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Abstract

The North Anatolian Fault Zone (NAFZ) in the north of Türkiye is considered one of the most active faults on earth and have caused many major earthquakes in the last century. Surface ruptures by those earthquakes indicate that this tectonic feature consists of many segments, which reveal different characteristics in terms of geometry and mechanism. NAFZ lies along between Bingöl in the eastern Turkey and Saros Gulf in the west. This study focuses on the central part of the NAFZ between Niksar and Ilgaz provinces. In addition to the main branch, the central section of the NAFZ also contains two sub-branches extending southward: Merzifon-Esençay and Sungurlu Faults. In the literature, there are several studies for the region, however a comprehensive study mainly focusing on the main branch of the NAFZ and its sub-branches along the central NAFZ has not been conducted yet, which would fully reveal the fault mechanism and seismic potential in the region. The aim of this study is to derive an up-to-date high-spa-tial-resolution Global Navigation Satellite Systems (GNSS) velocity field for the central NAFZ and to correlate with the strain accumulations along the faults. Based on this, a high-spatial-resolution GNSS network consisting of 60 sites was established enclosing the central NAFZ. The previously archived GNSS data for the same observation sites were collected from the different studies in the region and a new GNSS campaign measurement was conducted between October 2023 and February 2024. All GNSS data were processed using GAMIT/GLOBK software, and the results indicate the GNSS velocities ranging from 3-30 mm/year and their associated uncertainties of maximum ± 1.5 mm/year with respect to the Eurasian tectonic plate.

Keywords: NAFZ, earthquake, GNSS velocity field, GAMIT/GLOBK, Sungurlu Fault, Merzifon-Esençay Fault.

INTRODUCTION

Türkiye is a part of highly active seismic region, which extends from Gibraltar to Indonesia and is referred as "Alpine-Himalayan Belt" (Jackson and McKenzie, 1984). So as, the potential seismic hazard in Türkiye revealed recently in the districts of Kahramanmaraş (Pazarcık and Elbistan) with the earthquakes of their magnitude Mw 7.8 (01.17 UTC) and Mw 7.6 (10.24 UTC Time) on February 06, 2023, respectively (AFAD 2023, KOERİ 2023).

The tectonic motion in Türkiye is mainly accommodated along the major active faults by three tectonic plates namely Eurasia, Arabia and Anatolia. Specifically, the Anatolian plate is located among the Arabian and African plates at the south and Eurasian plate at the north. Due to the northward motion of the southern plates towards to the relatively stable Eurasia plate, the Anatolian plate hosts a westward movement and substantial fault systems with different regimes (Figure 1) (Emre et al.2018). These fault systems have witnessed many major earthquakes in the recent past, and the North Anatolian Fault Zone (NAFZ) have made its mark at most among of the active faults in the region in terms of seismic events. The NAFZ extends from Karlıova, Bingöl at the eastern edge to the Saroz Gulf, Aegean Sea at the western terminal, passing through many provinces between Erzincan and Kocaeli, and continues beneath the Marmara Sea to Şarköy, Tekirdağ (Şengör et al. 2005, Yavaşoğlu et al. 2020). NAFZ has mainly a right-lateral strike-strip fault mechanism ranging between 0.4 mm–1 m with an accompanying dip-slip component (Ketin 1969, Şengör et al. 2005).

The major earthquakes along the NAFZ during the instrumental period, such as 1939 Erzincan (M_s 7.9), 1942 Niksar – Erbaa (M_s 7.0), 1943 Ladik – Tosya (M_s 7.2), 1944 Bolu – Gerede (M_s 7.4), 1999 Izmit (Mw 7.4) and Düzce (Mw 7.2), indicate that this fault mechanism is tectonically active (Barka 1996, Takcı 2015, Bohnhoff et al. 2016). The paleosismological and geological studies have also a consensus about the same conclusion (Ambraseys and Finkel, 1995). Considering the surface ruptures and distribution of the epicentres of the instrumental earthquakes in the last century, the NAFZ consists of 10 segments, some of which are longer and have different geometry and characteristics (Barka and Kandinsky-Cade 1988, Barka 1992, Barka 1996, Köksal 2011, Emre et al. 2018) (Figure 2). There are three main segments of the NAFZ ranging from 150 to 350 km in length: the Erzincan Segment (ruptured in 1939), the Ladik-Tosya Segment (ruptured in 1943), and the Gerede Segment (ruptured in 1944). There are also minor segments at the eastern and western terminals of those major segments, which are shorter than 10 km (Barkaand Kadinsky-Cade 1988, Barka 1996, Şengör et. al. 2005, Köksal 2011, Emre et. al. 2018).

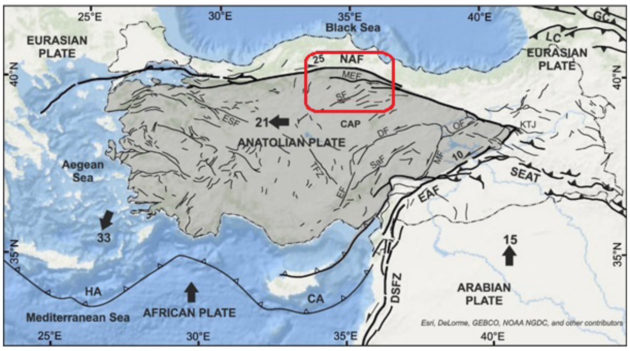

Figure 1 Active fault mapping for the East-Mediterranean (after Emre et al. 2018). (CA) Cyprian Arc, (HA) Hellenic Arc, (EAFZ) East Anatolian Fault Zone, (DSFZ) Dead Sea Fault Zone, (NAFZ) North Anatolian Fault Zone, (SEATZ) Southeast Anatolian Thrust Zone, (LC) Lesser Caucasus, (GC) Great Caucasus, (ESF) Eskişehir Fault, (TFZ) Tuzgölü Fault, (MEF) Merzifon-Esençay Fault, (SF) Sungurlu Fault, (EF) Ecemiş Fault, (DF) Deliler Fault, (SaF) Sarız Fault, (MF) Malatya Fault, (OF) Ovacık Fault. Thick lines within solid triangles indicate contractional tectonic regimes. Thick black arrows show the direction of plate movements and associated plate velocity. Red rectangle represents the study area.

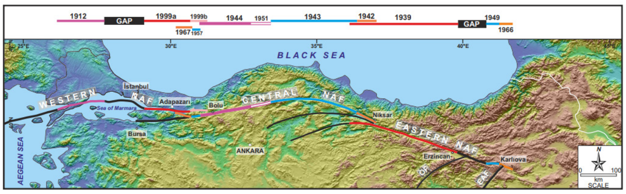

Figure 2 The major segments of the NAFZ and instrumental period earthquakes with M_s>6.8, since 1912 (Emre et al. 2021).

The NAFZ has two sub-branches NE-SW oriented towards to the south at the central section, which these are entitled Ezinepazarı–Sungurlu and Merzifon–Esençay fault segments. The tectonic zone between these fault segments have had significant deformation during the neotectonic period (Erturac M. K. and Tuysuz O., 2012). The southern branch, Ezinepazarı–Sungurlu Fault, stretches out westward while delineating the Amasya–Aydınca Basin and Amasya–Deliçay Valley, and approaches to the south of Sungurlu province and the north of Mecitözü (Gökhöyük Fault) (Yavaşoğlu et al. 2011, Emre et al. 2018) (Figure 3). The geological structures and morphological features on the surface topography exhibit distinct characteristics correlated with the fault extension (Şaroğlu et al. 1987). The most interesting event along the fault zone is the Erzincan earthquake (1939, Ms 7.9). The surface ruptures of the earthquake reveal the potential of the probable activities in the fault system (Ketin 1969, Şaroğlu et al. 1987, Barka 1996), however the seismic data in the instrumental period were limited for the Geldingen Basin and the western parts, which is also known as Sungurlu Fault. The lack of a distinct seismic network and scientific studies in the region leads to a weak understanding about the tectonic mechanism (Amasya İRAP Report, 2021, Çorum İRAP Report, 2021).

The northern branch, called Merzifon – Esençay Fault, is an ESE-WNW oriented right-lateral strike-slip fault that lies almost parallel to the main branch of the NAFZ and extends to the north of the İskilip Province of Çorum (Erturaç and Tuysuz 2010). The paleosismological studies along the fault indicate that the earthquake recurrence interval ranges between 1320 and 2200 years during the Holocene period, with an interseismic cycle about 3700 years (Emre et al. 2020). According to the records about the historical and instrumental events along this fault, which lack seismic data, it is one of the unruptured segments of the NAFZ in the last century (Emre et al. 2020). Empirical evaluations for the region indicate an earthquake with a magnitude of ~7.2 (Wells and Coppersmith, 1994). Additionally, the fault segments surrounding have also been reported about the similar risk of a probable earthquake (Emre et al. 2018). Besides, there are several blocks bounded by the main branch of the NAFZ and its southern branches (Yavaşoğlu et al. 2011) (Figure 3).

Synthetic Aperture Radar-InSAR techniques), geology (field observations and paleoseismology studies), geophysics (gravimetry and seismic refraction techniques), satellite imaging and geographical information systems analyses (Stein and Wysession 2003, Lay and Wallace 1995, Herring 1999, Yavaşoğlu et al. 2011, Massonnet and Feigl 1998, Michetti et al. 2005, , McCalpin and Nelson 1996, Kaiser et al. 2009, Özalaybey et al. 2009). The geodetic techniques, which are very useful in such cases and economically efficient, serve for precise positioning in a short period of time by terrestrial networks, GNSS, InSAR, Light Detection and Ranging (LIDAR). (Massonnet and Feigl 1998, Herring 1999, Schowengerdt 2007, Yavaşoğlu et al. 2011, Ghilani and Wolf 2012, Solak et al. 2024). The recent geodetic studies focusing on the tectonically active regions demonstrate the power of new generation of geodetic techniques (Yavaşoğlu 2009, Tiryakioğlu 2012, Solak 2020, Özkan 2021). In order to reveal the strain accumulations along the faults, the GNSS networks consisting of periodically observed sites and permanent stations are established considering the fault geometry in the study region. Thanks to velocity field derived from GNSS observations, we are able to estimate the potential magnitude and location of a probable major earthquake and also average recurrence intervals for large earthquakes, apart from the exact time of a seismic event (McClusky et al., 2000; Reilinger et al., 2006; Aktuğ et al., 2009; Yavaşoğlu et al., 2011; Tiryakioğlu 2012; Aktuğ 2017; Poyraz et al., 2018; Tiryakioğlu et al., 2018, 2019; Akyar 2020, Solak 2020, Yıldız et al. 2020; Eyübagil et al. 2021, Gezgin et al. 2022, Özkan et al., 2023).

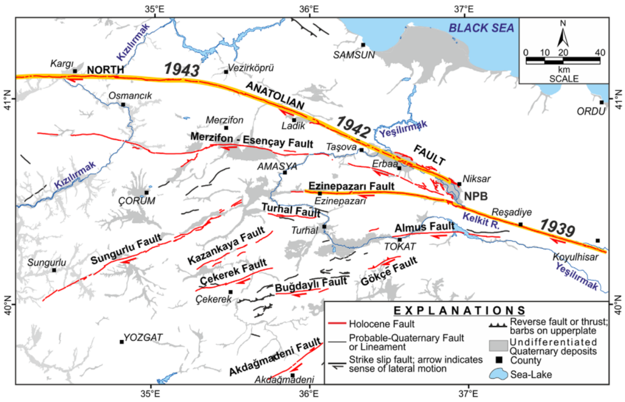

Figure 3 The detailed geological map of the study area (Emre et al. 2021).

The tectonic movements and lithospheric crustal deformations causing earthquakes are studied by different disciplines using several techniques, such as seismology (seismic array networks), geodesy (GNSS and Interferometic

In this study, the interseismic lithospheric deformations are investigated at the central part of the NAFZ (Figure 3). There are several blocks bounded by the main branch of the North Anatolian Fault Zone (NAFZ) and its sub-branches extending southward in the region. In order to model the plate motions and so as minor blocks in the region using a high-spatial-resolution geodetic dataset, a wide GNSS network consisting of 60 sites was established, and the GNSS data for the same observation sites previously archived were obtained from the different studies. In addition to permanent GNSS stations in the study region, the GNSS observations were periodically performed at each survey site in the network during campaign measurement sessions between 2023 and 2024. Thus, the latest velocity field with respect to Eurasian tectonic plate was derived from present-day GNSS observations. Since it is expected to have more comprehensive findings and conclusions to better understand the complex tectonic mechanism of the mid-section of the NAFZ through our ongoing studies, we initially have the goal to provide the preliminary results of our geodetic observations here in this study.

MATERIAL AND METHODS

The GNSS Network and Observations

Due to complex tectonic structure, scattered topography, and challenges with the observation techniques, there are only few studies for the study region in the literature (Yavaşoğlu et al. 2011, Aktuğ et al. 2015, Kurt et al. 2022). The GNSS observation sites used in the Yavaşoğlu et al. (2011) was also integrated into our GNSS network design within the scope of this study. However, the most of the sites from that study have not been observed since 2004. Therefore, the long-term repeatability of the GNSS observations is crucial to derive latest velocity field and so as to precisely constrain the strain accumulations along the faults around the mid-section of the NAFZ. In order to investigate on the geological features and regional tectonic setting, the GNSS network established within this study has fault-perpendicular profiles around the main branch of the NAFZ and its southward sub-branches, including Merzifon–Esençay and Ezinepazarı-Sungurlu fault segments. The GNSS network for this study consists of 45 sites from the study of Yavaşoğlu et al. (2011) and also from the TUTGA network, different institutions and organizations. The remaining 15 sites out of 60 are the permanent stations that belong to the Turkish National Permanent GNSS Network-Active (TUSAGA-Active) (Figure 4).

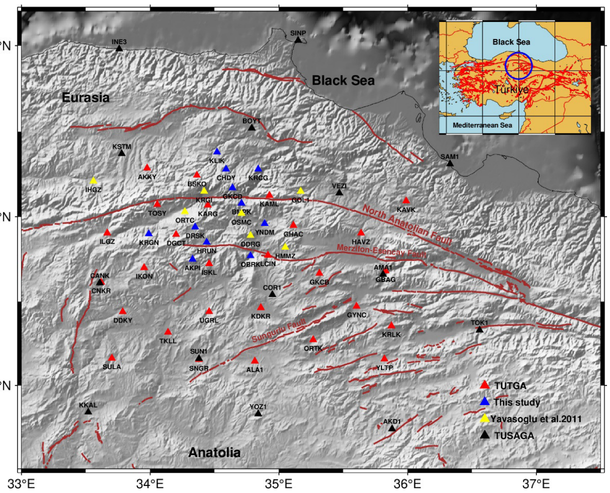

Figure 4 The GNSS observation network established for this study. Red lines represent the fault traces of the main branch of the NAFZ and its sub-branches. New sites represented in blue in this study have archive GNSS data from previous local studies in the region. Stations represented as triangles in the figure (red: Turkish National Fundamental GNSS Network (TUTGA) sites, yellow: sites from Yavaşoğlu et al. 2011, black: TUSAGA-Active stations, blue: this study).

Apart from the permanent stations within our network, the GNSS observations at the survey sites were performed during the campaign measurements between October 2023 and February 2024, having at least 8-h session lengths on two consecutive days and using 15-s measurement interval at each site. 40 point in the network are selected from pillars and 5 of them are bronze mast on the bedrock. In order to eliminate the deficiencies of observer and minimize the probable meteorological factors disturbing the observations, the fixed-height GNSS masts were used at the sites on the bedrock (Figure 5).

Figure 5 The GNSS sites periodically observed within the network named KAML (left), KARG (center), DRSK (right).

The archived dataset of previously observed TUTGA sites were gathered from the General Directorate of Mapping (HGM) according to the "Inter-institutional Collaboration and Data Distribution Protocol". Moreover, the GNSS observation files logged in Receiver Independent Exchange (RINEX) data format at the permanent stations belong to TUSAGA-Active network were downloaded from the official we bsite of the General Directorate of Land Registry and Cadastre (TKGM).

GNSS Data Processing

In this study, the GAMIT/GLOBK software developed by the Massachusetts Institute of Technology (MIT) was used for GNSS data processing (Herring et al. 2018). The GAMIT module is capable of parameter estimations such as station coordinates, satellite orbits, Earth Orientation Parameters (EOPs) and atmospheric delays using ionosphere-free linear combination of GNSS phase observables with the help of double-differencing technique. This module also can eliminate cycle slips for the GNSS observations at each site. In the second stage, the GLOBK module combines all the loosely-constrained daily GAMIT solutions using Kalman-Filtering approach and estimates the velocities and positions of the observation sites defined in a terrestrial reference frame (Herring et al. 2018). The short-term (daily) position repeatability plots were generated using the GNSS data from the consecutive days to reveal the possible centering errors, and the long-term (annual) position time series were produced to determine the trend of the motion for all the sites in the network (Figure 6, 7).

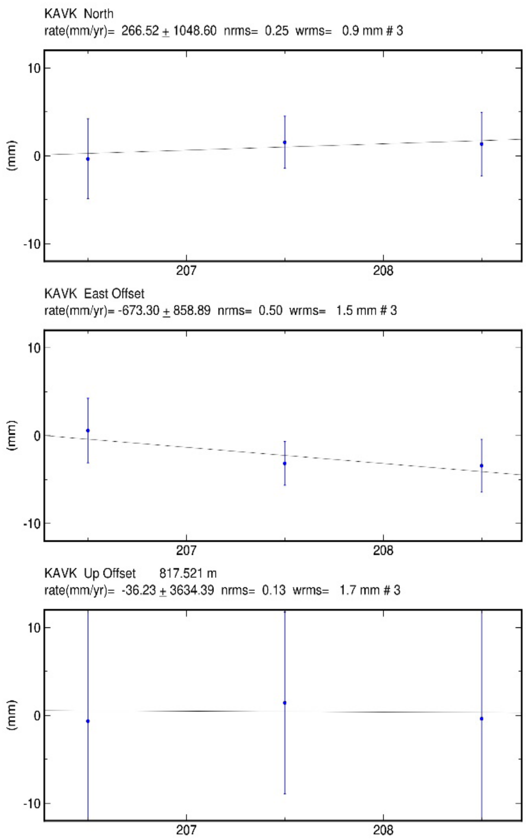

Figure 6 The plot of short-term (daily) position repeatability for the KAVK station (the north, east and up components are in order from top to bottom, respectively).

Table 1 The list of IGS stations used in the stabilization process.

S.N.	Station Name	Longitude	Latitude	S.N.	Station Name	Longitude	Latitude
1	ADIS	38.77	9.04	14	MATE	16.70	40.65
2	ANKR	32.76	39.89	**15**	NICO	33.40	35.14
3	BAHR	50.61	26.21	**16**	NOT1	14.99	36.88
4	BAKU	49.81	40.37	**17**	NSSP	44.50	40.23
5	BOR1	17.07	52.28	**18**	ONSA	11.93	57.40
6	BUCU	26.13	44.46	**19**	POLV	34.54	49.60
7	CRAO	33.99	44.41	**20**	POTS	13.07	52.38
8	DRAG	35.39	31.59	**21**	RAMO	34.76	30.60
9	GLSV	30.50	50.36	**22**	SOFI	23.39	42.56
10	GRAS	6.92	43.75	**23**	TELA	34.78	32.07
11	GRAZ	15.49	47.07	**24**	VILL	356.05	40.44
12	KOSG	5.81	52.18	**25**	WTZR	12.88	49.14
13	KUWT	47.97	29.33	**26**	ZECK	41.57	43.79

Following the generation of the position time series, the next step includes the stabilization of the network and the estimation site velocities using the 26 selected International GNSS Service (IGS) stations having stable long-term data and distributed along the relevant tectonic plates (Table 1). All the site velocities are derived in a Eurasia-fixed reference frame.

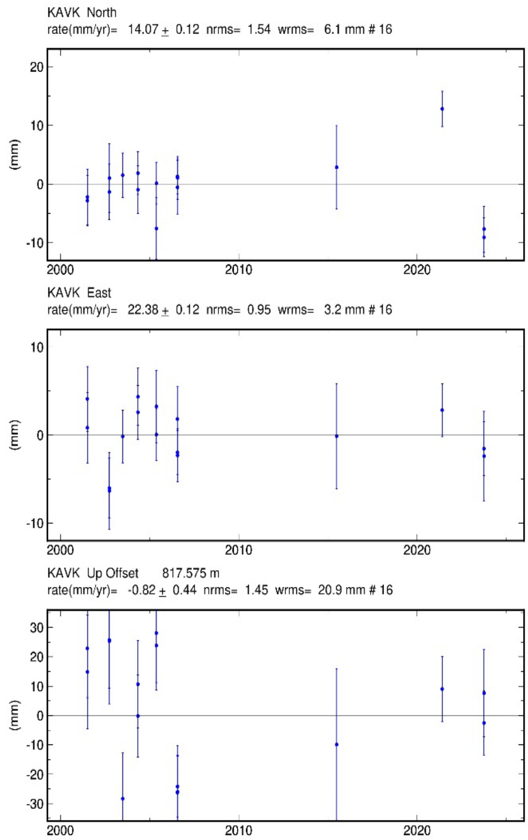

Figure 7 The plot of long-term (annual) position repeatability for the KAVK station (the north, east and up components are in order from top to bottom, respectively).

RESULTS AND DISCUSSION

The general pattern of the tectonic mechanism in the mid-section of the NAFZ, which is derived using GNSS sites with varying velocities in N-S direction, validates the rotational westward migration of the Anatolian plate. The site velocities on the Eurasian plate are estimated in a range of 2-3 mm/year, where the northern block bounding the main branch of the NAFZ is relatively stable. On the other hand, some of the sites having anomalous velocities does not reflect the characteristic features of the velocity field and discriminate from the regional trend (AKPI, SUN1, SNGR). It is argued that the discrimination of the site velocities is possibly the caused by the local deformations and relatively short observation spans. The velocity solution confirms the estimation of the site velocities ranging 3-30 mm/year with their associated uncertainties of maximum ±1.5 mm/year (Figure 8). Considering the relatively stable Eurasia plate, some of the sites located at the north of the main branch of the NAFZ (KRGI, GKCD, KAML, GOL5) have inconsistent velocities in a range of 5-10 mm/year unlikely their local characteristics.

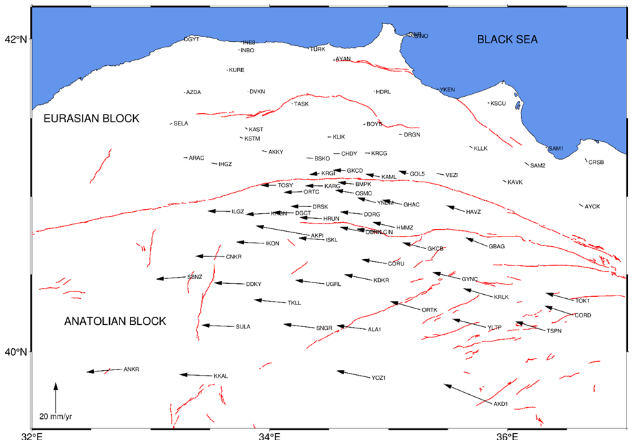

Figure 8 The velocity field referenced to ITRF2014 datum and derived with respect to the Eurasia-fixed reference plate in this study.

In order to provide the latest velocity field for the mid-section of the NAFZ, a GNSS network consisting of 60 sites was established, which also contains 15 permanent stations from TUSAGA-Active network. There are a number of 10 sites, in which the site velocities have been estimated for the first time. The uncertainty of our velocity estimation for the same sites used also in Yavaşoğlu et al. (2011) is less than 0.5 mm/year. On the other hand, the velocity field solution derived has some statistically poor estimation with 1 mm/year uncertainty for the sites namely KVAK, YLTP, INE3, SAM2 and OBRK compared to the others. This might be caused from the short time span between the first and last observations of these sites.

The velocity field derived in this study confirms the anti-clockwise rotation of the Anatolian plate reported in the previous studies (Hubert-Ferrari et al., 2002; Hartleb et al., 2003; Kozacı et al., 2007; Yavaşoğlu et al., 2011; Aladoğan et al., 2017, 2020; Aktuğ et al., 2015; Yavaşoğlu et al., 2020; Kurt et al., 2022).

The most important result of this study is that some sites at the north of the main branch of the NAFZ, specifically the sites around the Çorum-Kargı province, have larger velocities than 5 mm/year not alike the local trend. Accordingly, this study suggests that the deformation zone along the NAFZ in this region is wider than 10-15 km.

Although there are evident preliminary results based on the latest velocity field solution in this study, the regional strain accumulations and seismic potential of the fault segments at the mid-section of the NAFZ are planned to investigate further in details.

CONCLUSION

This study focused on the mid-section of the NAFZ, where a comprehensive GNSS network comprising of 60 sites with the permanent stations from TUSAGA-Active network and survey sites to be observed periodically, was established to precisely constrain the fault slip rates and plate motions. The initial results clearly confirm the westward migration of the Anatolian plate, on which site velocities range of 3-30 mm/year and are in consistent with the previously published studies (Hubert-Ferrari et al., 2002; Yavaşoğlu et al., 2020).

The one of the most important conclusions of this study is that the sites at the north of the main branch of the NAFZ, particularly the ones close to Çorum-Kargı province, have velocities larger than 5 mm/year indicating a significant deformation in this region. This suggests that the deformation zone of the NAFZ in this area may extend beyond 10-15 km.

While these preliminary results regarding the velocity field provide notable insights, ongoing geodetic studies are quite crucial to better understand the present-day deformations and seismic potential of the region. It is expected that the continuous monitoring and analyses will help us to refine our understanding of seismic hazards and to contribute more on effective earthquake risk mitigation strategies.

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