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GEOPHYSICS

Regional Displacement in Malatya and Adjacent Regions (Eastern Anatolia) Induced by the February 6, 2023 Kahramanmaraş Earthquakes (Mw 7.7, Mw 7.6)

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ABSTRACT

On February 6, 2023, two major earthquakes (Mw 7.7 and Mw 7.6) struck Kahramanmaraş, significantly affecting Eastern Anatolia. The tectonic structure of Malatya and its surroundings, including the East Anatolian Fault Zone (EAFZ) and the Malatya Fault, plays a crucial role in the region's seismicity. Following the Kahramanmaraş earthquakes, two moderate earthquakes (Mw 5.3 and Mw 5.0) occurred in Malatya in August 2023, causing panic among the locals. GNSS data from Continuously Operating Reference Stations-Turkey (CORS-TR) were analyzed in this study to investigate the tectonic activity in and around Malatya and assess how the stress accumulated after the February 2023 earthquakes may have influenced this region. Firstly, the displacements in Eastern Anatolia between January 1 and March 1, 2023, were calculated to evaluate the immediate effects of the February 6 earthquakes. Then, GNSS data from March 2 to December 31, 2023, were processed to examine the ongoing tectonic behavior. Additionally, seismic activity during the same period was analyzed, revealing the occurrence of several moderate earthquakes potentially linked to the February 6, 2023 Kahramanmaraş earthquakes. The GNSS results indicate that most stations show continued tectonic motion, suggesting that stress changes induced by the Kahramanmaraş earthquakes still influence the region. Furthermore, the lack of stabilization at the stations highlights the persistence of postseismic deformation. The spatial correlation between observed seismicity and displacement vectors emphasizes that the Malatya segment of the EAFZ remains a significant zone of strain accumulation and release. Stations such as MLY1 (Malatya), APK1 (Arapgir, Malatya), and ADY1 (Adıyaman) continued to move in the same direction observed during the mainshock, pointing to ongoing afterslip. Moreover, stations farther from the rupture zone (e.g., SUF1 (Sanlıurfa), HAT2 (Hatay), GURU (Gürün, Sivas)) exhibited consistent displacement patterns, indicating that postseismic deformation extended across a broad area, including the Arabian Plate and the back-arc region north of the fault. These findings underline the long-term impact of the February 6, 2023, earthquakes on regional seismic activity and demonstrate the importance of integrating geodetic and seismic data for ongoing hazard assessment in Eastern Anatolia.

Keywords: Malatya, Eastern Anatolia Fault zone, earthquake, GNSS, seismicity, deformation.

Desplazamiento regional en Malatya y alrededores (este de Anatolia) provocado por los terremotos de Kahramanmaraş del 6 de febrero de 2023 (Mw 7,7, Mw 7,6)

RESUMEN

El 6 de febrero de 2023, dos terremotos (Mw 7.7 and Mw 7.6) ocurrieron en Kahramanmaraş, y causaron afectaciones en el este de Anatolia (Turquía). La estructura tectónica de Malatya y sus alrededores, incluidas la Zona de Fallas de Anatolia y la falla de Malatya, juega un papel crucial en la seismicidad de la región. Despues de los terremotos en Kahramanmaraş, dos terremotos moderados (Mw 5.3 and Mw 5.0) en Malatya en agosto de 2023, y causaron pánico entre los habitantes. En este estudio se analiza la información GNSS de las estaciones de referencia de operacion continua de Turquía (CORS-TR) para investigar la actividad tectónica en y alrededor de Malatya y evaluar cómo el estrés acumulado después de los terremotos de febrero de 2023 pueden haber influenciado en la región. Inicialmente se calcularon los desplazamientos en el este de Anatolia entre el primero de enero y el primero de marzo de 2023 para evaluar los efectos inmediatos de los terremotos del 6 de febrero. Luego se procesó la información GNSS del dos de marzo hasta el 31 de diciembre de 2023 para examinar el comportamiento tectónico del período. Adicionalmente, se analizó la actividad sísmica en el mismo período, lo que revela la ocurrencia de varios terremotos moderados potencialmente relacionados con los terremos de Kahramanmaraş de febrero de 2023. Los resultados GNSS indican que la mayoría de estaciones muestran continuos movimientos tectónicos, lo que demuestra que los cambios de estrés generados por los terremotos de Kahramanmaraş aún tienen influencia en la región. Además, la falta de estabilización de las estaciones resalta la persistencia de la deformación postsísmica. La correlación espacial entre la sismicidad observada y los vectores de desplazamiento enfatiza que el segmento Malatya de la EAFZ sigue siendo una zona significativa de acumulación y liberación de deformaciones. Estaciones como MLY1 (Malatya), APK1 (Arapgir, Malatya) y ADY1 (Adıyaman) continuaron moviéndose en la misma dirección observada durante el sismo principal, lo que apunta a un deslizamiento posterior en curso. Además, las estaciones más alejadas de la zona de ruptura (por ejemplo, SUF1 (Sanlıurfa), HAT2 (Hatay), GURU (Gürün, Sivas)) exhibieron patrones de desplazamiento consistentes, lo que indica que la deformación postsísmica se extendió a través de un área amplia, incluyendo la Placa Arábiga y la región de retroarco al norte de la falla. Estos hallazgos subrayan el impacto a largo plazo de los terremotos del 6 de febrero de 2023 en la actividad sísmica regional y demuestran la importancia de integrar datos geodésicos y sísmicos para la evaluación continua de riesgos en Anatolia Oriental.

Palabras clave: Malatya; zona de fallas del Este de Anatolia; terremoto; GNSS; seismicidad; deformación.

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1. Introduction

The neotectonic period of Türkiye (Anatolia) began approximately 13 million years ago with the complete closure of the south of the Neotethys Ocean along the Bitlis-Zagros Suture Zone (Şengör and Yılmaz, 1981; Şengör et al., 1985). In the eastern Mediterranean, the main tectonic reasons for the deformation are the ongoing collision in the Bitlis-Zagros Suture zone and the Anatolian Plate's motion to the west as a result of subduction and rollback processes in the Hellenic arc (Şengör et al., 1985; Reilinger et al., 2006; Le Pichon and Kreemer, 2010).

Several studies (e.g. Stein et al., 1992; Jaume and Sykes, 1996; Stein et al., 1997; Nalbant et al., 1998, 2002; Toda et al., 2011; Li et al. 2023; Zhao et al., 2023) have shown that an earthquake can trigger nearby faults by transferring its energy. After an earthquake occurs, it has been observed that stress is loaded onto some areas while it is released in others. Additionally, after an earthquake occurs, its energy distribution and propagation directions can provide valuable information about the upcoming earthquake's direction and magnitude in the vicinity. Therefore, studying the stress distribution of an earthquake is significant for understanding the potential locations of upcoming seismic events.

In the studies of Stein et al. (1997) and Nalbant et al. (1998), before the 1999 Izmit earthquake, it was identified that the seismic risk of the Izmit Bay area was raised. A destructive Mw 7.4 earthquake struck this area on August 17, 1999. After this significant earthquake, Barka (1999) observed an increase in stress loading on the fault segments at both ends of the rupture zone, which led to the rupture of the Bolu-Düzce segment and three months later, on November 12, 1999, another major earthquake (Mw 7.1) occurred in Düzce province.

Nalbant et al. (2002) pointed out that the EAFZ has been seismically quieter than the North Anatolian Fault Zone (NAFZ) in the last century and emphasized significant stress accumulation along the EAFZ. In this study, Nalbant et al. (2002) calculated the stress changes along the fault zone to identify regions that are highly stressed and potentially defenseless to future seismic events, and it was pointed out that the Kahramanmaraş-Malatya region could be a source of significant seismic activity with a magnitude of around Mw 7.3. In the study of Yıldız et al. (2020), it was observed a strike-slip rate of 7.5 mm/yr was through the main sinistral stretch of the EAFZ, and it was estimated that a major earthquake with Mw 7.2–7.6 might happen if the entire 90 km length ruptures. As predicted in the studies of Nalbant et al. (2002) and Yıldız et al. (2020), on February 6, 2023, Kahramanmaraş struck with two major earthquakes with Mw 7.7 and Mw 7.6. Fourteen days later than these earthquake on February 20 2023, a large aftershock with Mw 6.4 recorded in Hatay (AFAD, 2023; Büyüksaraç et al., 2024; DEU, 2023; He et al., 2023; KOERI, 2023a; Li et al., 2023; Över et al., 2023; Özkan et al., 2023; Toker et al., 2023; Zhao et al., 2023; Kobayashi et al., 2024; Köküm, 2024; Ayso et al., 2025). Li et al. (2023) showed significant variations in fault slip rates and locking depths through the EAFZ's west and central parts, highlighting the heterogeneous fault behavior in the region and presented that the primary earthquake significantly amplified the static Coulomb failure stress on adjacent faults, triggering the following earthquake. In the studies of Zhao et al. (2023) and Doğanalp et al. (2024) InSAR and GPS data were used to analyze the coseismic fault model and postseismic surface movement of the Kahramanmaraş earthquakes. Similar to Li et al. (2023), Zhao et al. (2023) reported that the primary earthquake triggered the following earthquake by increasing the Coulomb rupture stress along the fault. Additionally, Över et al. (2023) used moment tensor inversion to determine fault characteristics and regional kinematics. They applied Coulomb stress transfer analysis to calculate static stress changes, demonstrating how the primary earthquake amplified the stress along the Sürgü-Çardak Fault, likely triggering the following earthquake.

In previous studies (Pamukçu et al., 2015; Çırmık et al., 2017, 2018, 2024; Çırmık and Pamukçu, 2017; Tiryakioğlu et al., 2017, 2018; Çırmık, 2018b; Kahveci et al., 2019; Yildiz et al., 2021; Özkan et al., 2023) the surface deformation caused by the significant earthquakes was identified clearly by using high-resolution GNSS network. Özkan et al. (2023) used a GNSS network to study the fault slip distributions and displacements caused by the Kahramanmaraş earthquakes. The authors emphasized the importance of using high-resolution geodetic data to accurately estimate surface displacements and understand the interaction between fault segments during significant seismic events.

This study initially concentrated on the seismicity induced by the August 2023 earthquakes in the Malatya region. It was subsequently expanded to assess the coseismic and postseismic tectonic deformation across a broader area. For this purpose, coseismic displacements associated with the February 6, 2023 earthquake sequence were quantified using GNSS observations from the CORS-TR network from January 1 to March 1, 2023. GNSS data from March 2 to December 31, 2023, were analyzed to evaluate the postseismic deformation. The results from both time intervals were compared to identify and characterize ongoing postseismic deformation patterns in the region.

In addition, to further investigate postseismic activity following the February 6, 2023 earthquakes, seismic events with magnitudes of Mw ≥ 4.0 that occurred between March 2 and December 31, 2023, were examined. The most significant event recorded during this period was a moderate earthquake (Mw 5.5) near Kozan, Adana. These seismic observations were evaluated with GNSS-derived displacements to assess the spatial and temporal correlation between seismic and geodetic postseismic signals.

Considering that Malatya is located near significant fault structures such as the EAFZ, the Sürgü Fault, and the Malatya Fault, understanding the spatial and temporal evolution of deformation in this region is essential for assessing seismic hazards. Therefore, this study aims to contribute to understanding the regional tectonic behavior and postseismic response of the crust by combining seismic observations with high-resolution GNSS data. The findings will help identify zones of ongoing strain accumulation and release, improving the scientific basis for future seismic hazard assessment and risk mitigation strategies in Eastern Anatolia.

2. Main Tectonic Features of Malatya Province and its surroundings

Deformation in the Anatolian region is mainly governed by several tectonic processes. The main mechanism is the convergence between the Arabian and Eurasian plates through the Bitlis-Zagros Suture Zone, which causes the Anatolian Plate to move westward. Moreover, the process of plate detachment beneath Eastern Anatolia was significant on the dynamic uplift of the Eastern Anatolian Plateau and facilitated the formation and activity of major strike-slip fault systems such as NAFZ and EAFZ (McKenzie 1972; Westaway et al. 2007; Özeren and Holt 2010). The NAFZ and EAFZ correspond to the relative motion between the surrounding plates and slip rates on the Malatya-Ovacık Fault Zone (MOFZ) (Fig. 1) and other internal fault zones vary from 1.2 to 2.5 mm/year (Aktuğ et al., 2013). The activity of these fault systems has led to large-scale deformation in the Anatolian region, characterized by local zones of compression, extension and strike-slip movement. This contributed to the development of pull-apart basins, mountain ranges and volcanic centers (Ekici et al., 2007). Numerous researchers (e.g. Nalbant et al., 2002; Şengör et al., 2003; Sandvol et al., 2003; Zor et al., 2003, Türkelli et al., 2003; Pamukçu et al., 2007; Özener et al., 2010; Pamukçu and Akçığ, 2011; Aktuğ et al., 2013; Bayrak et al., 2015; Gülerce et al., 2017; Yazıcı et al., 2018; Çırmık, 2018a; Acarel et al., 2019; Sançar et al., 2019; Yılmaz, 2019; Bletery et al., 2020; Şahin and Öksüm, 2021) studied in EAFZ and its surroundings for investigating its seismic activity and tectonism.

The Malatya-Ovacık Fault Zone (MOFZ) is a left-lateral strike-slip fault system, extending approximately 240 km in a NE-SW direction (Westaway et al., 2003, 2007) (Fig. 1). According to the studies of Westaway and Arger (1996) and Westaway et al. (2003, 2007), the MOFZ was active during the Early Pliocene and acted as the earlier boundary between the Anatolian and Arabian plates, but the formation of the EAFZ has made MOFZ inactive. The MOFZ has two main segments, namely the Malatya Fault (MF) in the southwest and the Ovacık Fault (OF) in the northeast and both of them have a significant role in the deformation of the Anatolian microplate (Koçyiğit and Beyhan, 1998; Kaymakçı et al., 2006; Ekici et al., 2007, Westaway et al., 2007). The southwestern branch of MOFZ; The Malatya Fault (MF) is a NE trending sinistral strike-slip fault with the length of 165 km (Fig. 1) (Ekici et al., 2007; Westaway et al., 2007). Özener et al. (2010) indicated by using GPS measurements that the strain accumulation is much higher than previously estimated, suggesting active deformation in the region between the NAFZ and the EAFZ. Additionally, the paleoseismic studies (Koçyiğit and Beyhan, 1998; Kaymakçı et al., 2006; Zabcı et al., 2017) indicated that four

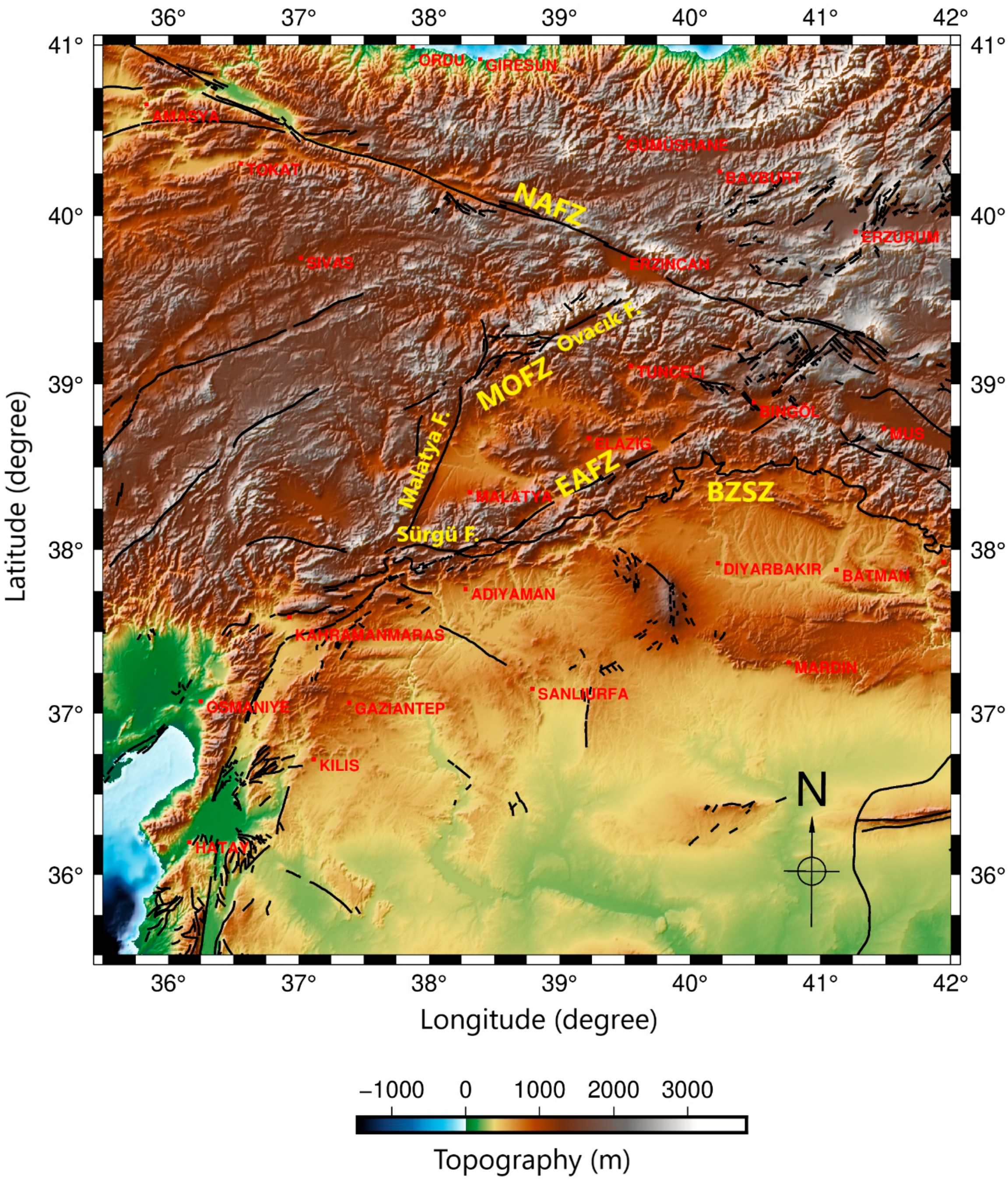


Figure 1. The main tectonic features of Malatya and its surroundings. NAFZ; North Anatolian Fault Zone, EAFZ; Eastern Anatolian Fault Zone, MOFZ; Malatya-Ovacık Fault Zone, BZSZ; Bitlis-Zagros Suture Zone.

significant earthquakes occurred over the past 10.000 years with a repetition interval of approximately 2.275 years in the MF. The researchers (Koçyiğit and Beyhan, 1998; Kaymakçı et al., 2006; Zabcı et al., 2017) presented that MF has a potential for a future large earthquake with an approximately M7.4. Therefore, paleoseismological and geodetic studies (Koçyiğit and Beyhan, 1998; Kaymakçı et al., 2006; Westaway et al., 2007; Özener et al., 2010, Aktuğ et al., 2016; Zabcı et al., 2017) indicated that the MOFZ (including MF and OF) is an active fault zone.

3. Methodology

Seismicity of Malatya Province and its surroundings

In the Türkiye Earthquake Hazard Map (prepared by AFAD in 2019), the maximum acceleration value of PGA 475 (year) in Malatya province varies between 0.2-0.7g. This indicates that the seismic hazard of the region is very high. The south-southeast of the province is generally under the influence of the

EAFZ. Sürgü Fault in the south, the part of the EAFZ passing through the east of Malatya province, and the Malatya Fault are important tectonic structures in the region (Fig. 1). In addition, the NAFZ passes through the north of Malatya province, and the EAFZ passes through the south-southeast (KOERI, 2023b). In the historical period (1800 B.C.-1900 A.D.), an earthquake with an intensity Io=IX occurred in 1893 along the EAFZ (Soysal et al., 1981). The earthquakes of 1866 and 1874, which occurred southeast of Malatya province, are also essential earthquakes that were recorded during the historical timeframe (KOERI, 2023b).

In order to examine the earthquakes that affected Malatya province in the instrumental timeframe, the earthquakes that were recorded in Malatya and its vicinity (between longitudes 35.5°-41° and latitudes 35.5°-40°) between the days January 1, 1990 and December 31, 2023 with magnitude M≥4.0 were obtained from AFAD earthquake catalog (https://deprem.afad.gov.tr/event-catalog) and mapped (Fig. 2). It is examined that 1153 earthquakes with magnitude 4≤M<5, 117 earthquakes with magnitude 5≤M<6, 7 earthquakes with magnitude 6≤M<7 and 2 earthquakes with magnitude 7≤M (February 6, 2023 Pazarcık, Kahramanmaraş (Mw7.7); February 6, 2023 Elbistan, Kahramanmaraş, (Mw7.6) earthquakes) occurred between January 1990 and December 2023.

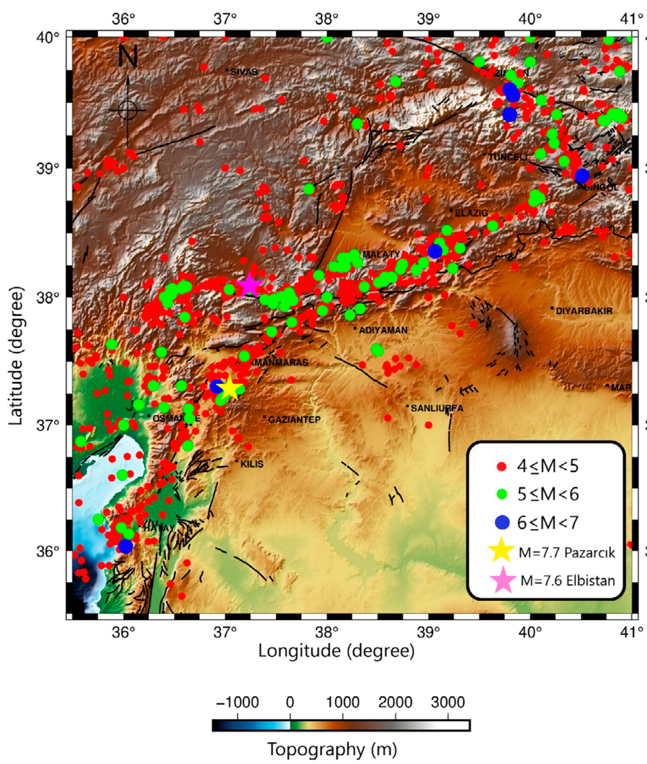


Figure 2. Distribution of epicenters of earthquakes with magnitude M≥4.0 in and around Malatya province between January 1, 1990 and December 31, 2023. Earthquake data were downloaded from https://deprem.afad.gov.tr/event-catalog.

On August 10, 2023, a moderate earthquake with a magnitude Mw=5.2 (KOERI, 2023b; USGS, 2023), Mw=5.3 (AFAD 2023) occurred in Malatya (in Yeşilyurt district) (Fig. 3). The focal depth of the earthquake was shallow and approximately 5 km (KOERI, 2023b). The earthquake was felt in Malatya and its surroundings. Besides, on August 24, 2023 and on November, 23 2023 other moderate earthquakes with magnitude Mw=5.0 (AFAD, 2023) and Mw=5.2 (AFAD, 2023), respectively occurred in Malatya provinces (Fig. 3).

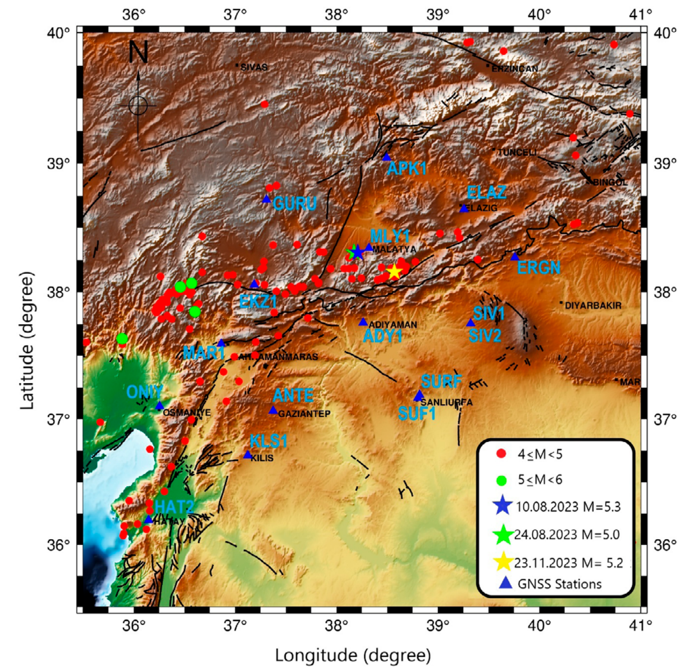


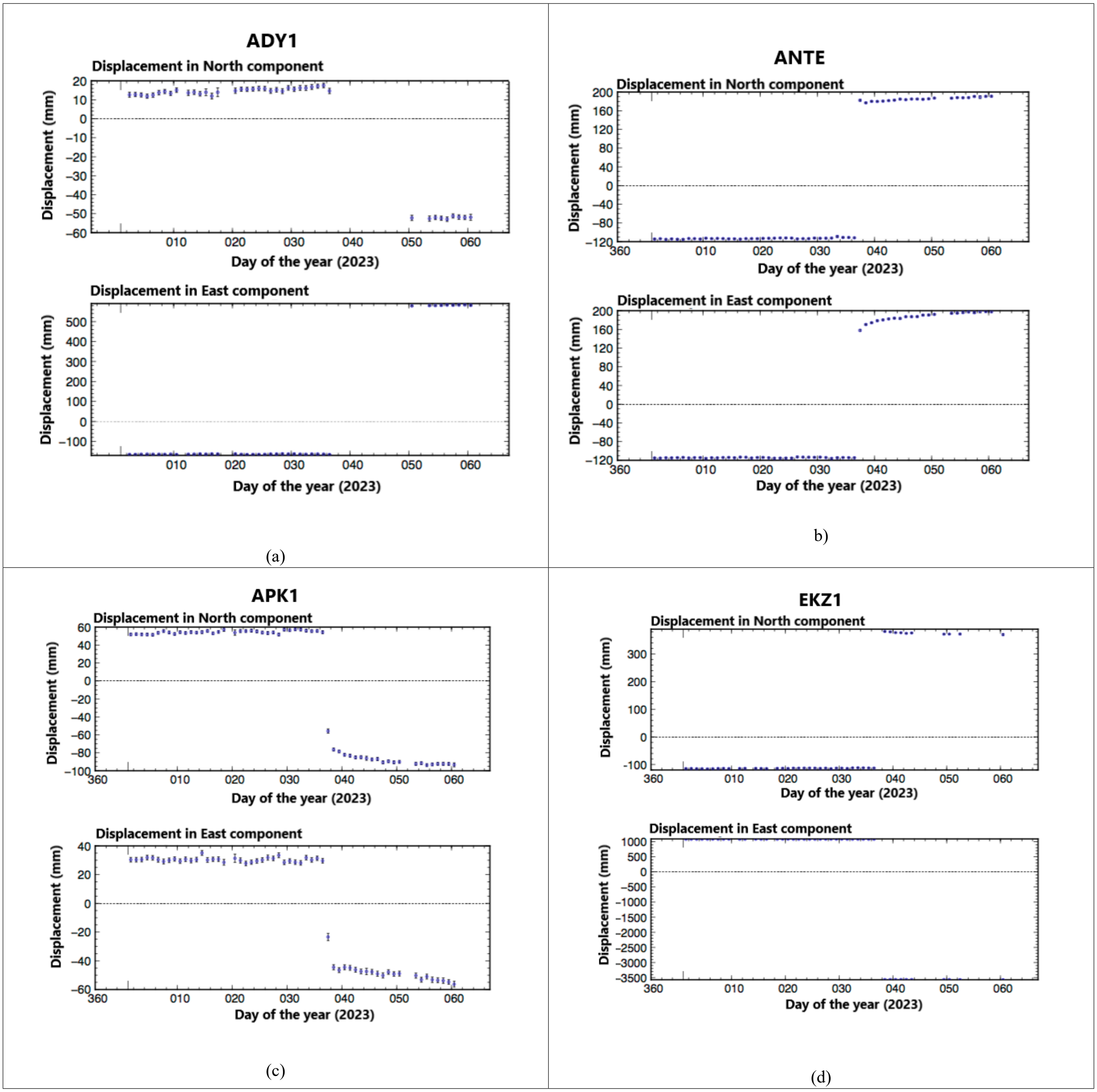
Figure 3. The epicenter distributions of the earthquakes with magnitudes M≥4 occurred in the region (longitudes 35.5°-41° and latitudes 35.5°-40°) after February 6, 2023 Kahramanmaraş earthquakes (between the days March 2, 2023- December 31, 2023) and the locations of the permanent stations of CORS-TR used in the study.

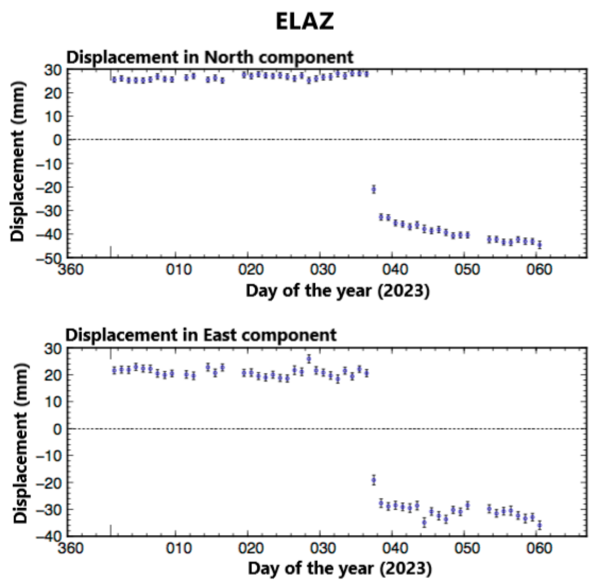
3.2. GNSS data analysis

The derivation of coseismic displacements from time series has been highlighted in recent studies (e.g., Aktuğ et al., 2010; Tiryakioglu et al., 2017, Çırmık, 2018b; Yildiz et al., 2021; Özkan et al., 2023; Çırmık et al., 2024). A thorough analysis of the time series of GNSS data can provide valuable findings about the GNSS station's movement (Özkan et al., 2023). Therefore, in this study, GNSS data of the permanent stations of the CORS-TR located around the epicenter of the February 6, 2023 Kahramanmaraş earthquakes were processed from January 1 to March 1, 2023, to calculate the displacement of the region with the effect of these earthquakes. Then, the GNSS data from March 2 to December 31, 2023, including the impact of the Malatya earthquakes, were evaluated to analyze the tectonic behavior in and around Malatya and the subsequent significant earthquakes.

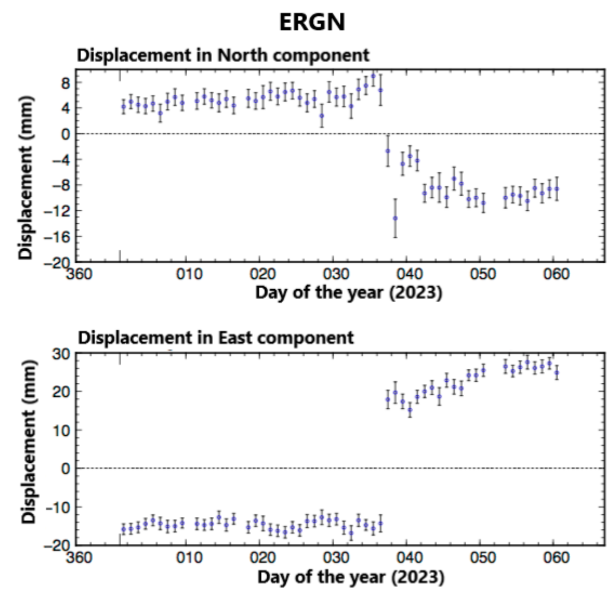
Meanwhile, the events (with magnitudes M ≥ 4.0) that occurred between March 2 and December 31, 2023, were analyzed to investigate the effects of the earthquakes on ground displacements. These events were obtained from the AFAD Earthquake Catalog (https://deprem.afad.gov.tr/event-catalog) and are located within the region bounded by longitudes 35.5°–41°E and latitudes 35.5°–40°N. During this period, 144 earthquakes with magnitudes of 4.0 ≤ M <5.0 and 7 earthquakes with magnitudes of 5.0 ≤ M <6.0 occurred in the region. The largest earthquake in this time frame occurred on July 25, 2023, in Kozan (Adana), with a magnitude of M = 5.5. In the Malatya province, three moderate earthquakes occurred on August 10, 2023 (Mw = 5.3; DOY 222), August 24, 2023 (Mw = 5.0; DOY 236), and November 23, 2023 (Mw = 5.2; DOY 296). Additionally, three other earthquakes with magnitudes of 5.0 and larger occurred within the boundaries of Kahramanmaraş province on March 3, 2023 (M = 5.0), March 23, 2023 (M = 5.3), and May 3, 2023 (M = 5.0) (Fig. 3).

In the first step of the analysis, to calculate the displacement that occurred in the region as a result of the February 6, 2023 (DOY: 37) Kahramanmaraş earthquakes, GNSS data (between January 1 and March 1, 2023) from 14 GNSS stations—ANTE (Gaziantep), ADY1 (Adıyaman), APK1 (Arapgir, Malatya), EKZ1 (Ekinözü, Kahramanmaraş), ELAZ (Elazığ), ERGN (Ergani, Diyarbakır), GURU (Gürün, Sivas), HAT2 (Hatay), KLS1 (Kilis), MAR1 (Kahramanmaraş), MLY1 (Malatya), ONIY (Osmaniye), SIV1 (Siverek, Şanlıurfa), and SURF (Şanlıurfa city center)—belonging to the CORS-TR network were processed (Fig. 3). Precise coordinates were calculated using the GAMIT/GLOBK software (Herring et al., 2015a, 2015b), and the time series were obtained (Figs. 4a–4n). In this processing, 11 IGS stations (ARUC, BSHM, DRAG, MADR, OP71, OPMT, POL2, RAMO, WTZA, YIBL, and ZIMM) were used to define the Eurasia-fixed reference frame within the ITRF2014 framework.

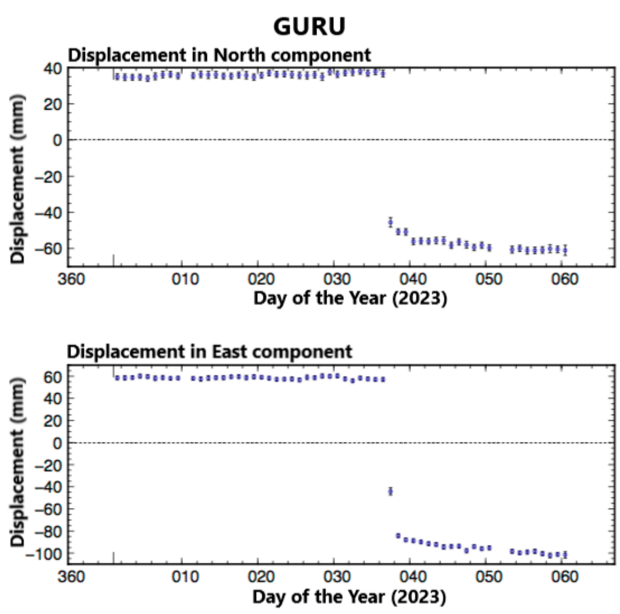



ELAZ
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

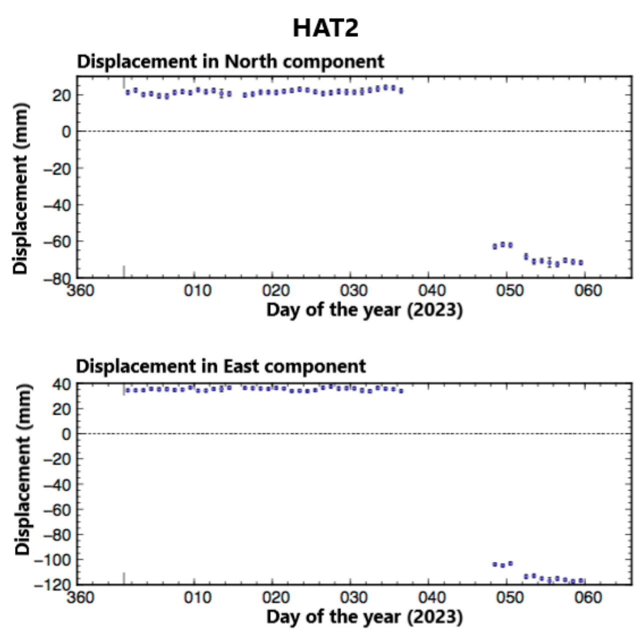
(e)


ERGN
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

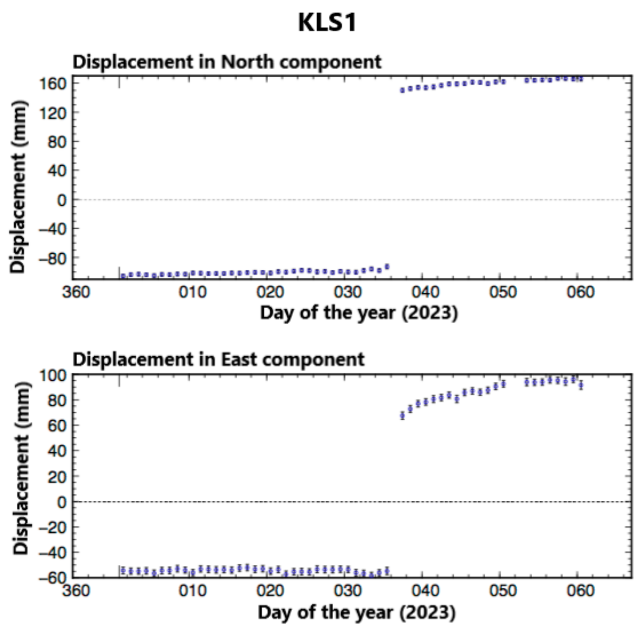
(f)


GURU
Displacement in North component
Displacement (mm)
Day of the Year (2023)
Displacement in East component
Displacement (mm)
Day of the Year (2023)

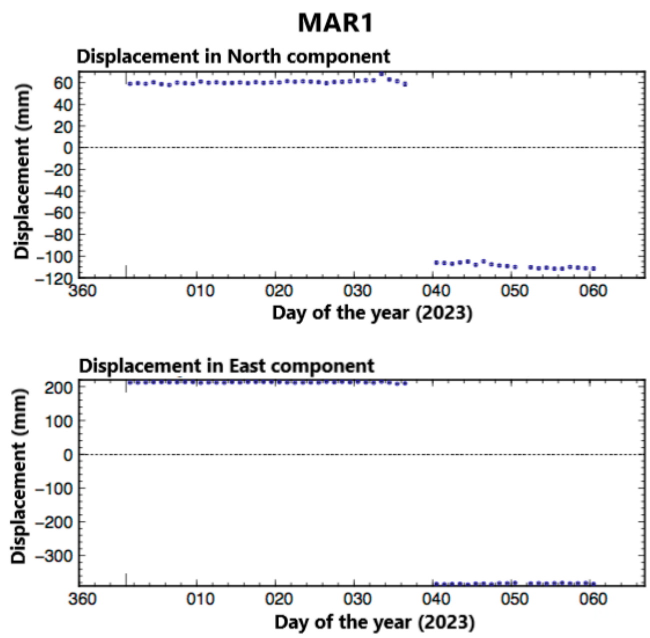
(g)


HAT2
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

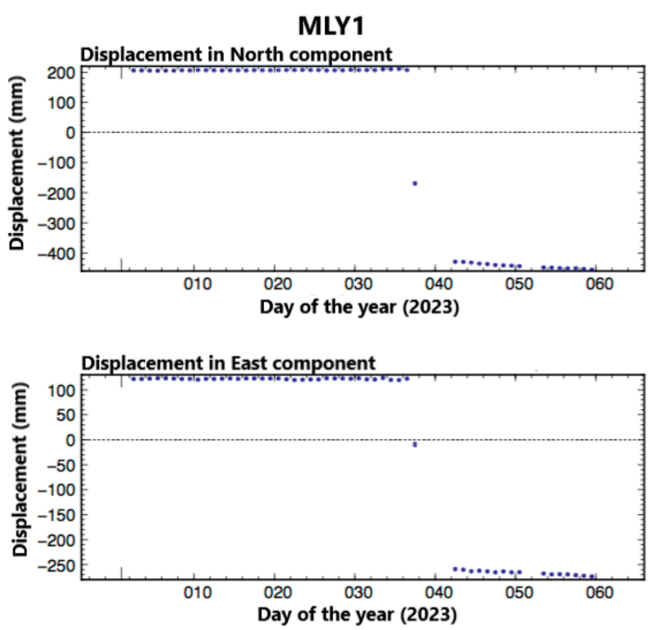
(h)


KLS1
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

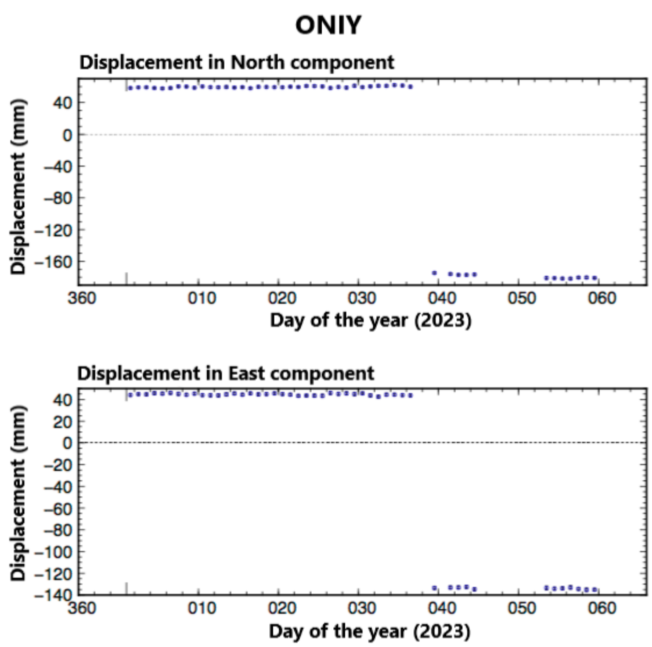
(i)


MAR1
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

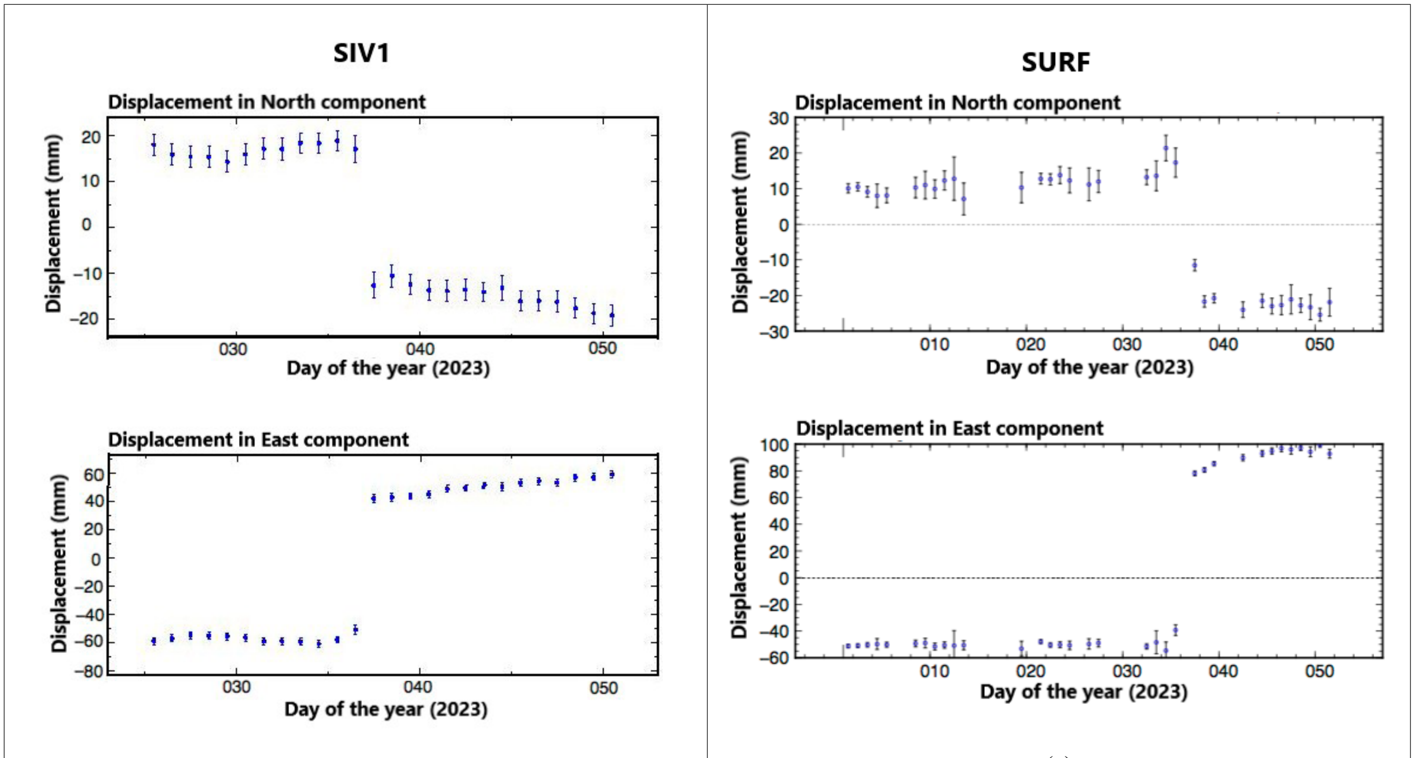
(j)


MLY1
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

(k)


ONIY
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

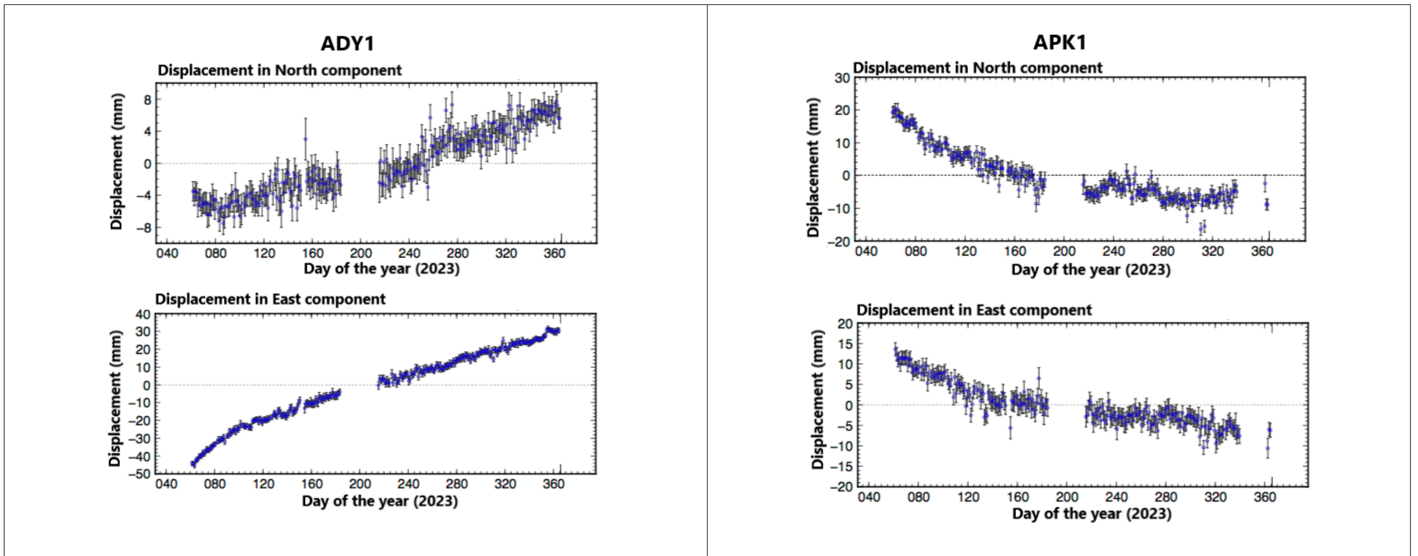
(l)



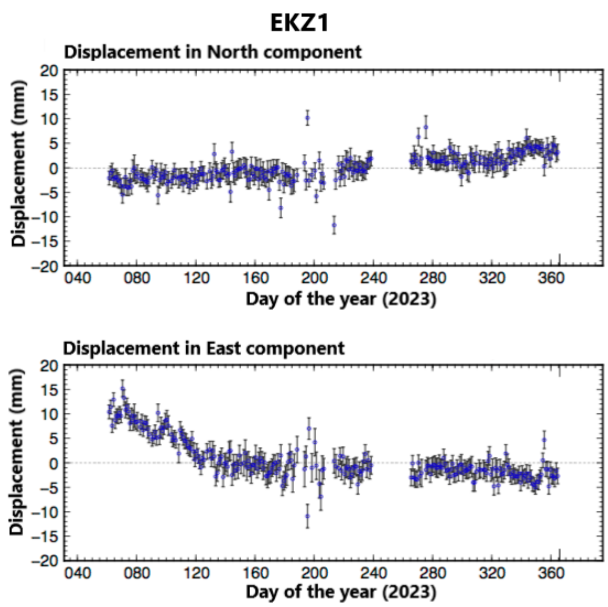
(m) (n)

Figure 4. The displacements at North and East components of the permanent GNSS stations based on the data between January 1, 2023 and March 1, 2023; a) ADY1, b) ANTE, c) APK1, d) EKZ1, e) ELAZ, f) ERGN, g) GURU, h) HAT2, i) KLS1, j) MAR1, k) MLY1, l) ONIY, m) SIV1, n) SURF

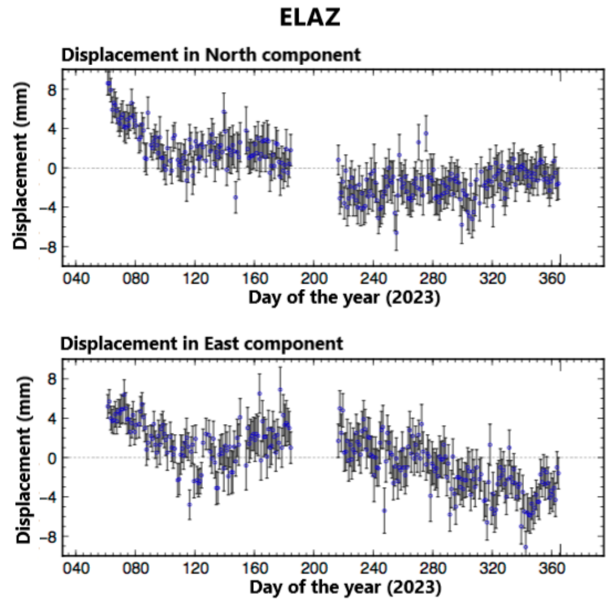
In the second step, to investigate the impact of the postseismic movements of the February 6 earthquakes on ground displacements, the data from the same GNSS stations were analyzed from March 2 to December 31, 2023, using the same processing steps. In this phase, the ANTE station (Gaziantep) was excluded from the analysis because its position was relocated after the February 6, 2023 earthquake. Similarly, the SIV1 station in Siverek, Şanlıurfa (37.75287°N, 39.32167°E) was replaced with the nearby SIV2 station (37.75252°N, 39.32273°E), and the SURF station in Şanlıurfa city center (37.19185°N, 38.81802°E) was replaced with the nearby SUF1 station (37.16771°N, 38.80055°E) (Fig. 3). Since the old and new locations of these stations are very close, SIV2 and SUF1 were used instead of SIV1 and SURF in this stage of the processing. The time series of the 13 stations used in this stage (ADY1, APK1, EKZ1, ELAZ, ERGN, GURU, HAT2, KLS1, MAR1, MLY1, ONIY, SIV2, and SUF1) were obtained (Figs. 5a–5m).



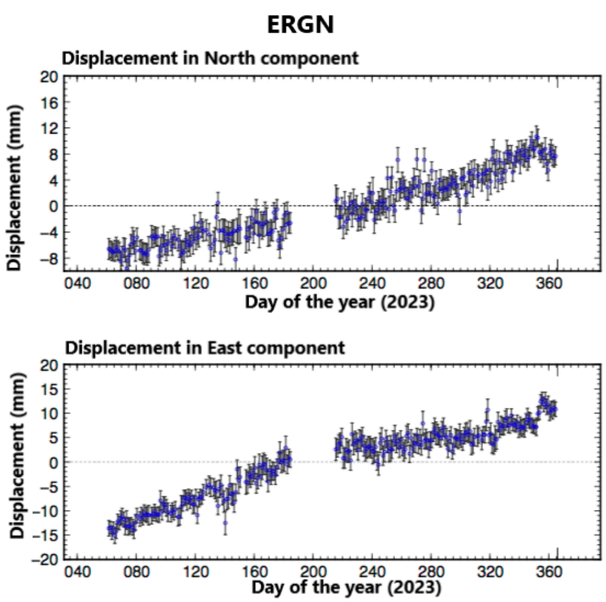
(a) (b)


EKZ1
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

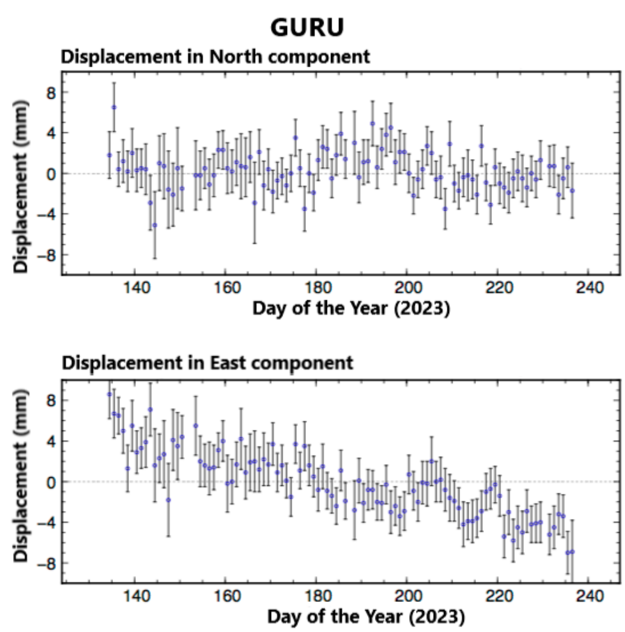
(c)


ELAZ
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

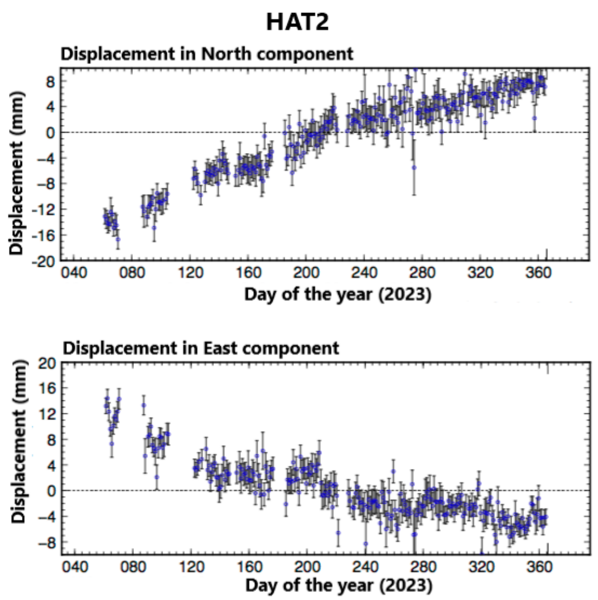
(d)


ERGN
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

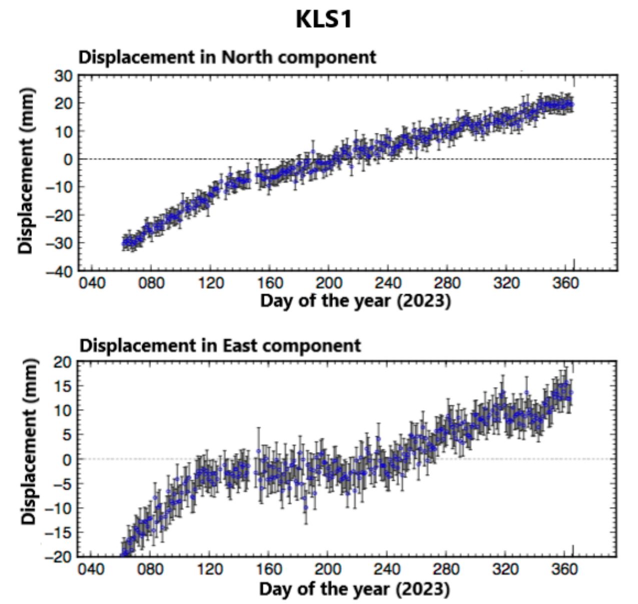
(e)


GURU
Displacement in North component
Displacement (mm)
Day of the Year (2023)
Displacement in East component
Displacement (mm)
Day of the Year (2023)

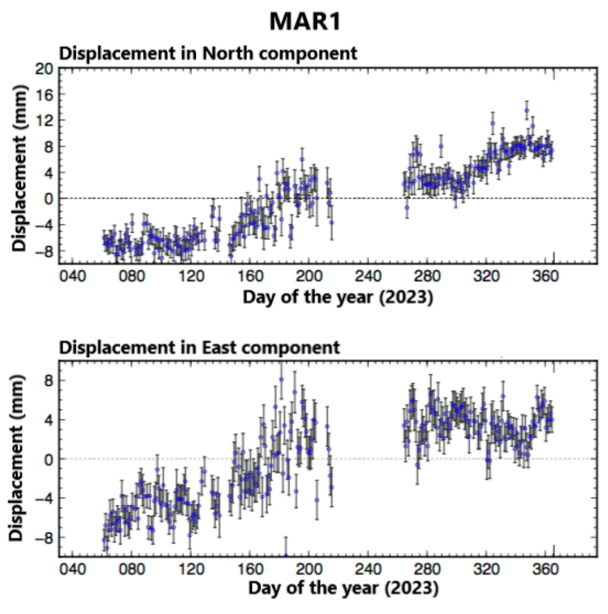
(f)


HAT2
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

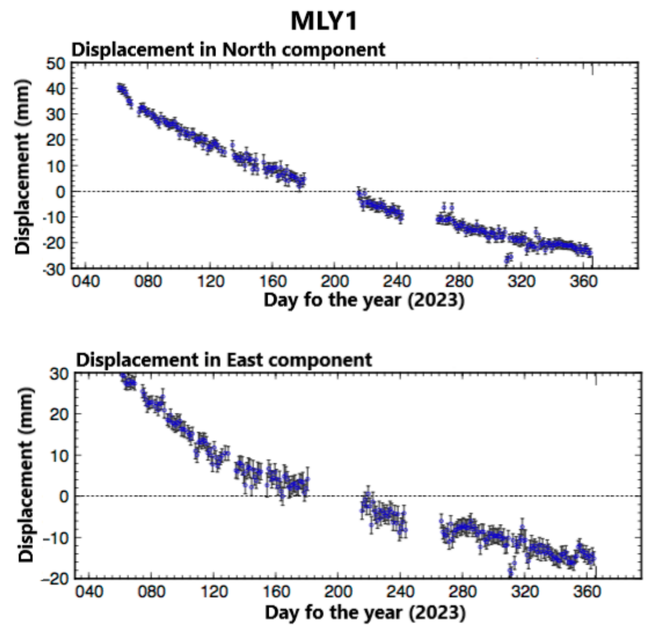
(g)


KLS1
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

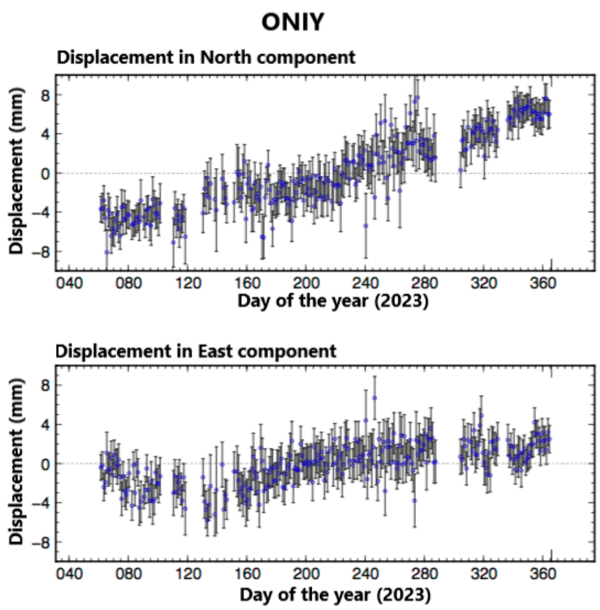
(h)


MAR1
Displacement in North component
Displacement (mm)
Day of the year (2023)
Displacement in East component
Displacement (mm)
Day of the year (2023)

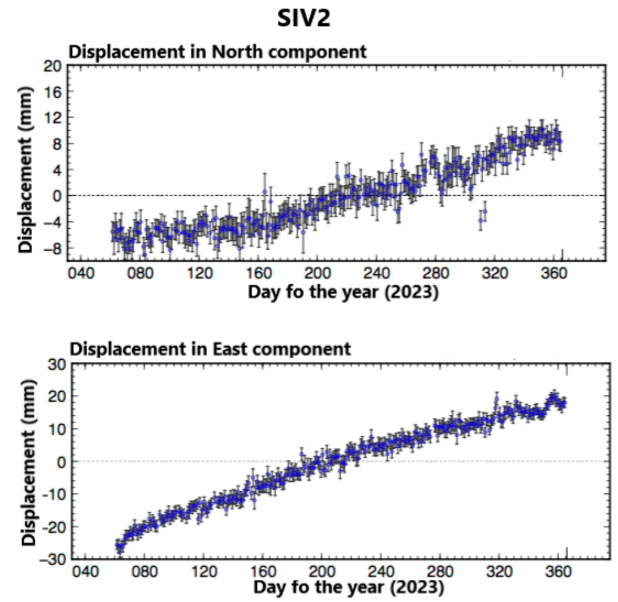
(i)


MLY1
Displacement in North component
Displacement (mm)
Day fo the year (2023)
Displacement in East component
Displacement (mm)
Day fo the year (2023)

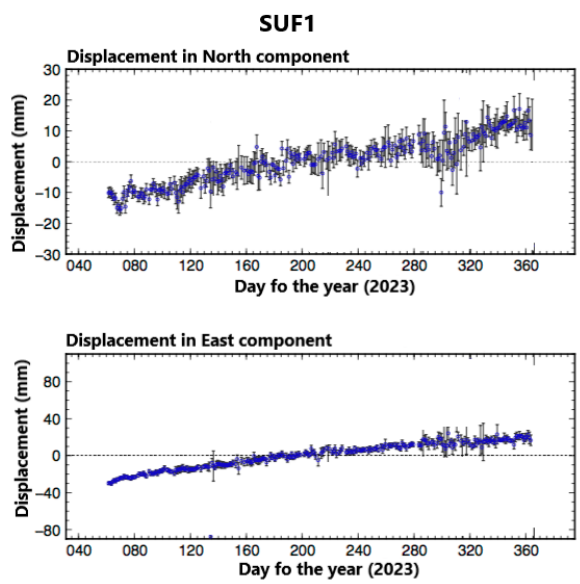
(j)



(k)



(l)



(m)

Figure 5. The displacements at North and East components of the permanent GNSS stations based on the data between March 2, 2023 and December 31, 2023; a) ADY1, b) APK1, c) EKZ1, d) ELAZ, e) ERGN, f) GURU, g) HAT2, h) KLS1, i) MAR1, j) MLY1, k) ONIY, l) SIV2, m) SUF1

In the next step, horizontal displacement estimates were derived from the obtained time series (Fig. 4 and Fig. 5) using the TSVIEW software (Herring, 2003). TSVIEW is a MATLAB-based application that enables the visualization of GNSS time series generated with the GLRED module of the GAMIT/GLOBK software, the evaluation of time series quality, the correction of the series, and the estimation of velocities and noise characteristics by applying various models (Herring, 2003; Özkan, 2009). The horizontal displacements obtained for January 1 to March 1, 2023, and March 2 to December 31, 2023, are presented in Tables 1 and 2, respectively. The displacement vectors are shown in Fig. 6 and Fig. 7, respectively.

Table 1. Horizontal displacements based on the data between January 1, 2023 and March 1, 2023 obtained by Tsview (Herring, 2003) software.

Station	North (mm)	East (mm)
ADY1	-459.39±52.45	5124.86±569.09
ANTE	2584.67±213.60	2594.41±222.84
APK1	-1195.68±108.55	-676.97±60.27
EKZ1	3314.28±564.93	-30759.05±5404.79
ELAZ	-551.37±51.50	-435.57±40.89
ERGN	-110.92±11.02	319.93±26.31
GURU	-811.90±72.30	-1345.14±118.04
HAT2	-646.26±63.67	-1046.84±105.81
KLS1	2318.96±182.97	1262.10±101.80
MAR1	-1426.75±116.40	-4958.94±425.61
MLY1	-5440.69±459.94	-3234.58±283.29
ONIY	-1793.25±187.37	-1322.22±144.65
SIV1	-290.22±33.56	940.42±92.05
SURF	-279.40±32.45	1261.82±124.04

Table 2. Horizontal displacements based on the data between March 2, 2023 and December 31, 2023 obtained by Tsview (Herring, 2003) software.

Station	North (mm)	East (mm)
ADY1	14.87±0.32	81.20±0.68
APK1	-30.48±0.90	-20.13±0.58
EKZ1	7.43±0.36	-12.74±0.64
ELAZ	-60.14±0.66	-7.86±0.46
ERGN	19.02±0.37	28.03±0.43
GURU	-5.99±2.02	-37.27±2.36
HAT2	26.03±0.47	-17.51±0.54
KLS1	56.86±0.70	29.80±0.72
MAR1	19.75±0.44	13.38±0.48
MLY1	-70.84±0.83	-47.94±0.84
ONIY	14.50±0.35	5.36±0.36
SIV2	20.29±0.37	50.93±0.44
SUF1	28.99±0.40	57.36±0.66

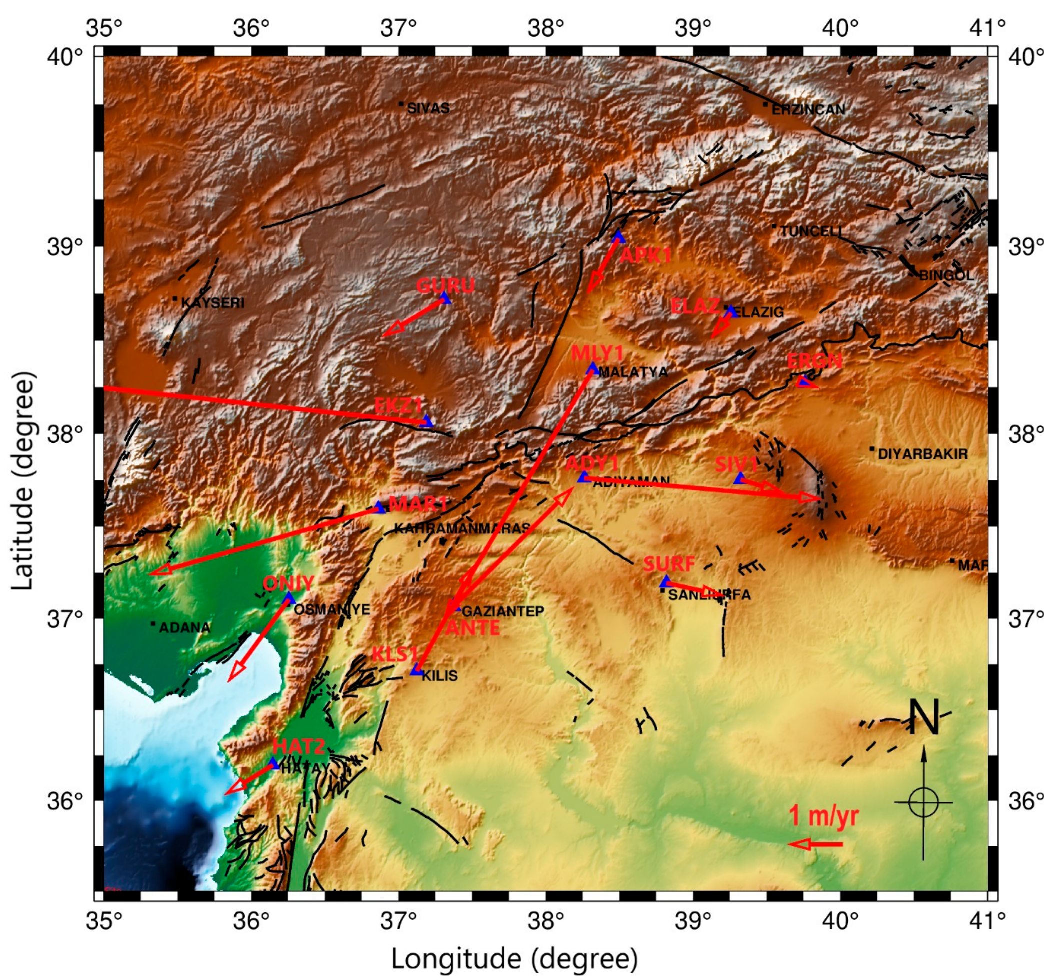


Figure 6. The horizontal displacements of the GNSS stations obtained from the time series of January 1-March 1, 2023 including February 6, 2023 Mw = 7.7 Pazarcık and Mw = 7.6 Elbistan earthquakes effects.

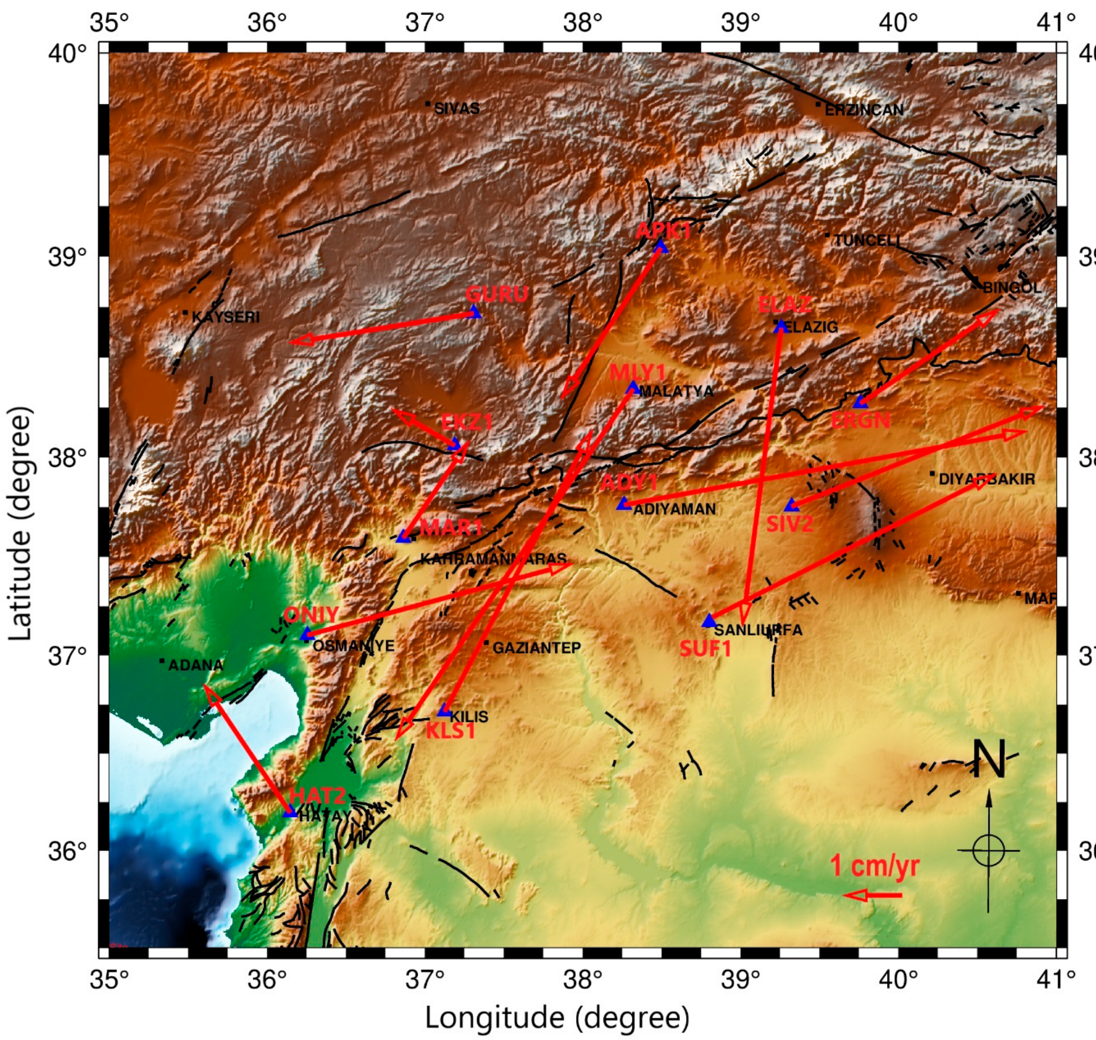


Figure 7. The horizontal displacements of the GNSS stations obtained from the time series of March 2-December 31, 2023.

Results

Previous studies (e.g., Stein et al., 1992; Jaume and Sykes, 1996; Stein et al., 1997; Nalbant et al., 1998, 2002; Toda et al., 2011; Li et al., 2023; Zhao et al., 2023) have shown that a major earthquake can induce stress changes in neighboring faults, potentially triggering them. The most recent example of this phenomenon recorded on February 6, 2023 with the Mw = 7.7 earthquake in Pazarcık (Kahramanmaraş), was followed by another major earthquake of Mw = 7.6 in Elbistan (Kahramanmaraş). Additionally, 14 days later, an Mw = 6.6 earthquake in Hatay provides another example of this triggering effect. The post-earthquake regional stress changes and the directions of energy propagation offer valuable insights into the possible location and magnitude of future seismic events. Therefore, analyzing the stress changing following an earthquake is crucial for understanding potential seismic activity zones and predicting future large earthquake scenarios.

Due to the presence of the Malatya Fault to the west, the Sürgü Fault to the south, and the EAFZ to the southeast, Malatya is a seismically active region (Fig. 1). Additionally, studies of Koçyiğit and Beyhan (1998), Kaymakçı et al. (2006), and Zabcı et al. (2017) emphasize the significant earthquake-generating potential of the Malatya Fault. According to the earthquake report prepared by Dokuz Eylül University, Faculty of Engineering, regarding the February 6, 2023 Kahramanmaraş earthquakes and the February 20, 2023 Hatay earthquake (DEU, 2023), the Coulomb analysis results of the Kahramanmaraş earthquakes indicate that there was stress loading in and around the Malatya region. Consistent with these findings, two earthquakes of magnitudes Mw = 5.3 and Mw = 5.0 occurred in Malatya Province on August 10, 2023 and August 24, 2023, respectively, six months after the February 6, 2023 earthquakes (Fig. 2).

Figure 2 presents the distribution of earthquake epicenters with magnitudes $M \geq 4.0$ that occurred in and around the Malatya province between January 1, 1990 and December 31, 2023. It is seen that the seismicity is predominantly aligned along the East Anatolian Fault Zone (EAFZ), highlighting its role as a major seismotectonic structure in the region. The distribution includes a significant number of low-to-moderate magnitude events ($4.0 \leq M < 5.0$), as well as several moderate-to-strong earthquakes ($5.0 \leq M < 7.0$). Two major earthquakes that struck the region on February 6, 2023—the Mw 7.7 Pazarcık and Mw 7.6 Elbistan events—are marked with star symbols and represent the most significant seismic events in the recent history of the region. The overall pattern reflects long-term active deformation concentrated along the fault zone, emphasizing the persistent seismic hazard in eastern and southeastern Anatolia.

Figure 3 shows the distribution of earthquakes with magnitudes $M \geq 4.0$ that occurred between March 2 and December 31, 2023, within the coordinates 35.5°–41°E and 35.5°–40°N. The events are predominantly clustered along the East Anatolian Fault Zone (EAFZ) and its associated branches, indicating continued seismic activity and potential postseismic deformation. 144 events with magnitudes between 4.0 ≤ M < 5.0 and 7 events between 5.0 ≤ M < 6.0 were recorded. Three moderate-magnitude earthquakes within Malatya province—occurred on August 10 (Mw = 5.3), August 24 (Mw = 5.0), and November 23 (Mw = 5.2). It is observed that the magnitude of the earthquakes occurring between March 1 and December 31, 2023, generally ranges from 4≤M<5, and these earthquakes are concentrated in the southern part of Malatya, the northern part of Kahramanmaraş, and the northern part of Adıyaman. Apart from the three earthquakes of M ≥ 5 in and around Malatya, no larger seismic activity was observed in the region during these 10 months. The observed spatial alignment of seismicity supports the interpretation of ongoing crustal adjustments following the February 6, 2023 earthquakes.

A comparison of Figure 2 and Figure 3 provides valuable insights into both the long-term and short-term seismic activity in and around the Malatya region. Figure 2 displays the distribution of earthquake epicenters with M ≥ 4.0 over 33 years (1990–2023), revealing a persistent concentration of seismicity along the East Anatolian Fault Zone (EAFZ). The alignment of events along this tectonic boundary suggests continuous strain accumulation and release over the decades. In contrast, Figure 3 focuses specifically on the postseismic period following the February 6, 2023 earthquakes, covering seismic events between March 2 and December 31, 2023. The clustering of events in Figure 3 largely mirrors the historical pattern seen in Fig. 2, particularly along the same fault segments, indicating that the February 6 earthquakes have reactivated portions of the fault system. Considering the epicenters of these earthquakes (Fig. 2 and Fig. 3), it is seen that the earthquakes generally occurred along the EAFZ and the magnitudes of the major earthquakes in and around Malatya province range between 5 ≤ M < 6. Moreover, several moderate-magnitude events (Mw ≥ 5.0) in both figures highlight the ongoing seismotectonic activity in the region. This temporal and spatial consistency between the long-term and postseismic datasets underscores the significance of continued monitoring through both geodetic and seismological methods.

The time series of the GNSS data between January 1 and March 1, 2023 (Figs. 4a-4n), the horizontal displacement values (Table 1) and the displacement vectors (Fig. 6), clearly reflect the coseismic deformation associated with the February 6, 2023 Kahramanmaraş earthquakes.

The EKZ1 station, located in Ekinözü (Kahramanmaraş) and in close proximity to the epicenter of the second mainshock (Mw 7.6) of the February 6, 2023 earthquake sequence, recorded the most substantial coseismic displacement among all stations analyzed. The total horizontal displacement reached approximately 30.94 meters, with the motion predominantly directed toward the west, comprising a north component of +3314.28 mm and a strikingly large east component of −30759.05 mm. The displacements presented here were obtained by calculating the vector sum of the north and east components listed in Table 1. This extreme displacement highlights the proximity of the station to the rupture zone and the intense crustal deformation imposed by the fault movement. EKZ1 is situated on the eastern block of the East Anatolian Fault (EAF), and the observed displacement pattern is consistent with the left-lateral strike-slip mechanism of the fault, where the eastern block moves westward relative to the western block. The remarkable magnitude and direction of motion at this site provide key evidence for characterizing near-field fault slip and stress release associated with the Mw 7.6 event.

The MAR1 station, located in Kahramanmaraş near the epicentral region of the February 6, 2023 earthquake sequence, experienced significant coseismic displacement associated with the rupture of the East Anatolian Fault (EAF) and its adjacent segments. The station recorded a total horizontal displacement of approximately 5.16 meters, with motion directed toward the west-southwest, composed of a north component of −1426.75 mm and an east component of −4958.94 mm. This displacement pattern reflects the intense localized crustal deformation that occurred in the immediate vicinity of the rupture zone, where complex fault interactions, including the EAF and secondary structures such as the Çardak and Sürgü faults, play a significant role. The observed southwestward motion at MAR1 is consistent with the left-lateral strike-slip mechanism of the EAF and supports the interpretation of large-scale strain release and block rotation during the mainshock sequence. The proximity of MAR1 to the rupture initiation zone makes it a key site for understanding near-field tectonic responses during the Kahramanmaraş earthquakes.

The MLY1 station, located in Malatya on the western block of the East Anatolian Fault (EAF), exhibited a substantial coseismic displacement following the February 6, 2023 Kahramanmaraş earthquake sequence. The station recorded a total horizontal displacement of approximately 6.28 meters, with motion directed toward the southwest, consisting of a north component of −5440.69 mm and an east component of −3234.58 mm. This southwestward movement aligns with the expected behavior of the western block of the EAF, which is known to shift left-laterally relative to the eastern block during rupture events. The observed displacement at MLY1 reflects the dynamic tectonic response of the western Anatolian crust to the rupture propagation along the EAF, particularly during the second mainshock (Mw 7.6). This motion provides critical evidence for understanding strain release and block kinematics in the vicinity of the fault during large-scale earthquake sequences.

The ADY1 station, located in Adıyaman on the eastern block of the East Anatolian Fault (EAF), recorded a significant displacement following the February 6, 2023 Kahramanmaraş earthquakes (Mw 7.7 and Mw 7.6). The total displacement at the site reached approximately 5.15 meters, with a dominant motion toward the east, characterized by a north component of −459 mm and an east component of +5125 mm. This eastward movement is consistent with the left-lateral strike-slip character of the EAF, where blocks located on the eastern side are expected to shift eastward relative to those on the western side. The observed displacement at ADY1 reflects the coseismic deformation associated with the rupture of the EAF and highlights the significant tectonic response of the eastern block to the stress release during the mainshock sequence. These findings provide important insights into the distribution of strain accumulation and release in the vicinity of the fault zone.

The ANTE station, located in the city center of Gaziantep and positioned southeast of the rupture zones of the February 6, 2023 Kahramanmaraş earthquakes, recorded a significant coseismic displacement of approximately 3.66 meters. The motion was directed toward the northeast, with a north component of +2584.67 mm and an east component of +2594.41 mm. Although located outside the primary rupture segments of the EAFZ, the displacement observed at ANTE reflects the broader regional stress redistribution and block interaction induced by the mainshock sequence. The northeastward motion of the station suggests a response consistent with the clockwise rotation and extrusion of the Anatolian Plate, and is compatible with the left-lateral strike-slip mechanism of the EAF, which plays a key role in accommodating the westward escape of Anatolia. The recorded movement at ANTE provides valuable information on the far-field tectonic effects and the spatial extent of deformation resulting from this major seismic event.

The KLS1 station, located in Kilis in the southern portion of the East Anatolian region, recorded a coseismic displacement of approximately 2.62 meters following the February 6, 2023 Kahramanmaraş earthquakes. The motion was oriented toward the north-northeast, with a north component of +2318.96 mm and an east component of +1262.10 mm. Although situated outside the immediate rupture zone of the EAFZ, the station lies within the broader deformational field affected by the earthquake sequence. The observed displacement at KLS1 reflects regional stress transfer and crustal adjustment related to the interaction between the Anatolian and Arabian plates. The north-northeastward motion is consistent with the broader tectonic escape pattern of Anatolia and the left-lateral displacement along the EAF. This movement supports the interpretation that significant strain accumulation and release extended beyond the main rupture area, influencing deformation in more distal parts of southeastern Anatolia.

The ONIY station, located in Osmaniye to the south of the EAFZ, recorded a coseismic horizontal displacement of approximately 2.22 meters in response to the February 6, 2023 Kahramanmaraş earthquake sequence. The motion was directed toward the southwest, consisting of a north component of −1793.25 mm and an east component of −1322.22 mm. Although the station is situated outside the immediate rupture zone of the EAFZ, the observed displacement indicates significant far-field deformation induced by the earthquake sequence. The southwestward motion is compatible with the regional tectonic framework involving the relative convergence of the Arabian and Anatolian plates and reflects strain transfer across broader zones beyond the main fault trace. ONIY's displacement highlights the spatial extent of coseismic deformation and the dynamic response of the upper crust in the southern margin of the affected region.

The HAT2 station, located in Hatay province in the southern part of the East Anatolian region, recorded a horizontal displacement of approximately 1.23 meters following the February 6, 2023 Kahramanmaraş earthquakes. The station's motion was oriented toward the southwest, with a north component of −646.26 mm and an east component of −1046.84 mm. Although HAT2 lies at a considerable distance from the main rupture segments of the EAFZ, the recorded displacement reflects the far-field coseismic effects and broader regional crustal adjustment induced by the earthquake sequence. The observed motion is consistent with the overall tectonic framework of the region, where convergence between the Anatolian and Arabian plates and interaction with nearby structures such as the Dead Sea Fault Zone and the Antakya Fault contribute to the complex deformation pattern. The southwestward displacement at HAT2 underscores the wide spatial extent of the tectonic response and the efficiency of stress transfer during large-magnitude seismic events in southeastern Anatolia.

The GURU station, located in Gürün district of Sivas province, lies northwest of the main rupture zone of the February 6, 2023 Kahramanmaraş earthquakes and on the western block of the EAFZ. The station recorded a horizontal displacement of approximately 1.57 meters, directed toward the southwest, with a north component of −811.90 mm and an east component of −1345.14 mm. Although located at a considerable distance from the epicentral region, the displacement at GURU reflects the propagation of coseismic strain through the broader deformational network of central-eastern Anatolia. This southwestward motion is consistent with the left-lateral kinematics of the EAFZ and indicates that stress release during the mainshock sequence extended into transitional zones between the East and North Anatolian fault systems. The recorded motion at GURU highlights the spatial extent and complexity of crustal deformation in tectonically diffuse regions during large-scale seismic events. The southwestward movement of GURU is consistent with other stations north of the fault, such as MLY1 and MAR1, indicating a coherent regional deformation pattern.

The APK1 station, located in Arapkir (Malatya) on the western block of the EAFZ, recorded a coseismic horizontal displacement of approximately 1.37 meters in response to the February 6, 2023 Kahramanmaraş earthquake sequence. The movement was oriented toward the southwest, with a north component of −1195.68 mm and an east component of −676.97 mm. Although APK1 is located at a moderate distance from the primary rupture zones, the station lies within a tectonically sensitive region bordered by secondary fault structures and the northern boundary of the Malatya Fault. The southwestward motion observed at APK1 is consistent with the left-lateral strike-slip behavior of the EAF system and suggests effective transmission of coseismic strain into the interior of the Anatolian Plate. This displacement highlights the broad spatial impact of the earthquake sequence and emphasizes the importance of transitional fault zones in the regional deformation field.

The SIV1 station, located in Siverek (Şanlıurfa) to the south of the EAFZ, recorded a horizontal displacement of approximately 0.98 meters following the February 6, 2023 Kahramanmaraş earthquakes. The motion was directed toward the east-southeast, with a north component of −290.22 mm and an east component of +940.42 mm. Although the station is located at a considerable distance from the main rupture zones, the observed displacement indicates the propagation of coseismic strain into the broader Anatolian–Arabian plate boundary region. The east-southeastward motion is consistent with the regional stress field and the left-lateral kinematics of the EAFZ. The recorded movement at SIV1 reflects far-field deformation resulting from the earthquake sequence and contributes to understanding the spatial extent of crustal response beyond the immediate rupture zone.

The SURF station, located in the city center of Şanlıurfa, recorded a horizontal displacement of approximately 1.29 meters in response to the February 6, 2023 Kahramanmaraş earthquake sequence. The movement was directed toward the east-southeast, with a north component of −279.40 mm and an east component of +1261.82 mm. Although situated far from the main rupture segments of the EAFZ, SURF locates within the broader deformation field influenced by stress redistribution along the Anatolian–Arabian plate boundary. The observed displacement is consistent with far-field tectonic adjustment and reflects the capacity of large-magnitude seismic events to induce crustal motion over wide regions. The east-southeastward motion at SURF highlights the extended reach of coseismic strain and provides insights into how distant intraplate areas respond dynamically to fault rupture processes.

The ERGN station, located in Ergani (Diyarbakır), recorded a horizontal displacement of approximately 0.34 meters in response to the February 6, 2023 Kahramanmaraş earthquakes. The motion was oriented toward the east-southeast, consisting of a north component of −110.92 mm and an east component of +319.93 mm. Although the station is situated at a considerable distance from the main rupture zones of the EAFZ, the recorded displacement reflects far-field coseismic deformation transmitted through the Anatolian–Arabian plate boundary zone. The relatively small but clearly measurable displacement observed at ERGN is consistent with the broader tectonic pattern of left-lateral shearing along the EAFZ and regional strain redistribution during large-magnitude seismic events. These findings highlight the widespread influence of the Kahramanmaraş earthquake sequence and underscore the dynamic crustal response observed in distal intraplate areas.

The ELAZ station, located in Elazığ near the eastern extension of the EAFZ, recorded a horizontal displacement of approximately 0.70 meters following the Kahramanmaraş earthquake sequence. The motion was directed toward the southwest, with a north component of −551.37 mm and an east component of −435.57 mm. Although situated outside the immediate rupture zone of the 2023 events, the station lies within a tectonically active corridor previously affected by the 2020 Mw 6.8 Elazığ–Sivrice earthquake. The southwestward displacement at ELAZ reflects continued postseismic and interseismic deformation in the region and demonstrates the far-reaching effects of coseismic stress redistribution along the EAFZ. The recorded motion contributes to a more comprehensive understanding of how strain is accommodated along the eastern segments of the fault during and after large-magnitude ruptures.

Relatively more minor displacements were recorded at ERGN (0.34 m) and ELAZ (0.70 m), indicative of diminished coseismic effects at greater distances. The vector orientations and magnitudes provide strong geodetic evidence for the left-lateral strike-slip behavior of the EAFZ and highlight the asymmetric distribution of coseismic strain across the region. The magnitude and direction of the displacement vectors, ranging from 0.34 m (ERGN) to 30.9 m (EKZ1), clearly illustrate the spatial distribution of coseismic deformation induced by the February 6, 2023 earthquakes. The values and directions of displacements (Table 1 and Fig. 4 and Fig. 6) provide strong geodetic evidence for the left-lateral displacement along the EAFZ, confirming the complex fault behavior and strain partitioning in the region.

The horizontal displacement vectors (Table 2, Fig. 5 and Fig. 7) derived from GNSS observations during the postseismic period between March 2 and December 31, 2023, reveal continued deformation across the East Anatolian region following the February 6, 2023 earthquakes. The displacements were calculated as the vector sum of the north and east components presented in Table 2. Although the amplitudes of these displacements are significantly smaller than those recorded during the coseismic period, their spatial distribution and vector orientations provide valuable insights into the ongoing strain redistribution and fault relaxation processes. Notable postseismic displacements were observed at several stations located both on and around the EAFZ.

According to the postseismic period between March 2 and December 31, 2023, (Table 2) MLY1 recorded a horizontal displacement of approximately 70.84 mm to the south (negative north component) and 47.94 mm to the west (negative east component), corresponding to a total displacement of 85.5 mm/yr in the southwest (SW) direction. This substantial displacement reflects the ongoing postseismic deformation following the February 6, 2023 Kahramanmaraş earthquakes and is indicative of the viscoelastic relaxation and stress redistribution processes affecting the region. The consistent southwestward motion, driven by both the north and east components shifting in negative directions, suggests that the station continues to respond to tectonic re-equilibration along the western segment of the EAFZ. Furthermore, the occurrence of $M > 5$ earthquakes in Malatya in August 2023 supports the notion that stress transfer and fault loading are still active across the region. The observed displacement at MLY1 likely captures the combined effect of both large-scale postseismic relaxation and localized crustal adjustments triggered by subsequent moderate-magnitude seismic events.

ADY1 exhibited a horizontal displacement of approximately 14.87 mm toward the north and 81.20 mm toward the east, resulting in a total displacement of 82.6 mm/yr in the east direction. This dominant eastward motion indicates that the station sustained to be significantly affected by postseismic deformation processes following the February 6, 2023 Kahramanmaraş earthquakes. ADY1 is located near the eastern continuation of the EAFZ, where the right-lateral strike-slip kinematics of the Arabian–Anatolian plate boundary result in substantial eastward and slightly northward motion. The large magnitude and strongly undirectional eastward displacement suggest that stress redistribution and viscoelastic relaxation are still ongoing in the region. The continued deformation recorded by ADY1 reinforces the idea that the postseismic signal remained prominent throughout the rest of 2023, particularly in regions along and near the EAFZ's eastern segments.

The SUF1 station was installed at a location close to the former SURF station, and effectively continues monitoring crustal deformation in the same area. It presented a horizontal displacement of approximately 28.99 mm toward the north and 57.36 mm toward the east, corresponding to a total displacement magnitude of 64.3 mm/yr in the northeast direction. This notable northeastward motion indicates that SUF1 continued to reflect the influence of postseismic deformation following the February 6, 2023 Kahramanmaraş earthquakes. Although situated outside the primary rupture zone, the station's location within the broader deformation field of the EAFZ and the Arabian–Anatolian plate boundary makes it sensitive to stress transfer and viscoelastic processes induced by the mainshock. The displacement pattern observed at SUF1 likely represents the combined effects of regional viscoelastic relaxation and ongoing crustal adjustment, providing evidence that the postseismic signal remained active in southeastern Anatolia well into late 2023.

KLS1 exhibited a horizontal displacement of approximately 56.86 mm toward the north and 29.80 mm toward the east, resulting in a total displacement of 64.2 mm/yr in the northeast direction. This significant northeastward motion indicates a continued influence of postseismic deformation caused by the February 6, 2023 Kahramanmaraş earthquakes. Although KLS1 lies outside the immediate rupture zone, it is positioned within the broader deformation field of the EAFZ and the adjacent Dead Sea Fault system. The displacement observed at KLS1 suggests that the region has remained tectonically active during the postseismic phase, with ongoing viscoelastic relaxation and stress redistribution influencing crustal motion. The northward component is dominant, yet the substantial eastward movement implies complex stress pathways in this transitional tectonic zone. KLS1's displacement pattern provides further evidence that the effects of the February 6 earthquakes extended well beyond the rupture areas, continuing to drive measurable crustal motion across southeastern Türkiye throughout 2023.

ELAZ presented a horizontal displacement of approximately 60.14 mm toward the south (negative north component) and 7.86 mm toward the west (negative east component). These values correspond to a total displacement of 60.7 mm/yr directed predominantly toward the south. This distinct southward motion indicates that ELAZ was still responding to the postseismic deformation induced by the February 6, 2023 Kahramanmaraş earthquakes. ELAZ lies within the eastern section of the EAFZ, a region that has already experienced major seismic activity in recent years, including the 2020 Elazığ earthquake (M6.8). The movement pattern observed at ELAZ during this period suggests that viscoelastic relaxation and stress transfer processes were still ongoing in the crust surrounding the EAFZ. The station's relatively linear southward displacement, with minimal east-west contribution, implies a predominantly vertical redistribution of stress along the fault system, possibly influenced by the broader tectonic re-equilibration occurring after the 2023 events. This reinforces the interpretation that the effects of the February 6 mainshocks extended eastward, continuing to drive crustal readjustment in areas that had already been structurally stressed in previous years.

SIV2 exhibited a horizontal displacement of approximately 20.29 mm toward the north and 50.93 mm toward the east, resulting in a total displacement of 54.8 mm/yr in the east-northeast direction. This displacement pattern reflects the continued postseismic deformation following the February 6, 2023 Kahramanmaraş earthquakes. Although Siverek is situated outside the primary rupture zones, its location in the southeastern Anatolian region places it within the broader deforming area influenced by stress changes along the EAFZ and the Arabian–Anatolian plate boundary. The strong eastward and moderate northward movement suggests that viscoelastic relaxation and stress redistribution remained active in the region during the observation period. The displacement direction is consistent with the general tectonic escape of the Anatolian plate toward the west-northwest, but modified locally due to the lingering effects of the February earthquakes. Overall, the kinematic behavior of SIV2 provides valuable insight into the regional-scale postseismic response of the southeastern Anatolian crust in the months following the 2023 seismic crisis.

GURU represented a horizontal displacement of approximately 5.99 mm toward the south (negative north component) and 37.27 mm toward the west (negative east component), corresponding to a total displacement of ~37.7 mm/yr directed toward the west. Although Gürün (Sivas) is positioned north of the main rupture zones of the February 6, 2023 Kahramanmaraş earthquakes, the displacement pattern observed at GURU suggests that the area continued to experience secondary postseismic effects, likely due to long-range viscoelastic relaxation and stress transfer propagating northward along the broader deforming corridor of eastern Anatolia. The predominantly westward motion of GURU may also reflect tectonic coupling variations across the region, where residual stress redistribution causes minor crustal displacements even in areas removed from the primary rupture zones. In this context, GURU's motion can be interpreted as part of the broader postseismic deformation field that extended into the interior of the Anatolian Plate. These findings indicate that the far-field impact of the 2023 earthquakes remained geodetically detectable across a wide region, including the northern periphery of the EAFZ.

APK1 recorded a horizontal displacement of approximately 30.48 mm toward the south (negative north component) and 20.13 mm toward the west (negative east component). This corresponds to a total displacement of 36.5 mm/yr directed toward the southwest. Situated northwest of the main rupture zones of the February 6, 2023 Kahramanmaraş earthquakes, the displacement at APK1 suggests that the station was still responding to postseismic deformation, likely due to delayed viscoelastic relaxation and regional-scale stress redistribution. The southwestward motion is consistent with the direction of coseismic and postseismic crustal flow observed across the EAFZ and its surrounding regions. Although the magnitude of displacement at APK1 is lower than at stations closer to the epicentral area, it still indicates tectonic sensitivity to the broader post-earthquake deformation field. The presence of this motion months after the mainshock sequence supports the interpretation that crustal adjustments remained active throughout the second half of 2023, even in locations removed from the principal fault rupture.

ERGN recorded a horizontal displacement of approximately 19.02 mm toward the north and 28.03 mm toward the east and the total displacement value of 33.9 mm/yr directed toward the northeast. Although ERGN is situated at some distance from the primary rupture zones of the February 6, 2023 Kahramanmaraş earthquakes, the station still recorded a measurable northeastward displacement during the postseismic period. This motion likely reflects the influence of long-wavelength viscoelastic relaxation processes affecting the broader Arabian–Anatolian collision zone. The displacement pattern is consistent with the overall tectonic escape of the Anatolian Plate toward the west and northwest, while also capturing the local expression of postseismic stress transfer extending into the southeastern regions of the deforming zone. The persistent northeastward motion observed at ERGN supports the notion that postseismic effects propagated over a wide area, with crustal adjustments continuing throughout the remainder of 2023.

HAT2 recorded a horizontal displacement of approximately 26.03 mm toward the north and 17.51 mm toward the west (negative east component). These values correspond to a total displacement magnitude of 31.4 mm/yr directed toward the northwest. Situated near the southern terminus of the EAFZ and within the rupture area of the February 6, 2023 earthquakes, HAT2 remains in a highly sensitive tectonic environment. The station's northwestward motion during the postseismic period likely reflects a combination of coseismic stress redistribution, viscoelastic relaxation, and possible interactions with the adjacent Dead Sea Fault and Cyprus Arc systems. The continued deformation recorded at HAT2 indicates that the postseismic signal remained geodetically detectable in Hatay well into late 2023. The displacement pattern is also consistent with the complex tectonic regime of the region, where multiple plate boundaries and fault systems converge, producing oblique deformation and heterogeneous crustal responses.

MAR1 recorded a horizontal displacement of approximately 19.75 mm toward the north and 13.38 mm toward the east, corresponding to a total displacement of 23.9 mm/yr directed toward the northeast. Positioned near the epicentral region of the devastating February 6, 2023 earthquakes, MAR1 lies within the zone that experienced intense coseismic ground deformation. The continued northeastward movement observed in the postseismic period highlights the station's sensitivity to ongoing viscoelastic relaxation, afterslip, and stress redistribution around the ruptured segments of the EAFZ. While the displacement magnitude is modest compared to the immediate coseismic offsets, it reflects a persistent postseismic signal that was still active nearly a year after the mainshock sequence. The direction of movement—toward the NE—is consistent with the overall kinematic pattern of crustal adjustment across southeastern Anatolia following the rupture of multiple fault strands in February 2023. The MAR1 data provide critical constraints for understanding long-term deformation transients in the core rupture area and for modeling the spatiotemporal evolution of postseismic processes in one of Türkiye's most complex tectonic settings.

ONIY recorded a horizontal displacement of approximately 14.50 mm toward the north and 5.36 mm toward the east, resulting in a total displacement value of 15.5 mm/yr in a generally north-northeast direction. Although Osmaniye lies just south of the EAFZ and outside the main rupture areas of the February 6, 2023 earthquakes, the displacement recorded at ONIY represents the continued regional crustal response to the seismic sequence. The modest north-northeastward motion is indicative of long-range viscoelastic relaxation and potential secondary stress adjustments within the Arabian–Anatolian plate boundary region. Given its location near the junction of the EAFZ, the Dead Sea Fault, and the Eastern Mediterranean subduction complex, the crustal dynamics around Osmaniye are inherently complex. The motion at ONIY likely reflects a combination of postseismic effects and broader tectonic coupling between interacting fault systems in this transitional zone. This displacement pattern reinforces the idea that measurable postseismic deformation persisted well into late 2023, even in peripheral areas such as Osmaniye.

EKZ1 recorded a horizontal displacement of approximately 7.43 mm toward the north and 12.74 mm toward the west (negative east component), corresponding to a total displacement magnitude of 14.7 mm/yr directed toward the northwest. Situated close to the northern edge of the rupture zone of the February 6, 2023 earthquakes, EKZ1 lies in a region that experienced strong ground shaking and intense coseismic deformation. The proceeded northwestward motion observed during the postseismic period reflects the influence of residual stress redistribution, after-slip, and viscoelastic relaxation processes still active in the crust surrounding the EAFZ. Although the displacement magnitude is moderate, its direction and persistence suggest that postseismic deformation remained measurable in this part of the fault system throughout the rest of 2023. The combination of northward and westward components is also consistent with the local tectonic geometry, where oblique convergence and strike-slip motion jointly shape crustal kinematics. EKZ1 serves as a valuable indicator of how the northern segments of the rupture system continued to deform following the mainshock, and contributes to a more complete understanding of the spatial extent of the postseismic response.

MLY1 station experienced a major coseismic displacement (6329.6 mm) toward the southwest during the February 6, 2023 earthquakes, indicating intense ground motion and proximity to the rupture zone. In the postseismic period, the station continued to move in the same southwestward direction, but with a reduced amplitude (85.5 mm), which is still substantial. The persistence of southwestward motion suggests ongoing postseismic deformation, likely due to viscoelastic relaxation and afterslip along the EAFZ. Although the amplitude of displacement decreased the directionality remained consistent, indicating that the tectonic forces and stress fields responsible for coseismic movement continued to influence the region for many months after the mainshock.

APK1 and ELAZ experienced coseismic southwestward displacements (1.37 m and 0.70 m, respectively), followed by additional postseismic movements of 36.5mm (APK1) and 60.7 mm (ELAZ). The continuation of movement along the same azimuth supports the hypothesis of afterslip and/or viscoelastic adjustment in the northern block. ADY1 and KLS1, located south of the fault, showed coseismic displacements of 5.15 m and 2.64 m, toward the east and northeast, respectively and continued moving in the same direction for each station postseismically (82.6 mm and 64.2 mm). These patterns indicate that the southern block, although less deformed than the northern block, is also undergoing postseismic relaxation consistent with left-lateral strike-slip motion. SIV2, SURF (SUF1), and ERGN, positioned farther east, experienced lower coseismic displacements (0.98 m, 1.29 m and 0.34 m., respectively toward east), and recorded continued postseismic movements of 54.8, 64.3 and 33.9 mm., respectively toward the northeast. This widespread response, despite the distance from the rupture zone, reflects strain propagation into the Arabian Plate. HAT2 experienced a coseismic southwestward displacement of 1.23 m and continued to move northwestward by 31.4 mm postseismically. This movement suggests continued deformation along the southern block of the fault, likely due to stress redistribution or afterslip near the Antakya segment. MAR1, which moved 5.16 m west-southwest during the mainshock, recorded 23.9 mm of postseismic displacement toward the northeast. This change in direction may indicate complex interactions in the central rupture zone, possibly involving local block rotations or secondary fault activity. ONIY shifted 2.23 m southwest coseismically, followed by 15.5 mm of northeastward movement postseismically. This reversal is particularly interesting, as it suggests postseismic strain recovery or re-equilibration within the southern block. Meanwhile, EKZ1 (Ekinozü, Kahramanmaraş), which underwent the largest coseismic displacement (30.94 m), exhibited very little postseismic motion (14.7 mm), indicating that strain release in that segment was nearly complete during the mainshock. GURU, which moved 1.57 m southwest during the mainshock, continued to experience westward displacement of 37.7 mm postseismically, supporting the presence of extended deformation in the northern back-arc region.

Consequently, it can be said that the stress changes caused by the February 6, 2023 Kahramanmaraş earthquakes continue to induce displacements in the region. Therefore, the region remains seismically active, and enhancing geoscientific and engineering studies in the area will be crucial in preventing loss of life and property in the event of potential future earthquakes.

Conclusions

The integrated analysis of seismic activity and GNSS-derived deformation patterns following the February 6, 2023 Kahramanmaraş earthquakes reveals the complex and ongoing tectonic response of the EAFZ. The coseismic phase was characterized by sudden, high-magnitude displacements, particularly at stations located near the rupture zone (e.g., EKZ1, MLY1, MAR1), illustrating the abrupt strain release associated with fault rupture. In contrast, the postseismic phase between March 2 and December 31, 2023 was marked by slower, lower-magnitude motions, reflecting a gradual redistribution of stress and continued crustal adjustment throughout the region.

The contrast between these two phases underscores the time-dependent nature of tectonic deformation. While many stations (e.g., MLY1, ADY1, KLS1) exhibited continued motion along the same vectors as during the mainshock—indicative of consistent stress relaxation—others (e.g., MAR1, ONIY) showed modified or even reversed displacement directions, suggesting localized variations in fault behavior, afterslip, viscoelastic relaxation, and possible secondary fault interactions. Though smaller in magnitude, the postseismic displacement vectors provide essential insights into the dynamic processes that occur after major seismic events.

The spatial distribution of both coseismic and postseismic displacements aligns with the left-lateral strike-slip kinematics of the EAFZ, extending well beyond the immediate rupture zone. Stations located further from the fault, such as GURU, SUF1, ERGN, and HAT2, also recorded significant postseismic movement, indicating regional strain propagation and the widespread impact of the February 6, 2023 earthquakes. This broader deformation pattern emphasizes that tectonic adjustments are not limited to the main fault trace but may influence adjacent crustal blocks, including back-arc and foreland regions.

Notably, the recurrence of moderate-magnitude earthquakes (Mw ≥ 5.0) in Malatya and surrounding areas in the months following the mainshock suggests that stress changes induced by the February 6,2023 events continue to influence seismic activity in the region. The temporal and spatial consistency between historical seismicity (1990–2023) and post-earthquake events further supports the interpretation of the Malatya segment as a persistent zone of strain accumulation and release.

These findings highlight the necessity of integrating both coseismic and postseismic observations to fully understand fault mechanics and the evolution of regional strain, particularly in tectonically complex settings like Eastern Anatolia. Continuous GNSS monitoring is essential for capturing long-term deformation trends, assessing evolving seismic hazards, and improving the accuracy of future earthquake forecasting models.

In conclusion, the East Anatolian region remains seismically active in the aftermath of the February 6, 2023 earthquakes. The observed patterns of postseismic motion, ongoing crustal adjustment, and repeated moderate-magnitude events underscore the urgency of enhancing geoscientific and engineering research, implementing early warning systems, and updating seismic risk mitigation strategies to reduce potential loss of life and property in future seismic events.

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Statements & Declarations

Author contributions: İbrahim Berkan Kırdök downloaded and regulated the GNSS and seismological data; Ayça Çırmık processed the data, performed the analysis, and drafted the manuscript; Ayça Çırmık and İbrahim Berkan Kırdök designed the figures. All authors discussed the results and commented on the manuscript and all authors contributed to writing the manuscript.

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