CHANGES IN COULOMB STRESSES AFTER STRONG EARTHQUAKES OCCURRED IN THE TERRITORY OF THE GREATER CAUCASUS FOR THE PERIOD 2012-2021

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Introduction

In the last decade, significant progress has been made in research related to the interaction of faults and how the occurrence of an earthquake perturbs the stress field in its vicinity, which can cause aftershocks and subsequent earthquakes. These studies are of great importance for assessing the seismic hazard of the region, since voltage changes can either delay or accelerate the occurrence of future earthquakes. In addition, since the seismic hazard assessment depends on the destruction parameters of past earthquakes, it is important to reliably estimate such parameters, viz. rupture location, geometry and extent of past earthquakes [11].

For many years, the territory of the Republic of Azerbaijan was characterized by high seismic activity. From a tectonic point of view, this is due to the dynamics of the Caucasus region, which is under the influence of the Arabian and Eurasian lithospheric plates.

It should be noted that since 2012, a number of strong earthquakes with Ml≥5.0 have been occurring on the territory of the republic. In 2012 and, after some lull, in 2014-2018. a series of strong earthquakes occurred here: Zagatala on May 7, 2012 with Ml=5.6, 5.7, Balakan on October 14, 2012 with Ml=5.8, which were felt in the epicenter with J0=7 b.; Ismayilli 07.10.2012 with Ml=5.3; Caspian 10.01.2014 with Ml=5.0, Hajigabulskoe 10.02.2014 with Ml=5.8, Zagatala 29.06.2014 with Ml=5.3, Gabala series 29.09 and 04.10.2014 with Mlmax=5.5; as well as Okhuz on September 4, 2015 with Ml=5.9, Imishli on August 1, 2016 with Ml=5.6, Lerik on August 28, 2018 with Ml=5, etc. The intensity of shaking in some of them at the epicenter reached 7 points. An analysis of the spatial distribution of epicenters shows that most of the sources of perceptible earthquakes are located in the zone of the junction of the Kura depression and the southeastern subsidence of the Greater Caucasus or the activation of the southern side of the Kura depression in the zone of transition to the fold system of the Lesser Caucasus [1].

With the deployment of regional and local networks of digital seismological stations and the accumulation of data, in the conditions of intensive growth of computer technologies, seismologists face completely new opportunities and prospects in studying the physics of earthquakes and seismic hazard prediction. In particular, an extensive instrumental database of digital data on earthquakes, including weak ones with M<2, makes it possible to study in detail the fine structure of the spatial and temporal distribution of sources, their energy characteristics, and to reveal the relationship of seismic processes with the features of the deep structure of the region and the seismotectonic setting.

Knowledge of the seismic moment tensors of the sources makes it possible to study the dynamics of seismic activity, taking into account the seismotectonic and structural-geological conditions of the region within the framework of deterministic models of the seismic flow of rock masses [5, 13, 16] or the interaction of faults, which use, for example, the concept of transfer of the dropped Coulomb stress on neighboring faults [6]. In turn, further quantitative development and experimental verification of these dynamic models in different seismotectonic conditions are of direct practical importance for the creation of methods for reliable earthquake prediction and an objective quantitative assessment of seismic hazard.

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Coulomb stresses

A change in the stress state can be critical in relation to the initiation of large technogenic earthquakes, we will consider using the approach used in seismology when analyzing aftershock sequences of large earthquakes [7]. According to this approach, a change in the stress field, as it were, "pushes" the neighboring fault somewhat closer to the threshold of Coulomb destruction. This process is often described by estimating the variation of the so-called Coulomb function on a site oriented in a certain way

$$\sigma_c=\tau-\mu(\sigma_n-p), \qquad (1)$$

where σ_n and τ - normal and tangential stresses to the fault plane; p is the pore pressure; μ is the coefficient of friction. At the stage of preparing a dynamic breakdown $\sigma_c<0$. In the case of an increase in shear stress τ or a decrease in effective normal stress (σ_n-p), the fault approaches the critical state $\sigma_c=0$. Although it is rather difficult to determine stress values at seismogenic depths in natural conditions, it is possible to estimate the stress change and, using this estimate, calculate the change in shear and normal stresses on nearby discontinuities. Thus, even without knowing the absolute values of stresses, one can calculate the change in the Coulomb function using the incremental equation

$$\Delta\sigma_c=\Delta\tau-\ \mu\ (\Delta\sigma_n\ -\Delta p) \quad (2)$$

from which it can be understood whether the fault was brought closer to the critical state (positive increment $\Delta\sigma_c>0$), or, conversely, moved to a more stable state ($\Delta\sigma_c<0$). Note that these calculations do not require information about the stress zone in the region and do not consider stress fields from other sources. The Coulomb theory of initiation has become widespread, being one of the popular explanations for the fact that earthquake aftershocks manifest themselves not only within the fault zone, but also in neighboring areas [2, 3]. Usually, the best correspondence between the change in the Coulomb stress and the distribution of aftershocks is observed at distances exceeding several kilometers from the earthquake fault, since the unknown details of the distribution of displacements and geometry play a significant role closer.

An important result of the research is the presence of negative Coulomb stresses for a large part of the faults, which are actually considered active in recent times. If the Coulomb stresses are greater than zero (≥ 0), then this means that the given stress state is above the dry friction line - the crack can become active. If they are close to the brittle strength limit, then crack activation becomes the most probable. Negative values of the Coulomb stresses mean the excess of friction forces over shear stresses on cracks

Based on the above, we constructed and analyzed the distribution of Coulomb stresses for the Zakatala, Gabala and Ismayilli earthquakes. The model parameters are set according to the two-dipole approximation of the seismic moment tensor [4]. The calculations were made in the Coulomb 3.3 program. [8] for depths of 8-12, 42 km, the friction coefficient is assumed to be $\mu' = 0.4$.

Influence of change in stress state on trigger seismicity

As mentioned above for the period 2012-2021. Several strong earthquakes with magnitude ml > 5.0 occurred in the Azerbaijan territory of the Greater Caucasus. In this article, we examined the most significant of them, namely: the Zakatala earthquake of 2012, the Balakan earthquake of 2012, the Gabala earthquake of 2014, the Okhuz earthquake of 2015 and the Ismayilli earthquake of 2012-2021. Let's consider each earthquake separately.

On May 7, 2012 in the Zakatala region with an interval of about 10 hours (t0=04h40m and t0=14h15m GMT) earthquakes with magnitudes of 5.6 and 5.7, respectively, occurred, characterized by intense aftershock (magnitude 3.5-5.0) activity.

According to instrumental observations, the coordinates of the earthquake are: φ=41,50°N, λ=46,58°E и φ=41,56°N, λ=46,63°E, depth h=8-12 km (Fig. 1). Earthquakes were felt in the cities of Zagatala, Belakany, and Gakh and in other environs with an intensity of 2-5 points. On fig. 1. The wave pattern of the first Zagatala earthquake that occurred at $t_0=04^h40^m$ is presented.

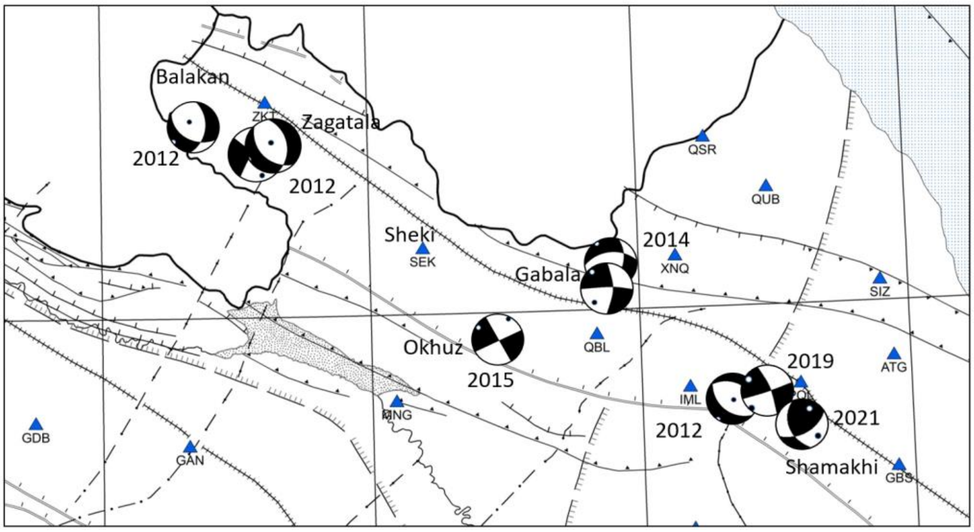

Fig. 1. Map of focal mechanisms of strong earthquakes (Mw>5.0) for the period 2012-2021. (fault map according to [15])

The Zakatala seismically active zone is located in the extreme northwest of the Azerbaijani part of the Greater Caucasus. Conventionally, its boundary in the east should be considered the Zakatalo-Shamkir transverse uplift. In the north, west and south, the zone merges with the highly active seismic zones of Southern Dagestan and Western Georgia. The area of the Zagatala seismically active zone within Azerbaijan is about 3500 km2. It should be noted that only one large earthquake is known in this zone for the entire seismostatistical period, which occurred in 1936 with a 7-point effect in a number of settlements. More often shocks with an intensity of 7 points in the Zagatala seismically active zone were felt from strong Dagestan and Georgian earthquakes, which sometimes caused excitations in local sources [10].

The focal mechanism of these earthquakes was characterized by near-horizontal (PL_P=10°) compressive and tensile (PL_T=14°) stresses. The type of movement along both steep (DP1=87°, DP2=72°) planes is shear. Plane NP1 has a southeast (STK1=125°) strike with a right-hand slip type, and NP2 has a south-west strike (STK2=216°), with a left-hand slip type. Comparison of the strike of nodal planes with fault lines shows the agreement of the first nodal plane NP1 with the right-sided Kazakh-Signakh and Ganjachay-Alazani transverse faults, which allows us to consider the NP1 plane to be active. The focal mechanism of the second earthquake occurred under the action of near-horizontal tensile stresses (PL_T=1°). The type of slip along the first nodal plane NP1 is a fault with elements of a right-sided shear, along the second - a fault with elements of a left-hand shear.

On October 14, 2012 at 10h13m36s, 28 km to the west of the city of Zagatala, an earthquake with magnitude ml=5.6 occurred in the Belakan region. According to instrumental observations, the coordinates of the earthquake are: lat=41.66N, lon=46.27E, and the depth h=8 km. On the basis of instrumental observations, it was revealed that the earthquake was felt with the greatest intensity in the territory of such villages as Halatala, Mesheshambul, Sharif, Yeni

Sharif, Saribulak, Talalar, Tulu, Kaisa and Kazma. Here, the intensity of the earthquake according to the MSK-64 table was estimated at 7 points.

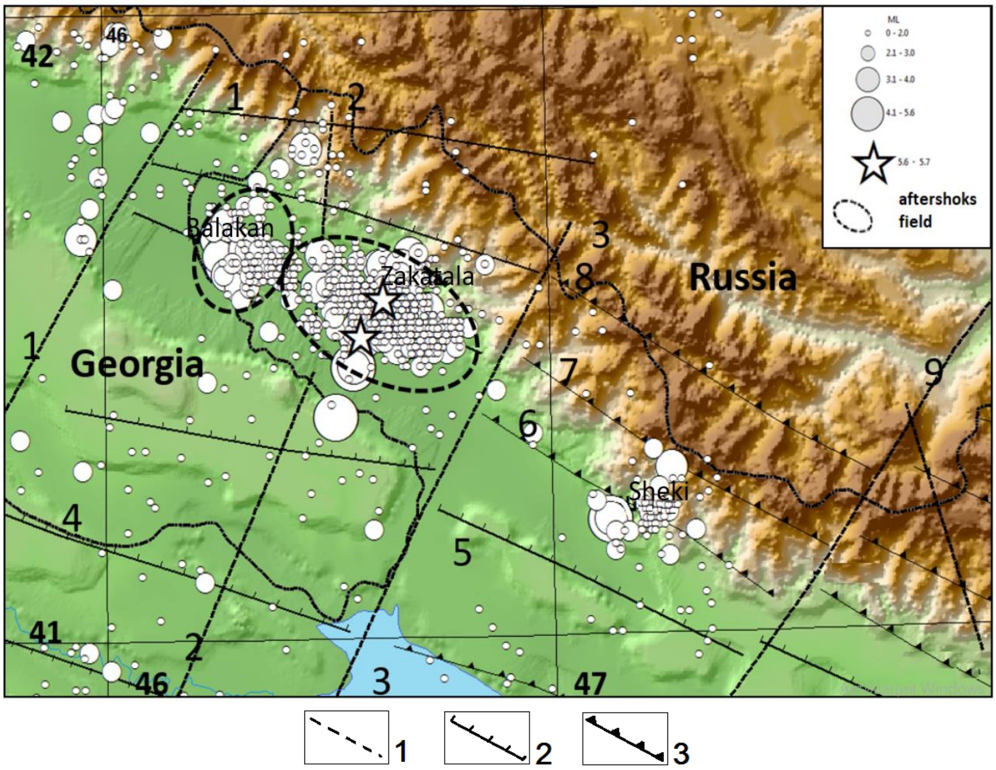

Fig.2. Map of epicenters of earthquakes in the study region that occurred in 2012
and diagram of the fault structure of the southern slope of the Greater Caucasus (fault map according by [12])

The main seismogenic faults that determine the features of the geodynamic regime of the earth's crust: 1-shifts 2-faults, 1-reverse faults. Faults: 1 - Kazakh-Signakh, 2 - Sharur-Zakatala [1], 3 - Ganjachay-Alazan, 4 - Iory, 5 - North Adjinour, 5 - Vandam, 6 - Dashgil-Mudresa, 7 - Zangi-Kozluchay, 8 - Arpa-Samur.

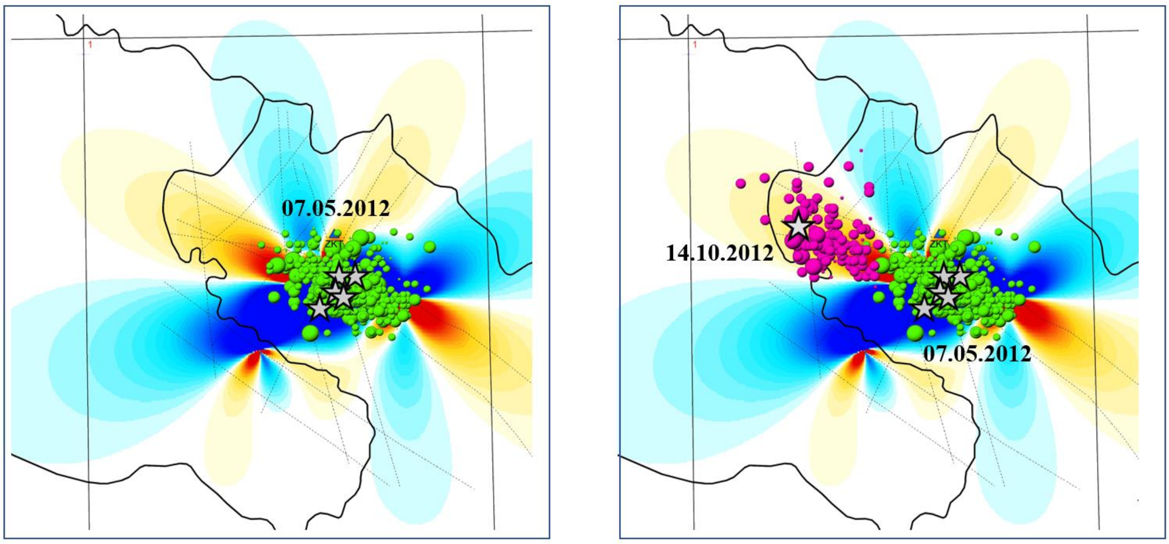

Fig. 3 Increment of critical Coulomb stresses initiated by Zakatala earthquakes in 2012

Based on the above, we analyzed the Coulomb stress after the strong Zagatala earthquake (Fig. 3). It can be assumed that the Zakatala earthquakes are a consequence of the geodynamic regime of the earth's crust of the Zakatala focal zone, the parameters of which are determined by the movements of the earth's crust along the system of longitudinal (general Caucasian strike) and transverse (anti-Caucasian strike) faults; among the latter, the main role probably belongs to a pair of transverse right-sided strike-slip faults – Kazakh-Signakh and Ganjachay-Alazan.

As seen in fig. The Zakatala earthquakes, as well as the aftershock field, are in the zone of negative values of the Coulomb stress, i.e. in the zone of released energy. However, after it, the zones of positive values are distributed in the NW-SE direction. As mentioned above, on October 14, 2012, a strong earthquake with a magnitude of ml=5.6 and an aftershock field radius of 25 km occurred in the NW stress state accumulation zone (Balakan region).

From a tectonic point of view, the earthquakes that occurred in Balaken are located in the southwest of the Azerbaijan part of the Greater Caucasus, surrounded by the Ayrichay-Alat and Vandam deep faults. It should be noted that the Tfansky anticlinorium is distinguished as the central uplift of the Mesozoic core of the meganticlinorium of the Greater Caucasus. On the southern wing of the Tfansky anticlinorium, the Zakatalo-Kovdagsky synclinorium is distinguished, filled with Cretaceous formations. The source mechanism of the Balakan earthquake on October 14, 2012 was characterized by horizontal (PLP=0°) tensile southwest orientation (AZM=239°) and nearly vertical compressive (PLT=48°) northwest orientation (AZM=329°) stresses (Fig. 10, Table 4). The type of movement along both (DP=57°) planes is fault with shear elements. Plane NP1 has east strike (STK1=115°), NP2 – north strike (STK2=2°). Comparison of the strike of nodal planes with fault lines shows the agreement of the second nodal plane NP2 with two transverse Kazakh-Signakh and Sharur-Zakatal faults. An analysis of the mechanisms of these earthquakes showed that one pair of tectonic faults was confined to the zone of influence. As seen in fig. The 3rd earthquake that occurred in the Zakatala region is a kind of trigger (initiated). On September 29 and October 4, 2014, to the NE of the city of Gabala, two earthquakes occurred with ml=5.5 and ml=5.0, respectively. The focal zone is controlled by the Damiraparanchai right-slip strike-slip fault, which complicates here the belt of the underthrust junction of the Kakheti-Vandam-Gobustan zone and the accretionary prism of the Greater Caucasus. Near-vertical (PLP=48°) compressive stresses oriented to the southwest (AZM=265°) prevailed in the source mechanism of the first earthquake. Type of movement on both steep (DP1=64°, DP2=53°) planes - fault-shift. Plane NP1 is latitudinal (STK1=265°), and NP2 is meridional (STK2=17°). Comparison of the strike of nodal planes with fault lines in Figs. 6 shows the agreement of the second nodal plane NP2 with the Ismaili-Gabala orthogonal fault.

The movement in the source of the second earthquake arose under the action of near-horizontal (PLP=23°) compressive stresses. The type of movement along both planes is shear with reset elements. Plane NP1 is latitudinal (STK1=268°), and NP2 is meridional (STK2=1°). Comparison of the strike of nodal planes with fault lines shows agreement of the first nodal plane NP1 with the Arpa-Samur transverse fault. Most likely it is this plane that is active.

One of the strongest earthquakes over the past 10 years is the earthquake that occurred in the Okhuz region on September 4, 2015. The seismic vibrations of this earthquake were recorded by 18 world agencies and almost 400 seismic stations in a wide azimuthal environment at distances from 300 to 13407 km from the epicenter. Based on macroseismic studies, it was revealed that the earthquake was felt with the greatest intensity in the territories of the Okhuz and Sheki regions (Fig. 4). Here, the intensity of the earthquake according to the MSK-64 table was estimated at 7 points. The earthquake was accompanied by more than 80 aftershocks with magnitudes from 0.5 to 4, of which 33 occurred on the first day. As seen in fig. 4, the epicenter of the earthquake is confined to the zone of intersection of the longitudinal Dashgil-Mudresinsky and transverse Arpa-Samur faults [9, 15]. It should be noted that the Arpa-Samur deep fault of ancient origin at all times from the Paleozoic to the present is a zone of active manifestation of tectonic movements, a conductor of magmatic melts, ore-bearing solutions and seismicity. According to Shikhalibeyli E.Sh. [15] The Arpa-Samur Transcaucasian seismically active metal-bearing fault zone unites the Mrovdag-Zod, Terter and Khachin faults of deep origin. Of the total number of aftershocks, the most significant occurred on October 13 at 00h 13m.

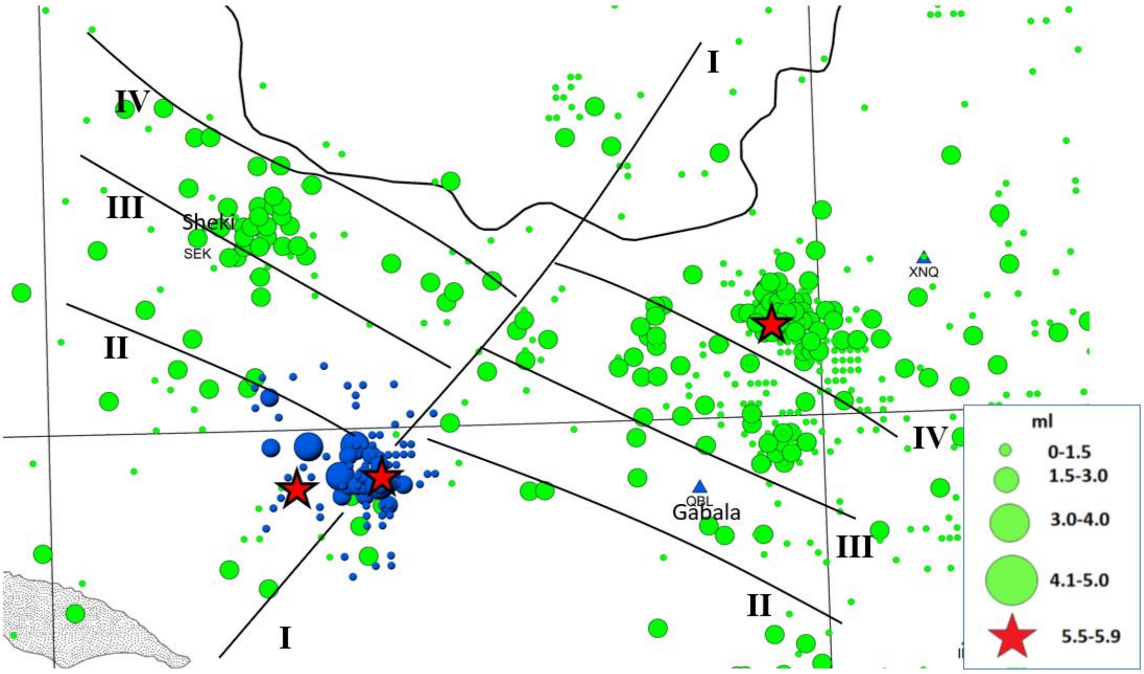

Fig. 4. Aftershock field of strong Gabala (2014) and Okhuz (2015) earthquakes
Faults: I - Arpa-Samur, II - North Adzhinour, III - Vandam, IV - Dashgil-Mudrese [15]

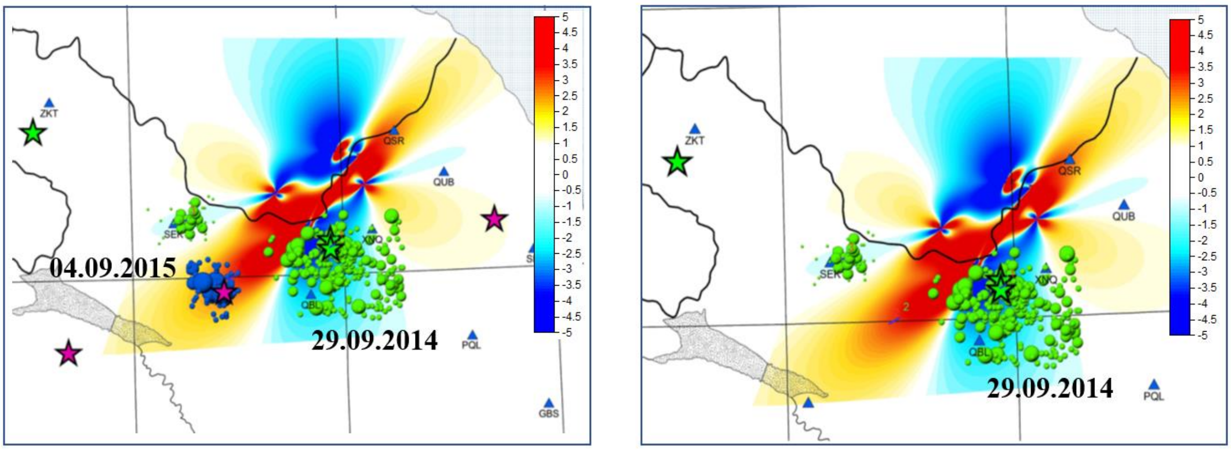

Fig. 5 Increment of critical Coulomb stresses initiated by the 2014 Gabala earthquake

For the reliability of the result, the mechanisms of two earthquakes were built and analyzed: 09/04/2015 with ml=5.9 (main shock) and 10/13/2015 with ml=4.0. The earthquakes that occurred in the Okhuz region on September 4 at 04h 49m and on October 13 at 00h 13m occurred under the action of close tensile and compressive stresses. Table 3 shows that the first nodal fault plane extends in the SE direction (153º), the second nodal plane has a NE strike (63º). At the same time, the compression stresses in the earthquake source were oriented in the northeast direction (azimuth 18) and acted near-horizontally (angle with the horizon 0-7), and

the tensile forces were directed in the west-southwest direction (287-288) at an angle of 0-2 to the horizon. The type of slip of these earthquakes is left-sided slip (Fig. 1).
An analysis of the distribution of Coulomb stresses for the Gabala and Okhuz earthquakes showed that after the 2014 earthquakes in the Gabala and Sheki regions, the accumulated energy was released (Fig. 5). However, the areas of positive values in 2014 were distributed in SW-NE orientation, which indicated that the faults (Arpa-Samur transverse fault) were in a subcritical, metastable state.

This was confirmed by seismic activity in 2015, when an earthquake with a magnitude of 5.9 occurred in the Okhuz region on September 4, 2015. The aftershock cloud spread up to 23 km in the S-N direction and 9 km in the W-E direction, however, the area of the main mass of the earthquake cluster was 88 km2. Despite the fact that the main source is located at a depth of 16 km in the granite layer, the depth of aftershocks varies between 11-34 km.Over the past 15 years, one of the strongest earthquakes in this region is the earthquake that occurred on October 7, 2012, at 15^h42^m, 17 km southeast of the Ismayilli seismic station in the Ismayilli region with ml = 5.3. The intensity at the epicenter of this earthquake on a 12-point scale was estimated at 6 points; in the nearby settlements of Pirkulu, Shamakhi, Ismaili and Akhsu, the earthquake was felt up to 4-2 points.

As is known, the epicentral zone of the Shamakhi earthquakes is located on the southeastern subsidence of the meganticlinorium of the Greater Caucasus. This region is composed of thick volcanogenic and sedimentary strata of the Meso Cenozoic. All strata are collected in large linear folds, elongated in the general Caucasian direction. The following structural units are distinguished in the Shamakhi zone: Zagatala-Kovdag synclinorium, Lagich synclinorium, Vandam anticlinorium, Shamakhi-Qobistan synclinorium (Marazi trough), Alazan-Agrichay trough.

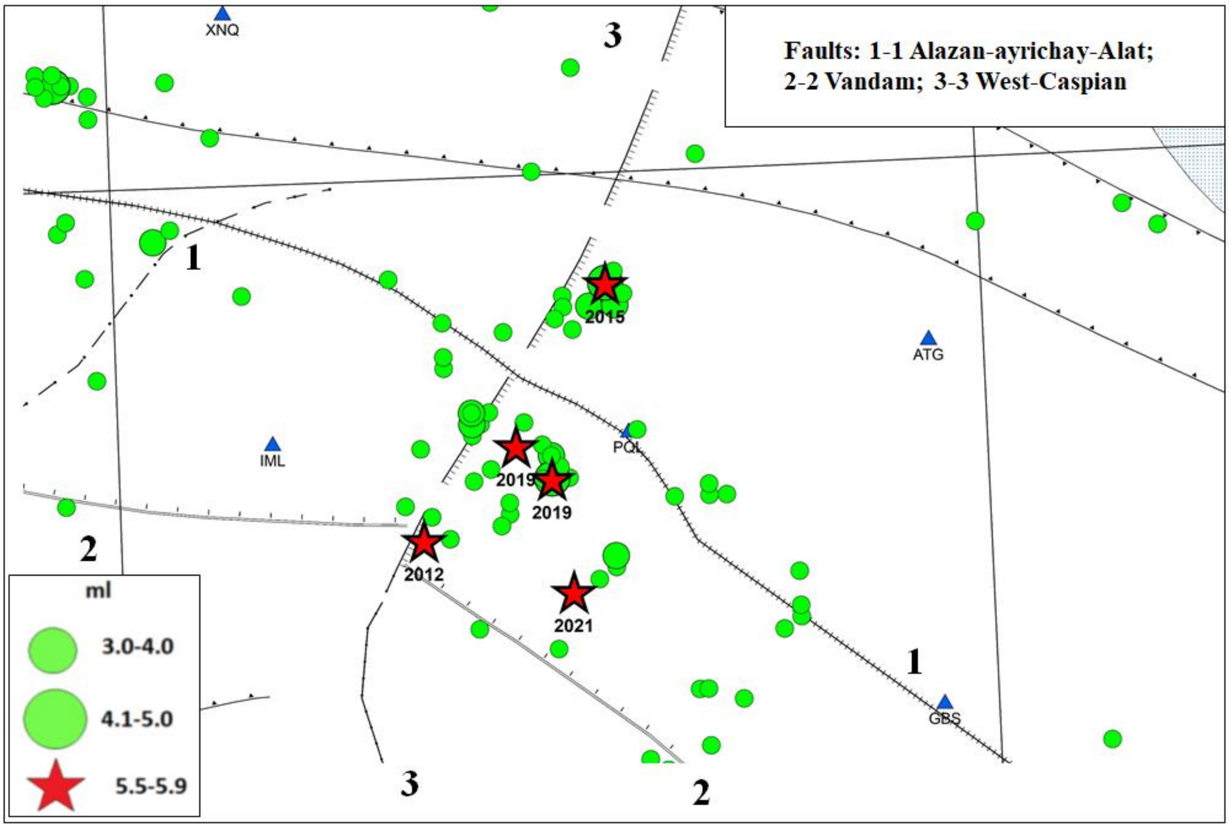

Fig.6. Map of the epicenters of strong earthquakes in the Shamakhi-Ismayilli seismogenic zone for 2012-2021. (fault map according to [15])

The earthquake that occurred on February 5, 2019 at 19^h31^m with ml=5.2, h=8 was no exception. The seismic activity in this zone began with the February 5 earthquake at $19^h 19^m 54^s$, with ml=4.4 which occurred 11 minutes before the main shock and is considered to be its strong foreshock, felt up to 3-4 points. In addition, a large number of weak foreshocks with ml<3 were recorded. Aftershock activity was also high. The most powerful aftershocks had magnitudes with ml>3.4, 3.0, 3.9. It should be noted that on the same day at 13:24:51 an earthquake occurred in the Talish region with ml = 3.9. According to instrumental observations, the coordinates of the Ismayilli earthquakes $19^h 19^m 54^s$ (foreshock) and $19^h 31^m 37^s$ (main shock) are equal: φ=40.77ºN, λ=48.50ºE and φ=40.78ºN, λ=48, 46ºE, depth h=8-11 km.

The highest magnitude earthquake of 2021 (ml = 5.1) occurred on November 20 at 16:46 local time in Shamakhi, 17 km south of Pirgulu station. It should be noted that this shock was a major seismic earthquake recorded in the territory of Azerbaijan during the year. The magnitude of the earthquake was 5 in the epicenter and 4-3 in the surrounding areas. Both the compression (P) and tensile stress (T) axes of the earthquake are oriented close to the horizon (PL = 17-36). A sharp (DP = 78-51) angle of incidence was determined for both nodal planes. The value of displacement in the furnace (SLIP = 140-15) indicates that the right-hand displacement-break-up movement is predominant. At 16:48 local time, an aftershock with a magnitude of ml = 4.5 was recorded in Shamakhi, 13 km south of Pirgulu station. The value of displacement in the furnace (SLIP = -109 - (- 64)) indicates that the fracture is dominated by right-sided displacement type movement and is associated with the West-Caspian fracture.
Analyzing the residual stress of the Shamakhi-Ismailli region, we interpolated these Coulomb stresses of 4-magnitude earthquakes that occurred in the period 2012-2019.

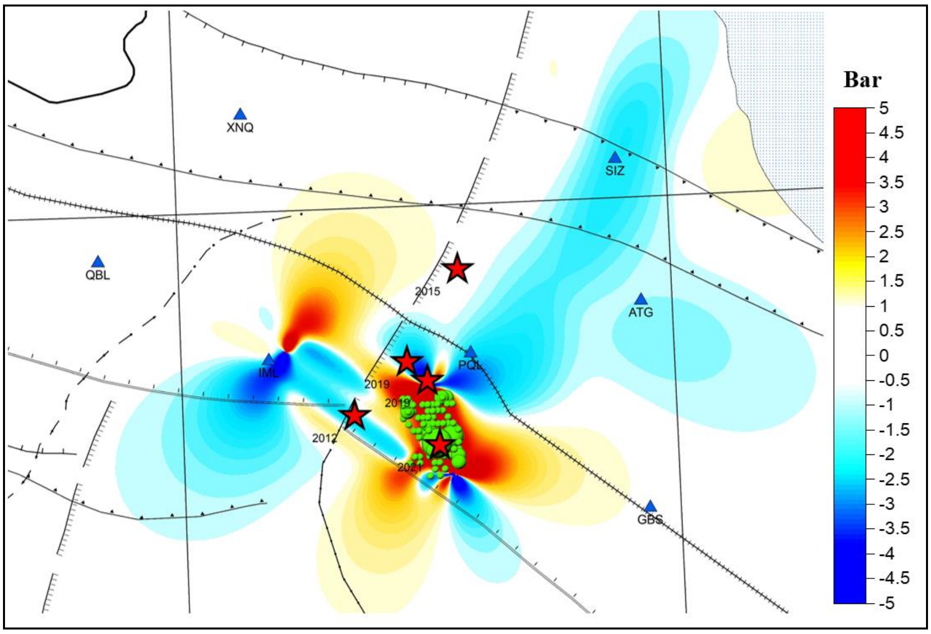

Fig. 7. The emergence of critical Coulomb tensions initiated by the Ismaili earthquakes in 2012-2019. (breaking map on [15])

A slow deformation process, the contribution of which to the integral value of the accumulated deformation can be quite significant. The displacement consists of a dynamic (co-seismic) and a slow (post-seismic) component. The ratio of the amplitudes of dynamic and slow displacement is determined by the stress-strain state of the contact. If the dynamic component prevails on weakly stressed contacts, then as the static load approaches the Coulomb limit, the amplitude of the slow movement can greatly exceed the initiating dynamic movements. The characteristics of the contact do not remain unchanged during the deformation process. In this case, both an increase and a decrease in the rigidity of the interblock contact, and, consequently, the rate of accumulation of the interblock displacement, can be observed. The increase in stiffness is due to two factors. The first one, the gradual increase in contact stiffness under multiple cyclic loading, is known for quasi-static cyclic loading. Under dynamic loading of cracks, this effect is less pronounced, but it is also quite significant. If the deformation of the contact occurs at a rate below some critical value, then the stiffness increases in proportion to the logarithm of time. In our case, the critical value of the rate of relative displacement of blocks is 4.0–5.0 mm/year, which is relatively small. As a result of the accumulation of the stress-strain state over the past 10 years, residual energy has accumulated at the junction of the Agsu and Shamakhi regions, which manifested itself in 2021 with a magnitude of 5.1 and an aftershock field radius of 15 km.

Conclusions:

The analysis showed that dynamic stresses alone cannot explain the spatial distribution of seismicity. So, for example, at a close level of dynamic stresses in the Zakatal and Balakan regions, in the first case, initiated seismicity was observed, and in the second, not. Based on this, an assumption arose that the faults on which initiated earthquakes occur must be in a subcritical, metastable state. This is supported by the fact that all triggered events occurred in areas of increased background seismicity. Many of the areas of initiation were areas, as a rule, confined to the boundaries of large geotectonic elements of the earth's crust and the intersection nodes of faults of various directions.

The foregoing suggests that the Zakatala earthquakes are a consequence of the geodynamic regime of the earth's crust of the Zakatala focal zone, the parameters of which are determined by the movements of the earth's crust along the system of longitudinal (general Caucasian strike) and transverse (anti-Caucasian strike) faults; among the latter, the main role probably belongs to a pair of dextral strike slips – Kazakh-Signakh and Ganjachay-Alazan.

Thus, the solutions of the focal mechanisms of the considered earthquakes are normal and antithetic sinistral strike-slip faults. The latter solution seems to be preferable, especially for the first Zagatala earthquake, since the presence of a sublatitudinal or general Caucasian reverse fault in this area is rejected by the geodynamic model of the region under study, as well as a pure normal fault without a horizontal component for the second earthquake.

Analyzing the sequence of seismic processes, one can notice that the sources considered have a certain relationship. It should be noted that the coincidence of the angles of dip DP, slip SLIP and strike azimuths STK of shears and normal faults does not exclude the possibility of movements of such types along the planes of some faults. Perhaps the Zagatala earthquake was the first shock that caused a series of strong earthquakes in the Balakan, Sheki, Okhuz, Gabala and Ismayilli regions. All these zones are in similar seismotectonic conditions. The geological structure of these zones involves the structural elements of the Tfan anticlinorium, the Zagatala–Govdag synclinorium, the Vandam anticlinorium, and the superimposed Alazano–Agrichai trough [14]. These structures of the general Caucasian direction are separated from each other by deep sublatitudinal faults.

A positive increment of the Coulomb stresses can be interpreted as an approach to the destruction threshold, while a negative increment, as it were, postpones the moment of the earthquake. To estimate the Coulomb stresses initiated by the Zakatala, Gabala and Ismayilli earthquakes, the source model was considered, which is set by the plane of east-southeast dip. The eastward dip of the plane along which the shift occurred is in the best agreement with the geological data of the regions. The spatial position of the earthquake epicenters (aftershock field) that occurred from 2012 to 2021 correlates with the zones of positive increments of critical Coulomb stresses. Their occurrence, apparently, is associated with the accumulation of tectonic stresses of sublatitudinal extension and the localization of static stresses initiated by the Zakatala earthquakes of 2012, which together led to the emergence of instability and shear movements along the fault. The obtained results testify to the prospects of the chosen approach for the rapid assessment of seismic shaking for implementation in automated monitoring systems.

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