UDC 553.98(262.81)
DOI: http://doi.org/10.17721/1728-2713.110.08

Huseynaga MAMMADOV, PhD (Geol.), Assoc. Prof.
ORCID ID: 0000-0001-6199-3892
e-mail: hsmp@rambler.ru
Azerbaijan State Oil and Industry University, Baku, Azerbaijan

Murad ABDULLA-ZADA, PhD (Earth sciences)
ORCID ID: 0009-0001-4150-8340
e-mail: murad.abdullazade@asoiu.edu.az
Azerbaijan State Oil and Industry University, Baku, Azerbaijan

HYDROCARBON PATTERNS ACROSS TIME AND STRUCTURE: A MULTI-METHOD STUDY OF THE BAKU ARCHIPELAGO PETROLEUM SYSTEMS

(Представлено членом редакційної колегії д-ром геол. наук, проф. В.А. Михайловим)

Background. ***The Baku Archipelago, situated within the western offshore margin of the South Caspian Basin, represents one of the most prolific hydrocarbon-bearing regions in Azerbaijan. Its tectonic continuity with the Southern Gobustan and Lower Kura Depression zones, coupled with the unique geological evolution of the South Caspian megadepression, has led to the formation of complex oil, gas, and gas-condensate systems within the Lower Pliocene Productive Series (PS). Despite decades of exploration and development, the mechanisms controlling the spatial distribution, migration pathways, and compositional variations of hydrocarbons across this region remain the subject of scientific debate.***

Methods. ***This study integrates a comprehensive suite of geological, geochemical, and geophysical data from multiple fields, including Duvanni-deniz, Sangachal-deniz, Bulla Island, Bulla-deniz, and Garasu. Analytical methods included gas chromatography for light and heavy hydrocarbon fractions, elemental analysis, hydrochemical classification of formation waters, and the calculation of geochemical indices such as n/isoalkane ratios, $\Sigma(nC_{13}–nC_{25})/\Sigma(nC_{12}–nC_{30})$, and $\Sigma(iC_{13}–iC_{16})/\Sigma(iC_{18}–iC_{23})$. Structural and stratigraphic interpretations were supported by seismic data and well logs.***

Results. ***The study identifies two distinct genetic groups of oils within the archipelago, corresponding to the southwestern and northeastern limbs of major structures. Hydrocarbon composition is shown to correlate with burial depth, structural position, and the mineralogical characteristics of surrounding formations. Vertical hydrochemical inversions, characterized by ultra-alkaline, low-mineralized waters underlying more mineralized strata, suggest significant upward migration of deep fluids. Increasing methane content and decreasing concentrations of methane homologs with depth, combined with rising gas dryness, support the concept of thermally driven compositional differentiation. Additionally, biodegradation signatures in high-molecular-weight fractions provide evidence of post-accumulation alteration.***

Conclusions. ***The findings highlight the dominant role of vertical migration and secondary geochemical processes – including catagenesis, phase separation, and biodegradation – in shaping the present-day distribution and composition of hydrocarbon fluids in the Baku Archipelago. The strong alignment between fluid composition, structural setting, and reservoir properties underscores the necessity of integrated basin modeling approaches for future exploration. These insights offer a refined framework for predicting hydrocarbon type and quality in untested segments of the Productive Series and deeper stratigraphic units of the South Caspian Basin.***

Keywords: ***South Caspian Basin, Baku Archipelago, hydrocarbon migration, gas-condensate systems, geochemistry, n-alkanes, isoprenoids, catagenesis, biodegradation, vertical transport, Productive Series.***

Background

The South Caspian Basin (SCB) is one of the world's most geodynamically active and hydrocarbon-rich regions. As the deepest and most sediment-filled segment of the broader Caspian depression, it forms a major petroleum province within the Alpine-Himalayan orogenic belt (Pogorelova, 2019; Mikhailov, 2017; Glumov et al., 2004). The basin's unique geotectonic evolution – characterized by rapid subsidence, overpressured clay sequences, and salt tectonics – has resulted in the accumulation of exceptionally thick sedimentary sequences, primarily of Neogene – Quaternary age, and the development of prolific petroleum systems (Javanshir et al., 2015).

Situated along the western margin of the SCB, the Baku Archipelago represents a southeastern offshore extension of the tectonic zones of Southern Gobustan and the Lower Kura Depression. This structural ensemble consists of a chain of submerged and partially emergent anticlines, fault blocks, and mud volcano systems, forming one of the most intensively explored oil- and gas-producing areas in Azerbaijan and the entire Caspian region (Aliyeva, 2021; Kerimov et al., 2015). Fields such as Duvanni-deniz, Sangachal-deniz, Bulla Island, Bulla-deniz, and Garasu Island have been the focus of sustained hydrocarbon exploration and production since the mid-20th century (Kerimov, Sharifov, & Zeynalova, 2023).

The principal petroleum-bearing interval in the Baku Archipelago is the Lower Pliocene Productive Series (PS), a thick sedimentary succession composed of alternating sandstones, siltstones, and claystones (Aliyeva, 2004). Reservoir quality is variable across the V, VII, and VIII horizons, which host most of the discovered accumulations (Katz et al., 2000). These strata are overlain and interbedded with regionally extensive sealing clay-rich intervals, creating favorable conditions for stratigraphic and structural entrapment. The underlying Prekirmaki (PK) Suite also contributes to the vertical fluid system, influencing migration and pressure regimes (Pashayev, Shahbazov, & Karimzada, 2024; Kerimova, 2023).

Hydrocarbon accumulations within the archipelago display significant lateral and vertical heterogeneity in terms of fluid composition, saturation, and phase behavior. This variability reflects a complex interplay between structural evolution, burial history, and secondary alteration processes such as catagenesis, biodegradation, and phase separation (Mammadov, 2010). Of particular interest are the geochemical signatures preserved in gas, oil, and condensate samples, including variations in *n*-alkane and isoprenoid distributions, carbon number profiles, and molecular markers indicative of source rock maturity and migration pathways (Petrov, 1974).

In recent years, increased attention has been devoted to deciphering the mechanisms of hydrocarbon migration in the

Baku Archipelago, particularly the relative roles of vertical versus lateral transport and the influence of abnormal pressure regimes and hydrochemical inversions (Mustaev, 2017; Abrams, & Narimanov, 1997). Understanding these processes is critical for reliable prediction of fluid phase, composition, and distribution in both existing and unexplored structures.

This study aims to characterize the geochemical and phase behavior of hydrocarbon systems across the Baku Archipelago through an integrated analysis of fluid composition, stratigraphy, and structural framework. The findings offer new insights into the genetic classification of hydrocarbons, the evolution of petroleum systems, and the mechanisms that control the spatial architecture of oil and gas accumulations in the South Caspian Basin (Javanshir et al., 2015) (Fig. 1).

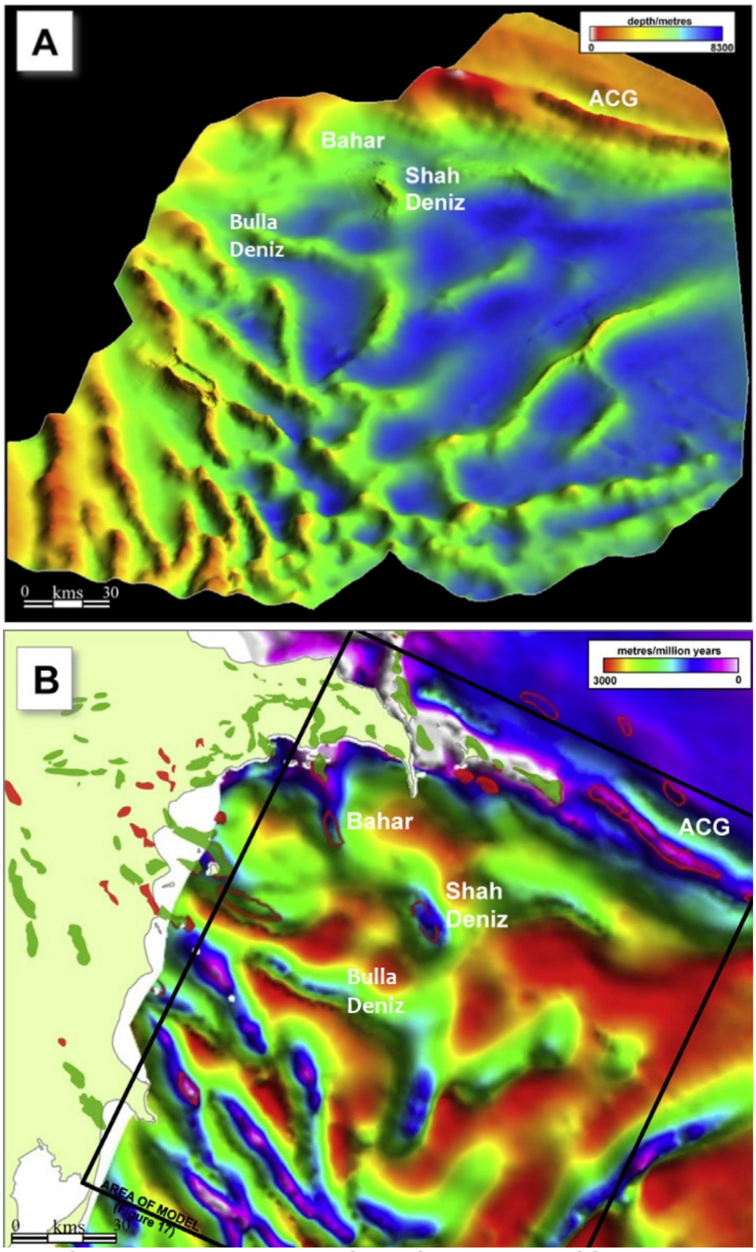

Fig. 1. A. The structural map of the Fasila suite within the South Caspian Basin (SCB) illustrates the pronounced relief of SCB anticlines, with the elevation change from syncline to the crest of the structure exceeding 3 kilometers. B. The sedimentation rate from the Pleistocene epoch to the present is depicted in meters per million years within the SCB, highlighting significant disparities in sedimentation rates between synclines and the crests of structures (According to Javanshir et al., 2015)

In Baku Archipelago industrial deposits were discovered in the VIII horizon of the Balakhkhany suite, the Fasila suite, and the Postkirmaky sandy suite. Deposits of the stratal type are associated mainly with crestal tectonically shielded deposits. A characteristic feature of the oil and gas content of the Productive Serie section is the regular replacement of oil deposits with gas and gas condensate deposits in the direction of the regional immersion of layers.

The Sangachal-deniz – Duvanny-deniz – Khara-Zira – Bulla-deniz anticline belt is located within the northern part of the Baku Archipelago oil and gas region. A characteristic feature of the tectonic structure of the anticline belt is the presence of large longitudinal faults in the axial parts of the structures. Foci of mud volcanic activity are often associated with longitudinal faults. Numerous transverse faults divide the structures into separate tectonic blocks (Alizade et al., 2018).

Methods

This study integrates geological, geochemical, and geophysical datasets obtained from multiple hydrocarbon fields within the Baku Archipelago, a region located on the western flank of the South Caspian Basin. The investigation focused primarily on the Lower Pliocene interval of the Productive Series (PS), including the V, VII, and VIII stratigraphic horizons, as well as the underlying Prekirmaki (PK) Suite.

Field data were derived from exploratory and production wells at Duvanni-deniz, Sangachal-deniz, Bulla Island, Bulla-deniz, and Garasu Island, covering both the northeastern and southwestern flanks of key structural features (Alizade et al., 2018). Core samples, fluid inclusions, and well logs were utilized for lithostratigraphic correlation and the delineation of reservoir and seal facies (Yusubov, & Guliev, 2015).

Formation waters were analyzed from multiple stratigraphic levels to determine their ionic composition and total salinity. Classification into Ca-Cl, Mg-Cl, Na-Cl-Ca, Na-SO_4, and Na-HCO_3 types was based on standard hydrochemical ratios, with measurements expressed in milliequivalents per 100 grams of water).

Gas samples were collected from V, VII, and VIII horizons as well as from the PK Suite. Gas composition was determined using gas chromatography, focusing on methane, methane homologs (C_2–C_4), nitrogen, carbon dioxide, and helium. Dryness coefficients and pressure gradients (P_res) were calculated to assess vertical and lateral migration trends (Mammadov, 2010; 2015).

Oil and condensate samples were subjected to detailed compositional analysis. Light hydrocarbon fractions (C_5–C_8) were separated by fractional distillation and analyzed by gas chromatography. Ratios of *n*-alkanes to isoalkanes, cyclohexanes to cyclopentanes, and mono-/di-/tri-substituted isoalkanes were determined following the methodology of Chakhmakhchev (1979). Elemental analyses (C, H, S, N, O) were conducted according to ASTM standards, and nickel-porphyrin complexes were quantified spectrophotometrically (Ashumov, 1961).

Heavier hydrocarbon fractions (C_{12}–C_{30}) were analyzed for *n*-alkane distribution, odd/even carbon number ratios, and isoprenoid content. The geochemical indices $\Sigma(nC_{13}–nC_{25})/\Sigma(nC_{12}–nC_{30})$, $\Sigma(iC_{13}–iC_{25})/\Sigma(nC_{12}–nC_{30})$, and $\Sigma(iC_{13}–iC_{16})/\Sigma(iC_{18}–iC_{23})$ were used to infer thermal maturity, catagenetic alteration, and migration pathways. Biodegradation patterns were evaluated by identifying selective depletion of low-boiling *n*-alkanes and isoprenoids.

Structural and hydrodynamic features were interpreted using seismic data and well correlations (Ganbarova et al., 2024). Particular attention was paid to hypsometric changes in structural elements over time, regional folding trends, and the presence of abnormally high formation pressures (AHFP), which were inferred from well test data and mud volcano activity (Nasibova et al., 2024; Mustaev, 2017).

Characteristics of formation waters. A downward decrease in mineralization is observed across the stratigraphic column. Formation waters of the Surakhany Suite are classified as belonging to the chlorocalcium (Ca–Cl) and chloromagnesium (Mg–Cl) types, characterized by elevated mineralization levels (137–165 mgeq/L per 100 g of water).

Waters of the V horizon are transitional – from alkaline to hard types – and correspond to a mixed chlorosodium-calcium (Na-Cl-Ca) type, with total mineralization ranging from 48.4 to 82.6 mgeq/L per 100 g of water.

Table 1

Chemical Composition of Formation Waters in Lower Pliocene Deposits

Parameter	Prekirmaki suite	Postkirmaki sandy suite	VII horizon	V horizon
Number of analyses	18	35	380	70
Total mineralization, g/dm³	16.5	18.8	19.7	20.1
Specific gravity at 20°C	1.0127	1.0136	1.0148	1.0156
Cl^-, mgeq/L per 100 g water	18.1	23.7	27.04	30.66
SO_4^{2-}, mgeq/L per 100 g water	4.67	3.66	1.50	2.35
HSO_3^-, mgeq/L per 100 g water	1.94	1.41	2.40	0.45
CO_3^{2-}, mgeq/L per 100 g water	0.40	0.47	0.72	0.10
$RCOO^-$, mgeq/L per 100 g water	1.30	1.11	0.50	0.30
Ca^{2+}, mgeq/L per 100 g water	0.19	0.80	0.40	2.31
Mg^{2+}, mgeq/L per 100 g water	0.14	0.34	0.29	0.82
Na^++K^+, mgeq/L per 100 g water	24.96	29.30	31.90	30.65
Σ(A+K), mequiv per 100 g water	51.70	60.79	64.75	67.64
Palmer water classes – S_1, %	88.08	90.02	88.16	90.63
S_2, %	–	–	–	6.96
A_2, %	8.48	6.38	10.38	–
A_1, %	3.44	3.60	1.46	2.41
rNa^+/rCl^-	1.38	1.24	1.18	1.00
$(rNa^+–rCl^-)/rSO_4^{2-}$	1.47	1.53	3.24	0.00
$rSO_4^{2-}/(rCl^-+rSO_4^{2-})$	0.20	0.13	0.05	0.07

Waters from the VII horizon, on the southwestern limbs of the Sangachal-deniz, Duvanni-deniz, and Bulla structures, are of the Mg-Cl, Ca-Cl, and bicarbonate-sodium (Na-HCO_3) types. On the northeastern limbs of these same uplifts, a clear trend is observed: chloride and alkali-metal-rich waters show decreasing mineralization in the southeastward direction, while bicarbonate concentrations increase. This pattern reflects a gradual transition in water types from Ca-Cl and sulfate-sodium (Na-SO_4) to predominantly bicarbonate-sodium (Na-HCO_3). Overall, within the northeastern limbs of the VII horizon, formation waters are predominantly of the Na-HCO_3 type, with mineralization in the range of 60–65 mgeq/L per 100 g of water.

Formation waters of the VIII horizon are also classified primarily as Na-HCO_3 type, with mineralization varying between 35.9 and 89.8 mgeq/L per 100 g of water, though instances of Na-SO_4 water types are also recorded. Formation waters of the Prekirmaki (PK) Suite are classified as belonging to the bicarbonate-sodium (Na-HCO_3) type, yet exhibit even lower mineralization levels, ranging between 35.6 and 48.0 mgeq/L per 100 g of water.

Across the Baku Archipelago fields – and likewise in other accumulations situated along the western and eastern flanks of the South Caspian Basin – a consistent vertical trend is observed: formation water salinity systematically decreases downward through the stratigraphic succession of Lower Pliocene deposits (Table 1).

Gas composition and zoning

The gaseous phase of hydrocarbon accumulations in the Baku Archipelago is composed almost entirely (97–99 %) of hydrocarbons.

In gases from the V horizon, methane content varies between 91.56 % and 96.51 %, showing a general increase from Duvanni-deniz towards Bulla Island.

The gases of the VII horizon display a wider range of compositional variability: methane ranges from 91.84 % to 94.06 %, methane homologs from 5.10 % to 7.50 %, nitrogen from 0.36 % to 2.11 %, carbon dioxide from 0.38 % to 1.20 %, and helium from 0.00050 % to 0.00056 %. As a rule, the abundance of individual hydrocarbons declines with increasing molecular weight. Within the Sangachal-deniz and Duvanni-deniz fields, a decrease in methane content is observed down the dip of the reservoir (Johnson et al., 2010). Regionally, in the southeastward direction, methane content decreases from Sangachal-deniz to Duvanni-deniz, then increases again toward Bulla Island. In contrast, the concentration of methane homologs declines from Duvanni-deniz both northwestward (toward Sangachal-deniz) and southeastward (toward Bulla).

In the VIII horizon, compositional fluctuations are relatively minor: methane ranges from 93.28 % to 95.28 %, methane homologs from 4.10 % to 5.70 %, and CO_2 from 0.16 % to 0.60 %.

Gases of the PK Suite in the Duvanni-deniz area consist predominantly of methane (97.62 %), with homologs comprising 2.18 % and carbon dioxide 0.20 %. In contrast, gases from the Bulla-deniz field contain 91.63 % to 93.11 % methane, 4.04 % to 5.85 % ethane, and 0.16 % to 0.48 % carbon dioxide. With increasing reservoir depth, there is a consistent rise in the proportion of higher molecular weight liquid hydrocarbon vapors, ranging from pentane to heptane. This stratigraphic deepening – along with a trend toward increased gas saturation – correlates with a progressive rise in methane concentration, accompanied by a steady decline in both methane homologs and CO_2 content.

Gases released by hydrocarbon-bearing mud volcanoes on Duvanni and Bulla Islands exhibit methane concentrations between 93.35 % and 94.11 %, with methane homologs comprising 4.19 % to 5.01 %.

Chemical and physical properties of oils and condensates

The oils of the Baku Archipelago are compositionally diverse, reflecting their varied reservoir settings, structural positions, and burial depths. These oils also demonstrate significant differences associated with specific tectonic blocks.

According to their molecular composition, the oils and condensates of the archipelago can be categorized into Type A^1 and A^2 (Petrov, 1974), corresponding to the methanic and naphtheno-methanic types, respectively.

Overall, two principal oil groups are distinguished across the studied fields:

Group I includes oils from the southwestern limb of the Bulla and Garasu structures. These oils are characterized by relatively high densities (0.935–0.961 g/cm³) and elevated concentrations of high-molecular-weight heteroatomic compounds – namely resins (22–28 %) and asphaltenes (14–17 %) – a pattern attributed to the relative accumulation of these heavy fractions following the loss of lighter hydrocarbons.

Group II comprises oils from the northeastern limbs of the Sangachal-deniz, Duvanni-deniz, Bulla Island, and Bulla-deniz structures.

It has been established that within the northeastern limbs of the Sangachal-deniz and Bulla structures, the density of VII-horizon oils increases from the crest and flanks of the folds toward their periclines. This pattern of gravitational differentiation – though varying in clarity – is also observed within most tectonic blocks of the Duvanni-deniz area.

Regionally, oil density first increases from Sangachal-deniz (0.870 g/cm³) to Duvanni-deniz (0.882 g/cm³), then decreases toward Bulla Island (0.871 g/cm³). Along with the direction of regional structural deepening, a general decrease is observed in the concentrations of paraffins, resins, and asphaltenes, although the trends exhibit local irregularities and are not always directly tied to changes in density. Resin content varies within a broad range (6 % to 18–25%), while asphaltene content fluctuates from 0.2–0.7 % up to 1.4–4.6 %.

It is suggested that the absence of consistent compositional trends in oils is primarily governed by the properties of the Upper Pliocene–Quaternary regional fluid seal during the primary and secondary stages of reservoir formation and reformation.

The studied oils are generally low in sulfur, with contents ranging from 0.124 % to 0.270 %. Ash content varies from 0.0032 % to 0.3624 %, while the concentration of nickel-porphyrin complexes ranges from 0.33 to 1.09 mg per 100 g of oil.

The elemental composition of oils from the VII horizon is characterized by the following average contents (wt.%): carbon – 86.80 %, hydrogen – 12.45 %, sulfur – 0.25 %, nitrogen – 0.15 %, and oxygen – 0.30 % (Ashumov, 1961).

The light fraction of these oils (initial boiling point: 150 °C) is distinguished by a low content of aromatic hydrocarbons (ranging from 11.37 % to 17.32 %), while the relative abundance of naphthenic (34.92–47.84 %) and methanic (40.56–49.35 %) hydrocarbons is nearly equivalent.

In the deasphalted fractions of oils from the VII horizon at the Sangachal-deniz field, a down-dip decrease in the number of naphthenic cycles (Kn/Ko ratio dropping from 0.93 to 0.70) is observed, accompanied by an increase in the proportion of aromatic rings (Ka/Ko increasing from 0.07 to 0.30). The aliphaticity index (Cm/Ca+Cn) also rises from the structurally elevated part of the reservoir to its deeper segments, ranging from 1.12 to 1.54. A similar trend is noted in the Duvanni-deniz field, where increasing burial depth within the VII horizon corresponds to a reduction in the Kn/Ko ratio (from 0.86 to 0.74), a growth in the Ka/Ko ratio (from 0.14 to 0.26), and an enhancement in aliphaticity (Cm/Ca+Cn rising from 1.10 to 1.21). Along the regional structural plunge traced by the profile Kyanyazdag – Sangachal-deniz – Duvanni-deniz – Bulla Island, the number of naphthenic rings varies as follows: 1.48 → 1.36 → 1.42 → 0.74, while the corresponding aromatic ring indices are: 0.42 → 0.49 → 0.44 → 0.58.

It has been firmly established that oil density, molecular weight, and condensate yield exhibit a direct correlation with burial depth. As stratigraphic depth increases, so do both density and the extent of the boiling range. These trends are interpreted as a consequence of rising reservoir temperatures and pressures at greater depths, leading to the dissolution of increasingly heavier hydrocarbon molecules in the gas phase. Consequently, deeper-sourced condensates tend to display higher densities and broader boiling intervals.

Geochemical indicators: alkanes, isoprenoids, maturity indices

The distribution of *n*-alkanes in the C_{12}–C_{30} fraction provides further insight into the classification of oils across the studied areas. Two principal groups are identified:

Group I – Oils from the southwestern limbs of the Bulla and Garasu structures (e.g., well 542 and well 25), where the peak concentrations of individual hydrocarbons are shifted toward the mid- and high-molecular-weight range (Fig. 2).

Group II – Oils from the northeastern limbs of the Sangachal-deniz, Duvanni-deniz, Bulla Island, and Bulla-deniz structures.

With increasing burial depth of the VII horizon – and accordingly, with stratigraphic deepening – the total content of *n*-alkanes rises. In the Duvanni-deniz area, marked differences are observed in the distribution pattern and peak position of *n*-alkane concentrations, along with a progressive southeastward decline in the odd-to-even carbon number ratios. The observed leveling of odd/even ratios in high-molecular-weight *n*-alkanes within VII-horizon oils has been attributed to the onset of destructive transformation reactions during migration (Mekhtiev, & Mamedov, 1977). Across the studied oils and condensates, odd/even ratios vary within a narrow range of 1.01–1.10.

The distribution of isoprenoid hydrocarbons in oils and condensates of the Baku Archipelago is predominantly unimodal in character (Fig. 3). All studied samples exhibit a well-defined maximum at pristane (iC_{16}), while a minimum is consistently observed in the iC_{12} component (C_{12}, 6,10-trimethylundecane).

The total content of isoprenoid hydrocarbons in the C_{13}–C_{16} range within oils and condensates varies between 1.43 % and 5.39 % across the examined areas.

With increasing burial depth of the VII horizon, a distinct geochemical trend is observed: the overall concentration of isoprenoid hydrocarbons, as well as the ratio $\Sigma(iC_{13}–iC_{25})/\Sigma(nC_{12}–nC_{30})$, systematically decreases. In contrast, the ratio $\Sigma(iC_{13}–iC_{16})/\Sigma(iC_{18}–iC_{23})$ exhibits a marked increase (Mekhtiev, & Mamedov, 1978).

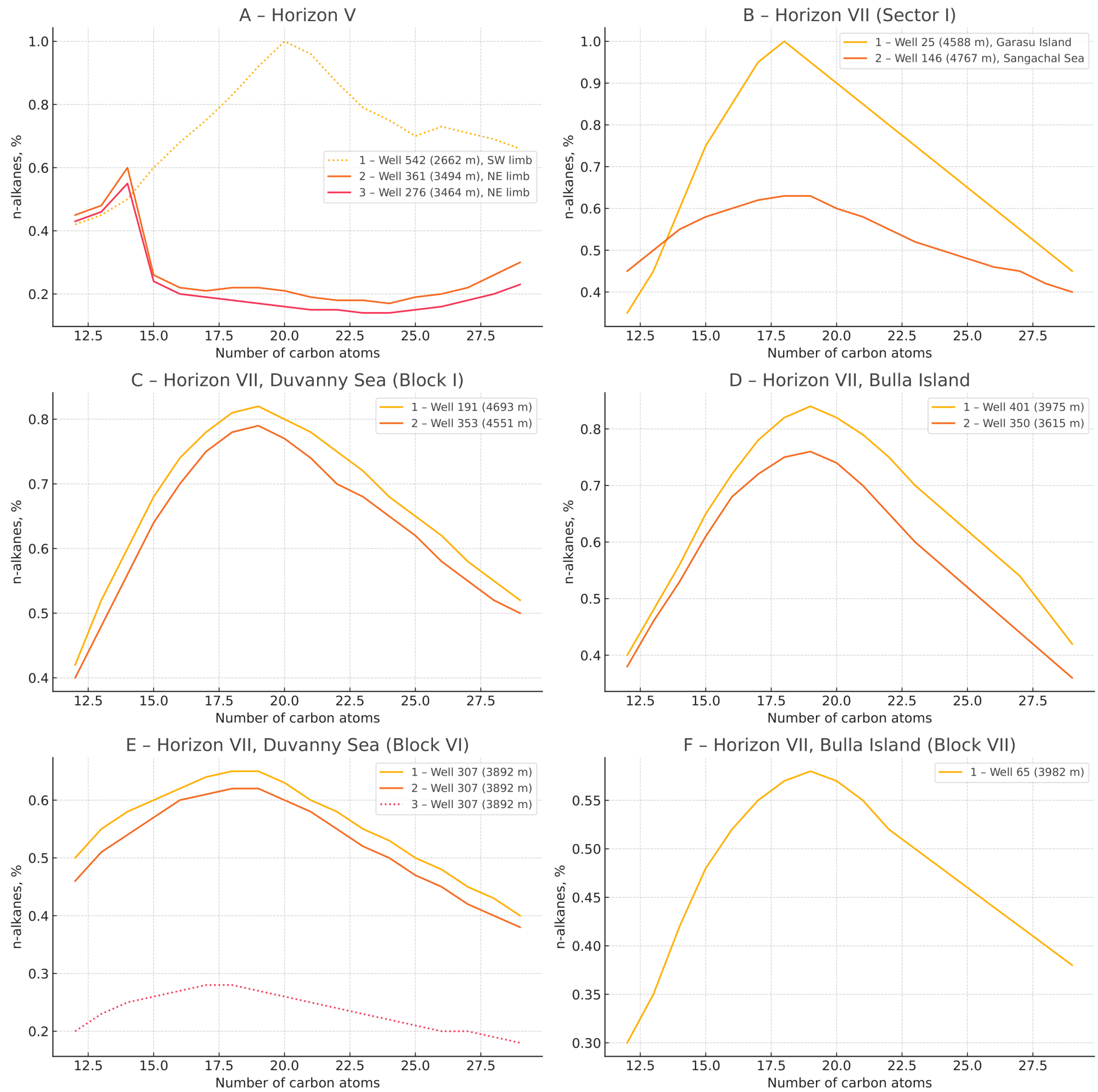

Fig. 2. Distribution diagram of *n*-alkanes in crude oils

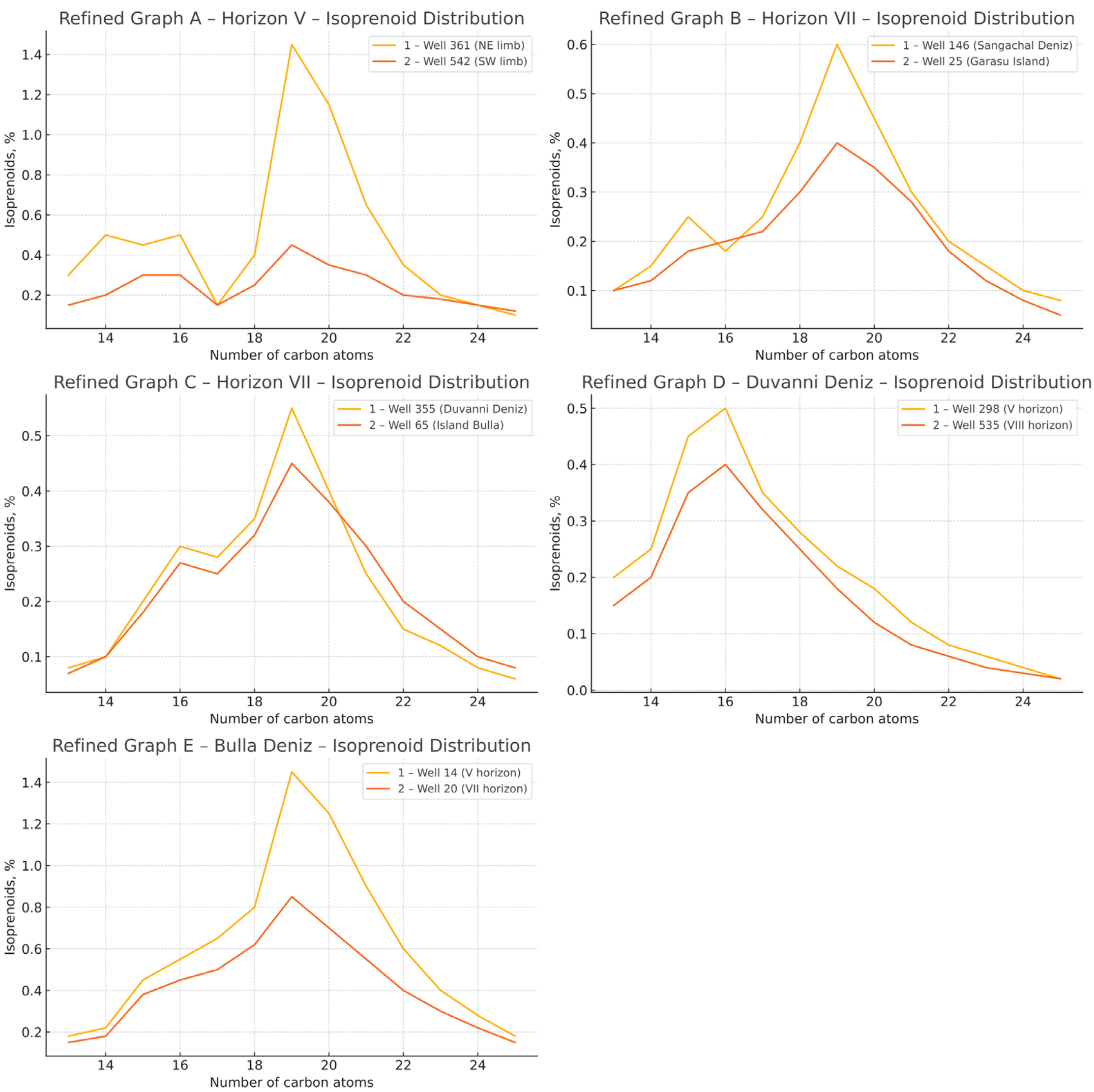

Fig. 3. Distribution diagram of isoprenoid hydrocarbons in crude oils (A, B, C) and condensates (D, E)

Gasoline fractions and isomeric composition

Within the gasoline fractions (initial boiling point: 150 °C), the relative contents of methanic and naphthenic hydrocarbons vary within the ranges of 48.13–52.70 % and 47.30–51.87 %, respectively. These proportions result in a narrowly constrained alkane/naphthene ratio, fluctuating between 0.92 and 1.11.

Methanic hydrocarbons are notably dominated by isoalkanes. The *n*-alkane/isoalkane ratio remains below unity (0.56–0.60); however, a distinct upward trend in this ratio is observed with increasing stratigraphic depth, progressing from the V to the VIII horizon.

Naphthenic hydrocarbons are composed primarily of cyclohexane derivatives (33.46–36.46 %) and cyclopentane derivatives (11.88–16.41 %).

The structural composition of the gasoline fractions also reveals a consistent predominance of isomers bearing a methyl group at the second carbon atom in hydrocarbons with even-numbered chains – notably C_6 and C_8 (i.e., 2MP>3MP; 2MNP>3MNP). Conversely, for odd-numbered hydrocarbons such as C_7, the reverse relationship holds (2MP<3MP).

Across the Sangachal-deniz, Duvanni-deniz, Bulla Island, and Bulla-deniz fields, a pronounced enrichment of gasoline fractions (boiling points 150–200 °C) in methanic hydrocarbons and arenes is observed, correlating with increasing hypsometric and stratigraphic depth of the V and VII horizon reservoirs. This enrichment is attributed to thermocatalytic transformation of high-molecular-weight naphthenic, aromatic, and naphtheno-aromatic hydrocarbons (Duppenbecker et al., 2009).

The influence of catagenesis on the hydrocarbon composition of the de-gasoline oil fractions was evaluated based on changes in the total content of *n*-alkanes and isoprenoid hydrocarbons within individual accumulations (V, VII, and VIII horizons), as well as along the stratigraphic column. Special attention was given to variations in the geochemical indices $\Sigma(nC_{13}–nC_{25})/\Sigma(nC_{12}–nC_{30})$ and $\Sigma(iC_{13}–iC_{16})/\Sigma(iC_{18}–iC_{23})$. In all cases, increasing burial depth (and associated temperatures) is accompanied by a systematic rise in the overall content of *n*-alkanes and the $\Sigma(iC_{13}–iC_{16})/\Sigma(iC_{18}–iC_{23})$ ratio, along with a concurrent decline in the abundance of isoprenoids and the $\Sigma(iC_{13}–iC_{25})/\Sigma(nC_{12}–nC_{30})$ ratio.

Evidence of biodegradation is discernible within the high-molecular-weight fraction ($C_{12}–C_{30}$) of oils from the southwestern limbs of the Bulla and Garasu structures. This process appears to primarily target the destruction of low-boiling *n*-alkanes, followed – though to a lesser extent – by the alteration of isoprenoid hydrocarbons (Fig. 2, 3).

The observed patterns in the variation of several parameters within the de-gasoline fractions of crude oils and condensates provide additional insight into the processes of hydrocarbon migration and accumulation. It has been established that, across the studied areas, there is a consistent upward increase in the ratio of low-molecular-weight *n*-alkanes and isoprenoid hydrocarbons to higher-molecular-weight compounds along the direction of hydrocarbon migration (Table 2).

Table 2

Specific features of the individual composition of the non-gasoline fraction of crude oils and condensates from hydrocarbon accumulations in the Baku Archipelago across different horizons

Indicators	Duvanny-deniz – Bulla Island				Bulla-deniz	
	V (Oil)	V (Condensate)	VII (Oil)	VIII (Condensate)	V (Condensate)	VII (Condensate)
$\Sigma(nC_{12}–nC_{15})/\Sigma(nC_{16}–nC_{19})$	1.69–1.76	3.20	0.56–1.14	1.14–1.54	1.50	1.25
$\Sigma(nC_{16}–nC_{19})/\Sigma(nC_{20}–nC_{23})$	1.01–1.19	2.95	0.85–1.07	1.34–1.95	1.90	1.26
$\Sigma(iC_{13}–iC_{15})/\Sigma(iC_{21}–iC_{25})$	1.69–2.45	5.37	1.02–1.34	2.95–4.13	2.72	1.12

These transformations are most likely the result of compositional differentiation occurring during the vertical migration of gas-oil (GNS) and gas-condensate (GCS) systems. This differentiation arises from a combination of chromatographic effects and the progressive reduction of pressure and temperature along the migration pathway.

From these observations, several key conclusions can be drawn:

1. The hydrochemical inversion identified in formation waters is interpreted as the result of mixing between sedimentary waters and deeply sourced, ultra-alkaline waters. The latter ascend through faults and eruptive conduits associated with mud volcanoes, and are geochemically foreign to the productive reservoir sequence.

2. The composition and physical properties of gases vary both vertically within individual petroleum systems and laterally along the regional structural plunge of equivalent stratigraphic units.

3. The observed variability in oil characteristics across the region is attributed primarily to secondary natural processes, including catagenesis, hypergenesis, and compositional differentiation during migration.

Results

The formation of hydrocarbon accumulations in the Baku Archipelago is characterized by a strong influence of vertical migration processes, which is supported by the presence of hydrochemical inversion. Oil accumulations are generally confined to strongly deformed anticlines, while gas-condensate accumulations are located in deeper, less deformed structural blocks. This spatial distribution reflects not only tectonic control but also the role of regional clay seals, pressure, and temperature gradients.

Overpressures and the injection of ultrabasic waters into the productive formation suggest a significant vertical fluid flow. The alignment between water chemistry and accumulation zones (e.g., alkaline waters in Horizons VII and VIII) further confirms the migration pattern.

Comparative analyses of hydrocarbon composition – particularly light hydrocarbon fractions and biomarker distributions – indicate a unified genetic type of oils and condensates across fields. Ratios of n/isoalkanes and cyclohexanes/cyclopentanes, as well as methyl-branched isomer distributions, show consistent patterns supporting a common origin.

Catagenetic trends, such as increasing n-alkanes, decreasing isoprenoids, and increasing maturity indices with depth, reveal the thermal evolution of hydrocarbons and support regional maturation models. Biodegradation effects, especially in high-molecular-weight fractions, are observed in southwest structures and appear to have selectively impacted low-boiling n-alkanes and isoprenoids.

Vertical and lateral facies transitions, tectonic compartmentalization, and cap rock integrity appear to control hydrocarbon phase differentiation – i.e., the shift from oil to gas-condensate systems with increasing burial depth. Regional zoning within Horizon VII from Kyanazdag to Bulla Island supports this trend, which cannot be fully explained by differential entrapment alone.

Geochemical markers, including dry gas ratios and formation pressure data, exhibit bidirectional trends away from the Duvanny-deniz area, implying possible upward migration from deeper Meso-Cenozoic sources. The similarity between gases in mud volcanoes and adjacent reservoirs supports deep vertical migration as the dominant process.

Genetic analysis and comparative characteristics

The study also touches briefly on the comparative characterization of oils and condensates, as well as possible causes of secondary compositional alterations.

To evaluate compositional variability in oils and condensates from the V and VII horizons, we employed a set of parameters related to light hydrocarbons as proposed by Chakhmakhchev (1979):

1. The ratio of *n*-alkanes to isoalkanes in the C5, C6, C7, and C8 fractions.

2. The ratio of cyclohexanes to cyclopentanes in the C6, C7, and C8 fractions.

3. The relative abundance of tri-, di-, and mono-substituted isoalkanes.

4. Homologous concentration series of cyclanes and alkanes with equivalent molecular weights.

The comparative values derived from these indicators are presented in Fig. 4.

It is well established that structurally and genetically similar oils exhibit a consistent order of decreasing abundance among individual hydrocarbons (Petrov et al., 1967). Our samples also follow this pattern. For instance, in the hexane series: n–C6>2MP>3MP>2,3DMB; in the heptane series: n–C7>3MP>2MP>2,3DMP>2,4DMP>3,3P>>2,2DMP>3,3DMP; and in the cyclopentane series (C7): 1,2DMCP(trans)>1,3DMCP(cis)≥1,1DMCP>3CP>1,3DMCP (trans)>1,2DMCP(trans).

The studied hydrocarbons are represented by mono-, di- and tri-substituted isomers. Among them, mono-substituted isomers dominate, followed by di-substituted and then tri- and poly-substituted alkanes. The mono-/di-substituted ratio ranges from 1.91 to 2.81 and shows a clear increasing trend with stratigraphic depth.

These findings support the conclusion that the oils and condensates from the studied areas share a common genetic origin. This inference is further corroborated by the congruent curve shapes in the graphical representations of *n*/isoalkane and cyclohexane/cyclopentane ratios across the C5–C8 hydrocarbon fractions (Fig. 4). The close similarity in calculated values between oils and condensates (1.4–1.6) reinforces this conclusion.

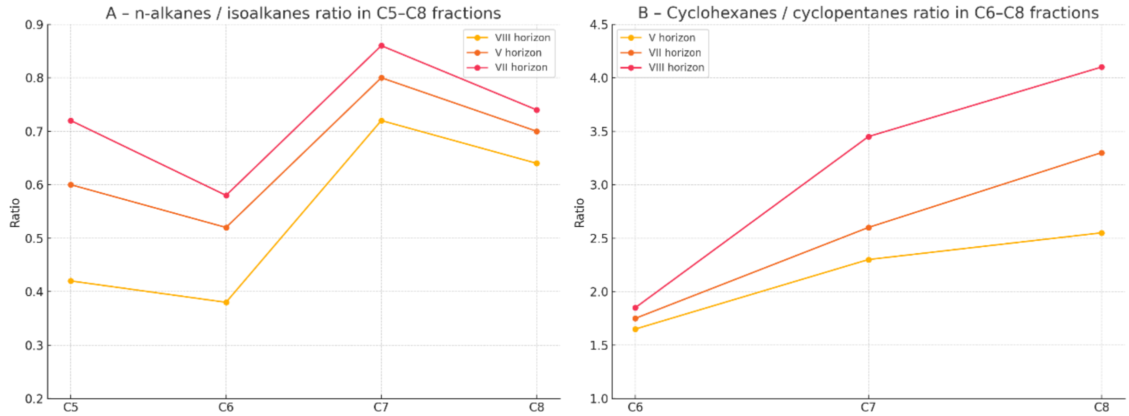

Fig. 4. Graphs showing the ratios of *n*-alkanes to isoalkanes (a) and cyclohexanes to cyclopentanes (b) in hydrocarbon fractions C_5, C_6, C_7, and C_8

Discussion and conclusions

The comprehensive geological and geochemical study of hydrocarbon accumulations in the Baku Archipelago reveals that their formation and spatial distribution are governed by a combination of tectonic architecture, lithological heterogeneity, vertical fluid migration, and the maturity of organic matter. Hydrocarbon fluids found in various fields and stratigraphic levels exhibit distinct yet genetically related compositions, indicating a common source and similar thermal evolution.

Key findings include the vertical geochemical zoning of reservoir fluids, evident transitions from oil to gas-condensate systems with increasing depth, and hydrochemical inversion patterns in formation waters that support the model of upward hydrocarbon migration. The correlation between the chemical composition of gases, oils, and waters, alongside the presence of ultrabasic waters and overpressures in deeper intervals, further confirms the dominant role of vertical migration processes.

Analyses of light hydrocarbon fractions, biomarker indices, and alkane/isoprenoid ratios show consistent catagenetic trends and minimal lateral compositional variability, indicating basin-scale controls on hydrocarbon generation and accumulation. The observed biodegradation effects are spatially restricted and primarily impact low-molecular-weight components.

These results not only enhance the understanding of petroleum systems in the Baku Archipelago but also provide predictive tools for identifying new prospective zones within the South Caspian Basin. Integration of tectonic, stratigraphic, and geochemical data is essential for optimizing exploration and development strategies in this structurally complex and hydrocarbon-rich offshore region.

Authors' contribution: Huseynaga Mammadov – writing, investigation, methodology, formal analysis, conceptualization, data curation, supervision; Murad Abdulla-zada – investigation, writing.

References

Abrams, M. A., & Narimanov, A. A. (1997). Geochemical evaluation of hydrocarbons and their potential sources in the western South Caspian depression, Republic of Azerbaijan. *Marine and Petroleum Geology*, 14(4), 451–468. https://doi.org/10.1016/S0264-8172(97)00011-1

Alizade, A. A., Guliyev, I. S., Mamedov, P. Z., Alieva, E. G., Feyzullaev, A. A., & Huseynov, D. A. (2018). *Productive serie of Azerbaijan (Vol. 1).* Nedra [in Russian]. [Ализаде А. А., Гулиев И. С., Мамедов П. З., Алиева Э. Г., Фейзуллаев А. А., Гусейнов Д. А. (2018). *Продуктивная серия Азербайджана (Т. 1).* Недра].

Aliyeva, E. G. (2004). Depositional environment and reservoir architecture of the Productive Series VII-V horizons in the Alyat ridge offshore part (Alyat-deniz, Bulla-deniz fields). Baku, 41–49. https://doi.org/10.13140/RG.2.1.4290.6006

Aliyeva, S. (2021). Methods for predicting the lithological and facies characterization of deeply submerged prospective oil and gas deposits. *Visnyk of Taras Shevchenko National University of Kyiv. Geology*, 1(92), 88–92 [in Russian]. [Алієва, С. (2021). Методы прогноза литолого-фациальной характеристики глубоко погруженных перспективно-нефтегазоносных отложений. *Вісник Київського національного університету імені Тараса Шевченка. Геологія*, 1(92), 88–92]. https://doi.org/10.17721/1728-2713.92.12

Duppenbecker, S. J., Riley, G. W., Abdullayev, N. R., Green, T. J., & Doran, H. (2009). Petroleum systems dynamics of the South Caspian Basin. *AAPG Hedberg Research Conference, May 3–7, 2009, Napa, California, U.S.A.* (abs.). https://doi.org/10.3997/2214-4609.20146084

Ganbarova, S., Zeynalova, S., & Zahidova, T. (2024). The risk of change in the thickness, sand and oil-gas content of the productive series sediments on the Northern slope of the South Caspian depression. *Reliability: Theory & Applications*, 19(SI 6 (81)), 1501–1512.

Glumov, I. F., Malovitsky, Ya. P., Novikov, A. A., & Senin, B. V. (2004). *Regional geology and oil and gas potential of the Caspian Sea*. Nedra-Business Center [in Russian]. [Глумов И. Ф., Маловицкий Я. П., Новиков А. А., Сенин Б. В. (2004). *Региональная геология и нефтегазоносность Каспийского моря*. Недра-Бизнес-Центр, с. 342]. https://doi.org/10.15593/2712-8008/2025.2.5

Javanshir, R. J., Riley, G. W., Duppenbecker, S. J., & Abdullayev, N. R. (2015). Validation of lateral fluid flow in an overpressured sand-shale sequence during development of Azeri-Chirag-Gunashli oil field and Shah-Deniz gas field: South Caspian Basin, Azerbaijan. *Marine and Petroleum Geology*, 59, 593–610. https://doi.org/10.1016/j.marpetgeo.2014.07.019

Johnson, C. L., Hudson, S. M., Rowe, H. D., & Efendiyeva, M. A. (2010). Geochemical constraints on the Palaeocene–Miocene evolution of eastern Azerbaijan, with implications for the South Caspian Basin and eastern Paratethys. *Basin Research*, 22(5), 733–750. https://doi.org/10.1111/j.1365-2117.2009.00427.x

Katz, B., Richards, D., Long, D., & Lawrence, W. (2000). A new look at the components of the petroleum system of the South Caspian Basin. *Journal of Petroleum Science and Engineering*, 28(4), 161–182. https://doi.org/10.1016/S0920-4105(00)00076-0

Kerimov, V. M., Sharifov, J. J., & Zeynalova, S. A. (2023). Intensification of oil production in long-term developed offshore fields. *Journal of Geology, Geography and Geoecology, Dnepr*, 31(2), 59–66. https://doi.org/10.15421/112326

Kerimov, V. Yu., Guliyev, I. S., Guseinov, D. A., Lavrenova, E. A., Mustayev, R. N., Osipov, R. N., & Serikova, U. S. (2015). *Forecasting of Oil and Gas Potential in Regions with Complex Geological Structure.* Nedra [in Russian]. [Керимов В. Ю., Гулиев И. С., Гусейнов Д. А., Лавренова Е. А., Мустаев Р. Н., Осипов Р. Н., Серикова У. С. (2015) *Прогнозирование нефтегазоносности регионов со сложным геологическим строением*. Недра].

Kerimova, K. A. (2023). Study of petrophysical parameters of productive series by use of well data. *Geophysical Journal*, 45(3), 135–142. https://doi.org/10.24028/gj.v45i3.282421

Khalilova, L. N., & Seyidov, V. M. (2023). Evolution of hydrocarbon deposits in the South Caspian Basin. *Geofizicheskiy Zhurnal*, 45(3), 126–134. https://doi.org/10.24028/gj.v45i3.282420

Mammadov, G. A. (2010). On the natural factors influencing the composition of gas condensates. *Proceedings of the Higher Educational Institutions of Azerbaijan*, 3, 16–21.

Mammadov, G. A. (2015). On the role and genetic significance of biomarkers in oil geochemistry. *Proceedings of the Higher Educational Institutions of Azerbaijan, Baku*, 4, 7–12.

Mykhailov, V. (2017). Comparative characteristics of Maikop series of Caspian-Black Sea region. *Visnyk of Taras Shevchenko National University* *of Kyiv. Geology*, 2(77), 59–71 [in Russian]. [Михайлов, В. (2017). Сопоставительная характеристика майкопской серии Каспийско-Черноморского региона. *Вісник Київського національного університету імені Тараса Шевченка. Геологія*, 2(77), 59-71]. https://doi.org/10.17721/1728-2713.77.07

Mustaev, R. N. (2017). Geochemical environment of oil and gas occurrences in the South-Caspian basin based on the results of the study of Mud Volcano Ejecta. *Oriental Journal of Chemistry*, 33(4), 2036–2044. http://dx.doi.org/10.13005/ojc/330452

Nasibova, G. J., Mukhtarova, K. Z., & Ganbarova, S. A. (2024). Modelling of geochemical properties of mud volcano eruption products and relationship with oil and gas prospects within the South Caspian megadepression of Lower Kura region. *Journal of Geology, Geography and Geoecology*, 33(2), 329–339. https://doi.org/10.15421/112431

Pashayev, N., Shahbazov, R., & Karimzada, F. (2024). Modeling structural-tectonic characteristics of eastern fields of Absheron peninsula and the risk of tectonic impact on oil-gas bearing. *Reliability: Theory & Applications*, 19(SI 6 (81)), 1430–1438.

Pogorelova, Ye. Yu. (2019). Geotectonic aspects of oil and gas potential of the intermountain segment of the Black Sea-Caspian Sea region. *Naukovyi Visnyk NHU*, 1, 5–12. https://doi.org/10.29202/nvngu/2019-1/1

Yusubov, N. P., & Guliev, I. S. (2015). The lithological-facies models of the Garadag, March 8, Sangachaly-deniz, Duvani-deniz, Bulla-adasy and Bulla-deniz fields, dated to the "interval break" according to GIS data. *Azerbaijan oil industry*, 5, 3–8.

Отримано редакцією журналу / Received: 21.04.25
Прорецензовано / Revised: 15.05.25
Схвалено до друку / Accepted: 30.06.25

Гусейнага МАМЕДОВ, канд. геол. наук, доц.
ORCID ID: 0000-0001-6199-3892
e-mail: hsmp@rambler.ru
Азербайджанський державний університет нафти та промисловості, Баку, Азербайджан

Мурад АБДУЛЛА-ЗАДЕ, д-р філософії (науки про Землю)
ORCID ID: 0009-0001-4150-8340
e-mail: murad.abdullazade@asoiu.edu.az
Азербайджанський державний університет нафти та промисловості, Баку, Азербайджан

ГІДРОВУГЛЕЦЕВІ ПАРАДИГМИ ЧАСУ ТА СТРУКТУРИ: БАГАТОМЕТОДНЕ ДОСЛІДЖЕННЯ НАФТОГАЗОВИХ СИСТЕМ БАКИНСЬКОГО АРХІПЕЛАГУ

Вступ. ***Бакинський архіпелаг, розташований у західній шельфовій зоні Південнокаспійського басейну, є одним із найпродуктивніших нафтогазоносних регіонів Азербайджану. Його тектонічна безперервність із зонами Південного Гобустану та Нижньої Кюрінської западини, а також унікальна геологічна еволюція Південнокаспійської мегавпадини зумовили формування складних нафтових, газових та газоконденсатних систем у межах Нижньопліоценової Продуктивної товщі. Незважаючи на десятиліття досліджень і розробки, механізми просторового розподілу, міграційних шляхів і варіацій складу вуглеводнів? у цьому регіоні досі залишаються предметом наукової дискусії.***

Методи. ***У дослідженні поєднано широкомасштабні геологічні, геохімічні та геофізичні дані з ряду родовищ, включаючи Дуванні-деніз, Сангачал-деніз, острів Булла, Булла-деніз та Гарасу. Аналітичні методи охоплювали газову хроматографію для легких і важких фракцій вуглеводнів, елементний аналіз, гідрохімічну класифікацію пластових вод і обчислення геохімічних індексів, зокрема співвідношень n/ізоалканів, $\Sigma(nC_{13}–nC_{25})/\Sigma(nC_{12}–nC_{30})$ та $\Sigma(iC_{13}–iC_{16})/\Sigma(iC_{18}–iC_{23})$. Структурно-стратиграфічні інтерпретації базувались на сейсмічних даних і каротажних дослідженнях свердловин.***

Результати. ***У межах архіпелагу виокремлено дві генетично відмінні групи нафт, пов'язані з південно-західним і північно-східним крилами головних структур. Склад вуглеводнів виявляє кореляцію з глибиною занурення, структурним положенням та мінералогічними особливостями навколишніх порід. Вертикальні гідрохімічні інверсії, що характеризуються ультралужними слабомінералізованими водами під більш мінералізованими шарами, свідчать про значну висхідну міграцію глибинних флюїдів. Зростання вмісту метану і зниження концентрації його гомологів із глибиною, поряд зі зростанням газової сухості, підтверджують концепцію термічно зумовленого фракційного розділення. Крім того, ознаки біодеградації у важких фракціях вуглеводнів свідчать про постакумуляційні зміни.***

Висновки. ***Отримані результати підкреслюють переважну роль вертикальної міграції та вторинних геохімічних процесів – катагенезу, фазового розділення та біодеградації – у формуванні сучасного розподілу й складу вуглеводневих флюїдів Бакинського архіпелагу. Чітка відповідність між складом флюїдів, структурними умовами та властивостями колекторів вказує на необхідність інтегрованого басейнового моделювання для майбутніх пошукових робіт. Отримані дані дають змогу уточнити прогнози щодо типу й якості вуглеводнів у неоцінених ділянках Продуктивної товщі та глибших стратиграфічних комплексів Південнокаспійського басейну.***

Ключові слова: ***Південнокаспійський басейн; Бакинський архіпелаг; міграція вуглеводнів; газоконденсатні системи; геохімія; n-алкани; ізопреноїди; катагенез; біодеградація; вертикальний транспорт; Продуктивна товща.***

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.