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DYNAMICS OF NAPHTHIDOGENESIS IN THE DEVONIAN DEPOSITS OF THE DOBRUDJA FOREDEEP

The aim of the work was to find out the dynamics of naphthidogenesis in the Devonian deposits of the Dobrudja Foredeep. The studies were conducted using retrospective analysis based on the fluid-dynamic concept of catagenesis. As a result, a difference in the catagenesis regime in different parts of the depression was established for the first time. The generation and accumulation of hydrocarbons in the Tuzliv Depression and the Furmanivsk-Prymorsk region exhibit distinct characteristics. The primary phase of oil formation in the Tuzliv Depression is associated with the first cycle of accumulation. In contrast, gas formation in the Furmanivsk-Prymorsk region is linked to the second cycle of catagenesis. Features of spatial and age heterogeneity of hydrocarbon accumulation were predicted. During the first cycle of catagenesis, the most intense flows of petroleum fluids were directed toward the closure of the Tuzliv Depression, which consists of Middle Devonian deposits. This flow pattern likely played a significant role in the formation of the East Sarata deposit. Additionally, it supports a positive assessment of the prospects for the surrounding areas, including the Saratska, Yaroslavska, Rozivska, Hryhorivska, and Saryyarska structures. At the same time, early-generation gas was formed in the Furmanivsk-Prymorsk Depression. During the second cycle of catagenesis, it is predicted that oil deposits will form in the Lower Devonian sediments on the northern side and in the Upper Devonian sediments on the southern side. Additionally, gas deposits are expected to occur in the Silurian and ancient layers along the western centricline. In the final cycle of catagenesis within the Tuzliv Depression, the processes leading to oil accumulation in the Middle Devonian deposits at the periphery of the depression and gas accumulation in the Lower Devonian formations along the centricline decreased. Conversely, the accumulation of gas hydrocarbons in the Lower Devonian and underlying formations became more pronounced in the Furmanivsk-Prymorsk Depression. The hydrocarbon deposits predicted in the Lower Devonian sediments and older formations may act as intermediate reservoirs. This would allow hydrocarbons from deeper layers to migrate upward into overlying formations via the extensively developed disjunctive faults in the region. The scientific novelty lies in the establishment of lateral heterogeneity of the catagenesis regime and the corresponding heterogeneity of oil and gas formation processes. The practical significance lies in the identified specificity of the development of oil and gas accumulation zones and the localization of promising areas.

Keywords: Dobrudja Foredeep, Devonian deposits, oil and gas system, dynamics of catagenesis, prospects for oil and gas potential.

Introduction

The Silurian-Lower Carboniferous sedimentary complex is the main oil and gas prospecting interest in the Dobrudja Foredeep, the productivity of which has been proven by the discovery of the Skhidnosaratske and Zhovtoyarske oil deposits in the Tuzliv Depression. The Furmanivsk-Prymorsk Depression and adjacent areas are classified as territories with uncertain prospects [Geology of the shelf..., 1986].

In previous studies [Volovik et al., 1988; Trofimenko, Gerasimov, 1991; Lukin, Trofimenko, 1992; Skachedub, 1998; Hnidets et al., 2003; Machulina, Oliinyk, 2021], researchers examined the lithological features and clarified the key aspects of sedimentogenesis in Devonian deposits, particularly in the Tuzliv Depression region. These findings have contributed to assessing the potential of the sedimentary strata, especially regarding the distribution of natural hydrocarbon (HC) reservoirs. However, developing oil and gas systems (*OGS*) in the region was not considered. Modeling the latter constitutes an important basis for determining the directions of exploration work.

Aim

To find out the previously ontogenesis of the discovered deposits and to evaluate the prospects of the eastern part of the Dobrudja Foredeep as a whole based on a retrospective analysis of the processes of oil and gas formation and oil and gas accumulation.

Method

Studies of the dynamics of *HC* formation, localization of their migration paths, and accumulation zones were based on the fluid-dynamic concept of

catagenesis [Hryhorchuk, 2012]. For a better understanding of the presented results, it is advisable to briefly review the main provisions and terms used in the following presentation.

The fluid-dynamic concept argues for the cyclical nature of catagenesis, which is closely related to the stages of the tectonic regime of the basin. At the same time, the main elements of the *OGS*, which according to [Magoon, Dow, 1994] consist of a generation center, transportation routes, and accumulation zones, develop diachronically. In areas where downward movements prevail (the passive substage of catagenesis) and where clayey, organic matter-rich sediments dominate, lithogenesis conservation is evident (as defined by [Kudelskii, 1982]). This process leads to the formation of hydrocarbon generation centers, referred to as "reactor layers" [Sidorova et al., 1991], where significant reserves of lithofluid energy are concentrated.

In this context, the transformation processes of layered dimetasilicate minerals play a crucial role. Initially, the illitization of montmorillonite releases water, resulting in the development of abnormally high reservoir pressures. Over time, however, this process slows down [Colten-Bradley, 1987], leading to a reverse reaction [Buryakovskii et al., 1983] that produces gas hydrate-montmorillonite formations. These formations can contain significant reserves of water and hydrocarbon compounds, even in small volumes [Guggenheim, Koster van Groos, 2003; Cygan et al., 2004]. The release of the latter occurs at an active substage of catagenesis during repeated illitization of montmorillonite during regional upward movements [Burley, Flish, 1989; Rowan et al., 2002]. The accumulated energy relaxes due to the development of zones of decompression, through which "avalanche" migration of fluids occurs due to the brittle destruction of rocks [Beach, 1977] and the formation of various-scale [Zaraiskii, Balashov, 1983] permeability systems.

Results

History of catagenesis and oil and gas formation regime

In the Tuzliv Depression, the parent deposits were the "black shale" horizons of several of its stratigraphic levels: the Rozivska and Kochuliiska formations of the Lower Devonian, the basal parts of nine cyclites of the Middle Devonian and the "black shale" horizons at the boundary of the Frasnian and Famenian stages [Hnidets et al., 2023]. Taking into account the data [Hnidets et al., 2003; Unconventional sources…, 2014] regarding the similarity of the lithological-facies structure of the Devonian layers in the Tuzliv and Furmanivsk-Prymorsk Depressions, it can be assumed that similar formations served as oil and gas generating systems in the past.

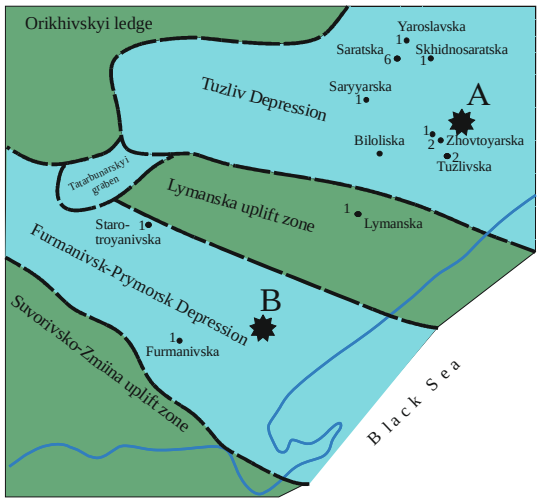

Fig. 1. Scheme of structural elements of the research area according to [Hnidets et al., 2003]. A, B are pseudo-wells.

A comparative analysis was conducted on the history of catagenesis and the lithofluid dynamics of sedimentary strata in the north-eastern and south-western regions of the Dobrudja Foredeep. The aim was to identify the characteristics of the development of oil and gas structures in these areas. For this purpose, pseudo-wells were used at the depocenters of the Tuzliv (A) and Furmanivsk-Prymorsk (B) Depressions (Fig. 1). The fundamental features of the first pseudo-well are considered in the work [Hnidets et al., 2023]. In constructing the second one, materials from [Hnidets et al., 2003; Lukin, 2005] on the geology of the main stratigraphic units were used.

As can be seen, the catagenesis regime of sedimentary formations of the Tuzliv and Furmanivsk-Prymorsk Depressions was different (Fig. 2). In the first case, two cycles of catagenesis were observed: the first cycle ended in the early Jurassic period, while the second cycle concluded in the early Cretaceous period. It is important to highlight the considerable length of the

active substage of the first cycle, which lasted from the Middle Carboniferous to the Early Jurassic. In the second case, three cycles are recorded, which ended in the Middle Carboniferous, Early Jurassic, and Paleogene. A significant duration of the active substage distinguished the third cycle (Early Cretaceous-Paleogene).

In addition, the intensity of sediment submersion and, accordingly, warming up during the first cycle were not the same. Thus, in the north-eastern part of the Dobrudja Foredeep, the rate of the sedimentary rock formation was 45–60 m/million years, and in the south-western part it did not exceed 30–45 m/million years (see Fig. 2). In the first case, the generating strata reached the catagenesis grades MC2 (Upper Devonian), MC3 (Middle Devonian), and MC4, MC5 (Lower Devonian). In the second case, however, only grades PC, MC1, and MC2 were achieved.

In the Furmanivsk-Prymorsk Depressions (see Fig. 2), unlike the Tuzliv Depression, there was intense subsidence during the Permian to Early Jurassic period (the second cycle of catagenesis), which allowed the Devonian sediments to reach a similar degree of catagenesis.

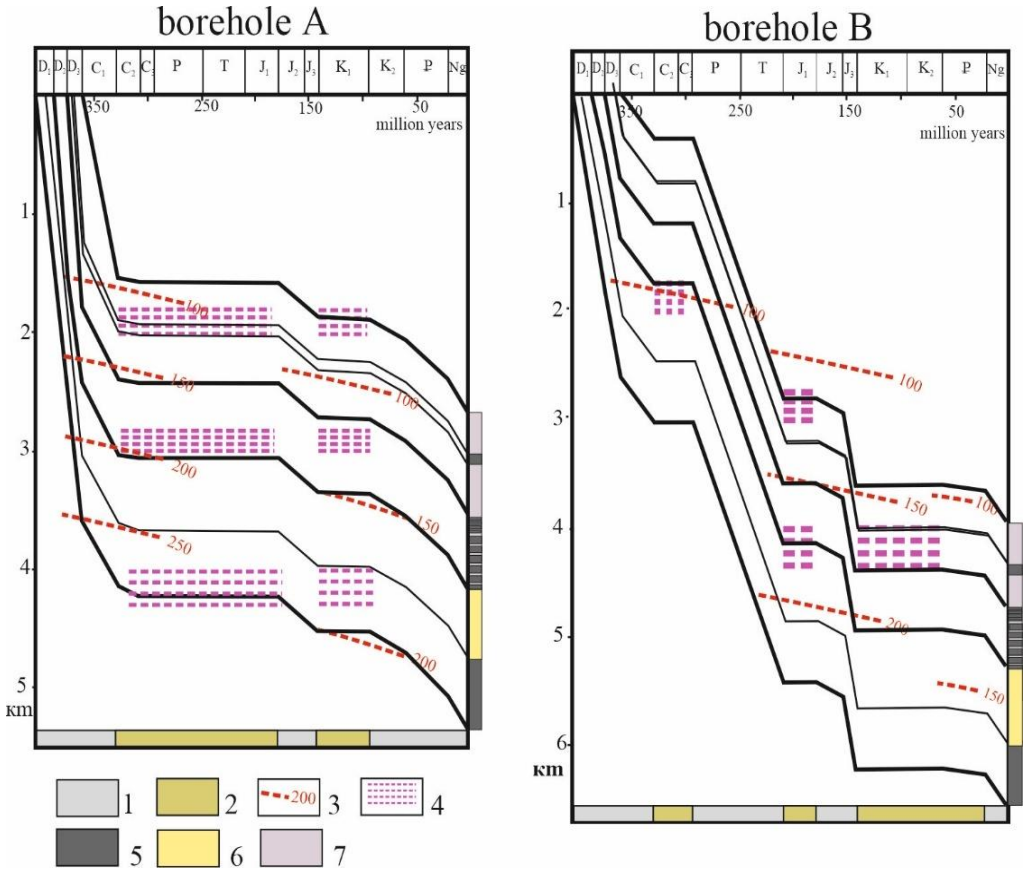

Fig. 2. Burial history and catagenesis periodization of Devonian sediments.

Exfiltration stage of catagenesis: 1 – passive substage; 2 – active substage; 3 – paleotemperatures; 4 – regional decompaction zones. Sedimentary complexes: 5 – clay, enriched with OM; 6 – terrigenous; 7 – sulfate-carbonate

At the end of the first cycle, favorable conditions emerged for the large-scale generation and migration of hydrocarbons with different phase compositions in the Tuzliv Depression. This migration occurred in three regional zones of decompaction (see Fig. 3).

In the upper zone, small amounts of early-generation gas were released from the “black shale” formations (Frasnian – Famennian) and migrated towards the north, south, and west. Oil hydrocarbons were primarily formed in the Middle Devonian strata, from which they migrated into the terrigenous deposits of the Lower Devonian near the edges of the depression, as well as into the plantar part of the Eifel formations along the western centricline. Gas hydrocarbons migrated from the Lower Devonian deposits along the lower zone of decompaction. The fluids entered mainly into the underlying strata and partially into the terrigenous part of the Lower Devonian, with subsequent movement in the direction of the regional rise of horizons.

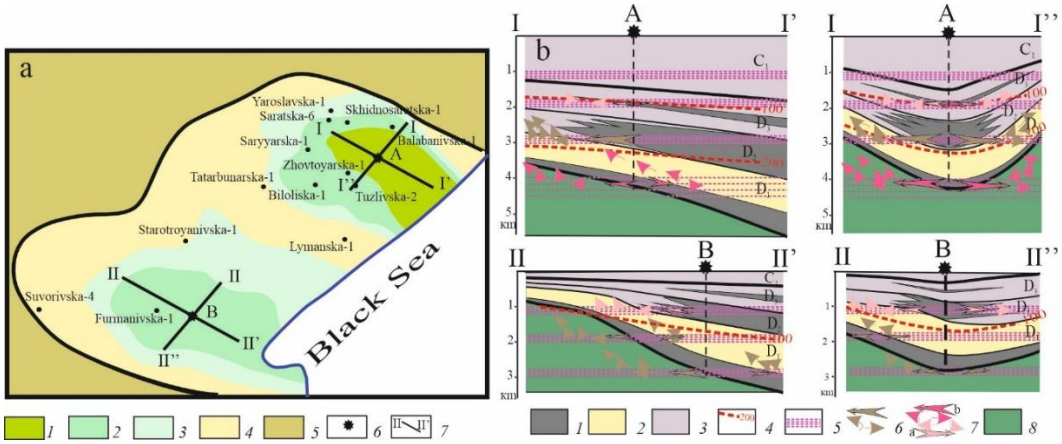

Fig. 3. The intensity of sediment burial at the passive substage (a) and the lithofluid dynamics model (b) at the active substage of the first cycle of catagenesis:

a: 1 – more than 45 m/million years, 2 – 30–45; 3 – 15–30; 4 – less than 15; 5 – absence of sediments. 6 – pseudo-boreholes; 7 – sections. b: Sedimentary complexes: 1 – clay, enriched with OM; 2 – terrigenous; 3 – sulfate-carbonate; 4 – paleotemperatures; 5 – regional fracturing zones; regional fluid flows: 6 – oil; 7 – gas: a – early generation; b – late generation; 8 – pre-Devonian sediments.

In the Furmanivsk-Prymorsk Depression, the hydrocarbon fluids also moved along three decompaction zones. Early-generation gas migrated along the upper formation, primarily entering the terrigenous strata of the lower formation in the western and southern directions. Toward the north, the gas moved into the sulfate-carbonate strata of the Middle Devonian. Small amounts of oil hydrocarbons were released from the "black shale" formations in this area, moving along two regional decompaction zones. These hydrocarbons mainly infiltrated the underlying sediments and partially reached the terrigenous part of the Lower Devonian. At the same time, the main flow of fluids was directed towards the western depression centricline, due to the involvement of a larger generating formations volume in the mass exchange.

During the Permian-Early Jurassic period, the active substage of the first catagenesis cycle continued in the northeastern part of the region. Consequently, the hydrocarbon migration processes continued along the above-mentioned decompaction zones. However, the intensity of the flows underwent some lateral transformation caused by the unevenness of tectonic activity at this time. The variability in the thickness of the Permian-Triassic deposits has been documented, with thickness ranging from 0 meters at the Skhidnosaratska-2 borehole to 643 meters at the Balabanovskaya-1 borehole (see Fig. 4). This variation allowed for the identification of three distinct zones with different rates of sedimentary rock formation: the central zone, with rates of less than 1 m per million years; the southern zone, with rates of 1 to 3 meters per million years; and the northern zone, with rates exceeding 3 meters per million years.

As a result, it can be predicted that the most intense fluid flows were directed towards the central cline of the Tuzliv Depression, particularly in the vicinity of the Saratska, Skhidnosaratska, and Yaroslavska structures. Meanwhile, less significant migration of fluids occurred in the southern and, especially, the northern directions.

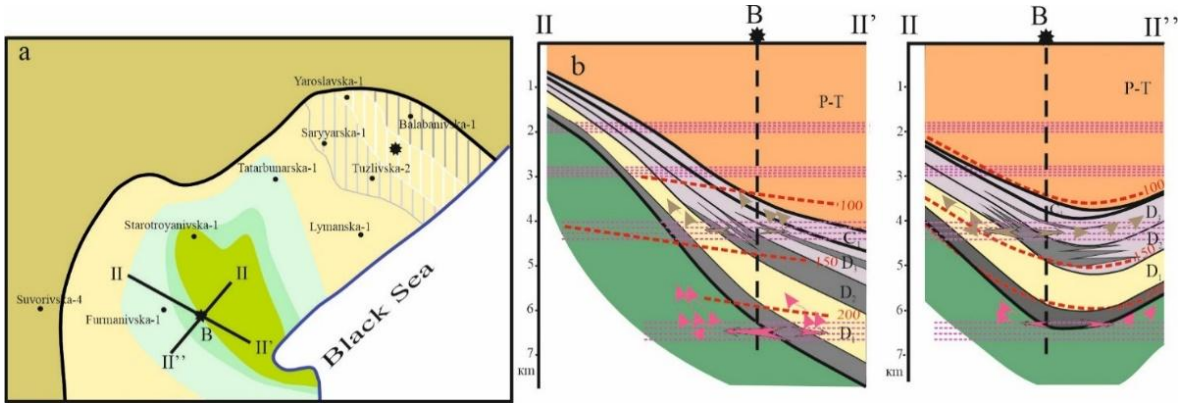

Fig. 4. The intensity of sediment burial at the passive substage (a) and the lithofluid dynamics model (b) at the active substage of the second cycle of catagenesis. Legend see Fig. 2.

In the Permian-Early Jurassic, the second catagenesis cycle appeared in the south-western part of the depression. It can be considered the main one in the history of oil and gas formation, because at this time there was intensive burial and, accordingly, heating of the generating strata (see Fig. 4). During the active catagenesis substage (Early Jurassic), hydrocarbons moved through two regional decompaction zones. The upper one drained the generating stratum of the Middle and Upper Devonian. The main mass of hydrocarbons (oil phase) migrated in a northeastern direction into the upper terrigenous section of the Lower Devonian deposits, followed by subsequent vertical movement. Some portions of the fluids may have migrated southwestward into the Upper Devonian and Lower Carboniferous strata, moving laterally along the rise of permeable horizons. Additionally, gas hydrocarbons primarily entered the underlying formations along the lower zone of decompaction from the Lower Devonian deposits, mainly moving in a north-northwest direction.

The third (Furmanivsk-Prymorsk Depression) and the second (Tuzliv Depression) cycles of catagenesis began in the Middle Jurassic. As mentioned above, they differed in the duration and the intensity of sediment burial: in the first case, these parameters were higher.

In the Tuzliv Depression, certain portions of hydrocarbons migrated along two zones of decompaction (Fig. 5). The volumes of fluids were most likely insignificant, given the low intensity of sediment burial and, accordingly, the insignificant accumulation of lithofluid energy during the Jurassic. Oil hydrocarbons migrated along the upper zone from the Middle and partly Upper Devonian deposits. At the same time, a certain asymmetry in the hydrocarbon supply is observed. Thus, in the north-west direction, the intensity of the hydrocarbon flow was insignificant and they entered mainly into the Middle Devonian deposits. In the north-eastern and south-western directions, the volumes of fluids were somewhat larger, and they migrated into the Lower and partly Middle Devonian.

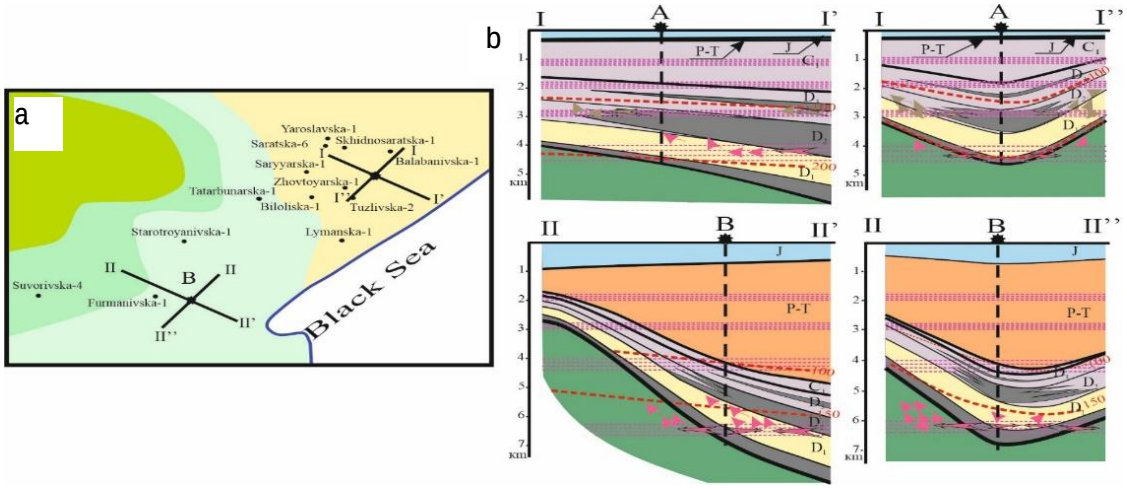

Fig. 5. The intensity of sediment burial at the passive substage (a) and the lithofluid dynamics model (b) at the active substage of the last cycle of catagenesis Legend see Fig. 2.

Fluid transfer along the lower zone of decompaction was also characterized by lateral heterogeneity. Thus, in the direction of the western centricline of the depression, an intense gas hydrocarbons flow is predicted, which were formed in the generating stratums of the Middle Devonian and entered the terrigenous layer of its lower section. Meanwhile, smaller volumes of gas migrated from the Lower Devonian into the underlying deposits on either side.

In the Furmanivsk-Prymorsk Depression, only the lower zone of decompaction was active, allowing gas to migrate into both the terrigenous strata of the Lower Devonian and underlying formation. At the same time, in the western part of the depression, there was also an oncoming flow from the Middle Devonian layers of the depocenter. In the future, the hydrocarbons could migrate further after the rise of permeable horizons. Towards the sides of the depression, hydrocarbons moved mainly into the underlying formations.

The history of the development of oil and gas accumulation zones

The established main features of the dynamics of the generation and migration of hydrocarbons became the basis for determining the spatial and age features of the localization of oil and gas accumulation zones within the Dobrudja Foredeep.

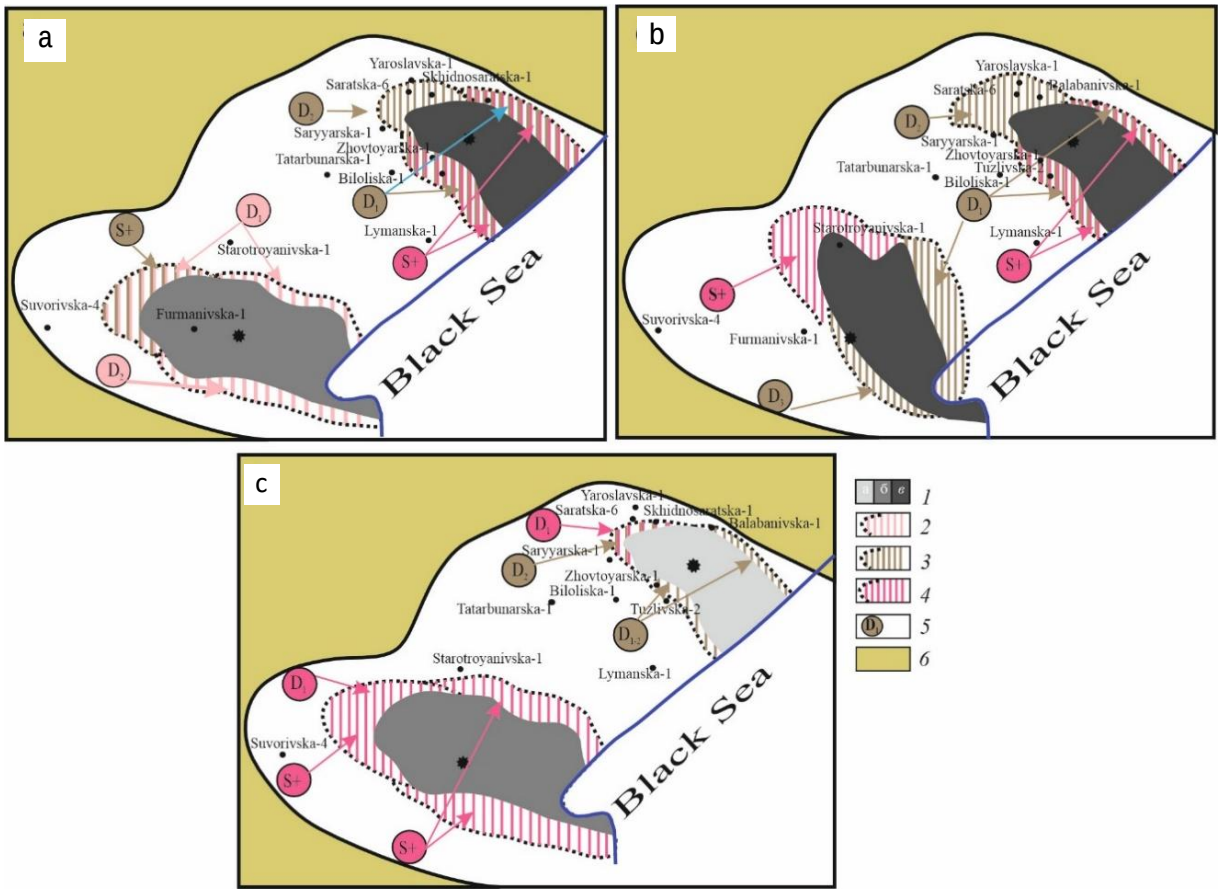

Fig. 6. Spatial and age features of the development of oil and gas accumulation zones:
1 – degree of preservation of lithogenetic processes: a – low; b – medium;
c – high. Predicted areas of maximum influence of fluid flow:
2 – early generation gas; 3 – oil; 4 – late generation gas; 5 – age of oil
and gas accumulating deposits; 6 – the absence of Devonian sediments.

During the first cycle of catagenesis, the largest oil and gas formation processes occurred in the northeastern part of the depression. In the center of the Tuzliv Depression, a significant area for hydrocarbon generation was located within the depocenter. During the passive substage of catagenesis, lithogenesis processes continued, leading to the large-scale accumulation of substantial reserves of fluid energy. On the periphery of this center, specific zones formed where these hydrocarbons accumulated (Fig. 6).

Using the lithofluid dynamics model (Fig. 3), it can be predicted that during the active substage of catagenesis, oil hydrocarbons accumulated in the Middle Devonian deposits situated within the northwestern centricline of the depression. This accumulation encompassed areas of the Skhidnosaratska and Saratska structures. Oil accumulations may have formed in the Lower Devonian strata on the southern side of the depression (Zhovtoyarsko-Tuzlivska area), while gas may be found in the underlying Silurian and ancient formations on the northern side (Balabanivska area).

The Furmanivsk-Prymorsk generation center supplied mainly small volumes of early generation gas, which entered the middle (southern side) lower (northern side and western centricline) Devonian deposits. And in the underlying sediments of the latter, accumulations of oil hydrocarbons could have formed.

In the Permian-Early Jurassic time, the post-diagenetic regime and, accordingly, the accumulation of oil and gas in the north-eastern and south-western parts of the Dobrudja Foredeep differed significantly. In the Tuzliv Depression, the active substage of the first cycle of catagenesis continued. At the same time, in connection with a certain slowdown in the upward movements on the sides of the depression (see Fig. 4), the intensity of hydrocarbon migration in these directions decreased somewhat with a corresponding decrease in the areas of oil and gas accumulation. Instead, to the western centricline of the depression, the scale of fluid transfer remained at the previous level, which gives grounds to predict an increase in the area of potentially oil-bearing Middle Devonian deposits in the area of the Yaroslavska, Rozivska, Hryhorivska, Saryyarska structures.

A full cycle of catagenesis was manifested in the Furmanivsk-Prymorsk Depression. During the Permian-Triassic period, there was significant burial

that marked the passive phase of catagenesis. This the necessary level of catagenesis required for the formation of hydrocarbon fluids. Additionally, it accumulated the energy needed for their rapid migration during the active phase, which occurred in the Early Jurassic. By examining the lithofluidynamic characteristics (see Fig. 4), we can predict the variability in hydrocarbon accumulation. This prediction reveals notable spatial differences in the age of potential hydrocarbon reservoirs. Thus, accumulations of oil hydrocarbons could have formed in the Lower Devonian deposits of the northern side of the depression and the Upper Devonian deposits of the southern side. Within the western centricline, gas accumulation occurred in Silurian and older strata.

In the last cycle of catagenesis, a certain difference in the processes of generation, migration, and accumulation of hydrocarbons is also observed in the studied parts of the Dobrudja Foredeep. First of all, this was caused by the uneven intensity of sediment submersion during the Middle-Late Jurassic, which led to the formation of a significant fluid-dynamic energy potential in the Furmanivsk-Prymorsk generation center. Therefore, in the northeastern part of the depression, small portions of oil migrated mainly into the Middle Devonian deposits, and gas into the Lower Devonian layers of the Tuzliv Depression centricline. On the other hand, in the southwestern part of the depression, the hydrocarbon formation was possible mainly in the underlying Devonian sedimentary formations.

Scientific novelty

For the first time, lateral heterogeneity of the catagenesis regime has been established, which led to the specificity of the processes of generation and accumulation of hydrocarbons in different parts of the Dobrudja Foredeep. In the Tuzliv Depression, the primary phase of hydrocarbon accumulation, mainly oil, is linked to the first catagenesis cycle. In contrast, the Furmanivsk-Prymorsk region primarily accumulates gas associated with the second catagenesis cycle.

Practical significance

The identified features of the spatial-age heterogeneity of the oil and gas accumulation made it possible to localize promising areas and predict the phase composition of probable hydrocarbon deposits.

Conclusions

The difference in the catagenesis regime of sedimentary formations in different parts of the Dobrudja Foredeep has been established. Two cycles of catagenesis were manifested in the Tuzliv Depression: the first ended in the early Jurassic, and the process allowed the generating rock layers to reach second in the early Cretaceous. At the same time, the active substage of the first cycle was characterized by a significant duration (Middle Carboniferous-Early Jurassic). Three cycles are recorded in the Furmanivsk-Prymorsk Depression, which ended in the Middle Carboniferous, Early Jurassic, and Paleogene. The active substage of the third cycle of catagenesis (Early Cretaceous-Paleogene) was longer.

The features discussed above highlight the differences in the dynamics of oil and gas formation. In the Tuzliv Depression, the main phase of oil and gas accumulation is associated with the first cycle of catagenesis, whereas in the Furmanivsk-Prymorsk Depression, it is linked to the second cycle. Overall, it can be concluded that oil formation predominated in the first case, while gas formation was more prevalent in the second. The primary source of hydrocarbons in these regions came from the deposits of the Middle and Lower Devonian periods, respectively.

Oil and gas accumulation zones located along the periphery of depressions were characterized by uneven accumulation of hydrocarbons of different phase compositions in space and time. Thus, in the first cycle of catagenesis in the Tuzliv Depression area, the formation of oil accumulations is predicted in the north-western centricline in the Middle Devonian deposits. In sides – productivity is associated with Lower Devonian strata (oil), Silurian, and older formations (gas). The spatial unevenness of tectonic movements led to some decrease in the intensity of fluid flows in the direction of the sides from the beginning to the end of the active substage of the first cycle of catagenesis; instead, active migration of hydrocarbons continued within the centricline. This has probably become the main factor in the formation of the Skhidnosaratske oil deposit; the prospects can be associated with the territory covering the structures: Saratska, Yaroslavska, Rozivska, Hryhorivska, Saryyarska. In the area of the Furmanivsk-Prymorsk Depression, small gas deposits of early generation could be formed in the middle (southern side) and lower (northern side and western centricline) Devonian deposits, and accumulations of oil hydrocarbons – in the underlying sediments of the latter.

During the Permian- Early Jurassic period, which marks the second cycle of catagenesis, oil deposits are expected to form in the Lower Devonian sediments located on the northern side of the Furmanivsk-Prymorsk Depression, as well as in the upper layers on the southern side. Within the western centricline, gas accumulation occurred in Silurian and older strata.

During the final cycle of catagenesis in the northeastern part of the depression, oil accumulation of low intensity occurred along the periphery of the depression in the Middle Devonian deposits, and gas accumulation occurred within the centricline in the Lower Devonian strata. In the southeast, the

accumulation of hydrocarbons in the Lower Devonian and underlying formations dominated.

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ДИНАМІКА НАФТИДОГЕНЕЗУ В ДЕВОНСЬКИХ ВІДКЛАДАХ ПЕРЕДДОБРУДЗЬКОГО ПРОГИНУ

Мета роботи полягала у з'ясуванні динаміки нафтидогенезу у відкладах девону Переддобрудзького прогину. Дослідження здійснено за допомогою ретроспективного аналізу на основі флюїдодинамічної концепції катагенезу. В результаті вперше встановлено відмінність режиму катагенезу в різних частинах прогину, що зумовило певні особливості генерації та акумуляції вуглеводнів: основна фаза їх нагромадження у Тузлівській депресії (переважно нафтоутворення) пов'язана із першим, а у Фурманівсько-Приморській (переважно газоутворення) – із другим циклом катагенезу. Спрогнозовано особливості просторово-вікової неоднорідності акумуляції вуглеводнів. На першому циклі катагенезу найінтенсивніші потоки нафтових флюїдів були спрямовані у бік центрикліналі Тузлівської депресії (відклади середнього девону), що могло стати основним чинником формування Східносаратського родовища і, крім того, дає підстави високо оцінювати перспективи території, що охоплює структури: Саратську, Ярославську, Розівську, Григорівську, Сариярську. В цей самий час у Фурманівсько-Приморській депресії відбувалося незначне утворення газу ранньої генерації. На другому циклі катагенезу в районі останньої прогнозується формування покладів нафти у відкладах нижнього девону на північному борті та верхнього – південному, а газу – у силурійських та давніших нашаруваннях західної центрикліналі. На завершальному циклі катагенезу в Тузлівській депресії ішли на спад процеси акумуляції нафти у відкладах середнього девону (периферія депресії) та газу в нижньому девоні (центрикліналь). У Фурманівсько-Приморській депресії домінувала акумуляція газових вуглеводнів у нижньодевонських та підстильних утвореннях. Поклади ВВ, формування яких прогнозується у відкладах нижнього девону та давніших утвореннях, могли слугувати проміжними резервуарами, звідки ВВ могли надходити у вищі нашарування по широко розвинених у регіоні диз'юнктивних порушеннях. Наукова новизна полягає у встановленні латеральної неоднорідності режиму катагенезу та відповідної гетерогенності процесів нафтогазоутворення, а практична значущість – у виявленій специфіці розвитку зон нафтогазонагромадження та локалізіції перспективних ділянок.

Ключові слова: Переддобрудзький прогин, девонські відклади, нафтогазова система, динаміка катагенезу, перспективи нафтогазоносності.

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