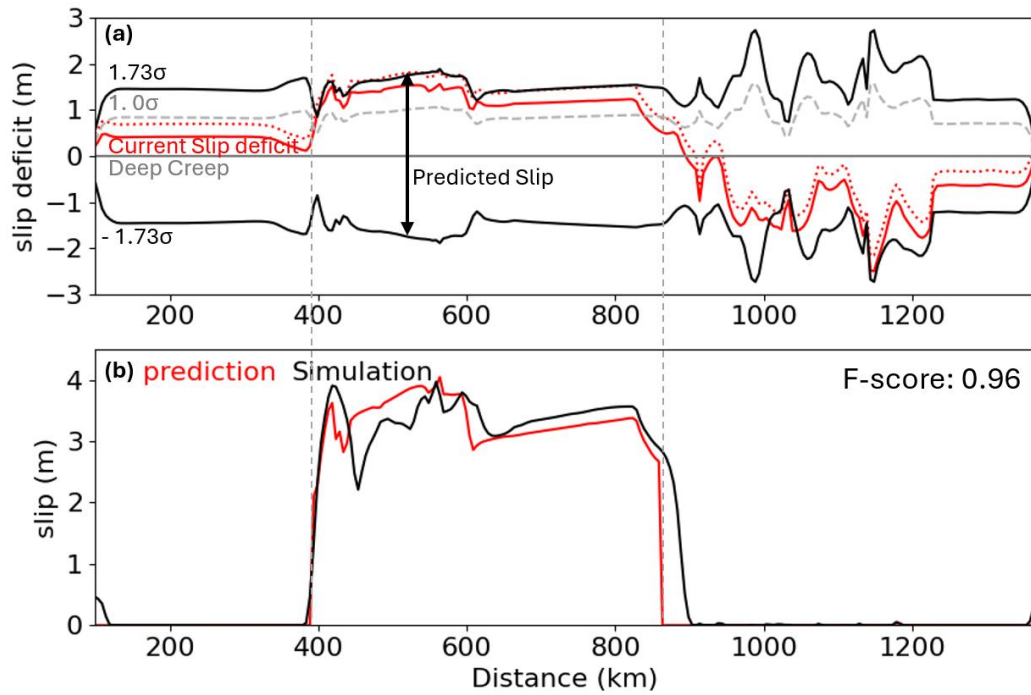


Figure 3. Earthquake prediction method with a data period of 200 years (1390-1590). In panel (a), the distribution of the slip deficit for surface slip is indicated in red, along with the upper and lower bounds in black (± 1.73 times the standard deviation) at the conclusion of the data period (year 1590). The red dashed line represents a 30-year extrapolation of the slip deficit, and the gray dashed line represents one standard deviation. Panel (b) compares the predicted slip distribution (in red) with the surface ruptures observed in our simulation (in black) over a 30-year prediction period. The vertical dashed lines represent the spatial extent of the predicted rupture, where the extrapolated slip deficit (red dashed line) meets the one standard deviation (gray dashed line). See Supplementary Fig. 4 for details.

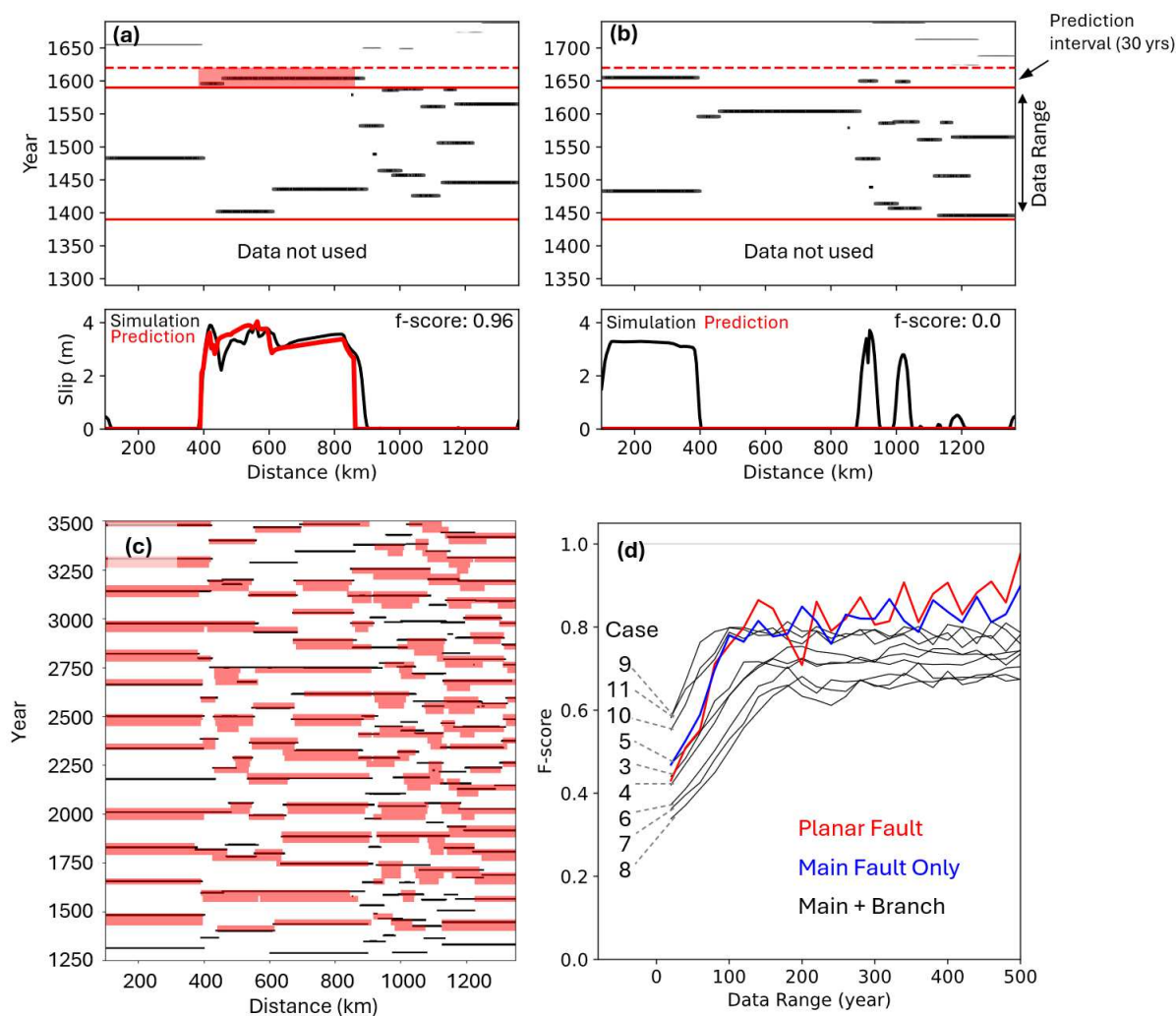


Figure 4. Earthquake Prediction. Predicted surface slip distribution expected over a period of 30 years (up to the red dashed line) prior to (a) and following (b) the event analog to the 2025 Mandalay earthquake (refer to Fig. 2a), respectively. The forecast is informed by the slip deficit calculated over a previous period of 200 years (marked by the red solid lines; a covering the period from 1390 to 1590, and b from 1440 to 1640). 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. (detailed prediction method can be found in Fig. 3 and Supplementary Fig. 4-7). (c) Prediction (red patches) and simulation (black lines), in the case where the data period is 200 years. Red patches represent the predicted earthquake range (i.e., panel a red patch), conducted over the entire simulation with a moving window of 30 years. (d) Assessment of the performance of the forecast for different fault geometries and different periods (20 to 500 years) over which the slip deficit is calculated (so assuming that surface ruptures are known over that period with no uncertainties and no data gap, and that interseismic loading is known as well). The red, blue, and black curves represent different fault types: the red curve indicates a planar fault (see Fig. 1a), the blue curve represents the case with only the main fault (see Fig. 1b), and the black curves illustrate realistic geometry cases with different friction parameters. Each case number for the realistic geometry displayed on the left side of the figure corresponds to its entry in Supplementary Table 1.

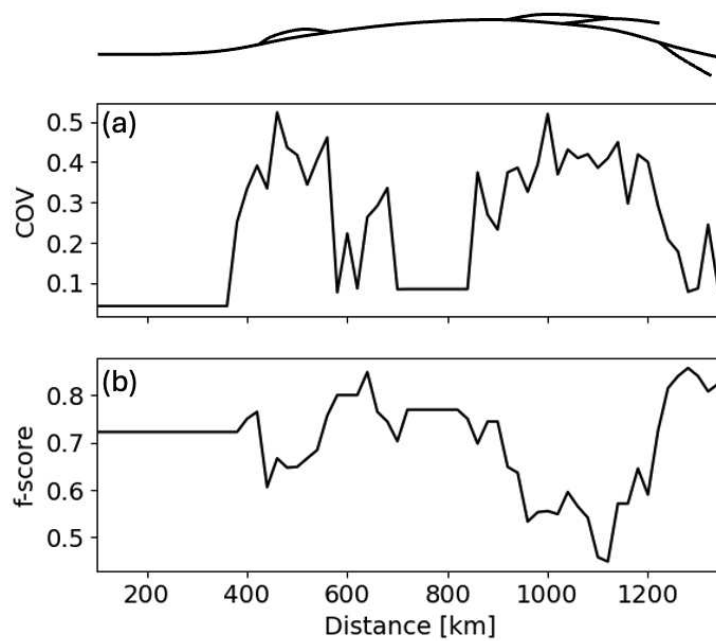


Figure 5. Distribution of the Coefficient of Variation (COV) and f-score. (a): COV. (b): f-score. These values are computed using simulation case 4 (the same as in Figure 1c) at every 20 km interval. The interevent time for both COV and the f-score is measured locally at each point, regardless of whether it is on the main or branch fault. See Method and Supplementary Fig. 8 for details.

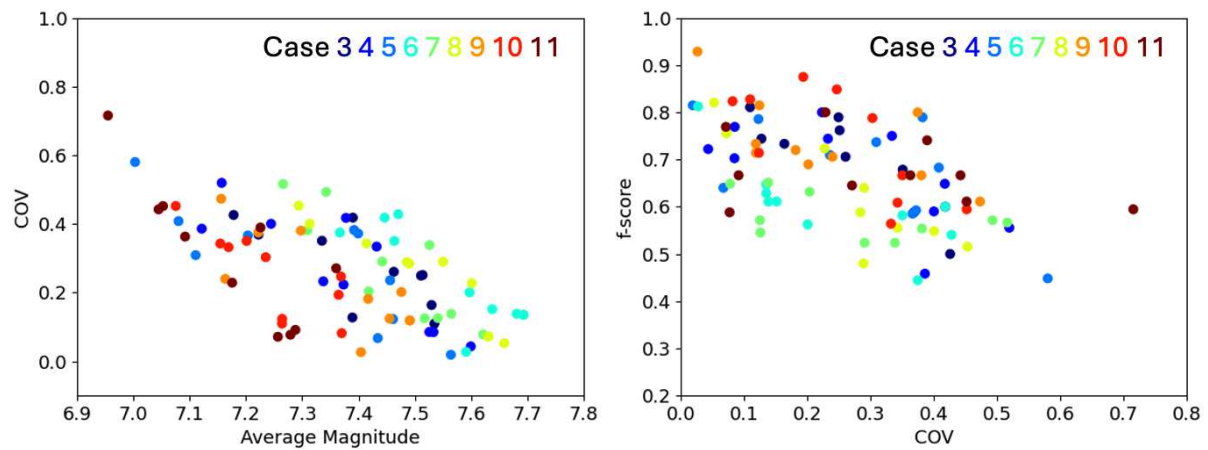


Figure 6. Relationship between earthquake magnitude, COV, and f-score. The values are measured using the same method as in the plot in Figure 5, but at 100 km intervals. Only complex fault cases (cases 3- 11; Supplementary Table 1) are used. COV and f-score are computed at a specific x-location point, while overall magnitudes that pass by the x-location are measured and averaged.

References

- Abercrombie, Rachel E., Duncan C. Agnew, and Frank K. Wyatt. "Testing a Model of Earthquake Nucleation." *Bulletin of the Seismological Society of America* 85, no. 6 (1995): 1873–78. <https://doi.org/10.1785/BSSA0850061873>.
- Antoine, Solene L., Rajani Shrestha, Chris Milliner, et al. "The 2025 M_w 7.7 Mandalay, Myanmar, Earthquake Reveals a Complex Earthquake Cycle with Clustering and Variable Segmentation on the Sagaing Fault." *Proceedings of the National Academy of Sciences* 122, no. 33 (2025): e2514378122. <https://doi.org/10.1073/pnas.2514378122>.
- Barbot, Sylvain. "Slow-Slip, Slow Earthquakes, Period-Two Cycles, Full and Partial Ruptures, and Deterministic Chaos in a Single Asperity Fault." *Tectonophysics* 768 (October 2019): 228171. <https://doi.org/10.1016/j.tecto.2019.228171>.
- Becker, Thorsten W. "Deterministic Chaos in Two State-Variable Friction Sliders and the Effect of Elastic Interactions." In *Geophysical Monograph Series*, vol. 120, edited by John B. Rundle, Donald L. Turcotte, and William Klein. American Geophysical Union, 2000. <https://doi.org/10.1029/GM120p0005>.
- Biasi, Glenn P., and Ray J. Weldon II. "Estimating Surface Rupture Length and Magnitude of Paleoearthquakes from Point Measurements of Rupture Displacement." *Bulletin of the Seismological Society of America* 96, no. 5 (2006): 1612–23. <https://doi.org/10.1785/0120040172>.
- Cattania, C. "Complex Earthquake Sequences On Simple Faults." *Geophysical Research Letters* 46, nos. 17–18 (2019): 10384–93. <https://doi.org/10.1029/2019GL083628>.
- Chen, Jianlong, Peizhen Zhang, Xin Qiao, Zicheng Huang, and Lejun Lu. "Frictional Heterogeneity Governs Slip Partitioning and Seismic Hazard in the 2023 Turkey Earthquake Doublet." *Geophysical Research Letters* 53, no. 6 (2026): e2025GL119502. <https://doi.org/10.1029/2025GL119502>.
- Cheng, Jinhui, Harsha S. Bhat, Michelle Almakari, Brice Lecampion, and Carlo Peruzzo. "FASTDASH: An Implementation of 3-D Earthquake Cycle Simulation on Complex Fault Systems Using the Boundary Element Method Accelerated by H-Matrices." *Geophysical Journal International* 242, no. 2 (2025): ggaf230. <https://doi.org/10.1093/gji/ggaf230>.
- Dieterich, James H. "Modeling of Rock Friction: 1. Experimental Results and Constitutive Equations." *Journal of Geophysical Research: Solid Earth* 84, no. B5 (1979): 2161–68. <https://doi.org/10.1029/JB084iB05p02161>.
- Epstein, Edward S. "Stochastic Dynamic Prediction." *Tellus* 21, no. 6 (1969): 739–59. <https://doi.org/10.1111/j.2153-3490.1969.tb00483.x>.
- Erickson, Brittany A., Junle Jiang, Michael Barall, et al. "The Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip (SEAS)." *Seismological Research Letters* 91, no. 2A (2020): 874–90. <https://doi.org/10.1785/0220190248>.
- Field, Edward H., Glenn P. Biasi, Peter Bird, et al. "Long-Term Time-Dependent Probabilities for the Third Uniform California Earthquake Rupture Forecast (UCERF3)."

546 *Bulletin of the Seismological Society of America* 105, no. 2A (2015): 511–43.
 547 <https://doi.org/10.1785/0120140093>.
 548 Griffin, Jonathan D., Mark W. Stirling, and Ting Wang. “Periodicity and Clustering in the
 549 Long-Term Earthquake Record.” *Geophysical Research Letters* 47, no. 22 (2020):
 550 e2020GL089272. <https://doi.org/10.1029/2020GL089272>.
 551 Griffin, Jonathan D., Ting Wang, Mark W. Stirling, and Matthew C. Gerstenberger.
 552 “Forecasting Recurrent Large Earthquakes From Paleoearthquake and Fault Displacement
 553 Data.” *Journal of Geophysical Research: Solid Earth* 130, no. 2 (2025): e2024JB029671.
 554 <https://doi.org/10.1029/2024JB029671>.
 555 Gualandi, A., J. P. Avouac, S. Michel, and D. Faranda. “The Predictable Chaos of Slow
 556 Earthquakes.” *Science Advances* 6, no. 27 (2020): eaaz5548.
 557 <https://doi.org/10.1126/sciadv.aaz5548>.
 558 Guvercin, Sezim E., and Sylvain Barbot. “Persistent Rupture Segmentation of the Main
 559 Marmara Fault.” *Communications Earth & Environment* 6, no. 1 (2025): 1028.
 560 <https://doi.org/10.1038/s43247-025-03007-4>.
 561 Hackbusch, W. “A Sparse Matrix Arithmetic Based on H-Matrices. Part I: Introduction to H-
 562 Matrices.” *Computing* 62, no. 2 (1999): 89–108. <https://doi.org/10.1007/s006070050015>.
 563 Harris, Ruth A., Ralph J. Archuleta, and Steven M. Day. “Fault Steps and the Dynamic
 564 Rupture Process: 2-D Numerical Simulations of a Spontaneously Propagating Shear
 565 Fracture.” *Geophysical Research Letters* 18, no. 5 (1991): 893–96.
 566 <https://doi.org/10.1029/91GL01061>.
 567 Harris, Ruth A., Michael Barall, Brad Aagaard, et al. “A Suite of Exercises for Verifying
 568 Dynamic Earthquake Rupture Codes.” *Seismological Research Letters* 89, no. 3 (2018):
 569 1146–62. <https://doi.org/10.1785/0220170222>.
 570 Howarth, Jamie D., Nicolas C. Barth, Sean J. Fitzsimons, et al. “Spatiotemporal Clustering of
 571 Great Earthquakes on a Transform Fault Controlled by Geometry.” *Nature Geoscience* 14,
 572 no. 5 (2021): 314–20. <https://doi.org/10.1038/s41561-021-00721-4>.
 573 Hubbard, Judith, Rafael Almeida, Anna Foster, Soma Nath Sapkota, Paula Bürgi, and Paul
 574 Tapponnier. “Structural Segmentation Controlled the 2015 Mw 7.8 Gorkha Earthquake
 575 Rupture in Nepal.” *Geology* 44, no. 8 (2016): 639–42. <https://doi.org/10.1130/G38077.1>.
 576 Im, Kyungjae, and Jean-Philippe Avouac. “Quake-DFN: A Software for Simulating
 577 Sequences of Induced Earthquakes in a Discrete Fault Network.” *Bulletin of the*
 578 *Seismological Society of America* 114, no. 5 (2024): 2341–58.
 579 <https://doi.org/10.1785/0120230299>.
 580 Kaneko, Yoshihiro, Jean-Philippe Avouac, and Nadia Lapusta. “Towards Inferring
 581 Earthquake Patterns from Geodetic Observations of Interseismic Coupling.” *Nature*
 582 *Geoscience* 3, no. 5 (2010): 363–69. <https://doi.org/10.1038/ngeo843>.
 583 Kaveh, Hojjat, Jean Philippe Avouac, and Andrew M. Stuart. “Data Assimilation in Machine-
 584 Learned Reduced-Order Model of Chaotic Earthquake Sequences.” *Geophysical Journal*
 585 *International* 244, no. 2 (2026): ggaf518. <https://doi.org/10.1093/gji/ggaf518>.
 586 Kaveh, Hojjat, Jean Philippe Avouac, and Andrew M. Stuart. “Spatiotemporal Forecast of
 587 Extreme Events in a Chaotic Model of Slow Slip Events.” *Geophysical Journal*
 588 *International* 240, no. 2 (2024): 870–85. <https://doi.org/10.1093/gji/ggae417>.

- King, Geoffrey, and John Nábělek. "Role of Fault Bends in the Initiation and Termination of Earthquake Rupture." *Science* 228, no. 4702 (1985): 984–87.
<https://doi.org/10.1126/science.228.4702.984>.
- Klinger, Y., M. Etchebes, P. Tapponnier, and C. Narteau. "Characteristic Slip for Five Great Earthquakes along the Fuyun Fault in China." *Nature Geoscience* 4, no. 6 (2011): 389–92. <https://doi.org/10.1038/ngeo1158>.
- Konca, A. Ozgun, Jean-Philippe Avouac, Anthony Sladen, et al. "Partial Rupture of a Locked Patch of the Sumatra Megathrust during the 2007 Earthquake Sequence." *Nature* 456, no. 7222 (2008): 631–35. <https://doi.org/10.1038/nature07572>.
- Kumar, Prabhat, Vineet K. Gahalaut, and Attreyee Ghosh. "Fault Geometry Control on Earthquake Segmentation and Locking Transition on Mid-Crustal Ramp in Kumaun-Garhwal, Central Himalaya: Implications for Regional Tectonics and Seismic Hazard." *Tectonics* 44, no. 5 (2025): e2025TC008855. <https://doi.org/10.1029/2025TC008855>.
- Lapusta, Nadia, James R. Rice, Yehuda Ben-Zion, and Gutuan Zheng. "Elastodynamic Analysis for Slow Tectonic Loading with Spontaneous Rupture Episodes on Faults with Rate- and State-Dependent Friction." *Journal of Geophysical Research: Solid Earth* 105, no. B10 (2000): 23765–89. <https://doi.org/10.1029/2000JB900250>.
- Lavrentiadis, Grigorios, Yongfei Wang, Norman A. Abrahamson, Yousef Bozorgnia, and Christine A. Goulet. "A Seismologically Consistent Surface Rupture Length Model for Unbounded and Width-Limited Events." *Earthquake Spectra* 41, no. 4 (2025): 2859–79. <https://doi.org/10.1177/87552930231205871>.
- Liu, Dunyu, Benchun Duan, Katherine Scharer, and Doug Yule. "Observation-Constrained Multicycle Dynamic Models of the Southern San Andreas and the Northern San Jacinto Faults: Addressing Complexity in Paleoearthquake Extent and Recurrence With Realistic 2D Fault Geometry." *Journal of Geophysical Research: Solid Earth* 127, no. 2 (2022): e2021JB023420. <https://doi.org/10.1029/2021JB023420>.
- McCann, W. R., S. P. Nishenko, L. R. Sykes, and J. Krause. "Seismic Gaps and Plate Tectonics: Seismic Potential for Major Boundaries." *Pure and Applied Geophysics* 117, no. 6 (1979): 1082–147. <https://doi.org/10.1007/BF00876211>.
- Milliner, C., J. P. Avouac, J. F. Dolan, and J. Hollingsworth. "Localization of Inelastic Strain with Fault Maturity and Effects on Earthquake Characteristics." *Nature Geoscience* 18, no. 8 (2025): 793–800. <https://doi.org/10.1038/s41561-025-01752-x>.
- Milliner, C. W. D., S. Aati, and J. P. Avouac. "Fault Friction Derived From Fault Bend Influence on Coseismic Slip During the 2019 Ridgecrest Mw 7.1 Mainshock." *Journal of Geophysical Research: Solid Earth* 127, no. 11 (2022): e2022JB024519. <https://doi.org/10.1029/2022JB024519>.
- Murray, Jessica, and Paul Segall. "Testing Time-Predictable Earthquake Recurrence by Direct Measurement of Strain Accumulation and Release." *Nature* 419, no. 6904 (2002): 287–91. <https://doi.org/10.1038/nature00984>.
- Oglesby, David. "Rupture Termination and Jump on Parallel Offset Faults." *Bulletin of the Seismological Society of America* 98, no. 1 (2008): 440–47. <https://doi.org/10.1785/0120070163>.

- Okada, Yoshimitsu. "Internal Deformation Due to Shear and Tensile Faults in a Half-Space." *Bulletin of the Seismological Society of America* 82, no. 2 (1992): 1018–40. <https://doi.org/10.1785/BSSA0820021018>.
- Rice, James R. "Spatio-Temporal Complexity of Slip on a Fault." *Journal of Geophysical Research: Solid Earth* 98, no. B6 (1993): 9885–907. <https://doi.org/10.1029/93JB00191>.
- Ried, HF. "The Elastic-Rebound Theory of Earthquakes." *Univ. California Publ. Bull. Dept. Geol.* 6 (1911): 413–44.
- Sasaki, Yutaka. "The Truth of the F-Measure." *Teach Tutor Mater*, January 1, 2007.
- Schwartz, David P., and Kevin J. Coppersmith. "Fault Behavior and Characteristic Earthquakes: Examples from the Wasatch and San Andreas Fault Zones." *Journal of Geophysical Research: Solid Earth* 89, no. B7 (1984): 5681–98. <https://doi.org/10.1029/JB089iB07p05681>.
- Shaw, Bruce E., Kevin R. Milner, Edward H. Field, et al. "A Physics-Based Earthquake Simulator Replicates Seismic Hazard Statistics across California." *Science Advances* 4, no. 8 (2018): eaau0688. <https://doi.org/10.1126/sciadv.aau0688>.
- Shimazaki, Kunihiko, and Takashi Nakata. "Time-Predictable Recurrence Model for Large Earthquakes." *Geophysical Research Letters* 7, no. 4 (1980): 279–82. <https://doi.org/10.1029/GL007i004p00279>.
- Stein, Ross S. "The Role of Stress Transfer in Earthquake Occurrence." *Nature* 402, no. 6762 (1999): 605–9. <https://doi.org/10.1038/45144>.
- Stein, Ross S., Aykut A. Barka, and James H. Dieterich. "Progressive Failure on the North Anatolian Fault since 1939 by Earthquake Stress Triggering." *Geophysical Journal International* 128, no. 3 (1997): 594–604. <https://doi.org/10.1111/j.1365-246X.1997.tb05321.x>.
- Tin, Tha Zin Htet, Takuya Nishimura, Manabu Hashimoto, et al. "Present-Day Crustal Deformation and Slip Rate along the Southern Sagaing Fault in Myanmar by GNSS Observation." *Journal of Asian Earth Sciences* 228 (May 2022): 105125. <https://doi.org/10.1016/j.jseaes.2022.105125>.
- Truttmann, S., T. Poulet, L. Wallace, M. Herwegh, and M. Veveakis. "Slow Slip Events in New Zealand: Irregular, yet Predictable?" *Geophysical Research Letters* 51, no. 6 (2024): e2023GL107741. <https://doi.org/10.1029/2023GL107741>.
- Tullis, Terry E., Keith Richards-Dinger, Michael Barall, et al. "Generic Earthquake Simulator." *Seismological Research Letters* 83, no. 6 (2012): 959–63. <https://doi.org/10.1785/0220120093>.
- United States Geological Survey (2025), M 7.7 - 2025 Mandalay, Burma (Myanmar) Earthquake. earthquakes.usgs.gov.
- Wang, Ting, Jonathan D. Griffin, Marco Brenna, et al. "Earthquake Forecasting from Paleoseismic Records." *Nature Communications* 15, no. 1 (2024): 1944. <https://doi.org/10.1038/s41467-024-46258-z>.
- Wang, Yu, Kerry Sieh, Soe Thura Tun, Kuang-Yin Lai, and Than Myint. "Active Tectonics and Earthquake Potential of the Myanmar Region." *Journal of Geophysical Research: Solid Earth* 119, no. 4 (2014): 3767–822. <https://doi.org/10.1002/2013JB010762>.
- Weldon, Ray, Katherine Scharer, Thomas Fumal, and Glenn Biasi. "Wrightwood and the Earthquake Cycle: What a Long Recurrence Record Tells Us about How Faults Work."

- 675 *GSA Today* 14, no. 9 (2004): 4. <https://doi.org/10.1130/1052->
676 5173(2004)014%253C4:WATECW%253E2.0.CO;2.
- 677 Wesnousky, Steven G. “Displacement and Geometrical Characteristics of Earthquake Surface
678 Ruptures: Issues and Implications for Seismic-Hazard Analysis and the Process of
679 Earthquake Rupture.” *Bulletin of the Seismological Society of America* 98, no. 4 (2008):
680 1609–32. <https://doi.org/10.1785/0120070111>.
- 681 Wesnousky, Steven G., and Glenn P. Biasi. “The Length to Which an Earthquake Will Go to
682 Rupture.” *Bulletin of the Seismological Society of America* 101, no. 4 (2011): 1948–50.
683 <https://doi.org/10.1785/0120110013>.
- 684 Zielke, Olaf, and Paul Martin Mai. “MCQsim: A Multicycle Earthquake Simulator.” *Bulletin*
685 *of the Seismological Society of America* 113, no. 3 (2023): 889–908.
686 <https://doi.org/10.1785/0120220248>.

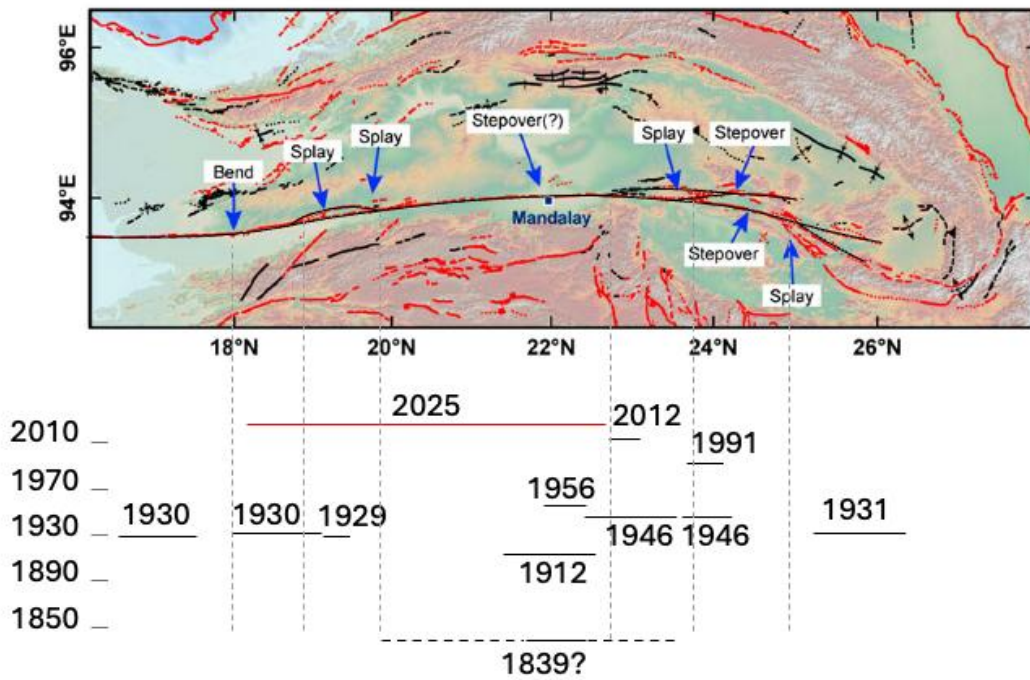
689 **Supplementary Table 1.** Friction parameters used for simulation.

No.	a	b	Dc (cm)	Geometry
1	0.004	0.008	3	Planar
2	0.004	0.008	3	Main fault only (No Branch)
3	0.004	0.008	3	Main fault + Branch Fault
4	0.004	0.008	4	
5	0.004	0.008	5	
6	0.005	0.010	3	
7	0.005	0.010	4	
8	0.005	0.010	5	
9	0.003	0.006	2	
10	0.003	0.006	3	
11	0.003	0.006	4	

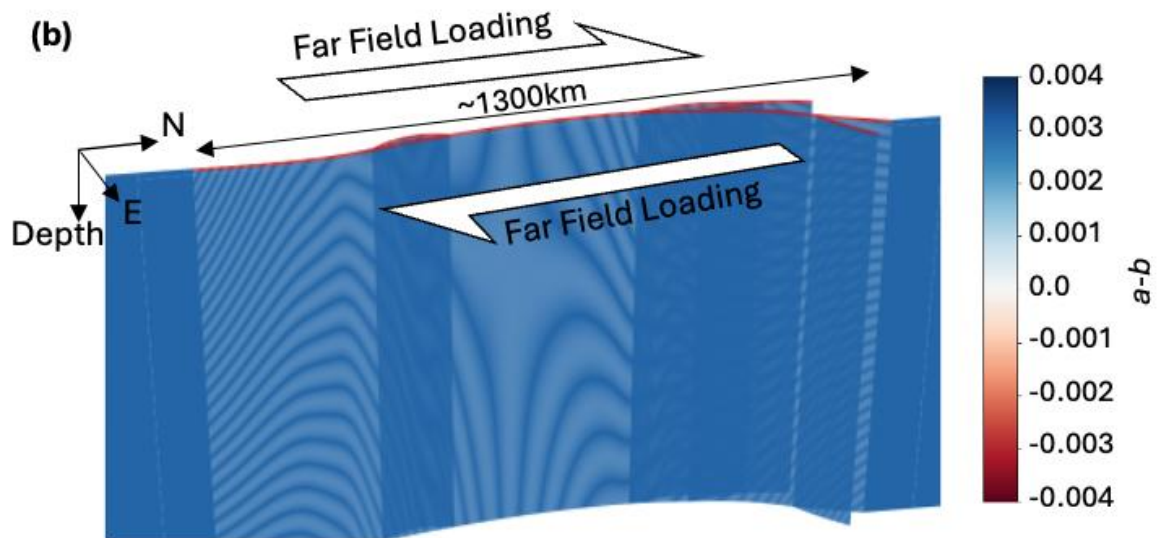
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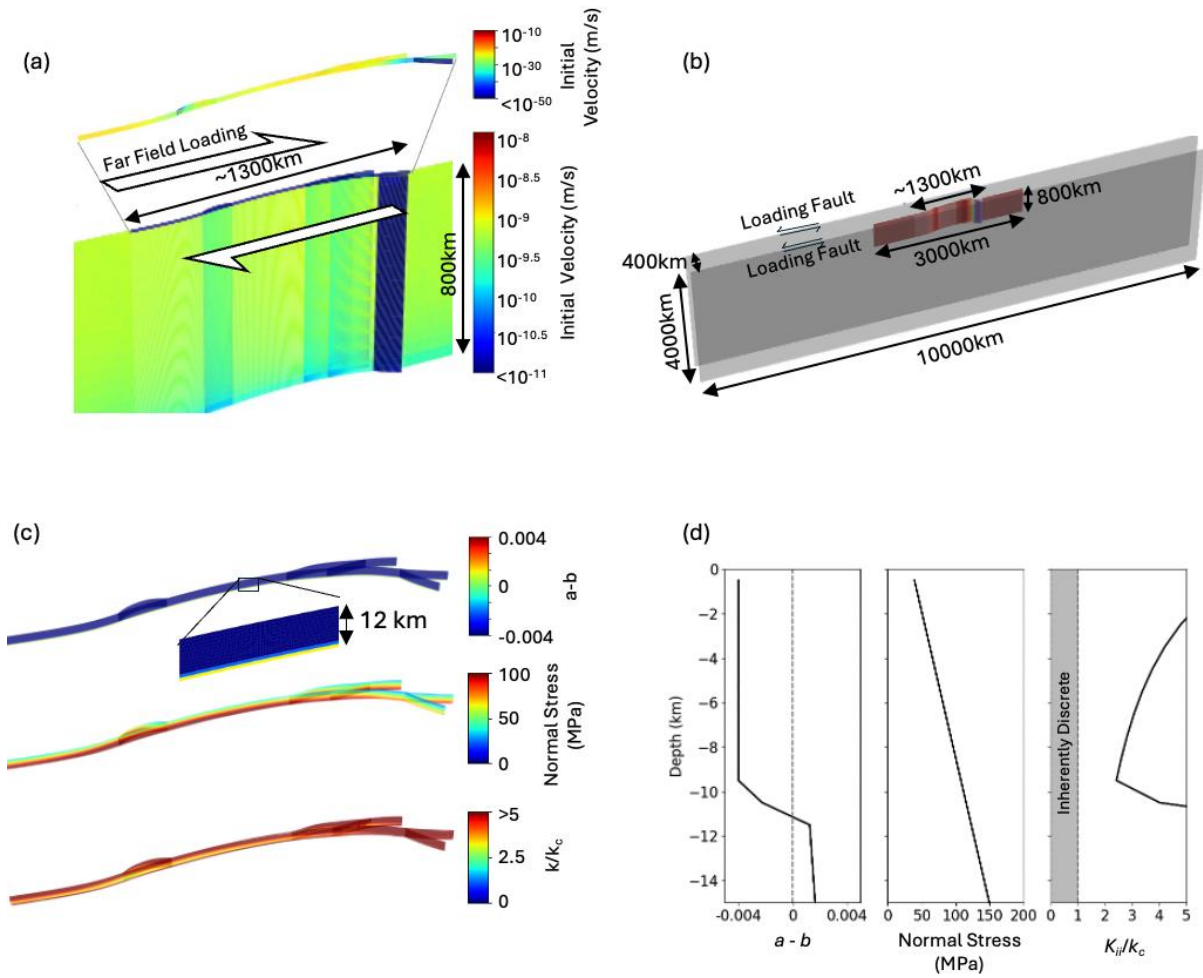
(a)



(b)

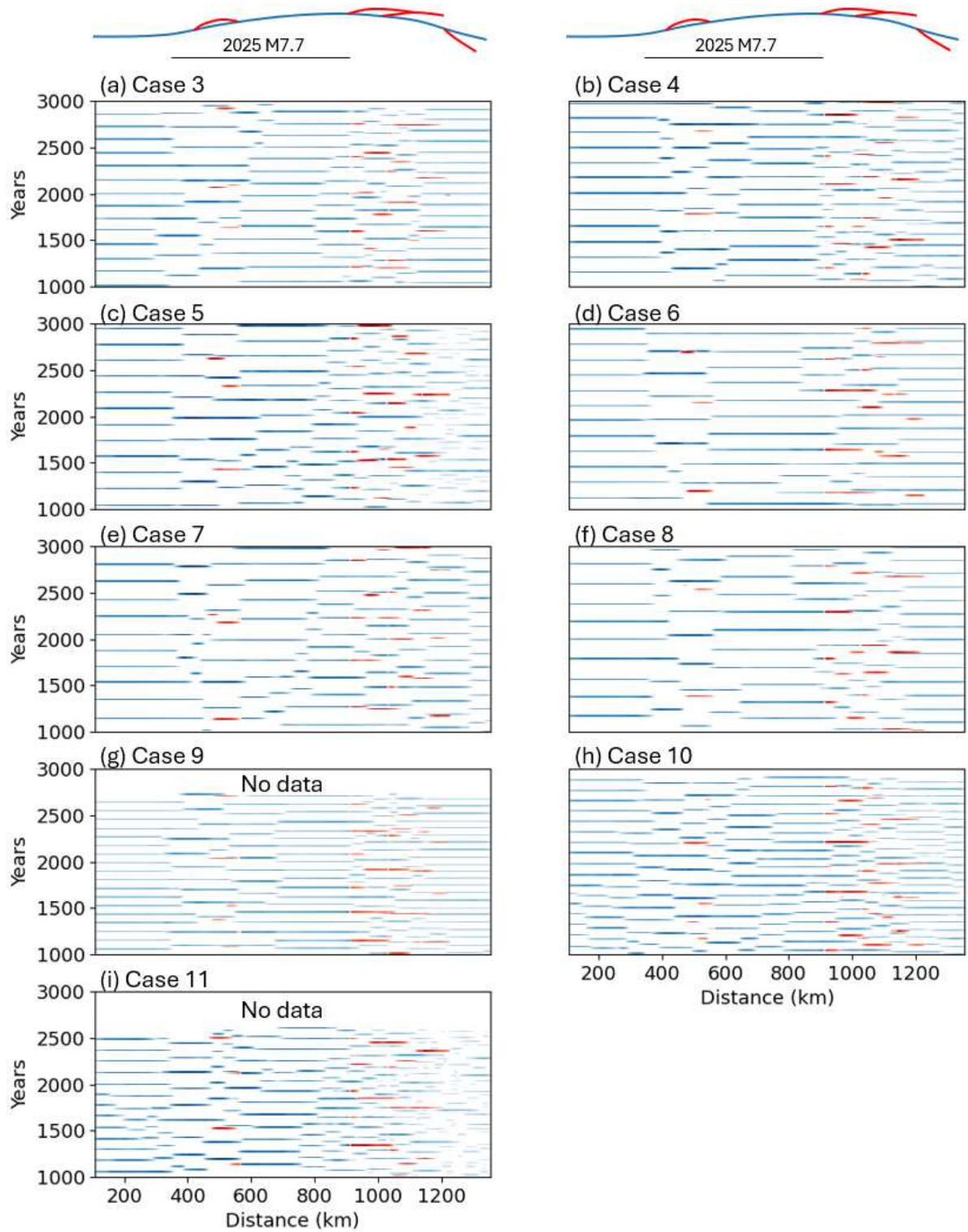


Supplementary Figure 1. Fault geometry and historical earthquakes. (a) Sagaing fault geometry and earthquake history based on Wang et al. (2014). The fault geometry is traced (black line) and is utilized to construct the simulation geometry depicted in panel (b). The lower panel in (a) represents the historical seismicity identified by Wang et al. (2014). (b): Simulation geometry: The colors represent the rate and state friction parameter $a-b$ (negative values represent velocity-weakening elements). The white arrows indicate the far-field loading.

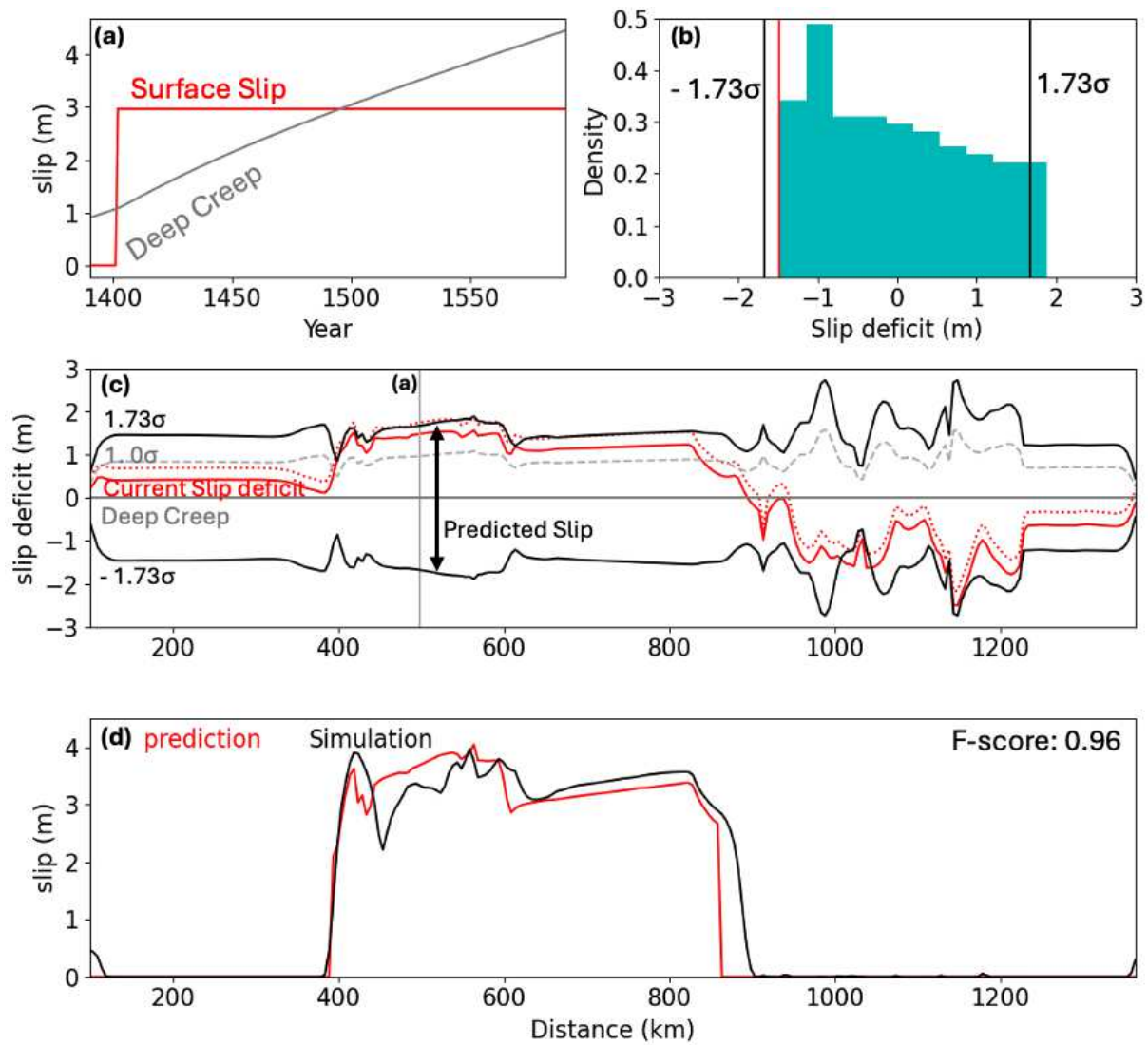


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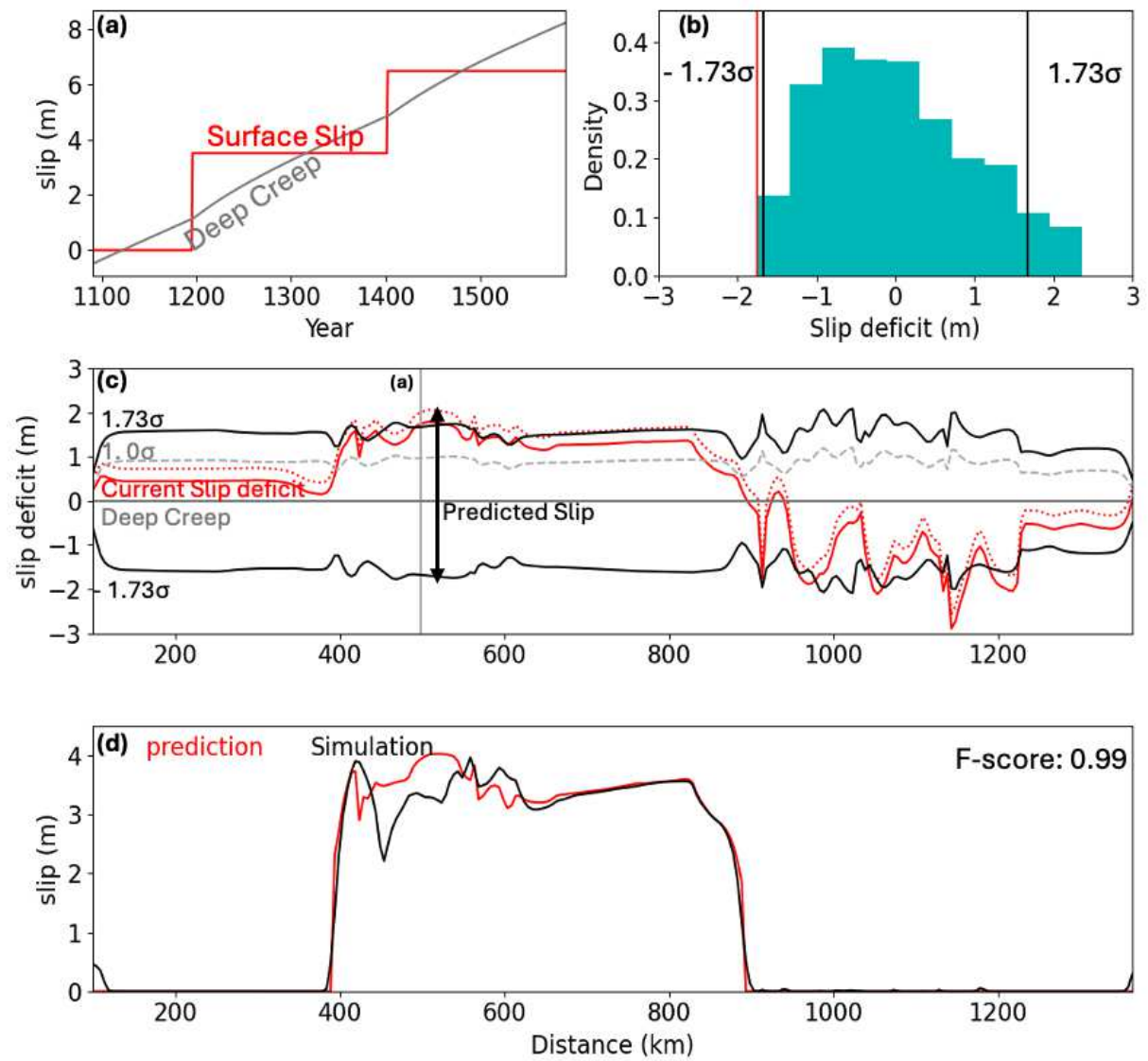
701 **Supplementary Figure 2. Simulation method.** (a) initial velocity. These initial velocities are
 702 assigned separately for velocity-strengthening (upper) and velocity-weakening (lower) elements. Note
 703 that the initial velocities vary due to fault curvature and exhibit a step change at the branching point as
 704 a result of strain distribution between the main fault and its branches. (see Method for more details)
 705 (b) Dimensions of geometry including loading faults (gray). The two loading faults are slipping at the
 706 slip speed to produce a long-term slip rate similar to the observation (panel a). (c,d) Friction
 707 parameters at the shallow, finely discretized elements. The normal stress is depth-dependent. It is
 708 shown that k_{ii}/k_c is larger than 3 at most velocity-weakening faults. The plots are vertically
 709 exaggerated by 3. Panel (d) is measured at the center of the simulation domain.
 710



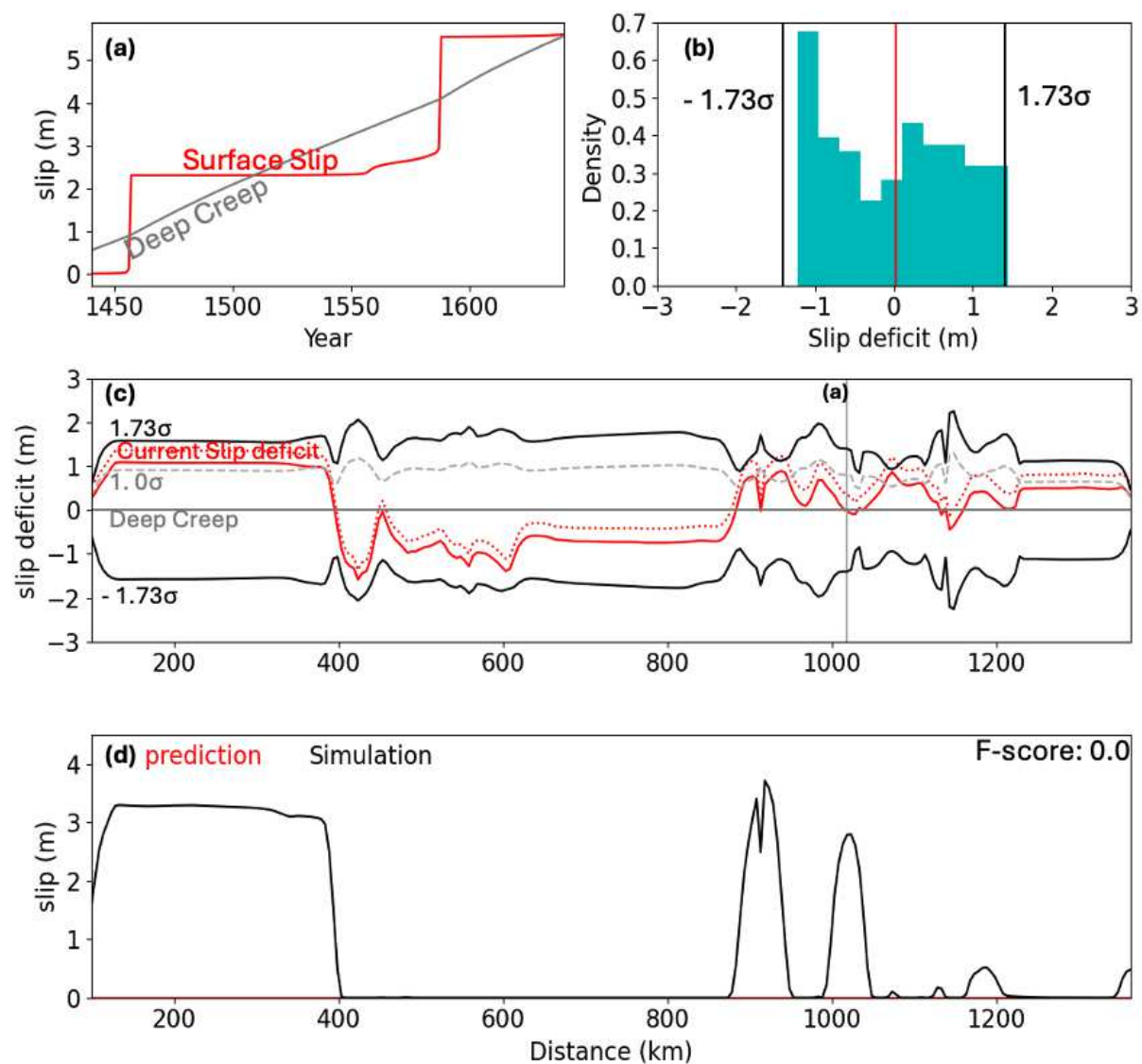
Supplementary Figure 3. All simulation results of complex geometry cases. The friction parameters for each case are presented in Supplementary Table 1. The "no data" in panels g&i is due to the fact that the simulation is over before reaching 3000 years.



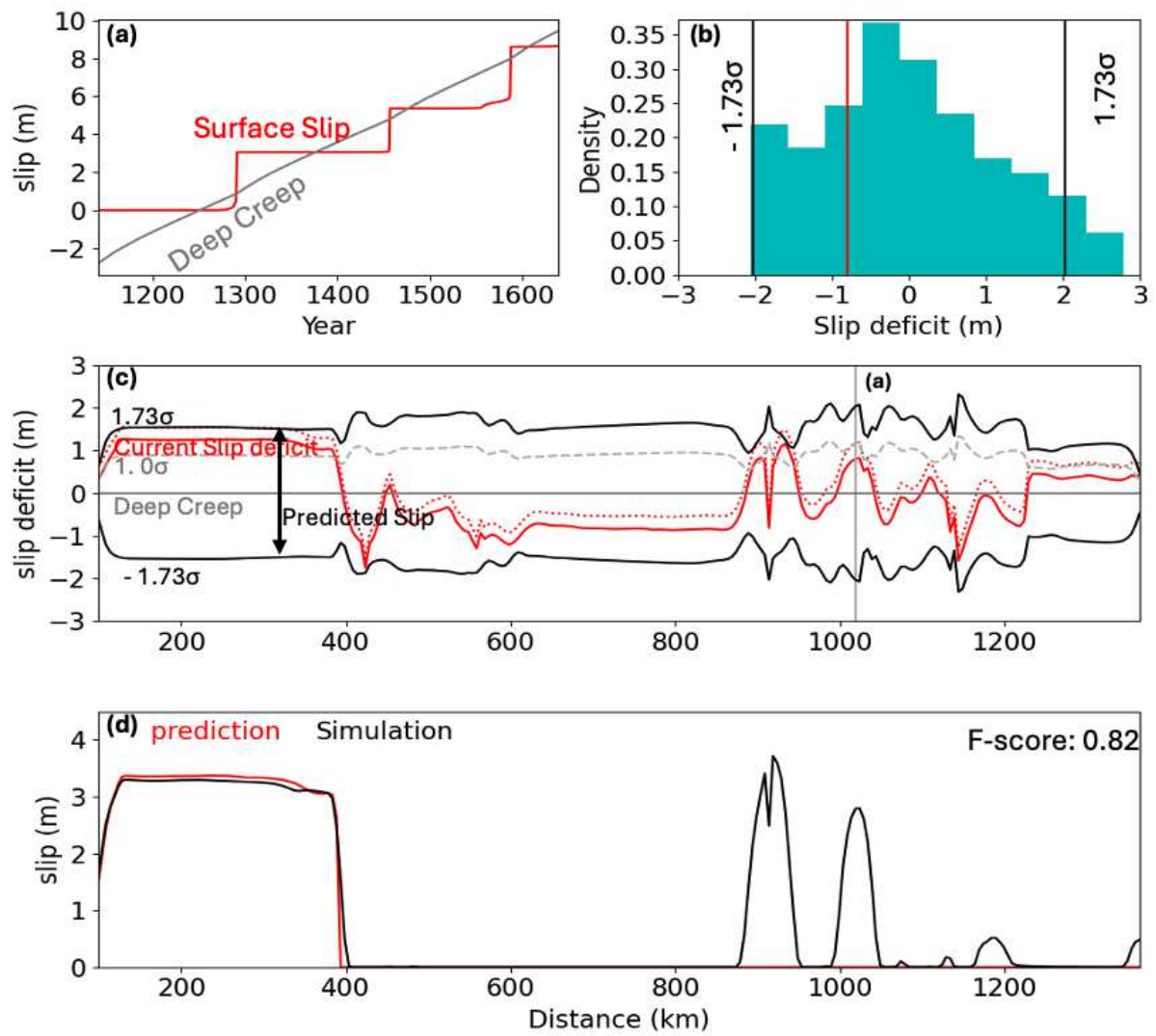
Supplementary Figure 4. Earthquake prediction method with a data period of 200 years (1390-1590). (a) Surface slip (red), long-term slip (gray; slip at ~ 25 km depth) at the locations shown by a vertical gray line in panel (c). (b): density distribution histogram of slip deficit (*i.e.*, deep creep – surface slip in panel a) and upper and lower bounds (± 1.73 times the standard deviation; black vertical lines). The average slip deficit is adjusted to be zero. The slip deficit for each year shown in panel a is used to create the density histogram. In panel (c), the distribution of the slip deficit for surface slip is indicated in red, along with the upper and lower bounds in black at the conclusion of the data period (year 1590). The red dashed line represents a 30-year extrapolation of the slip deficit, and the gray dashed line represents $\pm$ standard deviation. Panel (d) compares the predicted slip distribution (in red) with the surface ruptures observed in our simulation (in black) over a 30-year prediction period. Panels c and d are identical to Fig. 3.



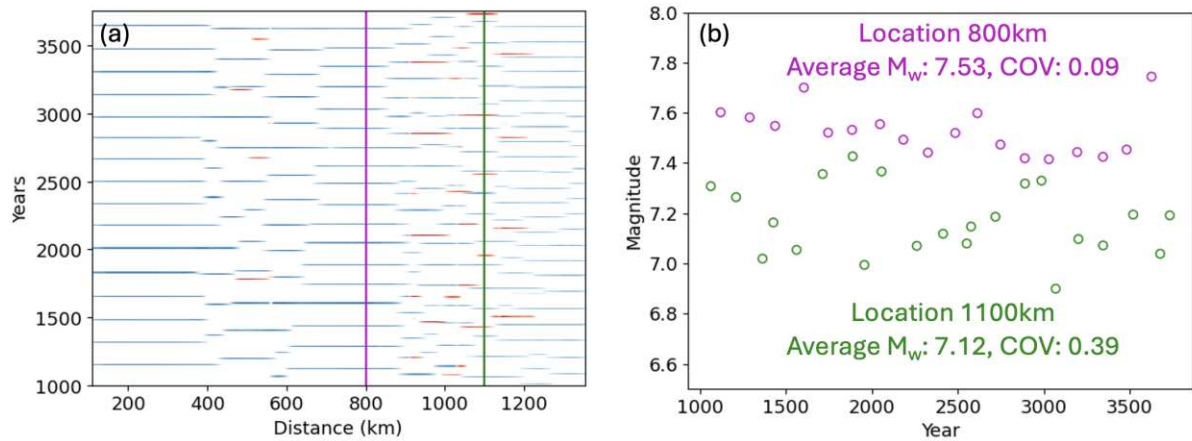
Supplementary Figure 5. Same as Supplementary Fig. 4 but with a data period of 500 years (1090-1590).



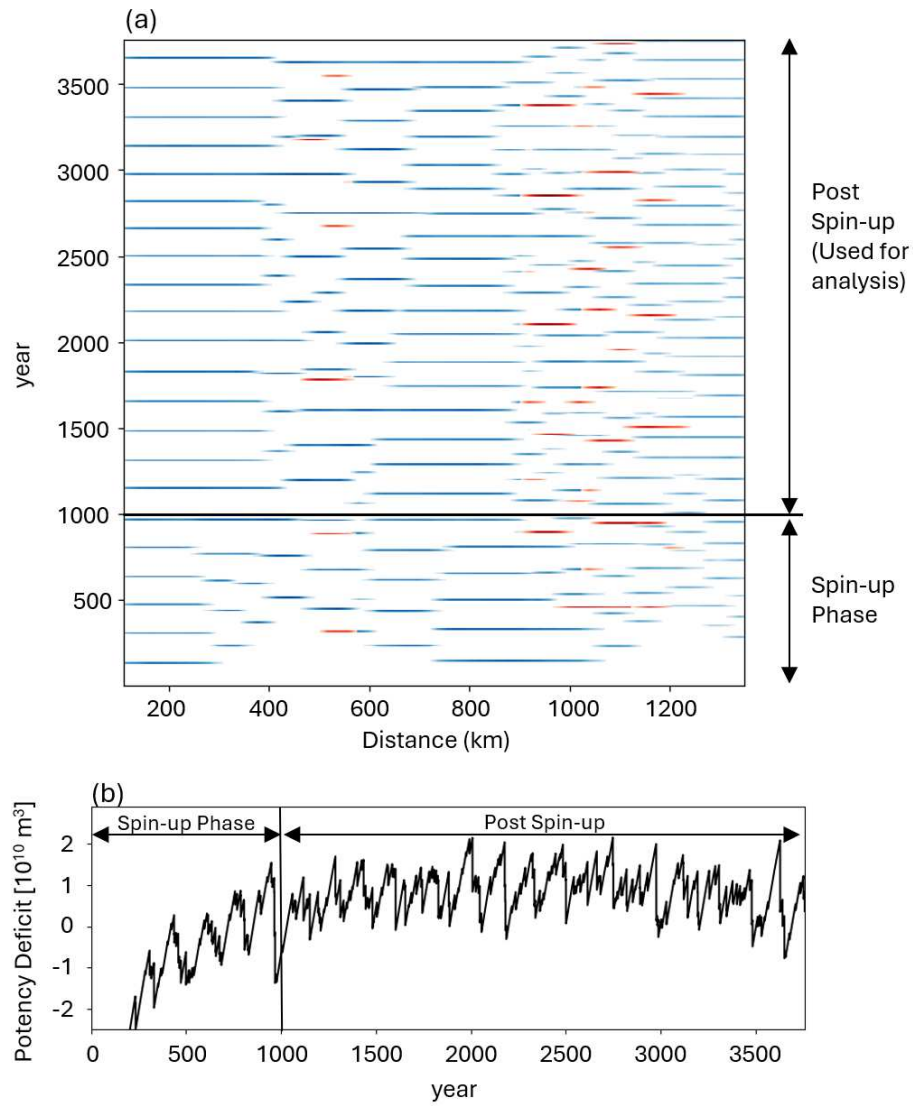
Supplementary Figure 6. Same as Supplementary Fig. 4 but with a different data period (1440-1640). This result corresponds to Fig 4b.



Supplementary Figure 7. Same as Supplementary Fig 6 but with 500 year data period (1140-1640).



Supplementary Figure 8. Example of COV and average Magnitude calculation. The COV and average magnitude are calculated at the x-locations of 800 km (purple) and 1100 km (green). Any event passing through these points is counted as an earthquake at that location, and the overall magnitude of each earthquake is used to calculate the average magnitude (panel b). This example shows the simulation results for the earthquake sequence in case 4 (panel a, same as Fig. 1c). Panel b displays the event times and magnitudes. The panel shows the computed average magnitude and COV based on detected events. The simpler fault segment at 800 km results in more regular (low COV) and larger average earthquake sequences (purple), whereas the more complex segment at 1100 km produces irregular (high COV) and smaller average earthquakes (green).



Supplementary Figure 9. Spin-up phase. (a) The plot is identical to Fig. 1c upper panel, but includes an initial spin-up phase of 1000 years. (b) slip potency (slip $\times$ area) deficit vs. time. Due to the initial conditions, the rupture sequence during the first 500 years is irregular. In all analyses presented in this work, we used only results from the period after the initial 1000-year period.