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Original paper

Integrated application of geophysical methods in the South Caspian basin (based on the Bulla-Deniz oil and gas field)

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Abstract: The relevance of the work is due to the fact that the studied territory is located in the collision zone of the Eurasian and Arabian lithospheric plates, where complex structures are formed that have a direct impact on fluid migration, trap formation and seismic activity. Considering that the main hydrocarbon reserves are concentrated at the intersection of tectonically active zones, it is important to identify geodynamic patterns in the Bulla-Deniz field zone, which is one of the largest in the region. This is of key importance both for assessing seismic risks and for planning rational resource extraction. **Aim.** This paper considers the geological and tectonic settings of the Bulla-Deniz structure, as well as the results of seismic studies that are of critical importance for the development of the country's oil and gas industry. **Methods.** The article uses a comprehensive application of geophysical, seismological, seismic tomographic, geodynamic methods, GPS monitoring and drilling to form a holistic view of the geological structure and geodynamic processes of the Bulla-Deniz field. Geophysical studies revealed key anomalies, seismology and seismic tomography clarified deep processes, GPS data described the kinematics of plates, and drilling provided direct data on productive layers. These methods provide a scientific basis for seismic risk assessment, geodynamic situation and efficient development of the field, emphasizing its strategic importance for the oil and gas industry of Azerbaijan. **Results.** Gravity studies have revealed the presence of both regional and local anomalies (Dibrar and East Dibrar maxima) associated with the deep structure and faults. These zones may play an important role in the formation of structures favorable for hydrocarbon accumulation. Seismological data indicate stable activity in the region, especially at depths greater than 35 km. The main types of movements are extension and subsidence, indicating complex earthquake generation mechanisms and potential seismic hazard. Comparison of earthquake focal mechanisms with GPS observations confirms the predominance of extension and strike-slip faults characteristic of the plate collision zone in the Central Caspian Basin. The deep structure of the region includes thin oceanic crust covered by thick sedimentary strata, which creates favorable conditions for the formation of oil and gas systems in depression and fault zones.

Keywords: Bulla-Deniz oil and gas field, the South Caspian Basin (SCB), geodynamical structure, gravitational field, seismological processes, oil and gas potential.

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Оригинальная статья

Комплексное применение геофизических методов в Южно-Каспийском бассейне (на основе нефтегазового месторождения Булла-Дениз)

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Резюме: Актуальность работы обусловлена тем, что исследуемая территория расположена в зоне столкновения Евразийской и Аравийской литосферных плит, где формируются сложные структуры, оказывающие прямое влияние на миграцию флюидов, формирование ловушек и сейсмическую активность. Учитывая, что именно на пересечении тектонически активных зон сосредоточены основные запасы углеводородов, выявление геодинамических закономерностей в зоне месторождения Булла-Дениз, являющегося одним из крупнейших в регионе, имеет ключевое значение, как для оценки сейсмических рисков, так и для планирования рациональной добычи ресурсов. **Цель исследования.** В данной работе рассматриваются геологические и тектонические условия структуры Булла-Дениз, а также результаты сейсмических исследований, имеющие решающее значение для развития нефтегазовой отрасли страны. **Методы исследования.** В статье использовано комплексное применение геофизических, сейсмологических, сейсмотомографических, геодинамических методов, GPS-мониторинга и бурения, что позволило сформировать целостное представление о геологической структуре и геодинамических процессах месторождения Bulla-Deniz. Геофизические исследования выявили ключевые аномалии, сейсмология и сейсмотомография уточнили глубинные процессы, GPS-данные описали кинематику плит, а бурение предоставило прямые данные о продуктивных слоях. Эти методы обеспечивают научную основу для оценки сейсмических рисков, геодинамической ситуации и эффективной разработки месторождения, подчеркивая его стратегическую важность для нефтегазовой промышленности Азербайджана. **Результаты.** Гравиметрические исследования показали наличие как региональных, так и локальных аномалий (максимумы Дибрар и Восточный Дибрар), связанных с глубинным строением и разломами. Эти зоны могут играть важную роль в формировании структур, благоприятных для накопления углеводородов. Сейсмологические данные указывают на устойчивую активность в регионе, особенно на глубинах более 35 км. Основные типы движений – растяжение и погружение, что говорит о сложных механизмах генерации землетрясений и потенциальной сейсмической опасности. Сопоставление механизмов очагов землетрясений с GPS-наблюдениями подтверждает преобладание растяжения и сдвигов, характерных для зоны столкновения плит в Центральной Каспийской впадине. Глубинное строение региона включает тонкую океаническую кору, перекрытую мощными осадочными толщами, что создаёт благоприятные условия для формирования нефтегазоносных систем в зонах прогибания и разломов.

Ключевые слова: нефтегазовое месторождение Булла-Дениз, Южно-Каспийская впадина (ЮКВ), геодинамическое строение, гравитационное поле, сейсмологические процессы, нефтегазовый потенциал.

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Introduction

The territory of Azerbaijan was assessed by seismic intensity at 8–9 points. The zone is located in the seismic Alpine-Himalayan fold belt and covers its seismically active part. In recent years, the interest of international companies in the Caspian sector of Azerbaijan has increased further, and more in-depth research has been carried out using various techniques. Accordingly, a deeper study of the zone has begun and more accurate information about the geological and geophysical structure of the area has been obtained. The basis of the formed database is two-dimensional and three-dimensional seismic data. As a result of all this extensive database, it has become possible to assess the hydrocarbon potential of the zone.

The Bulla Deniz oil and gas field, which is the basis of the study, covers the southwestern part of the Caspian Sea, is located 80 km south of Baku and 35–40 km southeast of the Oil Rocks. In this regard, the study of the field is of great importance, and as a result of the 6.8-magnitude earthquake that occurred in Azerbaijan in 2000, the installation of US-made “Kinometrics” type equipment in the country created conditions for a more in-depth study of both the seismological-geological and geological-tectonic properties of the Bulla-Deniz structure [Aliyev et al., 2010; Guliyev et al., 2015a; Mammadov, Guliyev, 2008; Guliyev et al., 2015b; Guliyev et al., 2012].

Bulla-Deniz oil and gas field

The Bulla-Deniz oil and gas field was first discovered in 1973, and exploitation began in 1975. Their location at such a depth, as well as the presence of layers with complex geological structures, sometimes causes serious difficulties [Guliyev et al., 2016]. However, the geophysical studies conducted have made it possible to more accurately study the geological structure of the productive layer. This has ensured more efficient extraction of hydrocarbons in the research area, as well as in the fields adjacent to it [Kadirov, 2006]. In a result of geological studies, it was determined and revealed that it is distinguished by high anomalous reservoir pressures. In recent years, scientific research conducted on this structure has been aimed at a detailed study of the geological properties of the layers, their petrophysical indicators and production capabilities. [Guliyev, Alizadeh, 2020; Abuzarova, 2024; Ahmadov, 2020; Yusifov et al., 2015]. The field is considered more relevant than other fields in terms of hydrocarbon production. An example of this is the well No. 123 drilled in the field with a depth of 6,132 meters. This well was drilled in 2017, produced 104,000 tons of condensate and 472 million cubic meters of gas in 2017 alone. In total, 69.9 billion cubic meters of gas and 12.4 million tons of oil and condensate were produced until last year [Guliyev, Alizadeh, 2020; Abbasov, Guliyev, 2019]. Based on all these indicators, it can be said how important the field is in the country’s energy security and the international energy market. Also, the Bulla Deniz oil and gas field plays an important role in further strengthening the role of Azerbaijan in the international arena from an economic perspective [Guliyev et al., 2016; Feyzullayev, Mammadova, 2022; Yusubov, Shikhmammadova, 2022].

Research methods

The Bulla-Deniz field is located in the South Caspian basin within the shelf zone of the Caspian Sea and complex research methods were used to assess the geological-structural features, tectonic structure and seismic activity of this field. This includes geophysical, seismological, seismic tomographic and geodynamic approaches, as well as analysis of GPS monitoring data and data obtained as a result of drilling operations. Each method provides an indepth analysis of geodynamic processes and productive layers through specific tools and procedures [Sikorskaya, 2025; Serikova, Allanazarova, 2023].

The Bulla-Deniz field is an area with a complex geological structure. For the first time, gravimetric studies were carried out here in 1952 with high-precision instruments. As a result of these studies, anomalously high reservoir pressures were detected and it was determined that these reservoir pressures can cause various technical and safety problems during the exploitation or drilling process. As a result of the conducted research, an upper pressure zone (600–1200 m) and a deep pressure zone (approximately 5 km or deeper) were discovered here [Feyzullayev, Lerche, 2009; Mammadov, 2022; Mirzayev et al., 2019].

Earthquake monitoring was carried out through the network of stations of the Seismological Survey Center of the Republic of Azerbaijan. Through this network, earthquakes with a magnitude of $M \geq 5.0$ that occurred in Baku and in the Caspian Sea were recorded. Then, data were collected based on the fund data received from the digital stations of the Seismological Survey Center of the Republic of Azerbaijan for 2003–2024 and seismicity analysis was conducted using this data. Also, the depth of earthquake occurrence during these years was found and a seismicity map of earthquakes with magnitudes $m_l \geq 0.1$ and $m_l \geq 3.0$ was compiled. The results of all these analyses made it possible to build a diagram reflecting the relationship between the number of earthquakes that occurred and the energy released at that moment. Thus, 192 earthquakes were detected in 2023, and peaks of activity were also detected in 2011, 2020 and 2023. The obtained data were collected in a database up to a depth of 70 km and two-stage (2D) seismic tomographic sections were prepared using the ArcGIS program. Analysis of geodynamic processes and GPS observations played a key role in determining the focal mechanisms of tectonic movements and earthquakes. The analysis of focal mechanisms conducted using the “MomentTensor” program showed that during 2003–2024, extensional and subduction-type movements predominated in the Central Caspian basin, while uplifts accompanied by faults were observed in the North Caspian zone. GPS monitoring was carried out using the GAMIT software and the directions and speeds of tectonic plate movements were determined with high accuracy. For this purpose, the Regional Seismic Stations Network was used.

Characteristics of the Gravity Field of the South Caspian Basin

One of the indicators reflecting the complex geodynamic and tectonic structure of the South Caspian Basin is the gravity field of the zone. Since the South Caspian Basin is promising in terms of oil and gas, the gravity anomalies observed in the area have aroused interest by a number of researchers. The cause of the -193 mGal gravity anomaly observed in the center of the Caspian Basin was determined to be the subsidence of the continental plates. It was also found that the reason for the existence of the gravity model is related to the location of the basin in an active tectonic zone [Kadirov, 2006].

In the Caspian Sea, the gravity anomaly is mainly estimated higher in the Middle Caspian, with more anomalous areas collected in the western part of the basin. Here, the highest gravity anomaly value was determined to be 60 mGal, and the lowest anomaly value was -130 mGal. In the study area, the thin consolidated crust and the gravity minimum coincide. As a result of the studies, it is assumed that a Benioff zone existed between the Lesser Caucasus and South Caucasus massifs [Guliyev et al., 2012]. The Bulla Deniz oil and gas field area of the South Caspian Basin is characterized by a relatively weak-medium gravity anomaly value. It varies between approximately -80 mGal and -10 mGal (fig. 1).

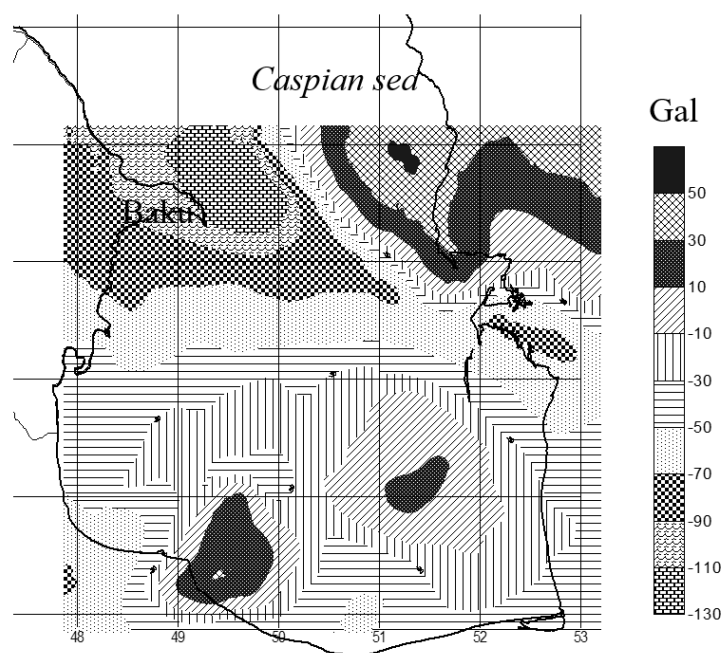


Fig. 1. South Caspian Gravity Anomalies / Гравитационные аномалии Южного Каспия

Seismological investigation

Since ancient times, the region is considered to be seismically active and has experienced major earthquakes. They include the 957 Caspian earthquake, which resulted in coastal alterations and the formation of new islands, the 1990 magnitude 7.4 Caspian earthquake in Iran, which resulted in fatalities, the 2000 magnitude 6.8 Caspian earthquake in Azerbaijan, which resulted in migration of seismic activity and stress variations, and so on. An example can be given [Yetirmishli et al., 2022].

Earthquake data of the “Bureau of Earthquake Research” of the Republic Seismological Service Center of the National Academy of Sciences of Azerbaijan were analyzed during the years 2003–2024, and using the fund data, earthquakes that occurred in the research area during those years were selected and a graph reflecting the statistics of earthquakes with the seismic energy released at the time of occurrence of those earthquakes was created. (Graph 2). The established graph shows the dependence between the number of earthquakes and the energy released at the moment of their occurrence. Here, the number of earthquakes is shown as red columns, and the amount of released energy is shown as blue lines. During the analysis of the visual image, it was observed that the number of earthquakes in the study area was the highest in 2011 (157 earthquakes) and 2023 (192 earthquakes), but the number of earthquakes between 2003–2024 reached its highest level

in 2023. However, weak seismic activity was observed in 2003–2009. Moderate seismic activity was observed in 2010, 2024 and 2012–2022.

The graph (fig. 2) reflecting the statistics of earthquakes in the Caspian Sea during 2003–2024 shows the changes between the number of seismic events by year (red columns) and the seismic energy released during that period (blue line). Visual analysis shows that the number of earthquakes has increased significantly since 2010 and this increase has continued in the following years, reaching a peak in 2023 with 192 earthquakes. The years 2020 and 2022 were also seismically active periods – in 2020, both the number of earthquakes and the amount of energy released increased dramatically. If we look at the amount of allocated energy, although the amount of allocated energy in 2011 is consistent with the number of earthquakes, it seems that in 2023 this agreement is not observed. At the same time, high seismic energy was released in the years when little seismic activity was observed. As a result of all this, there was no regular increase or decrease in the energy released by the number of earthquakes during these years. This can be directly based on the distribution characteristics of the cells as well as the mechanisms of their formation.

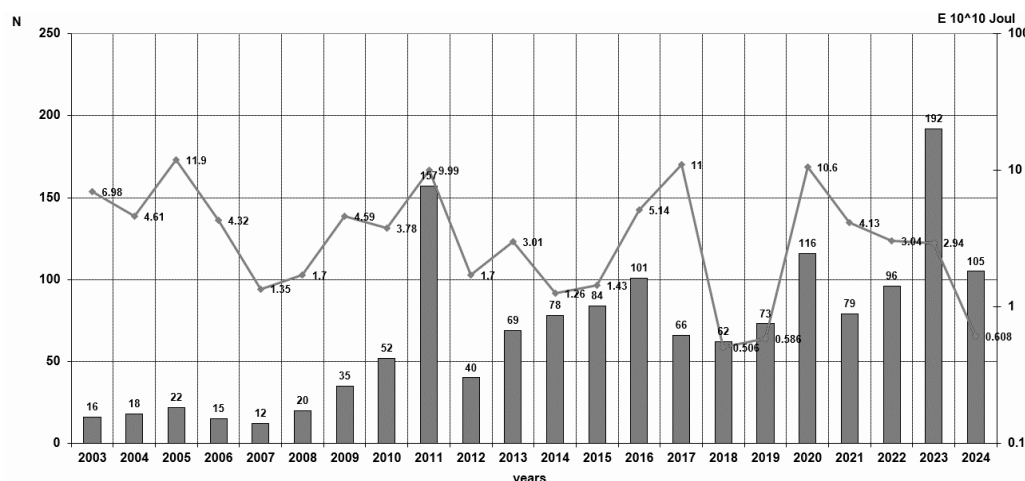


Fig. 2. Graph showing the relationship between the number of earthquakes and seismic energy released in the Caspian Sea from 2003 to 2024 / График, показывающий зависимость между количеством землетрясений и выбросами сейсмической энергии в Каспийском море с 2003 по 2024 год

Distribution of earthquake hypocenters by depth and distribution by region

Based on the number of earthquakes that occurred in the study area, their depths were selected by us and a diagram reflecting the relationship between them was constructed. (fig. 3). Based on the constructed diagram, the distribution of earthquakes by region was assessed. As a result of the comparative analysis, it was found that a large part of the earthquakes occurred in layers 30 km and deeper. Thus, it is possible to make a conclusion about the distribution of the earthquakes that occurred according to the tectonic structure. Unlike the relationship between the number of earthquakes and the energy released, a certain regularity was found between the number of earthquakes and the depth at which they occurred. That is, the geodynamic activity formed in deeper layers causes the occurrence of seismic events.

In figure 4, using the data of the Seismological Service Center of the Republic of Azerbaijan, earthquakes recorded in the Caspian Sea area during 2003–2024 were

selected according to their intensity and maps were drawn up accordingly. On the left side, a map of the epicenters of earthquakes that occurred during the years 2003–2024 is compiled, and it is shown that low-magnitude earthquakes occurred in the central and southeastern part of the Caspian Sea. On the right side, the distribution of earthquakes with a magnitude of $m_l \geq 3.0$ is reflected. Thus, it can be seen that strong earthquakes in the zone have spread from the northeast to the southwest during these years. Thus, it can be said about the uneven distribution of seismic activity in the area.

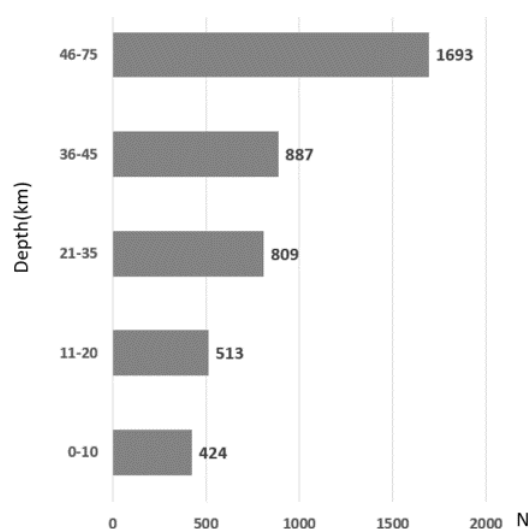


Fig. 3. Graph showing relationship between number of earthquakes and depth / График, показывающий зависимость между количеством землетрясений и глубиной залегания

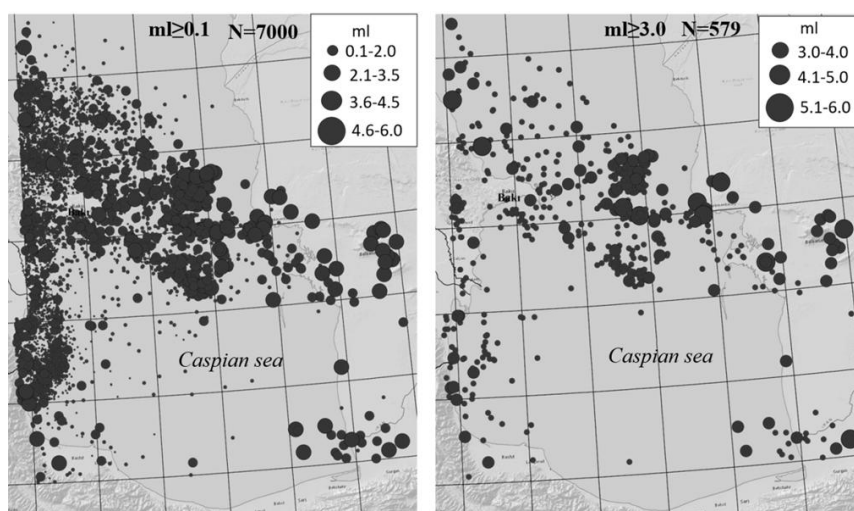


Fig. 4. Map of earthquake epicenters in Bulla-Deniz for 2003–2024 / Карта эпицентров землетрясений в Булла-Дениз на 2003–2024 гг.

In the South Caspian Basin, the majority of hydrocarbons are found in fault zones and their contact zones. For example, Bulla-Deniz, Gunashli, Neft-Dashlari, etc., which are located at the intersection of active tectonic zones or near them, constitute the basis of hydrocarbon production in the basin [Reynolds, Simmons, 2007].

In general, researchers have determined that the transition zones between the Karabogaz Uplift and the South Caspian Depression had a fragmented block-structural

model due to these tectonic activities [Ghassemi, Garzanti, 2019].

The map reflecting the distribution of seismic activity covers the period from 2003 until 2023. The right part of the constructed maps shows the level of seismic activity, expressed in different colors, increasing from minimum to maximum. Seismic activity in the Bulla-Deniz oil and gas field in 2003–2013 was estimated to be moderate at SSA 0.4–1.2, and in 2014–2023 at SSA 0.3–1.1 (fig. 5).

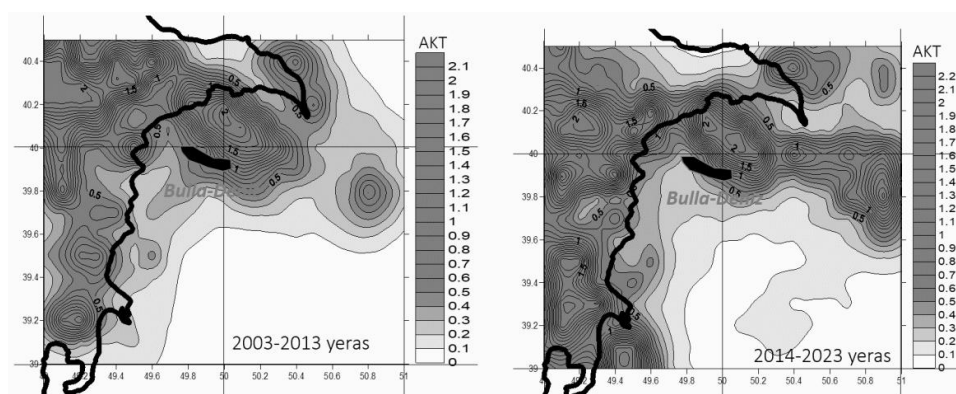


Fig. 5. Map of Seismic Activity on the Southern Caspian for the Periods 2003–2013 and 2014–2023 / Карта сейсмической активности на Южном Каспии за периоды 2003–2013 и 2014–2023 гг.

When analyzing the areas with high seismic activity in the region from 2003 to 2013, it can be seen that high activity is mainly concentrated in the central and NW parts of the study area. The total activity was determined to be about 1.5. However, when looking at the seismic activity in the study area during 2014 and 2023, it can be seen that the increase in activity occurred mainly in the central and SW parts. Based on all this, seismic activity has also increased in the Bulla-Deniz area and the seismic activity in the area was above 1.5. As can be seen from the maps, a decrease and redistribution of seismic activity has been observed in the area over the past 20 years. Even in the southern expanse of the area, where seismic activity was identified relatively little or not at all before the indicated period, newer active zones were created during this period. If we look at the northern part of the region, compared to the southern zone, it was observed that the seismic activity decreased relatively during 2003 and 2013. From 2013 to the present, seismicity in the region has expanded in the east and south directions. Thus, when looking at the research area, it was observed that the seismic activity remained stable, and even increased slightly. The maps show long-term changes in seismic activity, which are important for earthquake prediction and geodynamic assessment of the region. Figure 6 shows two seismic profiles. These seismic profiles reflect the distribution of earthquake epicenters based on depths. In the left part a map of seismic events is presented with earthquake epicenters classified in different colors according to their strength. The black lines numbered 1 and 2 reflect the profiles and directions of their intersections. In the upper right part, the distribution of earthquake depths in the Bulla-Deniz area is shown. The image shown is set in a southwest (SW) direction. In the lower left part, 3.0 magnitude earthquakes are shown as small circles, and 4.0 to 5.0 magnitude earthquakes are shown as red circles. Looking at figure 6, it can be seen that high-magnitude earthquakes occur in the depth range between 0 and 50 kilometers. However, a small number of seismic activity occurs at greater depths. Looking at the distance axis, it is observed that stronger earthquakes occur in the interval from 150 to 400 kilometers.

The profile shows a similar distribution of seismic activity, with a slightly different location. Here, however, the main seismic activity occurred in the interval from 10 to 50 kilometers.

Seismic activity in this area is of great importance for the efficiency of hydrocarbon production. Therefore, when looking at the range of earthquake occurrence, it is possible to observe that they occur at depths of 0-50 km. The active fault zones here are mainly associated with areas of increasing earthquake concentration. Earthquakes with a magnitude of 4.0–5.0, shown as large circles occur more frequently at shallow and intermediate depths and are distributed throughout the profile.

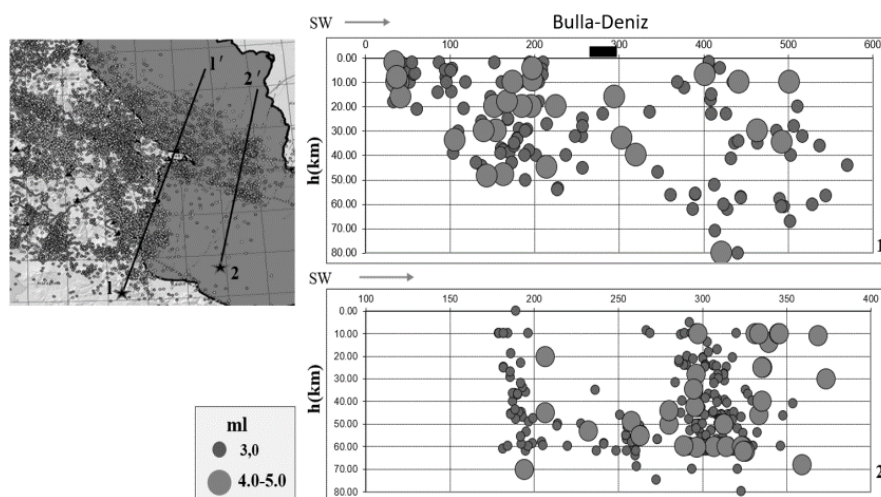


Fig. 6. Map of Caspian earthquake epicenters, along with two seismic profiles showing earthquake distribution by depth / Карта эпицентров каспийских землетрясений, а также два сейсмических профиля, показывающих распределение землетрясений по глубине

Earthquake focal mechanisms

The formation of earthquake focal mechanisms was also analyzed by us. Seismological studies were conducted in the research area, and a number of conclusions were drawn based on the analysis of the focal mechanisms of the earthquakes that occurred. The analysis was carried out comprehensively, taking into account tectonic elements, seismic faults, etc. As a result of the analysis, it was determined that in general, expansion-deepening movements prevail in the region, which is characteristic of expansion geodynamic conditions.

Deep structure of the studied region

The South Caspian Depression has a deep structural structure and is a tectonic depression consisting of sedimentary rocks. The study area in the current structural map, the Caspian region is characterized by a heterogeneous and diverse thickness of sedimentary rocks of more than 10 km belonging to the last quaternary period and is characterized by high activity both in terms of sedimentary dynamics and tectonic dynamics. The thickness of sedimentary rocks formed as a result of the sedimentary accumulation process in the region is estimated to be 25 km or more. The South Caspian megadepression is located on the oceanic crust and is characterized by a high rate of sedimentation. In addition, the zone has a complex tectonic structure as a result of the analysis of the above-mentioned depth characteristics. The sedimentary complexes located here have created a favorable

environment for the generation of hydrocarbons. Also, the earthquakes that occurred in the zone are associated with the subduction process [Abdullayev et al., 2023; Jackson et al., 2002].

Based on the background data of the Azerbaijan Republic Seismological Service Center, the depth, strength and other parameters of the earthquakes were analyzed, and the seismotomographic structure was studied based on all these data. That is, based on the seismic waves occurring in the study area, a three-dimensional model of the zone was built. Through seismography, the opaque properties of various geological structures, that is, the characteristics of anomalies, are studied. As a result of seismographic analyses conducted in the zone, it was determined that most of the earthquake foci that occurred were formed mainly at a depth of 50–70 km. Also, the presence of coke-like geological structures in the zone and the presence of a tectonic structure were proven. Also, a deep subduction zone was observed in the study area. Here, the transition zone and the Mokhorovicic boundary, unlike other geological zones, is located at a depth of 50–55 km [Abdullayev et al., 2023; Jackson et al., 2002; Kazimova et al., 2024; Kerimova, Samadli, 2024; Huseynov et al., 2019]. Thus, the deep structures of the Absheron-Balakany system can be shown. Here, the crust belonging to both the Mesozoic and Cenozoic eras was formed. However, the general nature of the formation is associated with a thin oceanic crust. Here, the thickness of the oceanic crust is estimated to be approximately 35 km. Deeper horizons consist of sediments covered with a basalt layer. The thickness of the layer here is estimated to be less than 22 km. These sediments were formed mainly in the modern period.

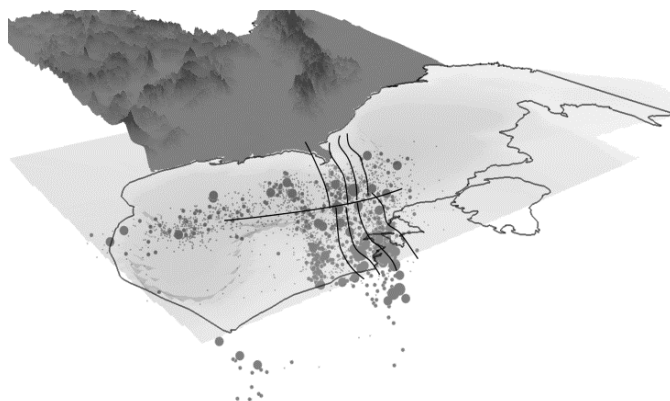


Fig. 7. 3D model of earthquake hypocenters occurring in the Caspian Sea in 2017–2024 /
3D-модель гипоцентров землетрясений, произошедших в Каспийском море в 2017–2024 гг.

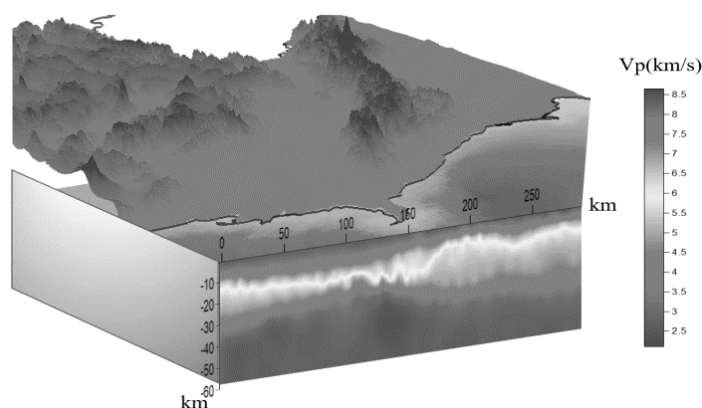


Fig. 8. 2D seismic tomography section in the SW to NE direction / 2D сейсмотомографический разрез
в направлении SW-NE

Discussion of results

Based on the above data, it can be said that the geodynamic activity of the study area is formed as a result of the interaction of tectonic plates as well as geological processes taking place in deep layers. The distribution of earthquake focal points in the Southern Caspian Basin with respect to depth and the distribution of tectonic stresses both near the surface and on deep faults have an impact on the assessment of seismic risk.

Therefore, additional studies are needed on fault mechanisms and stress transfer resulting from the discrepancy between the frequency of earthquakes and the amount of energy released to the region during earthquakes. The role of the collision zone is very important in the tectonic model of the area, additional forces within the basin (from the Arabian plate) and geodynamic processes create a complex stress field. This regime is directly responsible for creating favorable conditions for oil and gas accumulation. A thin crust and a thick sedimentary cover have been identified in the zone by seismic tomography, and it has been observed that the thick sedimentary cover increases the hydrocarbon potential.

Results

Comprehensive analysis of geophysical, seismological and tectonic data for the Southern Caspian Basin region, including the Bulla-Deniz region, allows us to identify a number of stable patterns that characterize the geodynamic development and oil and gas potential of the study area.

The results of gravimetric studies revealed the presence of regional and local anomalies, in particular the Dibrar and East Dibrar maxima, which reflect the features of the deep structure and interaction of tectonic blocks. The structure of the gravity field is closely associated with active uplift faults and zones, which confirms their role in the formation of tectonic relief and potential traps for hydrocarbons.

Seismological analysis showed stable seismic activity in the region over the last two decades with a marked concentration of epicenters at depths of more than 35 km. The high density of hypocenters in the subduction zone is particularly significant and may indicate the presence of active deep processes and possible seismic hazard. Data on the distribution pattern of earthquake foci and the released energy allow us to conclude that the mechanisms of seismic event formation are heterogeneous, with expansion and subsidence predominating.

Analysis of earthquake focal mechanisms in comparison with modern GPS observational data confirms the predominance of extensional and shear movements in the Central Caspian Depression. This is consistent with the model of tectonic interaction of lithospheric plates in the region, where the Eurasian and Arabian plate converge.

Conclusions

The South Caspian Basin is a geologically dynamic region characterized by significant gravity and magnetic anomalies, intense seismic activity and complex plate interactions. Integrated analysis of geophysical and seismic data reveals a basin shaped by extensional tectonics, deep fault systems and compressional forces from converging plates. Persistent seismic activity, particularly in the Bulla-Deniz area, highlights the need for ongoing hazard monitoring and assessment. The basin's thin crust and thick sedimentary sequences, along with fault-controlled structures, make it a key target for hydrocarbon exploration.

Future research should focus on refining fault models, improving earthquake prediction and understanding deeper crustal dynamics to enhance seismic risk management and resource development in this critical region.

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