Surface rupture during the 6th of February 2023 Mw 7.6 Elbistan-Ekinözü (Kahramanmaraş) earthquake: implications for fault rupture dynamics along the northern branch of East Anatolian Fault Zone

MUSTAFA SOFTA
mustafa.softa@deu.edu.tr

FİKRET KOÇBULUT
fbulut@cumhuriyet.edu.tr

ELİF AKGÜN
eliffiratliligil@gmail.com

ERCAN AKSOY
eaksoy@firat.edu.tr

HASAN SÖZBİLİR
hasan.sozbilir@deu.edu.tr

See next page for additional authors

Recommended Citation
SOFTA, MUSTAFA; KOÇBULUT, FİKRET; AKGÜN, ELİF; AKSOY, ERCAN; SÖZBİLİR, HASAN; TATAR, ORHAN; KARABACAK, VOLKAN; ÖZKAYMAK, ÇAĞLAR; UTKU, MEHMET; ÖZDAĞ, ÖZKAN CEVDET; ÇAKIR, RECEP; DEMİR, AHMET; and ARSLAN, GÖKHAN (2024) "Surface rupture during the 6th of February 2023 Mw 7.6 Elbistan-Ekinözü (Kahramanmaraş) earthquake: implications for fault rupture dynamics along the northern branch of East Anatolian Fault Zone," Turkish Journal of Earth Sciences: Vol. 33: No. 1, Article 2. https://doi.org/10.55730/1300-0985.1895
Available at: https://journals.tubitak.gov.tr/earth/vol33/iss1/2

This Article is brought to you for free and open access by TÜBİTAK Academic Journals. It has been accepted for inclusion in Turkish Journal of Earth Sciences by an authorized editor of TÜBİTAK Academic Journals. For more information, please contact academic.publications@tubitak.gov.tr.
Surface rupture during the 6th of February 2023 Mw 7.6 Elbistan-Ekinözü (Kahramanmaraş) earthquake: implications for fault rupture dynamics along the northern branch of East Anatolian Fault Zone

Authors
MUSTAFA SOFTA, FİKRET KOÇBULUT, ELİF AKGÜN, ERCAN AKSOY, HASAN SÖZBİLİR, ORHAN TATAR, VOLKAN KARABACAK, ÇAĞLAR ÖZKAYMAK, MEHMET UTKU, ÖZKAN CEVDET ÖZDAĞ, RECEP ÇAKIR, AHMET DEMİR, and GÖKHAN ARSLAN

This article is available in Turkish Journal of Earth Sciences: https://journals.tubitak.gov.tr/earth/vol33/iss1/2
Surface rupture during the 6th of February 2023 Mw 7.6 Elbistan-Ekinözü (Kahramanmaraş) earthquake: implications for fault rupture dynamics along the northern branch of East Anatolian Fault Zone

Mustafa SOFTA1,2,* , Fikret KOÇBUŁUT2, Elif AKGÜN4, Ercan AKSOY4, Hasan SÖZBİLİR1,2, Orhan TATAR3, Volkan KARABACAK4, Çağlar ÖZKAYMAK4, Mehmet UTKU2, Özkan Çevdet ÖZDAG2, Recep ÇAKIR8, Ahmet DEMİR3, Gökhan ARSLAN9

1. Department of Geological Engineering, Dokuz Eylül University, İzmir, Turkiye
2. Earthquake Research and Implementation Center of Dokuz Eylül University, İzmir, Turkiye
3. Department of Geological Engineering, Sivas Cumhuriyet University, Sivas, Turkiye
4. Department of Geological Engineering, Fırat University, Elazığ, Turkiye
5. Department of Geological Engineering, Eskişehir Osmangazi University, Eskişehir, Turkiye
6. Department of Geological Engineering, Afyon Kocatepe University, Afyonkarahisar, Turkiye
7. Department of Geophysical Engineering, Dokuz Eylül University, İzmir, Turkiye
8. Olympia, Washington State, Olympia, USA

Abstract: On the 6th of February 2023, Mw 7.7 Pazarcık (Kahramanmaraş) and Mw 7.6 Ekinözü (Kahramanmaraş) earthquakes that occurred in Türkiye are devastating earthquake series that filled the existing seismic gaps on East Anatolian Fault Zone on the same day. The first Mw 7.7 earthquake caught most people in their sleep and 9 h later, a second one was triggered, ending up with more than 50k death toll, widespread damage to buildings, and massive landslides. This study presents the surface rupture geometry and coseismic displacement characteristics determined with field observations immediately after February 6, 2023, Ekinözü (Kahramanmaraş, Türkiye) earthquake (Mw 7.6). Preliminary implications show that the total rupture length is 130 ± 10 km on the Çardak segment and Doğanşehir segment, known as the northern branch of the East Anatolian Fault Zone. Left lateral strike-slip faulting is developed with a maximum horizontal displacement of 6.60 m and an average displacement of 3.00 m. Furthermore, the pitches of slip lines ranging from 0° to 10° were measured on the neoformed fault planes. In addition to that, surface rupture exhibits restraining bends and releasing bends structure at small scales on the Çardak segment. From this point on, our preliminary results signify that Çardak and Doğanşehir segments were consecutively broken in Mw 7.6 Ekinözü (Kahramanmaraş, Türkiye) earthquake that traced between Göksun and Nurhak region and from there reached the Eskiköy regions. Furthermore, potential stress may be concentrated on not only the Sürgü segment which is on the transfer fault between the northern branch and the southern branch of East Anatolian Fault Zone but also the west of the Çardak segment and the northeast of the Doğanşehir segment near Yeşilyurt (Malatya).

Key words: East Anatolian Fault Zone, Ekinözü (Kahramanmaraş) earthquake, Çardak Segment, Doğanşehir segment, surface rupture

1. Introduction

Eastern Anatolia is an important region that exhibits the complex geometry of continental convergence. The convergence between the Arabian-African and Eurasian plates and the final amalgamation of Arabian-Anatolia have formed the tectonic framework of Eastern Anatolia (e.g., Şengör and Yilmaz, 1981; Şengör et al., 1985). This continental collision and the ongoing convergence led to compressional tectonic regimes such as thrust tectonics (e.g., Bitlis Suture Zone) and strike-slip tectonics in Eastern Anatolia (e.g., East Anatolian Fault Zone, Dead Sea Fault Zone), respectively. East Anatolian Fault Zone (EAFZ) is a prominent tectonic structure of the strike-slip tectonic regime in Eastern Anatolia. The EAFZ with a length of 580 km and NE-SW direction is a left lateral intracontinental fault zone consisting of parallel-subparallel fault segments (Şaroğlu et al., 1992; Herece, 2008; Duman and Emre, 2013; Emre et al., 2018). Numerous researchers (Arpat and Şaroğlu, 1972; 1975; Barka and Kadinsky-Cade, 1988; Herece, 2008; Duman and Emre, 2013) proposed

* Correspondence: mustafa.softa@deu.edu.tr
segmentation for the EAFZ that started at the Karlova triple joint based on the geomorphological characteristics of the strike-slip tectonic regime.

Duman and Emre (2013) divide the EAFZ into two strands, such as the northern and the main branches, based on detailed fault geometry and segment structure. EAFZ exhibits a broader deformation zone from the northern branch, which splays near Çelikhan (Figure 1). The northern branch, called the Sürgü–Misis fault system, is divided into two parts, east and west from the Göksun bend. The eastern part of the northern branch of EAFZ consists of the Sürgü and Çardak segments that display a complicated geometry with approximately E-W extending between Çelikhan and Göksun. Sürgü segment with a length of 64 km extends between Çelikhan (Adıyaman) and Nurhak (Kahramanmaraş). Çardak segment with a length of 85 km, which is the longest segment of the Sürgü-Misis fault system, runs through from the Nurhak (Kahramanmaraş) to the Göksun (Kahramanmaraş). The Sürgü and Çardak segments intersect with the NNE-SSW direction Malatya fault and Doğanşehir segments in the Nurhak mountains and form the Nurhak fault complex with restraining bends in this area (Duman and Emre, 2013).

Although EAFZ has many destructive earthquake records in the historical period, the EAFZ has been relatively quiet according to the North Anatolian Fault Zone (NAFZ) in the 20th century (e.g., Guidoboni et al., 1994; Ambraseys, 2009). The destructive earthquakes showed the recent activity at EAFZ in the instrumental period such as the 1971 and 2003 Bingöl earthquakes, 2010 Başyurt earthquake, and 2020 Sivrice-Doğanyol earthquake. The limited number of paleoseismological studies (Çetin et al., 2003; Karabacak et al., 2012; Yönlü et al., 2017; Duman et al., 2020; Balkaya, 2022; Balkaya et al., 2023) conducted in the EAFZ indicated which segments along the fault zone are seismic gaps. The Pazarcık segment of the main branch of the EAFZ, which was broken in the last 1513 earthquake and has been silent for about 500 years, is one of the most critical of these seismic gaps. The proposed location of Elbistan earthquakes between the 584–587 intervals (Guidoboni et al., 1994; Ambraseys, 2009) and the 1544 earthquake with M: 6.8 (Tan et al., 2008) in the historical period are close to Çardak and Sürgü segments (Duman and Emre, 2013). In the instrumental period, the M: 5.8 and M: 5.6 1986 Doğanşehir earthquakes have been recorded on the Sürgü segment with an interval of one month (Taymaz et al., 1991; Duman and Emre, 2013). While the activity of the northern branch is known seismically, seismic activity has shown that destructive earthquakes have generally developed on the main extent of the EAFZ. Duman and Emre (2013) have suggested that the eastern part of the northern and main branches

Figure 1. Tectonic scheme of eastern Türkiye. Segmentation of the East Anatolian Fault Zone and other major structural elements in the East Anatolia (Duman and Emre, 2013) with historical (Ambraseys, 1989; Ambraseys and Finkel, 1995; Ambraseys and Jackson, 1998; Tan et al., 2008;) and instrumental (AFAD⁺) earthquake locations on the East Anatolian Fault Zone.
(Pazarcık) of the EAFZ covers 1/3 of the slip partitioning and the recurrence interval as 800–1000 years (for M > 7.0) for the Sürgü and Cardak segments, depending on the earthquake activity at historical and instrumental period and annual slip rate (3 mm/yr).

The 2023 Mw 7.6 Ekinözü (Kahramanmaraş) earthquake occurred at 13:24 on 6 February 2023 Türkiye, with an epicenter located approximately 2.5 km north of the Ekinözü district and a hypocentral depth of approximately 7 km at the coordinates 38.089° N, 37.239° E (AFAD, 2023), resulted in a rupture approximately 130 km along the northern branch of EAFZ (Figure 2). Nearly exceeding 8k aftershocks moment magnitude up to 6.0 were flocculated on and around the northern branch of EAFZ within the first 21 days after the main shocks. These devastating earthquake series and extremely cold weather conditions resulted in heavily damaged or completely collapsed buildings, causing over 50k fatalities in eleven cities all located around the ruptured zone along the EAFZ. To collect and evaluate field data after the Mw 7.6 earthquake, we performed a field renaissance along the surface rupture in the first 10 days after the main shock. The geometry and surface rupture characteristics that correlated with orthophoto images were analyzed and rupture was drawn on the topographic maps with a scale of 1:25,000 immediately after the earthquake. This study gives preliminary field observations on the length of the surface rupture of the Ekinözü (Kahramanmaraş) earthquake (Mw:7.6) and its coseismic displacement characteristics.

2. Methodology
We have performed a field study and seismological evaluation after the earthquake series. The target sites for the field study were determined by Göktürk satellite images (using HGM Küre v4.2.98 software). Firstly, we...
have mapped the rupture on the printed topographic maps with a scale of 1/25k in the field. All the field data were digitized by ArcGIS 10.2 Pro software, GlobalMapper v18, and the surface rupture was then visualized on the DEM data obtained from digital elevation data at around 29 m ground pixel resolution (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (AsterG-DEM) V3-1 arc second resolution digital data). Most of the coseismic displacement measurements were collected in the field by tape measure, and all measurements by tape measure were supported by high-resolution maps of each location. Secondly, time series analyses related to the aftershocks and conducted in the present study are the behavior of aftershocks according to time, number of occurrences, both instantaneous and daily energy release, and the intensity-to-magnitude statistics were used by Gutenberg and Richter (1942; 1944).

3. Seismological characteristic
According to the location solution for the first main shock (Mainshock-1) that occurred on 2023/02/06 at 01:17:35 (UTC), the epicenter of this earthquake is located 26 km east of Nurdağ (Gaziantep) [(37.288°N, 37.043°E); AFAD\(^1\)]. According to this solution, the focal depth was estimated at 8.6 km and the magnitude as Mw7.7 (AFAD\(^1\); Karabacak et al. 2023; Mw7.8, USGS\(^2\)). This main shock followed a frequent aftershock activity, up to magnitude Mw6.6 (AFAD\(^1\) and, KOERI\(^3\); Mw6.7, USGS\(^2\)) in the following hours, and a second main shock (Mainshock-2) occurred on a different segment at 10:24:49 (UTC) on the same day. According to the location solution of Mainshock-2, the earthquake parameters are as follows: Epicenter, located at the 4 km SSE of Ekinözü (Kahramanmaraş) [(38.089°N, 37.288°E); AFAD\(^1\)] and its magnitude and focal depth are Mw7.6 (AFAD\(^1\)) and 7 km, respectively.

Both main shocks are within the deformation area of the EAFZ with these positions. In other words, it is a seismic activity produced by the southern segment of this zone. A total of 8321 events (0.8 < M < 7.8) occurred in 21 days from the first main shock. Two of these numbers are main shocks (Mainshock-1, Mainshock-2) and the remaining 8319 are aftershocks (0.8 < M < 6.7). Figure 3 shows the epicenter distribution of seismicity for the first 21 days of the seismic activity process beginning with Mainshock-1 and the fault plane solutions of characteristic events. The aftershocks used in this study are from the electronic earthquake catalog of Boğaziçi University Kandilli Observatory and Earthquake Research Institute (KOERI\(^3\)). Of the 8321 epicenters in Figure 3, 2 (M ≥ 7.0), 3 (6.0 < M < 7.0), 38 (5.0 < M < 6.0), 327 (4.0 < M < 5.0), and 1589 (3.0 < M < 4.0) are in the magnitude range, and the remaining 6362 events are (M < 3.0). As can be seen from Figure 3, the distribution of the epicenters is consistent with the location of the EAFZ and its southward continuation, the Dead Sea Fault. 4505 (±100) of the aftershocks probably belong to Mainshock-2. This conviction is derived from the visual examination of the distribution of epicenters on a large scale.

The W-phase Moment Tensor solution made by the AFAD\(^1\) and USGS\(^2\) for Mainshock-1 is given in Figure 3. The node planes of the fault diagram in Figure 3 has been estimated as (NP1: f = 233°, d = 74°, l = 18°; NP2: f = 140°, d = 77°, l = 168°; AFAD\(^1\); NP1: f = 318°, d = 89°, l = −179°; NP2: f = 228°, d = 89°, l = −1°; USGS\(^2\)). f, d, and l are the strike, dip, and rake parameters of the planes, respectively. From this solution, it is clear that the Mainshock-1 is the product of a characteristic strike-slip faulting mechanism. Therefore, from Mainshock-1’s epicenter location, aftershock sequences, and field observations, it appears that the fault plane in this moment of the tensor solution is the NE-SW directional nodal plane (NP2). In the moment tensor inversion was performed, the Double-Couple (DC) percentage ratio was calculated as 81%. The scalar seismic moment (Mo) is 5.39E+20 N-m.

According to the finite fault solution, the rupture caused by Mainshock-1 is 87 s (Finite Fault Solution; USGS\(^2\), 2023/02/13). Both 1D and 3D slab geometry are used in these solutions. Figure 4 shows the source time function of Mainshock-1 and -2. Looking at Figure 4, there are 3 ruptures that follow each other. Accordingly, the second rupture occurred after approximately the first 38th second, and the third rupture occurred after the 68th second. The maximum relative moment rate is 2.21E+19 N-m/s. Figure 5 shows the slip distribution sections during rupturing that occurred with Mainshock-1 and -2. Figure 5a, due to the variety of iterations in an inversion procedure, indicates slip distribution with respect to two consecutive planes, the orientation parameters were estimated as (f = 52°, d = 80°; f = 52°, d = 80°; USGS\(^2\)). As can be seen from Figure 5a, the maximum displacement took place between 10 and 50 s after the origin time of the earthquake, from 25 km to 125 km from the epicenter to SW, between 1 and 3.5 m. This is the slip variation from the levels near the earth’s surface to a depth of 30 km. After that, between 10 and 30 s, there is a slip toward NE reaching a maximum of 1.5 m (Figure 5a). From this, it is understood that the northward rupture occurs less. Likewise, in the plane with approximately N-S direction (f = 2°), between 50 and 70 s, the rupturing in the crust is around 80–120 cm (Figure 5a).

The node planes of the faulting mechanism diagram of Mainshock-2 in Figure 3 has been estimated as (NP1: $f_1 = 358^\circ$, $d_1 = 73^\circ$, $l_1 = 174^\circ$; NP2: $f_2 = 90^\circ$, $d_2 = 86^\circ$, $l_2 = 13^\circ$; AFAD); NP1: $f_1 = 276^\circ$, $d_1 = 82^\circ$, $l_1 = -6^\circ$; NP2: $f_2 = 6^\circ$, $d_2 = 85^\circ$, $l_2 = -172^\circ$; USGS) with respect to the Bodywave Moment Tensor solution (Mwb). In this solution, the DC percentage is calculated as 87%, and magnitude Mwb 7.53, depth 19 km, and seismic moment $2.47 \times 10^{20}$ N·m. From the epicenter location, aftershock sequences, and field observations of Mainshock-2, it appears that the fault plane in this moment of the tensor solution is the E-W oriented nodal plane (NP1).

The relative moment rate function, estimated from the finite fault solution of this earthquake, is given in Figure 4b. In this solution, the orientation plane of the W-phase Moment Tensor (Mww) solution ($f = 276^\circ$, $d = 82^\circ$, USGS) was used. From Figure 4b, it appears that Mainshock-2 lasts around 24 s. The maximum relative moment rate in this sequence is $3.0 \times 10^{19}$ N·m/s. The slip distribution cross-section from this solution is exhibited in Figure 4b.
Figure 4. Source time functions for the Nurdağı (Gaziantep) [2023/02/06 01:17:32(UTC) Mw7.7] (a), and the Ekinözü (Kahramanmaraş) [2023/02/06 10:24:47(UTC) Mw7.6] (b) main shocks (AFAD$^1$ and USGS$^2$). The red dashed line represents the interpreted end of the event.

Figure 5. Cross-sections of slip distribution estimated by finite-fault solution (USGS$^2$). (a) for the Nurdağı (Gaziantep) [2023/02/06 01:17:32(UTC) Mw7.7], (b) for the Ekinözü (Kahramanmaraş) [2023/02/06 10:24:47(UTC) Mw7.6] main shocks. The strike direction is indicated above each fault plane and the hypocenter location is denoted by a star. Slip amplitude is shown in color and the motion direction of the hanging wall relative to the footwall (rake angle) is indicated by arrows. Contours show the rupture initiation time in seconds.
As can be seen from Figure 4b, all the rupture took place in the first 20 km radius around the hypocenter. This is a displacement in the direction of about E-W, within the first 10 s and reaching a maximum of 11 m. Thus, it is just a bilateral rupture.

This seismic activity is referred to as the process of the Kahramanmaraş earthquakes in the Turkish public. In the following sections of this article, this nomenclature will be used when talking about the whole of this seismic activity.

On the 15th day of the Kahramanmaraş earthquakes process, another strong earthquake took place [2023/02/20 17:04:27-29(UTC), Mw6.4, AFAD1; Mw6.3, USGS2]. According to the location solution, the epicenter of this earthquake is [(36.037°N, 36.021°E); AFAD1]. This location corresponds to the 3 km SSW of Yağladağ (Hatay). In this solution, the depth is estimated at 21.7 km. According to the Body-wave Moment Tensor solution, the node planes are (NP1: f1 = 214°, d1 = 57°, l1 = –44°; NP2: f2 = 332°, d2 = 55°, l2 = –138°; AFAD1; NP1: f1 = 226°, d1 = 46°, l1 = –22°; NP2: f2 = 332°, d2 = 74°, l2 = –134°; USGS2) (Figure 3). According to this solution, the focal depth is 12 km, the DC percentage is 96% and the seismic moment is 2.8E+18 N-m.

In the area of deformation in which the process of Kahramanmaraş earthquakes was effective, which is the geography bounded by the coordinates (39.70°–39.50°N)–(39.30°–42.20°E), magnitude-frequency equation based on earthquakes 35774 (1.0 ≤ M ≤ 7.8) occurring in the period 1900-2023 is estimated as:

\[ \log N = 3.8535 - 0.7638 M, r = -0.9954 \]  

In Eq. (1), N indicates the number of earthquakes, M the magnitudes, and r the correlation coefficient. The mathematical form of Eq. (1) was first proposed by Gutenberg & Richter (1944, 1942). The completeness magnitude (Mc) is calculated as 2.1. Figure 6 shows the magnitude-frequency change of the deformation zone prior to the process 2023/02/06 01:17:35 (UTC). As seen from Figure 6, the projection of the change points to a major earthquake in the future. As can be seen from Eq. (1), the deformation area is an area with a high earthquake risk and with a moderate level of seismic activity. In other words, the process of the Kahramanmaraş earthquakes is an intermediate result of this equation.

A time series analysis of 21 days of seismic activity is given in Figure 7. The days in Figure 7 are the 24-h time periods from 2023/02/06 01:17:35(UTC), the origin time of the Mainshock-1. Figure 7a shows the change in the number of daily aftershocks over time. As can be seen from Figure 7a, the aftershock activity in the first 21 days occurs with a low-slope decreasing function behavior. In other words, there is a decline in activity, but it is both high-level and low-slope (slow). This means that the aftershock activity will last a very long time, which can be around 3 years at least. The regression curve in Figure 7 is the mathematical expression of this change. Due to the purpose of use in this study, it does not matter if the calculated correlation coefficient (r = 0.5) has a low value. These calculations of earthquake statistics are based on 21 days of data. In terms of the seismic character of a region or the behavioral character of an earthquake process, this period is very short. However, it sends the following
An important message: in the first 21 days, there is a high seismic energy release. This is in line with the character of a strike-slip faulting system. Despite this, it is also seen from Figures 7b–7d that there is a gradual decrease in seismic energy release.

Figure 7b reveals the change in the seismicity rate with respect to the days, Figure 7c the change in the daily energy rate, and Figure 7d the change in the seismic energy ratio with respect to the moment of each earthquake. As can be seen from Figure 7b, an average of 17.24 earthquakes occurs per hour on the first day, while this value decreases to 0.66 on the 21st day. A regular and obvious reduction prevails over this figure (Figure 7b). The change in Figure 7b means the seismicity velocity of the Kahramanmaraş earthquakes process. Figure 7c gives the amount of seismic energy released in 1 hour for each day. The reduction in the change in Figure 7c is also very uniform and very pronounced. In these calculations, the empirical relations of Gutenberg & Richter (1956) were used. Accordingly, on the first day, an average of 1.13E+23 erg seismic energy is released in 1 hour, while on the 21st day, this value decreases to 5.44E+21 erg. In Figure 7d, there is a cumulative seismic energy velocity at the time each earthquake occurs after Mainshock-1. This value increases from 3.23E+20 erg/hour in the 1st aftershock to the maximum value of 2.97E+23 erg/hour during the third aftershock and decreases to 5.44E+21 erg/hour in the 8320th earthquake. The value in the 8320th event is equal to and means the average per hour of the last day in Figure 7c. Also, there is a characteristic peak in Figure 7d. This is the instantaneous seismic energy that rises to 2.95E+23 erg/hour in the 160th earthquake. This energy is so evident because it is generated by Mainshock-2. Mainshock-2 occurred 9 h 7 s after Mainshock-1.

4. Characteristics of surface ruptures
According to the preliminary analysis of the field survey and its correlation with orthophoto as well as seismic distribution of the main shock and aftershock, the surface rupture of the Mw 7.6 Ekinözü earthquake was determined to have two parts, namely, Çardak segment and Doğanşehir segment. Çardak segment was broken.
into a discontinuous zone of approximately 100 km long, it extends along the southwestern of Göksun region to Fındıkköy village (Figure 8a) with N40E trending, the southeastern Çardak region to Hacılar village (Figure 8b) with an E-W trending, and from south of Karadut village to the southern Bıçakçı village (Figures 9a and 9b) with an N60W trending. The rupture does not exhibit clear evidence in some specific locations due to the winter seasonal effect, lithology effect, and possibly disseminating the offset along the splay fault when it encountered the fault zone; therefore, we mapped it as probable in these sections. Similarly, the Doğanşehir segment having the ruptured zone was interruptedly mapped approximately 30 km long, it extends along the east of Söğüt village to the west of Eskiköy village (Figure 10) with an N30E trending. The coseismic surface rupture is mainly characterized as en-echelon tensional cracks, pressure ridges, pull-apart, shear cracks, and seismogravitational deformations.

4.1. Çardak segment
N40E trending of the coseismic surface rupture is quite distinct on the orthophoto and can be recognized with the naked eye near Göksun region to Fındık village. It developed between the contact of pre-Miocene basement rock and Quaternary alluvium. This part extends continuously for approximately 25 km starting from the south of Fındıklı village (Figure 11). It is single-stranded and shows the pure left lateral offset ranging from 1.10 m to 3.55 m, which is clearly visible on road and field borders. No vertical displacement is observed here (Table 1).

Further northeast, it can be laterally visible in the south of Çardak region (Figure 12) to Hacılar village (Figure 13) with ~E-W trending approximately 15 km long.

Figure 8. Surface rupture geometry of the Elbistan (Kahramanmaraş) Earthquake along the Çardak segment of the EAFZ and slip distribution locations. a. Göksun subsegment, b. Hacılar subsegment.
Moreover, it passes Hacılar village, which has a maximum sinistral offset on the tree lines and field border yield of 6.60 m (Figure 13c), with E-W and WNW-ESE direction towards the south of Karadut village to north and south where it steps over left and right, respectively. The rupture here shows a compressional ridge with an NW direction at a small scale. Then, it follows the N60W direction interruptedly for approximately 60 km long towards the south of Bıçakçı village passing through Kandil Dam (Figure 14), Gözpınar, Barış (Figure 15), and Kullar (Figure 16) villages. While the horizontal displacements range from 2 m to 6.6 m, the vertical displacements are up to 3 m at the specific three locations (Table 1). Further, the rupture formed fresh fault planes and the pitches of slip lines ranging from 0° to 10° were measured on the road where it left lateral displaced in between Kandil and

Figure 9. Surface rupture geometry of the Elbistan (Kahramanmaras) Earthquake along the Çardak segment of the EAFZ and slip distribution locations. a. Ekinözü subsegment, b. Nurhak subsegment.
Kandilköy villages and towards the northwest (Figures 14f–14i). Except for seismogravitational deformation such as huge landslides, rockfall, and lateral spreading, no surface rupture was traced between the eastern of Barış village and Kullar village, where the fault splayed.

4.2. Doğanşehir segment

N30E trending of the rupture here is interruptedly mapped approximately 30 km long starting from the northeast of Bıçakçı village towards the western of Eskiköy village. Passing the northeast of Bıçakçı village, it exhibits releasing bends structure and vertical displacement up to 0.80 m and the width of the ruptured zone reaches at least 15 m (Table 1). Further northeast, the rupture passes the east of Söğüt village through Topraktepe, Çığlık, and Kelhalil villages in the NE direction (Figure 17). According to the field studies, the rupture cannot be traced not only between the northeast of Bıçakçı village and Söğüt village but also further the northeastern of Eskiköy village. The maximum sinistral offset was measured as 1.65 m in the

Figure 10. Surface rupture geometry of the Elbistan (Kahramanmaraş) Earthquake along the Doğanşehir segment of the EAFZ and slip distribution locations. (a) 1.10 m left lateral displacement on the field border around the Kelhalil settlement (location 2), (b-c) surface rupture tracks on the field.
Figure 11. Displacements on the satellite images at the west end of the Çardak segment (a) 1.95 m left lateral offset on the road at the eastern of the Göksun (location 37), (b) 1.15 m left lateral displacement on the tree lines around the south of the Kaleköy (location 36), (c and d) 2.30 m and 2.60 m left lateral displacements on the road and canal, respectively. See Figure 8a for the locations of the rupture.
riverbed, as well as the same offsets, visible road, and field border. Further northeast, the rupture having horse tail splay geometry near northeast of the Kelhalil village, offset ends by decreasing (see Figure 10). Moreover, vertical displacements are up to 2 m at the north of the Doğanşehir region. Even though the rupture cannot be mapped further northeast of Eskiköy village, tectonic morphology and seismic distribution allows the fault to extend to reach the Yeşilyurt (Malatya) region.

5. Discussion

5.1. Slip distributions
Our field data and slip distribution in seismological analysis indicate that the surface rupture for Mw 7.6 Ekinözü (Kahramanmaraş) earthquake was formed passing the Gökşun village through the western of Eskiköy village with a range of 130 km long along the Çardak segment and Doğanşehir segment. Obtained from field data and orthophotos offset distribution signifies that

Figure 12. (a) View of the newly formed pressure ridge as a result of the surface fracture stepping to the right around the Çardak (see the location on Figure 8b), (b) sketch drawing, (c and d) surface rupture on the field.
while displacements gradually decrease at the end of the segments, the maximum displacement is observed at the center of the segments which ultimately points to the differential displacements along the northern branch of EAFZ. According to the offset distribution, the maximum left lateral displacement was measured as 6.60 m along the Çardak segment at the Hacılar village while the displacements vary from 1.1 m to 3.55 m between Göksun and Çardak regions, and ranges from 2.0 m to 5.75 m between Çardak and Nurhak regions. Moreover, the maximum left lateral displacement was calculated as 3.10 m along the Doğanşehir segment at the Topraktepe village, while the displacements vary from 0.75 m to 1.65 m around the Doğanşehir region (Figure 18).

Following the main shock of the Mw 7.6 Ekinözü earthquake, the aftershocks reaching Mw 6.0 are mainly

Figure 13. View of the surface rupture (a) and displacement (b) on the satellite images around the Hacılar settlement (c) 6.60 m left lateral displacement on the tree lines around the Hacılar, (d) surface rupture on the field, (e) vast surface rupture on the ridge and 2 m left lateral displacement on the stream and (f) lateral spreading on the road around the south of Ericek (see the location on Figure 8b).
Figure 14. (a and b) View of the surface rupture and displacements on the satellite images around the Kandilköy settlement (c) surface rupture trace on the field (d) lateral spreading on the road (e) 2.63 m left lateral displacement on the stabilized road, (f) newly formed fault slip data on the mud-sand materials with E-W/65° N, 6° W SI (sinistral inverse), (g and h) vast surface rupture on the ridge and neoformed fault planes dipping south and north (i) (see the location on Figure 8b).
flocculated on the southeast of Göksun and northeast of Doğanşehir regions. From this point on, relatively lower displacements observed at these localities are consistent with the seismological data. Besides, the maximum displacement and the possible fault rupture length can be computed on the revealed moment magnitude of the earthquake as described by Wells and Coppersmith (1994). According to the equations of Wells and Coppersmith (1994), regression of surface rupture length (Eq. 2) and regression of maximum displacement (Eq. 3) can be expressed as in the following equations:

\[
\log(\text{SRL}) = -3.55 + 0.74M, \quad (2)
\]

\[
\log(\text{MD}) = -7.03 + 1.03M, \quad (3)
\]

where M is the moment magnitude, SRL is the fault rupture length, MD is the maximum displacement. Based on Eq. (2) and Eq. (3), the estimated possible surface displacement and fault rupture length can be calculated.

Figure 15. (a and b) View of the surface rupture and displacements on the satellite images around the Barış settlement, (c) surface rupture trace on the field (d) 5.75 m left lateral displacement on the field border, 4.70 m (e) and 3.76 m (f) left lateral offsets on the fences (see the location on Figure 9a).
rupture length is 120 km, and the maximum displacement is 6.5 m. Although these estimations are computed based on empirical equations, the values are consistent with the measured field data.

Although limited paleoseismological studies were conducted on Çardak and Sürgü segments (Balkaya, 2022), no paleoseismological studies have been conducted on the Doğanşehir segment. According to Balkaya (2022) and Balkaya et al (2023) at least two surface rupturing events have been determined during the Holocene time interval and it obviously signifies that the Çardak and Sürgü segments show Holocene activities, albeit the results of the dating studies have not been national or internationally published. Lastly, considering the Çardak and Doğanşehir
Figure 17. (a and b) view of the en-echelon surface rupture and tension cracks on the field around the Kelhalil settlement and sketch drawing, (c) 3.10 m left lateral displacement on the stream, and (d) 1 m vertical displacement on the field around the north of Doğanşehir (see the location on Figure 10).

Figure 18. Distributions of left-lateral displacement along the surface rupture of the Elbistan (Kahramanmaras) Earthquake.
Table 1. Surface rupture characteristics of the Ekinözü Earthquake (from northeast to southwest). While field data represents highest reliability rank level (A), orthophoto data signifies high reliability level (B).

<table>
<thead>
<tr>
<th>Location</th>
<th>Coordinates (UTM)</th>
<th>Displacements (m)</th>
<th>Rupture zone (m)</th>
<th>Offset structure</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Easting</td>
<td>Northing</td>
<td>Horizontal</td>
<td>Vertical</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>408649</td>
<td>4222130</td>
<td>0.95 ± 0.20</td>
<td>0 ± -</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>406980</td>
<td>4221110</td>
<td>1.10 ± 0.20</td>
<td>? ± -</td>
<td>?</td>
</tr>
<tr>
<td>3</td>
<td>403779</td>
<td>4218904</td>
<td>1.03 ± 0.20</td>
<td>0 ± -</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>402941</td>
<td>4218532</td>
<td>1.60 ± 0.20</td>
<td>0 ± -</td>
<td>Railroad</td>
</tr>
<tr>
<td>5</td>
<td>401352</td>
<td>4217767</td>
<td>3.10 ± 0.20</td>
<td>2.00 ± 0.05</td>
<td>Stream+road</td>
</tr>
<tr>
<td>6</td>
<td>400312</td>
<td>4217153</td>
<td>1.20 ± 0.20</td>
<td>0.15 ± 0.05</td>
<td>Road</td>
</tr>
<tr>
<td>7</td>
<td>395759</td>
<td>4214331</td>
<td>0.75 ± 0.20</td>
<td>1.50 ± 0.05</td>
<td>Field</td>
</tr>
<tr>
<td>8A</td>
<td>380847</td>
<td>4205639</td>
<td>1.65 ± 0.20</td>
<td>? ± -</td>
<td>15</td>
</tr>
<tr>
<td>8B</td>
<td>380847</td>
<td>4205639</td>
<td>- ± -</td>
<td>0.80 ± 0.05</td>
<td>Field</td>
</tr>
<tr>
<td>9</td>
<td>373861</td>
<td>4203966</td>
<td>2.00 ± 0.20</td>
<td>2.00 ± 0.05</td>
<td>Road+canal</td>
</tr>
<tr>
<td>10</td>
<td>356526</td>
<td>4207555</td>
<td>3.50 ± 0.20</td>
<td>? ± -</td>
<td>2 Field border</td>
</tr>
<tr>
<td>11</td>
<td>356302</td>
<td>4206879</td>
<td>3.60 ± 0.20</td>
<td>0 ± -</td>
<td>2 Field border</td>
</tr>
<tr>
<td>12</td>
<td>355985</td>
<td>4206955</td>
<td>4.70 ± 0.20</td>
<td>? ± -</td>
<td>6 Field</td>
</tr>
<tr>
<td>13</td>
<td>355438</td>
<td>4207125</td>
<td>4.60 ± 0.20</td>
<td>? ± -</td>
<td>5.5 Field</td>
</tr>
<tr>
<td>14</td>
<td>354628</td>
<td>4207331</td>
<td>5.40 ± 0.20</td>
<td>? ± -</td>
<td>5 Field border</td>
</tr>
<tr>
<td>15</td>
<td>353852</td>
<td>4207533</td>
<td>3.50 ± 0.20</td>
<td>? ± -</td>
<td>3 Field border</td>
</tr>
<tr>
<td>16</td>
<td>352045</td>
<td>4208239</td>
<td>3.90 ± 0.20</td>
<td>? ± -</td>
<td>5 Field border</td>
</tr>
<tr>
<td>17</td>
<td>350875</td>
<td>4208459</td>
<td>3.40 ± 0.20</td>
<td>? ± -</td>
<td>4 Field border</td>
</tr>
<tr>
<td>18</td>
<td>350340</td>
<td>4208496</td>
<td>3.30 ± 0.20</td>
<td>? ± -</td>
<td>3 Field border</td>
</tr>
<tr>
<td>19</td>
<td>348017</td>
<td>4208937</td>
<td>5.75 ± 0.20</td>
<td>0 ± -</td>
<td>Field border</td>
</tr>
<tr>
<td>20</td>
<td>347855</td>
<td>4208991</td>
<td>4.60 ± 0.20</td>
<td>? ± -</td>
<td>4 Field border</td>
</tr>
<tr>
<td>21</td>
<td>347511</td>
<td>4209051</td>
<td>4.10 ± 0.20</td>
<td>0 ± -</td>
<td>4 Field border</td>
</tr>
<tr>
<td>22A</td>
<td>346878</td>
<td>4209159</td>
<td>4.40 ± 0.20</td>
<td>? ± -</td>
<td>4 Tree line</td>
</tr>
<tr>
<td>22B</td>
<td>346878</td>
<td>4209159</td>
<td>4.70 ± 0.20</td>
<td>0 ± -</td>
<td>4 Fence</td>
</tr>
<tr>
<td>23</td>
<td>339344</td>
<td>4210696</td>
<td>5.90 ± 0.20</td>
<td>? ± -</td>
<td>3 Field border</td>
</tr>
<tr>
<td>24</td>
<td>338352</td>
<td>4210944</td>
<td>5.00 ± 0.20</td>
<td>? ± -</td>
<td>3 Road</td>
</tr>
<tr>
<td>25</td>
<td>337977</td>
<td>4211033</td>
<td>4.95 ± 0.20</td>
<td>? ± -</td>
<td>3 Road</td>
</tr>
<tr>
<td>26</td>
<td>328063</td>
<td>4213545</td>
<td>2.63 ± 0.20</td>
<td>? ± -</td>
<td>Road</td>
</tr>
<tr>
<td>27</td>
<td>326061</td>
<td>4213983</td>
<td>6.30 ± 0.20</td>
<td>2.50 ± 0.05</td>
<td>Stream+road</td>
</tr>
<tr>
<td>28</td>
<td>325030</td>
<td>4214200</td>
<td>- ± -</td>
<td>3.00 ± 0.05</td>
<td>Fault plane</td>
</tr>
<tr>
<td>29</td>
<td>318343</td>
<td>4215810</td>
<td>6.60 ± 0.20</td>
<td>? ± -</td>
<td>Field border+tree line</td>
</tr>
<tr>
<td>30</td>
<td>313673</td>
<td>4216092</td>
<td>2.03 ± 0.20</td>
<td>- ± -</td>
<td>Stream</td>
</tr>
<tr>
<td>31</td>
<td>312225</td>
<td>4216194</td>
<td>3.45 ± 0.20</td>
<td>? ± -</td>
<td>1.5 Road</td>
</tr>
<tr>
<td>32</td>
<td>297104</td>
<td>4214737</td>
<td>3.20 ± 0.20</td>
<td>? ± -</td>
<td>4 Tree line+field border</td>
</tr>
<tr>
<td>33</td>
<td>292587</td>
<td>4213003</td>
<td>3.55 ± 0.20</td>
<td>? ± -</td>
<td>1.5 Road</td>
</tr>
<tr>
<td>34</td>
<td>292518</td>
<td>4212962</td>
<td>3.30 ± 0.20</td>
<td>? ± -</td>
<td>? Road</td>
</tr>
<tr>
<td>35</td>
<td>292425</td>
<td>4212922</td>
<td>1.10 ± 0.20</td>
<td>? ± -</td>
<td>1.5 Field border</td>
</tr>
<tr>
<td>36</td>
<td>292206</td>
<td>4212901</td>
<td>2.60 ± 0.20</td>
<td>1.40 ± 0.05</td>
<td>2 Road</td>
</tr>
<tr>
<td>37</td>
<td>292176</td>
<td>4212887</td>
<td>2.30 ± 0.20</td>
<td>1.40 ± 0.05</td>
<td>1 Road+canal</td>
</tr>
<tr>
<td>38</td>
<td>286160</td>
<td>4210245</td>
<td>1.15 ± 0.20</td>
<td>? ± -</td>
<td>2 Tree line</td>
</tr>
</tbody>
</table>
segments ruptured in the Mw 7.6 Ekinözü earthquake, the moment magnitude of this earthquake is not expected to be equal or higher throughout these segments, whereas Sürgü segment, west of the Çardak segment, and northeast of Doğanşehir segment near Yeşilyurt (Malatya) are under stress.

5.2. Moment tensor
The fault mechanism diagram for Mainshock-1, estimated according to the Centroid Moment Tensor solution made by the USGS\(^2\) and AFAD\(^1\), shows the orientation parameters (NP1: \(f_1 = 234^\circ, d_1 = 79^\circ, l_1 = 14^\circ\); NP2: \(f_2 = 142^\circ, d_2 = 76^\circ, l_2 = 169^\circ\)). Since the DC percentage of this solution is 76%, the W-phase Moment Tensor solution was preferred for this earthquake. For the Mainshock-2, both Body-wave and W-phase Moment Tensor solutions were made by USGS\(^2\) and AFAD\(^1\). Fault orientation parameters according to Mww are (NP1: \(f_1 = 277^\circ, d_1 = 78^\circ, l_1 = 4^\circ\); NP2: \(f_2 = 186^\circ, d_2 = 87^\circ, l_2 = 168^\circ\)). In this solution, the depth is 13.5 km. The percentage of DC estimated in the W-phase solution is 34%. The low value of this value is the reason why the Mwb solution is preferred. [2023/02/20 17:04:29(UTC), Mw6.3] earthquake also has Regional Moment Tensor and W-phase Moment Tensor solutions (USGS\(^2\)). Their DC percentages are 57% and 34%, respectively. Although the predicted fault plane solutions appear to be similar in form to Mwb, the contribution of the normal faulting component in Mwb is higher. With this feature, there is a high probability that there will be an earthquake further south, triggered by Mainshock-1 in particular. Although the magnitude (Mw) reaches up to 6.3 (Mwb6.23, Mwr6.25, Mww6.34; USGS\(^2\)) in the 3 solutions (Mwb, Mwr, Mww) for this earthquake, this magnitude was documented as Mw6.4 in AFAD\(^1\) solutions.

All in all, the slip estimations are still in progress and in order to provide reliable data for all kinds of modeling outputs, it is highly recommended that such studies should be synchronous in comparison with the robust field studies.

6. Conclusion
1. The mapped surface rupture of February 6, 2023, Mw 7.6 Ekinözü (Kahramanmaraş) earthquake is 130 ± 10 km.
2. The surface rupture for the Çardak segment while extending to the Nurhak region in the NW direction and terminating near the Kapıdere village, for the Doğanşehir segment passes the Doğanşehir region in the NE direction and terminated near the Eskiköy village.
3. The maximum left-lateral displacement is measured on the Çardak segment as 6.60 m while it is determined as 3.10 m for the Doğanşehir segment, which signifies that our results observed from the field are in concordance with the seismological data.

Acknowledgments
This research is supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK), 1002C-Natural Disasters Focused Fieldwork Emergency Support Program. The authors would particularly like to thank the Disaster and Emergency Management Authority of Türkiye (AFAD) and TÜBİTAK for kindly allowing their indispensable support in the field studies during this stressful period. The author also thanks the General Directorate of Mapping of Türkiye (GDM) for providing high-quality orthophoto images to scientists immediately after the earthquakes. More so, special thanks must go to Mustafa Yücel who is the director of the Çelikhan teachers’ lodges at the Ministry of National Education of Türkiye, Çelikhan- Adıyaman for accommodation even if it reached full capacity during this period. Lastly, the authors would like to thank the editors and three anonymous reviewers for their great improvements on the paper.

Table 1. (Continued)

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>285772</td>
<td>4210077</td>
<td>1.95</td>
<td>±</td>
<td>0.20</td>
<td>?</td>
<td>±</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>284331</td>
<td>4209632</td>
<td>1.90</td>
<td>±</td>
<td>0.20</td>
<td>?</td>
<td>±</td>
<td>-</td>
</tr>
<tr>
<td>41</td>
<td>282440</td>
<td>4209216</td>
<td>1.20</td>
<td>±</td>
<td>0.20</td>
<td>?</td>
<td>±</td>
<td>-</td>
</tr>
</tbody>
</table>
References


