https://doi.org/10.59849/2219-6641.2024.1.3 3

CHANGES IN COULOMB STRESS DURING CASPIAN EARTHQUAKES IN 2023 WITH M=5.6

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ABSTRACT

The article analyzes two significant Caspian earthquakes that occurred on July 4, 2023 local time 00:01 and December 7, 2023 local time 08:15 with a local magnitude of M=5.6. For this purpose, the source mechanisms of these earthquakes were constructed, and two stress state coefficients were analyzed - Lode-Nadai and Coulomb stress. In 2023, as in previous years, the Caspian Sea water area is characterized by high seismicity. The highest density of hypocenters was observed at a depth of 42-68 km. The magnitude of the displacements in the source shows that fault-slip type movements predominate here. A total of 19 earthquakes were plotted and analyzed in the Caspian Sea in 2023. These earthquakes were associated with the zone of influence of the Agrakhan-Krasnovodsk, Turkmenbashi, Sangachal-Ogurchi, Shakhov-Azizbekov, Siyazan and Garabogaz-Safidrud faults. Based on these mechanisms, the Lode-Nadai coefficient was constructed and it was established that the sources of Caspian earthquakes are located in the extension zone. The solution of the moment tensor showed that the movement at the source of the July 4 earthquake arose under tension conditions. Movement in the source along both planes is shear. The length of the outbreak was 6.1 km, width – 4.53 km. The movement along the fault was 24 cm. In the source of the earthquake that occurred on December 7, 2023, according to the solution of the mechanism, movement in the source also occurred under tension conditions. The type of movement, along the first plane NP1 of a northwest strike and along the second plane NP2 of an east-southeast strike, is a strike-slip fault with fault elements. The moment magnitude was determined to be Mw=5.4. Seismic moment $1.56*10^{24}$ dyn*sm. The depth of the source is 48 km. The length of the outbreak was 6.58 km, width – 5.49 km. The movement along the fault was 24 cm.

Key words: Source mechanism of the earthquake, moment tensor, Columb stress coefficient, seismotomography, Caspian Sea.

2023-CÜ İLDƏ MAQNİTUDASI M=5,6 OLAN XƏZƏR DƏNİZİNDƏ BAŞ VERMİŞ ZƏLZƏLƏLƏR ZAMANI KULON GƏRGİNLİYİNİN DƏYİŞMƏSİ

Yetirmişli Q.C., Kazımova S.E.

XÜLASƏ

Məqalədə 4 iyul 2023-cü il yerli vaxtla saat 00:01 və 7 dekabr 2023-cü il yerli vaxtla saat 08:15-də lokal maqnitudası M=5,6 olan baş vermiş iki güclü Xəzər zəlzələsi təhlil edilir. Bu məqsədlə zəlzələlərin ocaq mexanizmləri qurulmuş, iki gərginlik əmsalı - Lode-Nadai və Kulon gərginliyi təhlil edilmişdir. 2023-cü ildə, əvvəlki illərdə olduğu kimi, Xəzər dənizinin akvatoriyası yüksək seysmiklik ilə səciyyələnir. Hiposentrlərin ən yüksək sıxlığı 42-68 km dərinlikdə müşahidə olunur. Ocağda yerdəyişmələrin ölçüləri göstərir ki, burada qırılma-düşmə tipli hərəkətlər üstünlük təşkil edir. 2023-cü ildə Xəzər dənizində ümumilikdə 19 zəlzələnin ocaq mexanizmləri qurulmuş və təhlil edilmişdir. Bu zəlzələlər Aqraxan-Krasnovodsk, Türkmənbaşı, Səngəçal-Oğurçu, Şaxovo-Əzizbəyov, Siyəzən və Qaraboğaz-Səfidrud qırılmalarının təsir zonası ilə əlaqədardır. Bu mexanizmlər əsasında Lode-Nadai əmsalı qurulmuş və müəyyən edilmişdir ki, Xəzər zəlzələlərinin

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ocaqları gərilmə zonasında yerləşir. Moment tenzorunun həlli 4 iyul zəlzələsinin ocağında hərəkətin gərilmə gərginliyi şəraitində yarandığını göstərir. Mənbədə hər iki müstəvi boyunca hərəkət horizontal yerdəyişmədir. Ocağın uzunluğu 6,1 km, eni 4,53 km-dir. Qırılma boyunca hərəkət 24 sm təşkil edir. 2023-cü il dekabrın 7-də baş vermiş zəlzələ gərilmə gərginlik şəraitində baş vermişdir. Şimal-qərb istiqamətində yönəlmiş birinci müstəvi NP1 və şərq-cənub-şərq istiqamətində yönəlmiş ikinci nodal müstəvisi NP2 boyunca qırılıb düşmə elementli horizantal hərəkətlər müəyyən olunub. Moment maqnitudası Mw=5,4 müəyyən edilmişdir. Seysmik moment 1.56*1024 dn*sm-dir. Ocağın dərinliyi 48 km-dir. Ocağın uzunluğu 6,58 km, eni 5,49 km təşkil edir.

Açar sözləri: Zəlzələnin ocaq mexanizmi, Moment tenzor, Kulon gərginlik əmsalı, seysmotomoqrafiya, Xəzər dənizi.

ИЗМЕНЕНИЯ НАПРЯЖЕНИЯ КУЛОНА ВО ВРЕМЯ КАСПИЙСКИХ ЗЕМЛЕТРЯСЕНИЙ М=5.6 В 2023 ГОДУ

Етирмишли Г.Дж., Казимова С.Э.

АННОТАЦИЯ

В статье анализируются два значительных прикаспийских землетрясения, произошедшие 4 июля 2023 года по местному времени в 00:01 и 7 декабря 2023 года по местному времени в 08:15 с локальной магнитудой M=5,6. Для этого были построены механизмы очагов этих землетрясений и проанализированы два коэффициента напряженного состояния - Лоде-Надаи и кулоновское напряжение. В 2023 году, как и в предыдущие годы, акватория Каспийского моря характеризуется высокой сейсмичностью. Наибольшая плотность гипоцентров наблюдалась на глубине 42-68 км. Величина смещений в очаге показывает, что здесь преобладают движения сбросо-сдвигового типа. Всего в 2023 году на Каспии было построено и проанализировано 19 землетрясений. Эти землетрясения были связаны с зоной влияния Аграханско-Красноводского, Туркменбашинского, Сангачал-Огурчинского, Шахово-Азизбековского, Сиязанского и Гарабогаз-Сафидрудского разломов. На основе этих механизмов был построен коэффициент Лоде-Надаи и установлено, что очаги прикаспийских землетрясений расположены в зоне растяжения. Решение тензора момента показало, что движение в очаге землетрясения 4 июля возникло в условиях напряжения растяжения. Движение в источнике по обеим плоскостям является сдвиговым. Длина очага составила 6,1 км, ширина – 4,53 км. Смещение по разлому составило 24 см. В очаге землетрясения, произошедшего 7 декабря 2023 г., согласно решению механизма, движение очага также происходило в условиях напряжения растяжения. Тип движения - по первой плоскости NP1 северо-западного простирания и по второй плоскости NP2 восточно-юго-восточного простирания - сдвиг-с элементами сброса. Моментная магнитуда была определена как Mw=5,4. Сейсмический момент 1,56*10^{24} дин*см. Глубина очага - 48 км. Длина очага составила 6,58 км, ширина – 5,49 км. Смещение по разлому составило 24 см.

Ключевые слова: Механизм очага землетрясения, тензор момента, коэффициент кулоновского напряжения, сейсмическая томография, Каспийское море.

Introduction

The submeridionally oriented megadepression of the Caspian Sea covers a vast space from Elburz in the south to the Caspian Lowland in the north and has a length of about 1200 km with an average width of 320 km and an area of 422 thousand sq km. In the modern structure of the earth's crust, the Caspian Sea is an intracontinental depression with a heterogeneous base structure, which is confined to the meridional zone of subsidence, superimposed on a number of structural elements belonging to the southeastern margin of the

Precambrian East European Platform, the Scythian-Turanian Epihercynian Plate and the Mediterranean (Alpine-Himalayan) fold belt [12].

The Caspian Sea is an important seismically active zone of Azerbaijan. The spatial distribution of source zones is irregular. The source zones of the Caspian Sea region reach a depth of 60–80 km. The depth of strong earthquakes with $M \geq 5.0$ reaches 30–50 km. According to the catalog of the RSSC ANAS, over the past century, a number of strong earthquakes have been recorded in the Caspian waters, with an intensity of 6 points or more at the epicenter. Most of the known most powerful earthquakes in this zone occurred in the North Absheron waters of the Caspian Sea. Their intensity at the epicenter (earthquakes of 1842, 1963, 1986 and 1989) reached VIII points [16]. The source of the earthquake on November 25, 2000 is located in the southern part of the Absheron zone and is confined to the Absheron-Cheleken threshold.

The outbreaks that occurred in 2023 in July and December with a magnitude of $M=5.6$ were no exception. In this article, we analyzed the parameters of the source of these earthquakes and identified the geodynamic situation. For this purpose, two stress state coefficients were analyzed - Lode-Nadai and Coulomb stress. The Coulomb initiation theory 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 [1, 3]. Typically, the best agreement between the Coulomb stress change and the aftershock distribution is observed at distances greater than a few kilometers from the earthquake fault, since unknown details of the displacement distribution and geometry play a significant role closer to the earthquake fault.

Note that changes in stress leading to the initiation of deformation processes are very small. A comparison of the results of calculations of changes in the static stress field with the prevalence of aftershocks shows that changes in stress of the order of 1–3 bar are sufficient to initiate seismicity, while a decrease by the same amount restrains it. However, this picture is not always observed [2]. Such small values, being an insignificant part of the total stress release during an earthquake, indicate that quasi-static stress changes are not the cause of the earthquake, but only bring the moment of the event closer or further away. In order to assess the change in the variation of the Coulomb function on the plane of a future rupture of a tectonic earthquake as a result of rock excavation, it is necessary to know the geometric parameters of the fault zone. In this article we will use fault tectonics compiled based on materials: Agabekov M.G. et al. 1971; Alikhanov E.N. 1978; Gasanov I.S.1990; Babaev D.Kh. et al. 2005; Mamedov A.V.1984; Kangerli T.N. 2005; Shikhalibeyli E.Sh.1996; Khain V.E. et al. 2003 [5-7, 13, 18, 19].

Tectonic structure of the Middle Caspian megazone

The Middle Caspian megazone covers a tectonically complex section of the earth's crust in the area of conjugation of the Alpine and Cimmerian folded structures of the Greater Caucasus, Mangyshlak and platform structures of the Scythian-Turanian plate. Within the Azerbaijani water area, the megazone is represented in the north by the Samur-Peschanomys uplift, limiting the Terek-Caspian trough from the south, in the central part - by the North Absheron trough, which continues the Guba zone of the Gusar-Devechi superimposed trough in the sea, and in the south - by the Absheron-Pribalkhan uplift zone. The latter is bounded from the south by the Krasno Polyansko-Zangin deep fault, separating the Middle Caspian block with a relatively high position of the pre-Jurassic basement from the deeply submerged South Caspian block of the megadepression [17]. The west-southwest border of the megazone can be conditionally drawn along the Derbent fault and the Mugtadyr fault, which continues it within Azerbaijan, with contrastingly lowered northeastern wings. Until recently, tectonic zoning of the Middle Caspian was based on data from gravimetric and magnetic surveys and single regional seismic profiles. In recent years, in the Caspian Sea, the geophysical exploration trust has carried out comprehensive geophysical research on a large scale, including geophysical exploration work. The Jurassic-Quaternary sedimentary cover of the megazone, reaching its maximum thickness in the Dagestan coastal zone (8-10 km) and the central part of the North Absheron depression (14-15 km or more), is underlain by a partially dislocated Permian-Triassic complex and metamorphic Paleozoic, formed together with the trough of the Kazakh Gulf on the reworked and submerged northern part of the vast Paleozoic Middle Caspian massif of the Scythian-Turanian plate, the thickness of the sedimentary cover is 3-4 km. Moreover, in many areas, various rock complexes, including Upper Jurassic ones, fall out of the section, which is explained by breaks in sedimentation at various stages of development, the most significant of which is the Pre-Pliocene regression. The Triassic–Jurassic boundary is characterized by a regional unconformity associated with Early Cimmerian tectonic activity and a hiatus in sedimentation. According to new data from gravimagnetometric studies, to the north of the indicated shelf zone in the pre-Jurassic basement there are magmatic bodies (depths from 5-6 to 7-9 km), which may be eastern fragments of the ophiolite belt of the Front Range of the Greater Caucasus (North Caspian ophiolite belt), traced to the periphery of the Karabogaz massif. The thickness of the crust of the Middle Caspian megazone is about 40 km, and the thickness of the lithosphere is 150 km. In the direction to the Absheron threshold, there is a significant increase in the depth of the Moho boundary and a relative increase in the depth of the surfaces of the granite and basalt layers. Several structural and material complexes are distinguished within the sedimentary cover [9-11, 14]. The Upper Pliocene-Quaternary complex is represented by shallow marine clays, sands and shell rocks, which lie very calmly, weakly repeating the local dislocations of the underlying sediments. At the base of this complex lie alluvial-deltaic sandy-clayey sediments of the Paleo-Volga valley and delta, the valley incision of which is clearly visible on seismic profiles. Further in the descending section lie Paleocene-Eocene carbonate-terrigenous, Upper Cretaceous marl-limestone, Lower Cretaceous terrigenous, Upper Jurassic carbonate and Lower-Middle Jurassic sandy-clayey formations [17].

Based on seismic tomography data, a deep velocity model was built along profile 1-1 in the south-north direction. As can be seen on the profile, the thickness of the sedimentary cover in the center of the profile plunges to a depth of 20 km. Next is a granite layer to a depth of 35 km. At a depth of 45-50 km, the Moho boundary is observed, however, at an epicentral distance of 100-160 km, a subsidence of the Moho boundary to a depth of 70-75 km is observed, probably corresponding to the boundaries of deep faults. As can be seen in the profile (Fig. 1), the sources of strong Caspian earthquakes correspond to this subsidence zone**.**

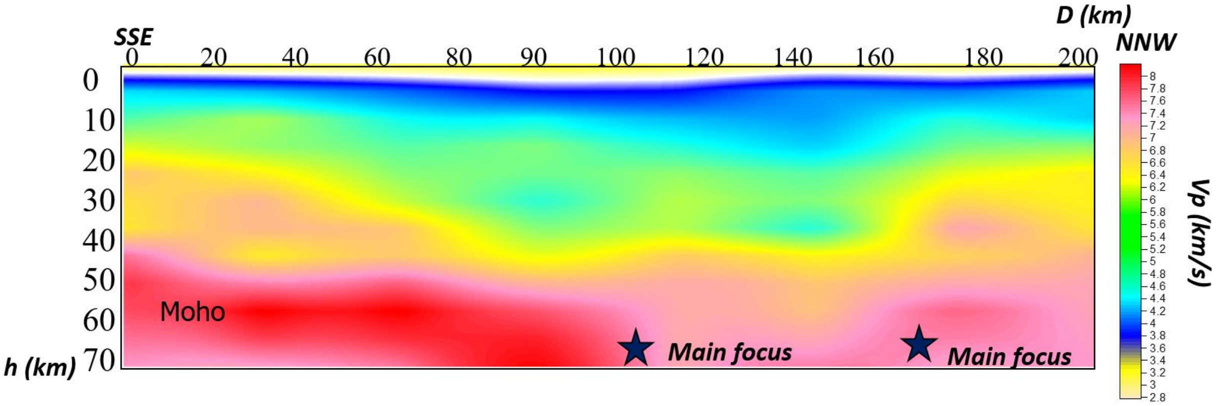


Figure 1. Seismic tomographic profile along the source zone of the Caspian earthquakes in 2023.

The North Absheron zone is a deep trough extending in the pan-Caucasian direction for a distance of more than 110 km, located on the southeastern continuation of the Guba depressed zone of the Gusar-Devechi superimposed trough and having a similar asymmetric structure with a relatively flat northeastern and steep southwestern sides. The latter adjoins from the north the Absheron-Pribalkhan zone of uplifts, grouped along the Miocene-Pleistocene complex into two (northern and southern) fold lines - the Gilyazi-Prigubadag and the Absheron-Pribalkhan proper, separated by the Pirallakhi trough [17]. According to the chalk complex, the zone is presented in the form of five synclines, the depth of which along the chalk surface is 7900-8300 m. The structural plan of the Paleocene-Miocene and Pliocene complexes in general remains similar to that of the Upper Cretaceous deposits, and a chain of isometric depressions separated by saddles can be traced throughout the Pliocene-Quaternary complex. Along the south-southwestern side of the North Absheron trough, Mesozoic sediments are uplifted and folded into anticlinal folds, which, in particular, include the Zarat-Deniz and Gyzylburun-Deniz structures, possibly the Shimali Absheron. Longitudinal faults identified on the more southern structures of Sumgayit-Deniz, Gosha-Dash, Shuraabad-Deniz, Absheron-Kyupasi, Ashrafi and others are interpreted as the eastern continuation of the Siyazan thrust, separating the trough from the Absheron-Balkhan uplift zone [17].

Various-scale tectonic stress fields

The nature of the distribution of stresses acting in fault zones is determined by regional tectonics or local anomalies in the temperature field of the earth's crust, and the stress values depend on the structural and material state of the rocks and the fluid regime of these zones. Since, unlike materials used for structures, the geological environment is significantly heterogeneous, this predetermines the presence of significant heterogeneity - mosaicism in the stress field, manifested at different scale levels of averaging, and, consequently, in the strong dependence of the values of the components of the natural stress tensor on the averaging scale. It should be noted that at different scales the causes and manifestation of this heterogeneity in the effective properties of the geoenvironment (average for a certain scale) are also different. Thus, inhomogeneities at the microscopic level, caused by the presence of crystals, grains and aggregates, dislocations and microcracks, micropores, can be smoothed out by averaging physical parameters with a linear size of less than 1 cm (uniform deformation of small samples), which will characterize the macroscopic level of averaging of the properties of the geomedium and components stress and strain tensors.

The waters of the Caspian Sea in 2023, as in previous years, are characterized by high seismicity. The highest density of hypocenters is observed at a depth of 22-68 km. Type of movements in 2023 in percentage: 45% - shift, 55% - reset. The magnitude of the displacements in the source shows that fault-slip type movements predominate here. A total of 19 earthquakes were plotted and analyzed in the Caspian Sea in 2023. These earthquakes are associated with the zone of influence of the Agrakhan-Krasnovodsk, Sangachal-Ogurchi, Shakhov-Azizbekov and Garabogaz-Safidrud faults. Based on these mechanisms, the Lode-Nadai coefficient was constructed. As can be seen in Fig. 2, the sources of Caspian earthquakes are located in the extension zone.

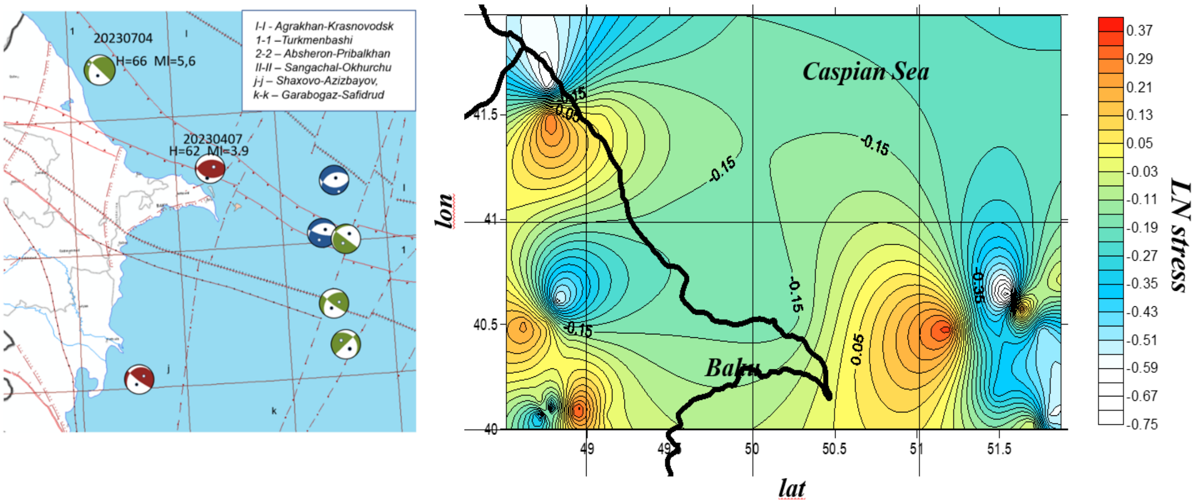


Figure 2. Map of earthquake source mechanisms

Let us dwell separately on two strong tangible centers of the Caspian Sea. On July 4, 2023, local time 00:01, an earthquake occurred in the Middle Caspian Sea, which was felt in Guba, Khachmaz, Shabran, Siyazan up to 6 points, in Sumgait, Absheron up to 5-4 points. The depth of the source was 66 km, magnitude M=5.6, coordinates lat = 41.52; long = 49.10. Then, on December 7, local time 08:15, 70 km southeast of the first source, another earthquake with a magnitude of M=5.6 occurred. This earthquake, like the first one in Altyagach, Siyazan, Guba, Gusar, Khachmakh, Shabran, Gobustan and Absheron, was felt up to 5-3 points. The depth of this earthquake is 68 km, coordinates lat = 40.96; long = 49.53.

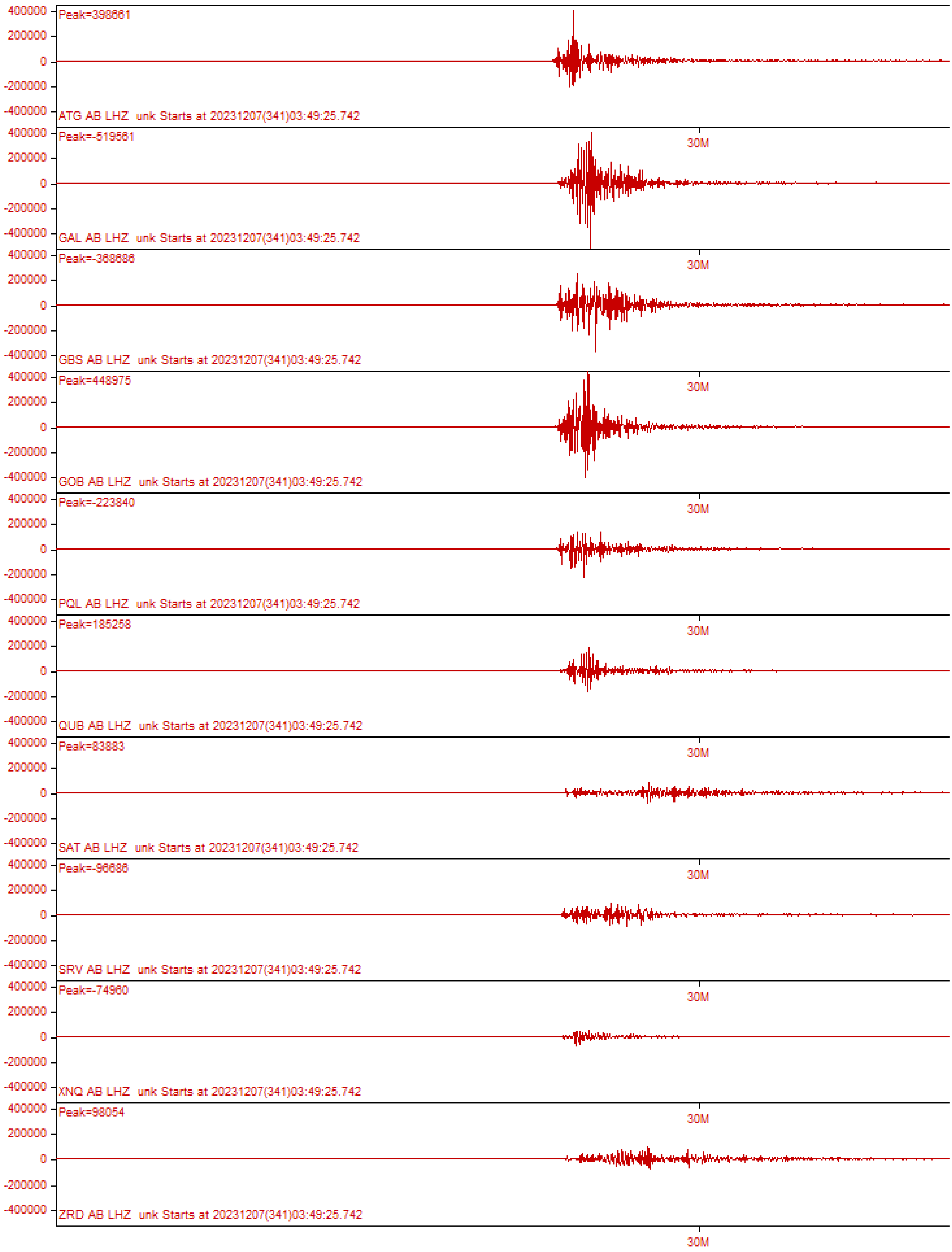


Figure 3. Wave recording the Caspian earthquake of 12/07/2023 via LH channels

Based on a program developed at the University of Oregon by Professor John Nabelek we have constructed a moment tensor for Caspian earthquakes. The rate of seismotectonic deformation directly characterizes the stage of discontinuity of the medium. It is determined by the total seismic moment of a fixed number of earthquakes that have occurred (1) [8]:

$$\acute{\varepsilon}_{i,j} = \frac{1}{2\mu VT} \cdot \sum_{k=1}^{N} M_{ij}^{k}, \tag{1}$$

where $\acute{\varepsilon}_{\mathrm{i,j}}$ - seismotectonic deformation rate tensor, μ - shear modulus in the region of the earthquake hypocenter. This value is determined in accordance with the parameters of the generalized Earth model PREM in the range of values (2,66÷9,76)$\cdot\ 10^{10}$ (Н/м^2). Seismogenic volume $V = \mathrm{SH}$. where S - rupture area, H - depth of the earthquake hypocenter. Other options: T- observation period, N - number of earthquakes и M_{ij}^{k} - seismic moment tensor of an individual earthquake; provided that inelastic movements in earthquake sources are small compared to the size of the seismogenic volume [8]. The last condition is always met. The small strain rate tensor differs from the strain tensor only by a time factor.

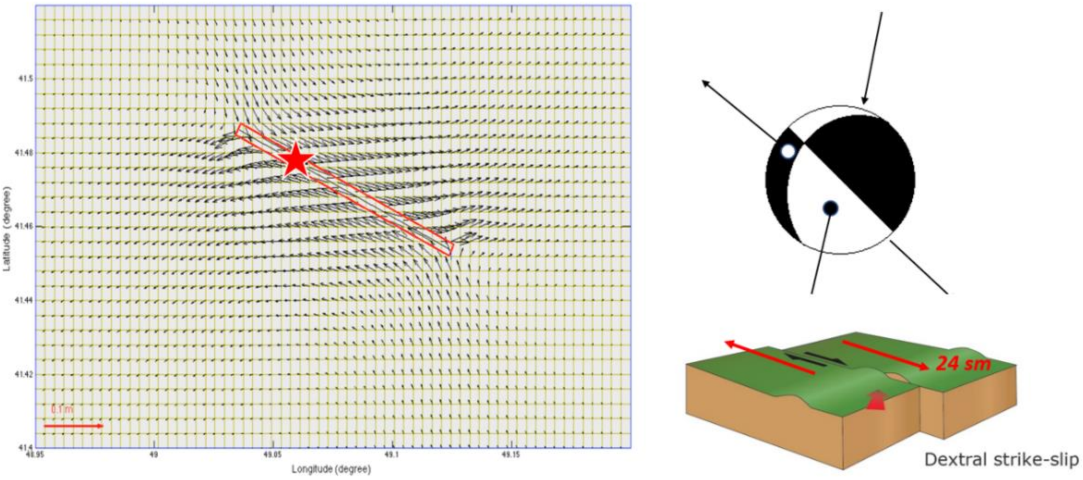


Figure 4. Source mechanism of the Caspian earthquake of 07.04.2023

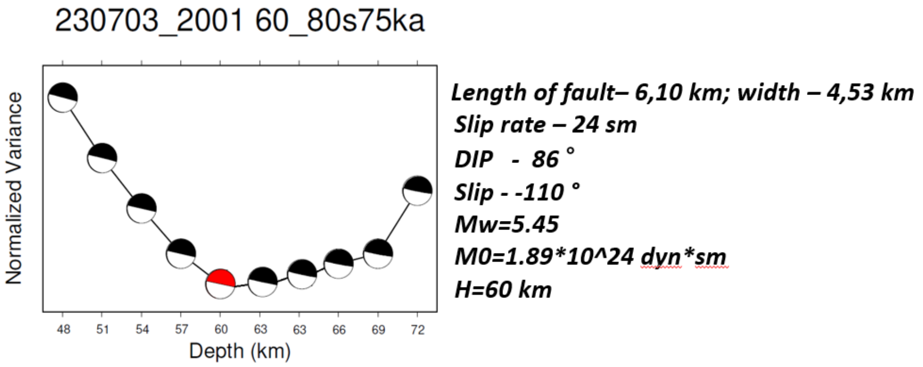
Assuming that during the process of rupture, the direction of shear relative to the rupture plane does not change in the source. the average displacement along the rupture Ū will be determined from the static seismic moment M_0:

$$M_0 = \mu \cdot \bar{\mathrm{U}} \cdot \mathrm{S},$$

where μ is the shear modulus, and S is the area of the rupture surface. The surface area of the rupture is estimated based on the empirical relation:

$$M_W = 0.98 lgS + 4.07 \tag{2}$$

where M_W – moment magnitude of earthquake [8].



Length of fault– 6,10 km; width – 4,53 km
Slip rate – 24 sm
DIP - 86 °
Slip - -110 °
Mw=5.45
M0=1.89*10^24 dyn*sm
H=60 km

Figure 5. Source parameters of the Caspian earthquake of 07/04/2023

The parameters of the source mechanism also include data on the magnitude and orientation of the main axes of the stress tensor released at the rupture. Since the stresses released at the rupture form the inelastic residual displacement in the source zone of the earthquake, they can be called residual. To determine the time of a possible future earthquake, the differences in the absolute values of the principal tension and compression stresses of the residual stress tensor were used: $\sigma_1 - \sigma_2$ [8] In this article, LH channels recorded by digital seismic stations of the RSSC at ANAS were used (fig. 3).

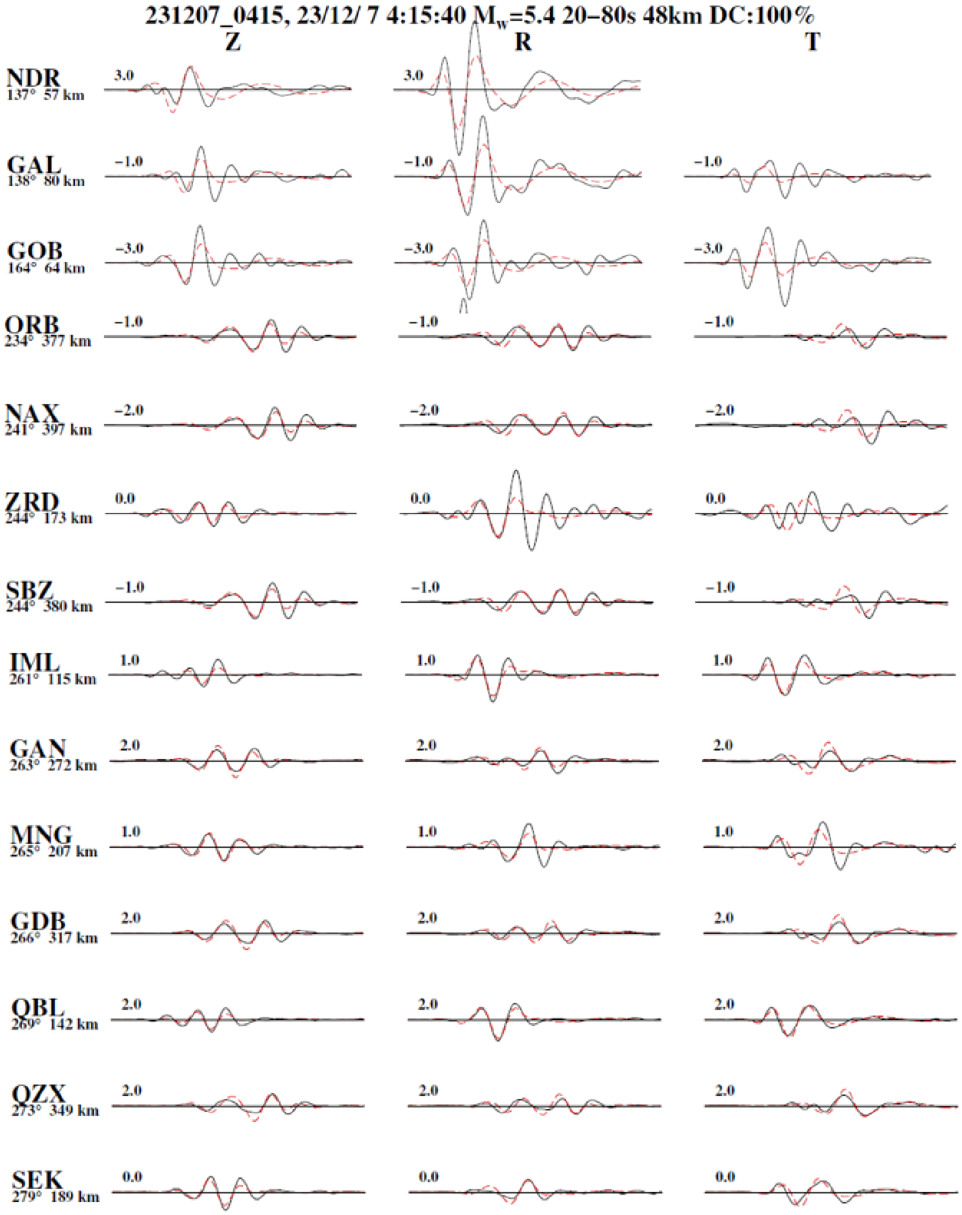


Figure 6. Waveform fitting between observed (black traces) and synthetic (red traces) seismogram of earthquakes of 07.12.2023

The movement in the source of the July 4 earthquake arose under tensile conditions: the axis of tensile stresses is horizontal (PL_P=46°) and oriented in the NE direction (AZM=22°), the axis of compression stresses is also near horizontal (PL_T=43°) and oriented towards SSW (AZM=194°). The movement in the focus along both planes is shear (SLIP=21°, SLIP=94°) (Fig. 4, 5). The angle of incidence is 88°. The orientation of the nodal planes of the NW-SE strike coincides with the strike of the Turkmenbashi longitudinal fault. The moment magnitude was determined to be Mw=5.4. Seismic moment $1.89 \cdot 10^{24}$ dyn·sm. The depth of the source is 60 km. The length of the outbreak was 6.1 km, width – 4.53 km. The movement along the fault was 24 cm.

In the source of the earthquake that occurred on December 7, 2023, according to the solution of the mechanism, movement in the source occurred under conditions of tension. The main tectonic stresses that acted in the source correspond to the near-vertical orientation of the compression axes ($PL_P = 59°$) and the near-horizontal orientation of the extension axes ($PL_T = 5°$). The inclination of the first nodal plane is DP1=57°, the second – DP_2=48°. Type of movement, along the first plane NP_1 with a northwest strike (STK_1=333) and along the second NP_2 with an east-southeast strike (STK_1=99°) shear with fault elements (Fig. 6).

The moment magnitude was determined to be Mw=5.4. Seismic moment $1.56 \cdot 10^{24}$ dyn·sm. The depth of the source is 48 km. The length of the outbreak was 6.58 km, width – 5.49 km. The movement along the fault was 24 cm (Fig. 7).

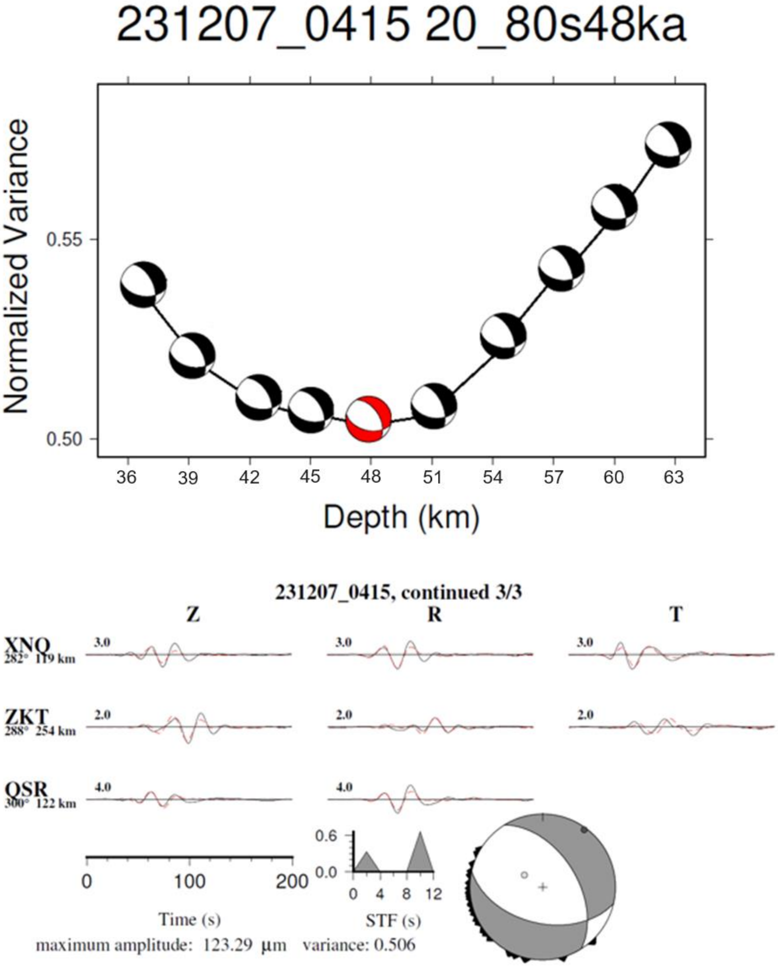


Figure 7. Best solution for DC and depth fitting for best solution DC

Coulomb stress environment of Caspian earthquakes

One of the main provisions of existing earthquake source models is the hypothesis of a high level of tangential stresses in most of the future earthquake source. It is believed that at the last stage of earthquake preparation, these stresses increase to a certain limiting value, and in the process of aftershock activity, stress relaxes in those areas of the source where they remained high after the earthquake. It is also assumed that the higher the intensity of stresses acting in the earth's crust, the higher the value of the released stresses and, therefore, the more destructive an earthquake can occur. However, studies based on the analysis of natural stresses and the results of laboratory experiments force us to significantly correct, and in some aspects, revise such ideas [15]. Based on the results obtained, geological models of the foci of the two Caspian earthquakes were constructed (Fig. 8).

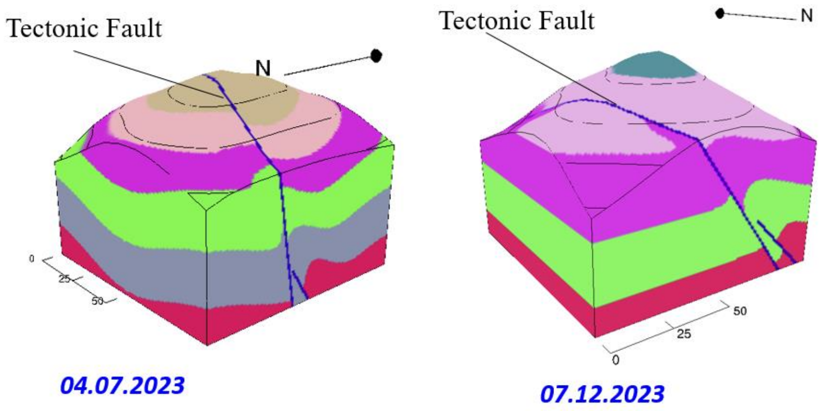


Figure 8. Geological model of the Caspian earthquakes in 2023

In the class of models associated with frictional destruction, direct initiation by dynamic loads is considered, providing the stress increment necessary to exceed the frictional strength of faults, thus leading to the occurrence of unstable slip. Since the use of the classical Coulomb model does not allow us to describe the observed effects, modified models are used to describe the frictional interaction, taking into account second-order effects - the dependence of the shear resistance force on time, speed, loading history, etc. [4]. According to this approach, when seismic waves pass through appropriately oriented faults, instability occurs due to the sum of static and dynamic stresses exceeding the frictional strength limit. As a result, despite the fact that exceeding the strength limit is short-lived, it is often sufficient to produce effects on the dependence of shear strength on speed and time. Such models describe a number of effects that do not follow from the simple Coulomb model. For example, the possibility of a decline in initiated seismicity similar to Omori’s law is allowed. One interesting consequence of friction in the conditionally stable regime is that dynamic stresses can temporarily convert stable slip into stick-slip slip. As discussed, [15], this represents “new seismicity” in the sense that earthquakes generated during the shear process might not have occurred in the absence of dynamic initiation. Subcritical crack growth or stress corrosion is a well-known crack instability process in materials science. The growth rate of small cracks within the fault zone gradually increases due to chemical reactions at the spout between the silicate rock and water. With a sharp dynamic change in the stress-strain state in the vicinity of a crack, especially in the presence of high temperatures and fluids, the growth rate of the defect can increase sharply, which can lead after some time to catastrophic failure. These processes are capable of changing the effective normal stresses enough to initiate failure or aseismic creep. The latter, in turn, after some time can lead to instability. Such models are supported by the fact that geothermal and volcanic areas are the most sensitive to dynamic initiation [15]. A number of proposed models are based on changes in the permeability of individual sections of the crust by dynamic deformations from a distant earthquake through, for example, decolmatation of cracks, thus leading to a redistribution of pore pressure. The fact that changes in permeability can be quite significant is indicated by recently published results, where the permeability value of a granodiorite layer increased several times as a result of the influence of vibrations from distant earthquakes [4].

Figure 9 presents the results of tectonophysical reconstruction of natural stresses for the crust of a section of the Caspian zone, according to data on the mechanisms of earthquake source, with Mw = 5.4. at a depth of 48-60 km. The reconstruction results show that the source of the earthquake of 07.03.2023, with a length of about 50 km, was located in an area of a reduced level of effective pressure (reduced Coulomb friction forces), and the beginning of the “explosion” (epicenter) of the earthquake was located near the place of local increase in effective pressure, which can be considered as a section of delayed shear flow (asperity). The area of increased effective pressure located to the north of the realized source can be considered as a section of the crust with increased Coulomb friction forces, which stopped the movement of the source in this direction. To the south of this source there is also an area of increased effective pressure, but the development of the source stopped 10 km before this section of the crust in a zone where there is no data on the stress state. The latter is due to the absence of a sufficient number of earthquakes, which indirectly indicates a subcritical stress state.

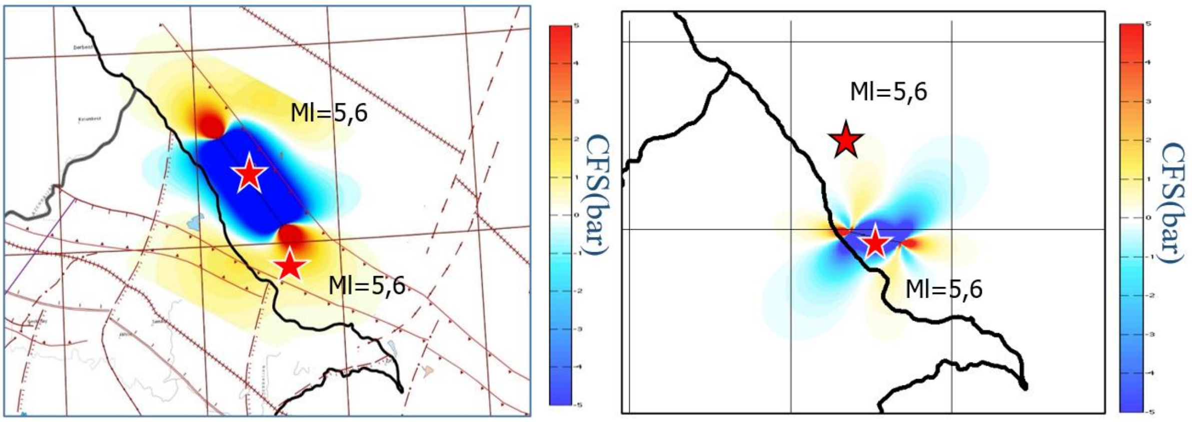


Figure 9. Coulomb stress distribution diagram for the Caspian earthquakes of 07.04.2023 and 12.07.2023.

Let us consider the influence of a rigid block on the initiation of rupture in a fault zone. It is assumed that the study area is under conditions of unequal tension, causing displacement along the fault. Near the fault there is a block that has higher elastic and strength characteristics. In what follows we will call this block rigid. A fault zone, on the other hand, is a strip of weakened material. Shear deformation along the fault due to differences in mechanical characteristics leads to a slight clockwise rotation of the rigid block. As a result of this rotation, zones of decreasing and increasing compression appear, which, in combination with the intensity of shear stresses, determine the distribution of Coulomb stresses that determine the shear strength of the material. Orthogonal to the fault, “tension” occurs as a result of clockwise rotation of the block, while along the fault, “tension” is associated with the action of shear. Obviously, under such conditions, destruction will be initiated in the “tension” region (and primarily orthogonal to the direction of the tension axis, or least compression), that is, the start of fault propagation will occur in the area of intersection of the zone, reducing compressive stresses with the Siyazan fault. In this section of the Siyazan fault, it is possible to stop the propagation of the rupture.

Conclusions

The waters of the Caspian Sea in 2023, as in previous years, are characterized by high seismicity. The highest density of hypocenters is observed at a depth of 42-68 km. Type of movements in 2023 in percentage: 45% – shift, 55% – reset. The magnitude of the displacements in the source shows that fault-slip type movements predominate here. A total of 19 earthquakes were plotted and analyzed in the Caspian Sea in 2023. These earthquakes were associated with the zone of influence of the Agrakhan-Krasnovodsk, Turkmenbashi, Sangachal-Ogurchi, Shakhov-Azizbekov, Siyazan and Garabogaz-Safidrud faults. Based on these mechanisms, the Lode-Nadai coefficient was constructed and it was established that the sources of Caspian earthquakes are located in the extension zone. The solution of the moment tensor showed that the movement at the source of the July 4 earthquake arose under tension conditions. Movement in the source along both planes is shear. The orientation of the nodal planes of the NW-SE strike coincides with the strike of the Turkmenbashi longitudinal fault. The moment magnitude was determined to be Mw=5.4. Seismic moment $1.89\cdot10^{24}$ dyn·sm. The depth of the source is 60 km. The length of the outbreak was 6.1 km, width – 4.53 km. The movement along the fault was 24 cm. In the source of the earthquake that occurred on December 7, 2023, according to the solution of the mechanism, movement in the source also occurred under tension conditions. The type of movement, along the first plane NP_1 of a northwest strike and along the second plane NP_2 of an east-southeast strike, is a strike-slip fault with fault elements. The moment magnitude was determined to be Mw=5.4. Seismic moment $1.56 \cdot 10^{24}$ dyn·sm. The depth of the source is 48 km. The length of the outbreak was 6.58 km, width – 5.49 km. The movement along the fault was 24 cm.

Based on data on the mechanisms of earthquake foci, reconstructions of natural stresses were constructed for the crust of a section of the Caspian zone. The reconstruction results showed that the source of the earthquake of 07.03.2023, with a length of about 50 km, was located in an area of a reduced level of effective pressure (reduced Coulomb friction forces), and the beginning of the "explosion" (epicenter) of the earthquake was located near the place of local increase in effective pressure, which can be considered as a section of delayed shear flow. The area of increased effective pressure located to the north of the realized source can be considered as a section of the crust with increased Coulomb friction forces, which stopped the movement of the source in this direction. To the south of this source there is also an area of increased effective pressure, but the development of the source stopped 10 km before this section of the crust in a zone where there is no data on the stress state. The latter is due to the absence of a sufficient number of earthquakes, which indirectly indicates a subcritical stress state.

Shear deformation along the fault due to differences in mechanical characteristics leads to a slight clockwise rotation of the rigid block. As a result of this rotation, zones of decreasing and increasing compression appear, which, in combination with the intensity of shear stresses, determine the distribution of Coulomb stresses that determine the shear strength of the material. Orthogonal to the fault, "tension" occurs as a result of clockwise rotation of the block, while along the fault, "tension" is associated with the action of shear. Obviously, under such conditions, destruction will be initiated in the "tension" region (and primarily orthogonal to the direction of the tension axis, or least compression), that is, the start of fault propagation will occur in the area of intersection of the zone, reducing compressive stresses with the Siyazan fault. In this section of the Siyazan fault, it is possible to stop the propagation of the rupture.

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