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HIGH-RESOLUTION DOUBLE-DIFFERENCE SEISMIC TOMOGRAPHY OF THE CRUST AND UPPER MANTLE BENEATH AZERBAIJAN: EVIDENCE FOR A SUBDUCTING OCEANIC SLAB

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Abstract

This study presents new insights into the crustal and upper mantle structure of Azerbaijan based on high-resolution local seismic tomography using the double-difference (TomoDD) method. Travel-time data from approximately 7,600 local earthquakes (M ≥ 2.0), recorded by a regional network of broadband seismic stations between 2011 and 2024, were used to jointly relocate earthquake hypocenters and reconstruct three-dimensional P- and S-wave velocity models of the crust.

The results reveal pronounced lateral and vertical velocity heterogeneities associated with major tectonic units, including the Greater and Lesser Caucasus, the Kura–Araks Depression, and the South Caspian Basin. Low seismic velocities at shallow depths reflect thick sedimentary cover in the Kura Depression and Absheron Peninsula, whereas higher velocities at depths of 20–35 km indicate a high-velocity lower crust beneath the basin. These features are interpreted as evidence for the presence of oceanic-type crust beneath the Kura–Araks Depression. Relocated earthquake hypocenters delineate several seismically active structures, including the Main Caucasus Thrust and the West Caspian Fault, the latter expressed as a linear zone of deep-focus seismicity oriented NNW–SSE. The identification of two distinct seismogenic horizons in the eastern Greater Caucasus supports the hypothesis of ongoing subduction of a remnant oceanic lithosphere beneath the region. The results provide important constraints on regional geodynamics and have significant implications for seismic hazard assessment, particularly for densely populated areas such as Baku.

Keywords: Seismic tomography; Double-difference method; Crustal structure; Upper mantle; Caucasus; Azerbaijan; Subduction; Seismicity; West Caspian Fault

ВЫСОКОТОЧНАЯ СЕЙСМОТОМОГРАФИЯ МЕТОДОМ ДВОЙНОЙ РАЗНИЦЫ КОРЫ И ВЕРХНЕЙ МАНТИИ ПОД АЗЕРБАЙДЖАНОМ: СВИДЕТЕЛЬСТВА СУБДУКЦИИ ОКЕАНИЧЕСКОЙ ЛИТОСФЕРЫ

Аннотация

В работе представлены новые данные о строении земной коры и верхней мантии Азербайджана, полученные на основе высокоразрешающей локальной сейсмической томографии с применением метода двойных разностей (TomoDD). Для совместного уточнения положений очагов землетрясений и восстановления трёхмерных скоростных моделей продольных и поперечных волн использованы времена пробега от около 7 600 локальных землетрясений с магнитудами M ≥ 2.0, зарегистрированных региональной сетью широкополосных сейсмических станций в 2011–2024 гг.

Полученные результаты выявляют значительные латеральные и вертикальные неоднородности скоростей, связанные с основными тектоническими структурами региона — Большим и Малым Кавказом, Кура-Араксинской впадиной и Южно-Каспийской впадиной. Низкие скорости на малых глубинах отражают мощный осадочный чехол Кура-Араксинской

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впадины и Апшеронского полуострова, тогда как повышенные скорости на глубинах 20–35 км указывают на наличие высокоскоростной нижней коры под впадиной, интерпретируемой как кора океанического типа. Уточнённые гипоцентры землетрясений очерчивают основные сейсмоактивные зоны, включая Главный Кавказский надвиг и Западно-Каспийский разлом, последний проявляется в виде линейной зоны глубинной сейсмичности северо-северо-запад — юго-юго-восточной ориентировки. Наличие двух чётко выраженных сейсмогенных горизонтов в восточной части Большого Кавказа подтверждает гипотезу о продолжающемся субдукционном процессе. Полученные результаты имеют важное значение для понимания геодинамики региона и оценки сейсмической опасности, особенно для густонаселённых районов, включая город Баку.

Ключевые слова: Сейсмическая томография; метод двойных разностей; земная кора; верхняя мантия; Кавказ; Азербайджан; субдукция; сейсмичность; Западно-Каспийский разлом

AZƏRBAYCAN ÜZƏRİNDƏ YER QABUĞU VƏ YUXARI MANTIYANIN İKİ QAT FƏRQLƏRİ METODU İLƏ YÜKSƏK DƏQİQLİKLİ SEYSMOTOMOQRAFİYASI

Xülasə

Bu işdə Azərbaycan ərazisinin yer qabığı və yuxarı mantiyasının quruluşu barədə yeni məlumatlar təqdim olunur. Məlumatlar, ikili fərqlər metodu (TomoDD) tətbiq edilən yüksək dəqiqlikli lokal seysmik tomoqrafiya əsasında əldə edilib. Zəlzələlərin epicentrlərinin dəqiq yerləşdirilməsi və P və S dalğalarının üçölçülü sürət modellərinin bərpası üçün 2011–2024-cü illərdə regional genişzolaqlı seysmik stansiya şəbəkəsi tərəfindən qeydə alınmış, $M \geq 2.0$ maqnituda malik təxminən 7 600 lokal zəlzələnin səyahət vaxtlarından istifadə olunub. Əldə olunan nəticələr regionun əsas tektonik strukturları — Böyük və Kiçik Qafqaz, Kür-Araz çökəkliyi və Cənubi Xəzər çökəkliyi ilə bağlı əhəmiyyətli lateral və şaquli sürət qeyri-homogenliklərini aşkar edir. Kiçik dərinliklərdə aşağı sürətlər, Kür-Araz çökəkliyi və Abşeron yarımadasının qalın çöküntü örtüyünü əks etdirir, 20–35 km dərinliklərdə yüksək sürətlər isə çökəkliyin altında okean tipli qabıq kimi şərh olunan yüksək sürətli alt qabığın mövcudluğunu göstərir. Dəqiqləşdirilmiş zəlzələ hipotsentrləri, Baş Qafqaz şelləri və Qərb-Xəzər fayını daxil olmaqla əsas seysmoaktiv zonaları göstərir. Qərb-Xəzər fayı, şimal-şimal-qərb – cənub-cənub-şərq istiqamətli xətti dərinlik seysmikliyi zonası kimi özünü göstərir. Böyük Qafqazın şərq hissəsində iki aydın seysmojen horizontun mövcudluğu, subduksiya prosesinin davam etdiyi hipotezini təsdiqləyir. Əldə olunan nəticələr regionun geodinamikasının başa düşülməsi və, xüsusilə Bakı şəhəri daxil olmaqla, sıx məskunlaşmış ərazilərdə seysmik təhlükənin qiymətləndirilməsi baxımından mühüm əhəmiyyət kəsb edir.

Açar sözlər:
Seysmik tomoqrafiya; ikili fərqlər metodu; yer qabığı; yuxarı mantiya; Qafqaz; Azərbaycan; subduksiya; seysmiklik; Qərb-Xəzər qırılması

Introduction

Seismic tomography is a key method for studying the internal structure of the Earth at scales ranging from a few meters to thousands of kilometers. It allows the investigation of active volcanoes, faults, glaciers, deep reservoirs and storage sites, as well as the planet as a whole. Tomography plays an important role in addressing practical challenges related to natural hazards, resource exploration, and underground storage, and its methods are applied in medical ultrasonography and helioseismology.

Since the first successful applications nearly 50 years ago [1, 2], seismic tomography methods have evolved significantly and become a cornerstone of geosciences. They provide high-resolution, accurate models that account for processes such as anisotropy, wave attenuation, poroelasticity, and the topography of internal discontinuities. Major development directions include improved data quality and coverage, reduction of forward and inverse modeling errors, advanced data processing techniques, and the use of modern computational resources.

Despite these advances, our understanding of the Earth's internal structure remains incomplete. Modern challenges require more precise models to address both fundamental scientific questions about the thermo-chemical state of the Earth and practical issues such as seismic and volcanic hazard assessment, geothermal exploration, underground storage, and resource management.

Seismic tomography is a method for constructing 2D and 3D models of the Earth's interior based on seismic observations. It involves solving a complex inverse problem: finding a seismic model that explains the observed travel times and other data. Typically, an iterative inversion approach is used with an initial model close to reality, gradually refining the structure to produce quantitative images.

A simple example is travel-time tomography, where first arrivals provide the primary information. The results show that reconstruction accuracy depends on ray-path coverage: poorly sampled areas remain poorly constrained, and low-velocity anomalies are often underestimated. Despite these limitations, the method is universal for various types of seismic tomography, including attenuation and anisotropy studies.

Method of double differences (TomoDD)

In this study, local seismic tomographic sections were constructed using the double-difference method. Commonly referred to as DD tomography, this approach enables the analysis and comparison of the resulting velocity model with the locations of aftershock hypocenters, as well as their relationship to block-bounding faults and surface-mapped deformation features.

The double-difference method [5, 8, 25, 26] is particularly effective for jointly refining hypocenter locations within clusters of closely spaced earthquakes. It allows the simultaneous relocation of a large number of earthquake hypocenters, even when they are observed at relatively distant stations. The key principle is that the travel-time difference between two nearby events primarily reflects the spatial separation of their hypocenters, making it possible to refine inter-event distances without relying on station-specific corrections.

When the distance between the hypocenters of two earthquakes is small relative to the distance to the recording station and the wavelength of the seismic waves, the ray paths from the source region to the station largely coincide. In this case, the observed travel-time difference between the two events can be directly attributed to the relative spatial offset of the sources.

Formally, the travel time T_k^i a P- or S-wave from the i-th earthquake, recorded at the k-th seismic station, can be expressed within the ray-theoretical framework as a path integral along the ray:

$$T_k^i = \tau_0^i + \int_i^k u ds \tag{1}$$

Here, где τ_0^i, i is the origin time of the i-th event, u is the slowness field along the ray path, and ds is the path element. In this framework, the travel-time residuals for the i-th event can be expressed as a linear function of the perturbations Δmi , corresponding to the four current hypocentral parameters Δx i , Δy i , Δz i , Δt i for each observed station k.

$$\frac{\partial t_k^i}{\partial m} \Delta m^i = r_k^i, \tag{2}$$

where $r_k^i = (t^{obs} - t^{cal})_k^i, t^{obs}$ and t^{cal}– are the observed and calculated travel times, respectively, and $\Delta m^i = (\Delta x^i, \Delta y^i, \Delta z^i, \Delta \tau^i)$. Equation (2) is applied together with the observed arrival times. However, cross-correlation techniques measure the difference in arrival times between events $\left(t_k^i - t_k^j\right)^{obs}$, so Equation (2) cannot be used directly. By considering the difference between Equation (2) for a pair of events, the relationship for the relative travel-time differences between the hypocenters of earthquakes i and j can be written as:

$$\frac{\partial t_k^{ij}}{\partial m}\Delta m^{ij} = dr_k^{ij}, \tag{3}$$

here $(\Delta m^{ij} = (\Delta dx^{ij}, \Delta dy^{ij}, \Delta dz^{ij}, \Delta d\tau^{ij})$ represents the change in relative positions between the two hypocenters i and j, and the partial derivatives of T with respect to m correspond to the components of the slowness vector along the ray connecting the source and receiver, evaluated at the source [1]. Partial corrections for velocity variations can be introduced either through station corrections in the calculation algorithm or by incorporating them into the Earth's crust velocity model. Errors in the initial velocity model are effectively minimized by using relative relocation methods for earthquake hypocenters [24].

When the distance between the hypocenters of two earthquakes is small relative to the distance to the recording station and the wavelength of velocity heterogeneities, the ray paths from the source region to the station largely coincide. In this case, the observed travel-time difference between the two events can be attributed directly to the spatial separation of their sources.

A key stage in seismic tomographic studies is **inversion**—the process of reconstructing the internal properties of the Earth, such as seismic-wave velocities, from recorded seismic data. This inverse problem can be addressed using various mathematical approaches, including:

1. **Least-squares methods**, which minimize the difference between observed and calculated travel times (the approach used in this study);

2. **Variational methods**, where a functional quantifying deviations between measured and modeled data is formulated and subsequently minimized;

3. **Optimization methods**, involving more advanced algorithms such as gradient and quasi-gradient techniques aimed at finding the best-fitting model parameters.

The result of the inversion is a three-dimensional model (tomogram) that represents the spatial distribution of physical properties within the Earth's interior. Such a model can, for example, map variations in seismic velocities, highlighting contrasts between solid and partially molten regions, and reveal structural features of the crust and mantle.

Data Used.

As input data, we utilized the catalogs of the Republican Center of the Seismological Service of Azerbaijan (RSSC), which includes 88 modern broadband seismic stations (Fig. 1).

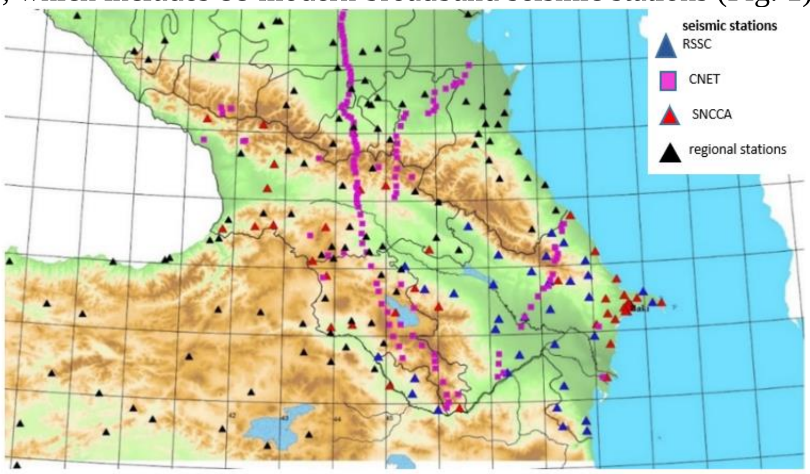

Fig. 1. Regional network of digital seismic stations located across the Caucasus and surrounding areas.

We used wave arrival times from the RSSC seismic catalog for the period 2011–2024. Only local earthquakes with magnitudes of 2.0 and above were selected for analysis, resulting in approximately 7,800 epicenters.

Seismic tomography is a method for reconstructing the internal structure of the Earth's crust and mantle based on the analysis of seismic wave propagation. Conceptually, it is analogous to medical CT scanning: the Earth’s interior is “imaged” by seismic rays traveling from sources (earthquake hypocenters) to seismic stations. The accuracy of the resulting model largely depends on the density and uniformity of ray coverage—higher overlap of ray paths in a given area increases the method’s resolution and the reliability of the retrieved velocity anomalies.

Figure 2 shows the seismic rays connecting each recorded epicenter with the seismic stations at different depths. Analysis of the figure indicates that ray density varies with depth: it is higher at shallow levels due to the proximity of sources and stations, while at greater depths coverage becomes less uniform. Overall, however, the ray distribution is sufficient to reconstruct the structure of the crust and upper mantle in the study region with acceptable accuracy.

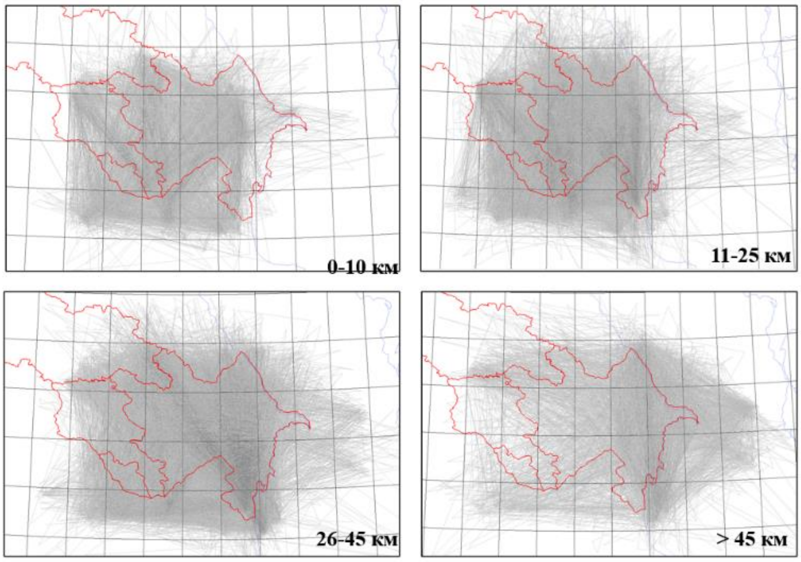

Fig. 2. Distribution of seismic tomography rays from earthquakes recorded during 2011–2024.

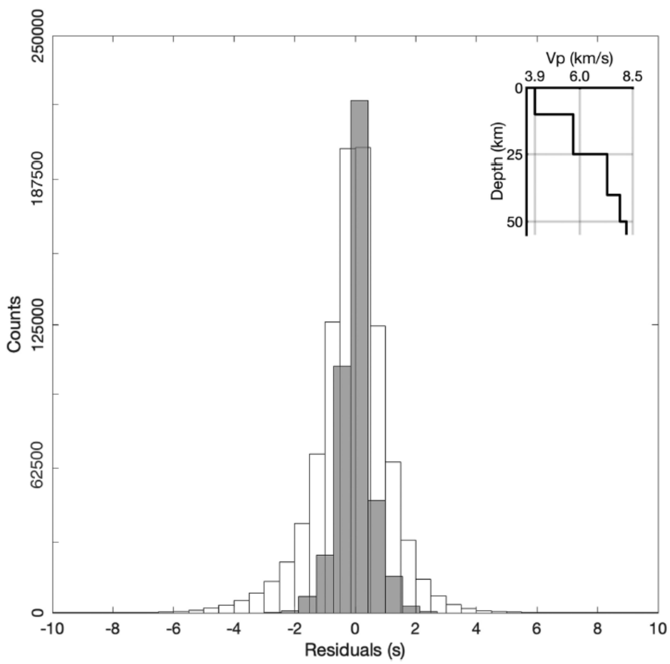

Fig. 3. Histogram showing seismic-wave travel-time residuals ($T_{obs} - T_{calc}$) for the initial model (white bars) and the final model after all inversion iterations (gray bars). The inset illustrates the initial P-wave velocity (V_p) model obtained using the VELEST program [14, 23].

Travel-time differences for earthquake pairs were calculated based on existing bulletins. The final dataset included over 56,000 P-wave arrival times, more than 58,000 S-wave arrival times, and nearly 287,000 differential times between event pairs, covering a total of 3,551 earthquakes.

For the calculations, we used initial one-dimensional velocity models previously obtained using the VELEST program [14, 15]. The resulting model is represented as a three-dimensional grid of nodes, evenly distributed across the region. The horizontal spacing between nodes is 55 km (approximately 0.5°), while the vertical spacing corresponds to the levels defined in the one-dimensional (1D) model.

Assessment of the Velocity Model

To evaluate the quality of the obtained seismic model, we used four criteria, previously applied in other double-difference studies [3, 8]:

1. The improvement in the fit between calculated and observed seismic-wave arrival times (i.e., the travel-time residuals).

2. The values of the derivative weight sum (DWS), which indicate how well each part of the model is constrained by the data.

3. The consistency of relocated earthquake epicenters with known active geological faults and other seismogenic structures.

4. The model's resolution, tested through synthetic "checkerboard" experiments.

Figure 92 shows the change in travel-time residuals between the initial and final models. Initially, the root-mean-square (RMS) difference between observed and calculated arrival times was approximately 112 ms. After inversion, it decreased to 4.1 ms. This substantial reduction indicates that the initial (1D) model did not adequately capture the complex structure of the crust in the Azerbaijan region.

Gaussian (normal) noise was added to the seismic-wave arrival times, with a standard deviation of 0.08 s for P-waves and 0.115 s for S-waves. The clearest and most reliably recovered anomalies are observed at depths of 25–35 km, where approximately 90% of the checkerboard pattern was successfully reconstructed. In the upper part of the model (depths shallower than 15 km), a "smearing" effect is observed, where small-scale velocity variations are not well resolved.

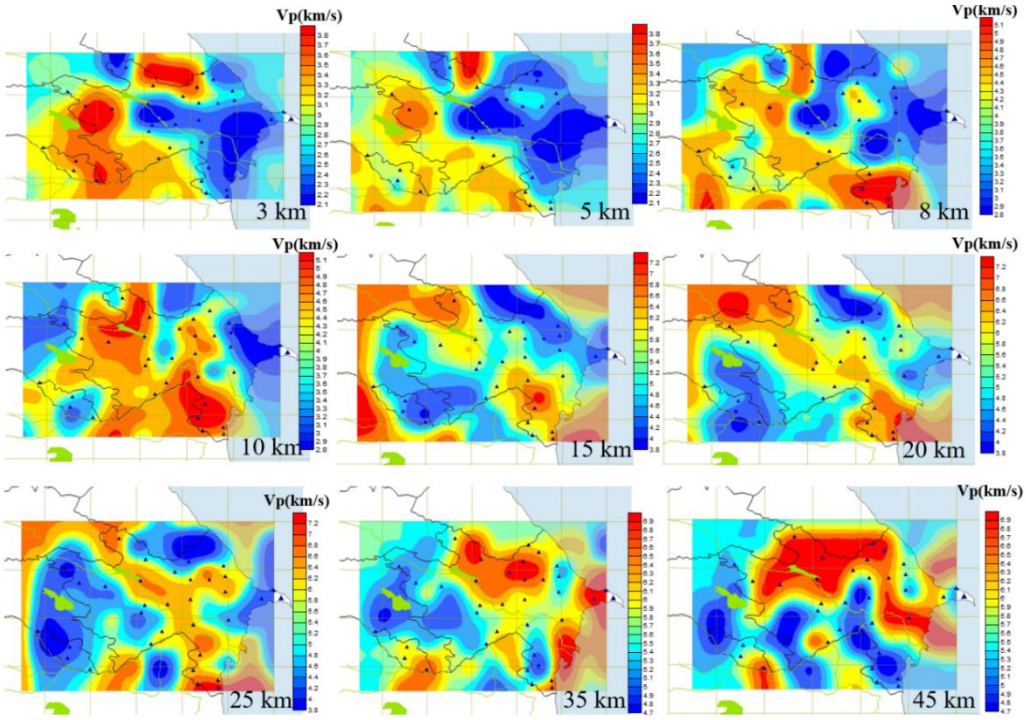

Fig. 4. Map of P-wave velocity (V_p) distribution at a given depth, showing only the portion of the model where the DWS value exceeds 200.

Crustal and Upper Mantle Structure of Azerbaijan from Seismic Tomography

Figure 4 shows maps of P-wave velocity (V_p) distribution at different depths, obtained from tomographic modeling. The final models were thresholded using a DWS value of 200, and contour lines were plotted at intervals of 0.5 km/s.

At a depth of 5 km, areas of minimum velocities are clearly observed, corresponding to the Vandam and Zakatala-Kovdag zones of the Greater Caucasus and the Proximal Lesser Caucasus region of the Middle Kura Depression, with P-wave velocities ranging from 4.5 to 5.5 km/s. Although velocities increase at depths of 5–8 km, the overall pattern of velocity anomalies remains consistent.

At a depth of 10 km, the Kura Depression, filled with sedimentary rocks, appears as a low-velocity zone (V_p ≈ 5.0 km/s). The anomaly is centered near 40.5°N, 48°E, with its southern boundary defined by the Lesser Caucasus. The lowest velocities are observed in the north, at the foot of the Greater Caucasus, while higher velocities are recorded in the southern and eastern parts of the model. Maximum velocities are found in the Sheki, Zakatala-Balakan, and Nakhchivan regions, with P-wave velocities ranging from 6.5 to 7.0 km/s.

At 15 km depth, anomalies corresponding to tectonic zones become more pronounced, showing sharp velocity contrasts between the Talysh Mountains, the Kura Depression, and the Greater Caucasus. P-wave velocities range from 6.1–6.3 km/s in the Lesser Caucasus to 5.0–5.5 km/s within the depression. The central parts of the Vandam and Zakatala-Kovdag zones of the Greater Caucasus, as well as the border region with Dagestan, exhibit minimum velocities of 5.5–6.0 km/s. S-wave velocities at this depth are 3.5–3.7 km/s in the Lesser Caucasus, but the Kura Depression shows more complex variations. Two distinct low-velocity zones (V_s ~2.75 km/s) are observed, likely corresponding to areas with the thickest sedimentary cover—one in the central part of the depression and another along the Caspian coastline.

The lowest velocities (V_p < 5.0 km/s, V_s ~2.75 km/s) are found on the Absheron Peninsula, reflecting the increasing sediment thickness toward the Caspian Sea. Significant velocity gradients persist down to 35 km. From 20 km depth, higher velocities are observed under the Kura Depression, whereas lower velocities remain beneath the Greater and Lesser Caucasus regions. By 35 km depth, velocities under the Kura Depression approach values characteristic of the upper mantle.

Thus, the double-difference method provides strong evidence that the crystalline basement beneath the Kura-Aras Depression has an oceanic origin. Furthermore, this approach allows for refined mapping of earthquake hypocenters and the geometry of major regional faults.

The main seismic activity in Azerbaijan is concentrated within the Greater Caucasus and adjacent frontal thrusts. Key tectonic structures include the Main Caucasus Thrust (MCT), the Kura Fold and Thrust Belt, and the West Caspian Fault (WCF). The largest earthquakes in the region (Mb > 6.0) historically occurred near the MCT [19, 20]. Although no such large events have been recorded during the operation of the modern Azerbaijani seismic network, numerous hypocenters are observed along the southern slope of the Greater Caucasus, where the MCT is located.

One of the most significant historical earthquakes is the 1902 Shamakhi event (Ms ~6.9 ± 0.2), with its epicenter near the city of Shamakhi. Its exact location remains uncertain, but it is believed to be associated either with the MCT or the frontal part of the Kura fold-and-thrust zone [19].

In recent years, higher-magnitude earthquakes have been recorded in deeper structures beneath Baku and along the Absheron peninsula in the Caspian Sea. While our data do not exclude activity along the MCT, making it a potentially hazardous seismic element, the Kura Fold and Thrust Belt also exhibits a comparable level of seismicity. This may indicate a southward shift of the active deformation zone of the Eastern Greater Caucasus toward the Kura-Aras Depression.

However, along the curved segment of the MCT near 41°N and 46.5°E, seismic activity sharply decreases. This may reflect either small-magnitude earthquakes undetected by the national seismic network or the accumulation of stress capable of triggering a major event. Data on deformation along this segment remain very limited: geomorphological indicators of large displacements are absent, and geodetic (GPS) measurements do not allow reliable assessment of strain variations along the fault.

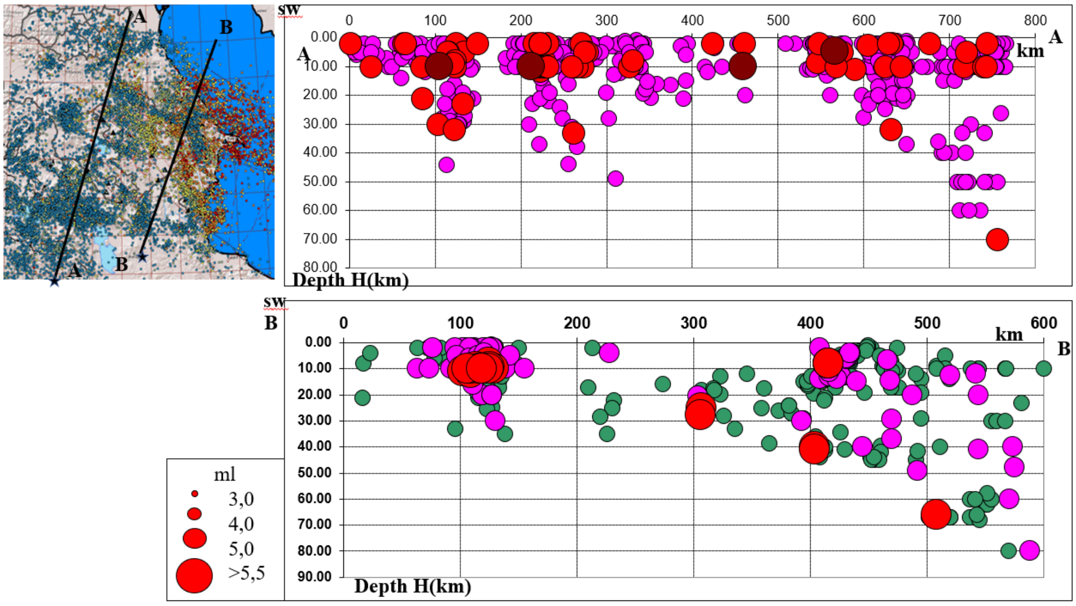

Fig. 5. Map of earthquake epicenters showing relocated (refined) hypocenters (2003-2024). The color scale represents depth: orange indicates earthquakes within 0–40 km, while blue denotes events deeper than 40 km. The 40 km threshold is chosen as the average thickness of the continental crust. Cross-section A–A′ demonstrates that seismicity in western Azerbaijan is largely confined to the crust. Cross-section B–B′ shows a pronounced increase in the number of subcrustal earthquakes.

Deep-focus earthquakes with hypocenters deeper than 30 km beneath the Kura Depression form a linear zone oriented roughly north-northwest to south-southeast (NNW–SSE). Focal mechanisms (strike-slip or dip-slip) and seismic tomography data indicate the presence of an active seismic structure known as the West Caspian Fault (WCF). Previous evidence for the WCF came from abrupt variations in sedimentary cover thickness (Allen et al., 2003) and gravity anomalies [10, 11]. Moreover, this fault has been incorporated into GPS-based block models as a structure accommodating the counterclockwise rotation of the Caucasus block [21].

Our hypocenter data confirm the existence of the WCF (see Fig. 4), but suggest that the seismicity associated with it is located west of its traditionally mapped position. Variations in the sedimentary cover within the Kura Depression are clearly observed in velocity sections at 20 and 25 km depth (Figs. 5 and 6), near 40.5°N and 48.0°E. These features manifest as a low-velocity protrusion (5.0–5.5 km/s) separating two high-velocity domains (~6.5 km/s). This structure is interpreted as oceanic crust underlying low-velocity sediments. The high-velocity lower crust appears to underlie nearly the entire Kura Depression, consistent with ongoing thrusting (subduction) beneath the Eastern Greater Caucasus.

Previously, deep seismicity beneath the Kura region was attributed either to westward thrusting of the South Caspian Basin beneath the Kura Depression [22] or to subduction beneath the Talysh zone to the south (Jackson et al., 2001), based on focal mechanisms and earthquake depths along Azerbaijan’s southern coast. We observe a similar seismicity pattern, though it lies at the edge of the monitoring network, and therefore the accuracy of epicenter locations in this zone is limited.

Within the main observation area, no convincing evidence for subduction of the Caspian Basin beneath the Kura Depression was detected. The recorded deep-focus events (deeper than 40 km), shown in blue on the figures, lie below the brittle-ductile transition and likely occur in the upper mantle. We infer that these events are associated with the presence of ancient, cold oceanic lithosphere beneath the Kura Depression, resulting in a low geothermal gradient and a deep transition boundary. Additionally, heat flow between the Kura and Caspian depressions ranges from 30 to 50 mW/m² and shows similar values in both structures. The reduced heat flow is likely related to low radiogenic heat production, characteristic of oceanic crust.

The presence of two clearly defined seismically active horizons in the eastern part of the Greater Caucasus supports the hypothesis of ongoing subduction—from the Caspian Sea beneath the eastern Greater Caucasus and further beneath the territory of Baku, which has a population of approximately 2.166 million [17]. To test this hypothesis, we constructed the first high-resolution three-dimensional models of P- and S-wave velocities in the crust, using travel-time data from approximately 7,600 earthquakes recorded by 35 broadband seismic stations continuously operating across Azerbaijan. The regional double-difference tomography method enabled us to simultaneously reconstruct the velocity structure and refine the locations of earthquake hypocenters.

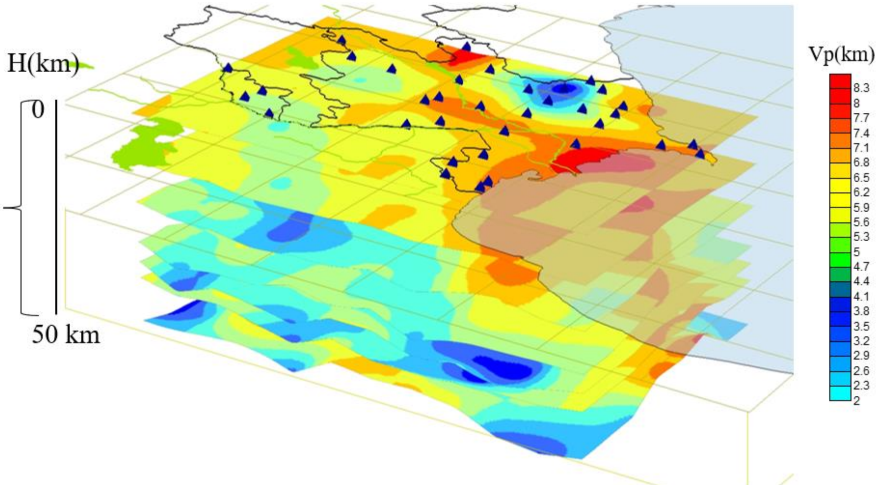

Fig. 6. 3D model of P-wave velocity distribution obtained using seismic tomography.

Significant lateral velocity variations at depths of ~30 km are interpreted as reflecting differences in rock composition between the Lesser/Greater Caucasus and the Kura–Araks Basin / South Caspian Basin. Specifically, beneath the basin, higher velocities are observed (Vp ~7.1 km/s, Vs ~3.9 km/s) compared to the Caucasus Mountains (Vp ~6.3 km/s, Vs ~3.4 km/s). The high-velocity zone at 30 km depth extends westward toward the western part of the Greater Caucasus, suggesting ongoing subduction in this direction, as proposed by Mumladze [17]. We infer that the crust beneath the Kura–Araks Basin is compositionally similar to that under the South Caspian Basin.

Our results thus support the hypothesis of Phillip et al. (1989) [18], indicating that the eastern Greater Caucasus still preserves structural features characteristic of the terminal stage of continent–continent collision. In our view, a full continental collision between the Arabian and Eurasian plates in the eastern Greater Caucasus has not yet occurred, as the Kura–Araks Basin represents a fragment of oceanic lithosphere that has not been fully subducted. The remaining subducting oceanic plate roughly corresponds to the width of the Kura–Araks Basin.

Consequently, the data presented here provide strong evidence for the presence of an oceanic slab beneath the eastern Greater Caucasus. Major historical earthquakes in the Shamakhi region (in 1191, 1667, 1859, and 1902) were accompanied by landslides, collapses, and numerous casualties. Eyewitness accounts suggest magnitudes reaching Ms 7–8 [19]. The existence of a subducting slab beneath the eastern Greater Caucasus may explain these destructive events. The most recent significant earthquake (M6.8) occurred on 11 November 2000, east of Baku.

Subduction zones often generate the strongest and most destructive earthquakes, and similar processes beneath the eastern Greater Caucasus and the Absheron Peninsula may pose a serious risk to the population of Baku.

The crustal model of the Nakhchivan region is characterized by P- and S-wave velocities ranging from 3.0 to 5.2 km/s in the sedimentary layer, 6.3–6.6 km/s in the "granite" layer, and 7.0–7.2 km/s in the "basaltic" layer. The upper sedimentary–granite portion of the crust is separated from the lower basaltic portion by a low-velocity layer. In the Lesser Caucasus, the velocity models commonly display well-defined boundaries corresponding to the top of the consolidated crust, a boundary at 12–14 km depth (within the “granite” layer), and the top of the “basaltic” layer. The magnitude and pattern of velocity contrasts at these boundaries vary regionally: in the Somkheto–Kafan and Ganja zones, a normal (positive) increase of velocity with depth predominates, while some blocks contain layers with alternating high and low velocities.

Conclusions:

1. The application of high-resolution double-difference seismic tomography has provided a robust three-dimensional image of the crust and upper mantle beneath Azerbaijan, significantly improving both earthquake hypocenter locations and the resolution of velocity heterogeneities compared to conventional 1D and absolute-location approaches. The strong reduction in travel-time residuals confirms that the obtained models adequately capture the complex lithospheric structure of the region.

2. The observed lateral and vertical variations in P- and S-wave velocities correlate well with major tectonic provinces of the Caucasus, including the Greater Caucasus, Lesser Caucasus, Kura–Araks Depression, and the South Caspian Basin. In particular, the persistence of low velocities at shallow depths beneath the Kura–Araks Depression reflects thick sedimentary successions, whereas the emergence of high velocities at depths of 20–35 km indicates a dense, mafic lower crust inconsistent with typical continental crust.

3. The high-velocity lower crust beneath the Kura–Araks Depression (Vp ~7.0–7.2 km/s; Vs ~3.8–3.9 km/s) is best explained by the presence of oceanic or strongly mafic crustal material. This interpretation is supported by the continuity of the high-velocity zone toward the South Caspian Basin and its westward extension beneath the eastern and central parts of the Greater Caucasus, implying ongoing underthrusting or subduction.

4. The spatial distribution of relocated earthquake hypocenters reveals two distinct seismogenic horizons beneath the eastern Greater Caucasus. The upper horizon is confined to the brittle continental crust, whereas the deeper horizon extends below 30–40 km depth and is interpreted as seismicity occurring within subducted, mechanically strong, and relatively cold lithosphere. This pattern is incompatible with a purely continental collision model and instead supports a hybrid subduction–collision regime.

5. Deep-focus seismicity beneath the Kura–Araks Depression and the Absheron region is spatially aligned along a NNW–SSE-trending zone, consistent with the geometry of the West Caspian Fault. The westward displacement of seismically active segments relative to their traditionally mapped surface traces suggests that this fault system may be deeply rooted and structurally decoupled from shallow geological expressions.

6. The presence of earthquakes below the brittle–ductile transition implies a reduced geothermal gradient beneath the Kura–Araks Depression, consistent with heat-flow values of 30–50 mW/m^2 and low radiogenic heat production. These thermal conditions are characteristic of old oceanic lithosphere and provide independent support for the interpretation of an oceanic slab beneath the eastern Greater Caucasus.

7. The tomographic results lend strong support to geodynamic models proposing that the eastern Greater Caucasus represents a late-stage, incomplete continent–continent collision, in which remnants of oceanic lithosphere are still being subducted beneath Eurasia. The width of the inferred subducting slab approximately corresponds to the present-day width of the Kura–Araks Depression.

8. From a seismotectonic perspective, the coexistence of active thrusting, strike-slip faulting, and deep subduction-related seismicity indicates a highly complex stress regime and strain partitioning in the region. This complexity may explain the occurrence of large historical earthquakes in the Shamakhi area and underscores the significant seismic hazard posed to densely populated regions, particularly Baku and the Absheron Peninsula.

9. Overall, the integration of high-resolution seismic tomography with refined earthquake relocation provides one of the most compelling geophysical datasets to date for the existence of a subducting oceanic slab beneath the eastern Greater Caucasus. These findings place important constraints on regional geodynamic evolution and should be incorporated into future tectonic models, seismic hazard assessments, and geodynamic simulations of the Arabia–Eurasia collision zone.

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