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Original paper

Ambient seismic tomography of the lithosphere of Azerbaijan region

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Abstract: The aim of this study is to construct two-dimensional tomographic models of the structure of the Earth's crust and upper mantle of the Caucasus region using the dispersion characteristics of Rayleigh waves extracted from ambient seismic noise. The relevance of the work is due to the high seismic activity and geodynamic complexity of the Caucasus – one of the key links of the Alpine-Himalayan orogenic belt, where the ongoing interaction of lithospheric plates generates intense deformation processes. Seismic interferometry based on cross-correlation of seismic noise records was used as the main method, which made it possible to restore Green's functions and extract dispersion curves for subsequent inversion of group and phase velocities. The study covers the period from 2012 to 2024 and uses data from more than 70 seismic stations installed in Azerbaijan, Georgia and Turkey. As a result of seismic noise analysis, maps of Rayleigh wave group velocity variations at depths from 20 to 200 km were constructed, which made it possible to identify pronounced lithospheric heterogeneities of the Caucasus region. In the South Caspian Basin, the Kura and Alazani depressions, areas of reduced velocities were discovered, indicating the presence of thick sedimentary strata and a thermally weakened crust. Similar anomalies were found under large volcanoes (Elbrus, Kazbek, Ararat), interpreted as potential magmatic centers. High-velocity anomalies corresponding to a thickened, dense crust were recorded in the areas of the Lesser Caucasus and northern Iran, and at depths of 50–200 km – stable zones of the lithospheric mantle. In the eastern part of the Caucasus, signs of subduction processes are traced: deep-focus earthquakes and increased velocities in the mantle. Sharp contrasts are observed across the region's mantle: from extremely low velocities in the west to extremely high velocities in the east and in the South Caspian zone.

Keywords: seismic noise, tomography, Rayleigh waves, South Caspian basin, lithosphere, upper mantle, cross-correlation, FTAN, group velocities.

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Оригинальная статья

Томография литосферы Азербайджанского региона на основе сейсмических шумов

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Резюме: Целью настоящего исследования является построение двумерных томографических моделей структуры земной коры и верхней мантии Кавказского региона с использованием дисперсионных характеристик волн Рэлея, извлечённых из амбиентного сейсмического шума. **Актуальность работы** обусловлена высокой сейсмической активностью и геодинамической сложностью Кавказа – одного из ключевых звеньев Альпийско-Гималайского орогенного пояса, где продолжающееся взаимодействие литосферных плит порождает интенсивные деформационные процессы. В качестве **основного метода** применена сейсмическая интерферометрия, основанная на кросс-корреляции записей сейсмического шума, что позволило восстановить функции Грина и извлечь дисперсионные кривые для последующей инверсии групповых и фазовых скоростей. Исследование охватывает период с 2012 по 2024 гг. и использует данные более 70 сейсмических станций, установленных на территории Азербайджана, Грузии и Турции. **В результате** анализа сейсмического шума были построены карты вариаций групповой скорости волн Рэлея на глубинах от 20 до 200 км, что позволило выявить выраженные литосферные неоднородности Кавказского региона. В Южно-Каспийском бассейне, Куринской и Алазанской впадинах обнаружены области пониженных скоростей, указывающие на наличие мощных осадочных толщ и термически ослабленной земной коры. Под крупными вулканами (Эльбрус, Казбек, Арарат) выявлены аналогичные аномалии, интерпретируемые как потенциальные магматические очаги. В районах Малого Кавказа и северного Ирана зафиксированы высокоскоростные аномалии, соответствующие утолщённой, плотной коре, а на глубинах 50–200 км – устойчивым зонам литосферной мантии. В восточной части Кавказа прослеживаются признаки субдукционных процессов: глубокофокусные землетрясения и повышенные скорости в мантии. По мантии региона наблюдаются резкие контрасты: от сверхнизких скоростей на западе до сверхвысоких – на востоке и в Южно-Каспийской зоне.

Ключевые слова: сейсмический шум, томография, волны Рэлея, Южно-Каспийский бассейн, литосфера, верхняя мантия, кросс-корреляция, FTAN, групповые скорости.

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Introduction

One of the key goals of modern seismology is to study the internal structure of the Earth. Scientific works of the last decades confirm that seismic approaches remain the most effective and reliable tools for studying the structure and physical characteristics of our planet. Since the mid-1970s, seismic tomography, first described in the works of Aki, Lee and others [Aki, Lee, 1976; Aki et al., 1977; Dziewoński et al., 1975], has become

a fundamental method of georesearch. Over the years, seismic tomography technologies have improved significantly, becoming an indispensable element of geoscientists. Three-dimensional (3D) models created with its help reflect variations in seismic velocities and density, revealing the dynamics and composition of the interior of the Earth and other planets. They help to study the structure of active volcanic zones and faults, determine internal flows in glaciers and polar caps, identify underground reservoirs and storage facilities, and accurately model earthquake-induced ground displacements. Seismic methods are divided into two main categories: the first is based on the analysis of the arrival time of body waves generated by earthquakes or explosions; the second uses the spectral characteristics of the waves, including the velocity dispersion of Rayleigh and Love surface waves. Seismic noise, previously considered a nuisance, is now regarded as a valuable source of data due to the development of seismic interferometry [Campillo, Paul, 2003; Wapenaar, 2004; Shapiro et al., 2005; Wapenaar et al., 2011]. This technique allows extracting useful signals from ambient noise, creating seismic velocity distribution maps and constructing tomographic images. The advantage of the approach is its universality: noise is present everywhere, which makes the method applicable even in regions with minimal seismic activity. Cross-correlation of noise records obtained at two seismic stations allows reconstructing the empirical Green's function describing the medium between them [Snieder, 2004; Weaver, Lobkis, 2001; Wapenaar, 2004]. This function is equivalent to the seismogram that would be recorded if one station acted as a source of an impulsive signal [Wapenaar, 2004]. The present study is aimed at constructing two-dimensional tomographic models of the structure of the Earth's crust and upper mantle of the Caucasus region using the dispersion characteristics of Rayleigh waves. The Caucasus is the subject of numerous seismic tomographic studies, which used various techniques, mainly based on the analysis of body waves, both in large-scale and local studies, including deep sounding [Kazimova, 2020; Svalova, 2019; Svalova, Zaalishvili, 2024; Giorgobiani, 2020; Stogny et al., 2023]. It should be noted that the amplitudes of surface waves significantly exceed the amplitudes of body waves, as a result of which the latter are often masked in seismic records, which complicates their processing and interpretation. Surface waves, due to their high sensitivity to the upper layers of the lithosphere, are an effective tool for studying the near-surface structure of the Earth's crust, which is especially important for engineering-geological and environmental problems.

Geodynamic and tectonic evolution of the Caucasus region

The Caucasus region is one of the most complex and active geotectonic zones of the Alpine-Himalayan orogenic belt, formed as a result of long-term collision tectonics between the Arabian and Eurasian plates within the Iranian segment (fig. 1). The modern structure of the region is due to the ongoing convergence of the Arabian and African plates with Eurasia for more than 100 million years, during which the lithosphere of the Neotethys Ocean gradually sank beneath the Eurasian continent.

The modern tectonic setting is characterized by active convergence in Eastern Turkey, the Caucasus and within the Anatolian plate. The westward displacement of the Anatolian block is compensated by the activity of the North Anatolian and East Anatolian faults. The segmentation of deformation processes in the collision zone covers both eastern Turkey and the Caucasus, influencing orogenesis and magmatic activity within the Turkish-Iranian Plateau. In the east of the region, the initial stage of subduction of the South

Caspian Basin under the continental crust of the Middle Caspian along the Absheron-Cheleken sill is recorded [Mammadli, Muradov, 2023]. The Greater Caucasus was formed as a result of tectonic inversion of the Mesozoic basin located on the continental crust north of the Neotethys subduction zone. The eastern Black Sea and the South Caspian are considered as residual oceanic basins formed in the Jurassic and Cretaceous periods. The Oligocene sedimentary strata of the Kura and Rioni basins are characterized by an asymmetric structure with predominant subsidence on the southern margins, which is probably associated with tectonic influence from the Lesser Caucasus [Ismail-Zadeh et al., 2020].

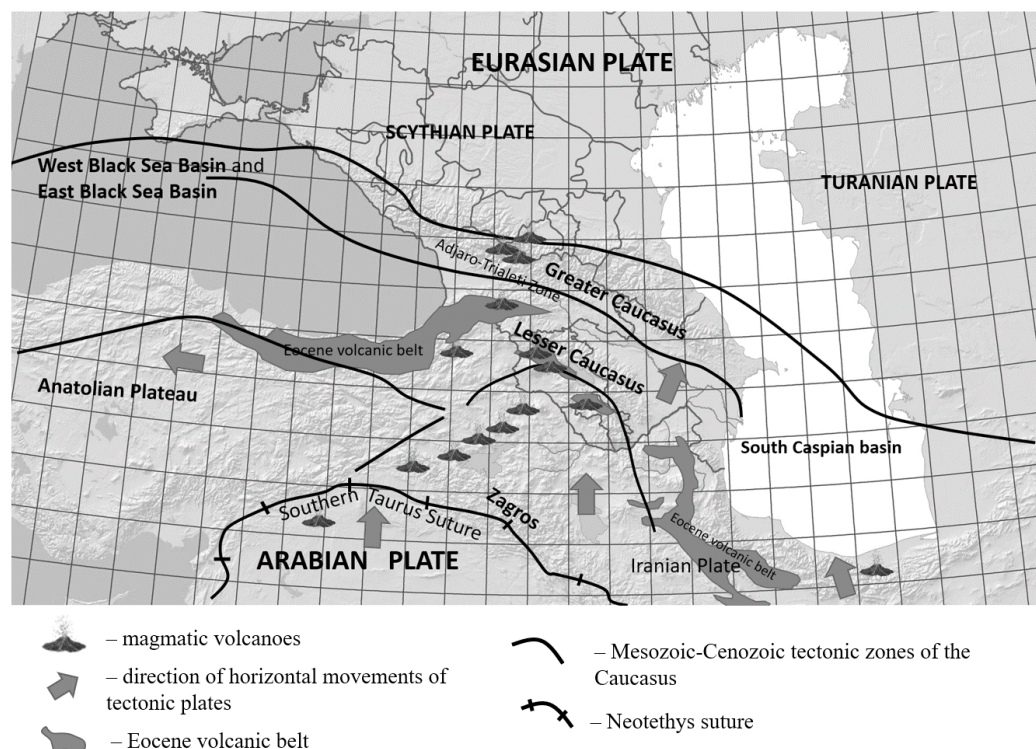


Fig. 1. Tectonic map of the Caucasus compiled according to data from Afanasev A.P., Nikishin A.M., Obukhov A.N. [2007]

Seismotectonic studies of the region indicate the prevalence of compression with the main axis oriented in the north-northeast direction, coinciding with the general strike of the Caucasus ranges. The extension axis is usually oriented vertically. These patterns are confirmed by the focal mechanisms of earthquakes identified on the basis of instrumental data. The set of geodynamic features corresponds to the plate tectonics model, according to which the collisional interaction of the Arabian and Eurasian plates causes transverse compression and determines the high seismic activity of the region. The southern slope of the Greater Caucasus demonstrates particular tectonic activity, where the most powerful earthquakes with a high level of seismic energy are observed. According to GPS measurements, the convergence rate between the Greater and Lesser Caucasus is about 10 ± 2 mm/year, with about 60% of the deformation concentrated within the Greater Caucasus. Despite the moderate current compression recorded within the ridge, the observed rates of shortening do not fully explain the existing geodynamic processes [Yetirmishli, Kazimov, 2022]. Geologically, the region is represented by Paleozoic metamorphic complexes, granitoid intrusions and Jurassic sediments, with signs of Mesozoic and

Cenozoic volcanism. The Lesser Caucasus is characterized by a basement of Paleozoic granitoid-metamorphic rocks overlain by Paleozoic and Triassic carbonates [Dilek et al., 2010]. Young magmatism of the region, which developed at the late stage of collisional interaction, is classified as post-collisional. Neogene-Quaternary volcanic formations are close in geochemical characteristics to intraplate basalts of the continental type. According to petrological data, the source of magmatic melts is metasomatized asthenospheric mantle, affected by subduction processes of the Neotethys remnants. Various petrogenetic models have been proposed to explain the mechanism of this magmatism. Of particular interest are areas where continental collision ended in the Neogene-Quaternary, allowing us to trace the transition from syncollisional to postcollisional and possibly intraplate magmatism. One key example is Eastern Anatolia, where the Neotethys Ocean closed and oceanic crust subducted beneath the active Eurasian margin in the late Mesozoic and early Cenozoic. The completion of this process in the Miocene was accompanied by significant vertical uplift, resulting in the formation of the modern relief with an average height of about 2 km. The dates of the last manifestations of suprasubduction magmatism in the region vary from 18.5 to 12.5 million years: 18.5–16.5 million years ago in Southern Armenia, 15.5 million years ago in Western Georgia, 13.0–12.5 million years ago in the Vardenis Plateau, and 15.0–12.5 million years ago in northeastern Turkey. The onset of post-collisional volcanism was recorded about 11–10 million years ago in Eastern Anatolia and 9.0–8.5 million years ago in the Lesser Caucasus. In Azerbaijan, the geodynamic structure is further complicated by the proximity of the Caspian Sea, located in a deep meridional depression. The northern part of the country is occupied by the eastern section of the southern wing of the Greater Caucasus with its intense deformation and complex geology. The southern regions are represented by the tectonically active systems of the Lesser Caucasus and the Talysh Mountains, each of which is characterized by unique structural, geodynamic and seismic features.

Research Methodology

Ambient seismic noise is predominantly formed by oceanic microseisms [Berger et al., 2004; McNamara, Buland, 2004], manifested in two frequency ranges: 0.05–0.10 Hz and 0.1–0.2 Hz. The main contribution to the noise is made by surface waves (Rayleigh and Love), which makes them the dominant component in the Green's functions obtained from cross-correlations. The dispersion properties of surface waves allow us to study the properties of the medium at different depths by analyzing different periods, which makes it possible to construct dispersion curves. These curves are used for tomographic inversion, where the surface wave velocities for each period serve as input data [Shapiro et al., 2005; Sabra et al., 2005].

Since the velocity of waves in the Earth's interior increases with depth, waves with a longer wavelength (lower frequency) are able to travel faster than waves with a shorter wavelength (higher frequency). The transmission velocity of seismic waves is determined by the density and elastic properties of the medium, as well as the nature of the wave itself. It tends to increase with depth in both the crust and mantle, but decreases sharply at the transition from the mantle to the outer core. For Rayleigh waves, velocities vary in the range of 1–5 km/s. Waves emanating from earthquakes in the crust or upper mantle exhibit higher velocities when passing through cold and dense regions and lower velocities when passing through hot rocks. Inversion of group velocities at the nodes of the computational grid allows one to create layered S-wave velocity profiles, which are

interpolated to construct two-dimensional maps. Since the amplitudes of surface waves significantly exceed those of body waves, the latter are often masked in seismic records, which complicates their processing and interpretation. The optimal approach to using surface waves to study subsurface structures is to calculate dispersion characteristics and then invert the obtained curves. Thus, constructing two-dimensional tomographic maps based on dispersion curves facilitates accurate reconstruction of the geological structure and study of the velocity characteristics of the region.

Ambient noise data processing includes four key stages: data pre-processing, cross-correlation, measurement of dispersion curves, and quality control. These methods are applicable at various scales, from regional to continental, and cover a wide range of periods. In this work, we used a standard technique for constructing Rayleigh wave dispersion curves based on seismic noise cross-correlation functions for pairs of stations. The procedure includes calculating daily cross-correlation functions, summing them over a long period (in this case, 10 years), filtering using narrow-band filters, determining time delays based on the maxima of the envelopes of the filtered functions, and calculating group velocities. To suppress earthquake signals, amplitude normalization based on a moving average was used. Data processing was performed according to the approach described by Bensen et al. [2007], taking into account the correction of instrumental distortions, time normalization to eliminate teleseismic events, and spectral cleaning. The dispersion curves of the Rayleigh wave group velocities for each source-receiver path were estimated using the `do_mft` package [Herrmann, 2013]. The figure 2 shows the cross-correlations for the IML and NAX stations.

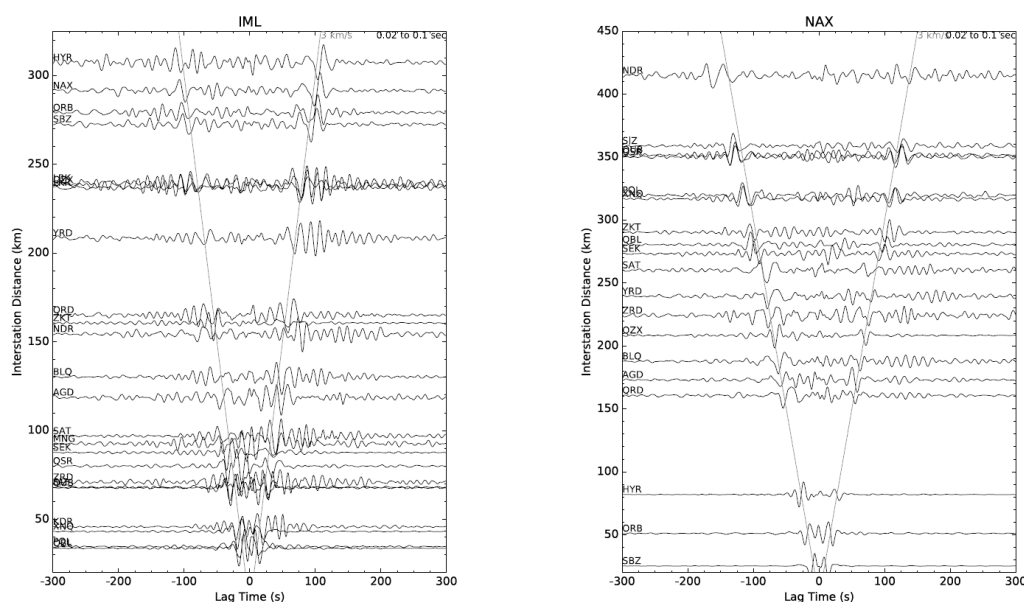


Fig. 2. Cross-correlations of ambient noise for the IML and NAX stations
(the location of the stations is shown in fig. 4)

Symmetrical correlations are obtained by convolution (adding the positive and negative components of the signal). Group and phase velocity measurements were made using time-frequency analysis with multiple filtering [Bensen et al., 2007; Levshin, Ritzwoller, 2001]. The cross-correlation functions were filtered with a series of narrow-band Gaussian filters with periods ranging from 5 to 75 s.

Group velocity measurements are made using an automated FTAN (Frequency-

Time Analysis) process. In this step, each step in the dispersion measurement process is decomposed, starting with the accumulation of cross-correlations to the application of time-frequency analysis. The process of obtaining group velocity is relatively simple and involves measuring the cross-correlation envelope and determining its peak for each frequency band.

Phase velocity curves are naturally obtained in the FTAN process, although the phase velocity measurement involves some subtle differences compared to the group velocity. The main difference is the need to carefully monitor the phase function $\phi(t, \omega_0)$, as it directly affects the phase velocity estimate. Figure 3 graphically illustrates the automated FTAN process. This process is shown for both group and phase velocity measurements, showing the flow from the initial waveform processing through the application of narrowband filters and the final group and phase velocity measurement.

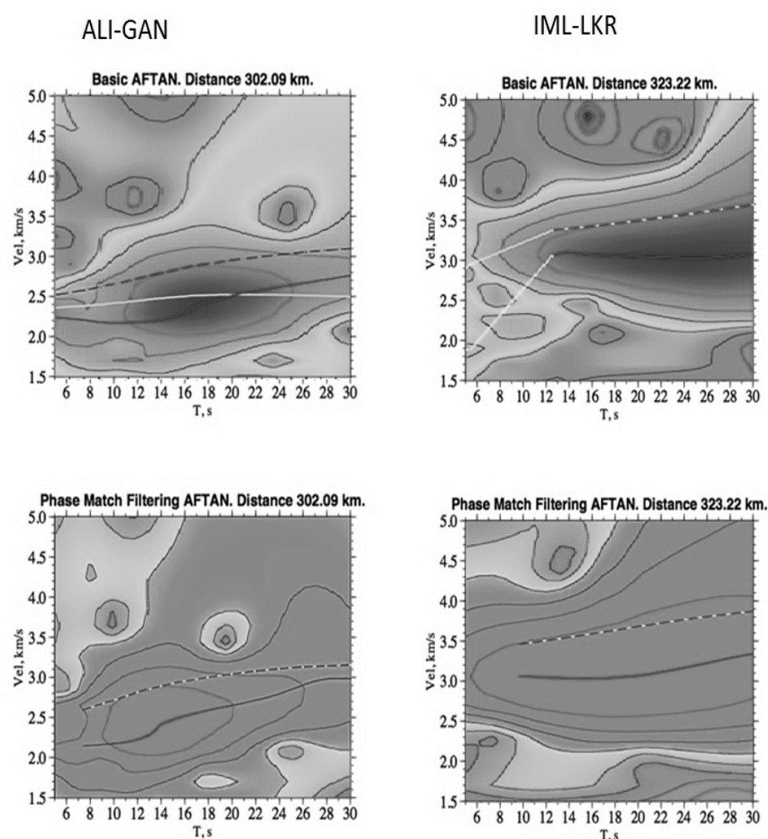
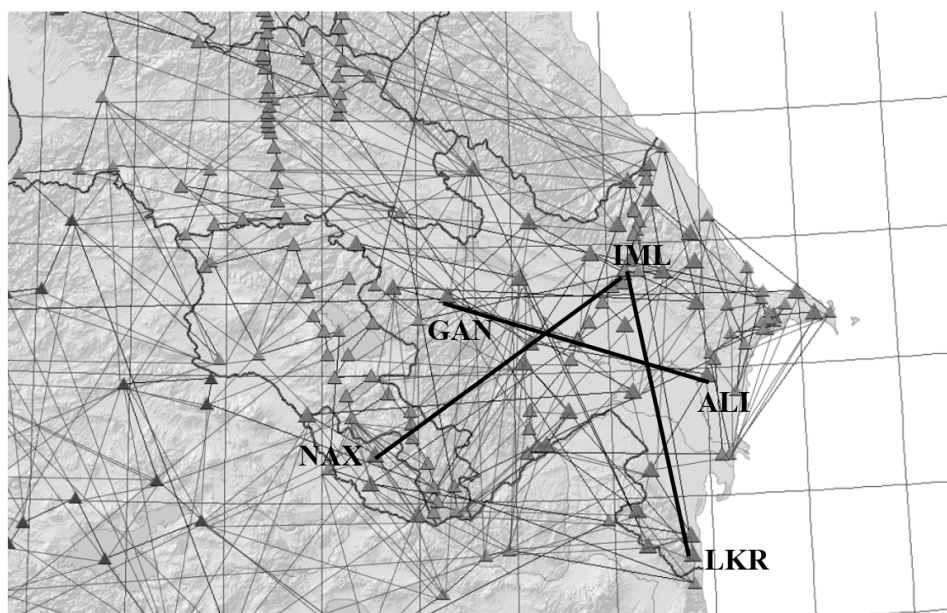


Fig. 3. Graphical representation of FTAN. 24-month stacked cross-correlation between stations ALI-GAN and IML-LKR (the location of the stations is shown in fig. 4)

Used data

In 2003, 35 permanent broadband stations were installed in Azerbaijan. Then, over the course of 20 years, new digital seismic stations were installed in the Caucasus and Turkey within the framework of various national networks (Azerbaijan, Georgia and Turkey), which provides an excellent opportunity to study the lithospheric structure. In these studies, we used data from 35 digital stations “Kinemetrix”, 22 stations installed within the framework of the CNECCA project, 17 stations installed within the CNET project, as well as data from Georgian and Turkish stations. (fig. 4).



▲ **Digital seismic stations**

Fig. 4. Network of digital seismic stations of Azerbaijan, Georgia, Turkey and scheme of station pairs used for tomographic analysis

Earthquakes that occurred in the Caucasus region in the period 2012–2024 were considered. Earthquake data for the period 2012–2021 were taken from the catalog considered in the articles [Bondar et al., 2024; Godoladze et al., 2024]. The figure 5 shows the maps of the epicenters of earthquakes with a magnitude greater than 3 presented in the form of four panels, each of which shows the distribution of epicenters depending on the depth of the foci. As can be seen in the figures, the main density of earthquakes is noted in the depth range of 5–35 km.

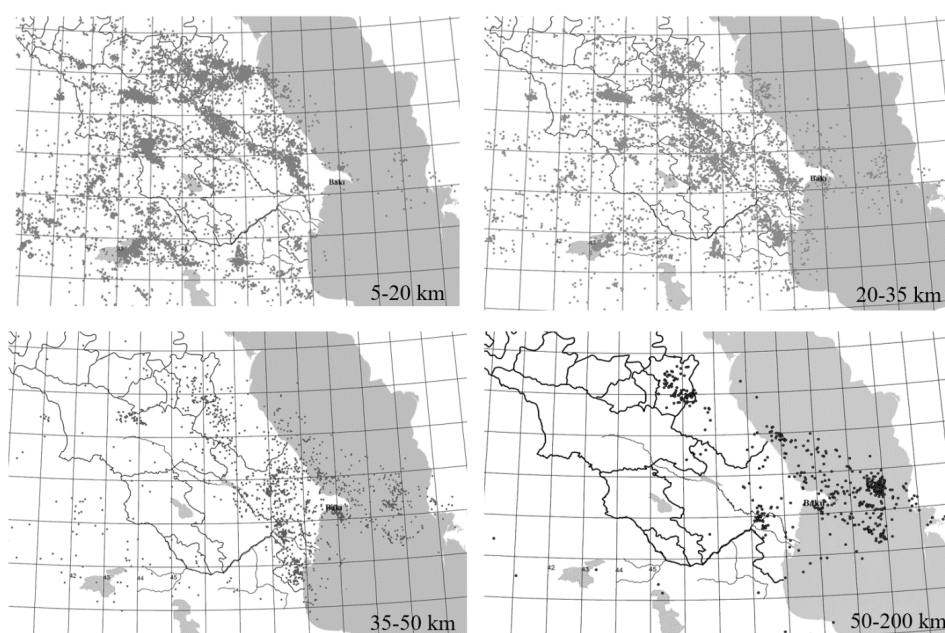


Fig. 5. Maps of earthquake epicenters for the period 2012–2024 at different depths

As a result, maps of the distribution of group velocities of Rayleigh waves were obtained within the study area, limited by longitude 44° – 52° E and by latitude 38° – 42.5° N. These maps, according to the method used, were calculated separately for each of the specified vibration periods. In total, 7 maps with a step variable by period were constructed in this way. Depth intervals of 20 km, 30 km, 40 km, 50 km, 100 km, 150 km and 200 km were considered (fig. 6).

Discussion of Results

The maps of group velocity variations obtained as a result of the studies indicate the presence of significant horizontal heterogeneities in the crust and mantle of the studied regions, which are revealed within the resolution of the method. These heterogeneities are expressed in zones with high velocity gradients corresponding to the boundaries of tectonically different structures, as well as in local anomalies of group velocities, manifested as maxima and minima. All maps presented in Fig. 3 show that the variations in group velocities range from -1.3% to $+1.3\%$ relative to the average velocity values for each vibration period. Although the configuration of the velocity variation isolines is complex, their distribution shows common characteristic features. Namely: increased values of velocities corresponding to depths of 20–30–40 km in the zone of the Lesser Caucasus, as well as a decrease in the values of velocities of 50–200 km, where the nature of the dispersion of surface waves is influenced mainly by the structural features of the mantle part of the lithosphere and the asthenosphere. Tectonically active structures, such as areas of intense mountain building in the Caucasus, manifest themselves as areas of reduced group velocities, i.e. the distribution features of horizontal velocity inhomogeneities in the mantle correspond with the geological structure of the region under consideration. For depths of 150–200 km, where the nature of the dispersion of surface wave velocities is influenced by the subasthenospheric layers of the upper mantle and lower mantle, such a connection is absent.

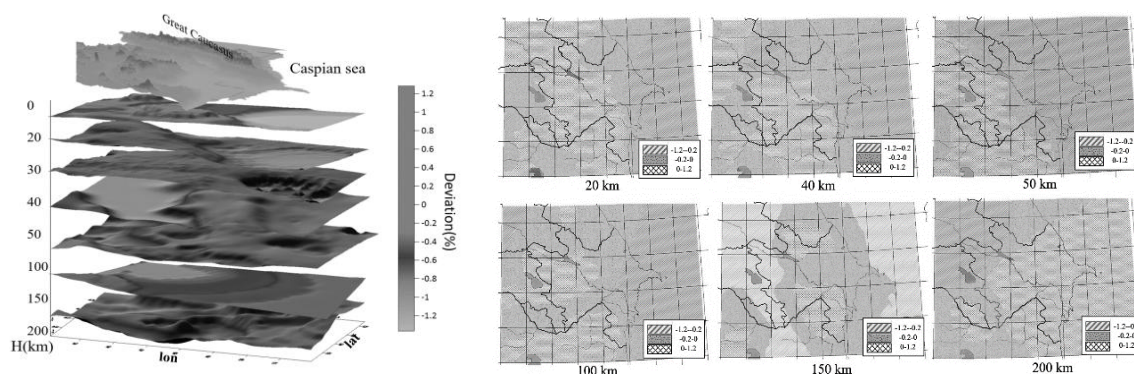


Fig. 6. Spatial sections of the distribution of group wave velocities in the Caucasus and Caspian sea regions by depth

Negative zones at a depth of 20–30 km prevail in the Caspian Sea, the Scythian Plate and the South Caspian Basin, the Alazani and Middle Kura Depressions. Negative deviations continue to dominate in the northeastern part of the region. The zone of positive changes increases, covering part of the Lesser Caucasus (0.8 – 1.2%). Taking into account the geological and tectonic structure of the region, it can be assumed that the reduced group velocities in the South Caspian, Kura and Alazani basins are due to the presence

of thick sedimentary layers (up to 20 km). At the same time, the low-velocity zone beneath volcanic complexes such as Elbrus, Kazbek and Ararat is probably associated with elevated volcanic rock temperatures or the presence of a shallow magma chamber. In contrast, high-velocity areas beneath volcanoes may be the result of low-temperature volcanic rocks or the location of a deeper magma source. In the Lesser Caucasus, there is some correlation between volcanic manifestations and low-velocity zones, but this relationship is less pronounced compared to the Greater Caucasus. Low velocities in northeastern Nakhichevan are explained by the presence of Upper Devonian and Permian deposits, which may be sources of oil.

The area of negative deviations narrows with depth. Positive changes are noticeably enhanced in the Kura Depression, Lesser Caucasus and Talysh. The central part of the region becomes the dominant zone of positive changes. The detected low-velocity anomalies in the Earth's crust may be caused by basaltic eruptions of the Quaternary period associated with Pliocene folding and tectonic activity of faults. It should also be noted that hot mantle material can penetrate into the Earth's crust through local displacements of the Moho boundary. Such intrusion results in thermal impact on the lower crust, causing its heating and, as a consequence, a decrease in seismic velocities in these horizons. Based on the obtained data, it can be assumed that the recorded low-velocity anomalies at depths of about 20–40 km are due to the combined effect of accretion, partial melting and erosion of the lower crust.

At a depth of 50–100 km, small areas of negative deviations remain in the northern part of the Caspian Sea. Positive values significantly expand. Positive deviations cover almost the entire South Caspian Basin, the Kura Depression and adjacent areas. The central and southern parts of the region demonstrate a steady increase in positive changes. High velocities in the lower crust of the South Caspian Basin compared to northwestern Iran are probably explained by the oceanic origin of the lower crust in this region.

At a depth of 150 km, positive values almost disappear, with the exception of small areas in the northern part of the Caspian Sea. Negative deviations become minimal. The dynamics show an increase in positive changes in the eastern and southern parts. At a depth of 200 km, the maximum positive deviations are observed in the South Caspian basin, the Kura depression, negative ones along the Lesser Caucasus and the Middle Kura depression. As is known, at depths greater than 100 km, the temperature reaches 1200 °C, which indicates the presence of hot molten material in the upper mantle. Low velocities are associated with pasty melt, and high ones are associated with metasomatic refertility of the upper mantle, increasing the density.

High velocity anomalies indicate the subduction of the South Caspian Basin under Talysh or the presence of a lithospheric root beneath the Kura Basin (fig. 7). In the eastern Greater Caucasus, deep earthquakes (100–200 km) indicate ongoing subduction there. On the rises of the Lesser Caucasus, Talysh, and Greater Caucasus, high and low velocity anomalies are noted at depths of 30–40 km and 50–100 km, respectively, which is interpreted as evidence of relative crustal thickening. High velocity anomalies are recorded in the Lesser Caucasus and northern Iran at a depth of 30 km, as well as in the Lesser and Greater Caucasus and northern Iran at a depth of 40 km. These anomalies may reflect the transition from warm-magmatic rocks to colder ones. Low velocity zones are likely related to the presence of sedimentary and Upper Paleozoic-Triassic metamorphic rocks in these geological supercomplexes.

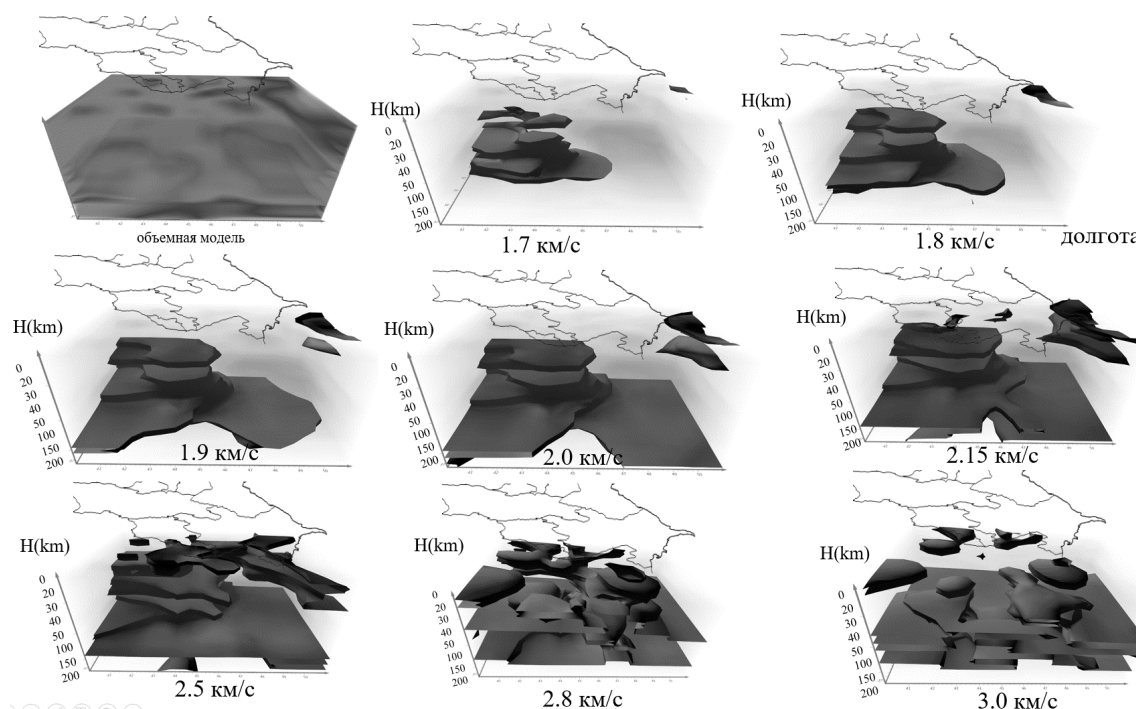


Fig. 7. 3D model of distribution of group velocities of 1.7- 3.0 km/s for the Caucasus region

At depths of about 150–200 km, the northern and western regions (western Greater Caucasus, Lesser Caucasus) show ultra-low velocities, while the eastern and southern regions (South Caspian Basin, Azerbaijan) show ultra-high velocities. This reflects the structure of the upper mantle, where low velocities are associated with a thin lithospheric mantle, and high velocities are associated with a stable mantle lid.

Conclusions

Maps of Rayleigh wave group velocity variations were constructed based on ambient seismic noise in the depth range of 20–200 km, which made it possible to characterize horizontal and vertical heterogeneities of the lithosphere of the Caucasus region.

Low-velocity anomalies were discovered in the South Caspian Basin, Kura and Alazani depressions, which are interpreted as zones of thick sedimentary strata and/or thermally weakened crust. Similar anomalies beneath the volcanoes of the Greater Caucasus (Elbrus, Kazbek, Ararat) indicate the possible presence of magmatic chambers or thermally modified crust.

High-velocity anomalies were revealed at depths of 30–40 km in the Lesser Caucasus zone and northern Iran, interpreted as thickened crust with the presence of dense metamorphic or igneous rocks. At depths of 50–200 km, an increase in positive velocity anomalies was found in the South Caspian Basin and the Kura Depression, which may be associated with the presence of a stable lithospheric mantle and, probably, the oceanic origin of the lower crust of the region.

Signs of subduction processes were recorded in the eastern part of the Greater Caucasus, as evidenced by deep-focus earthquakes (up to 200 km) and accompanying high-velocity anomalies in the mantle.

Ultra-low velocities were found in the upper mantle beneath the western part of the region (Lesser Caucasus, western Greater Caucasus) and ultra-high velocities were found

beneath the Eastern Caucasus and the South Caspian Basin, which reflects differences in the lithospheric structure: from heated asthenosphere to stable mantle with a lithospheric root. The high efficiency of using ambient seismic noise and FTAN analysis for reconstructing the three-dimensional structure of the lithosphere in seismically active regions, including automated extraction of dispersion curves and construction of tomographic models, has been confirmed.

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