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RESULTS FROM 25 YEARS (1998-2022) OF CRUSTAL DEFORMATION MONITORING IN AZERBAIJAN AND ADJACENT TERRITORY USING GPS

Kadirov F.[1], Yetirmishli G.[3], Safarov R.[1], Mammadov S.[1], Kazimov I.[3], Floyd M.[2], Reilinger R.[2], King R.[2]

[1]*Ministry of Science and Education of the Republic of Azerbaijan, Institute of Geology and Geophysics, Azerbaijan 119, H.Javid ave., Baku, AZ1143*

[2]*Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology 77 Massachusetts Ave., 54-918 Cambridge MA USA*

[3]*Republican Seismic Survey Center, Azerbaijan National Academy of Sciences 25, Rafibeyli str.,Baku, AZ1001*

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Summary. We present GPS observations of crustal deformation monitoring in Azerbaijan and adjacent territory which carried out since 1998. Unlike our previous studies there are more permanent GPS station and survey mode data aggregated, which accordingly allowed us more accurately determine the dynamics of the main tectonic structures.

Eight permanent stations were established by the Institute of Geology and Geophysics since 2006.In 2012, Republican Seismological Survey Center of Azerbaijan National Academy of Sciences started to construct permanent GPS stations, where totally 24 stations were established. Over 35 survey mode sites were measured repeatedly starting from 1998 to 2022.

On a broad scale, the GPS velocity field clearly illustrates the NNE motion of Caucasus and adjacent regions with respect to Eurasia south of the Main Caucasus Thrust Fault (MCT). An important note here is the sharp decrease in site velocities, and the clockwise rotation, between sites located to the west of West Caspian Fault (WCF) in Kura Depression and Talish region and sites to the east of WCF in Absheron Peninsula. This decrease and difference in GPS vector directions indicate high strain accumulation rates ~6 mm/yr south to Absheron Peninsula. We believe that the significant accumulation of elastic energy is responsible for the activation of seismic events and ofmud volcanoes in this region. Thus, spatial densification of the GPS observations is needed to better resolve localized deformation, and consequently the seismic hazard in the eastern Caucasus, Kur Depression, and Absheron area.

Introduction

Azerbaijan is caught in the active continent-continent collision of the Arabian plate with Eurasia (Mckenzie, 1972; Sengor et al., 1985; Philip et al., 1989). Plate tectonic reconstructions provide only broad constraints on the timing of the initial collision of the Arabian Plate with Eurasia of between 10-30 Ma BP (e.g., Robertson, 2000; Allen et al., 2004), and indicate that the rate of northward motion of Arabia relative to Eurasia has remained more or less constant at about 20 mm/yr since collision began (McQuarrie et al., 2003; Reilinger et al., 2006). These reconstructions imply that Arabia has progressed from 200-600 km “into” space formerly occupied by Eurasian continental lithosphere. This continuing “invasion” of the Arabian Plate into the Eurasian Plate determines the lithospheric shortening along the Main Caucasian Thrust (MCT), which extends in the meridional direction, and horizontal displacement of the lithosphere (McKenzie, 1972; Sengor et al., 1985; Jackson, 1992; Shevchenko et al., 1999; Guliev et al., 2002; Reilinger et al., 2006; Kadirov et al., 2008, 2012, 2023; Kadirov, 2004).

Since the Arabian Plate is moving north relative to Africa at a rate of 1.1-2.0 cm/year, a strong movement of the Arabian Plate towards Eurasia can be expected in advance. This causes the Caucasus to form a raised bridge separating two deep-water basins: the Black Sea and the South Caspian. Being responsible for crustal deformations, these regional tectonic processes cause earthquakes, which are historically documented throughout the entire Caucasus (Зоненшайн и Савостин, 1979; McKenzie, 1972).

In this paper we use Global Positioning System (GPS) observations in and around Azerbaijan in the period 1998-2022 to estimate present-day surface motions. The observed motions (site velocities) allow us to identify zones of rapid strain accumulation that we interpret as resulting from deep slip on faults that are presently locked at crustal depths and will likely give rise to future earthquakes. The GPS-derived surface motions allow estimation of fault geometry, slip rates, and locking depths (e.g., Okada, 1992), thereby providing an improved physical basis for estimating regional earthquake hazards. For example, the estimated rate of slip on the deep, freely sliding section of the Main Caucasus Thrust Fault (MCT) determined by GPS observations of surface motion, and estimates of slip in prior earthquakes (from study of historic and pre-historic earthquakes) allows estimation of the time required to accumulate sufficient strain to generate an earthquake, or equivalently, the earthquake recurrence time for individual fault segments (assuming the time-predictable earthquake model; Shimazaki and Nakata, 1980). Furthermore, the total coseismic slip from prior earthquakes, together with estimates of the locking depth of the fault (from the wavelength of the GPS deformation field), and the length of fault segments (from geological and geophysical studies) allow estimation of the magnitude of future events. Thus, our GPS observations have the potential to constrain the timing and magnitude of future earthquakes.

1. Tectonic Settings of the Caucasus Mountains

In the broadest context, the Lesser and Greater Caucasus Mountains lie within the zone of plate interaction where the African and Arabian plates are actively converging with the Eurasian Plate (Fig.1). McKenzie et al. (1970), McKenzie (1972), and Jackson and McKenzie (1984, 1988) provided a plate tectonic description of the region, recognizing active continental collision in eastern Turkey, the Caucasus, and the Zagros; lateral transport of Anatolia (Turkey) towards the west; subduction of African oceanic lithosphere (i.e., Neotethys) along the Hellenic and Cyprus trenches; N-S extension in the Aegean and western Turkey; and ocean rifting along the Red Sea and Gulf of Aden. Convergence of Arabia and Africa with Eurasia has been occurring for > 100 Ma as the intervening Neotethys Ocean lithosphere has been subducting beneath Eurasia. While ocean subduction continues at present along the Hellenic and Cyprus trenches, complete ocean closure north of the Arabian plate occurred ~27 Ma (e.g. McQuarrie and van Hindsbergan, 2013).

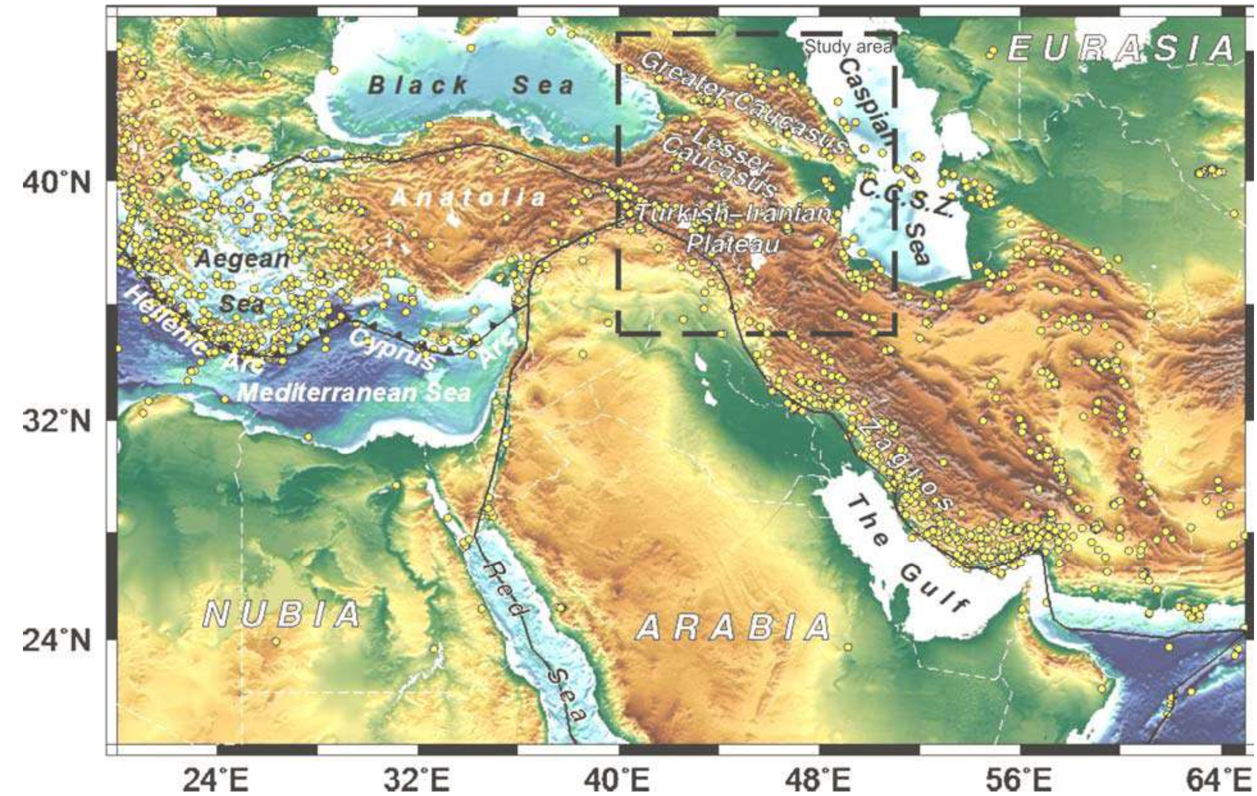

Fig. 1. Tectonic overview of the Arabia-Eurasia Collision Zone. Yellow dots are earthquakes from the EHB catalog (Engdahl et al., 1998) and updates thereof to 2008, plus ISC locations from 2009 onwards. Major plate boundaries are from Bird (2003)

Subsequent seismological, geophysical and geological studies added important refinements to this plate tectonic characterization, including the westward "extrusion" of Anatolia accommodated by the North and East Anatolian faults (Sengor et al., 1985), partitioning of crustal deformation in the eastern Turkey/Caucasus continental collision zone (Jackson, 1992; Allen et al., 2004;Copley and Jackson, 2006), the influence of slab detachment on uplift and volcanism of the Turkish Iranian Plateau (e.g.,Sengor et al., 2004;Barazangi et al., 2006), and early subduction of the S Caspian oceanic basin beneath the N Caspian Eurasian continental lithosphere along the central Caspian Seismic Zone (e.g., Jackson et al., 2002).

The Greater Caucasus Mountains are thought to have formed by tectonic inversion of a former back-arc ocean that opened during north-dipping subduction of the Neotethys (e.g. Zonenshain and Le Pichon, 1986; Forte et al., 2012; Alizadeh et al., 2016, 2017; Tye et al., 2021, 2022; Kangarli et al., 2018, 2021, 2022), where the eastern Black Sea, Kur Depression in Azerbaijan, and southern Caspian Sea are the remaining remnants of the back-arc basin. Both the timing and spatial evolution of shortening and exhumation remain uncertain, with preferred estimates of the timing being Late Miocene to Early Pliocene (e.g. Kopp and Shcherba, 1985; Philip et al., 1989; Vincent et al., 2007). Total shortening across the Greater Caucasus is also uncertain with estimates ranging from 150-400 km (e.g. McQuarrie and van Hindbergen, 2013), and an increase in total shortening from west to east (e.g. Kral and Gurbanov, 1996; Avdeev and Niemi, 2008; Forte et al., 2012).

2. Tectonics of the Africa–Arabia–Eurasia Plate System and GPS

During the past ~30 years, the active tectonics of theAfrica–Arabia–Eurasia plate system has been measured directly by geodetic observations, most importantly the GPS (Hager et al., 1991; Dixon, 1991). GPS consists of a system of 32 satellites 20,000 km above the Earth's surface that complete 2 orbits of the Earth each 24 h (http://tycho.usno.navy.mil/gpscurr.html). The satellites are operated by the US Department of Defense in cooperation with the Interagency GPS Executive Board. Other Global Navigation Satellite Systems (GNSS) have been developed by Russia (GLONASS), a European consortium (Galileo), Japan (QZSS), and China (Beidou), but these systems are not used in the results we report.

There are three components to use the GPS system for precise positioning: the satellite constellation, a global network of GPS tracking stations (Mueller and Beutler, 1992), and data processing involving applying physical models and parameter estimation. Most importantly for this chapter, positions are determined with an accuracy of ~2 mm in horizontal coordinates and 3-10 mm in heights by recording data over a 24-h period. These precisions are possible because of highly accurate timing provided by atomic clocks on the GPS satellites, precise orbital positions for the satellites provided by the International GNSS Service (http://igs.org/) (determined from the global network of observing stations), and processing software that uses advanced mathematical models to account for the Earth's rotation, solid Earth and ocean tides, and the ionospheric and atmospheric delays of the GPS signal, among other factors that influence position estimates (e.g., Herring et al., 2010).

3. Combined Azerbaijan – US Investigations: A Short Background

The Geology and Geophysics Institute of the Ministry of Science and Education of the Republic of Azerbaijan and Republican Seismic Survey Center of the Azerbaijan National Academy of Sciences and the Department of Earth, Atmospheric, and Planetary Sciences at Massachusetts Institute of Technology have been using the Global Positioning System (GPS) to monitor crustal deformation in the territory of Azerbaijan since 1998 (Reilinger et al., 2006; Kadirov et al., 2008,2009, 2013, 2014, 2015; Kadirov and Safarov, 2014; Ahadov and Kadirov, 2021; Ahadov and Jin, 2017; Ahadov and Jin, 2021; Ismail-Zadeh et al., 2020). These studies, coordinated and integrated with GPS studies in neighboring parts of the Arabia–Eurasia collision zone, provide new constraints on the fundamental geodynamic processes that are actively deforming the collision zone (e.g., Reilinger et al., 2006; Kadirov et al., 2012, 2015; Forte et al., 2012; Eppelbaum and Katz, 2022; Eppelbaum and Keshin, 2012). These geodynamic processes produced and maintain the high elevation of the Turkish–Iranian Plateau (Fig.1) and are the cause of the volcanic and earthquake activities that characterize this region.

The question of earthquake hazards has played a central role in our research because of the increasing vulnerability of the growing population and rapid infrastructure development expected maximum magnitude, and their likelihood of occurrence. This information is necessary in order to take appropriate preparedness and mitigation measures to reduce the risk to the population and infrastructure, including the vulnerable facilities associated with the petroleum industry that are critical to the economy of Azerbaijan.

In this chapter, we use GPS observations to constrain Arabia–Eurasia relative plate motions and the character of interplate deformations in the Arabia–Eurasia collision zone. Within this broader context, we focus on earthquake hazards in the Azerbaijan Caucasus and SW Caspian Basin.

4. Seismicity of Azerbaijan Territory. A Brief Background

Territory of Azerbaijan is located within the central part of the Mediterranean tectonic belt seismicity of which is caused by intensive geodynamic interaction of the Eurasian and Arabian lithospheric plates (Хаин, 2001; Азизбеков, 1968; Yetirmishli, 2020). Territory of Azerbaijan is characterized by high seismic activity where during historical period (registered), strong and catastrophic earthquakes with magnitude M ≥ 6 were observed. Azerbaijan territory may be subdivided by the level of seismic activity and character of space distribution of strong and weak earthquakes into the following manner:(1) Southern slope of the eastern part of the Greater Caucasus, (2) Kur Depression, (3) Talysh Mts., (4) Gusar-Shabran depression, (5) Northern slope of Lesser Caucasus, (6) Absheron Peninsula and (7) Caspian Sea (Telesca et al., 2017).

The history of seismic studies in Azerbaijan can be divided into two main periods: (1) pre-instrumental (historical)including all the information from ancient times reflected in the historical Arab chronicles, manuscripts, travel notes of travelers, etc., and (2) instrumental (contemporary) period which includes information about earthquakes from the beginning of the twentieth century (when after strong Shamakhi earthquake in 1902, the first seismic station in Azerbaijan "Shamakhi" was founded) till the present time.

Among the strong (historical) earthquakes, we can note such events as Azerbaijan earthquake of 427, Goygol of 1139,Ganja of 1235, Eastern Caucasian of 1668, Mashtaga of 1842,numerous Shamakhi events (1192, 1667, 1669, 1828, 1859,1868, 1872, 1902), Ardebil of 1924, Lankaran of 1913, and Caspian earthquakes (957, 1812, 1842, 1852, 1911, 1935,1961, 1963, 1986, 1989, 2000) triggered earth relief changing, building destructions, and numerous casualties.

One of the largest seismic events in Azerbaijan in twentieth century was a Shamakhi earthquake on February 13, 1902 (lat., 40.7 and long., 48.6; magnitude ≈ 7; depth offocus, 15 km; intensity of motions in the center, VIII–IX).

5. Role of GPS measurements on seismological studies in Azerbaijan

GPS observations play an important role in studying crustal deformation in the Arabia-Eurasia zone of plate interaction, and use these observations to constrain broad-scale tectonic processes within the collision zone of the Arabian and Eurasian plates. Within this plate tectonics context, we examine deformation of the Caucasus system (Lesser and Greater Caucasus and intervening Caucasian Isthmus), and show that most crustal shortening in the collision zone is accommodated by the Greater Caucasus Fold-and-Thrust Belt (GCFTB) along the southern edge of the Greater Caucasus Mountains. The eastern GCFTB appears to bifurcate west of Baku, with one branch following the arcuate geometry of the Greater Caucasus, turning towards the south and traversing the Neftchala Peninsula. A second branch (or branches) may extend directly into the Caspian Sea south of Baku, likely connecting to the Central Caspian Seismic Zone (CCSZ). Our studies indicate that strain is actively accumulating on the fault along the ~200 km segment of the fault west of Baku (approximately between longitudes 47-49°E). Parts of this segment of the fault broke in major earthquakes historically (1191, 1859, 1902) suggesting that significant future earthquakes (M~6-7) are likely on the central and western segment of the fault. We observe a similar deformation pattern across the eastern end of the GCFTB along a profile crossing the Kur Depression and Greater Caucasus Mountains in the vicinity of Baku. Along this eastern segment, a branch of the fault changes from a NW-SE striking thrust to an ~ N-S oriented strike-slip fault (or in multiple splays). The similar deformation pattern along the eastern and central GCFTB segments raises the possibility that major earthquakes may also occur in eastern Azerbaijan. However, the eastern segment of the GCFTB has no record of large historic earthquakes, and is characterized by thick, highly saturated and over-pressured sediments within the Kur Depression and adjacent Caspian Basin that may inhibit elastic strain accumulation in favor of fault creep, and/or distributed faulting and folding. Thus, while our analyses suggest that large earthquakes are likely in central and western Azerbaijan, it is still uncertain whether significant earthquakes are also likely along the eastern segment, and on which structure. Ongoing and future focused studies of active deformation promise to shed further light on the tectonics and earthquake hazards in this highly populated and developed part of Azerbaijan.

6. Estimating Surface Motions from GPS Observations

The GPS measurements presented in this paper include both continuously recording stations (cGPS) that remain in place indefinitely and survey-mode (sGPS) observations where the GPS antenna is positioned temporarily over a survey marker (Fig. 2). Over 35 survey mode sites were measured repeatedly starting from 1998 to 2022. By repeating the sGPS measurements episodically, we are able to estimate how the position has changed during the observation period.

Eight permanent stations were established by the Institute of Geology and Geophysics since 2006. In 2012, Republican Seismological Survey Center of Azerbaijan National Academy of Sciences started to construct permanent GPS stations, where totally 24 stations were established. Continuous GPS observations allow estimation of position on a daily basis or more frequently. However, reliable estimates of long-term, secular site velocities require a minimum of 2.5 years of observations even for cGPS because annual and semiannual systematic errors can bias estimates of steady-state motion (Blewitt and Lavellee, 2002).

While the precision of our site velocities varies with observation period, the GPS horizontal velocities we determine using the GAMIT-GLOBK processing software (Herring, 2004; Herring et al., 2010) have 1-sigma uncertainties in the range of0.2-0.9 mm/year, with most sites <0.5 mm/year. Because deformation rates across the Greater Caucasus Mountains vary from 2 to 14 mm/year from northwest to southeast, these precisions allow us to investigate details of the mountain building processes and associated earthquake hazards.

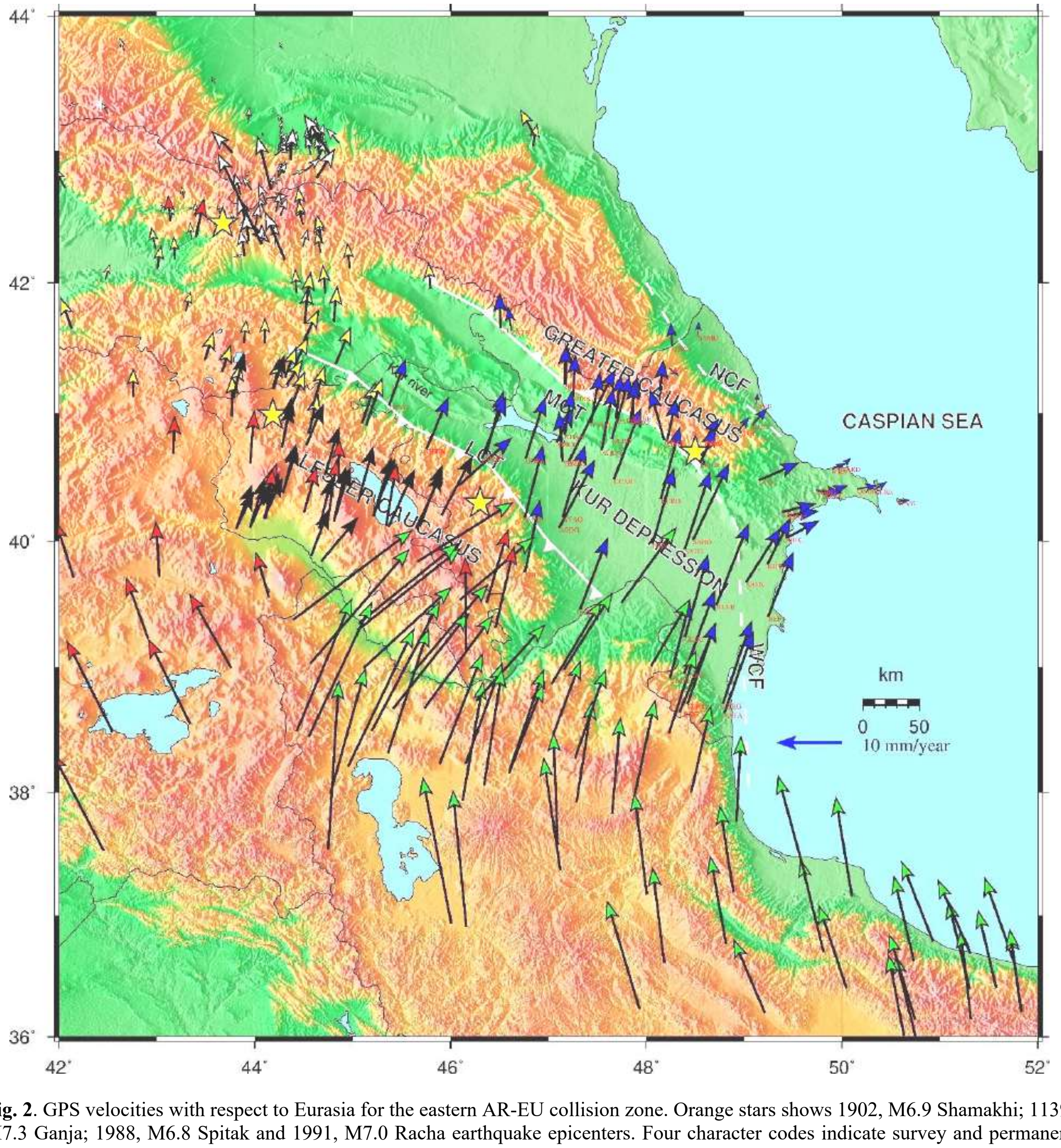

Fig. 2. GPS velocities with respect to Eurasia for the eastern AR-EU collision zone. Orange stars shows 1902, M6.9 Shamakhi; 1139, M7.3 Ganja; 1988, M6.8 Spitak and 1991, M7.0 Racha earthquake epicenters. Four character codes indicate survey and permanent GPS site names. Blue arrows indicate Azerbaijan GPS sites from these study, green arrows – Iranian GPS sites (Raeesi et al.,2017), Red arrows – Armenian GPS sites (Karakhanyan et al.,2013), Yellow arrows – Georgian GPS sites (Sokhadze et al., 2018), White arrows – Russian GPS sites (Milyukov et al.,2015), Black arrows are velocities from Reilinger et al., 2006.

Velocity estimates are determined in a global reference frame, that is, with respect to the global network of tracking stations. The reference frame is determined and maintained (updated) by the International Terrestrial Reference Frame (ITRF2014) Service (Altamimi et al., 2016) using well-positioned stations, with a long history of well-behaved observations, located around the globe and accounting for motions of the Earth's tectonic plates. We determine site velocities from Altamimi et al. (2016), but we present them in a reference frame fixed to the Eurasian Plate. It is important to bear in mind that the relative motion between measurement sites (i.e., deformation or strain rate) is invariant to changes in reference frame.

7. Present-Day Arabia–Eurasia Continental Collision

Fig.2 shows the velocities of GPS sites in the zone of interaction of the African, Arabian, and Eurasian plates (Reilinger et al., 2006 and updates thereof for sites in Azerbaijan). Virtually all major active tectonic processes are well resolved and quantified by the GPS observations, including the northward motion and counterclockwise (CCW) rotation of the Arabian Plate as a result opening of the Red Sea (e.g., ArRajehi et al., 2010), crustal shortening of the Zagros fold-and-thrust zone in Iran (e.g., Djamour et al., 2010), motion of the African Plate with respect to Eurasia (McClusky et al., 2003), and the change from NNW motion of Arabia to NNE motion of the Caucasus system (Reilinger et al., 2006; Vernant and Chery, 2006).

Reilinger et al. (2006) used the GPS velocity field to estimate how AR-EU convergence is partitioned between lateral "extrusion" of crustal blocks and crustal shortening. They found that a large majority (~70 %) of the convergence is accommodated by lateral transport, and ~15 %by shortening along the GCFTB (Greater Caucasus Fold-and-Thrust Belt), with the remainder being accommodated by other structures or distributed strain. The only slightly thickened crust in the Lesser Caucasus—E Turkey Plateau (Gok et al., 2003; Barazangi et al., 2006), in spite of 150–400 km of continental convergence (McQuarrie and van Hindbergen, 2013) – indicates that the geodetic results reflect long-term, tectonic deformation processes in the collision zone (i.e., if not for lateral transport, the crust would be expected to be much thicker). The utility of geodetic studies for constraining long-term geodynamic processes finds further support from comparison between present-day, geodetically derived Arabia–Eurasia convergence rates and longer-term plate convergence rates derived from plate tectonic reconstructions (e.g., McQuarrie et al., 2003) that indicate that these plate motions have been remarkably constant (±10–15 %) since the onset of continental collision in the Early Miocene (e.g., ArRajehi et al., 2010).

Results and discussion

Unlike previous years, in this study there are more permanent GPS station data and accordingly moreaccurate GPS observations made along the MCT (Reilinger et al., 2006; Kadirov et al., 2008, 2009, 2013, 2014, 2015; Kadirov and Safarov, 2014; Ahadov and Kadirov, 2021; Ahadov and Jin, 2017; Ahadov and Jin, 2021; Ismail-Zadeh et al., 2020; Yetirmishli et al., 2021, 2022a,b; Kazimov, 2021). Therefore it is possible to accurately track how the dynamics of the MCT changes from west to the east. Fig.3 shows a close-up of the GPS velocity field around the Greater and Lesser Caucasus, providing a quantitative basis to estimate the locations and slip rates and directions on the major structures that accommodate deformation.

On a broad scale, the GPS velocity field clearly illustrates the NNE motion of Caucasus and adjacent regions with respect to Eurasia south of the MCT (Fig.3).

The main shortening here in collision zone occurs along the southern boundary of the Greater Caucasus near the seismically active Greater Caucasus Fold-and-Thrust Belt (GCFTB).

This is well illustrated in the series of velocity profiles in Figs.4, 5 and 6, which show the rate of motion versus distance along profiles parallel to (AA$^/$) and traversing (B-C) the Caucasus system (profile locations on Fig. 3). Fig. 4a shows the component of velocity parallel to the direction of the profile; Fig. 4b shows the component normal to the direction of the profile (i.e. shortening or lengthening).

The plot in Fig.4b for the profile aligned along strike of the Greater Caucasus demonstrates the progressive increase in convergence rate with Eurasia from west to east, from 1-2 mm/yr in Georgia, to 13-14 mm/yr south of Absheron peninsula. The absence of any consistent change in rates in the direction of the profile traversing the Lesser Caucasus (i.e., Figs 5a and 6a) constrains active shortening in the Lesser Caucasus to < 2 mm/yr. These observations, and the low level of significant seismicity in the Lesser Caucasus (Fig. 3; the M6.8, 1988, Spitak, Armenia Earthquake being a notable exception), suggest that, within the resolution of our GPS observations, the Lesser Caucasus behaves like a coherent block rotating in a counterclockwise sense with respect to Eurasia, around a pole near the eastern end of the Black Sea (e.g. Lawrence, 2003; Reilinger et al., 2006; Copley and Jackson, 2006). Rotation may be related to the closure of an inter-continental back-arc basin separating the Lesser and Greater Caucasus, with the Caucasian Isthmus (Kur Depression in Azerbaijan) being the last remnants currently undergoing the final stages of subduction/closure (e.g. Cowgill et al., 2012).

However, when looking in more detail, we can see that along the MCT, the direction of the GPS velocity vectors west and east of the 48^0E -longitude changes from NNW to NNE, respectively. This can be explained by the separation of the MCT into a segment with more different dynamics near its intersection with 48^0E and/or by the presence of an active fault normal to the strike of MCT.

Along the southern slope of the Greater Caucasus, from west to east highest velocities are observed in KATE (5.51 mm/yr), OKUD (6.11 mm/yr), SEKC (6.10 mm/yr), YAGB (7.91 mm/yr), QABL (6.83 mm/yr), KEBE (5.46 mm/yr), ISMA (6.77 mm/yr) and IMLG (8.04 mm/yr) stations. The direction of the GPS velocity vectors at these points is mainly to the NNW, except for ISMA. Starting from GPS station MEDR (6.00 mm/yr) eastward from the epicenter of historical Shamakhi earthquake to Absheron Peninsula, the values of velocity vectors gradually decrease and reach 1.70 mm/yr at station JLVG, while the directions of movement are towards NNE.

Relatively smaller velocities are observed in the stations located on the northern slope of the Greater Caucasus and the northern part of the NCF. Thus, the earth's crust horizontal rates at QSRG, SAMU, SIYE stations are equal to 3.65, 2.19 and 1.71 mm/yr, respectively. Although the direction of motion is NNE at station XNQG (4.85 mm/yr), which is located slightly to the south, the velocity at station ANIX is 1.90 mm/yr, and the direction of motion is SW. Thesmall, but sharp difference from the regional crustal motion sense at the ANIX station may be a sign of the presence of a local active fault perpendicular to the strike of the Great Caucasus trust andfold system. This can be observed from the topographic structure of the area, as well.

We can observe how the Earth's crust horizontal movement ratesare gradually increase from west to east, in the GPS stations located in the northern slope of the Lesser Caucasus, the Kura depression and the Talish zone. In general, unlike the Greater Caucasus,here the velocities are higher. Thus, the horizontal crustal movement velocities starting from the territory of Georgia in the west, from the station QZXG (7.65 mm/yr) located in the territory of Azerbaijan increase towards the east, at stations BLVR (13.54 mm/yr), ASTA (13.40 mm/yr), and LKRG (13.54 mm/yr). In addition, it is observed that the Earth's crust movement direction along the Kura depression is towards the NNE in all the stations, except for the YEVL station, which suggests that the Lesser Caucasus, the Kura depression and the Talysh zone move as a coherentand single block. The same pattern is observed in the neighboring territories of Georgia and Armenia.

We believe that the observed NNW movement at the YEVL site is caused by the large number of multi-trajectory errors and the higher signal-to-noise ratio at this site (due to the presence of tall buildings and trees near the antenna).

In the areas located south of Goycha Lake and the Iran-Azerbaijani border, we encounter a more complex velocity field, which indicates the existence of an active fault system parallel to each other in the SE-NW direction, which is also observed in the territories of Armenia and Iran in the south, starting from the Hekari river valley.

It can be observed that the crustal movement velocities at the GPS stations located south of the Absheron Peninsula (starting from SALN)decrease from the WCF to the east and, at the same time, the movement directions change from NNE (SALN, KHİD) to East (SHİK, SANG, JANG, BAKU, GOBG, QALG, GURK, JLVG, PIERCE, NARD) (Figs 3, 6).

In addition, small azimuth differences are noticeable in the direction of PIRS and NARD GPS vectors located in the north of the Absheron Peninsula and GOBG, BAKU, QALG, GURK and JLVG stations located in the south. This can be explained by the dynamics of the fault, which is characterized by weak activity passing in the subparallel direction from the northern part of the Absheron Peninsula, suggesting that significant deformational energy can be accumulated here along the boundary.

We estimate shortening across the eastern segment of the MCT from the velocity difference between site KURD in the Kura Depression and SAMU on the northernmost site of the Pre-Caspian-Guba region (Fig. 2). The total velocity difference is 9 ± 1 mm/yr, corresponding to the rate of shortening across the MCT at ~48° E longitude. The total velocity difference between SATG in the central Kura Depression and SIYE on the north of the Absheron peninsula is almost 11 ± 1 mm/yr (Fig. 2). In western Azerbaijan the rate of crustal shortening derived from QZXG and ZKTG GPS site velocity differences is about 4 ± 1 mm/yr, indicating that the strain accumulation rates across the MCT is different from west to east.

An important note here is the sharp decrease in site velocities, and the clockwise rotation, between sites located to the west of WCF in Kura Depression and Talish region (GOSM, YARD, BILE, SATG, SABD) and sites to the east of WCF in Absheron Peninsula (SHIK, SANG, GOBG, BAKU and further to the east) (Fig. 2). This decrease and difference in GPS vector directions indicate high strain accumulation rates ~6 mm/yr south to Absheron Peninsula.

This is best illustrated by the GPS velocity profiles shown in Fig.6a, and b. The location of the profile $CC^{/}$is shown on Fig. 3. Fig.6a shows the component of site velocity parallel to the WCF at this location (rate of right-lateral strike slip), and Fig.6b the component of site velocity normal to the WCF (i.e., rate of fault-normal motion). Fig.6a indicates11 ± 1 mm/yr right-lateral strike slip motion across the WCF, while Fig.6b indicates 3 ± 1 mm/yr fault-normal motion along the segment of the MCT/WCF south of the Absheron Peninsula.

As noted earlier, the small difference on crustal motions for sites in northern Absheron (PIRS, NARD) and those located in southern side indicates left lateral, strike slip on the fault, which is probably the southern segment of NCT, where it turns to the south inland from the Caspian coast line and crosses the peninsula from west and continues eastward to the Caspian Sea. This geometry for the NCT is roughly consistent with some earlier interpretations of the regional tectonics (e.g., Philip et al., 1989), and indicates that the Baku area is located at a highly complex junction between four fault systems, the MCT, the Central Caspian Seismic Zone, the North Caspian Fault, and the West Caspian Fault.

A decrease in the velocity and a significant accumulation of elastic energy in the southern Absheron Peninsula is responsible for the activation of seismic events and of mud volcanoes in this region. The strong earthquake in the Caspian Sea at the end of 2000 and its aftershocks probably represent a response to the deformational processes which continue in recent years, and the related stress accumulation at foothills of the Greater Caucasus and the Absheron Peninsula and middle Caspian regions (Kadirov et al. 2005).

While the available GPS data provide fundamentally new constraints on fault geometry and rates of strain accumulation, spatial densification of the GPS observations is needed to better resolve localized deformation, and consequently the seismic hazard in the eastern Caucasus, Kura Depression, and Absheron area.

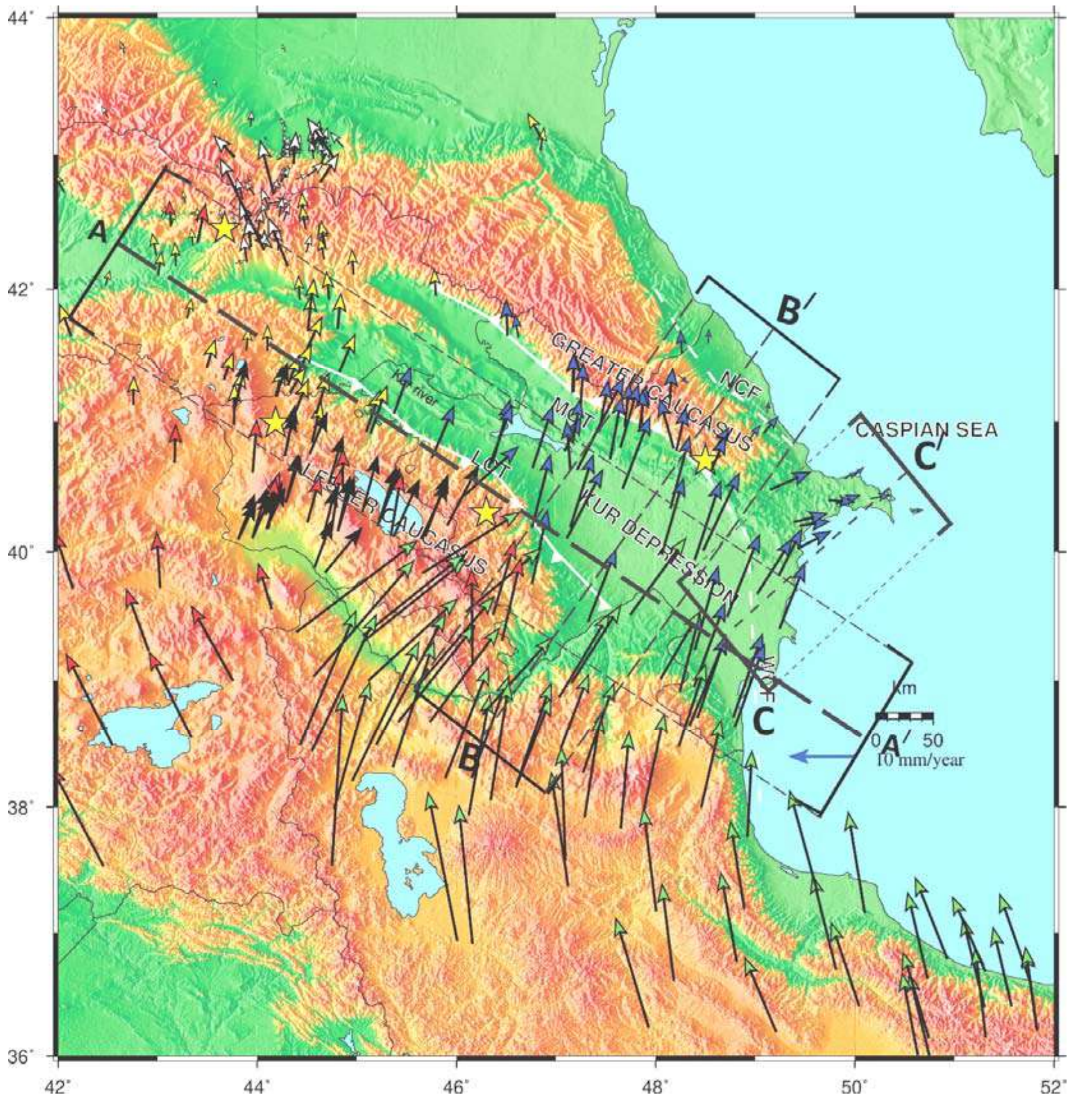

Fig. 3. GPS velocities with respect to Eurasia for the eastern AR-EU collision zone. Orange stars shows 1902, M6.9 Shamakhi; 1139, M7.3 Ganja; 1988, M6.8 Spitak and 1991, M7.0 Racha earthquake epicenters. Velocity profiles A-C are shown in Fig. 4-6. Locations and widths (brackets) of velocity profiles crossing the Kura Basin (A–A/) across strike of the Greater Caucasus (B-B/), and Absheron Peninsula (C-C/), respectively.

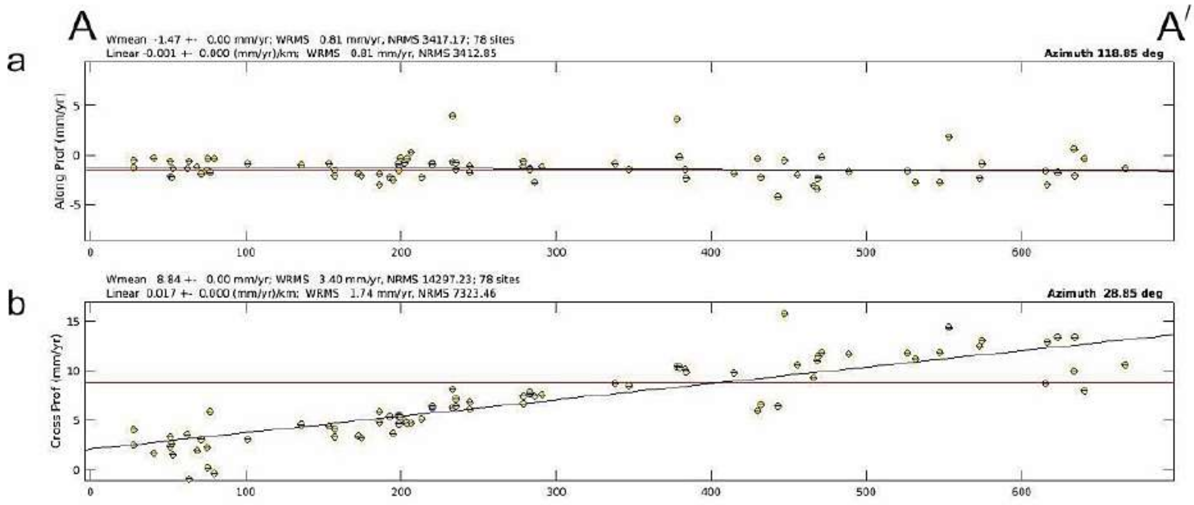

Fig. 4.GPS velocities with respect to Eurasia plotted versus distance along profile A-A/ shown in Fig. 3. The widths ofthe profile is indicated by brackets in Fig. 3. (a) The component of motionparallel to the profile, (b) The component of motion normal to the strike of the profile.

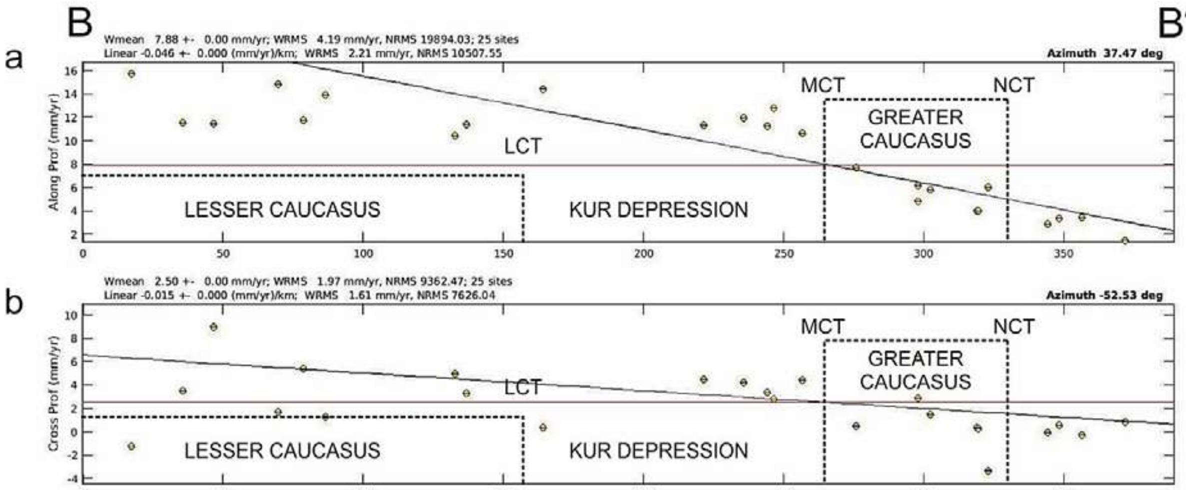

Fig. 5. GPS velocities with respect to Eurasia plotted versus distance along profile B-B/ shown in Fig. 3. The widths of the profile is indicated by brackets in Fig. 3. (a) The component of motion parallel to the profile, (b) The component of motion normal to the strike of the profile.

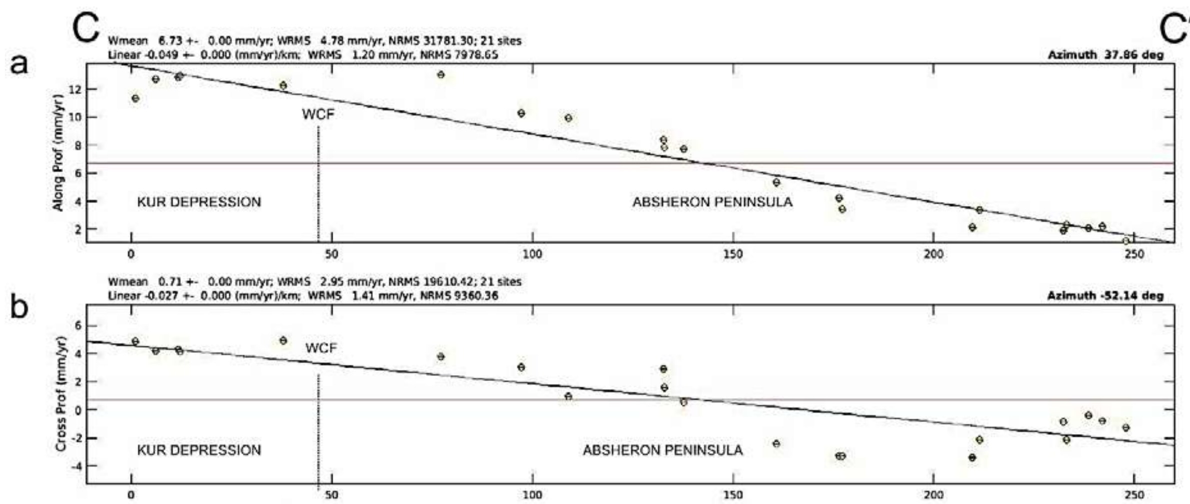

Fig. 6. GPS velocities with respect to Eurasia plotted versus distance along profile C-C/ shown in Fig. 3. The widths of the profile are indicated by brackets in Fig. 3. (a) The component of motion parallel to the profile, (b) The component of motion normal to the strike of the profile

Structures accommodating deformation may merge offshore with the thick, folded sediments south of the Absheron Peninsula. This offshore geometry is supported by GPS velocities in the SW corner of the Caspian Basin in Iran (Djamour et al., 2010) that indicate northerly motion with rates similar to those in the adjacent Lesser Caucasus to the west.

Conclusions

Repeated GPS surveys in Azerbaijan and more permanent station data for the period 1998 – 2022 are providing direct observations of present-day surface motions. They clearly define active convergence between the Lesser Caucasus/Kura Depression and the Greater Caucasus with strain concentrated along the Main Caucasus Thrust Fault (MCT).

On a broad scale, the GPS velocity field clearly illustrates the NNE motion of Caucasus and adjacent regions with respect to Eurasia south of the MCT.

Present-day slip rates on the MCT decrease from 10 ± 1 mm/yr in eastern Azerbaijan to 4 ± 1 mm/yr in western Azerbaijan. These new observations further indicate that the strain accumulation rates along MCT gradually changes from west in Georgia, to the east of the Absheron Peninsula.

GPS velocity vectors west and east of the 48^0E suggests that MCT separates into a segments byan active fault normal to the strike of MCT characterized by different dynamics near its intersection with 48^0E.

It is observed that the earth's crustal movement direction along the Kura depression is towards the NNE in all the stations, except for the YEVL station, which suggests that the Lesser Caucasus, the Kura depression and the Talysh zone move as a coherentand single block.

WCF is a predominantly right lateral strike slip fault with a slip rate of 11± 1 mm/yr south of the Absheron Peninsula.

GPS-derived motions in the northern slope of Greater Caucasus and along the Caspian coast in Azerbaijan north of the Absheron Peninsula require that thrust faulting along the south-dipping North Caucasus. Thrust turns to the south inland of the Caspian coast, crosses the peninsula from west and continues eastward to the Caspian Sea, presumably accommodating left-lateral strike slip motion on this segment.

These interpretations of the GPS velocity field place Baku at the junction of four active fault systems, the MCT, the North and West Caspian faults (likely left and right-lateral, strike slip respectively), and the Central Caspian Seismic Zone. More focused geodetic monitoring of surface motions are needed in the Absheron region and Kura Depression, as well as in the immediate vicinity of other active faults and mud volcanoes.

The geodetic observations presented in this study demonstrate that strain is accumulating along all segments of the Greater Caucasus Fold-and-Thrust Belt from the Shamakhi region (~70 km west of Baku) to the Azerbaijan-Georgian border.

Geodetic observations across the Kur Depression and Absheron Peninsula in the densely populated and highly developed easternmost part of Azerbaijan show a similar deformation pattern across the GCFTB as the observations crossing the central and eastern segments of the fault. While this may indicate active strain accumulation that could generate earthquakes, the absence of large historic earthquakes, the change in strike of the fault west of Baku, and the thick highly saturated sediments in the eastern Kur Depression and south Caspian Basin may preclude large events like those known to occur on the fault further east.

However, given the rapid increase in the population and the extensive infrastructural development in this part of Azerbaijan, and the likelihood of gaining new insights from additional geodetic observations and complex fault models, it is essential that further studies be focused on the possibility and effects of damaging earthquakes along the eastern segment of the GCFTB. In particular, densifying GPS coverage along and across the eastern Caucasus, Kur Basin, and Greater Caucasus, constraining the subsurface geometry of the GCFTB and it's extension into the Caspian Sea with seismic studies, and investigating the historic earthquake record and paleoseismic observations to extend the earthquake record will provide the constraints needed to clarify better earthquake hazards in Azerbaijan.

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РЕЗУЛЬТАТЫ 25-ЛЕТНЕГО (1998-2022) МОНИТОРИНГА ДЕФОРМАЦИИ ЗЕМНОЙ КОРЫ В АЗЕРБАЙДЖАНЕ И НА СОПРЕДЕЛЬНОЙ ТЕРРИТОРИИ С ИСПОЛЬЗОВАНИЕМ GPS

Кадиров Ф.[1], Етирмишли Г.[3], Сафаров Р.[1], Мамедов С.[1], Казимов И.[3], Флойд М.[2], Рейлингер Р.[2], Кинг Р.[2]

[1]Министерство науки и образования Азербайджанской Республики, Институт геологии и геофизики, Азербайджан AZ1143, Баку, просп. Г.Давида, 119

[2]Факультет наук о Земле, атмосфере и планетах, Массачусетский технологический институт 54-918 Кембридж, Массачусетс, США, Массачусетс авеню, 77

[3]Республиканский центр сейсморазведки Национальной академии наук Азербайджана Азербайджан, Баку Az 1001, ул. Н.Рафибейли 25

Резюме. Мы представляем GPS-наблюдения за мониторингом деформаций земной коры в Азербайджане и на прилегающей территории, которые проводились с 1998 года. В отличие от наших предыдущих исследований, здесь собрано еще больше данных постоянных GPS-станций и съемки, что, соответственно, позволило нам более точно определить динамику основных тектонических структур.

С 2006 года Институтом геологии и геофизики было создано восемь постоянных станций. В 2012 году Республиканский центр сейсмологической службы Национальной академии наук Азербайджана приступил к строительству постоянных станций GPS, всего было установлено 24 станции. С 1998 по 2022 год неоднократно проводились измерения на более чем 35 пунктах наблюдения.

В широком масштабе поле скоростей GPS четко иллюстрирует движение Кавказа и прилегающих регионов в северо–северо-восточном направлении относительно Евразии к югу от Главного Кавказского надвига (ГКН). Здесь важно отметить резкое уменьшение скоростей на пунктах измерения и вращение по часовой стрелке между пунктами, расположенными к западу от Западно-Каспийского разлома (ЗКР) в Куринской впадине и Талышском районе, и участками к востоку от ЗКР на Абшеронском полуострове. Такое уменьшение и различие в направлениях GPS-векторов указывает на высокие скорости накопления деформации – ~6 мм/год к югу от Абшеронского полуострова. Мы полагаем, что значительное накопление упругой энергии является одной из основных причин активизации сейсмических событий и грязевых вулканов в этом регионе. Таким образом, пространственное уплотнение GPS- наблюдений необходимо для лучшего разрешения локализованных деформаций и, следовательно, сейсмической опасности на Восточном Кавказе, в Куринской впадине и на Абшероне.

Ключевые слова: *Деформация, тектонические структуры, мониторинг, GPS, землетрясение, сейсмическая опасность*

AZƏRBAYCAN VƏ QONŞU ƏRAZİLƏRDƏ GPS VASİTƏSİLƏ YER QABIĞI DEFORMASİYALARININ 25 İLLİK (1998-2022) MONİTORİNQİNİN NƏTİCƏLƏRİ

Qədirov F.[1], Yetirmişli Q.[3], Səfərov R.[1], Məmmədov S.[1],
Kazımov I.[3], Floyd M.[2], Reylinger R.[2], Kinq R.[2]

[1]Azərbaycan Respublikasının Elm və Təhsil Nazirliyi, Geologiya və Geofizika Institutu, Azərbaycan
AZ1143, Bakı, H.Cavid prosp., 119
[2]Yer, atmosfer və planetlər elmləri fakültəsi, Massaçusets Texnologiya Institutu
54-918, ABŞ, Massaçusets, Kembric, Massaçusets Avenyu, 77
[3]Azərbaycan Milli Elmlər Akademiyasının Seysmik Kəşfiyyat Mərkəzi
AZ1001, Bakı, N.Rəfibəyli küç., 25

Xülasə. 1998-ci ildən Azərbaycanda və ona bitişik ərazilərdə aparılan yer qabığı deformasiyalarının GPS monitorinq nəticələri təqdim edilmişdir. Əvvəlki tədqiqat işlərindən fərqli olaraq, burada daha çox fasiləsiz işləyən GPS stansiyaları və ölçü məntəqə məlumatları cəmlənmişdirki, bu da regionun əsas tektonik strukturlarının dinamikasını daha dəqiq müəyyən etməyə imkanvermişdir.

2006-cı ildən başlayaraq, Geologiya və Geofizika İnstitutu tərəfindən səkkiz fasiləsiz işləyən stansiya qurulmuşdur. 2012-ciildənisə Azərbaycan Milli Elmlər Akademiyası nəzrində Respublika Seysmoloji Xidmət Mərkəzi tərəfindən GPS stansiyalarının qurulmasına başlanmış və burada ümumilikdə 24 stansiya yaradılmışdır. 1998-ciildən 2022-ciilə qədər 35-dən çox ölçü məntəqəsində dəfələrlə müşahidələr aparılmışdır.

Böyük miqyasda, GPS sürət sahəsi Əsas Qafqaz Üstəgəlmə Qırılmasından (MCT) cənubda olmaqla Qafqaz və ona bitişik rayonların Avrasiyaya nəzərən şimal-şimal-şərq istiqamətində hərəkətini aydın şəkildə təsvir edir. Burada qeyd edilməli mühüm məqam Kür çökəkliyi və Talış bölgəsində Qərbi Xəzər qırılmasından (QXQ) qərbdə yerləşən məntəqələrlə QXQ-nin şərqində Abşeron yarımadasında yerləşən məntəqələr arasında sürətlərin kəskin azalması və saat əqrəbi istiqamətində fırlanmadır. GPS vektor istiqamətlərindəki bu azalma və fərq Abşeron yarımadasının cənubunda ~6 mm/il olmaqla deformasiyaların yüksək sürətlə toplanmasını göstərir. Belə hesab edirik ki, elastik enerjinin əhəmiyyətli dərəcədə toplanması bu regionda seysmik hadisələrin və palçıq vulkanlarının aktivləşməsinin səbəblərindəndir. Beləliklə, Şərqi Qafqazda, Kür çökəkliyində və Abşeron ərazisində toplanmış deformasiyanı və nəticədə seysmik təhlükəni daha dolğun qiymətləndirmək məqsədilə GPS müşahidə məntəqələrinin sıxlığının artırılmasına ehtiyac vardır.

Açar sözlər: *Deformasiya, tektonik strukturlar, monitorinq, GPS, zəlzələ, seysmik təhlükə*