Nafta-Gaz 2026, no. 1, pp. 46–51, DOI: 10.18668/NG.2026.01.04

Studying radioactive fields and geodynamic regime in oil-producing depression zones of Azerbaijan

Badanie pól radioaktywnych i reżimu geodynamicznego w zagłębiach naftowych Azerbejdżanu

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ABSTRACT: The issue of radioactive fields in oil-producing depression zones is one of the important directions among studies of depressions where the thick cover of Quaternary formations makes it difficult to identify active structures, geodynamic zones, non-anticlinal traps which are associated with prospective oil-bearing areas in Azerbaijan. Our research has established that gamma anomalies form under the influence of tectonogenesis and are controlled by deep-seated tectonic activity. Regardless of trap type, subsurface hydrocarbon accumulations manifest in surface gamma fields as negative anomalies. This has stimulated further development of radiometric methods for addressing various issues related to geological processes and the exploration of oil fields. Our previous studies indicate that the radioecological situation in certain areas can be considered hazardous due to the increase in background radiation. To stabilize the radioecological situation and reduce the background radiation as far as possible, analyzing the causes responsible for the rise in background radiation in a given territory is of high relevance. Natural background radiation on the ground surface is conditioned by radioelements found in the uppermost layer of the Earth's crust, as well as by the influence of the deep tectonic processes. The concentrations and ratios of radioactive elements in any area result from various geological processes occurring deep within the Earth. Our research established a correlation between radioactive anomalies, geophysical fields and modern vertical movements of the Earth's crust.

Keywords: radioecological situation, radiation background, oil production, radiometric and gamma spectrometric methods.

STRESZCZENIE: Zagadnienie pól radioaktywnych w zagłębiach naftowych stanowi jeden z istotnych kierunków badań dotyczących zagłębień, gdzie pod grubą pokrywą utworów czwartorzędowych trudno jest zidentyfikować aktywne struktury, strefy geodynamiczne oraz nieantyklinalne struktury akumulacji, które są powiązane z potencjalnymi obszarami roponośnymi Azerbejdżanu. Nasze badania wykazały, że powstawanie anomalii gamma zachodzi pod wpływem tektonogenezy i jest determinowane aktywnością tektoniczną wnętrza Ziemi. Niezależnie od typu struktury akumulacji, nagromadzenia węglowodorów w strefie podpowierzchniowej znajdują odzwierciedlenie w polu gamma powierzchni Ziemi jako anomalie ujemne. Stanowiło to bodziec do dalszego rozwoju metod radiometrycznych służących rozwiązywaniu różnych zagadnień związanych z procesami geologicznymi oraz poszukiwaniami złóż ropy naftowej. Nasze wcześniejsze badania pozwalają stwierdzić, że sytuacja radioekologiczna na niektórych obszarach może być uznana za niebezpieczną ze względu na wzrost promieniowania tła. W celu stabilizacji sytuacji radioekologicznej i zmniejszenia promieniowania tła w jak największym stopniu, szczególnego znaczenia nabiera analiza przyczyn odpowiedzialnych za wzrost promieniowania tła na danym terytorium. Naturalne promieniowanie tła na powierzchni Ziemi jest uwarunkowane obecnością pierwiastków promieniotwórczych w najwyższej warstwie skorupy ziemskiej, a także wpływem głębokich procesów tektonicznych. Stężenia i proporcje pierwiastków promieniotwórczych na danym obszarze zależą od różnych procesów geologicznych zachodzących we wnętrzu Ziemi. W naszych badaniach ustaliliśmy korelację pomiędzy anomaliami promieniotwórczymi, polami geofizycznymi oraz współczesnymi ruchami pionowymi skorupy ziemskiej.

Słowa kluczowe: sytuacja radioekologiczna, promieniowanie tła, wydobycie ropy naftowej, metody radiometryczne i gamma-spektrometryczne.

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Article contributed to the Editor: 10.03.2025. Approved for publication: 17.12.2025.

Statement of the problem

The aim of this research is to explore the patterns and conditions of the formation of radioactive fields in oil-producing depression zones of Azerbaijan, their connections with the deep structure of the Earth's crust and tectonic activity, and to search for oil and gas-bearing structures by radiometric methods in combination with other geophysical studies.

To address these objectives, the radioactive fields of oil--producing depression zones and the concentration of radioactive elements in various lithological and stratigraphic rock complexes were studied, while also developing the principles of radiometric and geophysical methods. In particular, it was necessary to identify the relationship between gamma-radiation intensity and the morphology of gamma structures characteristic of the studied zones.

Material and methods

Radiometric and gamma spectrometric methods have a well-established theoretical and methodological foundation (Durrance, 1986; Minty, 1997; IAEA, 2014). In accordance with the objectives of the study, the investigated area was subjected to a series of gamma surveys aimed at measuring the total gamma-radiation field. The main goal was to integrate available radiometric data and construct a detailed map of natural radioactivity within the studied oil and gas zone, enabling a comprehensive analysis of background distribution patterns (Aliyev and Kazimova, 2023).

Field sampling and study area

Rock samples for laboratory gamma-spectrometric analyses were collected from different lithological complexes and anomalous zones identified during the field radiometric survey. The study area covers a segment of the Absheron Peninsula, which is part of the Absheron Formation belonging to the Upper Pliocene–Lower Quaternary sedimentary sequence. This formation is composed mainly of clayey, sandy-clayey, and marly deposits of shallow marine and continental origin (Brückner et al., 2003). These deposits are characterized by variable textural and mineralogical composition, influencing their radiometric properties and natural radionuclide content.

A total of 115 samples were systematically collected from representative lithological outcrops to ensure adequate spatial coverage of both background and anomalous areas. The sampling network was designed based on lithological boundaries and geomorphological features to capture local and regional variations in natural radioactivity.

Instrumentation and laboratory analysis

Gamma-spectrometric measurements were performed using a NaI(Tl) scintillation detector (3" × 3" crystal) coupled with a multichannel analyzer. The detector was calibrated using reference radioactive sources of known activity for potassium (K-40), uranium (Ra-226), and thorium (Th-232) series isotopes. Energy calibration was verified prior to each measurement session to ensure spectral stability and measurement accuracy.

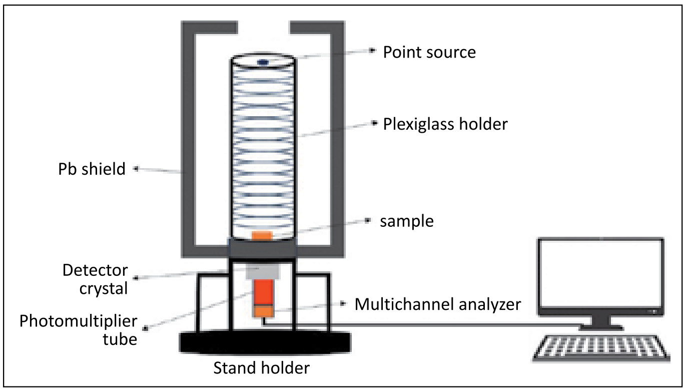

Figure 1. NaI(Tl) scintillation detector and its components (source: Nuclear-Power.com, based on Wikipedia, CC BY-SA)

Rysunek 1. Detektor scyntylacyjny NaI(Tl) i jego elementy składowe (źródło: Nuclear-Power.com, na podstawie Wikipedii, CC BY-SA)

Each rock sample was dried at 105°C for 24 hours, ground, homogenized, and sealed in Marinelli beakers for at least 30 days to establish secular equilibrium between radon and its progeny. Measurements were conducted under controlled laboratory conditions, with acquisition times ranging from 1800 to 3600 s, depending on sample activity. The minimum detectable activity (MDA) for the detector system was determined according to IAEA guidelines (IAEA, 2014).

Data processing and statistical evaluation

The obtained spectra were processed using standard software to determine the specific activity concentrations of K, U, and Th. All radiometric data were corrected for background radiation and detector efficiency. Confidence intervals were assessed at the 90–95% confidence level, confirming the statistical significance of the results. These evaluations demonstrate that the dataset is sufficiently representative to describe geochemical and radiometric variability within the Absheron Formation.

We based the above-mentioned analysis on classical inferential statistical methods, which allowed us to assess the reliability of mean gamma field rates at a 90–95% confidence level, ensuring that the obtained averages are statistically representative of the radiometric variability within the studied formations (Table 1).

Table 1. Radiometric variability within the studied formations
Tabela 1. Zmienność radiometryczna w badanych formacjach

Depression	Mean value [µR/h]	± Error [µR/h]	*n* [number of measurements]
Lower Kura	5.0	±0.5	$n = 12$
Middle Kura	6.0	±0.5	$n = 10$
Absheron	4.0	±0.8	$n = 8$
Caspian-Cuban	4.0	±0.6	$n = 9$

These ±0.5 and ±0.8 values can be considered 90–95% confidence intervals if calculated as follows (Davis, 2002):

$$C = \bar{x} \pm t_{(0.95n-1)} \cdot \frac{s}{\sqrt{n}} \tag{1}$$

where:
$\bar{x}$ – mean value,
s – standard deviation,
n – number of samples,
$t_{(0.95n-1)}$ – t-coefficient (approximately 1.96 for 95% confidence).

The coefficient of variation (CV) for the gamma field values ranges between 10–15%, which is generally regarded as stable and reliable for geological and radiometric studies. The narrowness of the 90–95% confidence intervals (±0.5–1.0 µR/h) indicates that the measured data exhibit low dispersion, implying that the dataset is representative and homogeneous in nature.

The confidence intervals for the mean gamma field rates were calculated using the t-distribution at the 90–95% confidence level. The resulting intervals (±0.5–1.0 µR/h) indicate a low relative variance ($CV = 10–15\%$), confirming the statistical stability and representativeness of the dataset. The close agreement between the calculated and fixed gamma field rates ($\Delta \leq 1.0$ µR/h) further supports the reliability of the obtained results in characterizing the geochemical and radiometric variability within the Absheron Formation and adjacent depressions.

Furthermore, the difference between the calculated and fixed (reference) values is minimal (on average 0.8–1.0 µR/h), confirming the accuracy and robustness of the model.

Geology and tectonics

In the Absheron region, the productive stratum is represented by a rhythmic alternation of sandy-silty and clayey rocks and characterized by high-capacity reservoirs with good filtering properties, serve as an industrial oil-gas bearing suite for the peninsula. Favorable conditions for the formation of deposits are typical of the sandy reservoirs of the Akchagyl-Absheron stages. The Akchagyl Stage corresponds to the Late Pliocene, while the Absheron Stage belongs to the Early Pleistocene epoch. These stages are characterized by rhythmic alternations of sandy, silty, and clayey sediments that form productive oil–gas-bearing strata across the Absheron Peninsula and adjacent areas.

When sedimentary rocks are formed under conditions of primary sedimentation dispersion, radioactive elements are distributed in accordance with the known patterns. Accordingly, the concentration of radioactive elements increases from limestones and sandstones to clays, and the dependence of gamma radiation on the facies composition of rocks is expressed by equation (2) shown below (Young et al., 2016):

$$\bar{y} = AlgC_f + B \tag{2}$$

where:
$\bar{y}$ – natural radiation background, expressed in [µR/h],
C_f – fraction content [%],
A and B – experimentally determined coefficients.

The formation of sedimentary strata is closely related to the geotectonic regime, the change of transgression periods and the proximity of sources of demolition. The facies composition of the strata reflects all phases of uplifts and periods of sediment accumulation.

The depression zones in the western edge of the South Caspian Depression – Kura, Absheron, and Caspian-Cuban – have played a huge role in the geological history of Azerbaijan. The major parts of the industrial reserves of oil and gas and the prospects of oil production in Azerbaijan are associated with these zones.

The most important oil and gas complex consists of the productive Pliocene strata. The oil and gas bearing perspectives are associated with both structural deposits within known anticlinal structures and traps of non-anticlinal type.

In the modern structure of the Alpine folding, these depression zones are the depressions that arose in the Cenozoic era. They formed synchronously with the orogenies of the Greater and Lesser Caucasus. In the pre-orogenic era, the depressions developed on different foundations and belonged to different geodynamic systems. In Kura Depression, the foundation is the base of the molasse complex, whereas in the Absheron depression the foundation is the base of Mesozoic deposits, and for the Caspian-Cuban zone it is represented by pre-Alpine deposits. This likely explains the differing depths of the geological bodies influencing the surface gamma field.

Initially, the geotectonic regime contributed to the creation of an equally low radioactive background of the Earth's surface for all depressions, since the sources of demolition during the formation of the Quaternary strata were rocks with a low content of radioactive elements (Anekwe et al., 2013). This concerned the Cretaceous rocks of the northern slopes of the Greater Caucasus for the Caspian-Cuban zone, the Shahdag and Vandam ridges for the Absheron depression, and the volcanogenic series for the Kura depression.

Theoretically, the gamma field rate calculated by the formula is (Young et al., 2016):

$$J = \frac{2\pi K Q_{eq} \rho}{\mu_{ef}} \tag{3}$$

where:

K – gamma radiation constant [μR/h] [cm^2/g],

Q_{eq} – equivalent uranium content [%],

μ_{ef} – effective gamma radiation absorption coefficient,

ρ – density of rocks [g/cm^3], which should be similar for all three zones and vary around 4–5 μR/h (Aliyev and Kazimova, 2022).

In practice, the intensity of gamma radiation of the Earth's surface in depression zones varies in a wide range, from 4 to 12 μR/h, reaching in some cases 20–25 μR/h. Each zone has its own average rate of gamma radiation. Thus, on Absheron Peninsula it is about 5.0 ±0.7 μR/h, in the Kura depression it is 6.0 ±0.5 μR/h, and in the Caspian-Cuban zone it is 7.0 ±1.0 μR/h (Table 2).

These studies indicate that the high values in the Lower and Middle Kura regions are associated with increased radiogeochemical activity and fluid migration through deep-seated faults and young tectonic structures, leading to the accumulation of radionuclides and heavy metals. In contrast, the Absheron and Caspian-Cuban zones show lower background levels due to their lithological composition and reduced deep fluid influence.

In compliance with the structure of the Quaternary substage, represented by a homogeneous mass of sandy-pebble and sandy-clayey rocks and also horizontally lying and weakly dislocated rocks, a simple structure of the gamma field would have been observed here. However, the gamma fields of the Earth's surface of all three zones are strongly dislocated, have a complex configuration of gamma structures, and sharp gradients of radioactivity in anomalous areas are observed (Aliyev and Kazimova, 2024).

Results and discussion

Comparison of the characteristics of the gamma field with the structural plans of various tectonic levels allowed us to identify the most active part of the deep crustal section, corresponding mainly to the Upper–Middle Miocene structural complexes. The most suitable region for comparing gamma-field structure with subsurface geological structure is the Caspian-Cuban zone.

In the Quaternary period, the subsidence processes here were relatively smooth in nature. The Earth's surface is composed of a nearly homogeneous layer of conglomerate and pebbles. Taking into account the history of geological development of the northern slope of the Greater Caucasus, which is the source of demolition, the degree of processing and gravitational separation of the detrital material, one would expect a quiet gamma field with an average radioactivity level of 5–6 μR/h. However, the gamma-field of the Caspian-Cuban zone has a complex configuration with irregular shapes, variable orientation, and sharp gradient transitions, and reflects the tension of the buried Mesozoic level. It can be assumed that the surface of the disturbing masses is located at a depth of 4000–5000 m.

The differences in the structure of gamma fields of depression zones reflect the features of the distribution of radioelements in surface deposits, which in turn is the result of various natural processes. To develop understanding of the formation of gamma field anomalies and their relationships with geological processes, geophysical fields and hydrocarbon deposits, the laws of distribution of radioelements in various lithological and stratigraphic formations were explored.

As a result, it was found that uranium and thorium concentrations are relatively higher in clayey-marly formations, while sandy and carbonate layers exhibit lower radioelement contents. These variations correspond to gamma field anomalies, indicating possible relationships with the processes of hydrocarbon migration and accumulation (Rustamov and Ismaylova, 2022).

In contrast to the Caspian-Cuban zone, the gamma field of Absheron Peninsula is less intense. It reflects the geological

Table 2. Calculated and fixed gamma field rates of depression zones of the Western Caspian Sea (Aliyev and Kazimova, 2023)
Tabela 2. Obliczone i ustalone wartości pola gamma w zagłębieniach zachodniej części Morza Kaspijskiego (Aliyev i Kazimova, 2023)

Depression	Thickness of the quaternary strata [m]	Gamma field rate of the Earth's surface [μR/h]		Disturbant
		calculated	fixed	
Lower Kura	950–2100	5.0 ±0.5	6.0 ±0.5	sedimentary strata
Middle Kura	600–2200	6.0 ±0.5	6.0 ±0.5	mesozoic basement
Absheron	550–900	4.0 ±0.8	5.0 ±0.7	sedimentary strata
Caspian-Cuban	1300–2400	4.0 ±0.6	7.2 ±1.0	mesozoic basement

structure of the upper layers of the Earth's crust, composed of weakly radioactive rocks. Carbonate rocks of the Cretaceous period exhibiting very low natural radioactivity that served as a source for the formation of most of the younger strata, predetermined the low radioactivity of all sedimentary formations. Here, active tectonic faults are manifested in the gamma field by positive anomalies, whilst oil deposits are distinguished by negative anomalies, and oil-bearing layers reaching the surface are associated with weakly contrasting anomalies.

The geological history of Kura Depression is part of the general history of the development of its mountainous framing – the Greater and Lesser Caucasus. Here, Mesozoic and Paleocene-Eocene deposits are hidden by a powerful cover of Neogene-Quaternary formations.

The Kura Depression has a block structure. Here, ascending tectonic movements with the subsidence of individual sections are observed. The formation of tectonic faults continues, and mud volcanism is manifested. Active geodynamic zones are also formed, where the relief forms are constantly changing. Since it is a very active area of the Earth's crust, it is reflected in the structure of the gamma field.

According to the tectonic zoning scheme, the Kura Depression consists of two main structural elements – Middle and Lower Kura Depressions, which are different in terms of tectonic development. This is reflected in the structure of radioactive fields.

The Lower Kura Depression is characterized by the consedimentary growth of structures. Thus, there is a high correspondence between the tectonic background and the gamma field of the Earth's crust. The tectonic background here is represented by large synclinal zones separated by narrow anticlinal belts and faults. The gamma field both on the surface and at a depth of 1200 m has the same structure (Hudson et al., 2008).

In the Middle Kura Depression, the development of Mesozoic structures was not reflected in the overlying horizons. Anticlinal folds, clearly expressed in Mesozoic deposits, completely disappear in the upper layers of the Miocene. These folds are covered by a monoclinal underlying layer of the Pliocene and Quaternary periods. However, it is the structure of the Mesozoic floor that is reflected in the gamma field, so here the disturbing mass is the upper part of the Mesozoic basement. This indicates a high degree of tectonic stress within the Mesozoic basement and, despite the fact that the Mesozoic structure is not manifested in the upper floors, the nature of the gamma field corresponds to the structure of the Mesozoic deposits.

In case the structure loses its activity and the ascending tectonic movement does not manifest itself for a long time, then it is not reflected in the gamma field of the Earth's surface.

The main link between the deep structure and the Earth's surface consists of interlinked convection and migration processes, due to which the mass transfer of fluid flow occurs. Radionuclides are present in the Earth's crust in an atomic state, and, upon being involved in various geological processes form the gamma field of the Earth's surface.

It was established that disturbing masses can be found at different depths depending on the geotectonic regime. When assessing the depth of disturbing masses, the decision is made separately for each specific case, considering a number of geological and geophysical features, the nature of geotectonic development, and the correspondence of structural plans. In case the structural plans of geological floors do not coincide, the most tectonically active part of the Earth's crust is reflected in the gamma field.

Studies of the radioactive fields in the Western Caspian region indicate that it is a dynamically active area of the Earth's crust. Favorable conditions for the formation of mineral deposits are present in this region, which is developing during the current period.

Conclusion

This work addressed one of the important tasks of radiometric research: the regional radioactive background was studied, and the patterns of distribution of radioactive fields for the depression zone were identified.

As a result, the following findings were obtained:

- natural radioactivity within the oil-producing depression zones varies around 4–12 μR/h, and in some places around 20–25 μR/h;
- when studying gamma fields, a clear connection between the radioactivity rate and the morphology of gamma structures were identified: fields with low radioactivity are characterized by oval shapes with smooth transitions from background levels to anomalies, whereas fields with high gamma-radiation intensity display elongated linear forms with sharp gradients.

Acknowledgement

The authors would like to thank Azerbaijan State Oil and Industry University (ASOIU) and Institute of Geology and Geophysics (IGG) of Azerbaijan.

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