The effects of seismic activities following the 30 October 2020 Samos Island earthquakes in Izmir and its surroundings

Oya Ankaya PAMUKÇU[1], Ayça ÇIRMIK[1], Fikret DOĞRU[2], Ekrem TUŞAT[3], Fatih UYSAL[3], Hasan SÖZBILIR[4], Ufuk AYDIN[5], Özkan Cevdet ÖZDAĞ[6,*], Metehan ULUĞTEKIN[7], Fulya ÖZDEMIR[8], Zülfikar ERHAN[1]

[1] Dokuz Eylul University, Engineering Faculty, Geophysical Engineering, 35400, Izmir, Türkiye

[2] Atatürk University, Oltu Vocational College, Construction, 25400, Erzurum, Türkiye

[3] Konya Teknik University, Engineering and Natural Science Faculty, Map Engineering, 42250, Konya, Türkiye

[4] Dokuz Eylul University, Engineering Faculty, Geology Engineering, 35400, Izmir, Türkiye

[5] Atatürk University, Engineering Faculty, Civil Engineering, Geotechnical Department, 25240, Erzurum, Türkiye

[6] Dokuz Eylül University, Earthquake Research and Implementation Center, 35400, Izmir, Türkiye

[7] Dokuz Eylül University, Graduate School of Natural and Applied Sciences, 35400, Izmir, Türkiye

[8] Konya Teknik University, Graduate Education Institute, 42250, Konya, Türkiye

Abstract: With the increasing rate of subduction along the Hellenic Arc in the Eastern Mediterranean, the seismic activities of the Aegean plate and Western Anatolia have markedly increased over the past decade. The increase in seismic activity is quite remarkable, starting from the coasts of Çanakkale in the north of Western Anatolia, including Lesbos Island, Samos Island, Kuşadası Bay and Datca. In this context, in order to determine the current deformation after the Samos Island earthquake that occurred on October 30, 2020, measurements were performed at six continuous GNSS stations in and around Izmir. This study is jointly managed by Dokuz Eylül University, with contributions from Konya Technical University and Atatürk University, focusing on both GNSS and seismological analyses. The preliminary results of this investigation include the evaluation of seismic impacts on the continuous GNSS stations from July 1st to December 31st, 2022.

Key words: earthquake, GNSS, subduction, seismic, Izmir, Western Anatolia

*corresponding author, e-mail: cevdet.ozdag@deu.edu.tr

doi: 10.31577/congeo.2024.54.4.2

1. Introduction

With the Samos earthquake of 30 October 2020 (Mw = 6.6), it was understood that the active faults in Izmir and its immediate surroundings have the potential to produce earthquakes reaching magnitude 7 in the future. These earthquakes are likely to be produced by active faults located near Izmir urban settlement. Simulation studies have shown that there is a significant amount of stress accumulation on various faults in Izmir and the surrounding region and that the Izmir fault, which is located in the city centre, can produce an earthquake of magnitude 6.9 (*Bjerrum et al., 2013*).

Izmir and its surroundings have experienced very destructive earthquakes in historical times. Izmir and Orhanlı-Tuzla Fault Zones are among the most active faults in this area. The city centre of Izmir, located on the hanging wall block of the Izmir fault was displaced 60 cm by the earthquake which had a magnitude of (Mw: 6.8) in 1688 (*Gok and Polat, 2014*).

The study area, which includes Izmir and its vicinity, is located in a region that deforms under the influence of expansion forces in the N–S direction of Western Anatolia (*Dewey and Şengör, 1979; Şengör et al., 1985*) (Fig. 1). There are Tavşanlı Zone, Afyon Zone, Menderes Massif and Lycian Nappes in the Western Anatolia Extension Region (*Okay et al., 1996*). These zones are separated from each other by tectonic contacts. As a result of the extensional tectonics that developed during the Miocene period, the region was divided by dip-slip and strike-slip faults and the formation of basins containing sedimentary stacks with volcanic intercalations up to 2000–3000 metres high in the resulting deposit areas occurred (*Sözbilir, 2001; Sözbilir, 2002; Bozkurt and Sözbilir 2004*). These basins, extending in NE–SW, NW–SE and E–W directions, were fragmented due to the tectonic phase that developed after the Neogene and the formation of today's Quaternary basins took place (*Sözbilir et al., 2011; Özkaymak et al., 2013; Uzel et al., 2012*). For this reason, rock groups belonging to both the Palaeotectonic and Neotectonic periods are exposed within the borders of Izmir province. In particular, the metamorphic rocks of the Menderes Massif, which formed the pre-Miocene foundation of the basins, cover large areas around Kiraz-Ödemiş-Tire-Torbalı. The Yuntdağı uplift, which crops out between Soma and Bayraklı, is a Miocene-aged volcanic mountain extending in the NE–SW direction. Yuntdağı volcanics, which are located along large-scale fault zones that developed in the NE–SW direction during

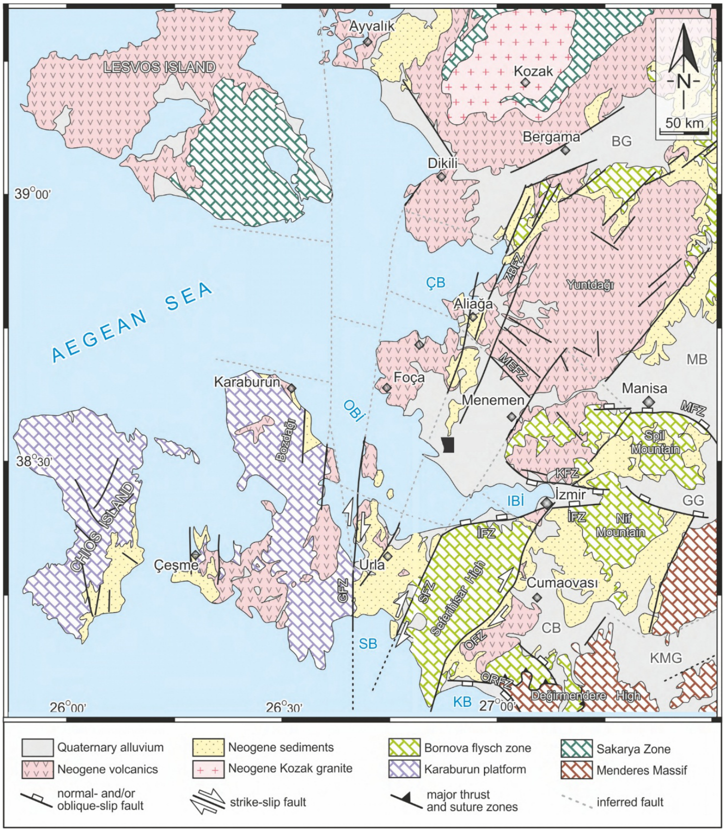


Fig. 1. Geology map of study area (revised from *Uzel et al., 2012*).

the Miocene period, contain outlet centers that cut the Late Cretaceous-Paleocene aged Bornova Flysch Zone (Bornova Complex) rocks. The east and west of this volcanic mountain are surrounded by volcano-sedimentary and lacustrine sediments of the same age.

The Izmir and its surroundings, characterized by complex geological and tectonic features, have once again been highlighted as an area of high seismic risk due to recent seismic events. These include the 2005 Seferihisar earthquake, the 2017 Aegean Sea earthquake (offshore Izmir/Karaburun and Lesbos Island), and most recently, the 2020 Samos Island earthquake (offshore Izmir-Seferihisar), along with the subsequent aftershocks. These events underscore the significant seismic hazard present in the region. Especially due to the effect of the 2020 Samos Island earthquake, a tsunami occurred in Seferihisar, the southern coast of Izmir. The main point of discussion regarding this earthquake is that the buildings that collapsed (in Bayraklı/Izmir) were located at a considerable distance from the earthquake's epicentre. Earthquake waves amplify as they propagate along paths that best accommodate their physical properties. Moreover, these waves can increase seismic risk by activating kinematic mechanisms in the regions they traverse. The amplitude and velocity of earthquake waves are influenced by various factors, including the nature of the tectonic regime (compression or tension), fault density, and the rigidity of the medium through which they travel.

Following the Seferihisar earthquake in 2005, which left a significant mark on Izmir and its surroundings, GNSS measurements, time-dependent gravity and profile gravity measurements throughout Izmir, and the general kine-

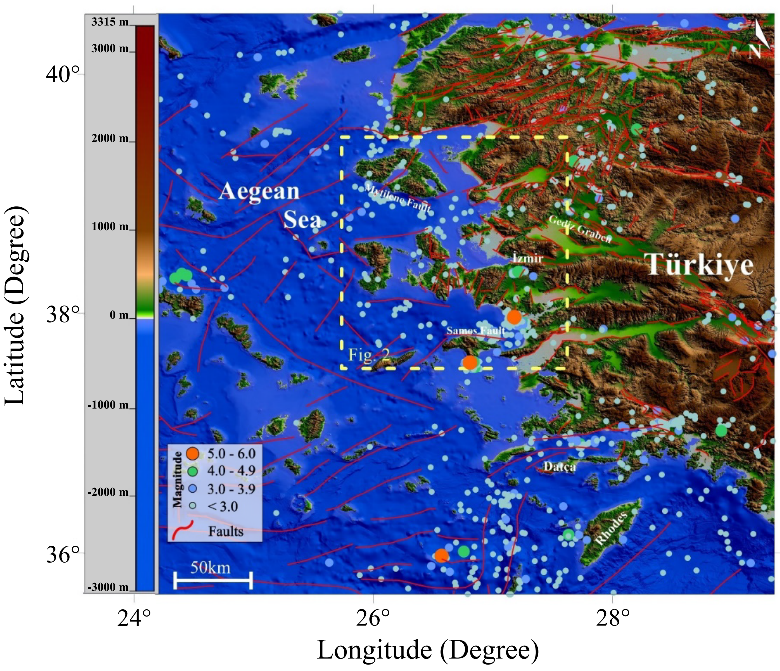


Fig. 2. Distribution of 1077 earthquakes obtained from the AFAD earthquake catalogue, with magnitudes $2 < M < 6$, occurring in Izmir and its surroundings between July 1st, 2022 and December 31st, 2022 (faults are compiled from *Emre et al., 2013; Sözbilir et al., 2020*).

matic structure in the region and the deformation character of these structures were determined before the 2020 Samos Island earthquake (*Çetiner, 2012; Pamukçu et al., 2012; Pamukçu et al., 2014; Pamukçu et al., 2015a; Pamukçu et al., 2015b; Çırmık et al., 2016; Çırmık et al., 2017a; Çırmık et al., 2017b; Kahveci et al., 2019; Malaliçi, 2019; Pamukçu et al., 2022*). Additionally, in the study of (*Gürçay and Çifçi, 2021*) performed in the Aegean Sea to analyze the structure responsible for the 2005 Seferihisar earthquake revealed that the study region possesses a highly complex tectonic mechanism.

Within the scope of this study, the earthquakes that occurred in the region between July 1st and December 31st, 2022 after the October 30,

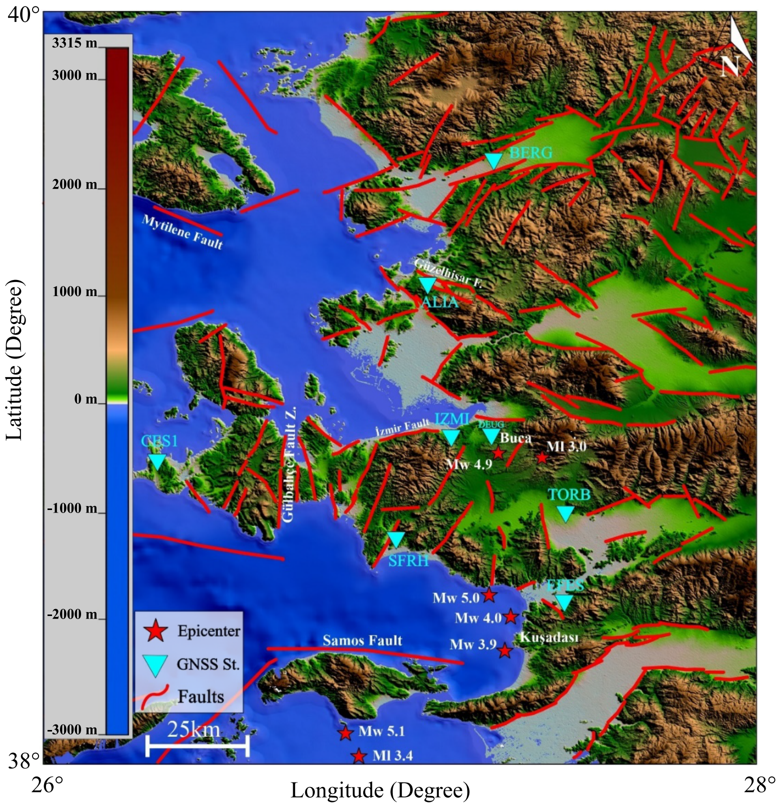


Fig. 3. Locations of continuous GNSS stations used in the study (reverse green triangle shows the locations of the stations – faults are compiled from *Emre et al., 2013; Sözbilir et al., 2020*).

2020 Samos earthquake (Fig. 2) were examined with GNSS data of continuous GNSS stations located in and around Izmir. These are: ALIA (Aliağa/Izmir), BERG (Bergama/Izmir), EFES (Selçuk/Izmir), SFRH (Seferihisar/Izmir), TORB (Torbali/Izmir) (built within the scope of this study), DEUG (located in Dokuz Eylul University, Buca/Izmir) (Fig. 3). Additionally, CES1 (Çeşme, Izmir) and IZMI (Izmir city center) (Fig. 3) stations belonging to CORS-Tr were included in the analysis and the GNSS data were processed with GAMIT/GLOBK software v.10.71 (*Herring et al., 2018*) by using the ITRF2014 datum and the Eurasian plate as fixed.

2. Materials and methods

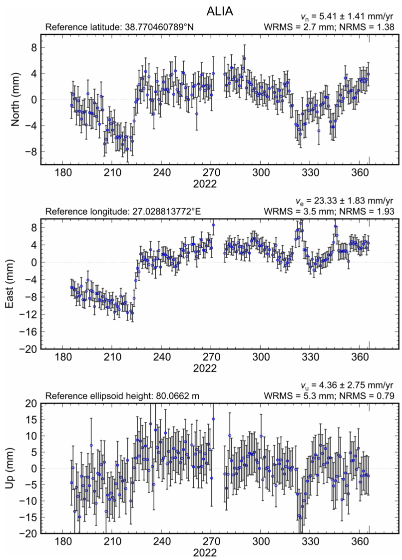
2.1. Analysis of GNSS data

The continuous stations ALIA, BERG, EFES, SFRH, TORB (Fig. 3) were built within the scope of this study and started receiving GNSS data on July 1, 2022 (Fig. 4). The data between July 1st and December 31st, 2022 of these stations, the continuous station (DEUG) located in Dokuz Eylül University and CORS-Tr stations, IZMI (Izmir, City centre) and CES1 (Cesme, Izmir) stations (Fig. 2) were processed with GAMIT/GLOBK (*Herring et al., 2018*) software with the evaluation parameters given in Table 1 and the time series were obtained (Fig. 5a–h).

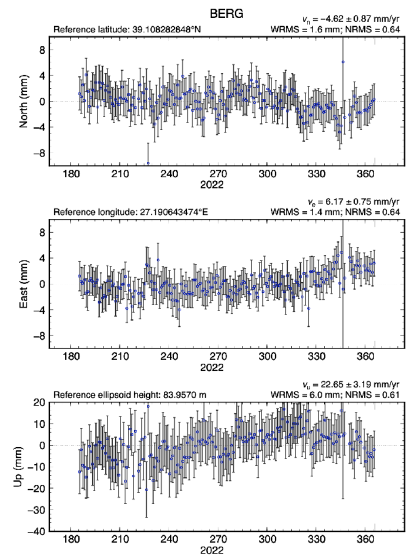
Fig. 4. View of a permanent station (TORB; Torbalı, Izmir) built within the scope of the study.

Table 1. The process parameters of GNSS measurements.

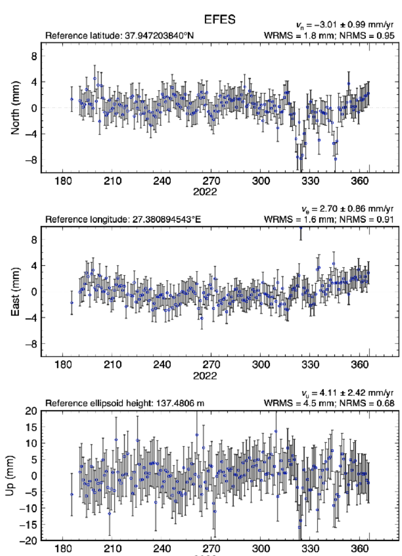
Parameter	**Parameter value**
Data frequency	30 seconds
Satellite elevation angle	For data collection: 0 degrees, for evaluating GNSS measurements: 5 degrees
Orbit information	IGS result in trajectory and ERP
Antenna phase centre information	Phase centre model with elevation angle-dependent weighting (PCV-antmod.dat)
Troposphere parameter	VMF (Vienna Mapping Function) model, zenith delay parameters for each hour
Used IGS Stations for Eurasian fixed frame solutions	IGS stations: ANKR (Ankara, Turkey), ARTU (Russia), ARUC (Armenia), BAHR (Bahrain), BOR1 (Poland), CRAO (Ukraine), DRAG (Israel), GLSV (Ukraine), GOPE (Czechia), GRAZ (Austria), ISTA (Istanbul, Turkey), JOZE (Poland), KIT3 (Uzbekistan), MATE (Italy), NICO (Cyprus), NOT1 (Italy), NSSP (Armenia), ONSA (Sweden), PENC (Hungary), POLV (Ukraine), POL2 (Kyrgyzstan), POTS (Germany), RAMO (Israel), TRAB (Trabzon, Turkey), TUBI (Kocaeli, Turkey), VILL (Spain), WSRT (Netherlands), WTZR (Germany), YEBE (Spain), YIBL (Oman), ZIMM (Switzerland), ZWE2 (Russia), ZWEN (Russia)
Carrier wave phase ucertainty solution method	WL (Wide Lane) and NL (Narrow Lane) methods are used.
Correlation	All correlations between observations and unknowns will be taken into account (full correlation).
Result coordinate calculation	A 1 mm restriction was applied to the IGS point coordinates to be taken as continuous in the calculations, and the combining of different days was done with GLOBK.



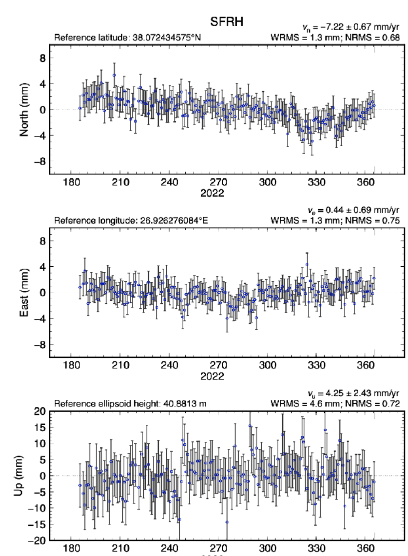
(a)



(b)

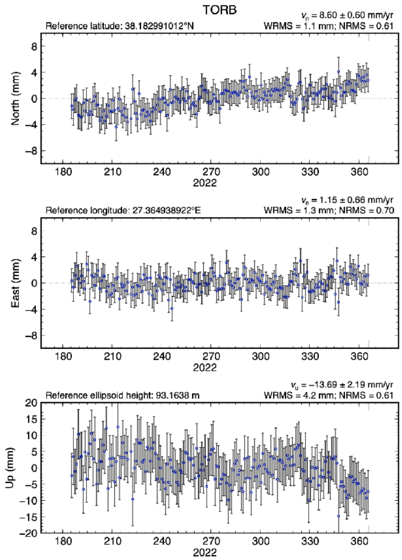


(c)

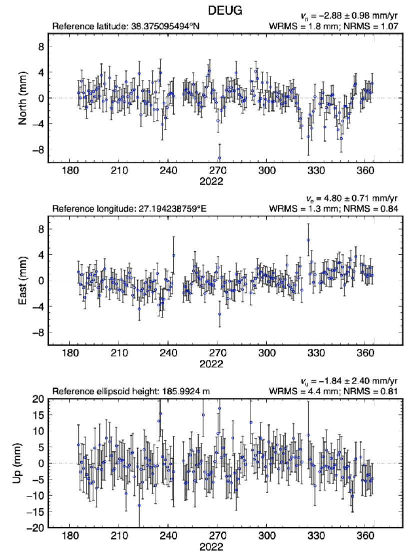


(d)

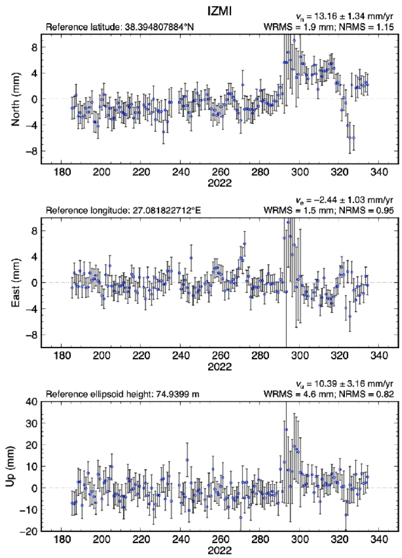
Fig. 5. Continued on the next page.



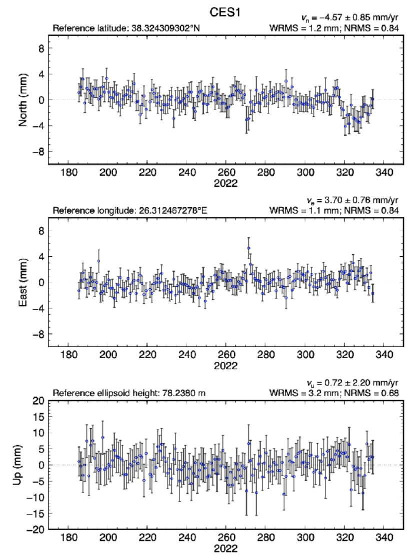
(e)



(f)



(g)



(h)

Fig. 5. Time series of a) ALIA (Aliağa), b) BERG (Bergama), c) EFES (Selçuk), d) SFRH (Seferihisar), e) TORB (Torbalı), f) DEUG (Dokuz Eylül University, Buca), g) IZMI (Izmir City Center), h) CES1 (Çeşme) stations.

2.2. Study of deformation analysis

Deformation analysis is a crucial dataset for identifying of earthquake-prone areas. In this study, the deformation was determined through the analysis of GNSS data. In its simplest terms, deformation is defined as the change in shape of an object due to an applied force. Depending on the magnitude of the stress exerted, the object may either return to its original shape, undergo permanent deformation, or even fracture (*Turcotte and Schubert, 2002*). In light of this information, it is possible to predict that the recent earthquakes in the study area created a new deformation and stress regime in the rock units and micro-scale plates in the region. It is important for the region to reveal the current tension and the deformation occurring. The deformation analysis carried out within the study was carried out using GeodSuit software developed by MDSoft (purchased within the scope of project no. DEU 2018.KB.FEN.010). The mathematical basis of this software deformation analysis is based on (*Shen et al., 1996; Aktuğ et al., 2009*) improved this basis by modifying it. In this way, deformation rates were calculated and mapped using velocity and displacement data obtained from GNSS data analysis (*Malaliçi, 2019*).

At the crustal-scale, deformation can be described by a tensor expressed as longitudinal change and rotational changes. In this tensor, the deformation of movement in one direction in that direction or perpendicular direction is defined as ε:

$$E = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} \\ \varepsilon_{yx} & \varepsilon_{yy} \end{bmatrix}. \tag{1}$$

In Eq. (1), E is the strain tensor.

With these approximations and using the velocity data from previously mentioned and the other GNSS stations located in and around Izmir a deformation map is generated for Western Anatolia and surroundings of Izmir (Fig. 6).

3. Results and discussion

The impact of the Aegean Sea and Western Anatolia earthquakes on GNSS locations after July 1, 2022, the date of the establishment of stable GNSS stations in the study area, is summarized in Table 2.

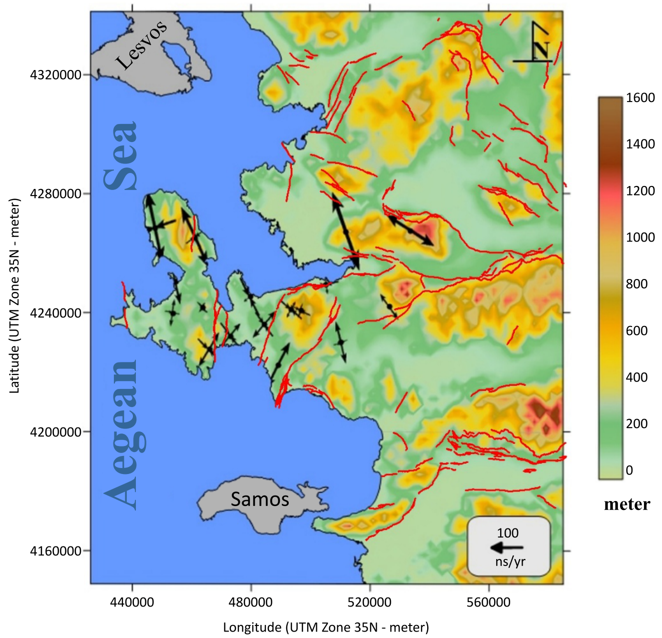


Fig. 6. The deformation map of the study area. The arrows represent strain rates (nanostrain/yr) (faults are compiled from (red lines) *Emre et al., 2013; Sözbilir et al., 2020*).

The horizontal (North-East) and vertical (Up) components of the time series of continuous GNSS stations presented in Fig. 5, which have been collecting GNSS data continuously since July 1, 2023, after the Samos earthquake of October 30, 2020. The distribution of 1077 earthquakes (Fig. 2), which occurred between 1 July and 31 December 2022, had a magnitude of $2 < \mathrm{M} < 6$ and were procured from the AFAD earthquake catalogue, were examined together.

Considering the time series of the stations (Fig. 5), the time series of the ALIA station located in Aliağa district of Izmir and the effect of earthquakes can be seen in detail in Fig. 7. The earthquake that occurred on August 14, 2022 in the Aegean Sea-Kuşadası Gulf of the ALIA station affected the North and East components of the station and caused the station to move north and east. It was observed that the earthquake that occurred in the Aegean Sea on September 26, 2022 had an impact on the Eastern component of the station and caused an eastward movement in the station. It is seen that both horizontal (North and East) and vertical (Height) compo-

Table 2. Comparing earthquakes which occurred in the study area and its vicinity after 30th October 2020 Samos earthquake with the data of the continuous GNSS stations built in this study and the continuous GNSS stations located in the study area. (Earthquakes were procured from AFAD earthquake catalogue (`https://deprem.afad.gov.tr/event-catalog`), "×" represents the earthquake impact in the table).

Earthquake Date/Location/ Magnitude	**Days of the year in the time series of GNSS stations (Fig. 5)**	**ALIA**	**BERG**	**EFES**	**SFRH**	**TORB**	**DEUG**	**IZMI**	**CES1**
14 August 2022/ Aegean Sea-Kuşadası Gulf/ Mw = 5.0	226th day	×	×	–	–	–	×	–	–
31 August 2022/ Aegean Sea-Kuşadası Gulf/ Mw = 5.1	243th day	–	–	–	–	–	×	×	–
26 Sept. 2022/ Aegean Sea and Izmir-Buca/ Ml = 3.4 Ml = 3.0	269th day	×	–	–	–	–	×	×	×
4–21 Nov. 2022/ Izmir-Buca/ Ml = 5.1	308 – 325th days	×	×	×	×	×	×	×	×
8 Dec. 2022/ Aegean Sea-Kuşadası Gulf/ Mw = 4.0	342th day	×	–	–	×	–	×	×	×
13 Dec. 2022/ Aegean Sea-Kuşadası Gulf/ Mw = 3.9	347th day	×	×	×	–	×	×	×	×

nents were affected by the Izmir-Buca earthquakes between 4–21 November 2022. This earthquake caused the station to collapse by moving south and east. It is seen that the earthquake that occurred on December 8, 2022 was effective in the Northern and Eastern components and caused movement towards the south and east. It was observed that the December 13, 2022 earthquake was effective in the Northern and Eastern components and caused movement towards the north and west.

When the time series of the BERG station located in the Bergama district of Izmir and the effects of earthquakes (Fig. 8) are examined, the

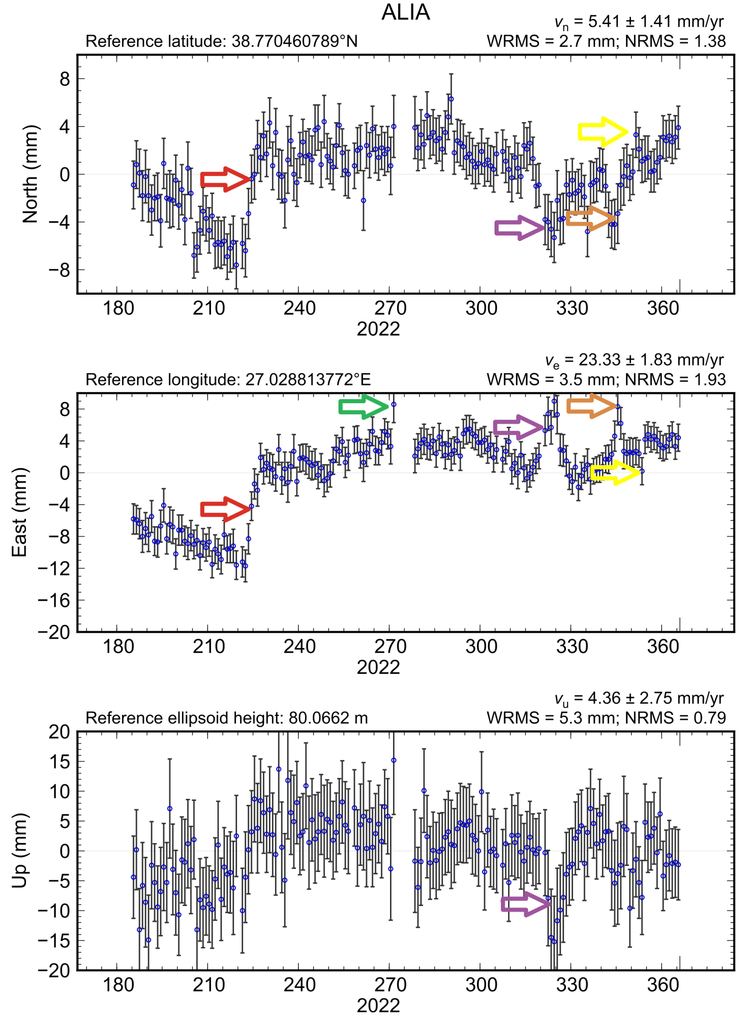


Fig. 7. Time series of ALIA station located in Aliağa district of Izmir and the image of the effects of earthquakes in the region. Red arrow: 14 August 2022, green arrow: September 26, 2022, purple arrow: 4–21 November 2022, orange arrow: December 8, 2022, yellow arrow: it represents the earthquakes that occurred on December 13, 2022.

earthquake that occurred on 14 August 2022 at the BERG station affected the North and East components of the station and caused the station to move south and east. It is seen that the eastern component was affected by the Izmir-Buca earthquakes that occurred between 4–21 November 2022.

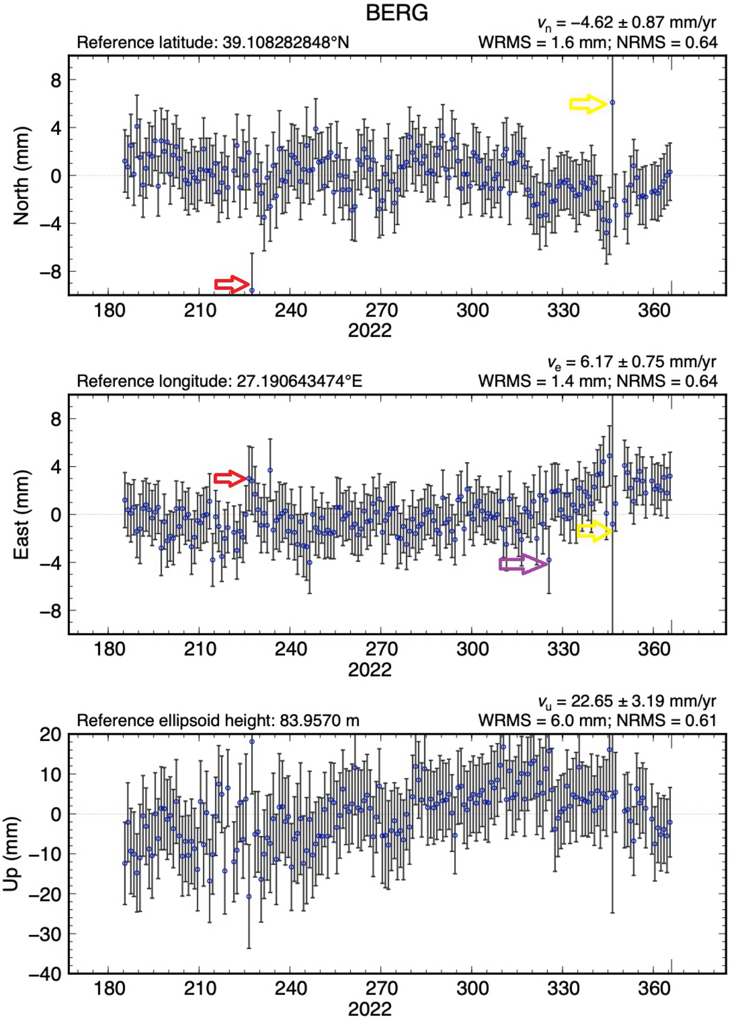


Fig. 8. Time series of the BERG station located in the Bergama district of Izmir and the image of the effects of earthquakes in the region. Red arrow: 14 August 2022, purple arrow: 4–21 November 2022, yellow arrow: it represents the earthquakes that occurred on December 13, 2022.

With this earthquake, the station moved westward. The December 13, 2022 earthquake was effective in the North and East components and movement occurred towards the north and west. When the time series of the EFES station located in the Selçuk district of Izmir and the effect of earthquakes

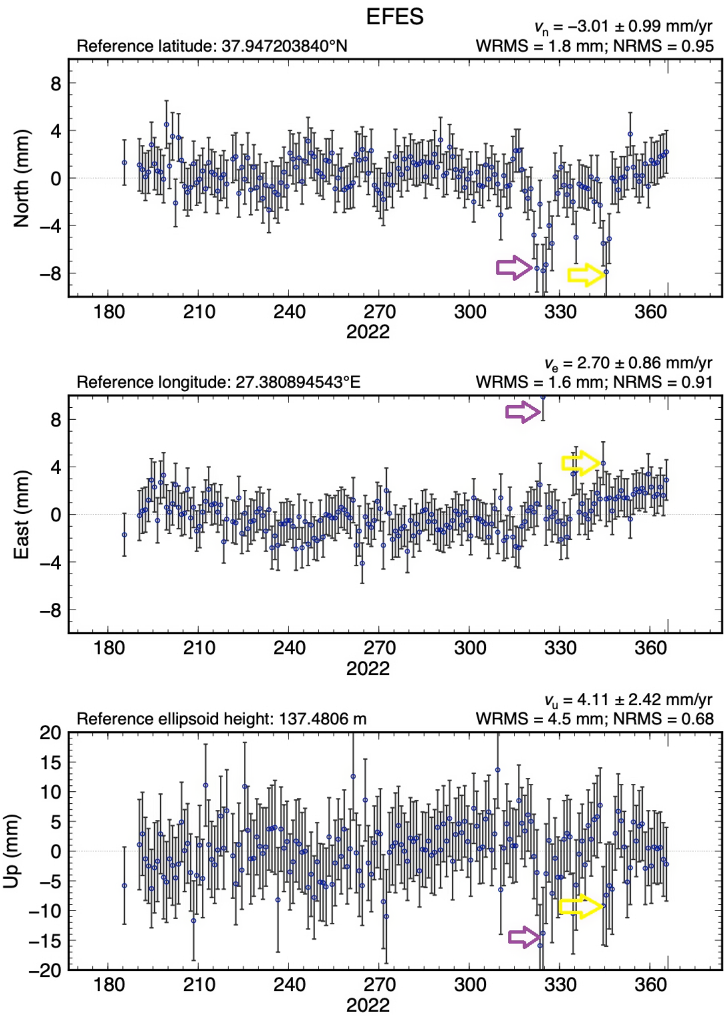


Fig. 9. Time series of the EFES station located in the Selçuk district of Izmir and the image of the effects of earthquakes in the region. Purple arrow: 4–21 November 2022, yellow arrow: it represents the earthquakes that occurred on December 13, 2022.

(Fig. 9) are evaluated together, it is seen that both horizontal and vertical components of EFES were affected by the earthquakes that occurred between 4–21 November 2022 and showed a collapse movement while moving towards the south and east. It is seen that both horizontal and vertical

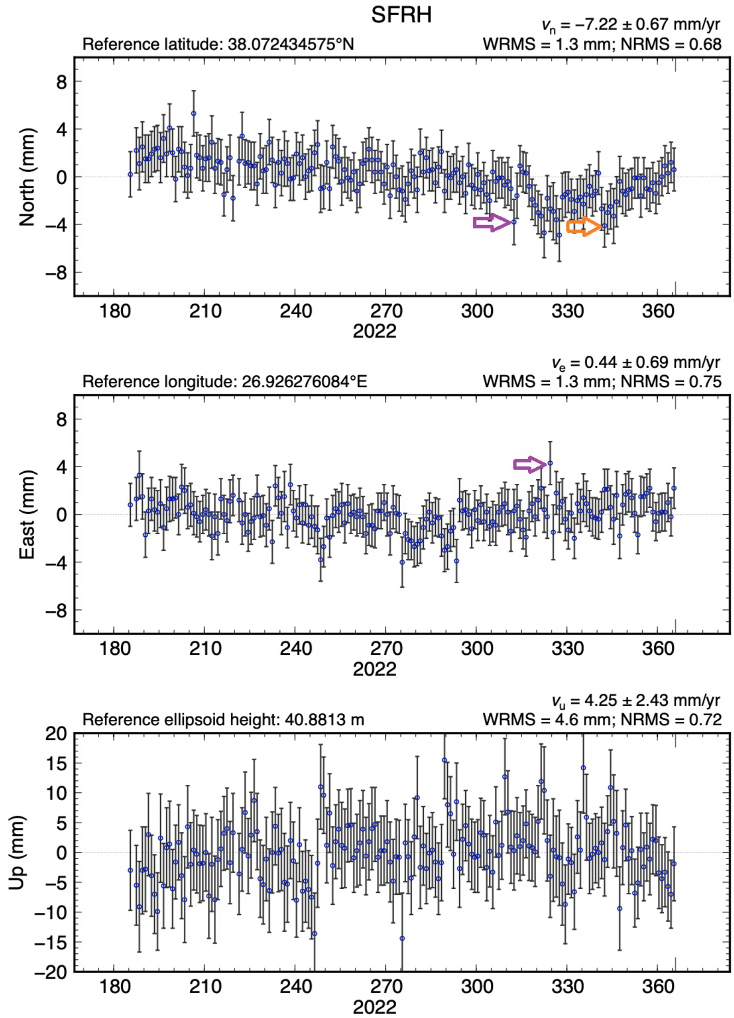


Fig. 10. Time series of the SFRH station located in the Seferihisar district of Izmir and the image of the effects of earthquakes in the region. Purple arrow: 4–21 November 2022, orange arrow: it represents the earthquakes that occurred on December 8, 2022.

components of the December 13, 2022 earthquake were affected and collapse occurred while moving towards the south and east. When the time series of the SFRH station located in the Seferihisar district of Izmir and the effect of earthquakes (Fig. 10) are evaluated together, it is seen that the northern

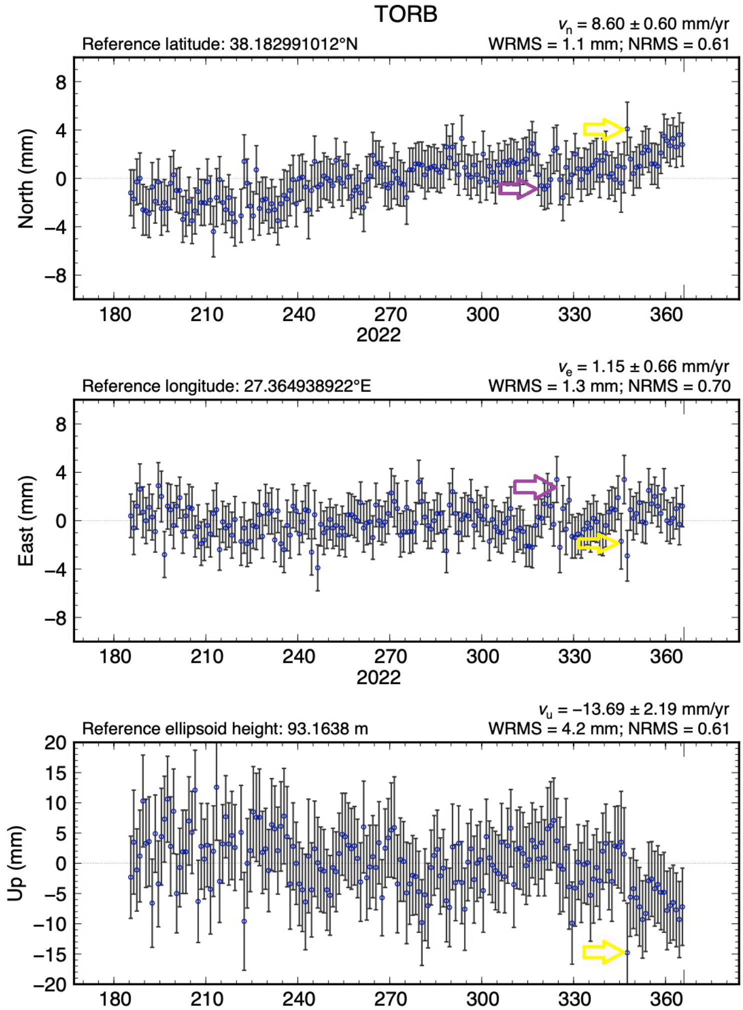


Fig. 11. Time series of the TORB station located in the Torbalı district of Izmir and the image of the effects of earthquakes in the region. Purple arrow: 4–21 November 2022, yellow arrow: it represents the earthquakes that occurred on December 13, 2022.

and eastern components of the SFRH were affected by the earthquakes that occurred between 4–21 November 2022 and moved towards the south and east. It was observed that the December 8, 2022 earthquake affected the northern component and caused movement towards the south. When the

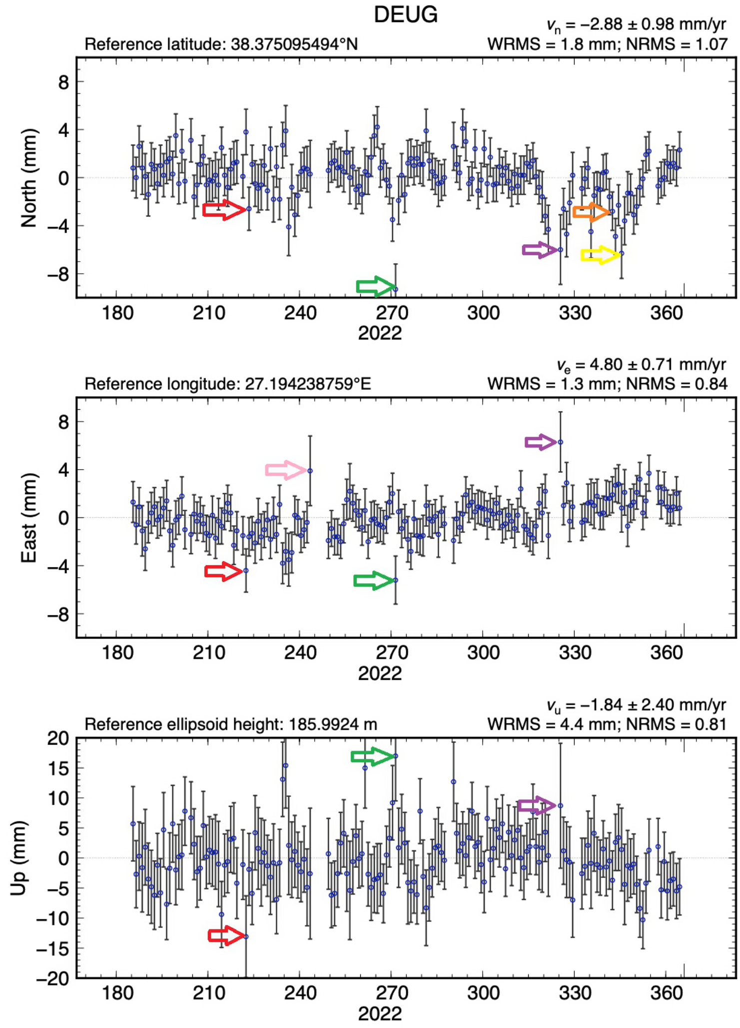


Fig. 12. Time series of the DEUG station located in the Buca district of Izmir and the image of the effects of earthquakes in the region. Red arrow: August 14, 2022, pink arrow: 31 August, green arrow: September 26, 2022, purple arrow: 4–21 November 2022, orange arrow: December 8, 2022, yellow arrow: it represents the earthquakes that occurred on December 13, 2022.

time series of the TORB station located in the Torbalı district of Izmir and the effect of earthquakes (Fig. 11) are evaluated together, it is seen that the northern and eastern components of TORB were affected by the earthquakes that occurred between 4–21 November 2022 and moved towards the south and east. It is seen that both horizontal and vertical components of the December 13, 2022 earthquake were affected, and movement towards the north and west and collapse occurred in the vertical direction.

When the time series of the DEUG station located at DEU Tınaztepe Campus in the Buca district of Izmir and the effect of earthquakes (Fig. 12) are evaluated together with the earthquake that occurred on August 14, 2022, both the horizontal and vertical components of the DEUG station were affected, and while movement towards the south and west was observed, a collapse occurred. While the eastern component was affected by the earthquake on August 31, 2022, an eastward movement was observed. With the earthquake that occurred in the Aegean Sea on September 26, 2022, both the horizontal and vertical components of the station were affected, and while movement towards the south and west was observed, an elevation occurred. It is seen that both horizontal and vertical components were affected by the earthquakes between 4–21 November 2022, causing the station to move and rise towards the south and east. It is seen that the earthquake that occurred on December 8, 2022 was effective in the northern component and caused movement towards the south. It was observed that the earthquake of December 13, 2022 was again effective in the Northern component and caused movement towards the south.

4. Conclusions

It was observed that the stations were generally affected by the earthquakes that occurred in the Aegean Sea-Kuşadası Gulf and Izmir-Buca between 4–21 November 2022 (Table 2), but the earthquake storm that occurred in the region, especially in Izmir-Buca, was quite effective. When the time series of EFES, SFRH and TORB stations were examined (Figs. 7, 8 and 9, respectively), it was observed that the vicinity of Selçuk, Seferihisar and Torbalı, where these stations are located, was affected by a small number of earthquakes. On the other hand, it is observed (in the time series of ALIA, in Aliağa district) that ALIA is affected by almost every earthquake with a dominant amplitude. It is seen that a similar situation is valid for the DEUG station located in Buca, Izmir, and this station is also intensively affected by earthquakes (Fig. 12).

In the deformation analysis studies, it was determined that the strain-induced deformation values at YEN1, AYVL, BERG, ALIA, DEUG, IZMI stations in Fig. 5 were high. It is noteworthy that these situations are along the N-S direction from the Izmir centre to the north. It has been observed that the seismicity around the DEUG in the Buca district of Izmir has been quite active in recent years. However, the number of earthquakes has not increased yet in the locations where other stations are located. In this case, the trapped energy is most likely in Aliağa and its vicinity. In the study conducted by (*Öztürk, 2014*), a combined forecast map was prepared for possible strong earthquakes in the Western Anatolia region. According to this study, the faults in Aliağa are also within this prediction. In the studies conducted by (*Bayrak and Türker, 2016*), the average b value of Aliağa was found to be 1.84.

In the study which was conducted in the region (*Pamukçu et al., 2021*), the seismic hazard character in the region was calculated after the earthquake that occurred off the coast of Samos Island, 70 km away from Izmir, on October 30, 2020. It is stated from the graphs of these values that the earthquake risk in the region continues. In addition, the elastic thickness (Te) value, which is parallel to the crustal rigidity in the region, is approximately 8 km, indicating that the geodynamic activity in the region will continue on the geological time scale (*Pamukçu et al., 2021*). When these findings and the results in Table 2 are evaluated together, it is clear that the seismic activity in the region has continued since the 2020 Samos earthquake.

Statements and declarations

Funding. This study was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) project number 121Y272.

Authors' contributions. All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Oya Ankaya Pamukçu, Ayça Çırmık, Fikret Doğru, Fatih Uysal, Özkan Cevdet Özdağ, Metehan Uluğtekin, Fulya Özdemir and Zülfikar Erhan. The first draft of the manuscript was written by Oya Ankaya Pamukçu and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of interest. The authors have no relevant financial or non-financial interests to disclose.

References

Aktuğ B., Nocquet J. M., Cingöz A., Parsons B., Erkan Y., England P., Lenk O., Gürdal M. A., Kılıçoğlu A., Akdeniz H., Tekgül A., 2009: Deformation of western Turkey from a combination of permanent and campaign GPS data: limits to block-like behavior. J. Geophys. Res. Solid Earth, **114**, B10, B10404, doi: 10.1029/2008JB006000.

Bayrak Y., Türker T., 2016: The determination of earthquake hazard parameters deduced from Bayesian approach for different seismic source regions of western Anatolia. Pure Appl. Geophys., **173**, 1, 205–220, doi: 10.1007/s00024-015-1078-x.

Bjerrum L. W., Sørensen M. B., Ottemöller L., Atakan K., 2013: Ground motion simulations for İzmir, Turkey: parameter uncertainty. J. Seismol., **17**, 4, 1223–1252, doi: 10.1007/s10950-013-9389-9.

Bozkurt E., Sözbilir H., 2004: Tectonic evolution of the Gediz Graben: field evidence for an episodic, two-stage extension in western Turkey. Geol. Mag., **141**, 1, 63–79, doi: 10.1017/S0016756803008379.

Çetiner M., 2012: İzmir ve çevresindeki mikrogravite verilerinin değerlendirilmesi (Evaluation of microgravity data in Izmir and its surroundings). MSc thesis, Dokuz Eylül University, The Graduate School of Nature and Applied Sciences, 78, İzmir (in Turkish).

Çırmık A., Pamukçu O., Akçığ Z., 2016: Mass and stress changes in the Menderes Massif (Western Anatolia, Turkey). J. Asian Earth Sci., **131**, 109–122, doi: 10.1016/j.jseaes.2016.09.013.

Çırmık A., Doğru F., Gönenç T., Pamukçu O., 2017a: The stress/strain analysis of kinematic structure at Gülbahçe Fault and Uzunkuyu Intrusive (İzmir, Turkey). Pure Appl. Geophys., **174**, 3, 1425–1440, doi: 10.1007/s00024-017-1474-5.

Çırmık A., Pamukçu O., Gönenç T., Kahveci M., Şalk M., Herring T., 2017b: Examination of the kinematic structures in İzmir (Western Anatolia) with repeated GPS observations (2009, 2010 and 2011). J. Afr. Earth Sci., **126**, 1–12, doi: 10.1016/j.jafrearsci.2016.11.020.

Dewey J. F., Şengör A. M. C., 1979: Aegean and surrounding regions: Complex multiplate and continuum tectonics in a convergent zone. Geol. Soc. Am. Bull., Geological Society of America Bulletin, **90**, 1, 84–92, doi: 10.1130/0016-7606(1979)90<84:AASRCM>2.0.CO;2.

Emre Ö., Duman T. Y., Özalp S., Elmacı H., Olgun Ş., Şaroğlu F., 2013: 1/1.125.000 ölçekli Türkiye diri fay haritası (Active fault map of Türkiye, 1/1.125.000 scale). General Directorate of Mineral Research and Exploration, Special Publications Series, Ankara, Turkey (in Turkish).

Gok E., Polat O., 2014: An assessment of the microseismic activity and focal mechanisms of the Izmir (Smyrna) area from a new local network (IzmirNET). Tectonophysics, **635**, 154–164, doi: 10.1016/j.tecto.2014.08.003.

Gürçay S., Çifçi G., 2021: Sığacık Körfezi ve Küçük Menderes Grabeni (Batı Anadolu) Açıklarının Denizaltı Aktif Tektoniği (Submarine Active Tectonics of Sığacık Bay and offshore Küçük Menderes Graben (Western Anatolia)). 74th Turkish Geology Congress, Ankara, 67 (in Turkish).

Herring T. A., King R. W., Floyd M. A., McClusky S. C., 2018: Introduction to Gamit/ Globk, Release 10.7. Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, available at: http://geoweb.mit.edu/gg/Intro_GG.pdf.

Kahveci M., Çırmık A., Doğru F., Pamukçu O., Gönenç T., 2019: Subdividing the tectonic elements of Aegean and Eastern Mediterranean with gravity and GPS data. Acta Geophys., **67**, 2, 491–500, doi: 10.1007/s11600-019-00270-w.

Malaliçi B. C., 2019: Gülbahçe fayı ve çevresinin jeodinamik yapısının irdelenmesi (Examination of the geodynamic structure of the Gülbahçe fault and its surroundings). MA thesis, Dokuz Eylül University, Institute of Science and Technology, İzmir, 77 (in Turkish).

Okay A. I., Satir M., Maluski H., Siyako M., Monie P., Metzger R., Akyüz S., 1996: Paleo- and Neo-Tethyan events in northwest Turkey: Geological and geochronological constraints. In: YinA., Harrison T. M. (Eds.): The Tectonic Evolution of Asia. United States, Cambridge University Press, 420–441.

Özkaymak Ç., Sözbilir H., Uzel B., 2013: Neogene–Quaternary evolution of the Manisa Basin: Evidence for variation in the stress pattern of the İzmir-Balıkesir Transfer Zone, western Anatolia. J. Geodyn., **65**, 117–135, doi: 10.1016/j.jog.2012.06.004.

Öztürk S., 2014: Türkiye'nin Batı Anadolu bölgesi için deprem istatistiği ve olası güçlü depremlerin orta vadede bölgesel olarak tahmini üzerine bir çalışma (A study on earthquake statistics and the forecasting for the intermediate-term locations of possible strong earthquakes for the western Anatolian region of Turkey). Gümüşhane Univ. J. Sci. Technol. Inst., **4**, 1, 75–93, (in Turkish with English abstract), doi: 10.17714/gufbed.2014.04.006.

Pamukçu O., Gönenç T., Yurdakul Çırmık A., Kahveci M., 2012: Sismik riski yüksek olan İzmir-Karaburun'un güneyinde yapılmış mikrogravite ve GPS çalışmaları (Microgravity and GPS studies in the south of Izmir-Karaburun, a highly seismic-risky area). Jeofizik Dergisi, **26**, 2, 59–66 (in Turkish).

Pamukçu O., Gönenç T., Uyanik O., Sözbilir H., Çakmak O., 2014: A microgravity model for the city of İzmir (western Anatolia) and its tectonic implementations. Acta Geophys., **62**, 4, 849–871, doi: 10.2478/s11600-014-0203-z.

Pamukçu O., Gönenç T., Çırmık A., Sındırgı P., Kaftan İ., Akdemir Ö., 2015a: Investigation of vertical mass changes in the south of Izmir (Turkey) by monitoring microgravity and GPS/GNSS methods. J. Earth Syst. Sci., **124**, 1, 137–148, doi: 10.1007/s12040-014-0533-x.

Pamukçu O., Gönenç T., Çırmık A. Y., Kahveci M., 2015b: Investigation of the Sığacık Bay's displacement characteristic by using GPS and gravity data in Western Anatolia. J. Asian Earth Sci., **99**, 72–84, doi: 10.1016/j.jseaes.2014.12.007.

Pamukçu O., Doğru F., Cirmik A., Göneş D., 2021:Seismic a and b-values and crustal parameters of Samos Island-Aegean Sea, Lesvos Island-Karaburun, Kos Island-Gökova Bay earthquakes. Turk. J. Earth Sci., **30**, 8, 833–850, doi: 10.3906/yer-2107-13.

Pamukçu O., Çırmık A., Doğru F., Ünlü E., Malaliçi B. C., 2022: Assessment of crustal thinning and tectonic stress distribution of Gülbahçe fault zone and its surroundings

(İzmir, West Türkiye) using gravity and magnetic anomalies. Bull. Miner. Res. Explor., **169**, 105–119, doi: 10.19111/bulletinofmre.1029265.

Şengör A. M. C., Görür N., Şaroğlu F., 1985: Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In: Biddle K. T., Christie-Blick N. (Eds.): Strike-Slip Deformation, Basin Formation and Sedimentation. Soc. Econ. Paleontol. Mineral. Spec. Publ., **37**, 227–264, doi: 10.2110/pec.85.37.0211.

Shen Z.-K., Jackson D. D., Ge B. X., 1996: Crustal deformation across and beyond the Los Angeles basic from geodetic measurements. J. Geophys. Res. Solid Earth, **101**, B12, 27957–27980, doi: 10.1029/96JB02544.

Sözbilir H., 2001: Extensional tectonics and the geometry of related macroscopic structures: Field evidence from the Gediz detachment, western Turkey. Turk. J. Earth Sci., **10**, 2, 51–67.

Sözbilir H., 2002: Geometry and origin of folding in the Neogene sediments of the Gediz Graben, western Anatolia, Turkey. Geodin. Acta, **15**, 5-6, 277–288, doi: 10.1080/09853111.2002.10510761.

Sözbilir H., Sarı B., Uzel B., Sümer Ö., Akkiraz S., 2011: Tectonic implications of transtensional supradetachment basin development in an extension-parallel transfer zone: the Kocaçay Basin, western Anatolia, Turkey. Basin Res., **23**, 4, 423–448, doi: 10.1111/j.1365-2117.2010.00496.x.

Sözbilir H., Softa M., Eski S., Tepe Ç., Akgün M., Pamukçu O., Çırmık A., Utku M., Özdağ Ö. C., Özden G., Özçelik Ö., Evlek D. A., Çakır R., Baba A., Uzelli T., Tatar O., 2020: 30 Ekim 2020 Sisam (Samos) Depremi (Mw: 6,9) Değerlendirme Raporu (30 October 2020 Samos earthquake (Mw: 6.9) evaluation report). Dokuz Eylül University Earthquake Research and Application Center (in Turkish).

Turcotte D. L., Schubert G., 2002: Geodynamics, 2nd ed. Cambridge: Cambridge Press, 472 p.

Uzel B., Sözbilir H., Özkaymak Ç., 2012: Neotectonic evolution of an actively growing superimposed basin in western Anatolia: The inner bay of Izmir, Turkey. Turk. J. Earth Sci., **21**, 4, 439–471, doi: 10.3906/yer-0910-11.