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# Geologic Structure and Hydrocarbon Generation Potential of Devonian Terrigenous Strata in the Perm' Territory

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**Abstract**—The work is a study of the geologic structure and hydrocarbon generation potential of Devonian terrigenous strata in the Perm Territory. Prediction for new oil fields is made using quantitative criteria for determining the scale of oil generation by the petroleum source rocks of this petroleum system and the scale of the oil migration. An integrated approach is used, which makes it possible to follow all stages of petroleum generation in the Devonian terrigenous strata. The above petroleum system is the most buried of all commercial ones in the region; it has an intricate geologic structure and is less drilled than others but is considered to be promising for oil resource enhancement. Therefore, a comprehensive assessment with regard to both quantitative criteria and genetic parameters is a necessary step in the future planning of geological surveys. The results obtained during this work point to a low hydrocarbon generation potential of the Devonian terrigenous strata within the study area. This research has first established no genetic relationship between the oils and the organic matter of the Devonian terrigenous strata but has revealed a genetic relationship between these oils and the oils and organic matter of the Upper Devonian–Tournaisian petroleum system. It is shown that oil fields where oil deposits are present in Devonian terrigenous strata usually have reservoirs in the overlying Upper Devonian–Tournaisian petroleum system as well. This phenomenon is most often observed on the flanks of the Kama–Kinel' depression system. The development of oil fields there gives a high chance of discovering new oil deposits. Taking into account the new data, it is necessary to revise the search criteria and perform geological surveys in the Devonian terrigenous strata, primarily in the areas of explored oil fields where oil is localized in the Upper Devonian–Tournaisian petroleum system.

*Keywords:* hydrocarbon generation potential, scale of migration, petroleum source formations, geochemical parameters, oil metalloporphyrins, Devonian terrigenous strata, Perm Territory

## INTRODUCTION

The Perm Territory has long been a leader in hydrocarbon (HC) production among the oil-producing regions of the Volga–Ural petroleum province. Seven petroleum systems are recognized in the sediment section there (from bottom to top): Devonian terrigenous, Upper Devonian–Tournaisian carbonate, lower–middle Visean terrigenous, upper Visean–Bashkirian carbonate, Vereiskian terrigenous–carbonate, Kashirskian–Gzhelian carbonate, and lower Permian carbonate. The main hydrocarbon reserves are localized in the Upper Devonian–Tournaisian, lower–middle Visean, and upper Visean–Bashkirian petroleum systems.

The Devonian terrigenous petroleum system is the most buried and less studied of all systems but contains up to 20% of commercial oil reserves. It has been studied for several decades, but the source of its oil is still debatable. There are several viewpoints of the oil source: (1) The Riphean–Vendian sediments (Sharonov, 1971); (2) the local petroleum source formations of the system (Kalachnikova et al., 1977; Frik et al., 2007); and (3) the petroleum source formations of the system that are localized within the Cisuralian trough (Kamaleeva, 2014), although there is a firmly held view of complete scattering of hydrocarbons during their migration to a distance of more than 15–20 km (Hantschel and Kauerauf, 2009).

Upper Devonian–Tournaisian domanikites and domanikoids spread mostly in the axial zone of the Kama–Kinel' depression system (KKDS) were recognized by most geologists to be the main zones of hydrocarbon generation as early as the late 1960s–early 1970s. This led to a discovery of many oil fields in the region. The discovery of oil deposits in the Devonian terrigenous strata was rather accidental, because only 0.3% of assumed hydrocarbon (HC) resources of these sediments in the south of the region were confirmed, although the Bashkir Arch area has been best studied by drilling.

Earlier studies of the petroleum potential of the Devonian terrigenous system (Stashkova et al., 2015) were based on the lithological and petrographic description of core samples containing organic matter (OM). The researchers also considered a change in some geochemical parameters, such as the content of bitumens, the isotope composition of carbon,

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the content of metalloporphyrins, and the pristane/phytane ratio in oils and bitumens, taking into account a few Rock-Eval pyrolysis data on the petroleum potential of the Devonian terrigenous strata.

This research is based on integrated geophysical, geological, and geochemical data, which made it possible to reconstruct the geologic conditions of the strata formation and the scale of HC generation in the Devonian terrigenous petroleum system within the Perm Territory. We have first applied the modern technology of revealing oil systems, presented by Magoon and Dow (2012), to this region. It is based on the organic (sedimentation–migration) theory of oil genesis, which serves as a basis for successful petroleum prospecting all over the world.

## METHODS

This research was based on the information about the thicknesses of stratigraphic units, the description of cores, and the data on OM contents and the geochemical parameters of oils and OM. Differentiation of oil systems is an example of integrated geological, geochemical, and geophysical studies during petroleum-geological zonation and prospecting. According to modern concepts (Magoon and Dow, 2012), an oil system is a complex of sediments in which oil and gas formed at the particular stage of evolution of a petroleum basin. This system includes petroleum source rocks, HC migration paths, reservoir rocks, seals, and traps and is controlled by their favorable association in geologic time and space. In this research we have first recognized the components of an oil system in the Devonian terrigenous petroleum system of the Perm Territory.

This work is a summary of the main results of our study of the Devonian terrigenous strata in the south of the Perm Territory in 2011–2014, supplemented by the latest research data on the Devonian terrigenous sediments in the central and northern parts of the region. To reconstruct the sedimentation conditions, we made correlations for Devonian terrigenous sediments in the sections of more than 1000 wells, using the results of electric and radioactive logging as the most informative ones. The seismic reflector localized in the bottom of the Sargaev limestones is best revealed by radioactive logging, and microlaterolog data permit the most accurate tracing of thin Pashian sediments in the well sections.

Stratigraphic division of the section makes it possible to study the distribution of the petroleum system thicknesses. At the diagenesis stage, clayey sediments are the most favorable for the preservation and burial of OM. Using the log data, we recognized clayey rocks and determined their thicknesses in order to establish the scale and sources of petroleum generation. Unfortunately, Rock-Eval pyrolysis was performed for only few core samples from the south of the study region, and mostly on clastic rocks rather than mudstones. For this reason, it is difficult to evaluate the parameters of petroleum generation in the source rocks and is impossible to draw conclusions for the entire Perm territory, using data of only this method. The HC generation potential of the Devonian terrigenous strata was estimated from data obtained from 48 exploratory wells located throughout the study region, including 114 values of the total organic carbon (TOC) content in the rocks. During the study of the Devonian terrigenous strata, we calculated the OM content density, or the OM stock ($Q_{OM}$), oil generation density ($Q_{gen}$), and oil migration (into a reservoir) density ($Q_m$).

Genetic correlations were made mainly on the basis of the carbon isotope composition of oils and OM of rocks, the content of metalloporphyrins in the oils and OM bitumens, and the pristane/phytane ratios in oils and rock bitumens determined at AO KamNIIKIGS (Stashkova et al., 2015). Note that there were few studies of genetic parameters. For example, a carbon isotope composition was studied only for 17 oil and 20 OM samples, and the content of metalloporphyrins and the pristane/phytane ratio, for 24 oil and 22 OM bitumen samples. Nevertheless, the available data cover the entire study area and the entire Devonian terrigenous area.

## MODERN CONCEPTS OF THE PETROLEUM POTENTIAL OF THE DEVONIAN TERRIGENOUS STRATA

Stratigraphically, the Devonian terrigenous strata are made up of sediments of the Upper Emsian substage, the Biiskian and Afonian horizons of the Eifelian stage, all horizons of the Givetian stage, and the lower Frasnian substage. The Givetian sediments include a productive bed $D_2$; the Pashian sediments, a bed $D_1$; and the Timanian sediments, a bed $D_0$. The thickness of the sediment section is greatly variable within the Perm Territory, being maximum (up to 180 m) in the central part of the region, in the sublatitudinal zone of the Upper Kama–Chusovaya paleodepression, and gradually diminishing to the north and southeast (Fig. 1). The minimum section thicknesses (≤40 m) are revealed in the southeast of the region and are due to the long existence of the Krasnoufimsk paleoland, up to late Timanian time. Analysis of the available data shows no regular relationship between the thickness and stratigraphic completeness of the section and the distribution of oil fields. On the contrary, most of the HC fields with oil pools deposits in the Devonian terrigenous strata are localized in the south of the Perm Territory, where the petroleum system thicknesses are below their average value.

Within the study region, HC fields are confined to the flank and near-flank zones of the Kama–Kinel' depression system. Most of the HC fields with oil pools deposits in the Devonian terrigenous strata are localized in the south of the region (95%), three fields were discovered in its central part, near the city of Perm, and only one field was found in the north of the region, near the city of Cherdyn'. The HC fields whose oil reservoirs occur only in the Devonian terrigenous sediments are confined to the axial zone of the KKDS (Fig. 1).

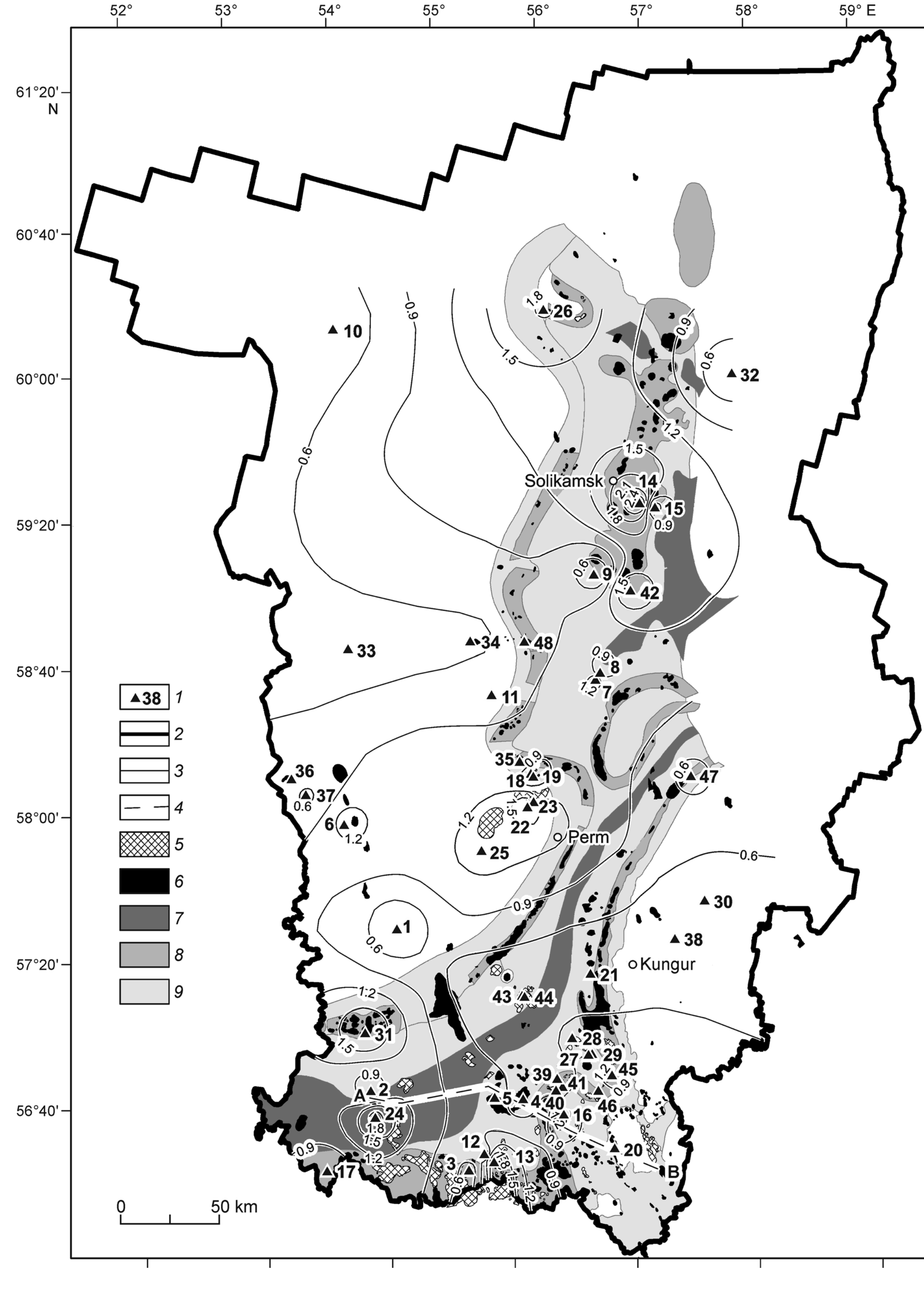


**Fig. 1.** Distribution of the thicknesses of Devonian terrigenous strata. *1*, well and its number; *2*, administrative boundary of the Perm Territory; *3*, isopachs of the thicknesses of Devonian terrigenous strata, m; *4*, paleoprofile; *5*, HC fields with oil deposits in the Devonian terrigenous strata; *6*, HC fields; zones of the Kama–Kinel' depression system: *7*, axial; *8*, flank; *9*, near-flank.

## THE GEOLOGIC CONDITIONS OF FORMATION OF THE DEVONIAN TERRIGENOUS SEDIMENTS

The Devonian sedimentation period began with the transgression of the shallow-water sea basin from the Ural zone onto the pre-Devonian peneplain platform surface. Analysis of data obtained by different researchers (Sharonov and Danilov, 1966; Kuznetsov, 1974, 1975; Kutukov, 1981) made it possible to reconstruct the sedimentation conditions of the Devonian terrigenous rocks. During the Devonian terrigenous sedimentation, which lasted throughout the early Emsian and early Frasnian, transgressions were changed by regressions in the study area, and sea level changes led to erosion of sediments accumulated earlier. The existing conditions favored the formation of sediments with a well-pronounced cyclic structure and a frequent lithologic heterogeneity. The replacement of reservoirs by impermeable rocks, often observed within local structures, complicates the development of HC fields. In addition, productive beds are often replaced by compact rocks in the structural arches, which significantly complicates petroleum prospecting and exploration.

The geochemical facies were determined with regard to the diagenesis conditions established from petrographic data and single data on sulfur and iron species in the studied rocks. Geochemical facies are crucial for the formation of petroleum source rocks, because they govern the redox conditions influencing the OM preservation. Highly reducing conditions are most favorable for the formation of such rocks, and oxidizing conditions are least appropriate. Petrographic studies and few chemical analyses for reactive sulfur and iron species gave an insight into the redox conditions of diagenesis during the formation of Devonian terrigenous strata in the south of the Perm Territory. It was established that the content of pyrite iron, $Fe_{pyr}$, in most of the samples is <0.5% and that $Fe_{pyr}$ amounts to <30% of all reactive iron. These data point to predominant weakly reducing and oxidizing diagenesis conditions (Kozhevnikova, 2013). An exception is single samples of Pashian and Timanian sediments, with $Fe_{pyr}$ = 0.76 and 0.92%, respectively. The calculation results are confirmed by petrographic data, e.g., the Pashian sediments include siderite and chamosite. The presence of siderite indicates more oxidizing conditions, because it often forms at the expense of carbon dioxide produced during OM oxidation. In places, pyrite is present in rocks, which indicates the most reducing sedimentation conditions. Frequent changes in tectonic modes led to a periodic subsidence of the redox boundary, which was usually located near the sediment surface; this caused oxidation of earlier formed rocks. Pyrite is present in Timanian sediments almost throughout the study area, which is evident of reducing and weakly reducing conditions. The above data indicate that the geochemical conditions at the diagenesis stage were unfavorable for the formation of petroleum source rocks because of the proceeding OM oxidation.

## QUANTITATIVE ESTIMATION OF THE HYDROCARBON GENERATION POTENTIAL

To estimate the HC generation potential of sedimentary strata, we selected data on rocks with a TOC content of more than 0.3%, because even pure clays with TOC < 0.3% cannot generate hydrocarbons at any catagenesis stage (Larskaya, 1983). In addition to the content of OM, we took into account the degree of its catagenesis, which is influenced by tectonic processes. In the Paleozoic, the sedimentary strata in the study area subsided at a low rate, on average, 36.7 m/Myr (Krivoshchekov and Kozlova, 2012). The catagenetic transformations of rocks and their OM were caused by a number of mutually related factors, mainly temperature, pressure, and the geologic time. Catagenesis of the OM of Devonian terrigenous rocks in the study area was of grade $MC_1$ and reached grade $MC_2$ only in the small eastern part of this area (Frik et al., 2007).

In the course of a core study, TOC is usually determined not throughout the well section but only in its certain intervals; therefore, this parameter varies over a wide range of values within the well. For this reason, we consider the most optimistic variant and take the TOC content for each well as the difference between the average TOC content throughout its Devonian terrigenous section and the TOC content in sandstones.

A detailed correlation with separation of OM-enriched clay strata and their assignment to stratigraphic units shows their irregular character. Petroleum source rocks are present in all stratigraphic complexes, but they are discontinuous in the region, except for the Timanian sediments, in which they are found almost over the entire study area. There is a regional zoning in the distribution of petroleum source rocks: They are revealed mainly in Eifelian sediments in the central part of the Perm' Territory and prevail in Timanian rocks in the south and north of the region (Fig. 2).

The scale of HC generation was assessed with regard to the type of OM. According to micropetrographic studies, the Devonian terrigenous sediments contain predominantly humic OM of type III (Frik et al., 2007). The most informative indicator, characterizing not only the OM content in the sample but also the OM distribution throughout the sediment section, is the OM stock calculated by the formula $Q_{OM} = C_{org} \cdot H \cdot d \cdot 10^7$, where $C_{org}$ is the average carbon content in rocks, %; $H$ is the rock thickness, km; and $d$ is the density of rocks, g/cm$^3$ (Korchagina and Chetverikova, 1983). It is this criterion that makes it possible to recognize petroleum source formations (PSFs), i.e., strata that contain not just organic inclusions but OM in the amount sufficient for a large-scale HC generation, up to the formation of commercial HC deposits (Chernikov, 1988). Based on the data obtained, we compiled a distribution map of the OM stock (Fig. 2) and recognized PSFs in the central part of the Perm Territory, where sedimentary strata have the most complete section, from upper Emsian to Timanian sediments.

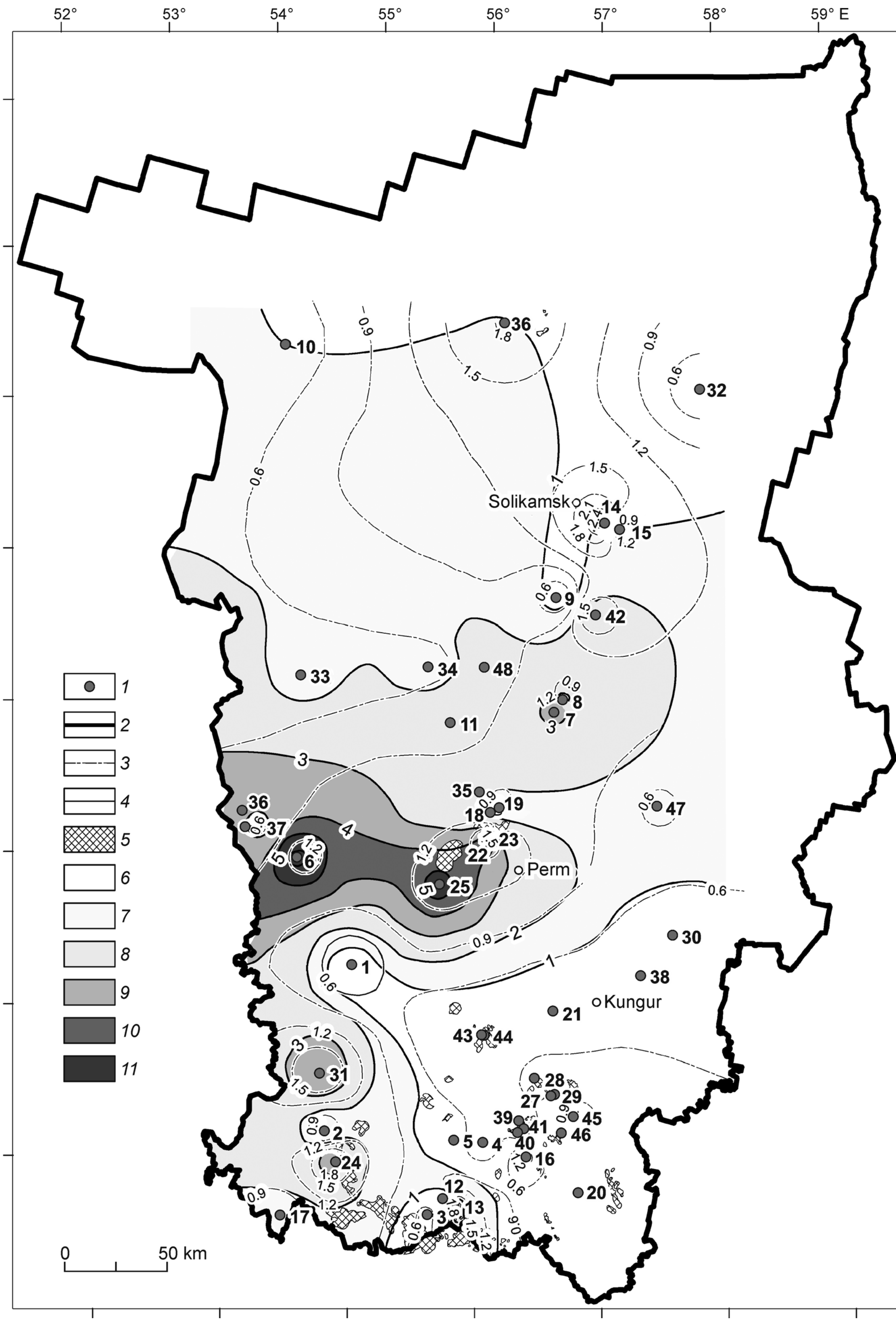


**Fig. 2.** Distribution of OM stock in the Devonian terrigenous strata. *1*, well and its number; *2*, administrative boundary of the Perm Territory; *3*, TOC (%) isopachs; *4*, OM stock isopachs; *5*, HC fields with oil deposits in the Devonian terrigenous strata; OM stock, mln tons/km$^2$: *6*, 0–1; *7*, 1–2; *8*, 2–3; *9*, 3–4; *10*, 4–5; *11*, >5.

Usually, the distribution of HC reserves over an area is directly determined by the distribution of OM ($Q_{OM}$) (Rodionova, 1967), but this regularity is not observed in the Devonian terrigenous strata in the Perm Territory. On the contrary, the operated oil fields are localized in zones with minimum OM content densities. For example, only 16 of 41 discovered oil fields are in the zone of Devonian terrigenous PSFs. The calculated OM content densities show that the developed oil fields in the Devonian terrigenous strata cannot form in situ, because more than half of them are localized in an area with $Q_{OM}$ < 1 mln tons/km$^2$, i.e., lower than the critical value. Even with regard to lateral oil migration, usually no further than 15–20 km, the oil deposits of the Devonian terrigenous strata in the southeast of the region cannot be generated from the local OM.

Note that the high $Q_{OM}$ values indicate only a significant amount of OM, but the process of HC generation is intricate and multifactorial. In the calculations, we used a parameter that takes into account most of the factors affecting oil generation, namely, the HC generation density, which was calculated by the formula $Q_{gen} = C_{org} \cdot \rho_{sr} \cdot h_{sr} \cdot K_o^{gen} \cdot 10^6 / C^{res} \cdot M_{res}$, where $C_{org}$ is the content of residual organic carbon in the source rocks, %; $\rho_{sr}$ is the density of the source rocks, tons/m$^3$; $h_{sr}$ is the thickness of the source rocks, m; $K_o^{gen}$ is the oil generation coefficient, % of the initial mass of OM; $C^{res}$ is the content of carbon in the residual OM at this stage of catagenesis, %; and $M_{res}$ is the residual mass of OM, % of the initial mass (Kleshchev et al., 2000). According to the known concepts, the parameter $Q_{gen}$ must be equal to no less than few million tons/km$^2$ for the formation of oil deposits, but the calculated data (Table 1) show no zones with such values within the Perm Territory. This confirms that the PSFs of the Devonian terrigenous strata do not generate HCs in the amount sufficient to form commercially viable oil reservoirs.

The amount of migrated oils sufficient to form reserves in the strata is one of indicators of the genetic relationship of HC deposits with the host strata (Rodionova, 1967). The HC migration density ($Q_m$), characterizing the amount of migrated HCs that formed deposits, is also low and thus shows

**Table 1.** Generation parameters of the Devonian terrigenous strata

| Well | TOC, % | *H*, $D_{ter}$, m | $Q_{OM}$ | $Q_{gen}$ | $Q_m$ | Well | TOC, % | *H*, $D_{ter}$, m | $Q_{OM}$ | $Q_{gen}$ | $Q_m$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | million tons/km$^2$ | | | | | | million tons/km$^2$ | | |
| 1 | 0.36 | 73 | 0.662 | 0.029 | 0.001 | 25 | 1.31 | 166 | 5.480 | 0.241 | 0.008 |
| 2 | 0.68 | 84 | 1.439 | 0.063 | 0.002 | 26 | 1.81 | 21 | 0.958 | 0.042 | 0.001 |
| 3 | 0.48 | 48 | 0.581 | 0.026 | 0.001 | 27 | 0.6 | 23 | 0.348 | 0.015 | 0.001 |
| 4 | 0.3 | 39 | 0.295 | 0.013 | 0.000 | 28 | 0.62 | 31 | 0.484 | 0.021 | 0.001 |
| 5 | 0.72 | 46 | 0.835 | 0.037 | 0.001 | 29 | 0.6 | 26 | 0.393 | 0.017 | 0.001 |
| 6 | 1.3 | 185 | 6.061 | 0.267 | 0.009 | 30 | 0.45 | 15 | 0.170 | 0.007 | 0.000 |
| 7 | 1.39 | 112 | 3.923 | 0.173 | 0.006 | 31 | 1.8 | 88 | 3.992 | 0.176 | 0.006 |
| 8 | 0.64 | 103 | 1.661 | 0.073 | 0.003 | 32 | 0.46 | 30 | 0.348 | 0.015 | 0.001 |
| 9 | 0.35 | 64 | 0.564 | 0.025 | 0.001 | 33 | 0.45 | 137 | 1.554 | 0.068 | 0.002 |
| 10 | 0.5 | 83 | 1.046 | 0.046 | 0.002 | 34 | 0.48 | 124 | 1.500 | 0.066 | 0.002 |
| 11 | 0.75 | 154 | 2.911 | 0.128 | 0.004 | 35 | 1.16 | 82 | 2.397 | 0.105 | 0.004 |
| 12 | 0.63 | 50 | 0.794 | 0.035 | 0.001 | 36 | 0.8 | 165 | 3.326 | 0.146 | 0.005 |
| 13 | 2 | 48 | 2.419 | 0.106 | 0.004 | 37 | 0.56 | 177 | 2.498 | 0.110 | 0.004 |
| 14 | 0.8 | 52 | 1.048 | 0.046 | 0.002 | 38 | 0.48 | 36 | 0.435 | 0.019 | 0.001 |
| 15 | 0.78 | 50 | 0.983 | 0.043 | 0.002 | 39 | 0.42 | 32 | 0.339 | 0.015 | 0.001 |
| 16 | 1.37 | 27 | 0.932 | 0.041 | 0.001 | 40 | 0.6 | 37 | 0.559 | 0.025 | 0.001 |
| 17 | 0.71 | 94 | 1.682 | 0.074 | 0.003 | 41 | 0.39 | 35 | 0.344 | 0.015 | 0.001 |
| 18 | 0.8 | 87 | 1.754 | 0.077 | 0.003 | 42 | 1.77 | 66 | 2.944 | 0.130 | 0.005 |
| 19 | 0.57 | 89 | 1.278 | 0.056 | 0.002 | 43 | 0.36 | 61 | 0.553 | 0.024 | 0.001 |
| 20 | 0.6 | 21 | 0.318 | 0.014 | 0.000 | 44 | 0.59 | 64 | 0.952 | 0.042 | 0.001 |
| 21 | 0.3 | 30 | 0.227 | 0.010 | 0.000 | 45 | 1.29 | 22 | 0.715 | 0.031 | 0.001 |
| 22 | 1.08 | 82 | 2.232 | 0.098 | 0.003 | 46 | 0.7 | 34 | 0.600 | 0.026 | 0.001 |
| 23 | 2.16 | 82 | 4.463 | 0.196 | 0.007 | 47 | 0.55 | 86 | 1.192 | 0.052 | 0.002 |
| 24 | 1.89 | 70 | 3.334 | 0.147 | 0.005 | 48 | 0.8 | 120 | 2.419 | 0.106 | 0.004 |

Note. The well numbers follow Figs. 1 and 2. TOC is the average carbon content in the Devonian terrigenous rocks (%); *H*, $D_{ter}$ is the thickness of the Devonian terrigenous petroleum source rocks (m); $Q_{OM}$ is the OM density in the Devonian terrigenous rocks (million tons/km$^2$); $Q_{gen}$ is the density of HC generation by the Devonian terrigenous PSFs (million tons/km$^2$); $Q_m$ is the density of HC migration from the Devonian terrigenous PSFs (million tons/km$^2$).

no migration sufficient to form commercial oil reservoirs. The HC migration density was calculated by the formula $Q_m = Q_{gen} \cdot K_o^m$, where $K_o^m$ is the coefficient of oil migration, taken equal to 0.035. According to guidelines (Kleshchev et al., 2000), at the beginning of the oil window, where the rocks of the studied petroleum system are located, $K_o^m$ is usually 0.02–0.05. In this research we took its arithmetic mean value. All the obtained criteria that permit estimation of the scale of HC generation are presented in Table 1.

The calculation yielded low values of HC generation and migration potential for the Devonian terrigenous rocks in the Perm Territory. The rocks in the central part of the region correspond to zones with OM of low catagenesis grade. Humic OM of type III is predominant in the Devonian terrigenous rocks (Frik et al., 2007). According to modern geochemical concepts, it required high paleotemperatures for the beginning of HC generation. These facts indicate that the source formations of the studied petroleum system do not generate HCs in the amount sufficient to form the existing deposits.

## GEOCHEMICAL AND GENETIC OIL–OIL AND OIL-OM CORRELATIONS

The established low HC generation potential made it necessary to examine the correlation of oils of the Devonian terrigenous strata with OM of the host rocks and with oils of adjacent petroleum systems. Calculation of the OM stock showed that 16 of 41 oil fields are in the PSF zone (Fig. 2). A comparative analysis of the physical, chemical, and geochemical properties of oils of these fields and oils of the fields located beyond the PSF zone showed their similarity, which indicates that all these oils were generated from the same source.

Many researchers have already studied oils of Riphean–Vendian sediments and described their distinctive properties (Bashkova and Karaseva, 2006; Belokon' (Karaseva) et al., 2001). A discriminant analysis of oils of the studied Devonian terrigenous strata by physical and chemical parameters showed their similarity to oils of the Upper Devonian–Tournaisian strata and their difference from oils of the Riphean–Vendian sediments (Fig. 3*a*). The discriminant analysis was carried out using data on the oil density (d) and the contents of sulfur (s), resins (r), asphaltenes (asph), and paraffin (prf) in the oils. The first discriminant function clearly shows two groups of oils. All oil samples from the Devonian terrigenous and Upper Devonian–Tournaisian strata fall in the first group with $Z_1$ values from −4 to 3, and all oil samples from the Riphean–Vendian sediments are assigned to the second group with $Z_1$ = 7–9. The similarity of the physical and chemical parameters of oils is often associated with the similar conditions of their secondary alterations, whereas genetic parameters, such as the pristane/phytane ratio (pr/ph), the content of metalloporphyrins (VOp), and the carbon isotope composition of oils (is), give an insight into the type of initial OM and, accordingly, the source of oils. A discriminant analysis of the oils by genetic parameters also made it possible to divide them into two groups (Fig. 3*b*). The first group ($Z_1$ from −4 to 0) is the oils of the Devonian terrigenous and Upper Devonian–Tournaisian strata, and the second group ($Z_1$ from 3 to 8) is the oils of the Riphean–Vendian sediments.

The results of the performed mathematical analysis indicate no vertical migration of oils from the Riphean–Vendian sediments to the overlying Devonian terrigenous strata in the Perm Territory, as well as different sources of these oils. At the same time, the oils of the Devonian terrigenous strata and

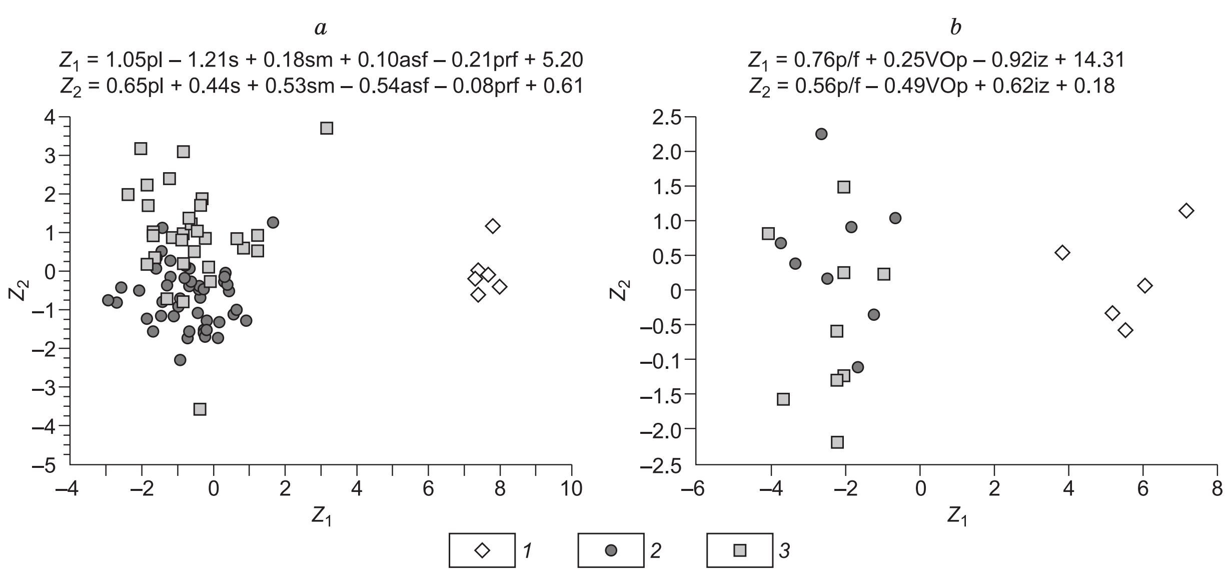


**Fig. 3.** $Z_1$–$Z_2$ correlation by physicochemical (*a*) and genetic (*b*) parameters for oils of the Riphean–Vendian (*1*), Devonian terrigenous (*2*), and Upper Devonian–Tournaisian (*3*) sediments.

Upper Devonian–Tournaisian petroleum system are similar in both physical and chemical, and genetic parameters.

Taking into account the calculated low HC generation potential of the Devonian terrigenous strata and no oil migration from the underlying rocks, we performed a comparative analysis of the physical, chemical and genetic parameters of oils from the Devonian terrigenous strata and Upper Devonian–Tournaisian petroleum system. The analysis showed a slight decrease in the oil density and viscosity and in the sulfur contents from west to east and a deterioration in the oil properties upsection (Kozhevnikova et al., 2014), but this is more likely due to the different hypsometric positions of oil reservoirs rather than different oil sources.

We also failed to separate the oils by genetic parameters. The pristane/phytane ratio reflects the specifics of the oil source material and the depositional environments and usually remains constant; therefore, this parameter can be used for a genetic correlation. The oils of both petroleum systems show pr/ph = 0.7, which indicates that they were generated from sapropelic OM. The oils are sapropelic according to the contents of metalloporphyrins: Vanadyl porphyrins (VOp) significantly dominate over nickel porphyrins (Nip). The minimum contents of metalloporphyrins, up to their absence, are specific to oils in the eastern areas, independently of their stratigraphic localization. This phenomenon is due to high paleotemperatures in the Cisuralian foreland basin, which led to the destruction of metalloporphyrins. The maximum contents of metalloporphyrins were found in oils on the Bashkir arch. The general tendency for an increase in the content of vanadyl porphyrins from east to west is typical of the oils of both the Devonian terrigenous and the Upper Devonian–Tournaisian petroleum systems (Kozhevnikova et al., 2014). The oils of these systems cannot be separated by the carbon isotope composition either; their $\delta C^{13}$ values vary from −27 to −29‰. The similarity of the oils of the Devonian terrigenous and Upper Devonian–Tournaisian petroleum systems is observed not only within the Perm Territory but also in the neighboring regions (Kozhevnikova, 2018).

Comparison of the genetic parameters of oils of the Devonian terrigenous sediments and of OM bitumens of the host rocks showed no genetic relation between them. As mentioned in the petrographic description above and confirmed by genetic parameters (pr/ph > 1, low contents of vanadyl porphyrins), the OM of the Devonian terrigenous strata is humic. Thus, the oils of these strata could not have formed from the OM of the host rocks, because they were generated by OM with a predominance of sapropelic material.

## CHARACTERISTICS OF THE RESERVOIRS AND SEALS

In the study region, the Devonian terrigenous reservoirs are fine-grained and, more seldom, inequigranular silty low-shale sandstones composed of semirounded, angular, subangular, and well-rounded quartz grains. There are also reservoirs formed by coarse-grained and, more seldom, inequigranular sandy low-shale siltstones composed of angular and scarcer semirounded quartz grains. The porosity coefficient of rocks within the HC deposits varies from 10.2 to 19.0%, and the permeability coefficient, from 0.003 to 0.53 $\mu m^2$. The reservoir properties of rocks significantly worsen with approaching the Cisuralian foreland basin.

In contrast to other regional petroleum systems, almost 80% of the traps in the lithologically different Devonian terrigenous sediments are screened, which, in turn, complicates search for HC reservoirs. A specific feature of the studied system is the abundance of oil-saturated sandstone lenses. They are usually confined to the Pashian sediments and occupy a small area, and the thickness of the productive beds is few meters. The permeable beds of the system, independently of their stratigraphic position, are highly heterogeneous within the study area. The reservoir is often replaced by compact rocks within a HC field (Balashova and Salai, 1970). Sheet, partly screened reservoirs are the most widespread, and sheet dome traps are somewhat scarcer.

There is no persistent seal within the studied petroleum system, as evidenced by the oil saturation of all permeable near-cap interbeds and by the water saturation of the underlying beds. This distribution of fluids indicates that the system can be saturated with oil migrating from the overlying source formations.

The permeable bed of the Devonian terrigenous petroleum system is separated from the overlying reservoirs by Timanian compact sand–mudstone rocks, which serve as seals. The poorly permeable rocks are of impersistent thickness varying from 3 to 20 m. The clay limestones of Sargaev age resting upon the Devonian terrigenous strata also have screening properties. Analysis of the data on the Devonian terrigenous seals shows that a 5–6 m thick impermeable bed is enough to preserve commercial HC reservoirs. An example is the HC reservoirs of the Aspinskoe and Sosnovskoe oil fields, where the thickness of the impermeable Timanian Horizon does not exceed 5–6 m. In places, the overlying clayey carbonates of the Sargaev Horizon serve as a cap for oil reservoirs in the Devonian terrigenous strata. For example, a 2 m thick oil reservoir underlying the compact rocks of the Timanian Horizon was discovered in the Dorokhovskoe field in the Timanian strata.

All HC fields of the study area can be divided into six types according to the relations between oil-saturated and water-saturated reservoirs in stratigraphic units (Fig. 4): (I) Hydrocarbon deposits are present in all strata; the Pashian and Givetian sediments form a single bed and have a common oil–water contact; (II) the Timanian reservoir is replaced by compact rocks, and oil is localized in the underlying Pashian and Givetian sediments; (III) the Timanian strata lack a reservoir, HC deposits are present only in the Pashian sediments, and the Givetian sediments are water-saturated; (IV) HC deposits in the Timanian and Pashian sediments are not related to each other; the Pashian sediments usually contain lenses, and the underlying bed is water-saturated; (V) oil

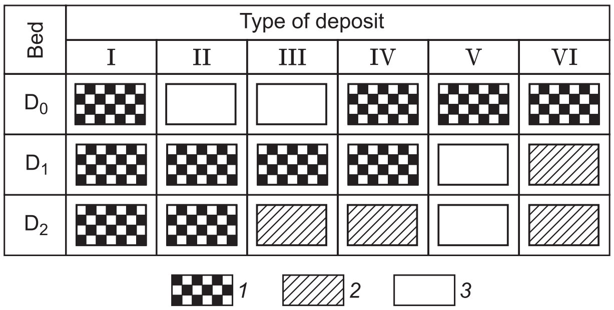


**Fig. 4.** Correlation between oil-saturated and water-saturated reservoirs in stratigraphic units. *1*, oil-saturated reservoir; *2*, water-saturated reservoir; *3*, replacement of the reservoir by compact rocks.

is localized only in the Timanian sediments, because the reservoir in the underlying sediments is replaced by compact rocks; (VI) oil is present only in the Timanian sediments, and the underlying reservoirs are water-saturated. Fields of types IV and VI are the most common.

All HC fields in the Devonian terrigenous strata have a complex structure, always with reservoir replacement or tectonic dislocations and with few meters thick oil-saturated beds.

## A PETROLEUM PRESENCE MODEL FOR THE DEVONIAN TERRIGENOUS SYSTEM

An oil system comprises petroleum source formations, reservoir rocks, seals, and migration paths. Formation of the Devonian terrigenous petroleum system began in the early Emsian, when sediments accumulated mostly in continental and seashore environments unfavorable for OM burial. Source formations gave rise to HC reservoirs in the Devonian terrigenous strata and began to accumulate in the late Timanian; this process lasted throughout the Late Devonian and part of the Tournaisian. The source formations of the Sargaev and Domanik horizons exerted a decisive influence on the accumulation of HC reservoirs in the Devonian terrigenous petroleum system. Generation of oil in source formations and its primary and secondary migration began at the end of the early Permian (the so-called “critical moment”) and continued until the area uplifting, when seals had already formed. Structural and nonstructural traps formed before oil generation processes, which favored the formation of oil reservoirs in the future.

It has been established that most of HC reservoirs formed in the Devonian terrigenous strata in the Perm Territory (mainly at the end of the early Permian) owing to the oil migration from the source formations of the Upper Devonian–Tournaisian petroleum system to the underlying reservoirs (Fig. 5). This is evidenced by the fact that the reservoirs of the Timanian bed $D_0$ located directly beneath the source formations are oil-filled in 80% of the oil fields. The absence of oil from the bed $D_0$ in the Byrkinskoe, Moskud’inskoe, and other fields is due to the replacement of the Timanian reservoirs by compact rocks. Note that the seals of this bed often include Sargaev sediments containing domanikites. On the flanks of the axial zone of the KKDS, with the most intense oil generation in domanikites, all beds might be saturated with oil as a result of its downward mi-

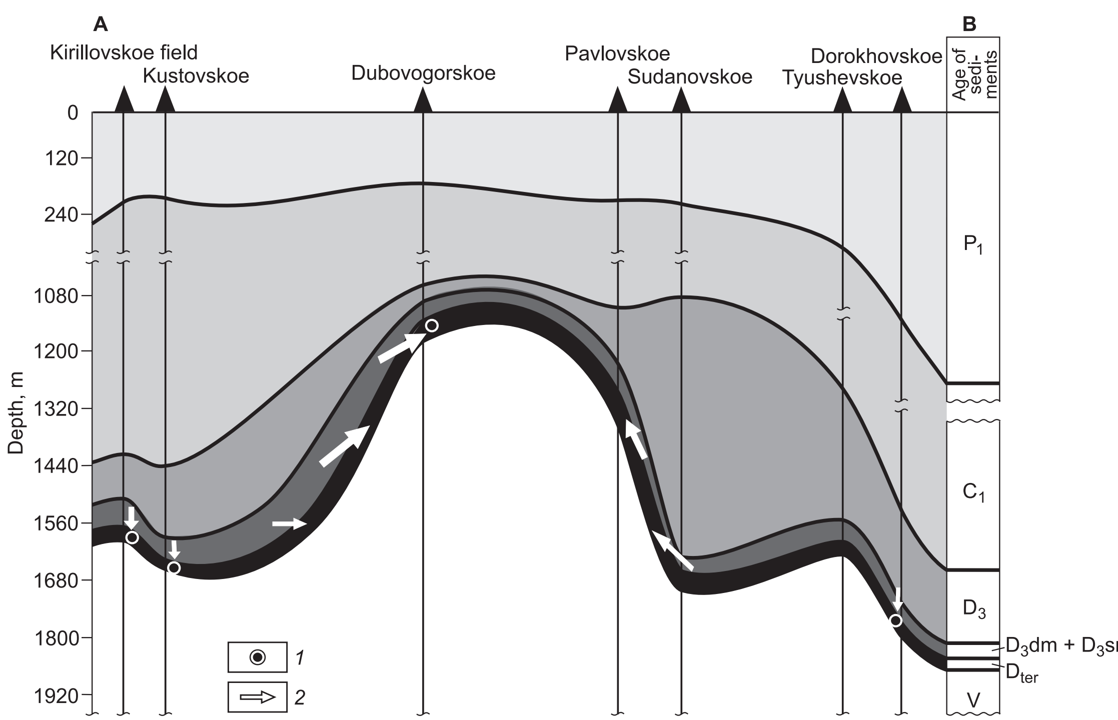


**Fig. 5.** A–B paleoprofile. *1*, HC deposits; *2*, probable HC migration paths; the position of the paleoprofile is shown in Fig. 1.

gration. When domanikites were located at a lower hypsometric position during the oil generation and accumulation, the lateral and sublateral oil migration was weaker, because reservoirs were replaced by compact rocks.

## CONCLUSIONS

The integrated approach to recognition of an oil system, used to study the hydrocarbon generation potential of the Devonian terrigenous petroleum system, is the most preferable in petroleum geology. It permits one to take into account the depositional environments, the type of organic matter, and the catagenesis stage.

Tracking of clay strata with a high TOC content in the Devonian terrigenous petroleum system has revealed their uneven distribution throughout the area and the section. They are most widespread in the Timanian sediments. The maximum TOC values are found in sediment samples in the north (in the vicinity of the town of Solikamsk) and in the central part of the Perm Territory.

The estimated HC generation potential of the Devonian terrigenous petroleum system indicates the presence of petroleum source formations in the terrigenous strata, but the organic matter in the study area is of low catagenesis grade and thus did not generate oils in the amount sufficient to form commercial reservoirs. According to the pyrolytic parameters $S_1$ (micro-oil content) and $S_2$ (residual oil potential) determined by the Rock-Eval technique, most of the studied clayey rocks are not *oil* source rocks. The total oil potential ($S_1 + S_2$) of the sediments is low (<1.0 mg HC/g rock). Higher $S_1 + S_2$ values have been established for Givetian mudstones in one of the wells. The hydrogen index (HI), which characterizes the residual oil potential, is also low (mainly <200 mg HC/g TOC). Thus, the Rock-Eval data confirm the established low HC generation potential of the source rocks.

The low oil migration density and the correlation between the geochemical parameters of oils and OM bitumens of the Devonian terrigenous strata indicate no relationship between the oils and the OM of the host rocks. Moreover, the correlation between the oils of the studied petroleum system and the oils of the Upper Devonian–Tournaisian system points to their single OM source with a predominance of a sapropelic component.

Based on the research results, we have established that the oil deposits in the studied Devonian terrigenous strata area could not have formed from the OM of these sediments or through the vertical oil migration from the underlying Riphean–Vendian sediments. However, there are no grounds to reject the probability of discovering new oil deposits in the Devonian terrigenous strata, because we have established a genetic relationship between the oils of the studied petroleum system and the oils of the Upper Devonian–Tournaisian system. Note that most of the HC deposits in the Devonian terrigenous strata are accompanied by HC deposits in the overlying Devonian–Carboniferous systems; this fact can serve as an oil search criterion but only in reef structure zones. Therefore, exploratory works must be planned with focus on studying Devonian terrigenous sediments in areas where HC reservoirs exist in the overlying petroleum system. The Devonian terrigenous strata of the axial zone of the Kama–Kinel' depression system are also oil-promising.

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