Dynamic rupture process of the Mw 7.8 Kahramanmaraş earthquake (SE Türkiye): Variable rupture speed and implications for seismic hazard

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Abstract

We considered various non-uniformities such as branch faults, rotation of stress field directions, and changes in tectonic environments to simulate the dynamic rupture process of the 6th February 2023 Mw 7.8 Kahramanmaraş earthquake in SE Türkiye. We utilized near-fault waveform data, GNSS static displacements, and surface rupture to constrain the dynamic model. The results indicate that the high initial stress accumulated in the seismic gap leads to the successful triggering of the East Anatolian Fault (EAF) and the supershear rupture in the northeast segment. Due to the complexity of fault geometry, the rupture speed along the southeastern segment of the EAF varied repeatedly between supershear and subshear, which contributed to the unexpectedly strong ground motion. Furthermore, the triggering of the EAF reminds us to be aware of the risk of seismic gaps on major faults being triggered by secondary faults, which is crucial to prevent significant disasters.

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Dynamic rupture process of the $M_w$ 7.8 Kahramanmaraş earthquake (SE Türkiye): Variable rupture speed and implications for seismic hazard

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Key Points:

- The high initial stress accumulated in the seismic gap leads to the successful triggering of the East Anatolian Fault.
- The change of fault geometry in the southwest segment prevented the sustained supershear rupture.
- We highlight the risk of earthquake nucleation on the secondary fault triggering the major fault rupture and the related disaster.
Abstract

We considered various non-uniformities such as branch faults, rotation of stress field directions, and changes in tectonic environments to simulate the dynamic rupture process of the 6th February 2023 $M_w$ 7.8 Kahramanmaraş earthquake in SE Türkiye. We utilized near-fault waveform data, GNSS static displacements, and surface rupture to constrain the dynamic model. The results indicate that the high initial stress accumulated in the seismic gap leads to the successful triggering of the East Anatolian Fault (EAF) and the supershear rupture in the northeast segment. Due to the complexity of fault geometry, the rupture speed along the southeastern segment of the EAF varied repeatedly between supershear and subshear, which contributed to the unexpectedly strong ground motion. Furthermore, the triggering of the EAF reminds us to be aware of the risk of seismic gaps on major faults being triggered by secondary faults, which is crucial to prevent significant disasters.

Plain Language Summary

On February 6, 2023, the south-central Türkiye was hit by two major earthquakes with magnitudes of $M_w$ 7.8 and $M_w$ 7.6 respectively. Among them, the complex rupture process and unexpected ground motion of the $M_w$ 7.8 event attracted the attention of seismologists. In this paper, the 3D dynamic rupture process of this mainshock is simulated based on complex multi-fault system and heterogeneous initial stress. And the simulation results are in good agreement with the observations. Our results show that high initial stress is required for the EAF to be triggered. And the supershear rupture has occurred, but due to the change of fault geometry or fault strength, the global supershear rupture has not developed. More importantly,
the dynamic model suggests that we must be alert to the risk of major fault being triggered by
earthquakes on nearby small faults, especially when there are seismic gaps on the major fault.

1 Introduction

On 6th February 2023, at 01:17:34 UTC, the $M_w 7.8$ earthquake struck the Nurdağı-Pazarcık
region in the Kahramanmaraş-Gaziantep province of south-central Türkiye, near the NW Syria
(Melgar et al., 2023). The 2023 SE Türkiye earthquake sequence occurred in a region where a
tectonically deforming complex network of faults controlled by the triple junction between the
Anatolian, Arabian, and African plates (Figure 1). The U.S. Geological Survey, National
Earthquake Information Center (USGS-NEIC) located the $M_w 7.8$ hypocenter south of the
EAF, with a strike-slip mechanism consistent with the left-lateral sense of motion of the East
Anatolian Fault Zone (EAFZ) (Goldberg et al., 2023a, b). The main shock’s epicenter and its
subsequent aftershocks were consistently located along the EAF and widespread structural
damage was reported in a wide region over eleven major cities and the NW Syria. The EAFZ is
the major plate boundary that accommodates the westward extrusion of the Anatolia toward the
Aegean Sea, and the fault zone has caused destructive earthquakes throughout recorded history
(e.g., Ambraseys, 1989; Emre et al., 2018). The 2023 sequence’s mainshock $M_w 7.8$ has been
the most significant and destructive earthquake along the EAFZ and surrounding fault
segments since the 22 May 1971 $Ms 6.9$ Bingöl, and 24 January 2020 $M_w 6.7$
Doğanyol-Sivrice earthquakes (Taymaz et al., 1991, 2021). To the south of the EAFZ, the
left-lateral Dead Sea Fault (DSF) accommodates northward motion of the Arabian Peninsula
relative to the African and Eurasian plates (Taymaz et al., 1991; Figure 1).
Figure 1. Tectonic map of the 2023 SE Türkiye-Syria earthquake doublet and strong-motion stations depicted by red-filled triangles. Two epicenters of $M_w$ 7.8 and $M_w$ 7.6 earthquakes and focal mechanisms from the AFAD are shown as red stars and red beachballs, respectively. Brown lines represents the fault segments used in the dynamic modeling, while black lines show fault traces of mapped surface ruptures from Reitman et al. (2023). The colored-filled circles show the first 11 days of relocated aftershocks (color varying according to the hypocenter depth) from Melgar et al. (2023). Inset illustrates two major tectonic plates (Arabian and Anatolian) and active faults (Emre et al., 2018) and plate boundaries (Bird, 2003), such as East Anatolian Fault Zone (EAFZ) and North Anatolian Fault Zone (NAFZ) (see also Taymaz et al., 1991).
After the doublet earthquakes, many preliminary results of finite-fault source inversion based on strong ground motion, near-field geodetic data and/or teleseismic data have been published (Delouis et al., 2023; Mai et al., 2023; Melgar et al., 2023; Goldberg et al., 2023,a, b; Okuwaki et al., 2023; Xu et al., 2023). However, a highly debated controversy exists regarding the presence of a supershear rupture during the $M_w$ 7.8 event. The controversy is multifaceted. Rosakis et al. (2023) speedly analyzed the waveforms of two near-fault stations, concluding that the supershear rupture occurred at a distance of about 19 km from the epicenter. Conversely, some inversion results do not support this conclusion (Delouis et al., 2023; Melgar et al., 2023). Through analyzing the rupture phase, Yao & Yang (2023) determined that the average rupture speed of the southwest section of the EAF is estimated to be ~3.1-3.4 km/s. However, this still does not eliminate the possibility of transient supershear. The preliminary dynamic rupture models also remain disputed. The first order model by Gabriel et al. (2023) is subshear, while Abdelmeguid et al. (2023) observe many transient supershear ruptures in the southwest segment and sustained supershear in the northeast segment of the EAF in their 2D simulation. Therefore, to comprehensively understand the rupture process of the Kahramanmaraş earthquake, it is necessary to conduct detailed data-constrained 3D dynamic simulations.

In this study, we utilize near-fault waveform data, GNSS static horizontal displacement, and surface rupture as constraints to develop a dynamic rupture model for the $M_w$ 7.8 Kahramanmaraş earthquake based on cascading multi-scale network of fault system and heterogeneous initial stress. We thoroughly analyzed the triggering process of the EAF and the rupture speed of our model, followed by a discussion on the implications for the
seismogenic environment and widespread earthquake disaster. Finally, we discuss the earthquake physics and the future improvement for the dynamic model of this earthquake.

2 Materials and Methods

Fault geometry, initial stress, and rock properties control the dynamic rupture process of tectonic faults. However, these data cannot always be measured directly in-situ. In this section, we will discuss the fault model and dynamic parameters adopted based on various previous studies of the EAFZ and introduce the numerical method used for this work.

We construct 3D non-planar fault geometry based on the mapped surface ruptures from Reitman et al. (2023) and earthquake relocation results provided by Melgar et al. (2023). Some smaller fault branches were ignored but we kept the two major ones (Figure 1). These two branches of faults have not been mapped before. Melgar et al. (2023) designated the fault where the rupture was initiated as the Nurdağı-Pazarcık Fault (NPF). In this work, we label another branch fault as the F3 segment (Figure 1). The dip of the EAF is set to 85° trending southeast but bends to 80° trending northwest in northeastmost segment. This dip transition is the same as the fault model of Melgar et al. (2023). The dip of the NPF is set to 80° (trending northwest) based on the earthquake relocation results. The F3 segment shares the same dip and trend as the main portion of the EAF. All fault widths are set to 20 km.

The EAF is located at the intersection of the Arabian, Eurasian, and African plates, resulting in a complex stress state (Taymaz et al., 1991, 2021). Güvercin et al. (2022) studied the stress orientations based on focal mechanisms and found that the orientation varies across different fault segments. In the region that ruptured in the 2023 $M_w$ 7.8 event, the direction of
maximum principal compressive stress $S_H$ is roughly between N169°E and N203°E, with a clockwise trend from southwest to northeast. Early research (Lyberis et al., 1992; Yilmaz et al., 2006) also confirmed the same features. Therefore, after trial-and-error, the $S_H$ orientation is set as shown in Figure 2a.

**Figure 2.** Model setting and dynamic rupture results. (a) The orientation of $S_H$. (b) Initial shear stress $T_s$. (c) The ratio of shear stress and normal stress ($\mu_0$). The closer $\mu_0$ is to the static friction coefficient $\mu_s$, the easier the earthquake is to rupture. (d)-(i) Key snapshots of the dynamic rupture process. A shared color bar is illustrated in (i). The black arrows indicate the supershear rupture. The red arrow indicates the dynamic triggering.
Another factor that can constrain the initial stress is the stress shape ratio $R$, which is defined as $R = (S_v - S_h)/(S_h - S_H)$, where $S_h$ is the minimum principal stress, $S_v$ is the vertical stress. Generally, considering lithostatic pressure and pore pressure, $S_v$ can be described as

$$S_v = (1 - \gamma)\rho gh. \quad (1)$$

Where $\rho$ is the density of rock, $g$ is the acceleration of gravity, $h$ is the depth, $\gamma$ is the pore-fluid factor, respectively. Therefore, using a lateral pressure coefficient expressed as $k = S_H / S_v$, we can obtain

$$S_h = (1 - k + kR)S_v / R. \quad (2)$$

According to the focal mechanism inversion conducted by Yilmaz et al. (2006), the average value of $R$ in the Kahramanmaraş to Çelikhan segment (KC segment) of the EAF is 0.715. This indicates that the tectonic environment in this region is characterized by transpression. But in the southwest segment of the EAF, the tectonic environment shifts to transtension (Lyberis et al., 1992), we assume $R = 0.3$ in this region.

After trial-and-error, we set $\gamma = 0.7$, and to prevent excessive stress drop in the deep part, the stress only increases to 5 km with depth. The final initial shear stress and the ratio of shear stress and normal stress $\mu_0$ are shown in Figure 2b-c, respectively. We set the location of the nucleation zone based on the hypoDD relocations of Melgar et al. (2023), with a radius of 1.8 km. And the shear stress of the nucleation zone is set to a value 0.1% higher than the shear strength to trigger the rupture. The distribution of $k$ and $R$ are illustrated in Figure S1.
Here, slip-weakening friction law (Ida, 1972) is applied in our simulation, and also in a recent study by Taymaz et al. (2022). Khalifa et al. (2018) investigated the rock strength of the EAFZ, they found that the rock strength varied from very low to moderate from west to east in the KC segment of the fault. Thus, the friction coefficients are also heterogeneous in the fault plane (Figure S2). The critical slip distance $D_c$ only varies with depth (Figure S3). The value of $D_c$ is set to 0.36 m in the depth of 0-15 km and is linearly increased when the depth is larger than 15 km to mimic the brittle-ductile transition in the crust.

A layered seismic velocity structure (Güvercin et al., 2022) is adopted in our dynamic modeling. This model only provides P and S wave velocity $V_p$ and $V_s$, hence we use the empirical formula (Brocher, 2005) to calculate the density $\rho$ according to $V_p$.

In this work, we use an open-source software DRDG3D, which was developed by Zhang et al. (2022) for the dynamic rupture modeling. DRDG3D is based on a nodal discontinuous Galerkin (DG) framework (Hesthaven and Warburton, 2007) with tetrahedral mesh adopted. Due to the flexibility for modeling geometric complex faults, DG methods has been widely used in dynamic rupture modeling of real or scenario earthquakes (Biemiller et al., 2022; Ramos et al., 2021; Ulrich et al., 2019; Wollherr et al., 2019). DRDG3D adopts an upwind/central mixed flux scheme, which remove numerical artifacts when the near-fault asymmetric unstructured tetrahedral mesh is generated. The numerical scheme of DRDG3D reduces the dependence of mesh quality thereby increasing the efficiency. The DRDG3D has been verified by many benchmark models in the SCEC/USGS Spontaneous Rupture Code Verification Project (https://strike.scec.org/cvws/, Harris et al, 2009). The accuracy and efficiency of DRDG3D has been analyzed in detail by Zhang et al. (2022).
3 Results

The fault element size of our dynamic simulation is 570 m, with the spatial-order-of-accuracy of 3. The time step is 0.0031 s and the total simulation time is 90 s. Figure 2d-i shows some key snapshots of the rupture process. The complete dynamic rupture process can be found in Movie S1. The rupture nucleated at the NPF and generated a supershear rupture at about 9 s (Figure 2d), supporting the preliminary analysis of Rosakis et al. (2023). And then, the EAF was dynamically triggered in the northeast of the junction (Figure 2e). After being triggered, the rupture propagated northeast on the EAF and transitioned to a supershear rupture very quickly (Figure 2f). As the fault strength increased along the strike, the rupture speed returned to subshear (Figure 2g). A few seconds later, the rupture began to propagate southwest. Due to the complex segmented fault geometry, the rupture speed varies frequently (see Figure 2g-i, Figure 3b). The supershear rupture eternally encounters barriers caused by fault geometry changes, making it unsustainable. The final slip distribution of our dynamic model is presented in Figure 3a. The maximum strike-slip displacement exceeds 7 m. Figure 3b shows the details of the rupture speed of three cascading faults, with the overall results being similar to that of Delouis et al. (2023).

The rupture duration for the earthquake simulated in this study is approximately 80 s, and the moment magnitude achieved is $M_w 7.8665$. Figure 3c compared the moment rate release process of this work, the inversion results of Melgar et al. (2023), Okuwaki et al. (2023), USGS (2023) (for details see Goldberg et al., 2023a, b). All the results show consistency in terms of duration and seismic moment release characteristics, with the
maximum peak occurring at 20-30 s and the second peak at 40-50 s. These two peaks correspond to the two periods of maximum energy release for this earthquake.

Figure 3. (a) Final slip distribution of the dynamic model. (b) The ratio of rupture speed $V_r$ and $V_s$. $V_r/V_s$ greater than 1 indicates the supershear rupture. The three faults are drawn separately and marked on the figure. There is no rupture in the crimson region except the nucleation zone. (c) Moment rate release comparison.

Figure 4a shows a comparison of the near-fault station waveforms (filtered to 0.01-0.4 Hz). Our results successfully reproduce the primary features of the observations, and the agreement in travel time between our simulation and the observations suggests that the rupture speed in our model is reasonable. Several stations at the most southwest segment of the fault
are not well fitted, which may be because we ignore some small branches at the end of the fault and the 3D heterogeneous velocity models are lacking. We noticed that the aforementioned stations are all located near the southwest segment of the EAF. Unfortunately, near-fault observations in the northeast segment of the EAF were missing because of the abrupt termination of station records, which made the rupture process in the northeast segment less constrained. Nonetheless, we still select 4 stations to compare the relevant waveforms in Figure S4. The stop time of the recording is very close to the arrival time of the waveforms, leading us to suspect that the cause of station damage is related to the arrival of rupture. Therefore, it is possible and acceptable that a supershear rupture occurred in the northeast segment of the EAF.

Figure 4. Comparison between simulation results and observation. (a) Comparison of waveforms of near-fault stations. The black line is the observed waveform, and the red line is the synthesized waveform, both of which are filtered to 0.01-0.4Hz. The station name is marked on the left. The maximum absolute values of each component of the observations (m/s) are listed at the end of each seismogram (see Figure 1 for the location of the stations). (b)
Comparison of surface strike-slip displacement. The red line is the simulation result, and the black line is the data provided by Mai et al. (2023). (c) Compared with the static horizontal displacement of GNSS. The black arrow is the observed value and the red arrow is the synthetic value.

The detailed investigation results of surface rupture have not been seen yet, hence the surface strike-slip is compared with the on-fault displacement measured by Mai et al. (2023) based on the satellite data (Liu et al., 2022a; 2022b; Figure 4b). We have captured the first-order characteristics of surface displacement. Notably, the surface displacement on the backward side of the fault intersection has changed suddenly because of the dynamic unclamping. We also calculate the static horizontal displacement based on the triangular elastic half-space dislocation model (Nikkhoo et al., 2015; Meade, 2007) and compare to the observations (Barbot et al., 2023; Figure 4c). The observational and synthetic displacements are a general match. Some differences in displacement magnitude may be due to the stronger spatial heterogeneity of the actual slip distribution, as well as the lack of consideration of complex medium models in the calculation of the synthesized displacement.

4 Discussions

4.1 Implications for seismogenic environment, process of EAF being triggered and earthquake disaster

Our dynamic model indicates a high initial stress level in the KC segment of the EAF. Actually, this segment has been identified as a seismic gap with Coulomb stress in an elevated state proposed by Sunbul (2019). Thus, the stress state is consistent with the current
seismogenic environment. This plays a crucial role in the triggering process of the EAF.

Because the angle between the NSF and the EAF is about 30°, if the direction of $S_H$ is close to the optimal stress orientation of one fault, it will be far from the optimal stress orientation of another fault in the range of N169°E-N203°E. In our model, the $S_H$ orientation of the fault junction is N184°E, closer to the optimal stress orientation of the EAF. Therefore, near the fault intersection, the slip rate on the NSF decreases and the dynamic stress decreases, which is not conducive to the rupture propagates to the EAF. However, because the stress in this segment of EAF is high enough, the rupture propagated to the EAF in the northeast of the fault intersection through dynamic triggering. Figure 5 and Movie S2 show the ratio of shear stress and normal stress during the triggering process. More importantly, the high initial stress also leads to the generation of supershear rupture in the northeast segment of the EAF (Figure 3b) and accumulated enough energy to make the rupture propagates backward (Figure 5f-h).

The 2023 Mw 7.8 Kahramanmaraş earthquake reminds us of the 2001 Kokoxili earthquake in China and the 2002 Denali earthquake in USA. These two events were also nucleated on secondary faults (Antolik et al., 2004; Eberhart-Phillips et al., 2003). After the rupture propagated to the main fault, a supershear rupture occurred, and the rupture length was also greater than 300km. The difference is that these two earthquakes were unilateral rupture. In addition, the change of rupture speed will produce high-frequency seismic radiation (Vallée et al., 2008), this may also be one of the reasons for the serious damage to Hatay province in southern Türkiye. Therefore, these earthquakes serve as a reminder to remain vigilant as major faults can be triggered by earthquakes nucleated on nearby
unrecognized small fault fragments, eventually evolving into giant earthquakes that cause significant damage. This is especially important when there are seismic gaps along the major fault.

Figure 5. The ratio of shear stress and normal stress during the triggering process. A ratio equal to $\mu_\sigma$ (0.4) indicates the position of the rupture front in the EAF. (a) Before the rupture front reaches the fault intersection. (b) The rupture front reaches the fault intersection. (c-d) The EAF is triggered, and the red boxes indicate the trigger location. (e) The rupture
propagates northeast and the stress ratio in the backward side is very low indicating it is
difficult to rupture. (f-h) Enough energy is accumulated, and the rupture begins to propagate
backward. The red boxes indicate that the rupture is beginning to propagate backward.

4.2 Open questions and future work

Previous studies have suggested that the EAF is an immature fault (Gallovič et al.,
2020; Melgar et al., 2020; Pousse-Beltran et al., 2020; Taymaz et al., 2021). However,
earthquake cycle research shows immature faults are more prone to moderate earthquakes
(Thakur & Huang, 2021), this is inconsistent with the situation of the 2023 Kahramanmaraş
earthquake. Therefore, does this earthquake manifest that the EAF is going to be mature? If
not, why does the rupture length of an immature fault reach 300 km? Thus, there remains
further research, such as radiation efficiency should be investigated in detail. Moreover, the
2023 Kahramanmaraş earthquake may be another example of transient supershear ruptures on
an immature strike-slip fault like the 2021 Madoi earthquake in China (Cheng et al., 2023).

We didn't consider the topography and the off-fault damage in the dynamic simulation,
which may also affect the results. For example, terrain fluctuation is not conducive to the
occurrence of free surface induced supershear rupture (Zhang et al., 2016). Off-fault
plasticity will also consume energy and influence the dynamic rupture process, necessitating
a higher initial stress (Gabriel et al., 2013). Future work should also consider the rate and
state friction law (Dieterich, 1994; Ruina, 1983), and discuss the impact of thermal
pressurization (Rempel & Rice, 2006; Wibberley & Shimamoto, 2005) or flash heating
(Goldsby & Tullis, 2011).
5 Conclusions

In this work, a data-constrained dynamic rupture model with a complex fault geometry of the 2023 Kahramanmaraş Mw 7.8 earthquake is established. The results show that high initial stress in the KC segment causes the EAF to be triggered. The transient supershear rupture occurs many times, and the change of fault geometry prevents the sustainability of the supershear rupture. Moreover, the triggering process of the NPF to the EAF reminds us that we should pay attention to the seismic activity of the secondary faults adjoining the major fault, and carefully study the risk of the main fault being triggered to prevent the severe casualties of this earthquake from repeating in the future.

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Open Research

The dynamic rupture software DRDG3D is available at https://github.com/wqseis/drdg3d (last accessed February 2022). The mapped surface rupture data are from https://doi.org/10.5066/P98517U2 (Reitman et al. 2023). The strong ground motion data are downloaded from the Disaster and Emergency Management Authority (AFAD, https://tadas.afad.gov.tr/event-detail/15499). The GNSS static horizontal displacement data are available in Table S1 of Barbot et al. (2023, https://zenodo.org/record/7879743).

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