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COMPREHENSIVE ANALYSIS OF PETROLEUM SOURCE ROCKS AND THE CONDITIONS OF HYDROCARBON GENERATION AND MIGRATION IN THE ZAYSAN DEPRESSION

Abstract. The article presents a comprehensive analysis of source rocks and the conditions of hydrocarbon generation and migration within the Zaisan Basin. The study focuses on Permian deposits (Taranchin, Maichat, and Akkolkan formations), which represent the principal source rocks of the region. The aim of the research is to evaluate their generative potential and to identify patterns of hydrocarbon migration. The study integrates seismic data, structural analysis. It is established that the central part of the basin exhibits the greatest thickness and burial depth of source rocks, providing the most favorable thermobaric conditions for hydrocarbon generation. The role of tectonic faults, pinch-out zones, and lithological seals in the formation of migration pathways and traps was comprehensively substantiated.
Key words: *Zaisan Basin, source rocks, Permian deposits, hydrocarbon generation, hydrocarbon migration, tectonic faults, petroleum potential, exploration geology.*

Зайсан ойпатындағы мұнайаналық тау жыныстарды, көмірсутектердің генерациясы мен миграциясы жағдайларын кешенді талдау

Аңдатпа. Мақалада Зайсан ойпатындағы мұнайаналық тау жыныстар мен көмірсутектердің генерациясы және миграциясы жағдайлары қарастырылған. Зерттеу нысаны ретінде аймақтың негізгі мұнай түзуші кешені болып табылатын пермь шөгінділері (Таранчи, Майчат және Акқолқан свиталары) алынған. Жұмыстың мақсаты – олардың генерациялық әлеуетін бағалау және көмірсутектердің көшу заңдылықтарын анықтау. Зерттеуде сейсмикалық барлау, құрылымдық талдау әдістері қолданылды. Нәтижесінде ойпаттың орталық бөлігінде тау жыныстардың ең үлкен қалыңдығы мен тереңдігі анықталып, қолайлы термобарлық жағдайлар қалыптасқаны көрсетілді. Тектоникалық бұзылыстардың, сыналу аймақтарының және литологиялық экрандардың миграция мен тұтқыштардың қалыптасуындағы рөлі кешенді түрде негізделді.
Түйінді сөздер: *Зайсан ойпаты, мұнайаналық жыныстар, пермь шөгінділері, көмірсутектердің генерациясы, көмірсутектердің миграциясы, тектоникалық бұзылыстар, мұнай-газ перспективтілігі, геологиялық барлау жұмыстары.*

Комплексный анализ нефтематеринских пород, условий генерации и миграции углеводородов в Зайсанской впадине

Аннотация. В статье рассмотрены нефтематеринские породы и условия генерации и миграции углеводородов в Зайсанской впадине. Объектом исследования являются пермские отложения (Таранчинская, Майчатская и Акколканская свиты), играющие ключевую роль в нефтегазообразовании региона. Целью работы является оценка их генерационного потенциала и выявление закономерностей миграции углеводородов. Использованы методы сейсморазведки и структурного анализа. Установлено, что центральная часть впадины характеризуется максимальной мощностью и глубиной залегания пород, обеспечивающих благоприятные термобарические условия. Роль тектонических нарушений, зон выклинивания и литологических экранов в формировании миграционных путей и ловушек была комплексно обоснована.
Ключевые слова: *Зайсанская впадина, нефтематеринские породы, отложения, генерация углеводородов, миграция углеводородов, тектонические нарушения, нефтегазоносность, геологоразведочные работы.*

Introduction

The Zaysan Depression, located in Eastern Kazakhstan, represents a promising area for petroleum exploration studies. Geological exploration works have led to the discovery of the Sarybulak oil and gas field, which has significantly increased scientific and industrial interest in the geological investigation of this region [1, 2].

This study aims to provide a comprehensive analysis of the distribution of source rocks, the conditions of hydrocarbon accumulation, and the assessment of future exploration potential. The research is based on data from previous studies, modern geological materials, and results obtained from original investigations.

Despite accumulated knowledge, the Zaysan Depression remains insufficiently studied in terms of its petroleum system characteristics, which makes the present analysis particularly relevant. Special attention is given to paleotectonic reconstruction, the timing of hydrocarbon generation and migration, as well as the formation of structural and stratigraphic traps.

The formation of the Zaysan Depression began in the Late Paleozoic. From a tectonic perspective, it represents a long-evolving intermontane basin with a sublatitudinal strike, bordered in the north by the Altai mountain system and in the south by the Saur-Tarbagatai mountain system [1, 2, 3]. The tectonic scheme is shown in Figure 1.

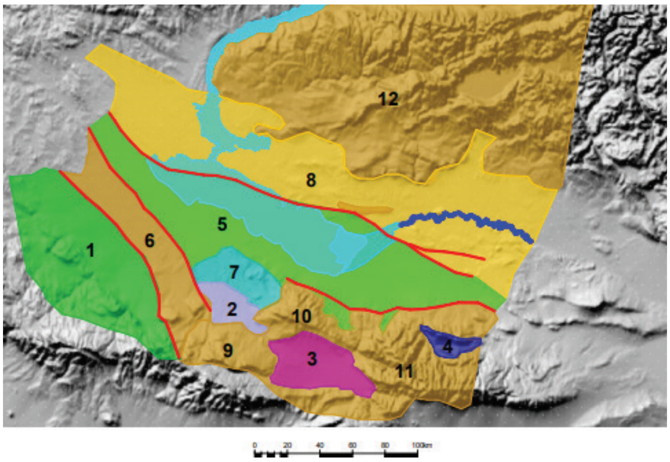
Within the studied area, several negative structural elements are distinguished, including the Baytogai trough, Aksuat subsidence, Akzhar subsidence, Fedoseev subsidence, and Kendyrlyk graben. Positive structures include the Arkarly uplift, Manrak uplift, and Aktobe block. The mountain ranges identified in the study area comprise the Eastern Tarbagatai Range, Manrak Range, Saikan Range, and the Altai Mountains.

The central part of the Zaysan Depression is occupied by the Baytogai trough, which represents its largest and most deeply subsided structural element. This area is characterized by the widest distribution of source rocks and preserves the most complete stratigraphic section of sedimentary deposits [3, 4, 5].

At present, commercially discovered and producing oil and gas accumulations are associated with the Sarybulak Central and Sarybulak East structures.

In total, 55 wells have been drilled in the Zaysan Depression over different periods (Figure 3). The primary target horizons of most recent wells include Paleogene, Jurassic, and Triassic deposits. Permian sediments have been penetrated by a limited number of wells. The most complete stratigraphic section is represented by the parametric well S-1P. In this well, oil shows were first identified within Permian deposits.

Geophysical data obtained from wells, including vertical seismic profiling (VSP), have enabled a more detailed interpretation of the geological structure of the area. Well data



Subsidence zones: 1 – Aksuat depression; 2 – Akzhar depression; 3 – Fedoseev depression; 4 – Kendyrlyk trough; 5 – Baytogai trough. Uplifts: 6 – Arkarly uplift; 7 – Manrak uplift; 8 – Aktobe block. Mountain ranges: 9 – East Kazakhstan Range; 10 – Manrak Range; 11 – Saikan Range; 12 – Altai Mountains.

Шөгу аймақтары: 1 – Ақсуат ойысы; 2 – Ақжар ойысы; 3 – Федосеев ойысы; 4 – Кендірлік прогибі; 5 – Байтоғай прогибі. Көтерілу аймақтары: 6 – Арқарлы көтерілімі; 7 – Маңырақ көтерілімі; 8 – Ақтөбе блоғы. Тау жоталары: 9 – Шығыс Қазақстан жотасы; 10 – Маңырақ жотасы; 11 – Сауыр жотасы; 12 – Алтай таулары.

Зоны опускания: 1 – Аксуатская впадина; 2 – Акжарская впадина; 3 – Федосеевская впадина; 4 – Кендырлыкский прогиб; 5 – Байтогайский прогиб. Поднятия: 6 – Аркарлинское поднятие; 7 – Манракское поднятие; 8 – Актобинский блок. Горные хребты: 9 – Восточно-Казахстанский хребет; 10 – Манракский хребет; 11 – Сауырский хребет; 12 – Алтайские горы.

Figure 1. Tectonic scheme of the Zaysan Depression.
Сурет 1. Зайсан ойпатының тектоникалық сызбасы.
Рис. 1. Тектоническая схема Зайсанской впадины.

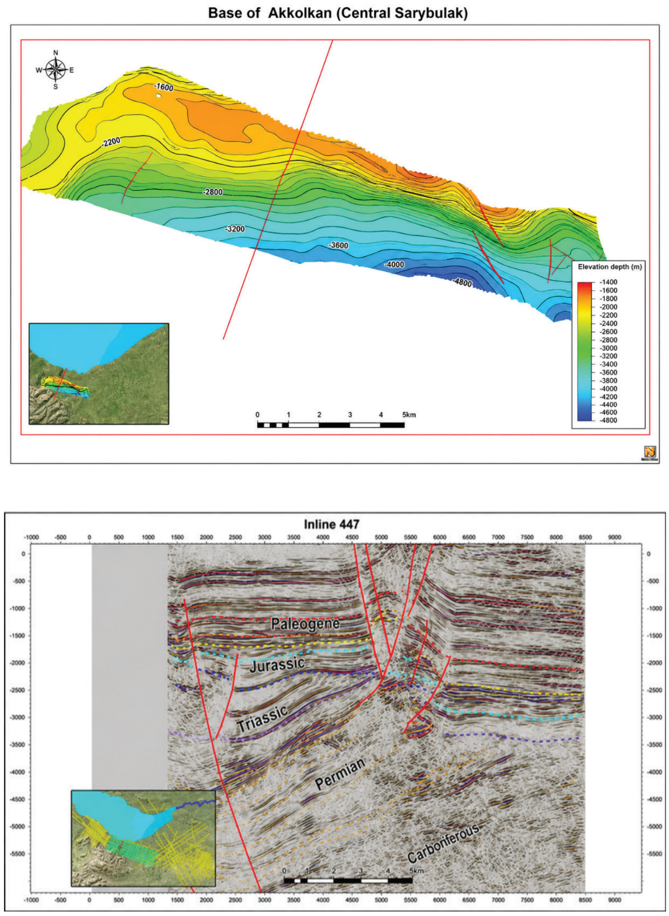


Figure 2. Seismic time section and structural map of the oil reservoir in the Central Sarybulak structure.
Сурет 2. Орталық Сарыбұлақ құрылымындағы мұнай коллекторының уақыттық қимасы және құрылымдық картасы.
Рис. 2. Временной разрез и структурная карта нефтяного коллектора в Центральной Сарыбулакской структуре.

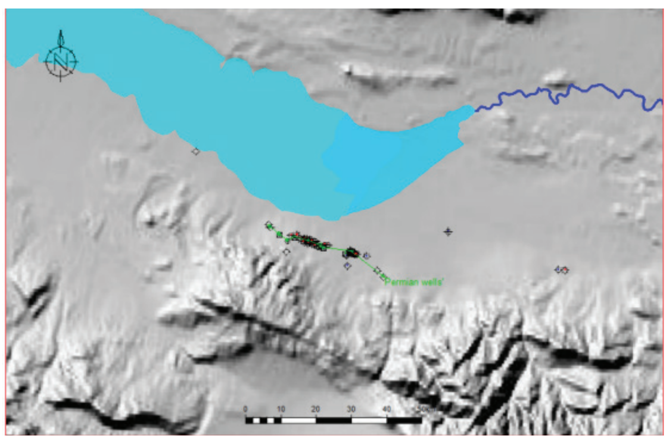


Figure 3. Location of drilled wells in the Zaysan Depression.
Сурет 3. Зайсан ойпатындағы бұрғыланған ұңғымалардың орналасуы.
Рис. 3. Расположение пробуренных скважин в Зайсанской впадине.

were integrated with the interpretation of 2D and 3D seismic surveys (Figure 4). Vertical seismic profiling was particularly important for refining the velocity model of the subsurface.

In addition, during drilling of modern wells, 184 meters of core were recovered from Permian deposits with a recovery rate exceeding 90%. Subsequently, standard and special laboratory analyses of the core samples were carried out in Kazakhstan and Russia to refine the reservoir porosity–permeability properties and to obtain data on the quality of the Permian horizon.

Methods / Research

The geological structure of the Zaysan Depression includes a complex assemblage of sedimentary rocks penetrated by wells, ranging in age from the Carboniferous to the Quaternary [6]. Five distinct structural stages can be clearly identified (Figure 5).

The Silurian-Carboniferous stage is highly deformed, contains numerous intrusive bodies, is metamorphosed, and represents the crystalline basement. Sedimentary cover sequences overlie the basement and can be subdivided into four structural stages.

Deposits ranging from the Middle Carboniferous to the Permian are strongly deformed in places. The next struc-

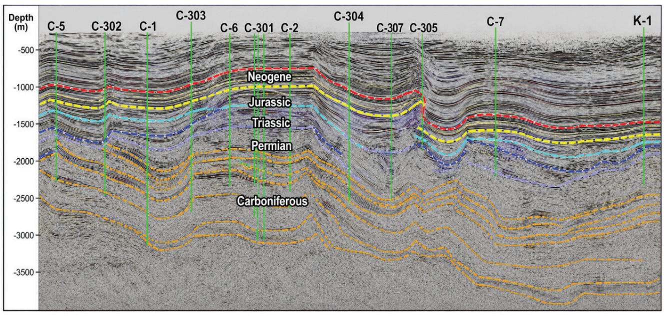


Figure 4. Correlation scheme and cross-section through wells penetrating Permian deposits (faults not shown).
Сурет 4. Пермь шөгінділерін кесіп өтетін ұңғымалар бойынша корреляция сызбасы және қима (жарылымдар көрсетілмеген).
Рис. 4. Схема корреляции и разрез по скважинам, вскрывающим пермские отложения (разломы не показаны).

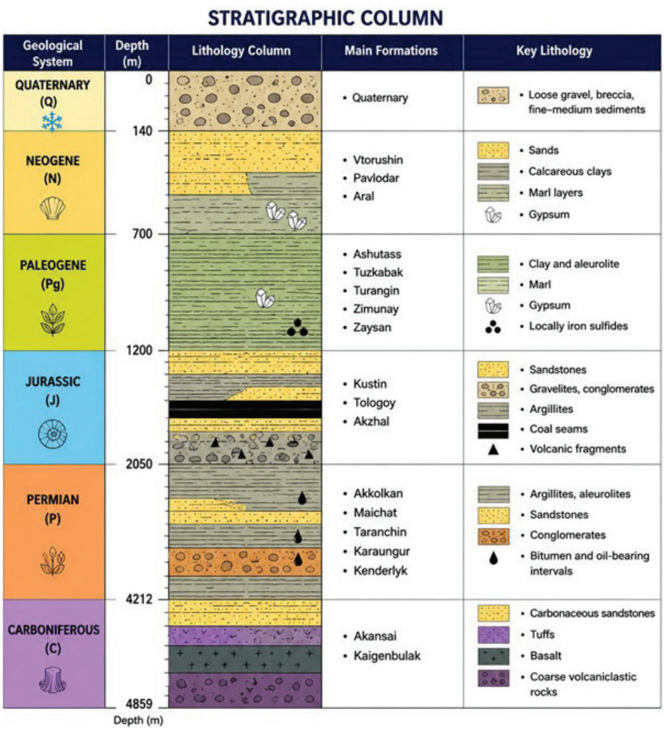


Figure 5. Lithological and stratigraphic description of the Zaysan Basin.
Сурет 5. Зайсан бассейнінің литологиялық және стратиграфиялық сипаттамасы.
Рис. 5. Литологическое и стратиграфическое описание Зайсанского бассейна.

tural stage includes Triassic sediments, which unconformably overlie the underlying formations both angularly and stratigraphically. Jurassic rocks, which also exhibit structural and stratigraphic unconformities with both overlying and underlying units, constitute the fourth structural stage. The uppermost structural stage is composed of Cenozoic deposits, which unconformably overlie Paleozoic and Mesozoic formations and, in some areas, even the folded basement.

The age determinations were carried out using laboratory core studies based on palynological (spore-pollen) and microfaunal assemblages. Within the Zaysan Depression, the oldest rocks penetrated by drilling are of Carboniferous age.

Source rocks: composition and distribution. Within the Zaysan Depression, the primary source rocks are represented by Permian deposits, including the Taranchin, Maichat, and Akkolkan formations. Their study is of critical importance for evaluating the petroleum potential of the region.

Permian sediments in the Zaysan Depression are unevenly distributed and have a limited areal extent. Zones of maximum subsidence and pinch-out areas can be distinguished. The main information regarding the depth and thickness of these deposits has been obtained through the interpretation of 2D and 3D seismic survey data, as well as drilling results [7].

The greatest extent and maximum burial depth of the Permian deposits are observed in the central part of the depression, where 3D seismic surveys have been conducted. The depth to the base of these formations reaches approximately -5400 m below sea level (Figure 6). In this zone, the source rocks are least affected by degradation and retain significant thickness, making the area a highly prospective hydrocarbon generation kitchen.

A progressive decrease in both thickness and burial depth of the Permian succession toward the northeast and west is associated with compressional tectonic processes. These processes led to uplift of the formations, their exposure at the surface, and subsequent erosion. To the south, the Permian deposits locally plunge beneath the thrust structures of the Saur-Tarbagatai mountain system.

According to 2D seismic profiles No. 76 and No. 66, a gradual thinning and pinch-out of Permian deposits occurs toward the northeast. These rocks are unconformably overlain by Mesozoic and Cenozoic sediments. The presence of pronounced angular unconformities indicates active tectonic deformation and subsequent erosion of earlier structural complexes.

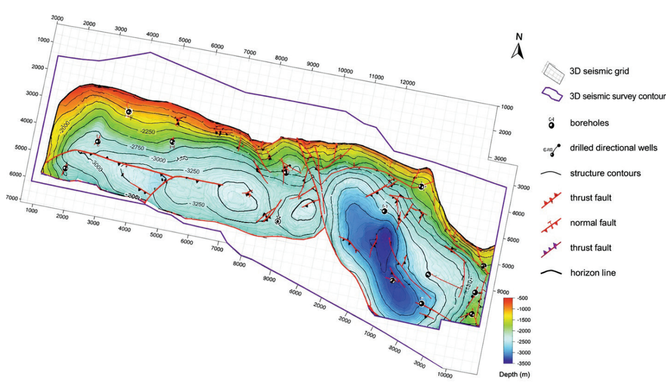


Figure 6. Structural map at the base of Permian deposits.
Сурет 6. Пермь шөгінділерінің табаны бойынша құрылымдық карта.
Рис. 6. Структурная карта по подошве пермских отложений.

Seismic profile 273, running through the central part of the Zaysan Depression, demonstrates the preservation of a more complete stratigraphic section and the presence of angular unconformities toward the basin margins. It should be noted that the Permian succession is complicated by a system of faults formed and reactivated at different stages during the tectonic evolution of the region (Figure 7).

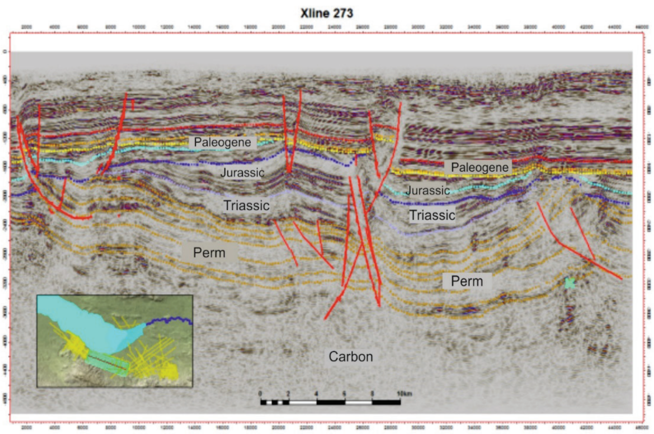


Figure 7. Time seismic profile along line 273.
Сурет 7. 273 сызық бойындағы уақыттық сейсмикалық профиль.
Рис. 7. Временной сейсмический профиль по линии 273.

The study of the distribution of Permian deposits shows that the greatest burial depth and areal extent of these formations are observed in the central part of the Zaysan Depression. Source rocks in the central basin area are least affected by partial or complete destruction, which is reflected in their greater preserved thickness.

Thus, the Permian source rock sequences exhibit the highest preservation and hydrocarbon generation potential in the central part of the Zaysan Depression. Toward the basin margins, especially in the northeastern sector, their degradation is observed due to tectonic movements and erosion. These results provide a basis for petroleum potential prediction and for identifying prospective exploration targets [8].

Discussion of Results

Analysis of source rocks. In the study of source rocks, an important aspect is the evaluation of their hydrocarbon generation potential. This work utilizes data from specialized core analyses conducted on samples from the Maichat Formation interval, as presented in Table 2.

The data obtained from the Rock-Eval pyrolysis analyzer include the following parameters:

S1 – amount of free hydrocarbons, mg/g;

S2 – amount of hydrocarbons released during pyrolysis, mg/g;

S3 – amount of released CO_2, mg/g;

Tmax – temperature of maximum hydrocarbon generation, °C.

Based on these measured parameters, the following geochemical indices are calculated:

HI (Hydrogen Index) – mg/g;

OI (Oxygen Index) – mg/g;

PI (Production Index) – mg/g.

The obtained and calculated pyrolysis data were systematized into diagrams to determine the quality of source rocks and its variation with depth (Figure 8). The organic richness of the studied interval of the Maichat Formation does not exceed 10%. The investigated interval is moderately enriched in total organic carbon. The hydrocarbon generation potential is considered relatively good, with values ranging from 20 to 70 mg/g.

The Hydrogen Index allows for the determination of the predominant type of organic matter. As shown in the diagram, most of the data indicate a marine depositional setting in which organic material was accumulated. The normalized oil content varies with depth, with most values clustering around 200.

In terms of thermal maturity, almost all vitrinite reflectance data are approximately 0.6%. It should be noted that these analyses were performed on Permian deposits sampled from a depth interval of 2424–2475 m (1903–1954 m below sea level) in a well located closer to the structural crest.

Accordingly, more mature Permian deposits with higher hydrocarbon generation potential are expected to occur at greater depths in the central part of the Zaysan Depression. Pyrolysis data from deeper-lying source rock intervals are not available.

The kerogen quality, type, and thermal maturity were evaluated using cross-plots based on the Van Krevelen diagram (Figures 9 and 10). The constructed plots indicate that the kerogen falls within the transitional zone between Type I and Type II.

In terms of thermal maturity, the organic matter is classified as mature and is located within the oil generation window.

Table 2

Results of pyrolysis analysis of source rocks

Кесте 2

Бастапқы тау жыныстардың пиролиздік талдау нәтижелері

Таблица 2

Результаты пиролизного анализа материнских пород

Глубина, м	SRA TOC	S1	S2	S3	Tmax (°C)	Calc. % Ro	HI	OI	S2/S3	S1/TOC *100	PI
2424.54	6.06	12.5	41	0.3	429.41	0.569	681	4.5	153	206	0.23
2424.85	6.39	13.7	45	0.3	430.71	0.593	704	4.5	155	215	0.23
2425.26	4.28	8.53	28	0.3	429.78	0.576	664	6.5	101	199	0.23
2425.54	4.7	9.83	31	0.3	429.15	0.565	654	6.4	102	209	0.24

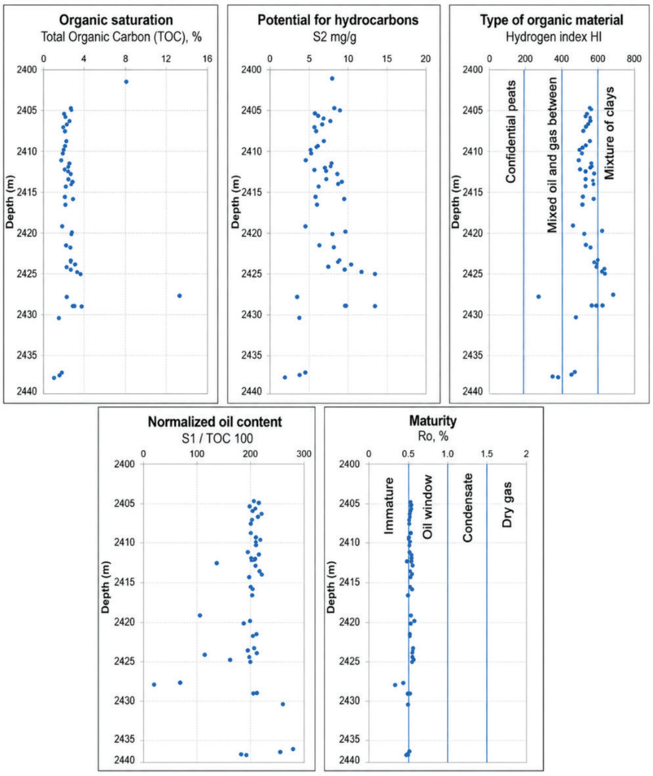


Figure 8. Summary results of pyrolysis data for source rocks.
Сурет 8. Бастапқы тау жыныстар бойынша пиролиз деректерінің жинақталған нәтижелері.
Рис. 8. Сводные результаты пиролизных данных по материнским породам.

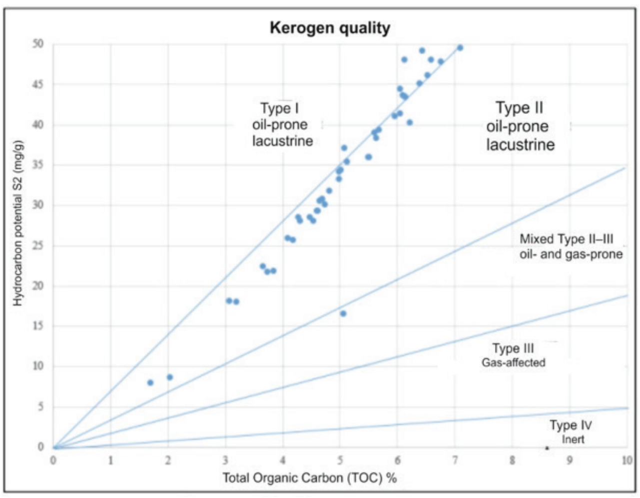


Figure 9. Kerogen type and thermal maturity.
Сурет 9. Кероген түрі және жылулық жетілуі.
Рис. 9. Тип керогена и термическая зрелость.

The pyrolysis results of the source rocks allow several conclusions to be drawn. The source rock interval of the Maichat Formation within the Permian deposits is characterized by kerogen that falls within the transitional zone between Type I and Type II. This interval exhibits a good hydrocarbon generation potential, and the kerogen is classified as mature, corresponding to the oil window.

Vitrinite reflectance data indicate a value of approximately 0.6%, which reflects the onset of thermal maturity of the source rocks. Thus, the hydrocarbon generation center is likely localized in the deeper parts of the central Zaysan Depression, where Permian deposits occur at maximum burial depths and provide optimal conditions for thermocatalytic decomposition of organic matter [9].

Conditions of Hydrocarbon Generation and Migration. Tectonic activity played a key role in the formation of structural and fault-sealed traps. The system of faults and steep bedding angles likely facilitated the migration of oil and gas from source rocks. At the same time, these tectonic movements also contributed to the partial destruction of accumulations and the leakage of hydrocarbons.

At the end of the Triassic, during the fourth stage of tectonic activity, the source rocks were buried to sufficient depths to initiate oil generation. This period was associated with the formation of Permian accumulations. However, as noted earlier, Permian strata locally reached the surface at steep angles, which may have led to partial loss of generated hydrocarbons, primarily the lighter oil fractions, leaving behind heavier components within the accumulations. Subsequently, these formations were overlain by Jurassic sediments. The dominant trap type at this stage was represented by fault-sealed traps.

At the end of the Jurassic, during the sixth compressional tectonic stage, new migration pathways were formed along newly created and reactivated faults. A portion of the Permian hydrocarbons migrated into overlying Jurassic deposits. Hydrocarbon accumulations formed in both structural and fault-sealed traps. Due to the exposure of parts of the Jurassic and Triassic deposits at the surface, a portion of hydrocarbons was lost.

During the final tectonic stage, biodegradation of oil occurred with associated gas generation, leading to the formation of gas accumulations. Compressional tectonics and faulting contributed to the development of structural and fault-controlled traps, which facilitated gas migration into Jurassic and Paleogene deposits. The scheme of hydrocarbon generation and migration is illustrated in profile 171 (Figure 10).

Migration of oil from source rocks occurred through several pathways. The presence of porous and permeable intervals within the Permian deposits provided pathways for initial migration. Steep bedding angles also played a positive role in facilitating hydrocarbon movement within the Permian succession. The abundance of faults cutting through the stratigraphic section enabled vertical migration into overlying formations[10].

The schematic migration process is illustrated on Xline profiles 315 (Figures 11 and 12).

Oil generated within Permian source rocks migrated along faults and permeable beds dipping at steep angles. As a result of this primary migration, lithological, stratigraphic, and structural oil accumulations were formed within Permian reservoir units.

Subsequent tectonic movements induced secondary migration of oil from Permian accumulations into overlying Jurassic deposits. During this process, heavier oil fractions tended to

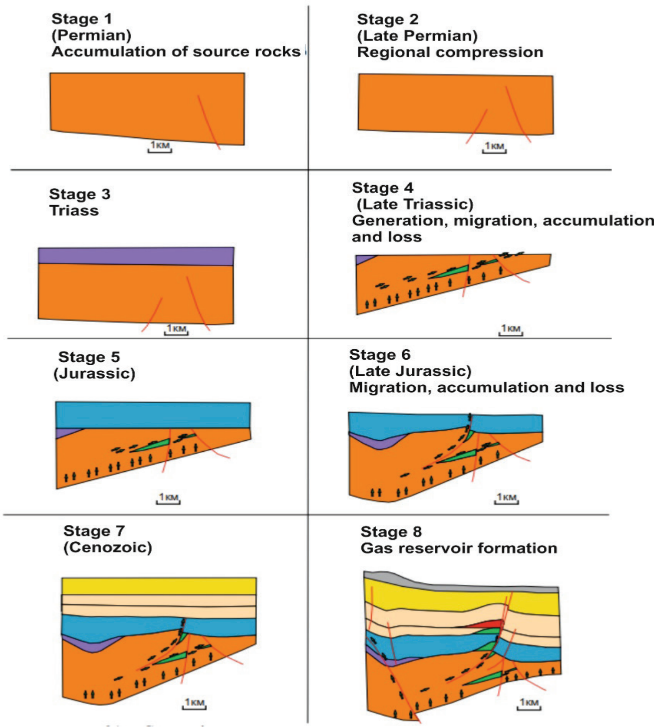


Figure 10. Model of hydrocarbon generation and migration.
Сурет 10. Көмірсутектердің генерациясы мен миграциясының моделі.
Рис. 10. Модель генерации и миграции углеводородов.

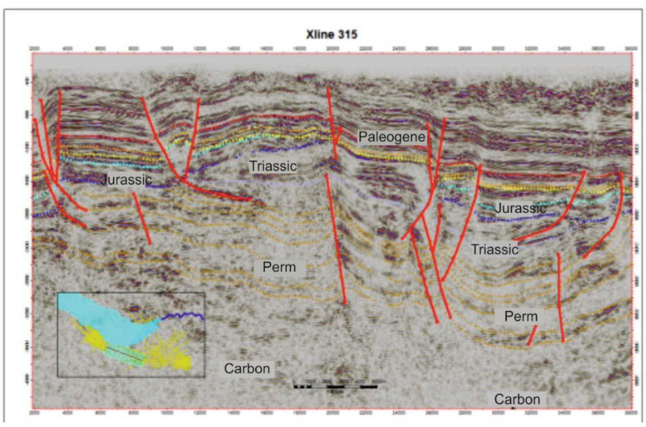


Figure 11. Seismic profile along line 315.
Сурет 11. 315 сызығы бойындағы сейсмикалық профиль.
Рис. 11. Сейсмический профиль по линии 315.

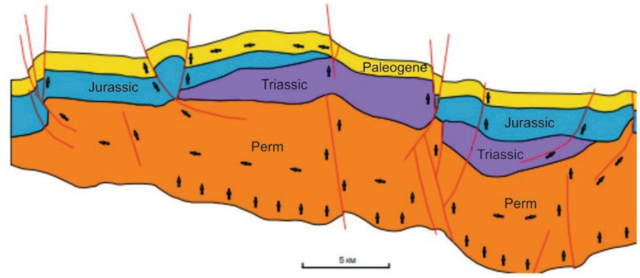


Figure 12. Schematic model of hydrocarbon migration pathways based on profile 315.
Сурет 12. 315 профиль негізінде көмірсутектердің миграция жолдарының сызбалық моделі.
Рис. 12. Схематическая модель путей миграции углеводородов на основе профиля 315.

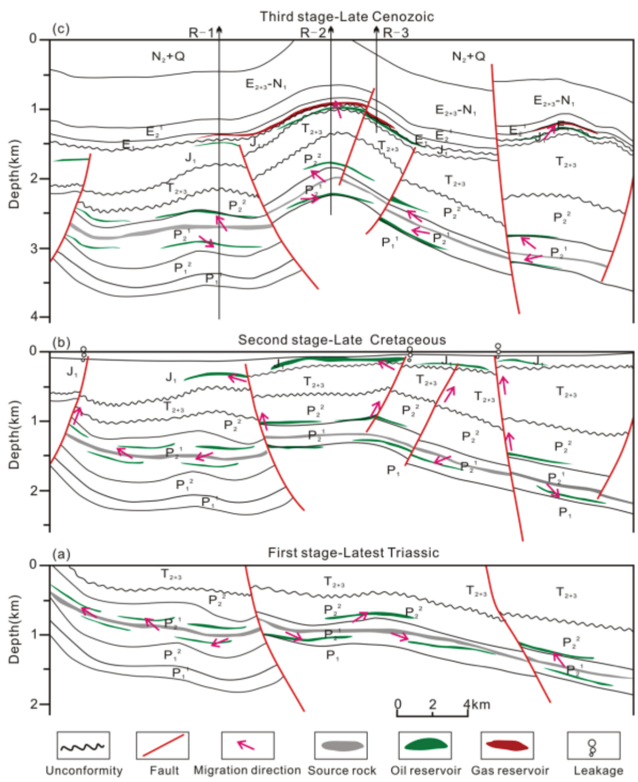


Figure 13. The model of multi-stage hydrocarbon migration and accumulation history.
Сурет 13. Көмірсутектердің көпсатылы миграциясы мен шөгу (жинақталу) тарихының моделі.
Рис. 13. Модель многоэтапной миграции и истории аккумуляции углеводородов.

remain within the accumulations, while lighter components could have been lost.

During the final tectonic stage, gas accumulations were formed within Jurassic and Paleogene deposits. These traps resulted from late-stage hydrocarbon migration and subsequent sealing by effective cap rocks [11].

Thus, the structure of hydrocarbon accumulations in the region represents a multi-stage system of migration and accumulation, in which oil and gas are distributed across stratigraphically different complexes ranging from the Permian to the Paleogene (Figure 13).

Conclusion

Comprehensive geological studies of the Zaysan Depression have demonstrated that Permian deposits (the Taranchin, Maichat, and Akkolkan formations) represent the primary source rocks of the region. Their greatest development and maximum burial depth are observed in the central part of the depression, where the most favorable conditions for hydrocarbon generation are established.

Seismic surveys, drilling data, and structural analysis have revealed the presence of pinch-out zones, tectonic discontinuities, and fault-sealed traps that facilitate both primary and secondary migration of oil and gas.

The central part of the Zaysan Depression is the most prospective area in terms of hydrocarbon generation, migration, and accumulation. The results obtained may serve as a basis for further petroleum potential assessment and for planning future exploration activities in the region.

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