GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2025 Volume 41 Issue 1 Pages 107–122

DOI: 10.24425/gsm.2025.153169

SHUN ZHANG[1], YONGGUI LI[2], ZHENGLIANG LIU[3], GUOJIN QIN[4], KAIYUAN LI[5]

Study of the pattern of oil and gas deposits and forecasting favorable targets on the southeastern side of the Caspian basin

Introduction

Research on oil and gas deposits in the southeastern Caspian Basin is driven by the region's strategic importance for energy security and economic development and the necessity to establish effective production and management strategies for hydrocarbon reserves amid evolving global markets and increasing environmental challenges. This area is a potential oil and gas source, and understanding its geological and geochemical characteristics will enhance production efficiency, resource management, and consideration of environmental and social factors.

✉ Corresponding Author: Shun Zhang; e-mail: shunzhang458@gmail.com
[1] Renmin University of China, China; ORCID iD: 0009-0004-6697-9415; e-mail: shunzhang458@gmail.com
[2] China University of Petroleum, China; e-mail: yongguili324@outlook.com
[3] Daqing Petroleum Institute, China; e-mail: zhengliangliu@hotmail.com
[4] Southwest Petroleum University, China; e-mail: guojinqin12@outlook.com
[5] Yangtze University, China; e-mail: kaiyuanli54@hotmail.com

The research problems of this topic lie in the complexity and multidimensionality of factors influencing the formation of oil and gas deposits on the southeastern side of the Caspian depression. Geologically, this area features a complex structure with varied rock formations and chemical characteristics coupled with dynamic hydrocarbon migration processes. Additionally, the variability of global market conditions and the increasing stringency of environmental regulations add layers of economic and regulatory complexity. It is essential to consider all these factors to determine optimal production and reserve management techniques. This requires effective interdisciplinary collaboration, integrating geology, geophysics, engineering, and economics expertise. Addressing these issues is critical to the successful and sustainable exploitation of hydrocarbon resources in the region.

The southeastern flank of the Pre-Caspian Basin has intrigued the oil and gas industry and geologists for its intricate geological history (Li et al. 2024). This area is noted for its complex subsurface structure, which includes a variety of sedimentary strata and tectonic formations formed over millions of years. The region's geology reveals a sequence of Paleozoic, Mesozoic, and Cenozoic deposits that suggest numerous phases of basin formation caused by tectonic activity, sea-level fluctuations, and climatic changes. The presence of massive salt deposits, deep-seated faults, and fold structures complicates the geological architecture, making hydrocarbon exploration challenging yet promising. The dynamic processes of hydrocarbon migration, combined with the basin's significant resource potential, have made the southeastern flank of the Pre-Caspian Basin a focal point for ongoing exploration and research efforts to understand its resource capacity better and optimize extraction techniques.

According to the work of A.K. Zhakai et al. (2023), the study of oil and gas formations in the Caspian Basin region is of strategic importance for energy security. With the growth of global energy consumption, regions with extensive oil and gas resources are becoming key players in the energy arena. M.M. Malikov (2022) emphasizes that the development of oil and gas fields in this region carries potential environmental risks associated with greenhouse gas emissions and impacts on the natural environment. It is necessary to emphasize the environmental aspects of resource development.

Researchers R.B. Sagi and M.S. Elesh (2022) note that efficient production and management of oil and gas resources can contribute to economic growth, job creation, and investment attraction. This study did not consider the details related to technological innovation and modern oil and gas resource management practices, which can also have a significant impact on economic growth and overall socio-economic benefits. Researcher T.T. Kaskabaeva (2021) points out the complexities associated with the diversity of geological structures in this region, which makes it necessary to investigate in more depth the formation of traps for oil and gas. The study does not address the analysis of the influence of climatic changes on the structure and operation of oil and gas traps, which seems to be a significant aspect for a region with a variable climate.

L.M. Sembieva's (2021) study emphasizes the significance of creating predictive models for production optimization, which aids in mitigating risks and enhancing the efficiency

of production projects. However, this study does not incorporate an analysis of social and economic factors' influence on the efficiency of oil production projects, an important consideration when developing predictive models. Z.T. Kozykhanova's (2022) work raises an important question about Kazakhstan's oil transportation methods. However, the study does not address the environmental aspects of Kazakhstan's oil transportation, including the environmental impact and measures to mitigate adverse effects.

The purpose of this study was to investigate the geological and geochemical characteristics that influence oil and gas formation and accumulation on the southeastern side of the Pre-Caspian Basin. The study aimed to identify key geological structures, reservoir properties, and factors affecting hydrocarbon migration to enhance the understanding of potential hydrocarbon reserves in this region. The study's objectives are:

1. To analyze the structural and stratigraphic features of the southeastern Pre-Caspian Basin, focusing on their role in hydrocarbon trapping.
2. To evaluate the physical and chemical properties of reservoir rocks, including porosity, permeability, and hydrocarbon content, to determine their suitability for hydrocarbon storage.
3. To assess the geological history of the region, including sedimentation patterns and tectonic activity, and their impact on hydrocarbon migration and accumulation.
4. To consider the environmental and social aspects of hydrocarbon exploration in the region, providing recommendations for sustainable resource management.

The hypotheses are that:

1. The structural features of the southeastern Pre-Caspian Basin, such as faults, fold belts, and salt domes, play a crucial role in trapping hydrocarbons, leading to significant oil and gas accumulations in the region.
2. High-porosity and high-permeability rocks, particularly sandstones and carbonates, in the southeastern Pre-Caspian Basin serve as effective reservoirs for hydrocarbons, with their chemical composition significantly influencing the quality and stability of the hydrocarbons stored.
3. The geological history of the region, including sedimentation patterns and tectonic activity, has a direct impact on the migration and accumulation of hydrocarbons, influencing their distribution across different geological strata.
4. The exploration and development of hydrocarbon resources in the southeastern Pre-Caspian Basin will have significant environmental and social implications, necessitating sustainable practices to mitigate potential adverse effects.

1. Materials and methods

This research used detailed analysis of existing geological, geochemical, and geophysical data to evaluate the features of oil and gas reserves in the southern Caspian Basin. The study concentrated on processing and analysing data from well logs, core sample studies,

seismic surveys, and geochemical reports that covered a wide variety of depths and locations throughout the basin.

The analytical method entailed a detailed evaluation of geological and geochemical properties, emphasizing critical factors such as porosity, permeability, and hydrocarbon concentration. Porosity was examined using data from mercury injection capillary pressure experiments, which gave information on the rocks' pore structure and storage capacity. Permeability data were obtained through gas permeametry studies, allowing for an assessment of how easily fluids may flow through the reservoir rocks. Pyrolysis and gas chromatography data were used to evaluate hydrocarbon content, allowing for the identification of prospective oil and gas production within various stratigraphic units. Statistical methods enabled the researchers to delve deeper into their investigation and, more precisely, predict the likelihood of oil and gas resources in various parts of the southeastern Caspian Basin. This strategy was also useful in predicting the quantitative properties of the resources and planning appropriate extraction procedures. The study used multivariate statistical approaches, such as principal component analysis (PCA) and cluster analysis, to uncover patterns and connections in the data. PCA was utilized to minimize the dimensionality of the data, focusing on the most important variables influencing reservoir quality and hydrocarbon presence.

The functional method investigated the links between geological, geophysical, and geochemical factors. The study employed correlation analysis to investigate the correlations between various geological, geophysical, and geochemical factors. Multiple regression analysis revealed the impact of factors such as mineral composition, fluid properties, and thermal maturity on hydrocarbon dispersion. This approach also made use of cross-plots to visually show the interactions between various factors and discover trends that might be used to influence exploration strategies.

A structural-functional method was used to study the internal links between geological features and hydrocarbon reservoir dynamics. Existing seismic data and structural maps were examined to see how faults, folds, and other structural characteristics influence the distribution and amount of oil and gas reserves. This method provides insights into the processes that regulate hydrocarbon trapping and accumulation, resulting in a better understanding of reservoir development. The deductive method was used to synthesize the collected data and reach logical conclusions about reservoir development processes. The researchers produced theories regarding the mechanisms driving hydrocarbon accumulation in the region after combining the results of geological, geophysical, and geochemical examinations. These ideas were then evaluated against existing data to improve our understanding of the elements that influence oil and gas distribution.

The synthesis method was utilized to incorporate the numerous data from different approaches to analysis. This approach also allowed for the comparison of various geological formations, showing regional patterns in hydrocarbon distribution. Finally, the classification approach was used to group the enormous geological data into cohesive groups. Geological formations were classed based on their lithological traits, structural features, and geochemical

composition. This categorization was critical for creating a stratigraphic framework that could anticipate the shape and magnitude of possible reservoirs. Cluster analysis was used to organize geological units with similar qualities, which helped identify viable exploration opportunities. This approach assisted in prioritizing sites for additional exploration based on the chance of finding economically viable hydrocarbon resources.

2. Results and discussion

2.1. Geological and geophysical overview of the southeastern Caspian Basin

The southeastern flank of the Pre-Caspian Basin is a region with a rich geological and geophysical history that has attracted the attention of the oil and gas industry and geological researchers for many decades. This region has remained an interesting research target because of its potential for oil and gas discovery. Forecasting favorable targets in this region plays an important role in determining prospects for future exploration and production activities. Investigating the pattern of oil and gas reservoir formation on the southeastern side of the Caspian Basin is a complex and important task that requires in-depth analysis of geological, geophysical, and geochemical data. This region is characterized by a wide variety of factors influencing the formation of oil and gas fields, and its study can reveal patterns important for predicting favorable targets.

The region's structure, tectonics, and rock lithology are key aspects of this study. Faults, fold belts, and other structural features can create traps for hydrocarbons. Understanding rocks' physical and chemical characteristics is critical for locating reservoirs and hydrocarbon migration pathways since they affect the porosity, permeability, and fluid retention capacity of the rocks (Luo et al. 2023). Reservoirs typically form in rocks with high porosity and permeability, facilitating efficient hydrocarbon storage and transmission (Kondrat and Horobets 2023). The chemical composition of the rocks can also impact the type of hydrocarbons found and the possibility of chemical reactions that alter hydrocarbon quality or movement. Recognizing these characteristics enables geologists to predict where hydrocarbons are likely to accumulate and how they migrate through the subsurface, leading to more accurate exploration and extraction efforts.

Equally important is an analysis of the region's geological history, including sedimentary processes, climate change, and tectonic events that may have influenced the accumulation of oil and gas. Only a comprehensive analysis of all these factors will reveal the patterns underlying the formation of oil and gas fields on the southeastern flank of the Pre-Caspian Basin. The Northern Pre-Caspian region has attracted the attention of researchers, and persistent efforts have been continuously made to penetrate the depths of this region in order to understand the regularities of its geological structure. However, the unique geological complexity, adverse natural conditions, limited water resources, and low salinity of the

Caspian Sea render the study of this region particularly challenging. Active study of the geological structure, tectonics, and stratigraphy of the Northern Pre-Caspian began in the late 20th century, and the main focus was on the Emba region (Lazarev et al. 2021). In the 90s of the 20th century, prospecting and exploration works began in the territories of Dossor, Iskin, Makat, Karachungul, and Karaton. Exploration wells were drilled in the vicinity of oil fields, which at that time represented the only justification for exploration. The geological structure of the Caspian Basin possesses distinct characteristics. There is a significant amount of sedimentary deposits here, reaching a thickness of 15–18 km. Hydrocarbons, including oil and gas, have been confirmed across the geological sections of the sediments.

Four horizons with the presence of hydrocarbons can be distinguished in the suprasalt rocks: Permo-Triassic, Middle Jurassic, Aptneocomian, and Neogene. It is also worth noting that the coastal zones of the Caspian Depression also contain oil and gas in salt deposits (Belayouni et al. 2023). The salt deposits are dominated by reservoirs consisting of terrigenous sediments. More than 20 horizons containing oil and gas have been identified in Permian, Triassic, Middle Jurassic, Neocomian Aptian, and Neogene sediments. The thickness of these productive horizons varies from 1 to 60 m. The main horizons containing oil in the salt sediments are of the Middle Jurassic age. Significant amounts of rock salt deposited during the Kungurian age led to a structure of salt dome tectonics in the sedimentary rocks above its position.

Deposits of gas, gas condensate, and oil in salt deposits are mainly associated with carbonate sediments that were formed during the Carboniferous and Lower Permian (Lin et al. 2023). The Karpenkovsky district is a notable exception, containing productive Middle and Upper Devonian sediments. Gas condensate fields mainly occupy the northern and south-western bluffs of the depression, while oil and gas-oil fields predominate on the eastern and southeastern bluffs. Pliocene sediments close to the surface have a regional presence of natural gas. There are several known fields with natural gas occurrences in the Caspian Basin. When drilling wells, it is not uncommon to encounter cases of intense gas emissions from shallow depths (from 110 to 300 m). The main constituent of gas in these cases is methane, with a small presence of nitrogen. The content of heavier hydrocarbons in such gases remains at a relatively low level, being only a fraction of a %. It was also found that the content of hydrocarbons with carbon chains from C2 to C5 in some samples of methane gases extracted from natural sources was low, at less than 0.1%.

2.2. Gas manifestations and composition in different geological zones

Manifestations of gas yields in natural sources were characterized by high intensity. These manifestations were encountered at various locations, such as Kali, Altynbay-Aral, Kukurte, and others. Numerous cases of intense gas outbursts were observed during the drilling of boreholes, pits, and wells. In some cases, there were even intense gas fountains

during the drilling of wells and the formation of griffins. Pliocene sediments also contain gas deposits with limited reserves, including such places as Azau, Melnikovskoye, Auketaychagyl, Port Arthur, and others (Tsuji et al. 2021; Tseng et al. 2023). The Upper Pliocene sediments are mainly dominated by gas. The identified minor oil manifestations at Auketaichagyl, Novobogatinsk, and Chernaya Rechka are secondary manifestations (Table 1).

Table 1. Composition of gases from natural seeps in the Caspian Basin

Tabela 1. Skład gazów z naturalnych wycieków w basenie Morza Kaspijskiego

Natural way out	CO_2	CH_{10}	C_2H_6	C_3H_8	C_4H_{10}	N_2	He	Ar
Burbaital	1.6	89.5	0.9	–	–	5.8	0.2	–
Irke-Chagyl	1.2	93	0.016	0.004	0.003	1.9	0.005	0.22
Azi-Sar	0.3	97.5	0.027	0.004	0.003	1.9	0.002	0.21
Big Skaryl	0.7	63.3	0.002	0.001	0.003	35.5	0.017	0.50
Shalten-Mula	0.5	51.5	0.008	0.001	0.002	47	0.007	0.96
Shoytyk-Sor	1.4	98	–	0.027	–	0.5	0.003	0.031
Azi-Chagyl	1.2	90.6	–	0.570	–	8	0.011	0.092
Azau	0.5	98	0.1	–	–	1.7	0.014	0.02
Lake. Baskunchak, northern shore, gas from a sinkhole	1.2	0.3	0.006	0.002	0.006	97.1	0.004	1.30
Dzhambay, griffin at well 3	0.3	86.7	–	0.028	–	13	0.045	0.059

Source: S. Mehay et al. (2021).

Natural gas emissions and gas from shallow wells are characterized by low concentrations of heavier hydrocarbons. Gases from Pliocene sediments sometimes had substantial nitrogen content, up to 30–40% or more. Gases from Cretaceous, Jurassic, and Permian sediments contained heavier hydrocarbons ranging from 5% to 10%. A few gas samples also had small amounts of hydrogen, at the level of tenths of a percent or slightly higher (Tsuji et al. 2021).

The gases found in the Aralsor research wells are also noteworthy. The gas composition in the rocks can be analyzed from gases dissolved in the drilling mud. Starting from a depth of about 500 m in the upper layers, an increase in methane content is observed, reaching 40% at a depth of 650–790 m (Cretaceous sediments), while the C2–C3 hydrocarbon content is 2–3%. In most drilling mud samples, the C4–C6 hydrocarbon content was 0.1–0.2% or lower. As the well goes deeper, an increase in nitrogen content is noted. At a depth of 3,275–3,315 m (Triassic), sediments with signs of oil were found, and at 3400 m, there was a release of nitrogen gas. As the well penetrates deeper into the Triassic sediments, nitrogen remains the dominant component in the drilling fluid gases (Table 2).

Table 2. Composition of gases from the Aralsor well, %

Tabela 2. Skład gazów z odwiertu Aralsor, %

Age	Zone	Depth, m	H_2	CH_4	C_2H_6	C_5H_8	$H_2S + CO_2$	N_2
Lower Triassic	Zone of hydrogen-nitrogen gas saturation	5,424	28.28	–	–	–	5.36	70.36
		5,428	13.81	–	–	–	46.19	39.3
		5,484	28.06	–	–	–	9.84	62.1
		5,487	24.34	–	–	–	28.93	46.75
Upper Permian	Zone of hydrogen sulfide-nitrogen gas saturation	5,583	–	0.1	–	–	17	83
		5,586	–	0.1	–	–	14.6	85.4
		5,592	0.12	0.1	–	–	76.2	23.68
		5,598	0.14	0.1	–	–	76.5	3.32
Upper Permian	Hydrocarbon (methane) saturation zone	5,919	–	52.1	–	–	3.83	44.07
		2,925	–	38.4	–	–	19.46	42.14
		2,928	–	22.56	–	–	5.21	72.23
		5,931	–	53.03	0.05	0.05	8	38.97
		5,940	–	85.75	0.05	0.05	3.1	11.15

Source: Mehay et al. (2021).

No hydrogen was detected during the drilling of the second wellbore, but significant concentrations of methane were recorded. The decrease in hydrogen content was due to its escape due to the formation of reduced pressure zones in the surrounding rocks around the wellbore. The presence of such hydrogen-nitrogen zones was also confirmed by testing a duplicate ultra-deep well. At a depth of 3,350 m, the formation water contained 27% hydrogen, 16% methane, 0.28% C2–C5 hydrocarbons, 55.4% nitrogen, and 1.3% carbon dioxide. It is important to note that during gas logging, the drilling mud injected into the well already contains dissolved air, which may explain the presence of nitrogen in the outgoing drilling mud caused by nitrogen input from the air (Knez and Zamani 2023).

2.3. Hydrogen dynamics and hydrocarbon trapping in the Pre-Caspian Basin

The question of the origin of hydrogen in the Earth's crust is a complex and poorly researched topic. In most cases, hydrogen is present in these gases in low concentrations. With the development of highly sensitive gas analysis methods using chromatography, it has become possible to systematically detect even small amounts of hydrogen (0.001–0.1%) in the composition of gases. This indicates the presence of significant partial pressures of

hydrogen in the subsurface. These pressures are capable of ensuring its diffusion through the pore space of rocks and to the earth's surface. Natural chemical processes, including the reduction of trivalent iron, sulfates, and organic matter in rocks, can slow down hydrogen diffusion. The high diffusion coefficients of hydrogen prevent it from accumulating in large quantities in hydrocarbon gas deposits.

Hydrogen is able to move through rocks that are not permeable to hydrocarbons. Therefore, accumulations of molecular hydrogen in sedimentary formations are possible only in the presence of extremely impermeable barriers, such as salt layers, amorphous sulfur, high-altitude rocks, and others (Figure 1). This explains the presence of hydrogen accumulations in salt deposits, ore deposits, and other well-isolated, closed systems (Veshareh et al. 2022).

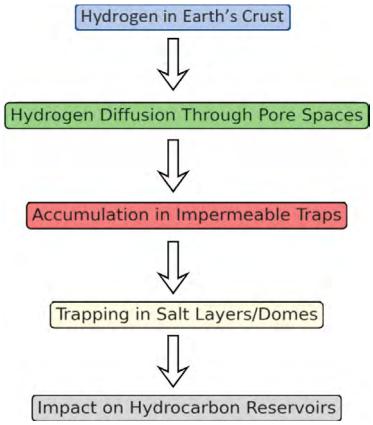

Fig. 1. Flowchart of hydrogen dynamics and hydrocardon trapping in the Pre-Caspian Basin

Rys. 1. Schemat dynamiki wodoru i wychwytywania hydrokardonów w Basenie Przedkaspijskim

Hydrogen, together with carbon dioxide, is often a common and, in some cases, even the main component of the gas phase of metamorphic and volcanic rocks. The detection of hydrogen is not limited to volcanic and metamorphic formations; it is also present in sedimentary rocks. At times, gases containing hydrogen can be detected by drilling boreholes. The study of hydrogen distribution characteristics in oil and gas-bearing regions of Western Siberia allowed the conclusion that hydrogen, together with carbon dioxide gases, penetrates sedimentary formations from deep underground through faults and fractures.

The region is characterized by complex geological formations like faults, fold belts, and salt domes, which trap hydrocarbons. The construction of these traps is critical to the accumulation of oil and gas (Luo et al. 2023). Salt tectonics, particularly the creation of salt domes, have played an important role in hydrocarbon trapping by forming impermeable barriers that prevent oil and gas from migrating upward, enabling them to concentrate in reservoirs. The stratigraphy of the southeastern Pre-Caspian Basin consists of sedimentary strata from many geological eras, including the Permian, Triassic, Jurassic, and Neogene.

These layers have varying capacities for storing and transferring hydrocarbons, depending on their depositional settings and subsequent diagenetic changes (Panevnyk 2023). The occurrence of numerous hydrocarbon-bearing horizons within these stratigraphic units suggests a complicated history of hydrocarbon movement and accumulation in the area. The lithological composition of the rocks, particularly the porosity and permeability of the reservoir rocks, is important in evaluating the quality and capacity of oil and gas reserves. Reservoirs in the region are frequently found in rocks with high porosity and permeability, such as sandstone and carbonates. These rocks not only store hydrocarbons but also help them move through the subsoil. The chemical composition of the rocks influences the types of hydrocarbons found and their stability inside the reservoir.

The extensive manifestations of gas activity in the Caspian Basin may be related to the flow of gases through faults in the saline sediments from deep Paleozoic rocks beneath them. In many areas of the southeastern part of the Pre-Caspian Basin, drilling of prospecting and exploration wells has revealed evidence of oil and gas in various horizons, including Neogene, Palaeogene, Jurassic, and Lower Permian deposits. Sediments of the Lower Bashkirian Stage have proved to be particularly productive.

2.4. Sustainable strategies for hydrocarbon production and management

The research emphasizes that geological structures, notably faults, folds, and salt domes, play an important role in hydrocarbon entrapment in the southern Caspian Basin. These structural characteristics generate natural traps for hydrocarbons to accumulate, making them important targets for exploration. The research additionally highlights the importance of reservoir parameters like porosity and permeability in determining the quality and capacity of oil and gas reservoirs.

High porosity and permeability rocks, like sandstones and carbonates, are crucial reservoirs in the region for effectively storing and transporting hydrocarbons, indicating that rock physical and chemical features significantly influence hydrocarbon migration and accumulation. Research by C. Sun et al. (2021) has also underlined the relevance of these features in forecasting reservoir location and quality, particularly in complicated basins like the southeastern Caspian. X. Liu et al. (2021) showed that using seismic tomography and other geophysical techniques may considerably increase the accuracy of subsurface models, assisting in identifying hydrocarbon-rich zones. The use of similar approaches in this study highlights their significance in the southern Caspian Basin, where complex geological features and various strata need a comprehensive approach.

Sustainable hydrocarbon production necessitates environmental considerations. Carbon management technologies such as Carbon Capture and Storage (CCS) may dramatically reduce greenhouse gas emissions from hydrocarbon extraction, therefore harmonizing with global climate objectives. The Pre-Caspian Basin's diverse geological formations provide suitable locations for CCS. F. Al Hameli et al. (2022) found that CCS technology

minimizes emissions when incorporated into large-scale industrial operations. Biodiversity preservation through habitat restoration and environmental monitoring programs can reduce the environmental impact of hydrocarbon production. Companies can invest in rehabilitating degraded ecosystems to restore natural habitats and maintain ecological balance. D.A. Alemzero et al. (2021) stress the need for complete environmental impact assessments in oil and gas developments. In the southern Caspian Basin, where ecological sensitivity is a concern, the study's emphasis on sustainable exploration procedures is especially relevant. The incorporation of environmental factors into the exploration process not only helps to mitigate any negative consequences but also adds to the long-term viability of resource development in the region.

Internal corrosion in pipelines must be predicted and managed to ensure the safety and dependability of oil and gas transport systems, especially in places with complicated geological characteristics, such as the southern Caspian Basin. M.E.A.B. Seghier et al. (2022) used ensemble learning approaches to forecast internal corrosion rates, which is an important part of pipeline integrity management. This approach entails evaluating a variety of parameters, including the chemical composition of pumped products, temperature, pressure, and flow rate, all of which are important in the context of hydrocarbon transportation. Incorporating such predictive methodologies into the Caspian Basin's exploration and production operations might improve infrastructure safety and durability, which aligns with the study's overall goal of sustainable resource management.

Production efficiency in hydrocarbon exploitation can be significantly improved through the adoption of advanced technologies. L. Kuang et al. (2021) and J.N. Desai et al. (2021) both emphasise the importance of combining artificial intelligence (AI) and big data analytics into future exploration initiatives. AI has the potential to alter the oil and gas sector by allowing for more precise and efficient analysis of big datasets, which is especially useful in complex areas like the southeastern Caspian Basin. Machine learning algorithms can examine seismic and geological data to detect trends and forecast the most potential exploration targets. Incorporating digital technologies like the Internet of Things and AI into production processes may improve real-time monitoring, predictive maintenance, and resource allocation optimization, resulting in more efficient and cost-effective operations. Furthermore, the adoption of Enhanced Oil Recovery (EOR) methods like carbon dioxide injection, water flooding, or thermal recovery can boost hydrocarbon production from more mature fields, extending reservoir life and increasing economic value. These procedures are essential in areas like the southeastern Pre-Caspian Basin, where complex geological formations may limit traditional recovery methods. According to A.O. Gbadamosi et al. (2019), EOR technologies can increase oil recovery rates by up to 15–20% compared to primary recovery methods, making them an important component of effective resource management.

Effective resource management in hydrocarbon exploitation requires a comprehensive approach that takes into account both commercial resource extraction and long-term environmental impact management. Water resources are essential for hydrocarbon

production. Therefore, integrated resource management strategies should include the implementation of appropriate water management processes. Adopting closed-loop water recycling and treatment systems, for example, can reduce water use while also minimizing contamination of local water bodies, which is especially important in areas with limited water resources, such as the Caspian Basin. R.B. Jackson et al. (2014) emphasized the necessity of sustainable water management in shale gas extraction and the need for industry-wide adoption of water-efficient technology and practices. Furthermore, taking a life-cycle approach to resource management, which considers the entire life cycle of hydrocarbon projects from exploration to decommissioning, can assist in identifying and mitigating environmental and social risks at each stage, ensuring that resource extraction is both economically viable and environmentally responsible.

The study of oil and gas formation patterns in the southeastern edge of the Pre-Caspian Basin revealed numerous critical characteristics important to the oil and gas sector. The findings highlight the necessity of effective drilling procedures and precise reservoir property evaluation, as demonstrated by U. Zhumadilov et al. (2023), into how rigorous hazard assessments may reduce drilling inefficiencies. Furthermore, the study underscores the importance of understanding diverse reservoir formation trajectories, consistent with the findings of J. Lu et al. (2023), who give insights into the effects of early-stage carbonate rock development on reservoir features.

The hydrocarbon sector requires a comprehensive strategy to increase productivity, resource management, and environmental and social concerns. This includes incorporating technical breakthroughs and sustainable practices, reducing environmental effects, collaborating with local people, and using adaptive management. The paper gives an overview of the elements that influence oil and gas reservoir growth in the southern Caspian Basin, highlighting the significance of geological structures and reservoir characteristics in hydrocarbon accumulation. The report also indicates that future research should use AI, big data analytics, and new drilling technology. Expanding upon findings and implementing new technologies can result in more efficient and sustainable extraction of resources in the region.

Conclusions

This study provided insight into the geological and geochemical factors influencing oil and gas development in the southern Pre-Caspian Basin. The investigation found numerous critical structural elements, including fault networks, fold belts, and salt domes, that play an important role in trapping hydrocarbons. These geological features are critical in identifying where hydrocarbons are likely to accumulate, making them suitable targets for exploration.

The study additionally discovered that the region's rocks had high porosity and permeability, notably sandstones and carbonates, which work as excellent hydrocarbon

repositories. The chemical composition of these rocks has been shown to directly impact the types of hydrocarbons present and their stability in the reservoirs, which is crucial in assessing the quality of reserves. Furthermore, the study emphasized the influence of the region's geological history on hydrocarbon activity and accumulation. Sedimentation processes, tectonic activity, and subsequent diagenetic alterations were discovered to have important roles in the distribution of hydrocarbons throughout strata. The significance of considering environmental and social factors while developing hydrocarbon resources in this region was also emphasized. The study highlighted regions where exploration and production operations might have an impact on local ecosystems and populations, emphasizing the importance of sustainable resource extraction strategies.

The study highlights how advanced technologies such as seismic tomography, AI, and EOR can significantly improve production efficiency and resource management in the hydrocarbon industry. It also stresses the importance of integrating environmental considerations into exploration processes to ensure sustainable development. Additionally, the research underscores the need for robust water management strategies and predictive methodologies to maintain pipeline integrity, particularly in the context of the Caspian Basin.

This study's findings offer to broaden our understanding of the southeastern Pre-Caspian Basin's potential as a hydrocarbon-rich area. Identifying major geological features, assessing reservoir attributes, and considering environmental and social consequences all contribute to a comprehensive framework for future exploration and resource management actions in the area. Further research should focus on improving our understanding of hydrocarbon migration pathways and assessing the environmental and socioeconomic consequences of resource development in this strategically vital region.

The Authors have no conflict of interest to declare.

REFERENCES

Al Hameli et al. 2022 – Al Hameli, F., Belhaj, H. and Al Dhuhoori, M. 2022. CO2 Sequestration overview in geological formations: Trapping mechanisms matrix assessment. *Energie* 15(20), DOI: 10.3390/en15207805.

Alemzero et al. 2021 – Alemzero, D.A., Iqbal, N., Iqbal, S., Mohsin, M., Chukwuma, N.J. and Shah, B.A. 2021. Assessing the perceived impact of exploration and production of hydrocarbons on household's perspective of environmental regulation in Ghana. *Environmental Science and Pollution Research* 28, pp. 5359–5371, DOI: 10.1007/s11356-020-10880-3.

Belayouni et al. 2023 – Belayouni, H., Guerrera, F., Martín-Martín, M., Tramontana, M. and Bullejos, M. 2023. Cenozoic tectono-sedimentary evolution of the onshore-offshore Tunisian tell: Implications for oil-gas research. *Marine and Petroleum Geology* 156, DOI: 10.1016/j.marpetgeo.2023.106426.

Desai et al. 2021 – Desai, J.N., Pandian, S. and Vij, R.K. 2021. Big data analytics in upstream oil and gas industries for sustainable exploration and development: A review. *Environmental Technology & Innovation* 21, DOI: 10.1016/j.eti.2020.101186.

Gbadamosi et al. 2019 – Gbadamosi, A.O., Junin, R., Manan, M.A., Agi, A. and Yusuff, A.S. 2019. An overview of chemical enhanced oil recovery: Recent advances and prospects. *International Nano Letters* 9, pp. 171–202, DOI: 10.1007/s40089-019-0272-8

Jackson et al. 2014 – Jackson, R.B., Vengosh, A., Carey, J.W., Davies, R.J., Darrah, T.H., O'Sullivan, F. and Pétron, G. 2014. The environmental costs and benefits of fracking. *Annual Review of Environment and Resources* 39, pp. 327–362, DOI: 10.1146/annurev-environ-031113-144051.

Kaskabaeva, T.T. 2021. On the question of structure and competence of the ministry of ecology, geology and natural resources of the Republic of Kazakhstan. *Current Scientific Research in the Modern World* 5(73), pp. 107–111.

Knez, D. and Zamani, O.A.M. 2023. Up-to-date status of geoscience in the field of natural hydrogen with consideration of petroleum issues. *Energies* 16(18), DOI: 10.3390/en16186580.

Kondrat, O. and Horobets, P. 2023. Increasing the efficiency of gas reservoir development in conditions of uneven gas consumption. *Prospecting and Development of Oil and Gas Fields* 23(4), pp. 50–57, DOI: 10.69628/pdogf/4.2023.50.

Kozykhanova, Z.T. 2022. Transportation of liquid cargo: How Kazakh oil is transported: Analysis of oil exports. [In:] *XVII International Scientific Conference of Students and Young Scientists "ǴYLYM JÁNE BILIM – 2022"*. Astana: L.N. Gumilyov Eurasian National University, pp. 6301–6305.

Kuang et al. 2021 – Kuang, L., Liu, H., Ren, Y., Luo, K., Shi, M., Su, J. and Li, X. 2021. Application and development trend of artificial intelligence in petroleum exploration and development. *Petroleum Exploration and Development* 48(1), pp. 1–14, DOI: 10.1016/S1876-3804(21)60001-0.

Lazarev et al. 2021 – Lazarev, S., Kuiper, K.F., Oms, O., Bukhsianidze, M., Vasilyan, D., Jorissen, E.L., Bouwmeester, M.J., Aghayeva, V., van Amerongen, A.J., Agustí, J., Lordkipanidze, D. and Krijgsman, W. 2021. Five-fold expansion of the Caspian Sea in the late Pliocene: New and revised magnetostratigraphic and $^{40}Ar/^{39}Ar$ age constraints on the Akchagylian Stage. *Global and Planetary Change* 206, DOI: 10.1016/j.gloplacha.2021.103624

Li et al. 2024 – Li, Y. B., Chen, H.T., Liu, Y.L., Li, T.H., Yang, F., Shen, S.B., Hu, Y.J., Nie, H., Li, Z.Z. and Li, L. 2024. Tectonic styles and hydrocarbon accumulation characteristics of concealed thrust belt in eastern margin of Pre-Caspian Basin. [In:] *Proceedings of the International Field Exploration and Development Conference 2023*. Singapore: Springer, pp. 621–633, DOI: 10.1007/978-981-97-0464-4_50.

Lin et al. 2023 – Lin, T., Sha, Z., Zhu, K., Nan, J., Ren, Y. and Li, B. 2023. Characteristics and geological implications of lacustrine carbonate of Nantun formation in Hailar Basin. *Lithosphere* 2022(Special 12), DOI: 10.2113/2022/6306735.

Liu et al. 2022 – Liu, X., Liu, B., Du, H. and Wang, M. 2022. Optimal and fast drilling technologies for ultra-deep horizontal wells in the fault zones of the Shunbei oil & gas field. *Medical Journal* 50(4), pp. 11–17, DOI: 10.11911/syztjs.2022072.

Lu et al. 2023 – Lu, J., Tan, X., Jin, Z. Chen, Y., Wang, S., Zhao, W. and Li, C. 2023. Differential reservoir formation paths of carbonate rocks in early stage and impacts on reservoir properties: A case study of KT-I and KT-II layers in N Oilfield, Pre-Caspian Basin. *Journal of Palaeogeography (Chinese Edition)* 25(1), pp. 226–244, DOI: 10.7605/gdlxb.2023.01.015.

Luo et al. 2023 – Luo, X., Zhang, L., Lei, Y. and Yang, W. 2023. Progresses and problems in the study of hydrocarbon migration dynamics. [In:] *Dynamics of Hydrocarbon Migration*. Singapore: Springer, pp. 1–62, DOI: 10.1007/978-981-19-5534-1_1.

Malikov, M.M. 2022. Prospects for environmental safety of road transport in Kazakhstan: From theory to practice. [In:] *Innovative Technologies in the Automotive Industry: Education. The Science. Practice*. Kostanay: Kostanay College of Road Transport, pp. 124–128.

Mehay et al. 2021 – Mehay, S., Hashem, M., Rouis, L., Mollianiyazov, E., Bennett, B. and Stankiewicz, A. 2021. Understanding lateral and vertical fluid variations in the Pliocene sandstone reservoirs in the eastern South Caspian Basin. *AAPG Bulletin* 105(11), pp. 2181–2205, DOI: 10.1306/06032119263.

Panevnyk, D. 2023. Study of hydraulic characteristics of jet device for preventing emissions of low-pressure petroleum gas. *Ecological Safety and Balanced Use of Resources* 14(1), pp. 43–53, DOI: 10.31471/2415-3184-2023-1(27)-43-53.

Sagi, R.B. and Elesh, M.S. 2022. Planning of innovative activities in the oil and gas industry of the Republic of Kazakhstan. *Colloquium* 8, pp. 168–175.

Seghier et al. 2022 – Seghier, M.E.A.B., Höche, D. and Zheludkevich, M. 2022. Prediction of the internal corrosion rate for oil and gas pipeline: Implementation of ensemble learning techniques. *Journal of Natural Gas Science and Engineering* 99, DOI: 10.1016/j.jngse.2022.104425.

Sembieva, L.M. 2021. *Modern aspects of the monetary policy of the Republic of Kazakhstan in the context of globalization challenges*. [Online:] https://rep.enu.kz/bitstream/handle/enu/8178/Сборник._КНК_p108-114.pdf?sequence=1&isAllowed=y.

Sun et al. 2021 – Sun, C., Nie, H., Dang, W., Chen, Q., Zhang, G., Li, W. and Lu, Z. 2021. Shale gas exploration and development in China: Current status, geological challenges, and future directions. *Energy & Fuels* 35(8), pp. 6359–6379, DOI: 10.1021/acs.energyfuels.0c04131.

Tseng et al. 2023 – Tseng, Y., Römer, M., Lin, S., Pape, T., Berndt, C., Chen, T.T., Paull, C.K., Caress, D.W. and Bohrmann, G. 2023. Yam seep at four-way closure ridge: A prominent active gas seep system at the accretionary wedge SW offshore Taiwan. *International Journal of Earth Sciences* 112(3), pp. 1043–1061, DOI: 10.1007/s00531-022-02280-4.

Tsuji et al. 2021 – Tsuji, T., Sorai, M., Shiga, M., Fujikawa, S. and Kunitake, T. 2021. Geological storage of CO_2-N_2-O_2 mixtures produced by membrane-based direct air capture (DAC). *Greenhouse Gases: Science and Technology* 11(4), pp. 610–618, DOI: 10.1002/ghg.2099.

Veshareh et al. 2022 – Veshareh, M.J., Thaysen, E.M. and Nick, H.M. 2022. Feasibility of hydrogen storage in depleted hydrocarbon chalk reservoirs: Assessment of biochemical and chemical effects. *Applied Energy* 323, DOI: 10.1016/j.apenergy.2022.119575.

Zhakai et al. 2023 – Zhakai, A.K., Urankhaeva, G.T. and Serikkalieva, A.E. 2023. Energy silk road: Prospects for the development of oil and gas cooperation between the people's Republic of China and the Republic of Kazakhstan. *Izvestia. Series: International Relations and Area Studies* 52(2). [Online:] https://bulletin-irr.ablaikhan.kz/index.php/j1/article/view/291.

Zhumadilov et al. 2023 – Zhumadilov, U., Baktybayeva, K., Tlepbergenov, N., Manakhayev, R., Sargunanov, M. and Puche, E. 2023. *Robust subsurface drilling hazards assessment reduces well drilling cycle and geological non-productive time in an onshore Pre-Caspian Basin oil field*. Baku: SPE Caspian Technical Conference and Exhibition, DOI: 10.2118/217547-MS.

STUDY OF THE PATTERN OF OIL AND GAS DEPOSITS AND FORECASTING FAVORABLE TARGETS ON THE SOUTHEASTERN SIDE OF THE CASPIAN BASIN

Keywords

energy security, economic development, optimal strategies, inventory management

Abstract

The study's relevance lies in the region's strategic importance for energy security and economic development and the need to devise optimal strategies for hydrocarbon reserves production and management in the face of global market changes and environmental challenges. This study aimed to investigate the geological and geochemical characteristics that influence oil and gas formation and accumulation on the southeastern side of the Pre-Caspian Basin. The research used analytical, classification, statistical, structural-functional, functional, deductive, and synthesis methods. As part of the study of the southeastern flank of the Pre-Caspian Basin, a comprehensive analysis of geological and geophysical data, including detailed seismic interpretation and geochemical analysis of rocks and fluids, was carried out. This multivariate analysis revealed the essential structural features of

the region and identified prospective traps for oil and gas. The findings of this study emphasize the strategic importance of the region as a potential source of energy resources while highlighting the importance of attention to environmental and social aspects in the development of these resources. This study represents a significant contribution to the oil and gas industry and helps guide the region's strategic development with sustainability and resource efficiency in mind. The practical significance of this study is to provide a basis for more efficient exploitation and management of oil and gas resources on the southeastern side of the Caspian Basin, contributing to the region's economic development and energy security.

BADANIE STRUKTURY ZŁÓŻ ROPY I GAZU ORAZ PROGNOZOWANIE KORZYSTNYCH CELÓW PO POŁUDNIOWO-WSCHODNIEJ STRONIE BASENU MORZA KASPIJSKIEGO

Słowa kluczowe

bezpieczeństwo energetyczne, rozwój gospodarczy, strategie optymalne, zarządzanie zapasami

Streszczenie

Trafność opracowania wynika ze strategicznego znaczenia regionu dla bezpieczeństwa energetycznego i rozwoju gospodarczego oraz konieczności opracowania optymalnych strategii wydobycia i zarządzania złożami węglowodorów w obliczu zmian na rynku światowym i wyzwań środowiskowych. Celem tej analizy było zbadanie cech geologicznych i geochemicznych wpływających na powstawanie i akumulację ropy i gazu w południowo-wschodniej części Basenu Przedkaspijskiego. W badaniach wykorzystano metody analityczne, klasyfikacyjne, statystyczne, strukturalno-funkcjonalne, funkcjonalne, dedukcyjne i syntetyczne. W ramach badań południowo-wschodniej flanki Basenu Przedkaspijskiego przeprowadzono kompleksową analizę danych geologicznych i geofizycznych, obejmującą szczegółową interpretację sejsmiczną oraz analizę geochemiczną skał i płynów. Ta wielowymiarowa analiza ujawniła podstawowe cechy strukturalne regionu i zidentyfikowała potencjalne pułapki dla ropy i gazu. Wyniki tego badania podkreślają strategiczne znaczenie regionu jako potencjalnego źródła zasobów energii, podkreślając jednocześnie znaczenie dbałości o aspekty środowiskowe i społeczne w rozwoju tych zasobów. Badanie to stanowi znaczący wkład w przemysł naftowy i gazowy i pomaga kierować strategicznym rozwojem regionu z myślą o zrównoważonym rozwoju i efektywnym wykorzystaniu zasobów. Praktyczne znaczenie niniejszego opracowania polega na stworzeniu podstaw dla bardziej efektywnej eksploatacji i zarządzania zasobami ropy i gazu po południowo-wschodniej stronie Basenu Morza Kaspijskiego, przyczyniając się do rozwoju gospodarczego regionu i bezpieczeństwa energetycznego.