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Redefinition of Earthquake Hypocenters by the Double Difference Method

S. E. Kazimova

Republican Seismic Survey Center, National Academy of Sciences of Azerbaijan
123 Guseyn Javid Str., Baku 1001, Azerbaijan, e-mail: sabina. k@mail. ru

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Abstract: Relevance. In the last decade, significant advances have been made in the theory and application of seismic tomography. These include refinements in model parameterization, 3D ray tracing, an inversion algorithm, sharing local, regional, and teleseismic data, and adding transformed and reflected waves to tomographic inversion. Explorations have shown that with the help of seismotomography it is possible to obtain reliable data on the deep structure of the Earth, its thickness, the mutual arrangement of layers, as well as tectonic structures identified in the earth's crust. Due to a significant increase in the number of seismic stations in the Republican Seismic Survey Center and equipping them with modern instruments of the MacOs system (made by "Kinemetrics"), it was possible to obtain a large volume of observed seismic material and solve rather complex methodological issues, which is relevant today. **The aim** of this article is to redefine the data of the hypocenters of earthquakes that occurred on the territory of Azerbaijan for the period 2010-2019 (ml>2.0) and calculate the velocity model of the earth's crust using algorithms that are not included in the mandatory processing when compiling a catalog of seismic events. The catalog data were taken from the "Bureau of Earthquake Research" of the Republican Seismic Survey Centerof Azerbaijan National Academy of Sciences. **Research methods**. Within the framework of present work, using the double difference method, we redefined the location of seismic events, showing that the obtained positions of the epicenters are lined up in systems of linear chainsalong the main and feathering faults, which is consistent with the relief and geological concepts. **Results**. Comparing the values of the velocities with the values of the one-dimensional velocity model, it was found that at depths of 5-10 km, there is good convergence in the regions of the Greater Caucasus. The middle Kura depression is mainly characterized by low velocities compared to the one-dimensional velocity model. At a depth of 15 km, the eastern part of the Middle Kura depression is characterized by good convergence, but in the western part high velocities are noted. The maximum convergence of velocities was noted at a depth of 35 km.

Keywords: seismic tomography, double difference method, travel times of seismic waves.

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ГЕОТЕКТОНИКА И ГЕОДИНАМИКА

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Оригинальная статья

Уточнение гипоцентров землетрясений методом двойной разности

С. Э. Казымова

Республиканский Центр Сейсмологической Службы, Национальная Академия Наук Азербайджана, Республика Азербайджан, 1001, Баку, ул. Гусейн Джавида, 123, e-mail: sabina. k@mail. ru

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Резюме: Актуальность работы. В последнее десятилетие были достигнуты значительные успехи в теории и применении сейсмотомографии. К ним относятся уточнения в параметризации модели, трассировка трехмерных лучей, алгоритм инверсии, совместное использование локальных, региональных и телесейсмических данных, а также добавление преобразованных и отраженных волн в томографическую инверсию. Исследования показали, что с помощью сейсмотомографии можно получить достоверные данные о глубинном строении Земли, ее толщине, взаимном расположении слоев, а также о тектонических структурах, выявленных в земной коре. Благодаря значительному увеличению числа сейсмических станций в РЦСС, оснащению их современными приборами системы MacOs (фирсы «Кинеметрикс»), удалось получить большой объем наблюденного сейсмического материала и решить довольно сложные методические вопросы, что является актуальным на сегодняшний день. **Целью** данной статьи является переопределение данных гипоцентров землетрясений произошедших на территории Азербайджана за период 2010-2019 гг. (ml>2,0) и вычислению скоростной модели земной коры с использованием алгоритмов, не входящих в обязательную обработку при составлении каталога сейсмических событий. Данные каталога были взяты в «Бюро исследований землетрясений» РЦСС при НАНА. **Методы исследования.** В рамках данной работы методом двойных разностей мы переопределили положения сейсмических событий, показав, что полученные положения эпицентров выстраиваются в системы линейных цепочек, положение которых согласуется с рельефом и геологическими представлениями, располагаясь вдоль главного и оперяющих разломов. **Результаты работы.** Сопоставляя значения скоростей со значениями одномерной скоростной модели, установлено что на глубинах 5-10 км наблюдается хорошая сходимость в областях Большого Кавказа. Среднекуринская депрессия в основном характеризуется малыми скоростями по сравнению с одномерной скоростной моделью. На глубине 15 км восточная часть Среднекуринской депрессии характеризуется хорошей сходимостью, однако в западной части отмечены завышенные скорости. Максимальная сходимость скоростей отмечена на глубине 35 км.

Ключевые слова: сейсмическая томография, метод двойных разностей, времена пробега сейсмических волн.

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Introduction

One of the main tasks in processing seismological observation data is to maximize the accuracy of determining the spatial position and mechanisms of earthquake sources. Among the main parameters of the focus, the most interesting is the depth of the hypocenter, which, as a rule, is determined with the least accuracy. Knowledge of the exact spatial position of the foci makes it possible to reveal their connections with the features of the deep structure of the earth's crust, primarily with active faults – the main zones of generation of destructive earthquakes [Konovalov et al., 2007; Solov'ev et al., 2003].

Studies of recent decades show that seismic methods are the main and most reliable in the study of the internal structure and physical properties of the Earth. These methods, in turn, are divided into two groups:

1) methods based on the use of the arrival times of body waves arising from earthquakes and explosions;

2) methods based on the use of the spectral properties of seismic waves and, in particular, the dispersion of the velocities of Rayleigh and Love surface waves.

Seismic tomography is an imaging technique that uses seismic waves generated by earthquakes and explosions to create 3D images of the interior of the Earth. If the Earth had a uniform composition and density, seismic rays would travel in straight lines. But our planet has a multilevel structure, as a result of which seismic rays propagating through various boundaries are refracted and reflected.

In the last decade, significant advances have been made in the theory and application of seismic tomography. These include refinements in model parameterization, 3D ray tracing, an inversion algorithm, sharing local, regional, and teleseismic data, and adding transformed and reflected waves to tomographic inversion. Studies have shown that with the help of seismotomography it is possible to obtain reliable data on the deep structure of the Earth, its thickness, the mutual arrangement of layers, as well as tectonic structures identified in the earth's crust. Owing to a significant increase in the number of observation points, equipping them with modern instruments, as well as the progress of computer technology, it was possible to obtain a large amount of observational material and solve rather complex methodological issues. Tomographic images of faults in earthquake zones, in regions such as Japan and California, show that the processes of initiation of ruptures and earthquakes are closely related to inhomogeneities of crustal materials and inelastic processes in fault zones, such as fluid migration.

The first works in the field of studying seismic tomography from body wave data belong to K. Aki and Lee V. [Aki et al., 1977; Aki, Lee, 1976] for the local and regional scale, and also A. Dzevonski [Dziewonski, 1984; Dziewonski et al., 1977] for the global scale. Surface wave tomography was initiated by Y. Nakanisi and D. Anderson [Anderson, Dziewonski, 1984], J. Woodhouse and A. Dzewonski [Woodhouse, Dziewonski, 1984] and T. Tanimoto and D. Anderson [Tanimoto, Anderson, 1984]. Surface wave tomography is more suitable for large-scale regional studies.

The purpose of this article is to redefine the data of the hypocenters of earthquakes that occurred on the territory of Azerbaijan for the period 2010-2019. (ml> 2.0) and calculation of the velocity model of the earth's crust using algorithms that are not included in the mandatory processing when compiling a catalog of seismic events.

Thus, due to a significant increase in the number of seismic stations in the RCSS, equipping them with modern instruments of the MacOs system (firms "Kinemetrix"), it was possible to obtain a large amount of observed seismic material and solve rather complex methodological issues, which is relevant today.

Double Difference Method (TomoDD)

The method of seismic tomography with double differences, or as it is commonly called DD tomography, allows one to analyze and compare the obtained velocity model and the positions of the hypocenters of the aftershock sequence with block-dividing faults and discontinuous deformations mapped on the surface.

The double difference method [Konovalov et al., 2007; Shikhalibeyli et al., 1956; Waldhauser, Ellsworth, 2001] is effective for joint redefinition of hypocenters in the case of a set of closely spaced foci and allows simultaneous redefinition of the locations of a large number of earthquake hypocenters at relatively large distances from the observing stations. In this case, the difference in the travel times of a wave from two close events is determined by the difference in the position of the hypocenters of these events. Thus, it is possible to refine the distance between events without using station corrections.

If the distance between the hypocenters of two earthquakes is small in comparison with the distance between the earthquake sources and the station, as well as the wavelength, then the ray paths from the source region coincide throughout almost the entire ray. In this case, the difference in travel times for the two observed events can be attributed to the spatial difference in the location of the sources. Let's formalize this approach. The calculated arrival time (P- or S-waves) from the i-th earthquake, observed at the k-th seismic station, is expressed, in the framework of ray theory, as the integral of the path along the ray:

$$T_k^i = \tau_0^i + \int_i^k uds, \tag{1}$$

where is the time at the source of the ith event, u is the deceleration field along the ray path, and ds is the path length element. Due to nonlinear relationships between travel times and positions of earthquakes, in the general case, truncated Taylor series [Geiger, 1912] are used to linearize equation (1). In this case, the difference in travel times for the ith event is linearly related to the disturbances Δm i (to the four current hypocentral parameters Δx i, Δy i, Δz i, Δt i for each observed 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 measured and calculated travel times, respectively, and $\Delta m^i = (\Delta x^i, \Delta y^i, \Delta z^i, \Delta\tau^i)$. Equation (2) is used in conjunction with the measured arrival times. However, cross-correlation methods determine the difference in arrival times between events $\left(t_k^i - t_k^j\right)^{obs}$, therefore equation (2) cannot be used directly. Considering the difference between equations (2) for a pair of events, the equation for the relative differences between the hypocenters of earthquakes i and j can be written in the form

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

where $(\Delta m^{ij} = (\Delta dx^{ij}, \Delta dy^{ij}, \Delta dz^{ij}, \Delta d\tau^{ij})$ – change in relative positions between two hypocenters i and j, partial derivatives of T with respect to m are the components of the slowness vector along the ray connecting the source and the receiver, measured at the source [Aki, Richards, 1983]. The system of linear equations (2) with four unknowns Am ' (three hypocentral parameters and time at the source) is solved by the least squares method using an iterative approach. First, a solution is set in the form of calculated travel times for the phases under consideration (in a certain region where the source is supposedly localized), which is then checked to find corrections to the initially specified position, then the corrected solution is the input, etc. This method was first proposed by Geiger [Geiger, 1912]. The iterative process usually converges quickly if the initial determination of the hypocenter is close to the true location. The calculations mainly use a one-dimensional velocity model of the structure of the earth's crust. The accuracy of determining the coordinates of hypocenters depends on the geometry of the network, available phases, the accuracy of measuring the arrival times and the velocity model of the structure of the earth's crust [Gomberg et al., 1990; Pavlis, 1992]. Using a one-dimensional velocity model to determine coordinates limits accuracy, as three-dimensional variations in seismic velocities can introduce systematic biases in the calculated travel times. Partial consideration of the velocity variation is possible by making a station correction to the calculation algorithm or to the velocity model of the earth's crust [Douglas, 1967; Douglas, 1967; Pujol, 1988].

One-dimensional velocity model

To calculate the velocity along the entire path of propagation of the wave beam, the time required for the seismic wave to arrive at the seismic station after the earthquake is used. Using the arrival times of various seismic waves, areas of slower (where waves slow down) or faster velocity zones at different depths of the Earth are determined. Various properties of the earth's crust control the speed and absorption of seismic waves. Seismic waves travel at speeds of several kilometers per second on Earth, with compression waves (P-waves) about 1.75 times faster than shear waves (S-waves). In addition, seismic wave velocities vary with the type and density of the rock.

With the advent of a denser network of digital stations on the territory of Azerbaijan, it became possible to apply techniques that allow obtaining more accurate solutions for local observations of individual seismogenic zones. The accuracy of determining the positions of hypocenters in the earth's crust can be increased by improving the one-dimensional velocity model of the earth's crust embedded in the algorithms. It is thanks to the velocity model that we can calculate the travel time of waves and the distance from the source to the seismological station [Yemanov et al., 2003]. At the same time, the discrepancy between the velocity model and the real environment introduces, perhaps, the biggest error in the calculation of the coordinates of seismic events. To clarify the position of the earthquake hypocenters in our previous works, we used the Velest program. [five]. To this end, we introduced a more accurate layered velocity model into the calculations, which made it possible to obtain more accurate absolute solutions. In this work, we used the double difference method, which is not very sensitive to the parameters of the model and gives a fairly accurate relative solution. The layered model presented in Table 1 was used as a reference model.

Results of redetermination of earthquake hypocenters by the double difference method

We have performed redefinition of the position of seismic events by the method of double differences [Yemanov et al., 2003; Poupinet et al., 1984; Waldhauser, Ellsworth, 2000]. The method of double differences gives a very accurate relative solution, that

Table 1

One-dimensional velocity model used in calculating hypocenter positions

Depthinterval, km	Density, g / cm^3	P-wave velocity, km / s	S-wave velocity, km / s
3	2.3	3.88	2.25
5	2.4	4.21	2.57
7	2.5	4.38	2.57
10	2.7	5.9	3.26
15	2.9	6.4	3.55
23	2.9	6.68	3.82
34	3.0	7.09	3.97
44	3.0	7.35	3.97
50	3.0	7.52	4.64
60	3.3	8.52	4.79

is, after the redefinition, the relative positions of events are established very accurately, while the entire redefined cluster can move to the side. This method arranges the scattered initial epicenters into narrow linear zones [Gol'din et al., 2003]. The calculations involved only those events that have a sufficient number of joint observations with neighboring events, i. e. at least 8 joint observations for each pair of events.

Thus, the relative position of 2572 events was redefined. The catalog of earthquakes was taken from the "Bureau of Earthquake Research" of the RCSS at ANAS. For redefinition, only data from the catalog of events and arrival times were used; cross-correlation differences in the travel times of seismic waves were not used.

We present hypocentral solutions that were made with the HYPODD program [Waldhauser, 2000] using a velocity model obtained from seismic tomography data [Kazimova, Kazimov, 2017]. This technique is used for the first time to determine hypocenters in the territory of Azerbaijan. Note that for both P and S waves we used only the first wave arrivals, the interpretation of whether the wave is direct or refracted (head) depends entirely on the velocity model. The technique used in standard processing has some advantage in this sense: it uses both forward and head waves. This advantage manifests itself in the case of a sparse regional network of stations, where, for a seismic event, most stations are located at a distance at which the head wave appears.

In the calculations, a rough approximation of the solution is first calculated using all data and a fixed depth, then it begins to be refined iteratively. When an accurate epicentral solution is reached, the depth is released and depth determination begins. In the course of calculations, at a given iteration, filtering and weighting of data is turned on by two parameters: by residual and distance [Yemanov et al., 2011; Telesca et al., 2018]. When weighting by distance, at a certain iteration, observations at stations located further than a certain distance from the epicenter are removed from the calculations, and the rest of the data are weighed. We used 250 kilometers as the cut-off distance, only in some cases we increased it to capture more stations.

Figures 2 and 3 show the definitions of earthquake epicenters in the territory of Azerbaijan before and after processing.

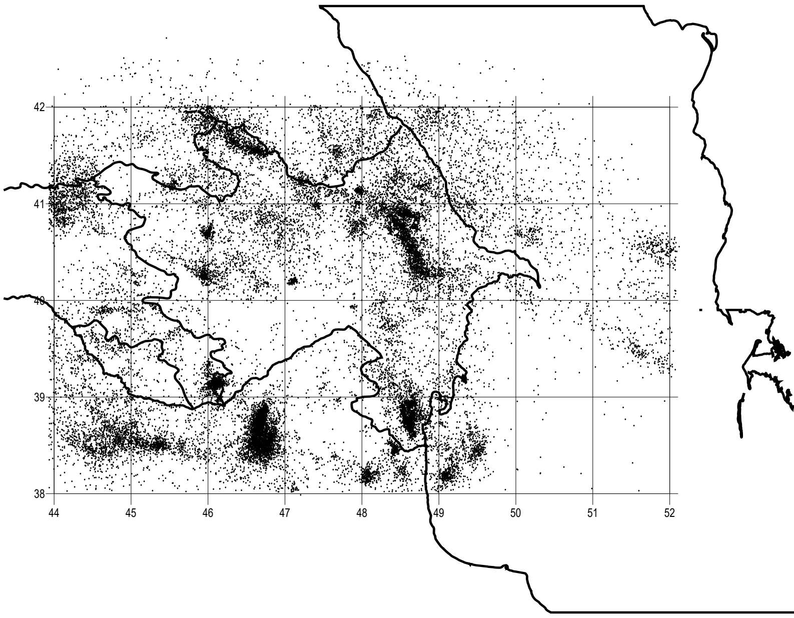

Fig. 2. Map of the epicenters of earthquakes obtained by the standard processing method

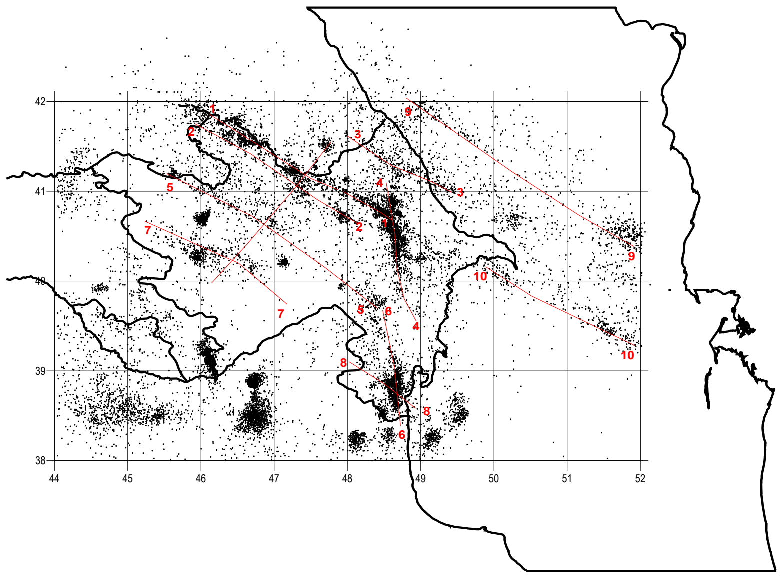

Fig. 3. Redefining the positions of hypocenters by the method of double differences. Fault tectonics based on [Kengerli, 2007; Shikhalibeyli, 1956].
Tectonic faults: 1 – Dashgil-Mudresa; 2 – Vandam; 3 – Siyazan; 4 – West Caspian; 5 – Kura; 6 – Astara-Derbend; 7 – Pre-Lesscaucasian; 8 – Pre-Talysh; 9 – Makhachkala-Krasnovodsk; 10 – Sangachal-Ogurchu.

Figure 3 shows how the accuracy of the resulting solution improves and how linear structures begin to emerge. So, the positions of the epicenters obtained by the method of double differences are aligned linearly or pointwise, and this linearity is consistent with the relief and geological representations. In the southern part of the region, the seismogenic zones of northern Iran and Talysh are well localized. In the zone of the Greater Caucasus, NW to SE, a zone of foci is formed corresponding to the Vandamand Dashgil-Mudresa longitudinal tectonic faults. In the Shamakhi-Ismailli zone, there is an area crossing the

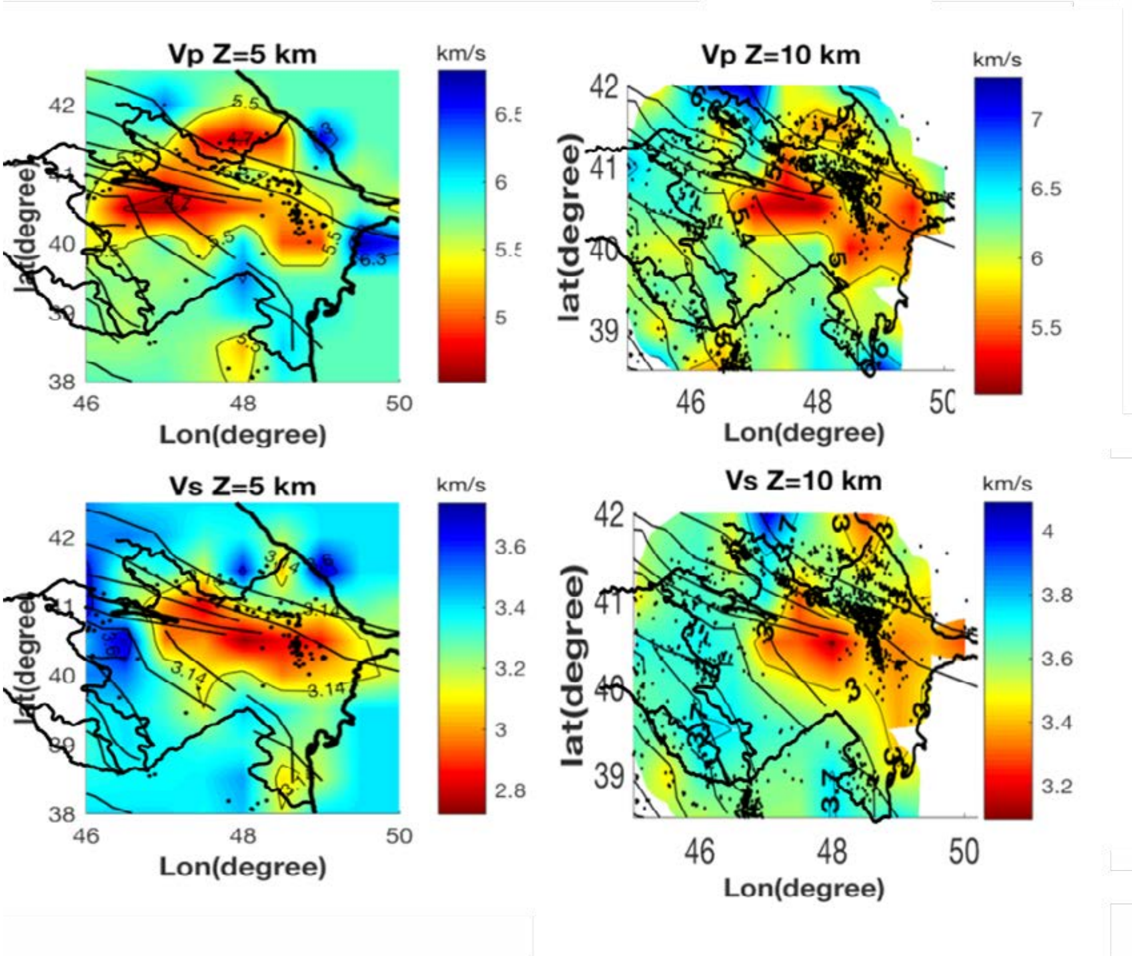

Fig. 4. Horizontal sections of the spatial velocity model at the depths of the earth's crust 5-10 km (Compiled by R. D. Kerimova).

Vandam fault, corresponding to an active orthogonal West Caspian fault. Then, using the algorithms of the TomoDD program, spatial velocity models were calculated (Fig. 4-5).

At the depth of 5 km, the region of minimum velocities is noticeably distinguished – the Vandamand Zakatala-Kovdag zones of the Greater Caucasus and the Pre-Caucasian zone of the Middle Kura depression, characterized by the values of P-wave velocities of 4.5-5.5 km/s. Despite the fact that at a depth of 10 km the values of velocities increase, however, the general trend of velocity anomalies remains. Basically, the territory of the Middle Kura depression is characterized by P-wave velocities of 5.9-6.1 km/s. The figure clearly shows two intervals of speeds. The zone of the Less Kura megazone, as well as the eastern part of the Vandam and Zagatala-Kovdag zones of the Greater Caucasus, are characterized by the values of the P-wave velocities of 5.5 km/s. The zone of Sheki and Zakatala-Balakan and Nakhchivan regions was distinguished by the maximum values of velocities, with the values of the velocities of longitudinal waves 6.5-7.0 km/s.

In fig. 5 shows a horizontal cross-section of the velocity distribution at a depth of 15 and 17.5 km. As seen in the figure, the distribution of velocities has a mosaic character. At a depth of 15 km, the zone of maximum values in the Sheki region has expanded and is widespread (7.0 km/s). The central part of the Vandam and Zakatala-Kovdag zones of the Greater Caucasus, as well as the border zone with Dagestan, characterized by the velocities of longitudinal waves of 5.5-6.0 km/s, are marked with the minimum values.

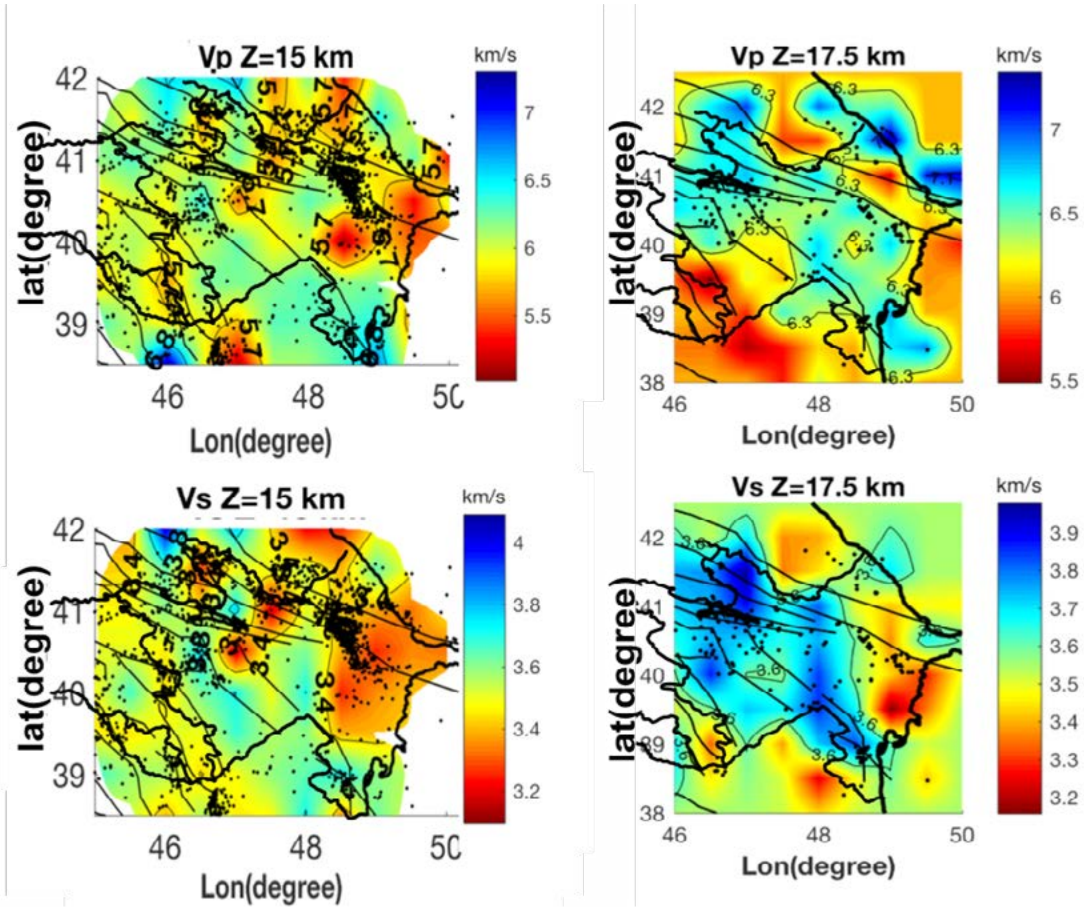

Fig. 5. Horizontal sections of the spatial velocity model at the depths of the earth's crust 15-17.5 km. (Compiled by R. D. Kerimova)

Conclusions

Comparing the values of the velocities with the values of the one-dimensional velocity model, it was found that at depths of 5-10 km, there is good convergence in the regions of the Greater Caucasus. The middle Kura depression is mainly characterized by low velocities compared to the one-dimensional velocity model. In the depth interval of 7-10 km, the roof of the pre-Alpine basement is revealed. In this interval, a decrease in velocity is observed in the Evlakh-Agdzhabedi and Kurdamir-Saatli zones of the Middle Kura depression, which indirectly confirms the fracturing of rocks and the presence of a decompaction zone. At a depth of 15 km, the interface between the two media is also revealed. The velocities in this interval increase from 6.2 km / s to 7.0 km/s. According to the literature, the velocities of 6.0-6.2 km/s correspond to edges, and 6.5-7.6 are characteristic of basalts. As you can see in the figures, different parts of the region are characterized by different speeds. However, the regularity of the distribution of speeds in general for the region is observed. It is important to note that not all velocity boundaries in the volcanic strata are determined by the change in the material composition of the rocks. Some boundaries are associated with different stressed state of matter at depth, with the superposition of secondary processes of metamorphism, with a change in the physical state of matter, they can be caused by rheological stratification. It can be noted that these depths reflect the surface of the substrate, formed over most of the region under consideration from metamorphosed rocks of the pre-Alpine basement, and in some areas from consolidated volcanic and metamorphosed rocks of the Mesozoic. In the depth interval of 17-25 km, the top of the basalt layer of the earth's crust is revealed. At a depth of 35 km, the Moho border. Based on the data obtained, it can be noted that the first interval from 5 to 17 km is associated with the boundary of the Kainazoi and Mesazoic deposits in the sedimentary cover, the second (17-25 km) – with the top of the consolidated part of the earth's crust (granite layer), the third (25-35 km) – refers to the basalt layer, the fourth (> 35 km) is associated with the upper boundary of the Moho (8-8.5 km/s).

In the course of the calculations, a modern improved approach to modeling the velocity field in the crust and upper mantle of the territory of Azerbaijan was applied, including the selection of data, determination of the optimal one-dimensional model, recalculation of the earthquake hypocenters relative to the found optimal one-dimensional model and the calculation of the spatial velocity model. The applied data processing system provided for the verification of compliance with the selection criteria before the calculations and during the calculations, which made it possible to reduce the a priori error introduced by the data into the solution.

References

1. Aki K., Richards P. Quantitative seismology. Theory and methods. In 2 volumes. Translated from English. Moscow. Mir, 1983, 880 p. (In Russ.)

2. Gol'din S. V., Seleznev V. S., Emanov A. F., Filina A. G. et al. Chuya earthquake of 2003 (M = 7.5). Online scientific information journal "Bulletin of the Department of Earth Sciences RAS". 2003. No. 1 (21). URL: http://www. scgis. ru/russian/cp1251/h_dgggms /1-2003/screp-7. pdf (In Russ.)

3. Emanov A.F., Leskova E.V. et al. Aftershock process of the Chuya earthquake of 27.09.2003. Dynamics of the physical fields of the Earth. 2011. pp. 173-185. (In Russ.)

4. Yemanov A.A., Valdhauser F., Leskova E.V. Application of the method of double differences to refine the coordinates of seismic events. In: Problems of seismology of the 111th millennium. Proceedings of int. geoph. conf. (Novosibirsk, September 15-19, 2003). Novosibirsk. Pub. SB RAS, 2003. pp. 161-168. (In Russ.)

5. Kazimova S.E., Kazimov I.E., Influence of one-dimensional velocity models on the determination of the main parameters of earthquake sources in Azerbaijan, Physics of the Earth, "Nauka", 2017, No.. pp. 72-86. (In Russ.)

6. Kengerli T.N. Features of the geological and tectonic structure of the Southeastern Caucasus and issues of oil and gas content. Elmiəsərlər (State Oil Company of the Republic of Azerbaijan). 2007. No. 9. pp. 3-12. (In Russ.)

7. Konovalov A.V. et al. The structure and features of the seismic regime of the focal zone of the Takoy earthquake of September 1, 2001 (M w 5.2). Pacific Geology. 2007. Vol. 26. No. 2. pp. 93-101. (In Russ.)

8. Solov'ev V. M., Seleznev V.S., Duchkov A.D., Liseikin A.V. Deformation-strength zoning of the earth's crust of the Altai-Sayan folded region. In: Problems of seismology of the 3rd millennium. Proceedings of the int. geoph. conf., Novosibirsk, 15-19 Sept. 2003 Novosibirsk, Publ. SB RAS, 2003. (In Russ.)

9. ShikhalibeyliE. Sh. Geological structure and development of the Azerbaijan part of the southern slope of the Greater Caucasus. Baku. Academy of Sciences of Azerbaijan SSR, 1956. 218 p. (In Russ.)

10. Aki K., Christoffersson A., Husebye E. Determination of the three-dimensional seismicstructure of the lithosphere. Journal of Geophysical Research, 1977. Vol. 82. pp. 277-296.

11. Aki K., Lee W. Determination of three dimen-sional velocity anomalies under a seismic array usingfirst P arrival times from local earthquakes, 1, Ahomogeneous initial model. Journal of GeophysicalResearch, 1976. Vol. 81. pp. 4381-99.

12. Anderson D., Dziewonski A. M. Seismictomography. Scientific American, 1984. Vol. 251. pp. 60-80.

13. Douglas A. Joint epicenter determination. Nature, 1967. Vol. 215. pp. 47-48.

14. Douglas A., Bowers D., and. Young J. B. On the onset of P seismograms. Geophys. J. Int., 1997. Vol. 129. pp. 681-690

15. Dziewonski A., Hager B., O'connell R. Large-scale heterogeneities in thelower mantle. Journal of Geophysical Research, 1977. Vol. 82. pp. 239-55

16. Dziewonski A. M. Mapping the lower mantle: determinationof lateral heterogeneity in P velocityup to degree and order 6. Journal of Geophysical Research, 1984. Vol. 89. pp. 5929-52.

17. Geiger L. Probability method for determination of earthquake epicenters from the arrival times only. Bul. St. Louis Univ, 1912. Vol. 8. pp. 60-71.

18. Gomberg J. S., Shedlock K. M., and Roecker S. W. The effect of S-wave arrival times on the accuracy of hypocenter estimation. Bull. Seism. Soc. Am., 1990. Vol. 80. pp. 1605-1628.

19. Paige C. C., Saunders M. A. LSQR: An algorithm for sparse linear equations and sparse least squares. ACM Transactions on Mathematical Software (TOMS), 1982. T. 8. No. 1. pp. 43-71.

20. Pavlis G. L. Appraising relative earthquake location errors. Bull. Seism. Soc. Am., 1992. Vol. 82. pp. 836-859.

21. Poupinet G., Ellsworth W. L., and Fre´chet J. Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras fault, California. J. Geophys. Res., 1984. Vol. 89. pp. 5719-5731.

22. Pujol J. Comments on the joint determination of hypocenters and station corrections. Bull. Seism. Soc. Am., 1988. Vol. 78. pp. 1179-1189.

23. Tanimoto T., Anderson D. Mapping convection in the mantle. Geophysical Research Letters, 1984. Vol. 11. pp. 287-90.

24. Telesca L., Kadirov F., Yetirmishli G., Safarov R., Kazimova S. Joint Use of Seismological and Topological Statistical Methods for the Analysis of 2010-2016 Azerbaijan Seismicity. Pure and Applied Geophysics, On-line, 2018. Vol. 175. pp. 4225-4239

25. Waldhauser F., Ellsworth W. L. A double-difference earthquake location algorithm: Method and application to the Hayward Fault, California, Bull. Seism. Soc. Am., 2000. Vol. 90. pp. 1353-1368

26. Waldhauser F., Ellsworth W. L. HypoDD – A Program to Compute Double-Difference Hypocenter Locations. US Geological Survey, Open-File Report, 2001. 113 p.

27. Woodhouse J., Dziewonski A. Mapping the upper mantle: three-dimensional modeling of earthstructure by inversion of seismic waveforms. Journal of Geophysical Research, 1984. Vol. 89. pp. 5953-86.