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Expected Development of Non-Anticlinal Hydrocarbon Traps in the Upper Devonian-Tournaisian Carbonate Deposits Within the Northern Regions of the Volga-Ural Oil and Gas Province

Nikolay E. Sosnin, Svetlana S. Filipyeva, Svetlana V. Makarova, Lyubov Yu. Korepanova, Irina A. Vilyuzheva

Kama Research Institute for Integrated Research of Deep and Superdeep Wells (15, Krasnoflotskaya st., Perm, 614016, Russian Federation)

Прогноз развития неантиклинальных ловушек углеводородов в верхнедевонско-турнейских карбонатных отложениях на территории северных районов Волго-Уральской нефтегазоносной провинции

Н.Е. Соснин, С.Г. Филипьева, С.В. Макарова, Л.Ю. Корепанова, И.А. Вилюжева

Камский научно-исследовательский институт комплексных исследований глубоких и сверхглубоких скважин
(Россия, 614016, г. Пермь, ул. Краснофлотская, 15)

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Volga-Ural oil and gas province, facies, non-anticlinal traps, clinoform bodies, reef, well, oil, gas, hydrocarbons, deposits.

Realisation of the issue for hydrocarbon deposit exploration and development, which are associated with non-anticlinal traps, has been given the utmost attention in recent years, since this is precisely the solution to the problem of providing proven oil and gas resources in the areas with developed oil production, where the main and general exploration directions are already largely worked out. In this regard, the search for non-anticlinal traps in the Upper Devonian-Tournaisian carbonate complex of such an old oil and gas producing region as the Volga-Ural Oil and Gas Province is highly relevant.
The types of non-anticlinal hydrocarbon traps found in the Upper Frasnian-Tournaisian carbonate deposits in the Perm Territory and the Udmurt Republic are considered, and their lateral distribution zones are identified. Among the many classifications, the genetic classification of non-anticlinal traps by N.S. Oknova et al. (1999) has been chosen as the basic one. Within the study area, lithologically screened traps limited by facies changes have been identified. Among the ones limited by facies changes, a biogenic subtype of traps has been found. Similar traps occur in reef systems, solitary reefs, banks, bioherms, biostromes, etc. Lithologically screened traps are formed as a result of updip reservoir pinchout or their facies replacement by low-permeable coeval rocks. Among them, traps in complex clinoform bodies of the Tournaisian infill are of particular interest, since the prospects for discovering new oil-bearing places associated with Late Devonian reef massifs are decreasing from year to year due to their high level of exploration. In the study area, we have traced five zones of the of non-anticlinal trap distribution.

Ключевые слова:
Волго-Уральская нефтегазоносная провинция, фация, неантиклинальные ловушки, клиноформные тела, риф, скважина, нефть, газ, углеводороды, залежь.

Реализации проблемы поиска и освоения углеводородных залежей, связанных с ловушками неантиклинального типа, в последние годы уделяется самое пристальное внимание, так как именно в этом видится решение задачи по обеспечению разведанными ресурсами нефти и газа районов с развитой нефтедобычей, где главные и основные направления поисков уже в значительной степени выработаны. В связи с этим весьма актуальным является поиск неантиклинальных ловушек к верхнедевонско-турнейском карбонатном комплексе такого старого нефтегазодобывающего района, как Волго-Уральская нефтегазоносная провинция.
Рассматриваются типы ловушек углеводородов неантиклинального типа, встречающиеся в верхнефранско-турнейских карбонатных отложениях на территории Пермского края и Удмуртской Республики, выявлены зоны их латерального распространения. Среди множества классификаций за основу принята генетическая классификация неантиклинальных ловушек Н.С. Окновой и др. (1999). В пределах изучаемой территории установлены литологически ограниченные и литологически экранированные ловушки. Среди литологически ограниченных обнаружен биогенный подтип ловушек. Подобные ловушки возникают в рифовых системах, одиночных рифах, банках, биогермах, биостромах и т.д. Литологически экранированные ловушки образуются в результате выклинивания пластов-коллекторов по восстанию слоев или их фациального замещения одновозрастными слабопроницаемыми породами. Среди них вызывают особый интерес ловушки в сложнопостроенных клиноформных телах турнейской толщи заполнения, поскольку перспективы обнаружения новых нефтеносных объектов, связанных с позднедевонскими рифогенными массивами, год от года сокращаются в связи с их высокой изученностью поисковыми работами. На изучаемой территории прослежены пять зон распространения неантиклинальных ловушек.

Nikolay E. Sosnin – PhD in Geological and Mineralogical Sciences, Head of the Volga-Ural Oil-and-Gas-Bearing Capacity Department (tel.: +007 (963) 012 15 52, e-mail: kamniikigs@rusgeology.ru).
Svetlana S. Filipyeva – Deputy Head of the Volga-Ural Oil-and-Gas-Bearing Capacity Department (tel.: +007 (902) 800 07 23, e-mail: sgfq@mail.ru). The contact person for correspondence.
Svetlana V. Makarova – Senior Researcher (tel.: +007 (919) 708 05 38, e-mail: kamniikigs@rusgeology.ru).
Lyubov Yu. Korepanova – Junior Researcher (tel.: +007 (912) 599 60 37, e-mail: l.yu.korepanova@gmail.ru).
Irina A. Vilyuzheva – Engineer (tel.: +007 (952) 659 07 20, e-mail: ika-199696@mail.ru).

Соснин Николай Евгеньевич – кандидат геолого-минералогических наук, начальник отдела нефтегазоносности Волго-Урала (тел.: +007 (963) 012 15 52, e-mail: kamniikigs@rusgeology.ru).
Филипьева Светлана Геннадьевна – заместитель начальника отдела нефтегазоносности Волго-Урала (тел.: +007 (902) 800 07 23, e-mail: sgfq@mail.ru). Контактное лицо для переписки.
Макарова Светлана Васильевна – старший научный сотрудник (тел.: +007 (919) 708 05 38, e-mail: kamniikigs@rusgeology.ru).
Корепанова Любовь Юрьевна – младший научный сотрудник (тел.: +007 (912) 599 60 37, e-mail: l.yu.korepanova@gmail.ru).
Вилюжева Ирина Александровна – инженер (тел.: +007 (952) 659 07 20, e-mail: ika-199696@mail.ru).

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Прогноз развития неанткалинальных ловушек углеводородов в верхнедевонско-турнейских карбонатных отложениях на территории северных районов Волго-Уральской нефтегазоносной провинции / Н.Е. Соснин, С.Г. Филипьева, С.В. Макарова, Л.Ю. Корепанова, И.А. Вилюжева // Недропользование. – 2021. – Т.21, №4. – С.156–162. DOI: 10.15593/2712-8008/2021.4.2

Introduction

The Volga-Ural oil and gas province is the oldest oil and gas producing region. Long-term prospecting and exploration works in its territory have depleted the stock of anticlinal traps; and in some constituent entities of the Federation there are discernible trends towards a decrease not only of reserves, but also of production. This puts searching for non-anticlinal traps and associated oil and gas deposits on the agenda.

Numerous publications of Russian and foreign petroleum geologists are devoted to the search and study of non-anticlinal traps [1–35]. Below is a forecast of the distribution of non-anticlinal hydrocarbon traps in the Upper Devonian-Tournaisian carbonate deposits in the Perm Territory and the Udmurtia Republic.

Background Information

In the Late Devonian and Early Carbonic, the east of the Russian platform was a shelf area of the passive continent margin before the Ural paleo ocean. The north of the Ural-Volga region is a part of it. In terms of geological development, the Sysolsko-Komi-Permyatskaya land was delineated on it, bordered by a shallow sea shelf. The northwestern and western margins of the shallow shelf are complicated by the Kama-Vyatka system of depressions – Ponomarevsko-Timsherskaya, Rekhinskaya, Lomikskaya and Chigirinskaya. The sea transgression, gradual subsidence of the basin bottom with a complex topography and repeated changes in the coastline led to the wide development of various facies, pinch-out zones, regional discordances and lithological replacement of sediments in the developed sedimentary strata. A significant event in the geological history of the territory was formation of the Kama-Kinel depression system (KKDS) to the east and south of the Ksenofontovsko-Kukmorsky shallow-water archipelago, which began in the late Frasnian time. This system includes several large depressions: Chermoz-Cherdyn, Dobriansk-Kizelovsk, Kalinin and Shalym – within the Perm-Kama region and Mozhginsk, Sarapulsk in Udmurtia. The depressions are separated by straits, carbonate and organogenic-carbonate massifs of different sizes, which caused noticeable differences in the facies of the rock strata and complicated the structure of a lot of previously formed paleotectonic elements of the Volga-Kama anteclise [36, 37].

The features of sedimentation in the Late Devonian – Early Carboniferous time, associated with tectonic processes and caused by transgressive-regressive movements of the sea basin, provided a complex lithofacies structure of the carbonate complex. Facies were built up and transformed [38]. The development of the transgression was accompanied by carbonate sedimentation and reef formation, with which a lot of oil and gas deposits were later associated. During the regressive phases, predominantly clayey packs were accumulated, which served as seals, and domanicoid deposits with characteristic facial variability and uneven thickness of the rocks over the area formed in depressions. The regressions led to erosion of the surfaces brought out from under the sea level, material drift into depressions with uncompensated sedimentation and their gradual compensation according to the lateral filling principle. As a result, the rock mass filling downfolds and depressions is a sequence of sedimentary, most frequently clinoform bodies, rejuvenating towards regressive retreat of the sea basin. Thus, the depressions developed akin to compensated sedimentation – they were filled mainly with terrigenous formations (clays, marls, clayey limestones), almost devoid of organic matter. There are few fauna remains since the abundant supply of terrigenous material and the high rate of sedimentation created unfavorable conditions for the life of most organisms. With compensation, the carbonate content of the section increased because over time deposits were formed in

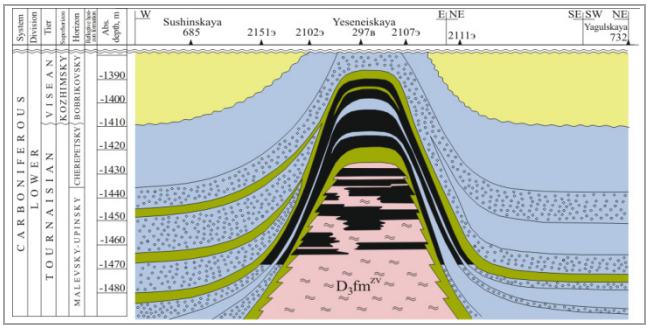

Fig. 1. Lithologically limited trap, biogenic, Oshvortsevsko-Dmitrievskoe deposit

an increasingly shallow environment. As a confirmation, limestones (from bottom to top along the section) contain increasingly more various fauna and algae. Over time, the axial zone of the depression shifted, rejuvenating, and the condensed section of deep-water formations decreased in area and thickness.

The paleogeographic and paleotectonic conditions for accumulating the Upper Devonian-Tournaisian carbonate deposits predetermined formation of non-anticlinal traps. Within the studшув area, lithologically screened traps limited by facies changes have been identified [39].

Among the ones limited by facies changes, a biogenic subtype of traps has been found. Such traps in carbonate rocks occur with calm tectonic regime and in the absence of mountain structures on the outskirts of continents: reef systems, single reefs, banks, bioherms, biostromes, etc. The traps are associated with the Late Devoniane carbonate-accumulative massifs in the KKDS zone. The role of reef massifs is quite diverse: on the one hand, they are reservoirs that form lithological traps. On the other hand, they act as consedimentary uplifts, around which zones of reservoir pinching-out develop, and enveloping structures develop in the overlying deposits. Promulgation of the Late Devonian carbonate-accumulative massifs is controlled by the depressions of the Kama-Kinel system. The reef massifs are concentrated in the near-axial part of KKDS (island structures), mainly on the margins of the Late Devonian shelf. Their occurrence was facilitated by the geotectonic regime – frequent fluctuations of small amplitude against the general background of ascending movements and simultaneous KKDS subsidence. Ultimately, this led to a complete or partial erosion of Tournaisian deposits in the northwest of the Perm Territory and most of the Kirov region with formation of cavernous zones directly in the reef body. Favorable conditions emerged to form traps under the regional Radaevian clay cap. Bereznikovo paleoplato and Yagano-Buranov reef massif separating Mozhginsk and Sarapulsk depressions are some examples.

Single reefs are also widespread in the inner KKDS zone: Gezhsky, Yurchuksky, Chashkinsky, Zabegalovsky, Vostochno-Postolsky, Timeevsky, Oshvortsevsko-Dmitrievsky (Fig. 1), etc., associated with same-name oil fields.

Seismic exploration works within Bashkir-Kynov and Udmurt-Perm paleoshelf revealed development of low-amplitude organogenic structures (bioherms, biostromes).

Bioherms are expressed morphologically by hilly, stock-like or lenticular organogenic structures that do not reach the sea level. Their thickness varies from several tens and hundreds meters , and the length is several kilometers.

Biostromes are sheet-like lenses of considerable length (tens and hundreds of meters), composed of organogenic limestones. They rose slightly above the ocean floor, wedging out to the edges.

In the southeastern part of the Perm Territory, between the Tanypsko-Tartinsky massif and the Dorokhovsky uplift, deep drilling has established Gabyshevsky, Soldatovsky, Sudanovsky and other low-amplitude bioherms with a height of 90 to 270 m. Cherchinsky, Tyushevsky

and Tavdinsky bioherms, and the western slope of Dorokhovsky are dissected by faults. The relationship between shelf bioherms and the oil-bearing capacity is manifested in different ways. In the presence of a carbonate-accumulative trap as such, a massive body serves directly as a reservoir of hydrocarbons, while the deposit is limited by its contours (Late Frasnian deposit at the top of the Dorokhovsky uplift). In other cases, Late Frasnian low-amplitude bioherms contribute to trap formation only in the overlying deposits (Famennian deposits above Cherchipsky, Korenevsky, Gabyshevsky and Gorbatovsky bioherms).

Lithologically screened traps are mainly associated with the side parts of paleobasins of sedimentation or depressions and downfolds that are isolated within their limits. It determines their advantage in terms of oil and gas accumulation over traps developed in the inner parts of sedimentation basins, where separate oil and gas suits are formed, possibly side zones, within which consedimentation structural-lithological traps are widely developed. Lithologically screened traps are formed as a result of updip reservoir pinchout or their facies replacement by low-permeable coeval rocks. Consequently, here reservoir rocks are screened by weakly permeable rocks only by their uprising.

Stratigraphic unconformity in rock bedding is the dominant factor in formation of lithologically screened structures. Two types are the most common. The first is wedging-out of a layer or a layer sequence on the sides or slopes of structures with development of clinoform oil traps. The second is erosional washing-out of rocks with development of structural forms such as incisions, karst sinkholes. In such cases, oil traps are limited to erosional surface. Clinoforms in Lower Carboniferous deposits formed as a result of pinching up a section of Tournaisian or Visean sandy layers are of practical interest. In the Tournaisian stage, sandy rocks of considerable thickness are developed in the Malevsky and Upinsky horizons in the inner zone of the Kama-Kinelian system of depressions near the northern flank (the Udmurt Republic). Sandy material was carried away from the North Tatar arch and deposited on the seabed, forming shoals, and depositions near obstacles. Overlapped by impermeable rocks, such non-anticlinal structural forms became traps for hydrocarbons in some cases. The length of the propagation area of Malevsko-Upinsky sandstones exceeds 100 km, the width reaches 45 km. According to the drilling data, the thickness of the sandstones is 5–120 m. In this area, the Yakshur-Bod'inskoye oil field is located, where the main oil-bearing capacity is associated with the Tournaisian sandstones pinching out on the sides of the same-name structure (Fig. 2). It is based on an Upper Frasnian-Lower Famennian reef. In the Trans-Volga period, this reef was covered with sedimentary carbonate rocks. In the Malevsko-Upinskoe time, clinoforms developed on the slopes of the uplift. Apart from sandstone pinching out on the slopes of local uplifts, their regional pinching out on the KKDS board is observed. This boundary is clearly recorded by seismic prospecting.

Karst processes occur in abundance in carbonate deposits in the Perm Territory. In the Upper Devonian carbonates, the height of the cavities reaches 2–4 m, the length is from one to several dozens of meters, which is determined by the fall of a drilling tool. The most striking cases of drilling fluid absorption and tool falls were noted on the Shumovsky, Maykor, Nozhovsky and Chermoz uplifts.

Lithological replacement traps are formed in the bed of paleorivers. Here, a lithological barrier is created due to the erosion-accumulative effect, when, as a result of erosion, cuts are formed into the underlying carbonate rocks, where sandy-silty rocks subsequently accumulate (Fig. 3, *a*) [40]. The main feature of the cuts is the older age of the rocks in the axial part of a cut than on its sides. Carbonate rocks underlying Visean terrigenous sediments underwent erosional destruction. During sedimentation that accompanied erosion and did not stop at a later time, such erosional depressions were filled with terrigenous material, which led to another distinctive feature of cuts: the thickness of terrigenous deposits in such depressions more than doubles the thickness of rocks in the adjacent territory. Fig.3, *b*, shows a geological model of the central part of the Elnikovskoye field based on the drilling results. Several carbonate outliers are noted out in the site combined into three uplifts, each of which is associated with a reservoir in the C1t-I layer. This formation is at the top of the Tournaisian stage, its thickness reaches 18 m and typically it is not dissected. The deposits are lithologically limited by the sides of erosional cuts, the depth of which is such that the Kizelovsky horizon is completely eroded.

Based on an analysis of the distribution of facies and the paleogeographic settings of their formation, a study of the patterns of spatial changes in the reservoirs of the Upper Devonian-Tournaisian carbonate complex and typification of the established non-anticlinal traps, the authors of the paper gave a forecast for development of non-anticlinal traps in the Perm Territory and the Udmurt Republic (Fig. 4). In the sediments of the complex under consideration, the dominant role is played by the side and inner near-side zones of the Kama-Kinel paleo-depression system, which are promising in terms of formation of non-structural traps in organogenic structures. Formed mainly in the Frasnian-Famennian time, the structures are a reservoir of hydrocarbons that accumulate under certain lithofacial conditions. Taking these conditions into account, the following zones are identified.

Characteristics of the Identified Zones

Zone I corresponds to the western side of the Kama-Kinelskaya system in the Perm Territory, passing westward to its northern side – on the lands of the Udmurt Republic. While the eastern boundary of this zone is controlled by the depressive part of the paleodepressions, which is a zone of generation and accumulation of hydrocarbons that subsequently migrate into the formed traps, as well as intraformational massifs of accumulations of these structures, the western boundary is more conditional. First of all, the fact that backreef lands are less studied both by seismic research methods and by deep drilling.

In the northern part of the Kama-Kinelskaya system (the Perm Territory), zone I coincides with a prospective zone for the presence of non-structural traps in the Devonian terrigenous complex. Thus, the range of tasks to be solved through seismic surveys on the lands of this zone expands.

In addition, within the boundaries of the regional zone I, it is quite reasonable to localize subzone Ia, the oil-bearing prospects of which are associated with developing Tournaisian clinoforms. Sedimentation of a thick argillite-carbonate Tournaisian sequence with a pronounced clinoform structure occurred under the conditions of lateral build-up of the side slopes of the paleo-depressions in the Kama-Kinel system. The mantle-like overlap of these strata by limestone-mudstone sediments of the Late Turnean age creates favorable conditions for preservation of potential hydrocarbon deposits in clinoform traps. Subzone Ia is identified in the junction zone of the Solikamsk depression and the Visim depression. Clinoforms are well traced in the wavefield of seismic profiles. It was confirmed by identification of Tournaisian clinoforms and the surface reflecting horizons $K_{л}^{к}$ and $K_{л}^{п}$ along the sections of seismic profiles in the Syn'vinskaya and Pesterovskaya areas – along the western side of the Chelvinskaya depression of KKS (Fig. 5) [41].

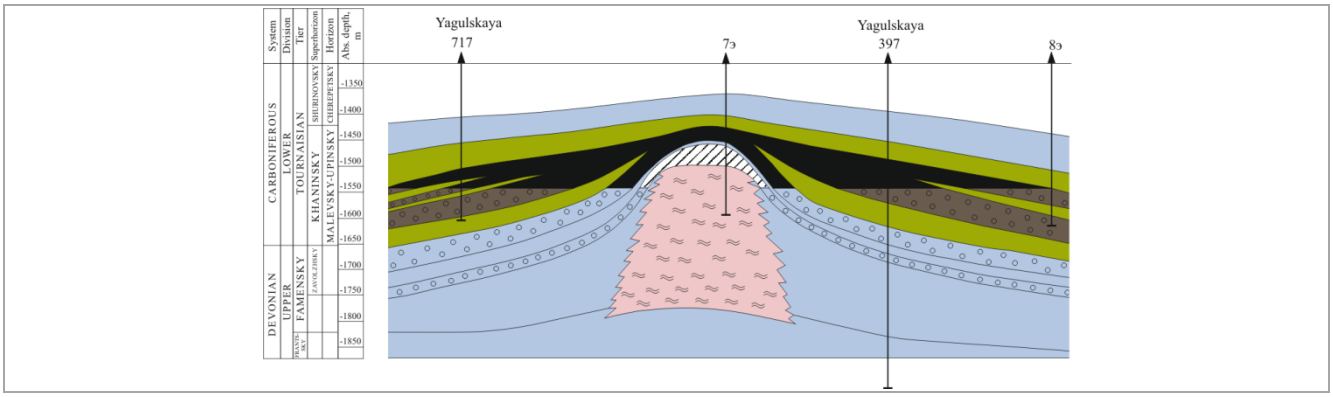

Fig. 2. Lithologically screened trap (clinoforms) Yakshur-Bod'inskoe field

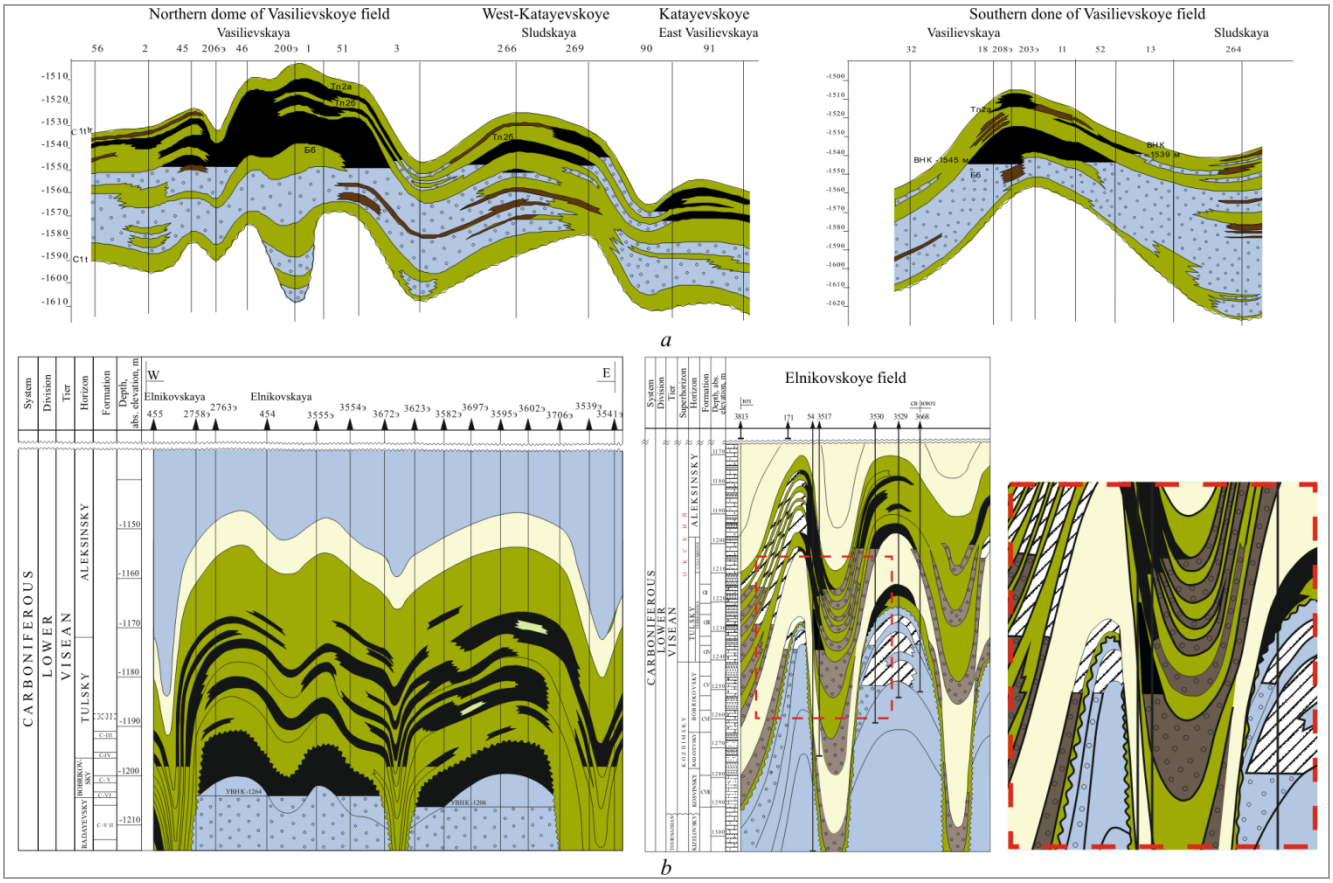

Fig. 3. Lithologically screened trap (cut): *a* – Vasilievskoye field; *b* – Elnikovskoye field

Zone II is allocated within the boundaries of the Udmurt Republic and the Kirov region and corresponds to the northern side of KKDS in its southern part. This site includes the western part of the Krasnogorsk swell, the northern slope of the Valamaz paleoplato as a zone of developing the Frasnian-Famennian reef structures and the Potemkin paleo-depression separating them. The paleo-depression is characterized by development of Upper Famennian (possibly Upper Famennian-Tournaisian) reef structures in the terrigenous-carbonate section of the Frasnian-Famennian sequence. Regional seismic surveys in the Nikolskaya area have already established the presence of such small-sized, but high-amplitude (up to 100 m and more) reefs (Fig. 6) [42].

Zone III that has prospects for discovering new lithologically limited traps in the organogenic structures of the Famennian-Tournaisian age, includes the eastern side of KKDS ("Veslyanskaya swell-like zone") and its outer slope (the Perm Territory). The zone boundaries include partially oil-and-gas prospective ground of the eastern edge of the Bym-Kungur monocline. Examples of identifying bioherm structures in the Zatanyp area are shown in Fig. 7 [43]. On the Tartinsky structure, the Tartinskoye oil field was discovered, where commercial oil-bearing capacity is associated with the Tula horizon (Tl_{2-b} layer), Tournaisian (T_1 and T_3 layers) and Famennian (F_{m2} layer) tiers.

Regional and zonal-regional seismic exploration works, carried out in the Sylven depression, also revealed the presence of massive organogenic structures of the paleoplato type, which constitute zones of accumulated as well as single (scattered) bioherm (or biostromic) structures. According to the age of formation, these organogenic structures belong to the Late Devonian-Tournaisian paleoshelf, presumably to the so-called Utkinsko-Serebryanskaya system of paleo-depressions, the nature and distribution boundaries of which require further careful study. The presence of such depressions was confirmed by deep drilling along the sections of wells No. 1 and 6 in the Ilimskaya area, as well as a superdeep Arakaevskaya 1 well.

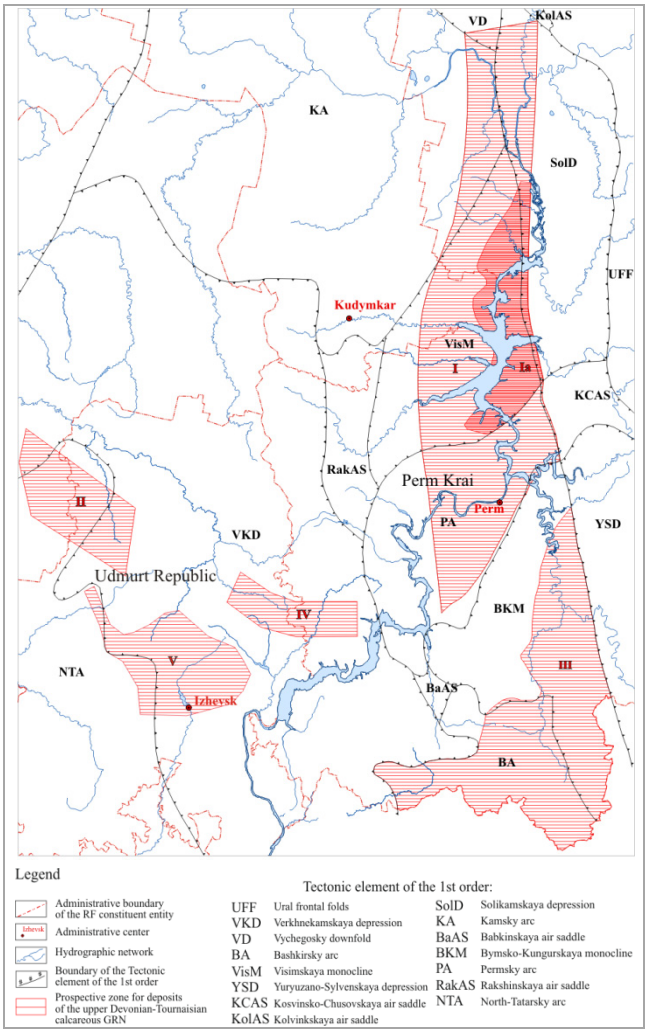

Fig. 4. Propagation scheme of the zones of non-anticlinal traps, with the prospects for detecting industrial accumulations of hydrocarbons in the Upper Devonian-Tournaisian carbonate complex

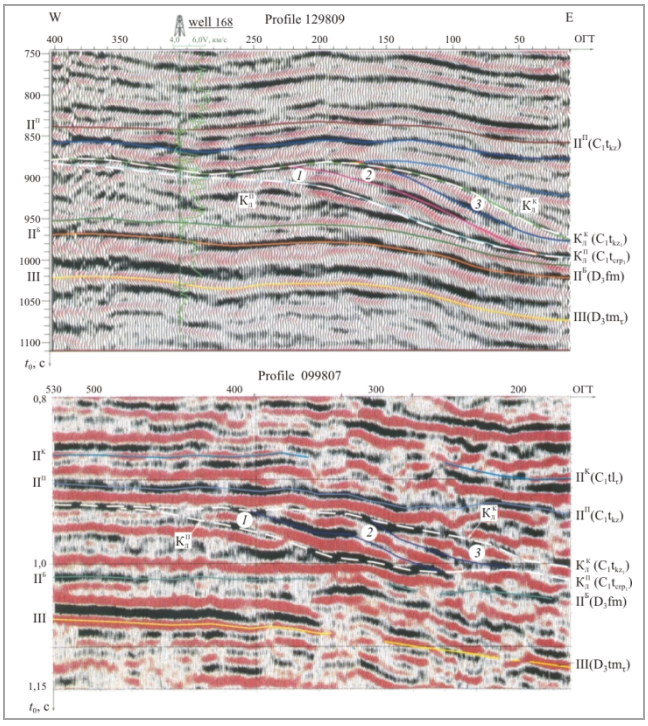

Fig. 5. Identification of Tournaisian clinoforms in Syn'vinskaya (pr. 129809) and Pesterevskaya (pr. 099807) areas: K^*_1 – reflecting horizon; *1*, *2*, *3* – clinoform numbers

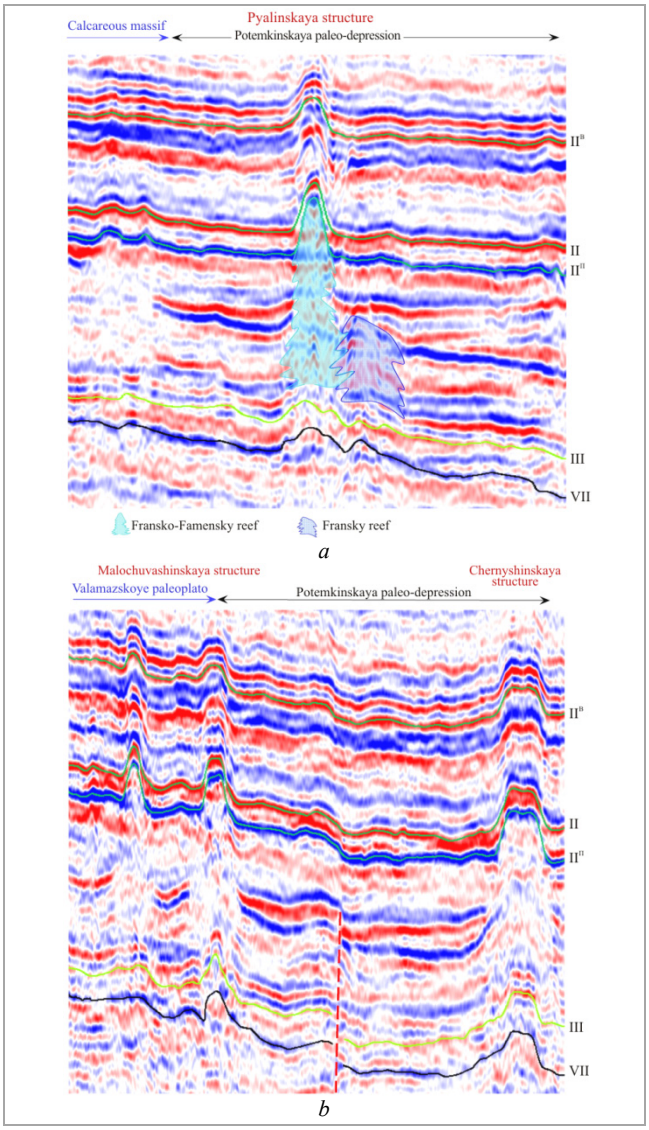

Fig. 6. Identification of: *a* – reef structures within the Potemkin paleo-depression; *b* – reef buildups within the Valamaz paleoplato

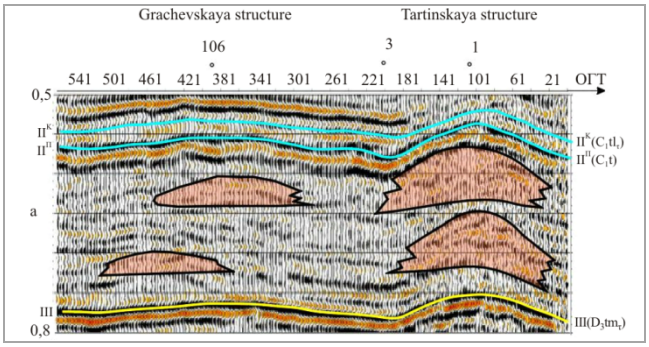

Fig. 7. Examples of identified bioherm buildups in the Zatanyp area

Zone IV has prospects for detecting traps in the bodies of organogenic structures.

Late Devonian (Frasnian) organogenic structures such as shallow-water shelf bioherms are widely represented 10–15 km north of the Upper Devonian barrier reef, framing from the north the Sarapul (Udmurtia) and Shalym (the Perm Territory) depressions of KKDS. This zone of the supposed development of Devonian reefs was identified in the early 1990s. Its width is 10–15 km and length is about 45 km in the Udmurt part of the paleoshelf and about 20 km in its Perm part.

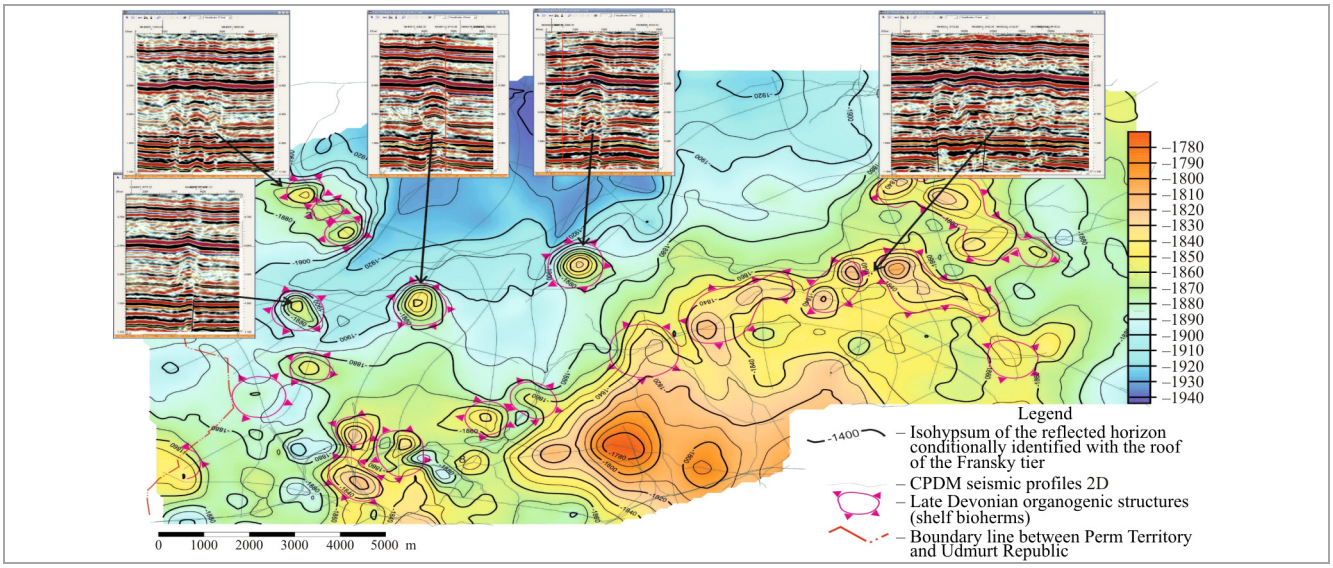

Fig. 8. Structural map of RH IIIf

Such organogenic structures are quite confidently identified by an increase in ΔT III – II^{P} by 0.006–0.010 s and a decrease in ΔT II^{P} – I^{P} by 0.005–0.009 s, as well as visually by a characteristic pattern of a seismic record. In terms of these parameters, they are not inferior, and in some cases even surpass the oil-bearing onboard reef structures. The most contrasting reef structures are manifested in RH IIIf, conventionally identified with the reflection near the top of the Frasnian stage (Fig. 8). Their amplitude along this horizon reaches 50–60 m. According to the reference RH II^{K} (the top of the Tula terrigenous deposits), the amplitudes of the structures of the overburden of organogenic buildups reach 20–30 m. Upsection, the amplitude rapidly decays to the first meters along RH I^{P} (the top of the Bashkirian stage), and the structures are completely leveled higher along the section.

Organogenic structures in the trans-reef zone are mainly grouped into two sublatitudinal bands, but there are also separate bioherms or their groups. In the southern strip, bioherms are located at the intervals of 0.5-1.5 km. In the northern zone, the interval between organogenic buildus increases to 2.5–3 km, and the bioherm amplitude also increases. The dimensions of the structures in the plan vary within 1–2 km. In the Perm Territory, both bioherm bands coincide in plan with the sublatitudinal disjunctive disturbances identified along the underlying horizons.

A number of similar structures have been identified or prepared for exploration drilling in the Udmurt Republic: for example, Novo-Lyalshurskaya, Gondyrvayskaya, Kivarinskaya and Bakainskaya structures. In the western part of the zone, the Central, Vukoshurskoye and Kykvinskoye oil fields are confined to the enclosing structures of such organogenic buildups. Oil deposits there are confined to the Famennian, Visean terrigenous and Middle Carboniferous deposits.

In 1993 the Sosnyakovskaya complex sedimentary-tectonic structure was prepared within the boundaries of this zone in the Perm Territory, and prospected by a well. Following the results of seismic data reinterpretation, it turned out that the well was not sunk in the optimal conditions, as the bioherm was not penetrated, and the well was stopped by drilling in the Tournaisian sediments. Accordingly, the structure requires additional study.

In contrast to onboard reef systems, the presence of zonal seals was established almost everywhere in the zones of the shallow (sub-reef) Upper Devonian shelf in the Famennian sediments, ensuring the safety of oil deposits in this complex. The closest example of such deposits in Udmurtia is the Debesskoye oil field. The most representative example for the Perm Territory is undoubtedly the southeastern outer edge zone of KKDS, where dozens of Famennian oil deposits are discovered.

In this aspect, the above-described low-amplitude (for traditional objects of the Lower and Middle Carboniferous) shelf bioherms can be considered as potential and numerous non-anticlinal traps.

In terms of developing non-anticlinal hydrocarbon traps, the prospects of Tournaisian terrigenous-carbonate deposits are also associated with clinoform formations on the slopes of the side parts of KKDS, the study of which is possible in parallel with studying the side zones to detect organogenic buoldups of the Frasco-Tournaisian age. Besides, the zones of sandy-siltstone rocks in the Malevsko-Upinskaya sequence, characterized mainly by the limestone-mudstone section type, are promising. Based on the results of field geophysical survey, it seems possible to trace the lines of facial replacement of reservoirs with synchronous argillite or limestone rocks (facial replacement traps) as in the Mozhginskaya paleo-depression in the Udmurt Republic (zone V). Here, a sandy stratum up to 115 m thick, composed of porous sandstones with interlayers of argillites and dense clayey siltstones, is underlain and overlain by argillites up to 5–6 m thick, and higher by limestones. The presence of this sandy stratum is confirmed by palynological studies in the wells of the Sushinskaya, Lyukskaya, Aksenovtsevskaya and Yagulskaya areas. Propagation of the sandy stratum, which has a lenticular shape with the maximum thickness near Aksenovtsevskaya well No. 485 and Yeseneiskaya well No. 796 in the eastern sublatitudinal direction, is limited by its gradual replacement with argillites or limestones [44, 45].

Conclusion

Thus, it is shown that two types of non-anticlinal traps are found in the sediments of the Upper Devonian-Tournaisian carbonate complex in the Perm Territory and the Udmurt Republic: lithologically limited and lithologically screened. Based on geophysical criteria, an analysis of facial propagation and paleogeographic conditions of their formation, a study of the patterns of spatial change in reservoir properties of rocks, five zones of non-anticlinal traps were identified, that are promising for detecting production-scale accumulations of hydrocarbons. The most widespread are organogenic buildups of the Famennian-Tournaisian age, confined to the side and inner near-side zones of the Kama-Kinel system of depressions, as well as to the Utkinsko-Serebryanskaya system of depressions.

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