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DETERMINATION OF THE DEPTHS OF THE ACTIVE BLOCKS ACCORDING TO THE DATA OF THE GPS STATIONS

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Introduction

The advent of satellite geodetic observations was marked by their widespread use to determine the velocities and direction of horizontal movements of lithospheric plates. The accuracy of measuring the horizontal component of displacements of the earth's surface in GNSS measurements turned out to be significantly higher than the vertical one at a large spatial scale of observations. The objective features of the technology of geodetic observations make it possible to measure the vertical component of the earth's surface displacements much more accurately by terrestrial methods, and the horizontal component by satellite methods. This leads to the conclusion that it is fundamentally impossible to jointly analyze the results of measuring identical motion components obtained by ground-based and satellite methods.

With the development of the era of navigation satellite systems GPS, GLONASS, GALILEO, and the expansion of the network of receivers receiving their signals, it became possible to use these systems to study the ionosphere, as well as for a more detailed examination of ionospheric structures that occur on the eve of destructive earthquakes. J.Y. Liu, I.I. Shagimuratov, V.E. Kunitsyn, S.A. Pulinets, I.E. Zakharenkov [11].

As is known, the deformations of the earth's surface that accompany the strongest earthquakes reflect the action of physical processes of various natures, differing both in intensity and in spatio-temporal characteristics. According to the time of action, these deformations are subdivided into co-seismic, occurring immediately at the moment of an earthquake, and post-seismic, which can last a month, a year, or decades after a seismic event. Co-seismic deformations can be observed by both seismological and geodetic methods, while post-seismic deformations can be observed only by geodetic methods. In many countries of the world where high seismic activity is observed, geodynamic polygons are deployed and GPS stations operate on a permanent basis, and receivers continuously record high-precision deformations of the earth's crust. Practice shows that such monitoring makes it possible to track the processes of tectonic deformations of the earth's crust, calculate co-seismic/post-seismic deformations and contribute to the study of changes in the stress-strain state, which ultimately contributes to solving problems of earthquake prediction [17]. This article attempts to study the seismic deformations of the earth's surface, which are the result of the strongest earthquakes. Co-seismic deformations are considered for most of the strongest earthquakes that have occurred over the past ten years of active GPS monitoring in various seismically active regions of the republic. The purpose of this work was to analyze the time series of GPS measurements to determine the directions and correlation of the obtained results with the hypocenters of strong earthquakes.

The principle of determining coordinates by satellite navigation method.

The determination of the coordinates of the GPS station by the satellite navigation method is carried out by calculating the coordinates of the satellites and the distances to them. Figure 1 shows the principle of determining the position on the plane: the found distance to the satellite *r* allows you to determine the coordinates on the set of solutions presented on a ring-shaped figure (in projection).

The appearance of a new satellite reduces the solution area. Thus, there are a required minimum number of satellites so that the area for three-dimensional coordinates is sufficient to determine the position with certain accuracy. The orbits of the satellites are mathematically described by ephemeris (almanac), which are the Keplerian elements of the orbit. Ephemerides are transmitted in the navigation message from satellites with a period of 12.5 minutes [12]. From them, you can determine the satellite coordinates at any time during which these ephemeris are valid. Mathematically speaking, if the ephemeris is represented as a vector of parameters E, which are obtained for the *i-ro* satellite, then the process of calculating the coordinates of this satellite is reduced to the formula:

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$$r_i\ (t) = f(t,E_i\ ),\ (1)$$

where $f(t,E_i)$ is a well-formalized function, which is specified strictly mathematically, and $r_i\ (t) = (X_i, ,Y_i\ ,Z_i\ )^m$ - the desired satellite coordinates at the desired time in the corresponding coordinate system. The first chapter provides a detailed algorithm for calculating the coordinates of satellites for the GPS system [12].

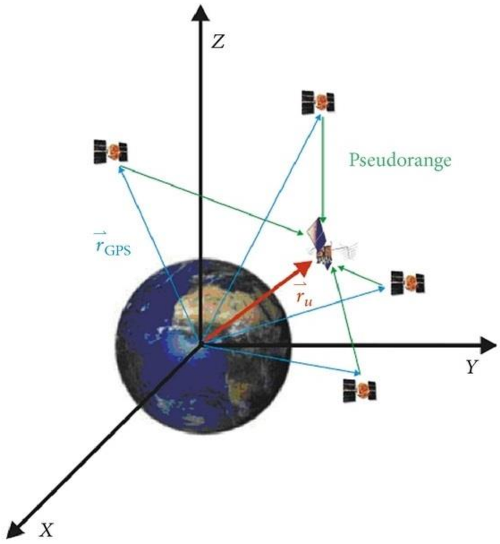


Figure1. Orbit determination using GPS [2]

The next step in solving the navigation problem is to determine the distances to each of the satellites. Traditionally, the distance to a satellite is determined by the propagation time of the phase-modulated signal multiplied by the speed of light. The propagation time of the navigation signal multiplied by the speed of light can be represented as a formula:

$$r_i = P_{Si} + d_{sat\,(i)} + D_{res} + r_{ion(i)} + r_{trop(i)} + r_{mp(i)} + e_{(i)},\ (2)$$

where r_i is the true (sought) range from the antenna to the satellite, P_{Si} is the measured range or pseudo-range (calculated by the receiver), $d_{sat\,(i)}$ is the satellite clock skew (the parameter is transmitted from the satellite), D_{res} is the receiver clock skew, $r_{ion(i)}$ and $r_{trop(i)}$ is the range error due to distortion in the ionosphere and troposphere, respectively, $r_{mp(i)}$ is the range distortion due to multipath signal propagation, $e_{(i)}$ is a random error including receiver internal noise. The main task of the navigation receiver is to simulate the propagation process in order to calculate all the parameters of the right side of equation (2) with a minimum error. The pseudo-range is corrected taking into account the calculated corrections and a navigation solution is made using the absolute method. It should be noted that the D_{res} correction applies only to the receiver and is calculated not at the stage of pseudo-range correction, but a little later, already during the solution itself [12]. The tropospheric effect on ranging can be calculated using special algorithms for modeling dry and wet atmospheres.

The ionospheric effect on ranging is calculated using the Klobuchar algorithm for ionospheric modeling (the algorithm is given in the first chapter). The algorithm allows eliminating up to 50% of the $r_{ion(i)}$ error. Next, the antenna coordinates are calculated by the absolute method. At the output of the algorithm, the coordinates and time of the receiver clock de-synchronization relative to the satellite system [12].

Satellite navigation

GPS (Global Positioning System) is a global positioning system that measures distance, time, and determines location in a coordinate system. Resolution is determined by the accuracy of measuring time and knowing the coordinates of the satellites. GPS consists of three main segments: space, control and user.

The idea of creating satellite navigation was born in the 50s. At that moment, when the USSR launched the first artificial satellite of the Earth, American scientists led by Richard Kershner observed the signal coming from the Soviet satellite and found that due to the Doppler Effect, the frequency of the received signal increases as the satellite approaches and decreases as it moves away. The essence of the discovery was that if you know exactly your coordinates on Earth, then it becomes possible to measure the position and speed of the satellite, and vice versa, knowing the exact position of the satellite, you can determine your own speed and coordinates. The GPS project started in 1973 under the direction of the US Department of Defense. The project started in 1994. Since 2000, the GPS system has become available to civilians. Countries with satellite navigation systems: GLONASS - Russia, GPS - USA, Galileo - Europe, Compass - China. Today, fully working, i.e. having the minimum required number of satellites in orbit, are two systems: the Global Navigation Satellite System (GLONASS), created in Russia and Navigation System with Timing and Ranging - NAVSTAR, created in the USA [10].

The total number of GPS satellites is 24, which covers almost the entire surface of the Earth except for the Polar Regions. The satellites revolve around the Earth (moving speed ~3.874km/s) in six different planes, 4 satellites in each. Satellites fly at an altitude of 20,200 km and have an orbital period of 11 hours 58 minutes; the satellite makes two orbits around the Earth in one day. An orbital inclination of 55° is also common to all satellites in the system. To date, to ensure greater reliability in orbits, the number of GPS satellites (NAVSTAR) is 30 and 24 GLONASS satellites [14].

Taking into account geomorphology, geotectonic, relief and taking into account the influence of external factors, in 2012 the Republican Center installed a network of 24 stationary GPS stations in Azerbaijan (Fig. 2). A set of 24 GPS stations cover the vast territory of Azerbaijan and form the GPS_RSSC geodetic network. Note that the stations are equipped with Choke Ring model antennas, the number of installed stations of this model is 10, Zephyr Geodetic2 - 14 and TrimbleNetR9-24 receivers (USA), registering the signal of the corresponding GPS and GLONASS satellites. The formed geodetic network allows solving regional problems of studying the main patterns of modern movements of the earth's crust in the territory of Azerbaijan. It should be noted that for the first time in the world on the territory of the Republic of Azerbaijan in the Saatli district, a GPS station was installed on the Saatli super-deep well (8324 meters).

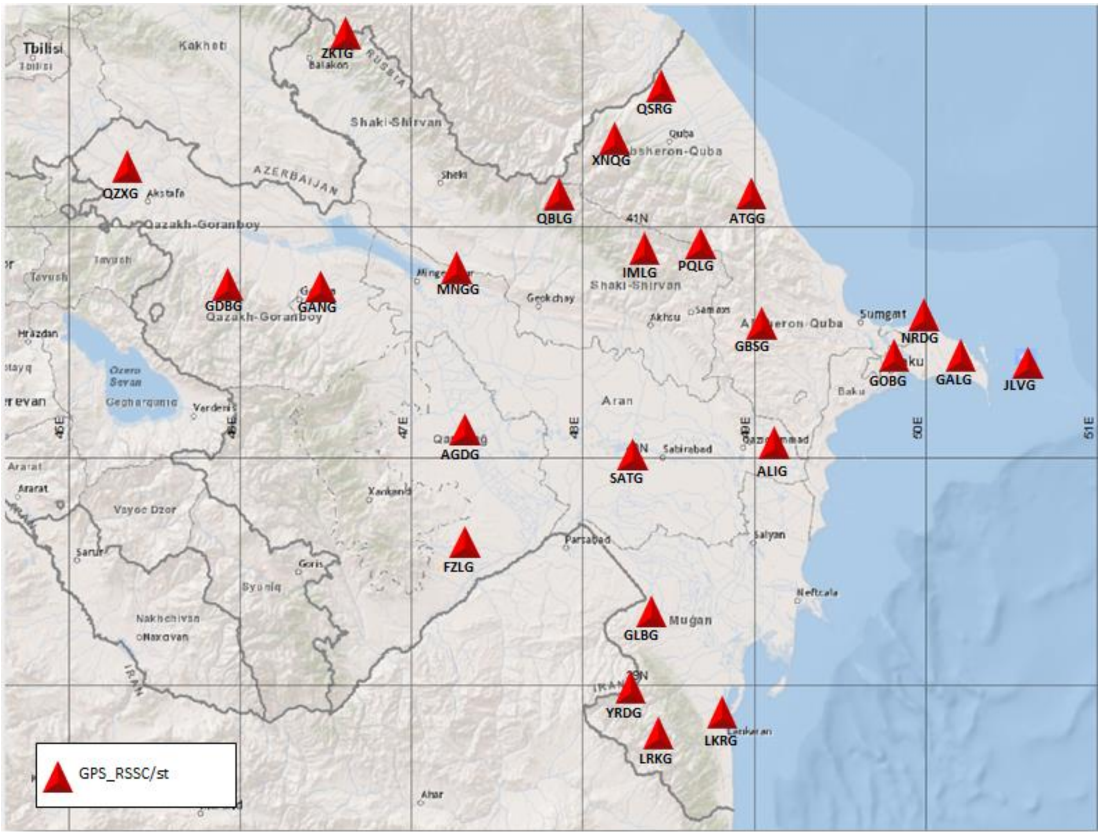


Figure 2. Network of RSSC GPS stations

Geodetic research

As is known, the stress state of the earth's crust is characterized not only by the surface layers themselves, which can be observed directly, but also by the deeper parts of the earth's crust, and the stress value is several hundred megapascals (MPa). The fact that rocks are under great stress has long been well known. It has been established that the stresses have not only a vertical, but also a horizontal component. The study of the stress state of the earth's crust to its entire depth as a whole and of rock masses is of not only scientific but also practical importance. Since all tectonic processes are associated with the current stress field in the earth's crust, knowledge of this field at the present time and the geological past is necessary for understanding geological phenomena [15].

The data obtained as a result of experimental work on the current stress-strain state of a rock mass and the patterns of its change over time, on the one hand, provide new fundamental knowledge about the nature of natural deformation processes occurring in the upper part of the earth's crust, and the impact on the formation of the stress state of a rock mass technogenic activity in the development of mineral deposits [15]. On the other hand, the data obtained serve to predict the development of the displacement process and make a whole range of technical solutions for safe and efficient field development.

Until now, geophysicists used GPS data to determine the speed and direction of horizontal movements of individual blocks or plates. In this article, we tried to connect the movement of blocks with the depths of strong earthquakes that occurred on the territory of Azerbaijan during the period 2012-2022 (Fig. 3). GPS data were processed and errors estimated using MIT's GAMIT software [6, 7] following the procedure described in [8, 9]. To estimate the speeds of the determined stations, it is necessary to have at least one reference point in the network, and preferably several. GNSS for geodynamics, YIBL_OMAN, SOFI_BULGARIA, ANKR_TURCIYA, ARTU_RUSSIAN, NICO_CYPRUS, NOT1_ITALY, POL2_KYRGYZTAN, POLV_UKRAINE, TEHN_IRAN, MDVJ_RUSSIAN, DRAG_ISRAEL, RAMO_ISRAEL, SOFI_BULGARIA, BUCU_ROMANIA, ISTA_TURKEY, GLSV_UKRAINE [1, 3]. The height cut off angle was taken as 10°.

Figure shows the velocity map of GPS points for Azerbaijan, which is used to calculate the two-dimensional deformations. The arrows in the figure show the direction of the velocity vectors, and the velocity values are characterized by the length of the arrows according to the scale, which is shown in the lower right corner of the map.

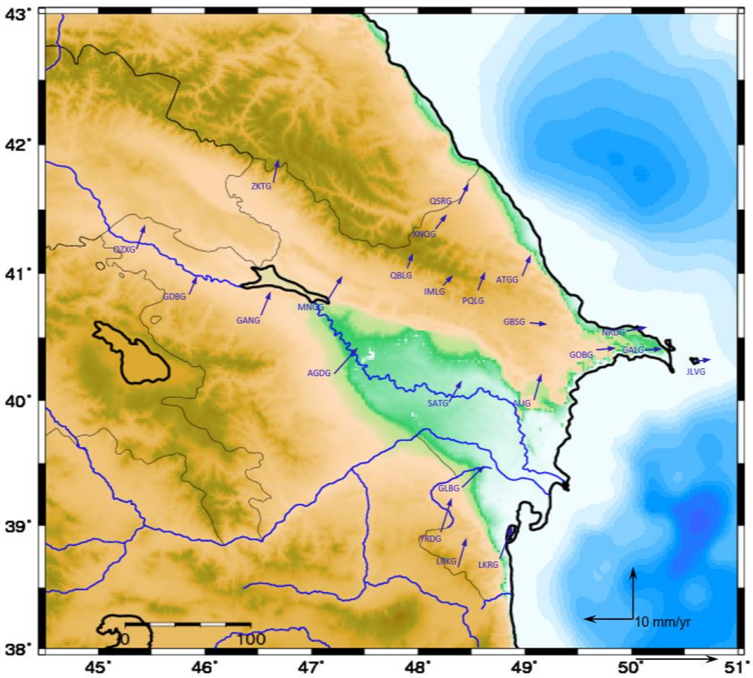


Figure 3. GPS velocity map of the territory of Azerbaijan

The velocity field of GPS observations on the territory of Azerbaijan clearly illustrates the predominance of the movement of the earth's crust in the N-NE direction relative to Eurasia. The most clearly manifested feature of the velocity field is a decrease in velocity at observation points located on the territory of the Greater Caucasus (Fig. 4). GPS observation points located along the main Caucasian thrust show a decrease in speed in an easterly direction, which is probably associated with the zone of influence of the West-Caspian Fault. N-NE movement of the earth's surface is interpreted as one of the reasons for the accumulation of stresses on this thrust. In addition, there is a tendency for horizontal movement within the Kura depression and the Lesser Caucasus, where the speed increases from west to east along the strike of the mountain range. In addition, the analysis of the azimuth angles showed an increase at the stations located on the Absheron Peninsula.

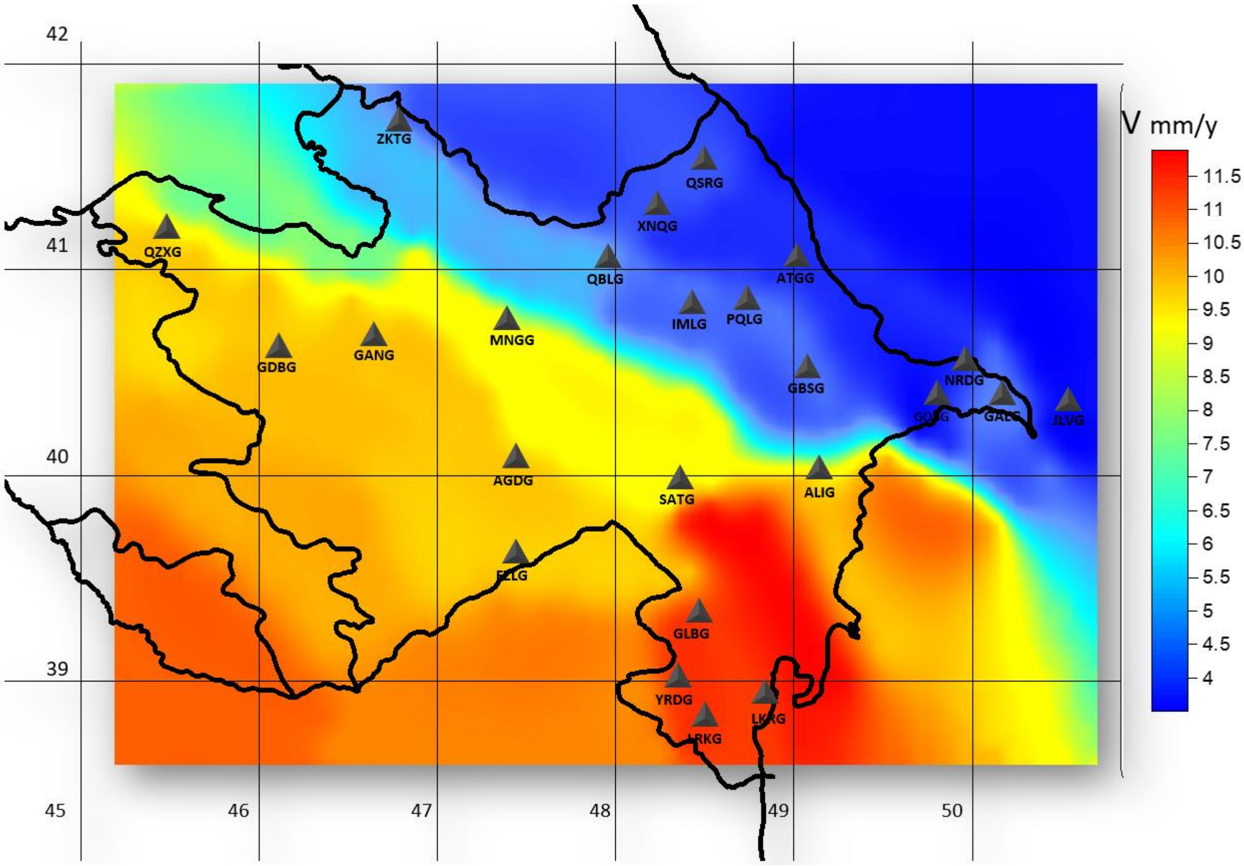
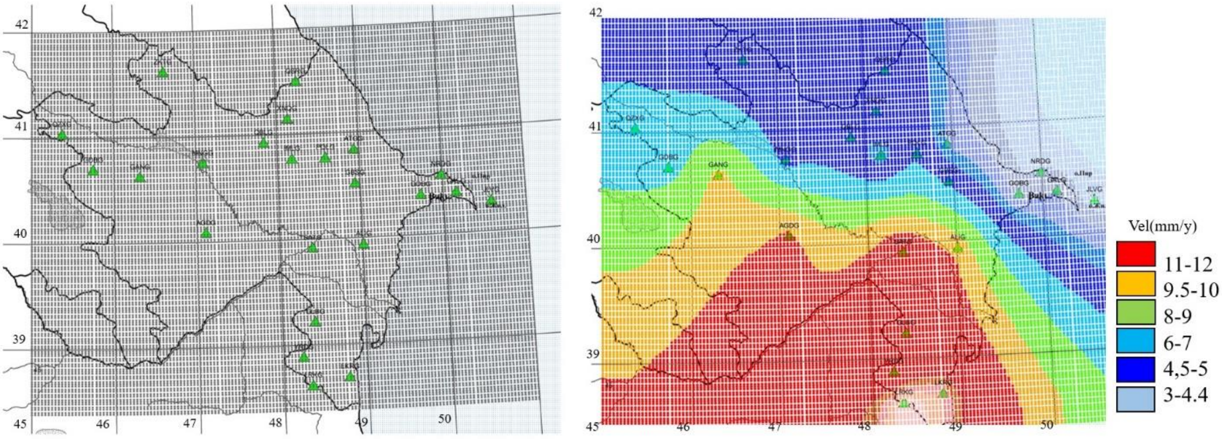


Figure 4. GPS velocity map of the territory of Azerbaijan

It has been established that along the Kura depression in the direction from the Middle Kura depression to the Low Kura depression (i.e. from NW to SE) there is a gradual increase in the rates of horizontal movements from 7.3 to 11.3 mm/year, which is characterized by the compression condition. It should be noted that in the last 3 years, the zone of the Kura depression is characterized by the manifestation of high seismic activity, expressed in several earthquakes with a magnitude of more than 5, characterized by a reverse-type movement. At the same time, within the northeastern side of the microplate corresponding to the Vandam-Gobustan megazone of the Greater Caucasus, the velocity vectors experience a decrease to 10-12 mm/y, and further north, i.e. directly within the accretionary prism, and completely decreases to 3.5-5 mm/year. In general, the tangential shortening of the earth's crust in the region is estimated at 6.1-11 mm/year.

This is confirmed by the observed directions and speeds of movement of the earth's surface in the territory of Azerbaijan and adjacent regions according to the results of measurements at GPS points. It should be noted that the regional patterns of neotectonic and modern geodynamic development and landforms of the Caucasus region can be considered as a result of mechanical impacts on it of adjacent geodynamically active areas [13].

The revealed heterogeneous nature of the velocity field of the region allows us to state the block model of the structure of the region, which is closest to the real one. A similar conclusion about the block structure was also obtained for other regions [16].
Based on the result obtained, we approximated the values of the horizontal motion velocities within the latitude coordinates 38.4-42.00 and longitude 45.00-51.00 150×150 points (Fig.5).



a) b)

Figure 5. Distribution map of approximated points (a) and points with values of horizontal motion velocities (b) according to GPS data of stations

Next, we plotted the epicenters of strong earthquakes (ml>3.0) for the period 2012-2022 years on the resulting grid of horizontal motion velocities. This transformation allowed us to match the depths of the hypocenters to the velocities. The k-nearest neighbor algorithm (k-NN) was used to select blocks. It is a metric algorithm for automatic object classification or regression. In the case of using the method for classification, the object is assigned to the class that is the most common among the neighbors of this element, whose classes are already known. In the case of using the method for regression, the object is assigned the average value of the objects closest to it, the values of which are already known. Having identified 4 depth intervals, we built spatial maps of the distribution of velocities with the selection of blocks (Fig.6).

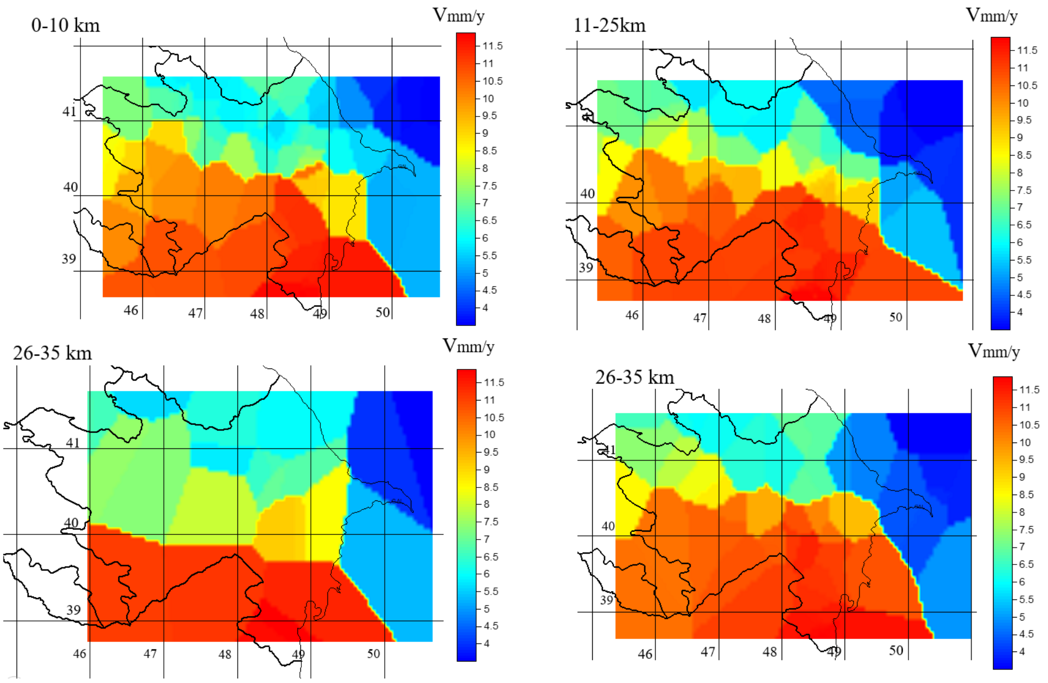


Figure 6. Map of tectonic blocks selected according to the data of GPS stations at different depth intervals

It was found that in the Guba-Gusar region in the direction NW-SE at a depth of 5 to 40 km, a block with velocities of 5.8 mm/y with a length of 55 km is distinguished. On the depth profile of Zakatala-Gobustan (NW-SE) in the southeast direction at an epicentral distance of 20 to 250 km, a gradual subsidence of the tectonic block is observed with velocities of 6.25 mm/y from a depth of 20 to 55 km. In the zone of the West-Caspian fault at depths from 5 to 35 km, a block boundary is distinguished with velocities of 7.25 mm/y. On the eastern side of this block, a block is distinguished at depths of 10–25 km with values of 9 mm/y.

In the direction from the Middle Kura depression to the Low Kura at an epicentral distance of 150 km in the depth interval of 10-30 km, a block with velocities of 7.85 mm/y was noted, then in the depth interval of 15-38 km - a block with velocities of 9,2-9,6 mm/y, and within the Lower Kura at a depth of 15-40-50 km, a block with velocities of 11-11.9 mm/y was identified. In the Lesser Caucasus, a block with high seismic activity is observed in the depth interval of 20-40 km with velocities of 10,7-11,4 mm/y. In the Talysh region, in the direction from the NNW to the SSE, the activation noted over the entire depth from 5-60 km gradually subsides to 40 km. In the south of this region, a block with maximum velocities of 11,5-12 mm/y and a length of 50 km, the depth of which varies from 20 to 40 km, is divided by a block with velocities of 11-11,3 mm/y.

Results:

Comparison of the measurement data obtained from GPS stations shows that the stations located in the Lesser Caucasus and in the zone of the Talysh Mountains move in the northeast direction almost identically. These facts allow us to state that the Lesser Caucasus and Talysh participate in the horizontal movement as a single bloc. On the other hand, the stations located on the territory of the Talysh Mountains are characterized by high horizontal movement rates, which allow us to delineate this region with average horizontal movement rates of 11.6 mm/year.

The velocity field clearly illustrates the movement of the earth's surface in the N-NE direction. 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 (Vandam-Gobustan megazone) with the accretionary prism of the Greater Caucasus.

In addition, within the Middle Kura depression and in the Lesser Caucasus, there is a trend towards horizontal displacement, which is reflected in an increase in the speed 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 shortening at a rate of ~ 5 mm/yr.

Based on the correlation of GPS data and hypocenters of strong earthquakes, the boundaries were identified and the depths of occurrence of active tectonic blocks in the areas of the southeastern subsidence of the Greater Caucasus, the Kura depression and the Talysh zone of Azerbaijan were determined. In the Guba-Gusar region in the direction NW-SE at a depth of 5 to 40 km, a block with velocities of 5.8 mm/g and a length of 55 km is distinguished. On the depth profile of Zakatala-Gobustan (NW-SE) in the southeast direction at an epicentral distance of 20 to 250 km, a gradual subsidence of the tectonic block is observed with velocities of 6.25 mm/y from a depth of 20 to 55 km. In the zone of the West Caspian fault at depths from 5 to 35 km, a block boundary is distinguished with velocities of 7.25 mm/y. On the eastern side of this block, a block is distinguished at depths of 10–25 km with values of 9 mm/y.

In the direction from the Middle Kura depression to the Low Kura at an epicentral distance of 150 km in the depth interval of 10-30 km, a block with velocities of 7.85 mm/y was noted, then in the depth interval of 15-38 km - a block with velocities of 9,2-9,6 mm/y, and within the Lower Kura at a depth of 15-40-50 km, a block with velocities of 11-11.9 mm/y was identified. In the Lesser Caucasus, a block with high seismic activity is observed in the depth interval of 20-40 km with velocities of 10,7-11,4 mm/y. In the Talysh region, in the direction from the NNW to the SSE, the activation noted over the entire depth from 5-60 km gradually subsides to 40 km. In the south of this region, a block with maximum velocities of 11,5-12 mm/y and a length of 50 km, the depth of which varies from 20 to 40 km, is divided by a block with velocities of 11-11,3 mm/y.

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