ANAS Transactions **Earth Sciences** **1 / 2025**

http://www.journalesgia.com

PALEOSEISMOLOGICAL STUDIES IN THE PLEISTOSEISMIC AREA OF THE 1668 AND 1902 SHAMAKHI EARTHQUAKES

Pierce I.[1], Guliyev I.S.[2], Yetirmishli G.J.[3], Kazimova S.E.[3], Walker R.[1], Kazimov I.E.[3], Abdullayev N.R.[2], Johnson B.[1], Marshall N.[1],

[1]*University of Oxford, United Kingdom*
3 S Parks Road, Oxford
[2]*Presidium of the Azerbaijan National Academy of Sciences, Azerbaijan*
30, Istiglaliyyat str., Baku, AZ1001
[3]*Republican Seismic Survey Center of Azerbaijan National Academy of Science, Baku, Azerbaijan*
123, Huseyn Javid ave., Baku, AZ1141

Keywords: *paleoseismic trenches, Shamakhi earthquakes 1902, Kur fold-thrust belt, satellite imagery, drone modeling, OxCal sequence model, surface rupture*

Summary. The Caucasus region located at the junction of the Eurasian and Arabian tectonic plates is a key area for understanding continental collision processes and their impact on seismic activity. The aim of this work is to analyze the region's tectonic processes, seismic history, and the risks associated with potential large earthquakes. The study employs modern methods including satellite imagery, GNSS data, drone-based modeling, and paleoseismic trenching. In April–May 2022, a team of scientists from the University of Oxford, in collaboration with early-career researchers from the RSSC, carried out the first geological fieldwork in Azerbaijan focused on paleoseismology and active tectonic processes. Two trenches were analyzed. One of the key findings was the identification of active faults, such as the Aghsu fault, and evidence of surface ruptures associated with historical earthquakes. Two surface rupture events (1713–1895 and 1872–2003) were identified likely linked to the surface displacements caused by the 1668 and 1902 earthquakes, which inflicted significant damage on the city of Shamakhi. Our reassessment of the 1902 earthquake suggests its magnitude may have reached Mw 7.4, whereas earlier estimates placed it at M 6.9. Additionally, evidence of a surface-rupturing earthquake dated between 334 and 118 BCE was found in a second trench located 60 km west of Aghsu near Goychay along with signs of another possible event within the past 2000 years. This work highlights the importance of continued field investigations to better constrain fault lengths, assess historical earthquake magnitudes, and improve regional seismic hazard maps.

1. Introduction

The Caucasus mountain system located at the junction of the Eurasian and Arabian plates represents a key site for understanding the complex geodynamic processes of continental collisions and their influence on seismic activity. Despite the fact that much of the structural paragenesis of orogenic zones has been thoroughly studied, the morphological features of mountain systems such as the Greater Caucasus still require further exploration. These mountain forms not only reflect the history of tectonic forces but also serve as indicators of underlying geodynamic processes offering valuable insights, especially when direct geological data is limited.

The seismicity of the Greater Caucasus has historically been significant with numerous destructive earthquakes recorded over the centuries. These events, such as the earthquakes of 1139, 1668, and the series from 1828 to 1902 have left an indelible mark on the history of the region. However, the lack of instrumental earthquake data for much of the region complicates our understanding of the full seismic potential of the area. Turning to historical earthquake records and modern geophysical data reveals that the fault systems of the region are active with the possibility of significant seismic events still looming. The goal of this study is to explore the geodynamic conditions of the Greater Caucasus focusing on historical seismicity and the active faults responsible for shaping the region's seismic landscape.

The research in this article presents a comprehensive analysis of the region's tectonic processes, seismic history, and current risks associated with potential future earthquakes based on modern technologies such as satellite imagery, drone modeling, GNSS technologies, as well as paleoseismic trenching.

On April – May, 2022, a team of five scientists from Oxford University Department of Earth Sciences led by Professor Richard Walker collaborated with young scientists from RSSC to conduct the first field geological studies focused on paleoseismology, earthquake geology, and active tectonics in Azerbaijan. The aim of this research was to understand the potential locations and frequency of strong destructive earthquakes (M7+) that occurred before the development of modern seismic networks.

At the conclusion of this research, a comprehensive article titled **"Surface Rupturing Earthquakes of the Greater Caucasus Frontal Thrusts, Azerbaijan"** was published. Our article is a summary of that study, which was published in 2024. It provides a concise overview of the research helping a broader audience quickly understand the key findings.

1.1. The Mountain System of the Greater Caucasus

To date, the structural paragenesis of orogenic zones has been thoroughly studied but the morphological features of the orogens themselves remain incompletely understood. These differences reflect geodynamic processes and can serve as indicators of these processes, particularly in cases where direct geological data are absent or insufficient. Structurally, orographic forms of orogens retain data on the geodynamic conditions of their formation (Makarova et al., 2000; Коркуганова, 2000). In recent decades, numerous studies in the fields of geology, geodynamics, geodesy, and geophysics have been conducted to investigate the evolution of the Caucasus and its surrounding areas, as well as to refine our understanding of current tectonic processes, lithospheric deformations, seismicity, and the associated seismic risks and hazards. The results of these studies are reflected in a number of papers published in international journals, as well as in those published in the former Soviet Union, Armenia, Azerbaijan, Georgia, and Russia. Furthermore, recent geological, geophysical, and geochemical studies have provided additional clarification on the tectonic framework of the region. The question of the age of continental collision remains unresolved with various studies suggesting a range from the Late Cretaceous to the Pliocene (Ismail-Zadeh et al., 2022).

The Caucasus region is known to be part of the ongoing continental collision between the Arabian and Eurasian plates. For over 100 million years, the lithosphere of the Neo-Tethyan Ocean has been subducted beneath Eurasia (Хаин, 1975; Adamia et al., 1985). This process has led to inversion and the formation of fold-and-thrust belts in the Greater and Lesser Caucasus (Mosar et al., 2010).

The diagram showing the tectonic structure of the Eastern Black Sea region is presented in Figure 1. The following key tectonic units can be identified within this region (Муратов, 1969; Letouzey et al., 1977; Starostenko et al., 2004; Saintot et al., 2006; Афанасенко и др., 2007; Rolland et al., 2011; Nikishin et al., 2012): (1) the South Crimea Orogen, (2) the Greater Caucasus Orogen, (3) the system of terranes of the Central and Eastern Pontides with Mesozoic volcanic belts (Middle Jurassic and Cretaceous), and (4) the Eastern Black Sea Basin with oceanic crust and strongly stretched continental crust due to rifting.

The Greater Caucasus mountain system, which stretches approximately 900 km between the Black and Caspian Seas, is considered to have formed as a result of tectonic inversion of a former back-arc basin that developed on continental crust and opened in the early Mesozoic above the northern subduction zone of Neo-Tethyan Ocean (Adamia, 1985; Mosar et al., 2010). Thermochronological studies have shown that the formation of the topography of the western Greater Caucasus began as early as the Oligocene (Vincent et al., 2018a,b). Estimates of total shortening across the Greater Caucasus remain uncertain ranging from 150 to 400 km with shortening increasing from west to east (Ismail-Zadeh et al., 2022). Continued convergence has generated compressive stress, which activated deformation and uplift of the Greater Caucasus during the Pliocene. According to McQuarrie and Van Hinsbergen (2013), the closure of the Neo-Tethyan Ocean to the north of the Arabian Plate occurred about 27 million years ago, although subduction continues along the Hellenic and Cyprian trenches. Cowgill et al. (2016) link the changes in the Arabian-Eurasian collision zone to the closure of the rift basin on the southern slope of the Greater Caucasus. However, Vincent et al. (2018a) argue that, sedimentological and seismological data suggest an earlier closure of the basin around the early Oligocene at least for the western part of the Greater Caucasus. Cowgill et al. (2018) propose that basin closure began around 35 million years ago and was completed around 5 million years ago when the Lesser Caucasus collided with the Scythian Platform forming the Greater Caucasus. The final collision of the Arabian and Eurasian plates and the formation of the modern intracontinental mountain structure of the Caucasus occurred during the Neogene-Quaternary period (Ismail-Zadeh et al., 2022).

The paper (Sengor et al., 2023) proposes a revision of traditional models highlighting the Pacific-type margin and the dynamic motion of the continent. The Cimmerian Continent was a complex tectonic structure that not only rifted from Gondwana but also underwent internal extension forming oceanic basins such as the Neo-Tethys (Fig. 2).

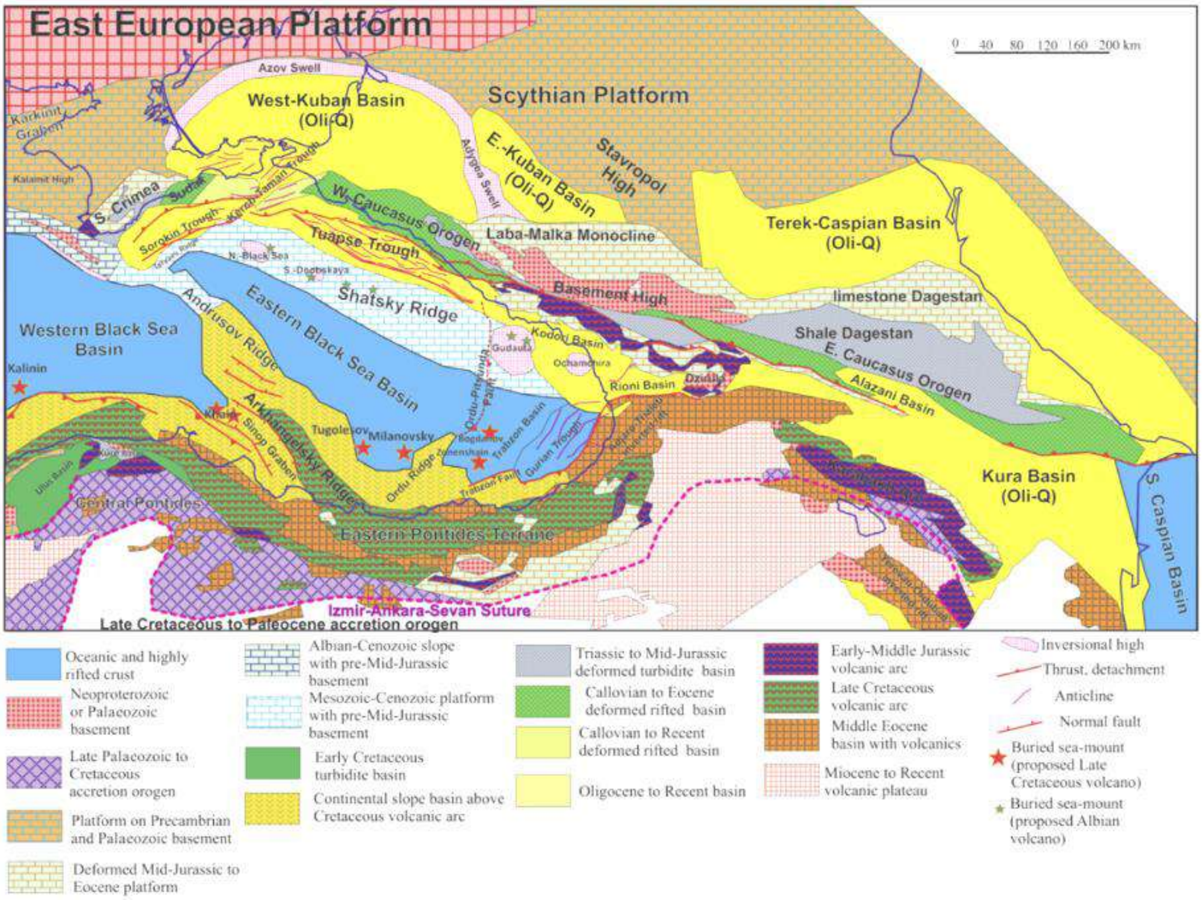


Fig. 1. Tectonic scheme of the Caucasus– Eastern Black Sea region. The scheme has been compiled in collaboration with A. Okay, O.Tüysüz and A. Demirer for the Black Sea region. Oli-Q, Oligocene–Quaternary (Nikishin et al., 2015)

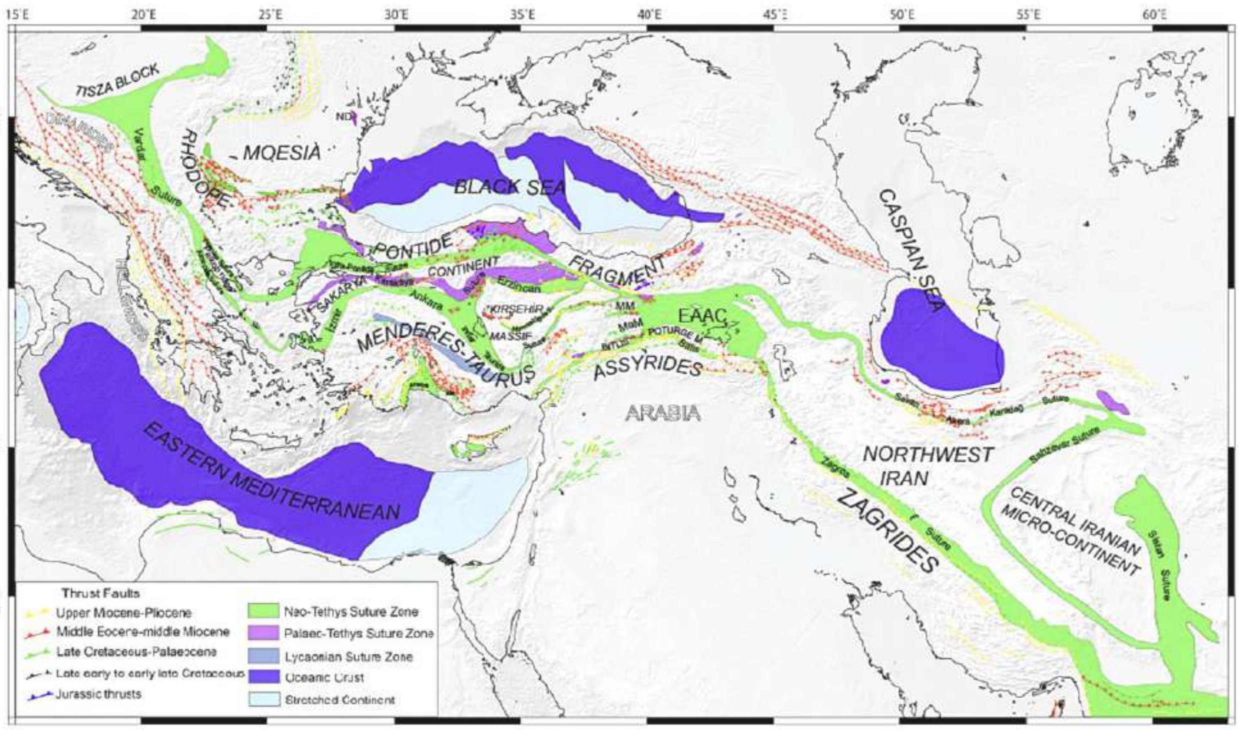


Fig. 2. Distribution of suture zones in and around Turkey afterwards (Sengor et al., 2023).

Its evolution is tied to the subduction of the Palaeo-Tethys and its subsequent closure as well as the opening of new basins and eventual collision with Laurasia. The northern margin of the Cimmerian Continent was of Pacific-type not Atlantic-type as claimed by some authors implying active subduction processes and back-arc basin formation.

The continent traversed the Tethyan realm in a "serpentine motion" making it impossible to reconstruct synthetic isochrons to precisely track its northward migration (except for simplified visualizations of its journey). Oceanic basins including the Neo-Tethys opened as back-arc basins behind the subducting slab.

The movement of the Cimmerian continent across the Tethyan region occurred between the Late Triassic and Late Jurassic and in some places possibly even in the Early Cretaceous, when the Cimmerian continent collided with the Laurasian margin. Due to the complex nature of this movement, the authors note that it is impossible to construct synthetic isochrons to accurately track the northward migration of the Cimmerian continent except for a simplified visualization of its path across the Tethyan region.

Many outstanding scientists have studied the tectonics, geodynamics, and seismicity of the Greater Caucasus and Azerbaijan including G.V.Abich, R.A.Agamirzoyev, Sh.A.Adamia, A.A.Alizade, F.S.Akhmedbeyli, B.K.Balavadze, G.Sh.Shengelia, G.I.Baranov, R.M.Gadzhiev, I.S.Guliyev, F.A.Kadirov, T.N.Kengerli, M.L.Kopp, V.V.Korobanov, E.E.Milanovsky, V.E.Khain, and others (Abich, 1862, 1873; Агамирзоев, 1987; Adamia, 1985; Ализаде и др., 1968; 1982; Ахмедбейли, 1991, 2001; Balavadze et al., 1975, 1966; Баранов и Греков, 1982; Гаджиев, 1965; Guliev et al. 2002; Kengerli, 1997; Копп, 1997; Korobanov, 1990; Милановский и др., 1963; Хаин, 1984; Хаин и др., 2005).

1.2. Paleoseismogeological studies and historical tectonic activity of the Greater Caucasus.

The first paleoseismogeological studies in the Greater Caucasus region began in the late 1960s based on the hypothesis that large earthquakes that occurred in the distant past leave traces on the Earth's surface in the form of paleoseismodislocations (Florensov, 1960). Evidence of such events was recorded in various parts of the Caucasus: on the southern slopes of the Northwestern Caucasus in the central Western Caucasus (Хромовских и др., 1979) near Mount Elbrus (Nikonov, 1991) in the vicinity of the Caucasian Mineral Waters (Белоусов и др., 2000) in North Ossetia (Никитин и др., 1993) in North Caucasus and in mountainous Dagestan, and on the coast of the Caspian Sea (Бунин, 1985; Korzhenkov et al., 2019; Овсюченко и др., 2014; Rogozhin et al., 2015; Gmyrya et al., 2019). These studies revealed that the seismic activity of the region might be significantly higher than previously believed on the basis of traditional seismicity statistics. Most of the identified ancient seismogenic structures were linked to gravitational processes. However, in most cases, researchers could not precisely determine the locations, magnitudes, and ages of ancient earthquake sources. One exception was the work led by V.P.Solonenko (Хромовских и др., 1979), where the first estimates of earthquake magnitudes and focal zones were obtained. In the late 1980s and early 1990s, several significant earthquakes occurred in the Caucasus region affecting both the Lesser and Greater Caucasus. These included the 1986 Paravan earthquake with a magnitude of 6.5, the 1988 Spitak earthquake with a magnitude of 6.9, the 1991 Racha earthquake (magnitude 7.0), the 1991 Java earthquake with a magnitude of 6.5, and the 1992 Barisakh earthquake with a magnitude of 6.2 (Рогожин и др., 2014).

The primary tectonic structure associated with this process is the Main Caucasus Thrust characterized by northward dip. Around 1.5 million years ago, deformation began to spread to the Kur foreland fold-thrust belt, which experiences shortening at a rate of 6.7–13.6 mm/yr as determined from reconstructed balanced cross-sections (Forte et al., 2015; Kangarli et al., 2018), and through GNSS measurements, which show a rate of around 10 mm/yr in the Kur Basin (Reilinger et al., 2006; Yetirmishli et al., 2022).

The Kur fold-thrust belt stretches from west to east for about 275 km, from the vicinity of Tbilisi in Georgia to the Shamakhi area in Azerbaijan. Its structure consists of a series of overlapping thrusts, the number of which varies from one to four depending on the section of the belt. Despite the fact that no earthquake with M>7.0 has been recorded in the southeastern part of the Greater Caucasus during the instrumental period, the region has experienced numerous destructive earthquakes in the pre-instrumental period. The region is known for its historical earthquakes, the most destructive of which were the events of 1139, 1668, and a series of earthquakes between 1828 and 1902 (Ismail-Zadeh et al., 2022; Pierce et al., 2024). The widely felt earthquakes of 1668 and 1902 devastated the medieval capital of Shamakhi (Fig. 3b), while moderate (M ~ 6) events in 1828, 1859, 1869, and 1872 caused serious damage to the city. The 1859 event claimed 100 lives and destroyed 741 buildings prompting the capital to move from Shamakhi to Baku. The 1872 event claimed 118 lives and destroyed all but 20 buildings (Шебалин, 1982). The 1902 event claimed 2,000 lives and destroyed 4,000 homes. In Fig. 3a, we have transformed the isoseists for the Shamakhi earthquakes of 1828–1902, initially recorded on the intensity scale developed by Weber. Weber (1903) constructed isoseists for the 1902 earthquake using observations from 120 villages throughout the region (Pierce et al., 2024).

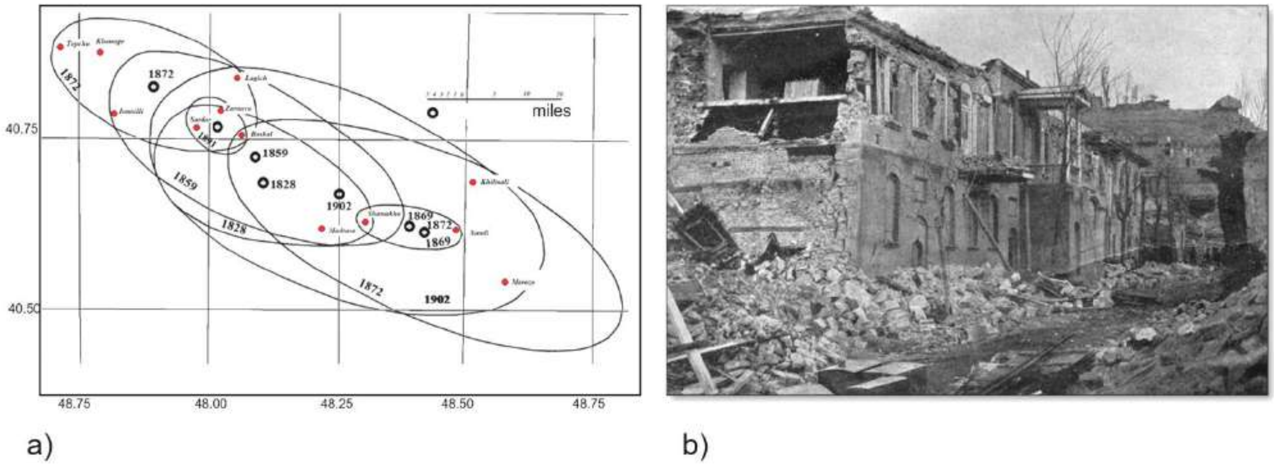


Fig. 3. MMI scale isoseismals of the 1828-1902 yy. Shamakhi earthquakes adapted from the original intensity scale (a) and destruction after the Shamakhi earthquake of 1902 developed by Weber (1903)

These isoseismal maps suggest that the epicenter was located near Shamakhi and that the rupture that occurred follows the general trend of the Kur thrust. Our paleoseismic trenching results from Aghsu indicate two surface-rupturing events since the early 18th century (1713–1895 and 1872–2003). The more recent of these rupturing events could be the surface rupture of the 1902 Shamakhi earthquake, while the penultimate event may correspond to the 1668 earthquake if we disregard two radiocarbon dates. Modern Shamakhi located just 18 km northeast on the hanging wall of the Aghsu basin would have experienced intense ground shaking if the northeast fault rupture occurred, so the destruction recorded during these events aligns with our paleoseismic results (Pierce et al., 2024).

According to the research by Jackson and Ambraseys (1997), historical seismicity data over the last 400 years account for only about 25% of the total crustal shortening in the Caucasus region. This presents significant challenges in estimating the seismic potential of the region, as it remains unclear whether the lack of major earthquakes west of Shamakhi is due to insufficient historical records, aseismic processes such as fault creep, or the buildup of unresolved tectonic stresses within the fold and thrust system.

2. Methodology

The study employed advanced technologies, including satellite imagery, drone modeling, GNSS technologies, seismic positioning, and paleoseismic trenching. Faults were remotely mapped using Google Earth and elevation models derived from Sentinel satellite stereo images (Smith, Johnson, 2022) before fieldwork conducted from 2020 to 2022. Field surveys included vehicle and on-foot exploration of fault sections as shown in Fig. 4. Key sections were carefully examined using photogrammetry, where images were captured with a Teokit-equipped DJI Phantom 4 Pro v2 drone (Pierce, Koehler, 2023). Teokit is a differential GPS system (dGPS) used for accurately geolocating the images, which were corrected then using the Post-Processing Kinematic (PPK) method via the Emlid Reach RS2 dGPS base station (Zhang et al., 2019).

The captured photographs were processed using Agisoft Metashape software to generate digital elevation models (DEMs) and orthomosaic images with a resolution of 6–10 cm/pixel and 3–5 cm/pixel, respectively. Two paleoseismic trenches were excavated across mapped faults, which were then cleaned, gridded, and documented (Fig. 4) (Pierce et al., 2022, 2023). Documentation was based on 3D models created using Structure-from-Motion (SfM) from photographs taken with Samsung Galaxy S20 Ultra (2022) and Pixel 7 Pro (2023) smartphones. These models were precisely adjusted, oriented, and scaled using reference points from LiDAR scans of the trench walls performed with an iPad. Before generating and exporting 2D orthomosaic images, this process yielded 2D images of the trench walls with centimeter-level geometric accuracy (Pierce et al., 2024).

Layers and faults were then drawn on these 2D images using an iPad. The units and faults were separated and described following standard paleoseismic methods (McCalpin, 2009), including sedimentary facies, cross-cutting relationships, and soil development. Samples of charcoal, plant material, bones, and soil were documented in trench logs, collected, processed, and then analyzed at the Beta Analytic laboratory in Miami, Florida. They were calibrated using OxCal v4.4 (Bronk, Ramsey, 1995) with the IntCal20 calibration curve.

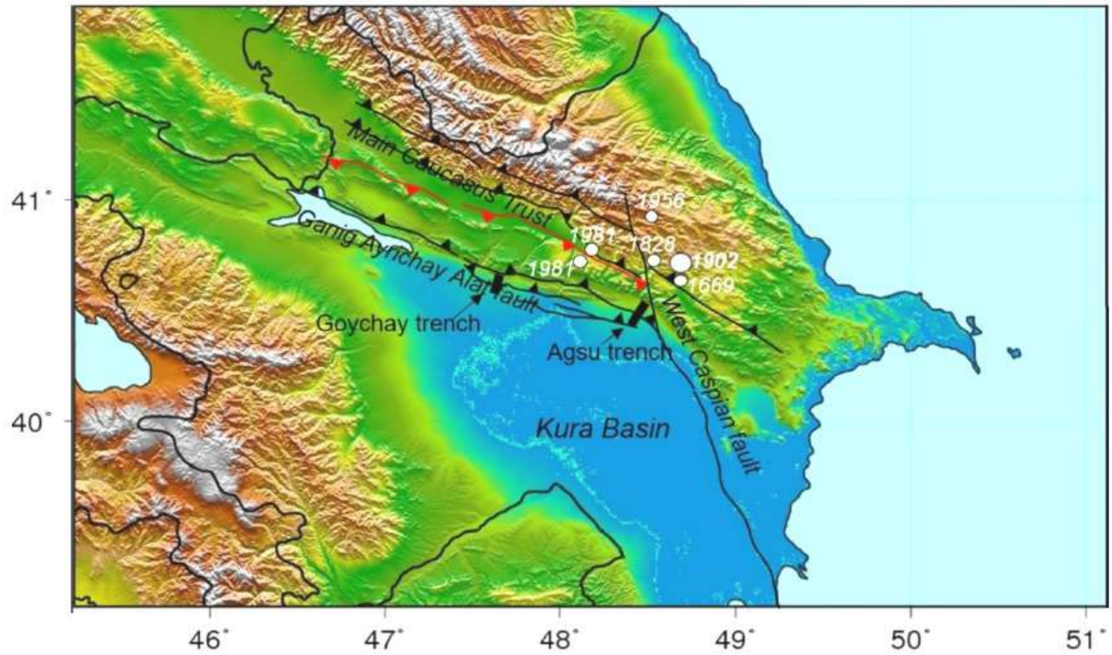


Fig. 4. Tectonic map of the southeastern part of the Greater Caucasus, paleoseismic trenches in the Aghsu and Goychay areas, and epicenters of major (M>5.0) historical earthquakes occurring between 1669 and 1956

2.1. Formation of covers in the Shamakhi-Gobustan trough

The study used advanced technologies including satellite imagery, drone modeling, GNSS technologies, seismic positioning and paleoseismic excavations. Horizontal movements at a rate of 10 mm/yr between the Arabian and Eurasian plates are mainly provided by the Main Caucasus fold-and-thrust belt, which extends between central Azerbaijan and Georgia along the southern front of the Greater Caucasus (45–48°E) (Pierce et al., 2022, 2023). In the southern foothills of the Greater Caucasus most fold-and-thrust faults arose under compressional conditions resulting in southerly and, occasionally, southwesterly displacements of the massifs. These faults are clearly visible on the seismic tomographic profile constructed from earthquake traveltime data for the period 2017–2023. The construction method is described (Gunnels et al., 2021; Kazimova, 2020) (Fig. 5). The modern structure of these dislocations consists of local folds, which are complicated by faults. In the Shamakhi-Gobustan trough, a large Perikyushkul-Baskal nappe stands out, which continues west almost to the Geychay River valley. Here, the displacement amplitude of the allochthonous part of the nappe is 20-25 km.

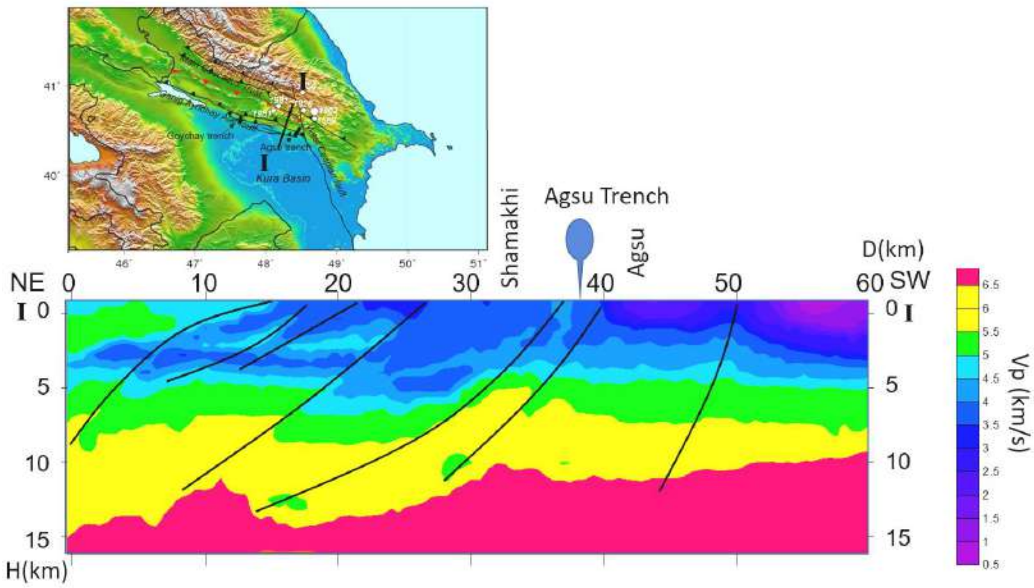


Fig. 5. Seismic tomographic section along profile 1-1 across the strike of the thrust structure in the NE-SW direction

In some places, the thrust plate overlaps the Miocene layers indicating active compressive stresses in the neotectonic period. Clayey rocks in the Upper Miocene were subjected to intense deformation and have many cracks. Similar stresses are observed in other local structures of Central Gobustan.

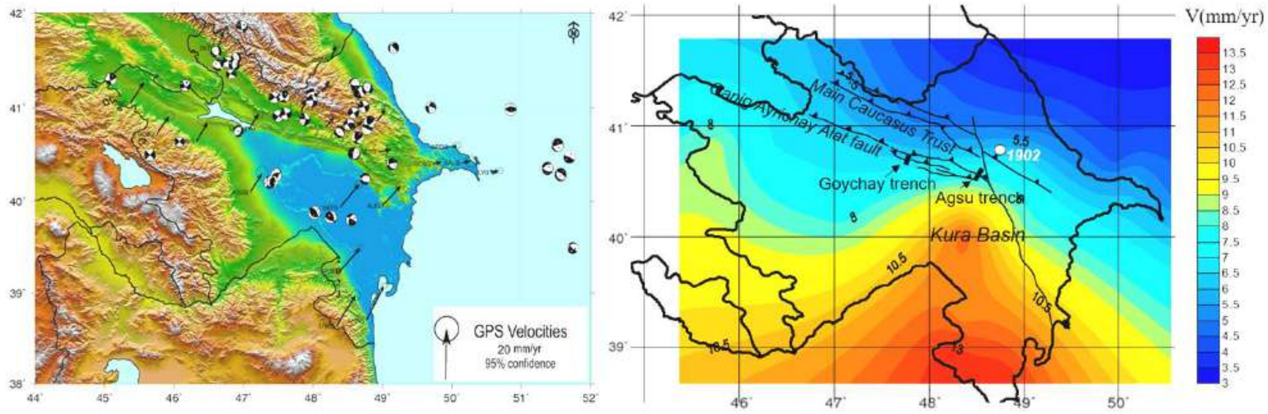
Thus, compression in the mountainous region of the Greater Caucasus is the main cause of horizontal movements in the above-mentioned structural elements: Gobustan, Ajinour and the Kur interfluve. It is also important to note the significant influence of the Ganykh-Ayrichay-Alat deep fault, which showed high activity in late orogenic tectonic processes. There is a high probability that the geodynamic impact of this fault contributed to the formation of rupture and fold dislocations in the Ajinour and Gobustan zones. If the current geological processes continue, it can be assumed that the young folded zones of the Kur-Ajinohur interfluve, as well as the Shamakhi-Gobustan trough are at the initial stage of the formation of the future orogen. Currently, the foothills of the southern clone of the Greater Caucasus are rising at a rate of 2-3 mm per year. Based on these observations, it can be concluded that the foothill zone is already beginning to form as an extended pile, which indicates the further development of late-orogen processes.

2.2. Space geodesy data (GNSS)

Based on the GNSS space geodesy data of the RSSC and seismological data, the current geodynamic conditions in the territory of Azerbaijan for 2014-2024 were analyzed. The data were taken from Yetirmishli et al. works (2022; 2023; 2024). One of the most noticeable features of the horizontal movement velocity field is the decrease in the velocity values perpendicular to the direction of the Greater Caucasus strike from south to north. The velocity field clearly illustrates the movement of the Earth's surface in the N-NE direction. (Fig. 6) This phenomenon reflects the process of successive accumulation of elastic deformations in the zone of subduction interaction of the structures of the northern side of the South Caucasian microplate with the accretionary prism of the Greater Caucasus. In addition, within the Middle Kur Depression and the Lesser Caucasus, a tendency toward horizontal displacement is observed, which is expressed in an increase in the velocity of movement from west to east along the continuation of the ridge. It has been established that on the Absheron Peninsula the Earth's crust is contracting at a rate of ~5 mm/yr. Earthquakes that occurred during this period are localized in the zones of the transition gradient from maximum to minimum velocities. These are mainly the Ismailly, Shamakhi, Aghdam and Shamkir regions. In this zone, a change in the magnitude of the GNSS velocity vectors is observed, which can be explained by the main reason for the accumulation of stress.

The maximum values of horizontal velocities were recorded at the stations of Aghdam, Lerik, Lankaran, Jalilabad, Fizuli, and Saatly with an average speed across the republic of 7.3 mm/yr. In 2021, the average speed across the entire territory of the republic was 7.6 mm/yr. The highest speeds were noted at the stations of Yardımlı (12.2 mm/yr), Lankaran (13.1 mm/yr), and Saatly (12.3 mm/yr).

Along the Kur Depression (from the Middle Kur Depression to the Lower Kur Depression, i.e., from NW to SE), there is a gradual increase in horizontal movement speed from 7.3 to 11.3 mm/yr, which characterizes a state of compression. The average speed of the mega-zone on the southern slope of the Greater Caucasus ranges from 4.2 to 5.4 mm/yr. The Middle Kur mega-zone is characterized by speed of 8.85 mm/yr.



a) b)

Fig. 6. Overview map of (a) Azerbaijan showing GNSS velocities relative to stable Eurasia (Kadirov et al., 2024), faults from the Active Faults of Eurasia Database, and focal mechanisms of earthquakes from the database of RSSC (Compiled by Kazimova), b) map of horizontal movement velocity distribution based on GNSS station data from the RSSC (Compiled by Kazimov)

3. Paleoseismic Trenches in Aghsu

The Kur thrust located immediately next to Aghsu runs along the front of the Greater Caucasus range. In this area, the active fault has created an uplifted bench approximately 50 meters high tilting back towards the northeast with a distinct fold at its crest. About 2.5 km east of Aghsu, a small alluvial valley cuts through this bench, where a stream has incised perpendicularly to the fault trace. Within this valley, two low terraces have formed T1, the lower terrace, and T2, which is elevated by about 1 meter. These terraces have smooth, flat surfaces and can be continuously traced upstream for approximately 300 meters from the valley mouth (Fig. 7).

At the entrance to the valley, both terraces exhibit vertical displacement marked by fault scarps approximately 2 meters in height. Along the western edge of the valley, a minor stream has deeply eroded the T1 terrace. A hillshade image obtained from drone data reveals signs of human alteration on the scarp of the T2 terrace; however, the T1 terrace shows no such modifications on either side of the fault allowing for clear correlation. A paleoseismic trench was dug across the 2-meter-high scarp intersecting the T1 terrace within this alluvial valley.

3.1. Stratigraphic and Structural Analysis of the Aghsu Trench Exposure

The length of the trench that was excavated in the Aghsu region was 22 meters, and the depth was 5 meters (Fig. 8). The eastern trench wall was meticulously documented through detailed logging and photography. The excavation exposed a sequence of clay, alluvial, and colluvial deposits that have been disrupted by a low-angle fault (F0), which branches into multiple splays (F1-F4) as it extends upward. The lowest stratigraphic layer, U1, consists of a colluvial deposit with a mixture of rounded cobbles and gravel embedded in a silty-sandy matrix.

Overlying U1 is U2, a fluvial deposit that thickens southward, comprising well-sorted, grain-supported sands, gravels, and rounded cobbles. The contact zone where U2 overlaps U1, marked in gray consists of fine-grained sediments potentially representing a paleosol. At the top of U2, a distinct ~40 cm thick, light-colored paleosol is visible extending across the southern part of the trench. In the hanging wall, U3 is a 1.5-meter-thick, laminated clay layer that fractures into prismatic blocks and shows significant shearing near the fault zone. Above this, U4 consists of finely laminated clays, silts, and sands. Units U4 and U5 are exclusive to the hanging wall with U5 containing laminated silts, sands, a thin cobble layer, and traces of modern plastic debris in its upper 20–30 cm.

Above U2 lies W1, a colluvial deposit composed of a poorly sorted mixture of small boulders, cobbles, and gravels within a fine-grained matrix. A ~20 cm thick light-colored paleosol caps W1, which is thickest near the fault scarp and gradually thins southward. Overlying W1 is W2, another colluvial deposit made up of angular clay blocks within a fine-grained matrix with sparse pebble inclusions. A nearly horizontal fault (F0) cuts across the trench branching into four distinct faults (F1–F4) in the hanging wall. F4 forms a shear zone within U3, while F3 and F2 enclose a shear band composed of U1 material, indicated by aligned cobbles and pebbles. F1 displaces the paleosol at the top of U2. The hanging wall units (U1–U4) show clear folding, whereas U2 in the footwall remains largely undisturbed.

Fig. 7. Paleoseismological investigations of a trench excavated in 2022 in the Aghsu area

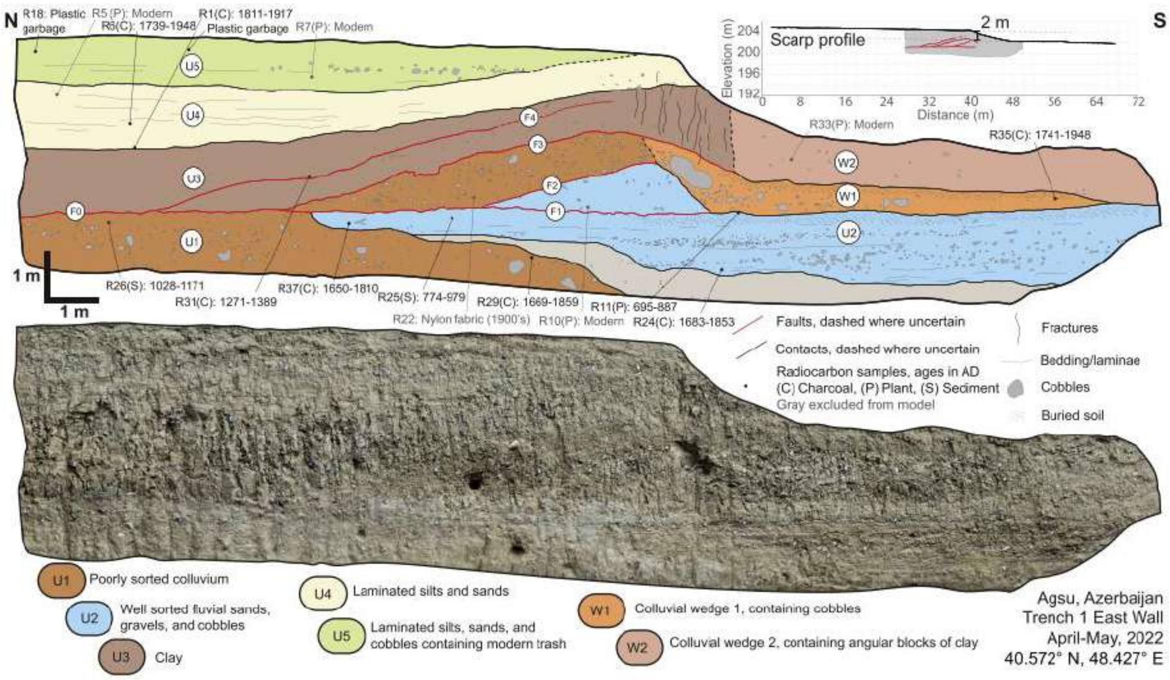


Fig. 8. Geological section of the Aghsu trench. The ages provided are modeled as outlined in the text. Evidence of two events is mainly inferred from the colluvial wedge stratigraphy on the footwall (W1 and W2) (Pierce et al., 2024)

The stratigraphy observed in the southern section of the trench reveals evidence of two distinct faulting events indicated by the presence of two colluvial wedges (W1 and W2) overlying the undisturbed fluvial deposits of unit U2 (Fig. 4). A reconstruction model of fault displacement is illustrated in Fig. 9. The earlier of these events (E1) led to the formation of the W1 colluvial wedge, which consists of an unsorted mixture of cobbles and gravels covering the paleosol that had developed atop the U2 fluvial sediments. Over time, a thin layer of fine-grained soil accumulated on the surface of W1. The more recent seismic event (E2) resulted in the deposition of the W2 colluvial wedge, primarily composed of angular clay blocks derived from U3. This wedge subsequently buried the thin soil layer that had formed on top of W1.

The contrast between the two colluvial wedges is highly pronounced. During the penultimate E1 event, the F0, F1, and F2 faults ruptured through the U1 colluvial layer and the upper portion of the U2 alluvial deposit at the base of the northern section of the trench following a sub-horizontal fault plane (Fig. 9). As F0 branched into F1 and F2, it caused a sharp fold in segments of U2 and the U1 colluvium, which subsequently collapsed, giving rise to the E1 wedge. The thick clay layer, U3 was deposited before the E1 event and may have accumulated behind a fold in U1, possibly formed by an earlier rupture along a different fault strand. However, as this strand is not visible in the trench exposure, this interpretation remains uncertain. In this scenario, U3 would have initially covered and laterally bordered U1 before the E1 rupture occurred.

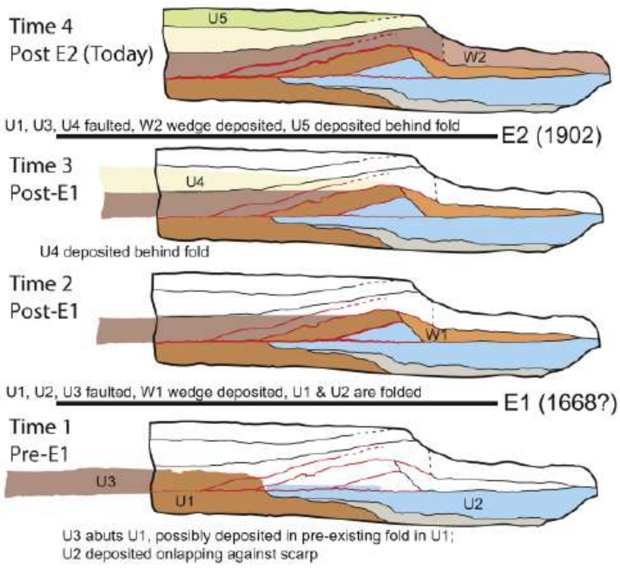


Fig. 9. Reverse-slip reconstruction of the Aghsu trench. The colors and symbols correspond to those used in Fig. 4. The most distinct evidence of seismic events is found in the colluvial wedge stratigraphy (W1 & W2) within the footwall (Pierce et al., 2024)

During the E1 rupture, the U1 unit was displaced into the near-surface fault zone along the nearly horizontal F0 fault. It is possible that the extreme flatness of F0 in this exposure is partly due to the trench's oblique orientation relative to the fault. Additionally, the U3 clay unit, being significantly more rigid than the U1 colluvial deposit may have influenced fault propagation, as the fault exploited this contrast in material strength. Initially, U3, which both capped and laterally bordered U1 remained unaffected by the surface rupture. It was only after further slip accumulation during the subsequent E2 event that U3 was incorporated into the fault zone.

Following the E1 rupture, fine-grained sediments of U4 were deposited atop U3 within the hanging wall accumulating behind the fold generated by the E1 event. By restoring the displacement of U1 along faults F1 and F2, a minimum of 6.6 meters of slip is estimated for the E1 rupture. During the more recent E2 event, fault F0 was reactivated, and fault F3 also ruptured at the base of U3 further folding U3 and U4 into a pronounced fold-scarp. This event resulted in the formation of a new colluvial wedge (W2). Similar to U4, U5 represents growth strata that accumulated behind the fold on the hanging wall. At least 3.5 meters of slip was necessary to thrust U3 over the crest of the fold in U1. However, due to the intense shearing of U1 and U3 within the fault zone, there is significant uncertainty in these displacement estimates.

The trench stratigraphy and reconstruction (Fig. 9) illustrate how shallow folding during surface-rupturing earthquakes contributes to the formation of growth strata on both the hanging wall and footwall of a thrust fault. This finding underscores the limitations of scarp diffusion modeling when applied without subsurface data and highlights the need for caution when estimating the age of thrust fault scarps based solely on surface observations.

3.2. Aghsu 14C Geochronology

The 14 radiocarbon sample locations from the Aghsu trench are plotted on Fig. 8. Table 1 shows the samples of charcoal, plant material, bone and soil that were documented in trench logs, processed and then analyzed at Beta Analytic in Miami, Florida. These samples, as noted above were calibrated using OxCal v4.4 (Bronk, Ramsey, 1995) with the IntCal20 calibration curve (Pierce et al., 2024).

Specimens – labeled R5, R7, R10, and R33 – were found to be contemporary plant remains. These were subsequently disregarded for further study. Specimen R18, identified as a plastic candy wrapper from the late 1990s is estimated to originate from around AD 1995 ± 5 and has been designated as the upper chronological marker for the stratigraphic sequence.

Samples R25 and R26 consisting of carbon from bulk sediment are considered less trustworthy than isolated charcoal fragments due to their tendency to show wide age discrepancies – sometimes spanning millennia – within a single horizon (e.g., Grützner et al., 2016). Specimen R22 retrieved from the faulted area (Unit U1) was a sizable piece of nylon cloth. Given nylon's invention in the mid-20th century, its presence at this depth suggests displacement by burrowing fauna, especially since other samples from Unit U1 date to the medieval period (R26: AD 1028–1171; R29: AD 1669–1859).

The trench's distinct layering combined with the scarcity of modern artifacts at deeper levels and an increased presence of plastics near the surface, discounts the possibility of extensive mixing across the profile. The usable age estimates were fed into an OxCal chronological model (Fig. 10) producing results that establish the timing of two ground-rupturing episodes: E1 is dated to AD 1713–1895, and E2 to AD 1872–2003, each within 95.4% confidence limits.

Table 1

Radiocarbon Sample Data from Aghsu trench

Sample name	Location	Unit	Lat(°)	Lon(°)	Sample material[a]	Radio-carbon age (BP)	Calibrated[b] age (AD or BC if noted)	OxCal[b] v4.4 modeled age (AD.95.4%)	Percent modern carbon (pMC)	813C(‰)
R1	Aghsu T1	U4	40.572	48.427	Charcoal	-20±30	1954-1957 (60.9%)	1811-1917	100.25±0.37	-27.0
R5	Aghsu T1	U4	40.572	48.427	Plant material	-2.08±30	1978-1979 (89.3%)	–	129.55±0.48	-24.8
R6	Aghsu T1	U4	40.572	48.427	Charcoal	190±30	1724-1812 (52.0%)	1739-1948	97.66±0.36	-24.9
R7	Aghsu T1	U5	40.572	48.427	Plant material	-770±30	1996-2000 (92.9%)	–	110.06±0.41	-28.0
R10	Aghsu T1	U2	40.572	48.427	Plant material	3.41±30	1967-1971 (93.2%)	–	152.88±0.57	-25.8
R11	Aghsu T1	U2	40.572	48.427	Plant material	1240±30	758-880 (55.8%)	695-887	85.7±0.32	-26.3
R18	Aghsu T1	U5	40.572	48.427	Plastic candy wrapper	–	–	1985-2006	–	–
R24	Aghsu T1	U2	40.572	48.427	Charcoal	70±30	1810-1919 (68.7%)	1683-1853	99.13±0.37	-23.5
R25	Aghsu T1	U2	40.572	48.427	Organic Sediment[c]	1160±30	820-978 (83.9%)	774-979	86.55±0.32	
R26	Aghsu T1	U1	40.572	48.427	Organic	940±30	1028-1172 (95.4%)	1028-1171	88.96±0.33	-26.2
R29	Aghsu T1	U1	40.572	48.427	Charcoal	120±30	1799-1940 (67.2%)	1669-1859	98.52±0.37	-26.3
R31	Aghsu T1	U3	40.572	48.427	Charcoal	690±30	1272-1317 (65.5%)	1271-1389	91.77±0.34	-25.4
R33	Aghsu T1	W2	40.572	48.427	Plant Medical	-150±30	1954-1956 (95.4%)	–	101.88±0.38	-29.0
R35	Asu T1	W2	40.572	48.427	Charcoal	160±30	1719-1786 (31.6)	1741-1948	98.03±0.37	-25.6

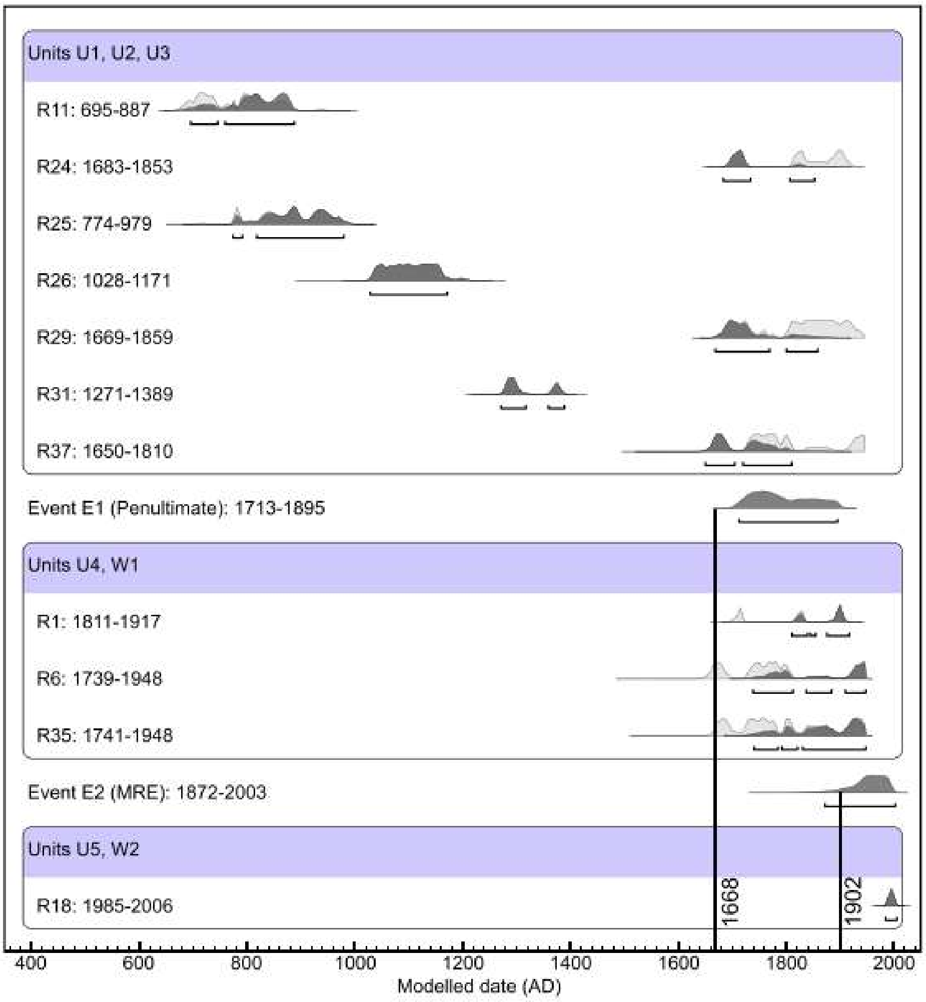


Fig. 10. The radiocarbon data with event timing from the Aghsu trench to establish a chronology. The timeframes for events E1 and E2 are defined as AD 1713–1895 and AD 1872–2003, respectively. The resulting probability density functions (PDFs) are depicted in dark gray, while the unadjusted calibrated age ranges are shown in light gray (Pierce et al., 2024)

3.3. Paleoseismic Trenches in Goychay

The Goychay trench measured 19 meters in length and 4 meters in depth. About 55 km west of Aghsu, in Goychay, the Kur thrust intersects the Goy River, creating a series of uplifted river terraces and heavily folded Pleistocene sediments. Upstream from this fault intersection, the Goy River flows through a broad valley with a very shallow structure. Near Goychay, the Kur thrust forms a 500 m high rangefront fold scarp, consisting of Unit 1 (2.2–0.88 Ma) from Forte et al. (2013) (Fig. 4). Around 5 km west of Goychay, a relatively young fault scarp is intermittently traceable over approximately 1 km. Here, a series of small uplifted hills in front of the main rangefront display a flattening near their leading edge, which we interpret as evidence of back-tilting and active folding. Additionally, a distinct ~1-meter-high south-facing fault scarp cutting across an alluvial fan forms a small terrace situated in a drainage channel between these hills (Fig. 11).

A survey of the area reveals that it is entirely made up of fine-grained sediments, primarily silty and clay-rich, which have weathered into a "badlands" landscape. The site has been heavily altered by human activities with a concrete foundation for a building located directly next to the trench site, downhill.

3.4. Stratigraphy in the Goychay Trench

We did not log the eastern side of the trench because this was benched for trench safety due to the depth of the trench (Fig. 12) although we undertook visual comparisons to track units across the trench. The trench revealed a sequence of mostly fine-grained silty/clayey deposits along with several in-filled anthropogenic canals, extensive charcoal and pottery layers, and some small lenses comprised of fine gravels and sand. Two low angle north-dipping faults (F1 and F2) displace units within the trench. Most of the unit contacts in the trench are gradational and/or wavy.

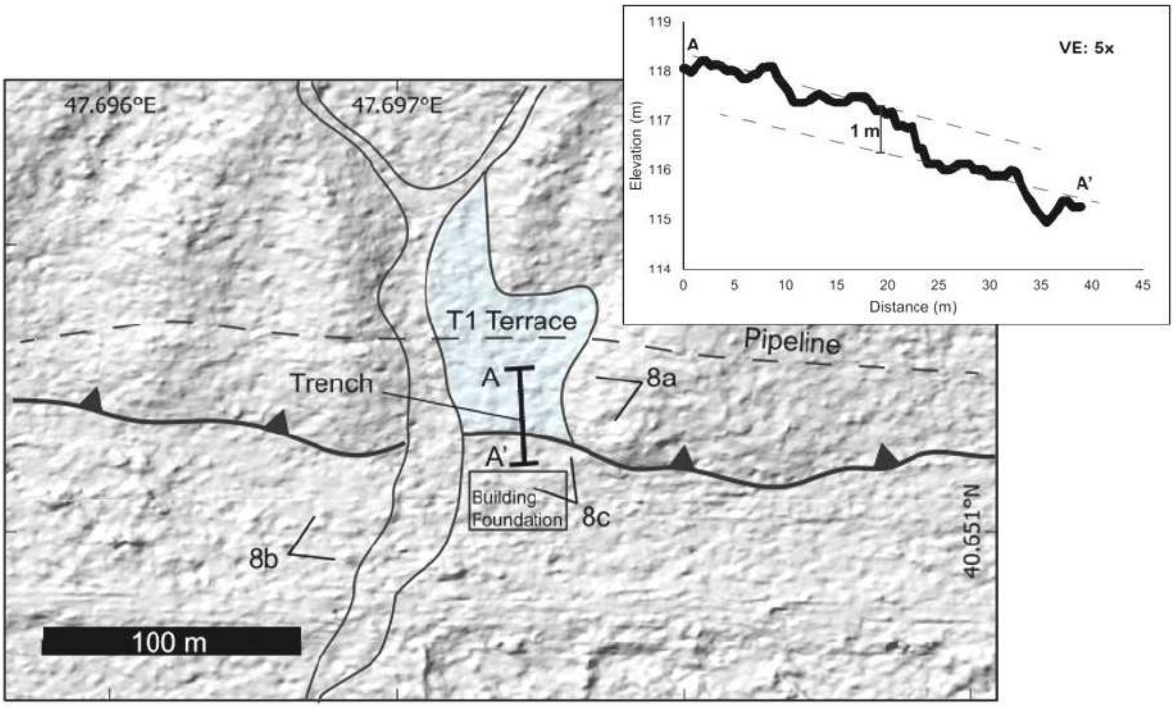


Fig. 11. The location of the Goychay trench on the relief, according to Pleiades satellite images and the topographic profile along the route of the trench (Pierce et al., 2024)

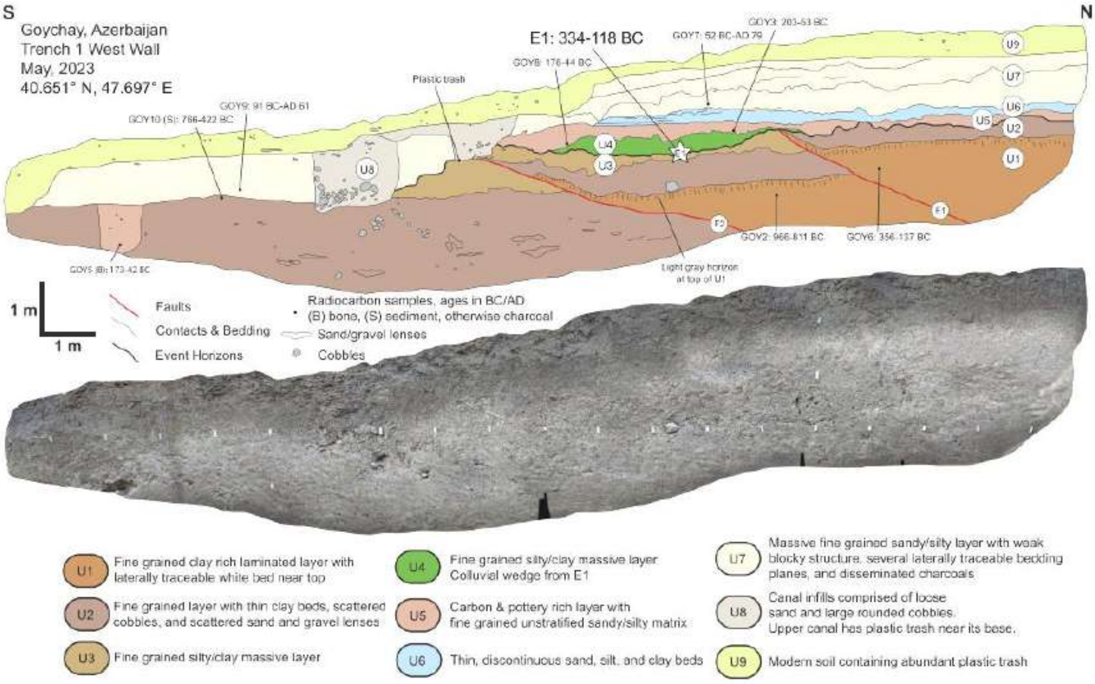


Fig. 12. Geological section of the Goychay trench. The ages provided are modeled ages. We interpret the evidence of a single event based on the capping of a distinct fault, marked by a narrow light gray horizon at the top of U1 (Pierce et al., 2024)

The trench exposed a sequence of predominantly fine-grained silty and clayey deposits along with several anthropogenic canals, layers of charcoal, pottery, and small lenses of fine gravels and sand. Two low-angle, north-dipping faults (F1 and F2) displace the units within the trench. Most unit boundaries are either gradational or undulating. The oldest layer in the trench, Unit 1 (U1) is a weakly laminated, fine-grained, clay-rich layer found in both the hanging wall and footwall of F1, and only in the hanging wall of F2. The upper portion of U1 contains a 5–10 cm thick, wavy grey marker horizon that clearly shows disruption across the faults, with upward warping in the hanging walls of both faults. Above U1 is U2, a slightly coarser and more stratified layer, which spans the entire trench exposure. While U2 is about 1 meter thick in the hanging wall of F2, it reaches about 2 meters thick in the footwall of F2. The hanging wall of F2 contains a single 20 cm diameter rounded cobble and several discontinuous silty/sandy laminae with a predominantly clayey matrix. In the footwall of F2, U2 contains several 10–20 cm thick sand and fine gravel lenses, in contrast to U1, which lacks such coarser sediment lenses. The upper portion of U2 in this area includes numerous scattered rounded cobbles up to 20 cm in diameter.

Overlying U2 in the footwalls of both F1 and F2 is U3, a fine-grained massive layer made primarily of silt and clay. Above U3 in the hanging wall of F2 and capping F1 is U4 another fine-grained silty/clayey layer, which thickens down-slope from F1. Above U4 is U5, which contains numerous 1–2 cm charcoal fragments and pottery shards. In the southernmost part of the trench, U5 includes an infilled canal unit containing mammal bone fragments and intact clay pots consistent with similar radiocarbon ages. Above U5 in the hanging wall of F2 lies U6, a thin layer with few charcoal fragments but several beds of sand and silt. Overlying U6 is U7, a layer that extends across the entire trench and consists mostly of clays and silts, forming a weak blocky structure. U7 also contains dispersed charcoal. Toward the southern end of the trench, near the base of the scarp, U8 consists of two infilled canals with well-defined boundaries. The lower canal is filled with cobbles at the base and loose gray sand above. Plastic trash found near the top of the higher canal suggests that it is of modern age. The top layer, U9, consists of modern soil and anthropogenic trash, and includes part of the concrete building foundation located near the trench site.

3.5. Tectonic activity in the Goychay Trench: Layer displacement and fault structures

Evidence for tectonic movement in the Goychay Trough is particularly evident through the truncation and offset of the light grey horizon that occurs at the top of the U1 layer in the zone of two faults (F1 and F2; Fig. 12). The older U1 block overlies the U2/U3 blocks. The light grey layer at the top of U1 is offset by 90 cm across the upper F1 fault, which has a northerly dip of 25°. This layer is not found in the footwall of F2, which we interpret as its offset below the trench level yielding a minimum offset estimate along F2 of 3.2 m since the formation of the upper U1. Thus, the total offset of the upper U1 across both F1 and F2 faults is at least 4.1 m. In the hanging wall of both faults, this layer bends along the fault remaining nearly horizontal in the footwall. Fault F1 is overlain by U4, which provides a clear horizon for Event E1, establishing a time frame between deposition of U3 and U4. We cannot exclude the possibility that Fault F2 may have been activated by a later event (E2) that eroded all blocks U1 to U7, which would postdate deposition of U7. Our fieldwork revealed that irrigation canals are often built at the foot of fault scarps suggesting that the U8 canals were located near an active fault. However, excavation of these canals makes it difficult to find clear evidence for the second event. The contact offset between U2 and U3 on Fault F2 is 1.7 m, which may represent the total offset along this fault for both Event E1 and potential E2 events. It should be noted that since the U2 layer is present throughout the length of the trench, we believe that during hanging wall uplift along both faults, the larger sand and gravel lenses found in the footwall of fault F2 were eroded from the hanging wall.

3.6. Goychay 14C Geochronology

Thus, in the Goychay trench, a total of eight radiocarbon samples were analyzed. Among them, six were charcoals, one was an organic sediment (GOY10), and one was a mammal bone (GOY5) located in the southern section of U3. All dates followed a clear stratigraphic sequence, with the exception of GOY6, which was slightly younger than other samples from similar layers. The OxCal stratigraphic model (Fig. 13) indicates that a distinct E1 event occurred between 334 and 118 BC.

4. Conclusions

The two recorded surface rupture events (1713–1895 and 1872–2003) identified in the Aghsu trench are likely linked to surface ruptures within the Kur fold-and-thrust belt instigated by historical earthquakes in 1668 and 1902 that caused significant damage to the city of Shamakhi, which was the capital of Azerbaijan. Our reevaluation of the 1902 earthquake's magnitude indicates it may have reached Mw 7.4 contrary to the earlier estimate of M 6.9. Research on cultural heritage sites affected by the 1902 earthquake in the vicinity of Shamakhi, particularly in the hanging wall of the Aghsu trench yields critical insights for further archaeoseismic investigations.

Additionally, the second trench situated 60 km west of Aghsu near Goychay provided evidence of a surface rupture earthquake that occurred between 334 and 118 BCE along with indications of another potential event in the last 2000 years. To validate these findings more extensive fieldwork is essential, which will assist in determining the potential lengths of faults, accurately assessing the magnitudes of historical earthquakes, and exploring the fault history in other regions of the Kur fold-and-thrust belt.

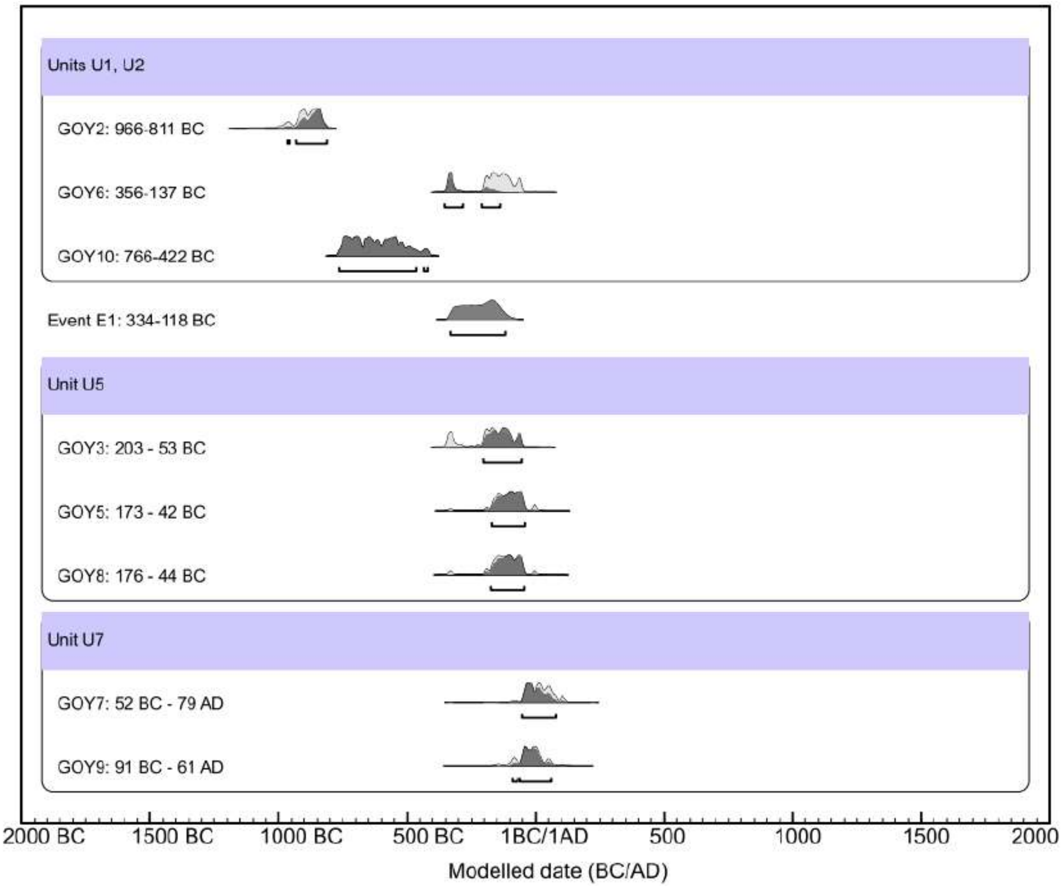


Fig. 13. Radiocarbon ages and event horizons from the Goychay trench. The E1 event is firmly dated between 334 and 118 BC with a potential subsequent event occurring within the last 2,000 years. The dark gray probability density functions (PDFs) represent the sequence model results, while the light gray indicates the full calibrated age ranges (Pierce et al., 2024)

The observed shortening rates and the absence of documented surface rupture events in the central and western sections of the Kur fold-and-thrust belt since 1668 (or earlier) suggest that significant stress has accumulated in the region. Given the historical record of major earthquakes along this belt, we hypothesize that this accumulated stress may be sufficient to generate an earthquake exceeding magnitude 7.7. This hypothesis aligns with previous geodetic and stratigraphic studies, which indicate convergence rates of 6.7–13.6 mm/year (Kadirov et al., 2012). Our findings reinforce the idea that the Kur fold-and-thrust system plays a key role in accommodating the collision between the Arabian and Eurasian plates in the eastern Greater Caucasus. Future studies involving more extensive field investigations and fault length assessments are necessary to further validate this hypothesis and refine seismic hazard estimates for the region.

5. Acknowledgements

This research was supported in part by the Leverhulme Trust projects ‘EROICA’ (RPG-2018-371) and ‘NEPTUNE’ (RPG-2018-243) by the NERC-ESRC Increasing Resilience to Natural Hazards program ‘Earthquakes without Frontiers’ (NE/J02001X/1), the NERC-funded COMET (GA/13/M/031) and allocation 0009090 from the Research England GCRF support fund. The authors are grateful for field assistance from Sarvat Gurbanzada, Ilyas Kazimov, Rashid Khalilov, Aslan Sadikov and Samandar Mammadov. Thanks to Arzu Javadova (SOCAR) and Nazim Abdullayev (BP) for both their scientific input and for helping to organize funding from BP for field and laboratory expenses.

REFERENCES

Abich G.V. Geological Observations in the Highland Region between the Kura and Aras Rivers. Proc. Caucasus Dept. of the Imp. Russian Geogr. Soc., 1873, Vol. VIII, Book 1 (in Russian).

Abich G.V. Earthquakes in Shemakha and Erzurum in May 1859. Proc. Caucasus Dept. of the Imp. Russian Geogr. Soc., 1862, Vol. V (in Russian).

ЛИТЕРАТУРА

Balavadze B.K. Towards Building a Model of the Earth’s Crust of the Caucasus and Adjacent Territories. – Bulletin of the USSR Academy of Sciences, Earth Physics Series, 1975, No. 2, pp. 75-83.

Balavadze B.K., Shengelia G.Sh. Some features of the structure of the Earth’s Crust in the Caucasus. In: Problems of Earth Physics. Kyiv, 1966, pp. 70-75.

Adamia Sh.A. Mechanism and geodynamics of the formation of the Alpine Fold Belts of the Caucasus. In Collection: Problems of movements and structural formation in the crust and Upper Mantle. Nauka. Moscow, 1985 (in Russian).

Afanasenkov A.P., Nikishin A.M., Obukhov A.N. Geology of the Eastern Black Sea. Nauchny mir. Moscow, 2007 (in Russian).

Agamirzoyev R.A. Seismotectonics of the Azerbaijani Part of the Greater Caucasus. Elm. Baku, 1987 (in Russian).

Akhmedbeyli F.S. Regional seismicity of Azerbaijan territory in connection with tectonic activity of the central segment of the Alpine-Himalayan Belt. Proc. IG NAS of Azerbaijan, No. 29, 2001, pp. 40-46 (in Russian).

Akhmedbeyli F.S., Babazade O.B., Gasanov A.G., Kuliev F.T., Panahi B.M., Shikhalibeyli E.Sh. New schemes of areas of strong earthquake foci and seismic zoning of Azerbaijan territory. In: Catalog of Seismological Observations in Azerbaijan in 1987. Elm. Baku, 1991, pp. 62-65 (in Russian).

Alizade A.A., Akhmedbeyli F.S., Akhmedbeyli F.F. et al. On the deep structure of the Kusaro-Divichi Superimposed Trough. Reports of the Azerbaijan SSR Academy of Sciences, 1982, Vol. 38, No. 1, pp. 52-57 (in Russian).

Alizade A.A., Akhmedov G.A., Akhmedov A.N., Kulikov V.I., Rajabov M.M., Tereshko A.D. Deep structure of the Earth's Crust of Azerbaijan and adjacent areas of the Middle and Southern Caspian Sea. Bulletin of the Azerbaijan SSR Academy of Sciences, Earth Sciences Series, 1968, No. 5 (in Russian).

Balavadze B.K. Towards building a model of the Earth’s crust of the Caucasus and adjacent territories. Bulletin of the USSR Academy of Sciences, Earth Physics Series, 1975, No. 2, pp. 75-83.

Balavadze B.K., Shengelia G.Sh. Some features of the structure of the Earth’s Crust in the Caucasus. In: Problems of Earth Physics. Kyiv, 1966, pp. 70-75.

Baranov G.I., Grekov I.I. Geodynamic model of the Greater Caucasus. In: Problems of Caucasus geodynamics. Nauka. Moscow, 1982, pp. 51-59 (in Russian).

Belousov T.P., Sholokhov V.V., Enman S.V. Geodynamics and Seismotectonics of the Stavropol Territory. OIFZ RAN. Moscow, 2000, 184 p. (in Russian).

Bronk Ramsey C. Radiocarbon calibration and analysis of stratigraphy: The OxCal program. Radiocarbon, 37(2), 1995, pp. 425-430, https://doi.org/10.1017/S0033822200030903.

Bunin G.B. On the seismogenic landslide at Cape Boynak in the coastal part of Dagestan. Seismicity and Seismotectonics of the Eastern Pre-Caucasus. Makhachkala: Transactions of the IG Dag. FAN USSR, Vol. 33, 1985, pp. 65-68 (in Russian).

Cowgill E., Forte A.M., Niemi N., Avdeev B., Tye A., Trexler C. et al. Relict basin closure and crustal shortening budgets during continental collision: An example from Caucasus sediment provenance. Tectonics, Vol. 35(12), 2016, pp. 2918-2947, https://doi.org/10.1002/2016TC004295.

Cowgill E., Niemi N.A., Forte A.M., Trexler C.C. Reply to comment by Vincent et al. Tectonics, Vol. 37, 2018, pp. 1017-1028.

Florensov N.A. On neotectonics and seismicity of the Mongolo-Baikal Mountain Region. Geology and Geophysics, No. 1, 1960, pp. 74-90 (in Russian).

Forte A.M., Cowgill E., Murtuzayev I., Kangarli T., Stoica M. Structural geometries and magnitude of shortening in the eastern Kura fold-thrust belt, Azerbaijan: Implications for the development of the Greater Caucasus Mountains. Tectonics, Vol. 32(3), 2013, pp. 688-717, https://doi.org/10.1002/tect.20032.

Forte A.M., Whipple K.X., Cowgill E. Drainage network reveals patterns and history of active deformation in the eastern Greater Caucasus. Geosphere, Vol. 11(5), 2015, pp.1343-1364. https://doi.org/10.1130/GES01121.1.

Gadzhiev R.M. Deep Geological Structure of Azerbaijan. Azerneshr. Baku, 1965, 201 p. (in Russian).

Bronk Ramsey C. Radiocarbon calibration and analysis of stratigraphy: The OxCal program. Radiocarbon, 37(2), 1995, pp. 425-430, https://doi.org/10.1017/S00338222000 30903.

Cowgill E., Forte A.M., Niemi N., Avdeev B., Tye A., Trexler C., et al. Relict basin closure and crustal shortening budgets during continental collision: An example from Caucasus sediment provenance. Tectonics, Vol. 35(12), 2016, pp. 2918-2947, https://doi.org/10.1002/2016TC004295.

Cowgill E., Niemi N.A., Forte A.M., Trexler C.C. Reply to comment by Vincent et al. Tectonics, Vol. 37, 2018,pp. 1017-1028.

Forte A.M., Cowgill E., Murtuzayev I., Kangarli T., Stoica M. Structural geometries and magnitude of shortening in the eastern Kura fold-thrust belt, Azerbaijan: Implications for the development of the Greater Caucasus Mountains. Tectonics, Vol. 32(3), 2013, pp. 688-717, https://doi.org/10.1002/tect.20032.

Forte A.M., Whipple K.X., Cowgill E. Drainage network reveals patterns and history of active deformation in the eastern Greater Caucasus. Geosphere, Vol. 11(5), 2015, pp. 1343-1364, https://doi.org/10.1130/GES01121.1

Gmyrya L.B., Korzhenkov A.M., Ovsyuchenko A.N., Larkov A.S., Rogozhin E.A. Probable Paleoseismic Deformations at the Rubas Archeological Site, Mid-6th Century AD, South Dagestan, Izvestiya, Atmospheric and Oceanic Physics, 2019, No. 10, pp. 1547-1558, https://doi.org/10.1134/s0001433819100037.

Grützner C., Reicherter K., Fernández-Steeger T. Paleoseismology in the Kura fold-and-thrust belt (Azerbaijan): First results from trenching the Agsu fault. Tectonophysics, Vol. 687, 2016, pp. 14-27, https://doi.org/10.1016/j.tecto.2016.08.005.

Guliev I.S., Kadirov F.A., Reylinger R., Gasanov R.I., Mamedov A.R. Active tectonics of Azerbaijan: Based on Geodetic, Gravimetric, and Seismic Data. Reports of the Russian Academy of Sciences, Vol. 382, 2002, No. 6, pp. 812-815.

Gunnels M., Yetrimishli G., Kazimova S., Sandvol E. Seismotectonic evidence for subduction beneath the eastern Greater Caucasus. Geophysical Journal International, Vol. 224(3), 2021, pp. 1825-1834, https://doi.org/10.1093/gji/ggaa522.

Ismail-Zadeh A., Adamia S., Chabukiani A., Chelidze T., Cloetingh S., Floyd M., et al. Geodynamics, seismicity, and seismic hazards of the Caucasus. Earth-Science Reviews, Vol. 207, 2022, 103222, https://doi.org/10.1016/j.earscirev.2020.103222.

Jackson J.A., Ambraseys N.N. Convergence between Eurasia and Arabia in eastern Turkey and the Caucasus. Historical and Prehistorical Earthquakes in the Caucasus, Vol. 28, 1997, pp. 79-90, https://doi.org/10.1007/978-94-011-5464-2_3.

Kadirov F., Floyd M., Alizadeh A., Guliev I., Reilinger R., Kuleli S. et al. Kinematics of the eastern Caucasus near Baku, Azerbaijan. Natural Hazards, Vol. 63(2), 2012, pp. 997-1006, https://doi.org/10.1007/s11069-012-0199-0.

Kadirov F., Yetirmishli G., Safarov R., Mammadov S., Kazimov I., Floyd M., Reilinger R., King R. Results from 25 years (1998-2022) of crustal deformation monitoring in Azerbaijan and adjacent territory using GPS. ANAS Transactions, Earth Sciences, No. 1, 2024, pp. 28-43.

Kangarli T.N., Kadirov F.A., Etirmishli G.D., Aliev F.A., Kazimova S.E., Aliev A.M., et al. Geodynamics, active faults and earthquake source mechanisms in the zone of pseudo-subduction interaction of continental microplates in the South and North Caucasus (southern slope of the Greater Caucasus, Azerbaijan). Geodynamics and Tectonophysics, 9(4), 2018, pp. 1099-1126, https://doi.org/10.5800/GT-2018-9-4-0385.

Kazimova S.E. Redefinition of earthquake hypocenters by the double difference method. Geology and geophysics of the south of Russia, Vol. 10(4), 2020, pp. 41-51, http://geosouth.ru/article/view/623/580.

Kengerli T.N. Relationship of surface and deep structure of the Shamakhi-Gobustan oil-gas bearing area. Proc. 4th Int. Congr.

Gmyrya L.B., Korzhenkov A.M., Ovsyuchenko A.N., Larkov A.S., Rogozhin E.A. Probable paleoseismic deformations at the Rubas Archeological Site, Mid-6th Century AD, South Dagestan. Izvestiya, Atmospheric and Oceanic Physics, 2019, No. 10, pp. 1547-1558, https://doi.org/10.1134/s0001433819100037.

Grützner C., Reicherter K., Fernández-Steeger T. Paleoseismology in the Kura fold-and-thrust belt (Azerbaijan): First results from trenching the Agsu fault. Tectonophysics, Vol. 687, 2016, pp. 14-27, https://doi.org/10.1016/j.tecto.2016.08.005.

Guliev I.S., Kadirov F.A., Reylinger R., Gasanov R.I., Mamedov A.R. Active tectonics of Azerbaijan: Based on geodetic, gravimetric, and seismic data. Reports of the Russian Academy of Sciences, Vol. 382, 2002, No. 6, pp. 812-815.

Gunnels M., Yetrimishli G., Kazimova S., Sandvol E. Seismotectonic evidence for subduction beneath the eastern Greater Caucasus. Geophysical Journal International, Vol. 224(3), 2021, pp. 1825-1834, https://doi.org/10.1093/gji/ggaa522.

Ismail-Zadeh A., Adamia S., Chabukiani A., Chelidze T., Cloetingh S., Floyd M. et al. Geodynamics, seismicity, and seismic hazards of the Caucasus. Earth-Science Reviews, Vol. 207, 2022, 103222, https://doi.org/10.1016/j.earscirev.2020.103222.

Jackson J.A., Ambraseys N.N. Convergence between Eurasia and Arabia in eastern Turkey and the Caucasus. Historical and Prehistorical Earthquakes in the Caucasus, Vol. 28, 1997, pp. 79-90, https://doi.org/10.1007/978-94-011-5464-2_3.

Kadirov F., Floyd M., Alizadeh A., Guliev I., Reilinger R., Kuleli S. et al. Kinematics of the eastern Caucasus near Baku, Azerbaijan. Natural Hazards, Vol. 63(2), 2012, pp. 997-1006, https://doi.org/10.1007/s11069-012-0199-0.

Kadirov F., Yetirmishli G., Safarov R., Mammadov S., Kazimov I., Floyd M., Reilinger R., King R. Results from 25 years (1998-2022) of crustal deformation monitoring in Azerbaijan and adjacent territory using GPS. ANAS Transactions, Earth Sciences, No. 1, 2024, p.28-43.

Kangarli T.N., Kadirov F.A., Etirmishli G.D., Aliev F.A., Kazimova S.E., Aliev A.M. et al. Geodynamics, active faults and earthquake source mechanisms in the zone of pseudosubduction interaction of continental microplates in the South and North Caucasus (southern slope of the Greater Caucasus, Azerbaijan). Geodynamics and Tectonophysics, Vol. 9(4), 2018, pp. 1099-1126, https://doi.org/10.5800/GT-2018-9-4-0385.

Kazimova S.E. Redefinition of earthquake hypocenters by the double difference method. Geology and geophysics of the south of Russia, Vol. 10(4), 2020, pp. 41-51, http://geosouth.ru/article/view/623/580.

Kengerli T.N. Relationship of surface and deep structure of the Shamakhi-Gobustan oil-gas bearing area. Proc. 4th Int. Congr. of the International Ecoenergy Academy, Vol. 1. Baku, 1997, pp. 319-321.

Khain V.E. Regional Geotectonics: Alpine Mediterranean Belt. Nedra. Moscow, 1984 (in Russian).

Khain V.E., Alizadeh Ak.A. Geology of Azerbaijan. Volume VI –Tectonics, Nafta-Press. Baku, 2005, 506 p. (in Russian).

Khain V.Y. Structure and main stages in the tectono-magmatic development of the Caucasus: An attempt at geodynamic interpretation. Am. J. Sci., A275, 1975, pp.131-156.

Khromovskikh V.S., Solonenko V.P., Semenov R.M., Zhilkina V.M. Paleoseismogeology of the Greater Caucasus. Nauka. Moscow, 1979, 188 p. (in Russian).

Kopp M.L. Lateral extrusion structures in the Alpine-Himalayan Collision Belt. Nauchny mir. Moscow, 1997, 306 p. (in Russian).

Korkuganova N.I. Neogene-Quaternary tectonics and geodynamic conditions for the formation of orogens in Eastern Eurasia. MSU Press. Moscow, 2000, 160 p. (in Russian).

Korobanov V.V. Geological structure and geotectonic development of the Vandamsky-Gog Anticlinorium (eastern segment of the Southern Slope of the Greater Caucasus). Dissertation Abstract for the Candidate Degree in Geological and Mineral Sciences. Baku, 1990.

Korzhenkov A.M., Novichikhin A.M., Ovsyuchenko A.N., Rangelov B.K., Rogozhin E.A., Dimitrov O.V., Larkov A.S., Lyu C. Search for traces of strong ancient earthquakes in the Western Caucasus: Archaeoseismological studies in Ancient Gorgippia. Geophysical Processes and the Biosphere, 2019, Vol. 18, No. 4, pp. 110-128.

Letouzey J., Biju-Duval B. et al. The Black Sea: a marginal basin: geophysical and geological data. In: Biju-Duval B., Montadert L. (eds.) Structural history of the Mediterranean Basins. Editions Technip. Paris, 1977, pp. 363-376.

McCalpin J. Paleoseismology (2nd ed.). Academic Press. Amsterdam-London, 2009, 615 p.

McQuarrie N., van Hinsbergen D.J.J. Retrodeforming the Arabia-Eurasia collision zone: Age of collision versus magnitude of continental subduction. Geology, Vol. 41(3), 2013, pp. 315-318, https://doi.org/10.1130/G33591.1.

Mosar J., Kangarli T., Bochud M., Glasmacher U.A., Rast A., Brunet M.F., Sosson M. Cenozoic-recent tectonics and uplift in the Greater Caucasus: A perspective from Azerbaijan. Geological Society, London, Special Publications, Vol. 340(1), 2010, pp. 261-280, https://doi.org/10.1144/SP340.12.

Nikishin A.M., Wannier M., Alekseev A.S., Almendinger O.A., Fokin P.A., Gabdullin R.R., Khudoley A.K., Kopaevich L.F., Mityukov A.V., Petrov E.I., Rubtsova E.V. Mesozoic to recent geological history of southern Crimea and the Eastern Black Sea region. Geological Society, London, Special Publications, November 3, 2015, pp. 1-24, https://doi.org/10.1144/sp428.1.

Nikishin A.M., Ziegler, P.A., Bolotov, S.N., Fokin P.A. Late Palaeozoic to Cenozoic evolution of the Black Sea-Southern Eastern Europe Region: a view from the Russian Platform. Turkish Journal of Earth Sciences, Vol. 20, 2012, pp. 571-634, http://doi.org/10. 3906/yer-1005-22.

Pierce I., Guliyev I., Yetirmishli G., Muradov R., Kazimova S., Javanshir R., Gregory P. et al. Surface rupturing earthquakes of the Greater Caucasus Frontal Thrusts, Azerbaijan. Tectonics, AGU, Vol. 43, No. 3, 2024, pp. 1-20, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023TC007758.

Pierce I., Kazimova S., Johnson B., Marshall N., Walker R. Trenching the Greater Caucasus Frontal Thrusts. PATA Days-2022: International Workshop on Paleoseismology, Active Tectonics and Archeoseismology, 2022, Aix-en-Provence (France), https://pataday2022.sciencesconf.org/data/pages/book_patadays_2022_en_1.pdf.

Pierce I., Koehler R. 3D Paleoseismology from iOS lidar and structure from motion photogrammetry: A case study on the Dog Valley fault, California. Seismica, Vol. 2(1), 2023, https://doi.org/10.26443/seismica.v2i1.208.

Pierce I., Marshall N., Walker R., Kazimova S., Gregory P., De Pascale. Surface rupturing earthquakes of the Greater Caucasus frontal thrusts, Azerbaijan. 2023 (SCEC) Annual Meeting, 2023, https://central.scec.org/publication/12953.

Reilinger R., McClusky S., Vernant P., Lawrence S., Ergintav S., Cakmak R., et al. GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions. Journal of Geophysical Research, Vol. 111(B5), B05411, 2006, https://doi.org/10.1029/2005JB004051.

tation Abstract for the Candidate Degree in Geological and Mineral Sciences. Baku, 1990.

Korzhenkov A.M., Novichikhin A.M., Ovsyuchenko A.N., Rangelov B.K., Rogozhin E.A., Dimitrov O.V., Larkov A.S., Lyu C. Search for traces of strong ancient earthquakes in the Western Caucasus: Archaeoseismological studies in ancient Gorgippia. Geophysical Processes and the Biosphere, Vol. 18, 2019, No. 4, pp. 110-128.

Letouzey J., Biju-Duval B. et al. The Black Sea: a marginal basin: geophysical and geological data. In: Biju-Duval B. and Montadert L. (eds.) Structural history of the Mediterranean Basins. Editions Technip. Paris, 1977, pp. 363-376.

Makarova N.V., Korkuganova N.I., Makarov V.I. Morphological types of orogens as indicators of the geodynamic conditions of their formation and development. Geomorphology, 2000, No. 21, pp. 14-26 (in Russian).

McCalpin J. Paleoseismology (2nd ed.). Academic Press. Amsterdam-London, 2009, 615 p.

McQuarrie N., van Hinsbergen, D.J.J. Retrodeforming the Arabia-Eurasia collision zone: Age of collision versus magnitude of continental subduction. Geology, Vol. 41(3), 2013, pp. 315-318, https://doi.org/10.1130/G33591.1.

Milanovsky E.E., Khain V.E. Geological structure of the Caucasus. Moscow State University Publishing. Moscow, 1963, 357 p. (in Russian).

Mosar J., Kangarli T., Bochud M., Glasmacher U.A., Rast A., Brunet M.F., Sosson M. Cenozoic-recent tectonics and uplift in the Greater Caucasus: A perspective from Azerbaijan. Geological Society, London, Special Publications, Vol. 340(1), 2010, pp. 261-280, https://doi.org/10.1144/SP340.12.

Muratov M.V. (ed.) Geology of the USSR. Vol.VIII. Crimea. Part 1. Geological Description. Nedra. Moscow, 1969 (in Russian).

Nikishin A.M., Wannier M., Alekseev A.S., Almendinger O.A., Fokin P.A., Gabdullin R.R., Khudoley A.K., Kopaevich L.F., Mityukov A.V., Petrov E.I., Rubtsova E.V. Mesozoic to recent geological history of southern Crimea and the Eastern Black Sea region. Geological Society, London, Special Publications, November 3, 2015, pp. 1-24, https://doi.org/10.1144/sp428.1.

Nikishin A.M., Ziegler, P.A., Bolotov, S.N., Fokin P.A. Late Palaeozoic to Cenozoic evolution of the Black Sea-Southern Eastern Europe Region: a view from the Russian Platform. Turkish Journal of Earth Sciences, Vol. 20, 2012, pp. 571-634, http://doi.org/10. 3906/yer-1005-22.

Nikitin M.Yu., Nikonov A.A., Bolotov S.N., Belyakov G.A. Paleoseismodislocations in the Ardon River Basin and their significance for assessing the seismic potential of the Greater Caucasus. DAN, Vol. 330, 1993, No. 6, pp. 740-744 (in Russian).

Nikonov A.A. Paleoseismodislocations in the Axial Part of the Main Caucasian Ridge (Pre-Elbrus). Reports of the Academy of Sciences of the USSR, Vol. 319, No. 5. 1991, pp. 1183-1186 (in Russian).

Ovsyuchenko A.N., Marakhanov A.V., Larkov A.S., Novikov S.S. Late Quaternary dislocations and seismotectonics of the Racha Earthquake Source Area (Greater Caucasus). Geotectonics, No. 6, 2014, pp. 55-76 (in Russian).

Pierce I., Guliyev I., Yetirmishli G., Muradov R., Kazimova S., Javanshir R., Gregory P. et al. Surface rupturing earthquakes of the Greater Caucasus Frontal Thrusts, Azerbaijan. Tectonics, AGU, Vol. 43, No. 3, 2024, pp. 1-20, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023TC007758.

Pierce I., Kazimova S., Johnson B., Marshall N., Walker R. Trenching the Greater Caucasus Frontal Thrusts. PATA Days-2022: International Workshop on Paleoseismology, Active Tectonics and Archeoseismology, 2022, Aix-en-Provence (France), https://pataday2022.sciencesconf.org/data/pages/book_patadays_2022_en_1.pdf.

Rogozhin E.A., Gorbatikov A.V., Stepanova M.Yu., Ovsyuchenko A.N., Andreeva N.V., Kharazova Yu.V. Structure and modern geodynamics of the mega-anticlinorium of the Greater Caucasus in light of new data on deep structure. Geotectonics, No. 2, 2015, pp. 36-49.

Rolland Y., Sosson M., Adamia Sh., Sadradze N. Prolonged Variscan to Alpine history of an active Eurasian margin (Georgia, Armenia) revealed by 40Ar/39Ar dating. Gondwana Research, Vol. 20, 2011, pp.798-815.

Saintot A., Brunet M.-F. et al. The MesozoicCenozoic tectonic evolution of the Greater Caucasus. Geological Society, London, Memoirs, Vol. 32, 2006, pp. 277-289, http://doi.org/10.1144/GSL.MEM.2006.032.01.16.

Şengör A.M.C., Altıner D., Zabcı C., Sunal G., Lom N., Aylan E., Öner T. On the nature of the Cimmerian Continent. Earth-Science Reviews, 247, 2023, 104520. Elsevier, https://doi.org/ 10.1016/j.earscirev.2023.104520.

Smith A., Johnson B. The impact of AI in Government Strategic Planning: Real-time Data Analysis. Government Analytics Journal, Vol. 15(2), 2022, pp. 45-58.

Starostenko V., Buryanov V. et al. Topography of the crust-mantle boundary beneath the Black Sea Basin. Tectonophysics, Vol. 381, 2004, pp. 211-233, http://doi.org/ 10.1016/j.tecto.2002.08.001.

Vincent S.J., Guo Li, Flecker R., BouDagher-Fadel M.K., Ellam R.M., Kandemir R. Age constraints on intra-formational unconformities in Upper Jurassic-Lower Cretaceous carbonates in northeast Turkey; geodynamic and hydrocarbon implications. Marine and Petroleum Geology, Vol. 91, 2018, pp. 639-657.

Vincent S.J., Saintot A., Mosar J., Okay A.I., Nikishin A.M. Comment on "Relict basin closure and crustal shortening budgets during continental collision: An example from Caucasus sediment provenance" by Cowgill et al. (2016). Tectonics, Vol. 37, 2018, pp. 1006-1016.

Weber V. Shamakhi earthquake of 13 February 1902. In Proceedings of the St. Petersburg geological committee, 1903, 65 p.

Yetirmishli G.J., Kazimov İ.E., Kazimova A.F. Modern seismogeodynamics of Turkey, northern Iran and Caucasus region. Seismoprognosis observations in the territory of Azerbaijan, Vol. 25, No. 1, 2024, pp. 25-36, https://doi.org/ 10.59849/2219-6641.2024.1.25.

Yetirmishli G.J., Kazimov İ.E., Kazimova A.F. Seismogeodynamics of the Greater Caucasus from GNSS data, Seismoprognosis observations in the territory of Azerbaijan, Vol. 24, No.2, 2023, pp. 33-42, https://doi.org/10.59849/ 2219-6641.2023.2.33.

Yetirmishli G.J., Kazimova S.E. Walker R.T., Pierse İ, Kazimov İ.E. The first results of paleoseismological studies between Oxford University and Republican Seismic Survey Center of ANAS. Seismoprognosis observations in the territory of Azerbaijan, Vol. 22, No. 2, 2022, pp. 3-8

Zhang H., Aldana-Jague E., Clapuyt F., Wilken F., Vanacker V., Van Oost K. Evaluating the potential of post-processing kinematic (PPK) georeferencing for UAV-based structure-from-motion (SfM) photogrammetry and surface change detection. Earth Surface Dynamics, Vol. 7(3), 2019, pp. 807-827, https://doi.org/10.5194/esurf-7-807-2019.

Абих Г.В. Геологические наблюдения в нагорной области между реками Кура и Аракс Записки Кавказского отдела Императорского Русского географического общества, 1873, Т. VIII, Кн. 1, с. 1-86.

Абих Г.В. Землетрясения в Шемахе и Эрзеруме в мае 1859 года. Записки Кавказского отдела Императорского Русского географического общества, Т. V, 1862, с. 15-42.

Агамирзоев Р.А. Сейсмотектоника азербайджанской части Большого Кавказа. Элм. Баку, 1987, 152 с.

Pierce I., Koehler R. 3D Paleoseismology from iOS lidar and structure from motion photogrammetry: A case study on the Dog Valley fault, California. Seismica, Vol. 2(1), 2023, https://doi.org/10.26443/seismica.v2i1.208.

Pierce I., Marshall N., Walker R., Kazimova S., Gregory P., De Pascale. Surface rupturing earthquakes of the Greater Caucasus frontal thrusts, Azerbaijan. 2023 (SCEC) Annual Meeting, 2023, https://central.scec.org/publication/12953.

Reilinger R., McClusky S., Vernant P., Lawrence S., Ergintav S., Cakmak R. et al. GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions. Journal of Geophysical Research, Vol. 111(B5), B05411, 2006, https://doi.org/10.1029/2005JB004051.

Rogozhin E.A., Gorbatikov A.V., Stepanova M.Yu., Ovsyuchenko A.N., Andreeva N.V., Kharazova Yu.V. Structure and modern geodynamics of the mega-anticlinorium of the Greater Caucasus in light of new data on deep structure. Geotectonics, No. 2, 2015, pp. 36-49.

Rogozhin E.A., Ovsyuchenko A.N., Lutikov A.I., Sobisevich A.L., Sobisevich L.E., Gorbatikov A.V. Endogenous hazards of the Greater Caucasus. IFZ RAN. Moscow, 2014, 256 p. (in Russian).

Rolland Y., Sosson M., Adamia Sh., Sadradze N. Prolonged Variscan to Alpine history of an active Eurasian margin (Georgia, Armenia) revealed by 40Ar/39Ar dating. Gondwana Research, Vol. 20, 2011, pp.798-815.

Saintot A., Brunet M.-F. et al. The MesozoicCenozoic tectonic evolution of the Greater Caucasus. Geological Society, London, Memoirs, Vol. 32, 2006, pp. 277-289, http://doi.org/10.1144/GSL.MEM.2006.032.01.16.

Şengör A.M.C., Altıner D., Zabcı C., Sunal G., Lom N., Aylan E., Öner T. On the nature of the Cimmerian Continent. Earth-Science Reviews, 247, 2023, 104520. Elsevier, https://doi.org/ 10.1016/j.earscirev.2023.104520.

Shebalin N.V. On the assessment of seismic intensity. Seismic scale and methods for measuring seismic intensity. Nauka. Moscow, 1975, pp. 87-109 (in Russian).

Smith A., Johnson B. The impact of AI in Government Strategic Planning: Real-time Data Analysis. Government Analytics Journal, Vol. 15(2), 2022, pp. 45-58.

Starostenko V., Buryanov V. et al. Topography of the crust-mantle boundary beneath the Black Sea Basin. Tectonophysics, Vol. 381, 2004, pp. 211-233, http://doi.org/10.1016/j.tecto.2002.08.001.

Vincent S.J., Guo Li, Flecker R., BouDagher-Fadel M.K., Ellam R.M., Kandemir R., Age constraints on intra-formational unconformities in Upper Jurassic-Lower Cretaceous carbonates in northeast Turkey; geodynamic and hydrocarbon implications. Marine and Petroleum Geology, Vol. 91, 2018a, pp. 639-657.

Vincent S.J., Saintot A., Mosar J., Okay A.I., Nikishin A.M. Comment on "Relict basin closure and crustal shortening budgets during continental collision: An example from Caucasus sediment provenance" by Cowgill et al. (2016). Tectonics, Vol. 37, 2018b, pp.1006-1016.

Weber V. Shamakhi earthquake of 13 February 1902. In Proceedings of the St. Petersburg geological committee, 1903, 65 p.

Yetirmishli G.J., Kazimov İ.E., Kazimova A.F. Modern seismogeodynamics of Turkey, northern Iran and Caucasus region. Seismoprognosis observations in the territory of Azerbaijan, V. 25, No.1, 2024, pp. 25-36, https://doi.org/10.59849/2219-6641.2024.1.25.

Yetirmishli G.J., Kazimov İ.E., Kazimova A.F. Seismogeodynamics of the Greater Caucasus from GNSS data. Seismoprognosis observations in the territory of Azerbaijan, Vol. 24, No. 2, 2023, pp. 33-42, https://doi.org/10.59849/2219-6641. 2023.2.33.

Адамия Ш.А. Механизм и геодинамика формирования альпийских складчатых поясов Кавказа. Проблемы движений и структурообразования в земной коре и верхней мантии. Наука. Москва, 1985, с. 72-89.

Ализаде А.А., Ахмедбейли Ф.С., Ахмедбейли Ф.Ф. и др. О глубинном строении Кусаро-Дивичинского наложенного прогиба. Доклады АН Азербайджанской ССР. Т. 38, No. 1, 1982, с. 52-57.

Ализаде А.А., Ахмедов Г.А., Ахмедов А.Н., Куликов В.И., Раджабов М.М., Терешко А.Д. Глубинное строение земной коры Азербайджана и прилегающих районов Среднего и Южного Каспия. Известия АН Азербайджанской ССР, Серия наук о Земле, No. 5, 1968, с. 14-26.

Афанасенков А.П., Никишин А.М., Обухов А.Н. Геология восточной части Черного моря. Научный мир. Москва, 2007, 210 с.

Ахмедбейли Ф.С. Региональная сейсмичность территории Азербайджана в связи с тектонической активностью центрального сегмента Альпийско-Гималайского пояса. Труды ИГ НАН Азербайджана, 2001, No. 29, с. 40-46.

Ахмедбейли Ф.С., Бабазаде О.Б., Гасанов А.Г., Кулиев Ф.Т., Панахи Б.М., Шихалибейли Э.Ш. Новые схемы районов очагов сильных землетрясений и сейсмического районирования территории Азербайджана. Каталог сейсмологических наблюдений по Азербайджану за 1987 год. Элм. Баку, 1991, с. 62-65.

Баранов Г.И., Греков И.И. Геодинамическая модель Большого Кавказа. В: Проблемы кавказской геодинамики. Наука. Москва, 1982, стр. 51-59.

Белоусов Т.П., Шолохов В.В., Энман С.В. Геодинамика и сейсмотектоника Ставропольского края. ОИФЗ РАН. Москва, 2000, 184 с.

Бунин Г.Б. О сейсмогенном оползне на мысе Бойнак в прибрежной части Дагестана. Сейсмичность и сейсмотектоника Восточного Предкавказья. Труды ИГ Даг. ФАН СССР, Махачкала, Т. 33,1985, с. 65-68.

Гаджиев Р.М. Глубинное геологическое строение Азербайджана, Азернешр. Баку, 1965, 200с.

Копп М.Л. Структуры латерального выжимания в Альпийско-Гималайском коллизионном поясе. Научный мир. Москва, 1997.

Коркуганова Н.И. Неогеново-четвертичная тектоника и геодинамические условия формирования орогенов в Восточной Евразии. Изд-во МГУ. Москва, 2000, 160 с.

Макарова Н.В., Коркуганова Н.И., Макаров В.И. Морфологические типы орогенов как индикаторы геодинамических условий их формирования и развития. Геоморфология, No. 21, 2000, с. 14-26.

Милановский Е.Е., Хаин В.Е. Геологическое строение Кавказа. Издательство МГУ. Москва, 1963, 357 с.

Муратов М.В. (ред.) Геология СССР. Т. VIII. Крым. Ч. 1. Геологическое описание. Недра. Москва, 1969.

Никитин М.Ю., Никонов А.А., Болотов С.Н., Беляков Г.А. Палеосейсмодислокации в бассейне реки Ардон и их значение для оценки сейсмического потенциала Большого Кавказа. ДАН, Т. 330, No. 6, 1993, с. 740-744.

Никонов А.А. Палеосейсмодислокации в осевой части Главного Кавказского хребта (ПреЭльбрусье). Доклады Академии наук СССР, Т. 319, No. 5, 1991, с. 1183-1186.

Овсюченко А.Н., Мараханов А.В., Ларьков А.С., Новиков С.С. Позднечетвертичные дислокации и сейсмотектоника очага землетрясения Рача (Большой Кавказ). Геотектоника, 2014, No. 6, с. 55-76.

Рогожин Е.А., Овсюченко А.Н., Лутиков А.И., Собисевич А.Л., Собисевич Л.Е., Горбатиков А.В. Эндогенные опасности Большого Кавказа. ИФЗ РАН. Москва, 2014, 256 с.

Флоренсов Н.А. О неотектонике и сейсмичности Монголо-Байкальской горной области. Геология и геофизи-

Yetirmishli G.J., Kazimova S.E. Walker R.T., Pierse İ., Kazimov İ.E. The first results of paleoseismological studies between Oxford University and Republican Seismic Survey Center of ANAS. Seismoprognosis observations in the territory of Azerbaijan, Vol. 22, No. 2, 2022, p. 3-8.

Zhang H., Aldana-Jague E., Clapuyt F., Wilken F., Vanacker V., Van Oost K. Evaluating the potential of post-processing kinematic (PPK) georeferencing for UAV-based structure-from-motion (SfM) photogrammetry and surface change detection. Earth Surface Dynamics, Vol. 7(3), 2019, pp. 807-827, https://doi.org/10.5194/esurf-7-807-2019.

ка. No. 1, 1960, с. 74-90.

Хаин В.Е. Региональная геотектоника: Альпийский средиземноморский пояс. Недра. Москва, 1984.

Хаин В.Е., Ализаде Ак.А. Геология Азербайджана. Том VI. Тектоника, Нафта-Пресс. Баку, 2005, 506 с.

Хромовских В.С., Солоненко В.П., Семёнов Р.М., Жилкина В.М. Палеосейсмогеология Большого Кавказа. Наука. Москва, 1979, 188 с.

Шебалин Н.В. О оценке сейсмической интенсивности. Сейсмическая шкала и методы измерения сейсмической интенсивности. Наука. Москва, 1975, с. 87-109.

ПАЛЕОСЕЙСМОЛОГИЧЕСКИЕ ИССЛЕДОВАНИЯ В ПЛЕЙСТОСЕЙСМИЧЕСКОЙ ОБЛАСТИ ШАМАХИНСКИХ ЗЕМЛЕТРЯСЕНИЙ 1668 И 1902 гг.

Пирс И.[1], Гулиев И.С.[2], Етирмишли Г.Дж.[3], Казимова С.Э.[3], Уолкер Р.[1], Казимов И.Э.[3], Абдуллаев Н.Р.[2], Джонсон Б.[1], Маршалл Н.[1]

[1]Оксфордский университет, Великобритания
3 S Паркс Роуд, Оксфорд
[2]Президиум Национальной академии наук Азербайджана, Азербайджан
Ул. Истиглалийят, 30, Баку, AZ1001
[3]Республиканский центр сейсморазведки Национальной академии наук Азербайджана, Азербайджан
123, просп. Гусейна Джавида, Баку, AZ1141

Резюме. Кавказский регион, расположенный на стыке Евразийской и Аравийской тектонических плит, является важной зоной для понимания процессов континентальных столкновений и их влияния на сейсмическую активность. Целью работы является анализ тектонических процессов региона, сейсмической истории и рисков, связанных с возможными сильными землетрясениями. В исследовании использованы современные методы, включая спутниковую съемку, данные GNSS, моделирование с помощью дронов и палеосейсмическое зондирование. В период с апреля по май 2022 года команда ученых из Оксфордского университета совместно с молодыми исследователями из РЦСС провела первые полевые геологические исследования, направленные на изучение палеосейсмологии и активных тектонических процессов в Азербайджане. Были проанализированы две траншеи. Одним из ключевых результатов исследования стало выявление активных разломов, таких как разлом Агсу, и обнаружение следов поверхностных нарушений, связанных с историческими землетрясениями. Было обнаружено два зарегистрированных события сдвига по поверхности (1713–1895 и 1872–2003), вероятно, связаны с поверхностными смещениями, вызванными историческими землетрясениями 1668 и 1902 годов, которые нанесли значительный ущерб городу Шемаха. По результатам нашей переоценки магнитуда землетрясения 1902 года, его величина могла достигать Mw 7.4, в то время как ранее она оценивалась как M 6.9. Кроме того, во второй траншее, расположенной в 60 км к западу от Агсу, недалеко от города Гёйчай, были получены свидетельства поверхностного сдвига, вызванного землетрясением, произошедшим между 334 и 118 гг. до н.э., а также указания на ещё одно возможное событие, произошедшее за последние 2000 лет. Работа подчеркивает важность дальнейших полевых исследований для более точного уточнения длины разломов, оценки магнитуд исторических землетрясений и уточнения карт сейсмических рисков в регионе.

Ключевые слова: *палеосейсмические траншеи, землетрясение в Шемахе 1902 года, складчато-надвиговый пояс Куры, спутниковые снимки, моделирование с помощью дронов, модель последовательности OxCal, поверхностные сдвиги*

1668-CI VƏ 1902-CI İLLƏRİN ŞAMAXI ZƏLZƏLƏLƏRİNİN PLEİSTOSESMİK BÖLGƏSİNDƏ PALEOSEYSMOLOJI TƏDQİQATLAR

Pirs İ.[1], Quliyev İ.S.[2], Yetirmişli Q.C.[3], Kazımova S.E.[3], Uolker R.[1], Kazımov İ.E.[3], Abdullayev N.R.[2], Conson B.[1], Marşal N.[1]

[1]Oksford Universiteti, Böyük Britaniya
3 S Parks Road, Oksford
[2]Azərbaycan Milli Elmlər Akademiyasının Rəyasət Heyəti, Azərbaycan
İstiqlaliyyət küç, 30, Bakı, AZ1001
[3]Azərbaycan Milli Elmlər Akademiyasının Seysmik Kəşfiyyat Mərkəzi, Azərbaycan
123, Hüseyn Cavid prospekti, Bakı, AZ1141

Xülasə. Bu tədqiqat Böyük Qafqaz regionunun geodinamik şəraitinin təhlilinə həsr olunmuşdur. Diqqət tarixi seysmikliyə, aktiv qırılmalara və gələcəkdə baş verə biləcək seysmik hadisələrə yönəlmişdir. Avrasiya və Ərəb tektonik plitələrinin qovşağında yerləşən Qafqaz regionu qitə toqquşmalarının və onların seysmik fəallığa təsirinin öyrənilməsi baxımından mühüm əhəmiyyətə malikdir. Orogen zonaları ilə bağlı geniş tədqiqatlara baxmayaraq, Böyük Qafqaz kimi dağ sistemlərinin morfoloji xüsusiyyətləri əlavə araşdırma tələb edir. Tədqiqatın məqsədi regiondakı tektonik prosesləri, seysmik tarixi və güclü zəlzələlərlə bağlı riskləri təhlil etməkdir. Tədqiqat zamanı peyk görüntüləri, GNSS məlumatları, dron vasitəsilə modelləşdirmə və paleoseysmik tədqiqatlar daxil olmaqla müasir metodlardan istifadə olunmuşdur. 2022-ci ilin aprel-may aylarında Oksford Universitetinin alimləri və RSSX-dən olan gənc tədqiqatçılar Azərbaycanda paleoseysmologiya və aktiv tektonik proseslərin öyrənilməsinə yönəlmiş ilk sahə geoloji tədqiqatlarını həyata keçirmişlər. İki qazılmış xəndək analiz olunmuşdur. Əsas nəticələrdən biri Ağsu qırılması kimi aktiv qırılmaların müəyyən olunması və tarixi zəlzələlərlə əlaqəli səthi qırılma izlərinin aşkarlanması olmuşdur. İki səthi qırılma hadisəsi (1713–

1895 və 1872–2003) qeydə alınmışdır və bunlar çox güman ki, 1668 və 1902-ci illərdə baş vermiş, Şamaxı şəhərinə ciddi ziyan vurmuş zəlzələlərlə əlaqəlidir. 1902-ci il zəlzələsinin yenidən qiymətləndirilməsi nəticəsində onun maqnitudasının əvvəlki M=6.9 dəyəri ilə müqayisədə Mw=7.4-ə qədər çata biləcəyi müəyyən edilmişdir. Bundan əlavə, Ağsu şəhərindən 60 km qərbdə, Göyçay yaxınlığında yerləşən ikinci xəndəkdə eramızdan əvvəl 334–118-ci illər arasında baş vermiş səthi qırılma zəlzələsinin sübutları, həmçinin son 2000 il ərzində baş vermiş ola biləcək başqa bir hadisənin əlamətləri müəyyən edilmişdir. Bu tədqiqat regionda fayların uzunluğunu dəqiqləşdirmək, tarixi zəlzələlərin maqnitudasını qiymətləndirmək və seysmik risk xəritələrinin dəqiqləşdirilməsi üçün gələcək sahə tədqiqatlarının vacibliyini vurğulayır.

Açar sözlər: *paleoseysmik xəndəklər, 1902 Şamaxı zəlzələsi, Kür üstəgəlmə-sıxılma zolağı, peyk görüntüləri, dron modelləşdirilməsi, OxCal ardıcıllıq modeli, səthi qırılma*