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Reconstruction of Paleogeochemical Data from the Riphean-Vendian Sediments of the Vychegda Depression of the Volga-Ural Oil and Gas Province

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Реконструкция палеогеохимических данных рифей-вендских отложений Вычегодского прогиба Волго-Уральской нефтегазоносной провинции

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Vychegda Depression, Riphean and Vendian sediments, pyrolytic data, paleogeochemical data, reconstruction, source rocks, generation potential, organic matter.

Reconstruction of paleogeochemical data is one of the important stages in of oil and gas content forecast and modeling of sedimentary basins. The present research is devoted to reconstruction of paleogeochemical data of the Riphean-Vendian source rocks of the Vychegda Depression, which occupies the territory of the northern Volga-Ural oil-and-gas province. Five oil-producing formations are traced in the studied area: Pez Formation RF_2pz, composed of argillites, siltstones and sandstones, Omen RF_3om and Nyafta RF_3nf Formations, of predominantly carbonate composition with interlayers of terrigenous sediments (argillites, sandstones, and siltstones), as well as the Ust-Pinega Formation V_2up and rocks of the Kudymkar Series V_2kd consisting of interbedded argillites, siltstones, and sandstones. Based on the analysis of the results of pyrolytic studies, it was established that the organic matter of the source rocks at the present stage is characterized by predominantly low values of the main geochemical parameters and high catagenetic transformation. Reconstruction of the paleogeochemical data included determination of the degree of realization of the initial generative potential by the source rocks, reconstruction of the paleo values of the hydrogen index, total organic carbon and generative potential. According to the results obtained, the Riphean-Vendian source rocks of the Vychegda Depression are enriched in the sapropelic (I/II) type of organic matter. The Pez, Omen and Nyafta formations of the Riphean have predominantly good and very good initial generative potential, while the initial potential of the Vendian sediments: Ust-Pinega Formation and Kudymkar Series is estimated as fair to very good. Initial generative potential of Riphean rocks is realized by 50-100 %, and Vendian – up to 60 %. The greatest perspectives of oil-and-gas content are connected with Vendian sediments. Riphean source rocks also have the ability to generate hydrocarbons, but in small volumes.

Ключевые слова:
Вычегодский прогиб, рифейские и вендские отложения, пиролитические данные, палеогеохимические данные, реконструкция, нефтематеринские породы, генерационный потенциал, органическое вещество.

Реконструкция палеогеохимических данных является одним из важных этапов при прогнозировании нефтегазоносности и моделировании осадочных бассейнов. Настоящая работа посвящена реконструкции палеогеохимических данных рифей-вендских нефтематеринских отложений Вычегодского прогиба, занимающего территорию севера Волго-Уральской нефтегазоносной провинции. На исследуемой территории прослеживаются пять нефтепроизводящих свит: пезская свита RF_2pz, сложенная аргиллитами, алевролитами и песчаниками, оменская RF_3om и няфтинская RF_3nf свиты, преимущественного карбонатного состава с прослоями терригенных отложений (аргиллитов, песчаников и алевролитов), а также усть-пинежская свита V_2up и породы кудымкарской серии V_2kd, состоящие из переслаивания аргиллитов, алевролитов и песчаников. На основании анализа результатов пиролитических исследований установлено, что органическое вещество нефтематеринских пород на современном этапе характеризуется преимущественно низкими значениями основных геохимических параметров и высокой катагенетической преобразованностью. Реконструкция палеогеохимических данных включала определение степени реализации нефтематеринскими породами исходного генерационного потенциала, восстановление палеозначений водородного индекса, общего органического углерода и генерационного потенциала. Согласно полученным результатам, рифей-вендские нефтематеринские породы Вычегодского прогиба обогащены сапропелевым (I/II) типом органического вещества. Пезская, оменская и няфтинская свиты рифея обладают преимущественно хорошим и очень хорошим исходным генерационным потенциалом, а начальный потенциал вендских образований: усть-пинежской свиты и кудымкарской серии оценивается от удовлетворительного до очень хорошего. Исходный потенциал рифейских пород реализован на 50–100 %, а вендских – до 60 %. Наибольшие перспективы нефтегазоносности связаны с вендскими отложения. Рифейские нефтематеринские породы также обладают способностью генерировать углеводороды, но в небольших объемах.

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Introduction

Tectonically, the Vychegda Depression is an ancient Proterozoic graben, a part of the Pre-Timan pericratonic Depression [1, 2]. Administratively, it extends across the northern territory of the Perm Krai and the southern part of the Komi Republic from the Polyudovo-Kolchimskoe uplift in the northwest for about 400 km, with a width of 50–120 km (Fig. 1) [3, 4] The structure involves deeply metamorphosed and crystalline Archean-Early Proterozoic basement, as well as sedimentary cover with a total thickness of up to 10,000-12,000 m [5], formed by carbonate-terrigenic sediments of the Riphean RF, terrigenous sediments of the Vendian V and terrigenous-carbonate sediments of the Upper Palaeozoic PZ_2 [6, 7], overlain by insignificant terrigenous strata of Mesozoic-Cenozoic MZ-KZ.

The Vychegda Depression is one of the least studied areas of the Volga-Urals oil and gas province. Prospecting and exploration carried out in the study area since the 1940s [8] did not allow to discover commercial hydrocarbon (HC) deposits. However, numerous wells have revealed various intensity of bitumen, oil and gas shows in the Upper Proterozoic and Upper Paleozoic sedimentary cover complexes [9-11].

The main object of interest is the Riphean-Vendian complex, which has a significant thickness of more than 7,000 metres. The problem of prospects for oil and gas bearing capacity of the ancient Riphean-Vendian deposits of the Vychegda Depression in terms of geology is studied in the works of O.K. Bazhenova [12-14], T.K. Bazhenova [15], V.G. Getsen [16], V.A. Dedeev [17], T.V. Karaseva [18], V.A. Koniukhova [19], D.A. Kuzmin [20]. In total, their works provide a basis for tracing a number of oil-producing strata of Riphean and Vendian age.

One of the main problems in oil and gas content forecast of Riphean and Vendian rocks is their significant catagenetic transformation [21-27] and, as a consequence, low values of the main geochemical parameters [28, 29] – the content of organic carbon (TOC, %) and hydrogen index (HI, mg HC/g TOC). To solve this problem, the procedure of restoration of palaeovalues of geochemical parameters of petroleum mother rocks at the beginning of HC generation is applied. Recovery of TOC and HI palaeovalues makes it possible to estimate the initial potential of rocks, to determine the genetic type of organic matter (OM), generation products and their volumes.

Reconstruction of palaeogeochemical data is an urgent task when forecasting oil and gas content of poorly studied areas using modern technologies (e.g., basin modelling).

Thus, the object of study is palaeogeochemical data of the Riphean-Vendian complex of the Vychegda Depression.

The aim of the study is to restore the initial values of the main geochemical parameters of oil source rocks.

Materials and research methodology

The work is based on the analysis of the results of pyrolytic studies of Riphean and Vendian deposits from the wells of the Vychegda basin. A total of 189 TOC measurements, 67 HI measurements, and 69 maximum hydrocarbon release temperatures during kerogen cracking (T_{max}, °C) were analyzed from 10 wells. The total volume of the actual material is presented in Table 1.

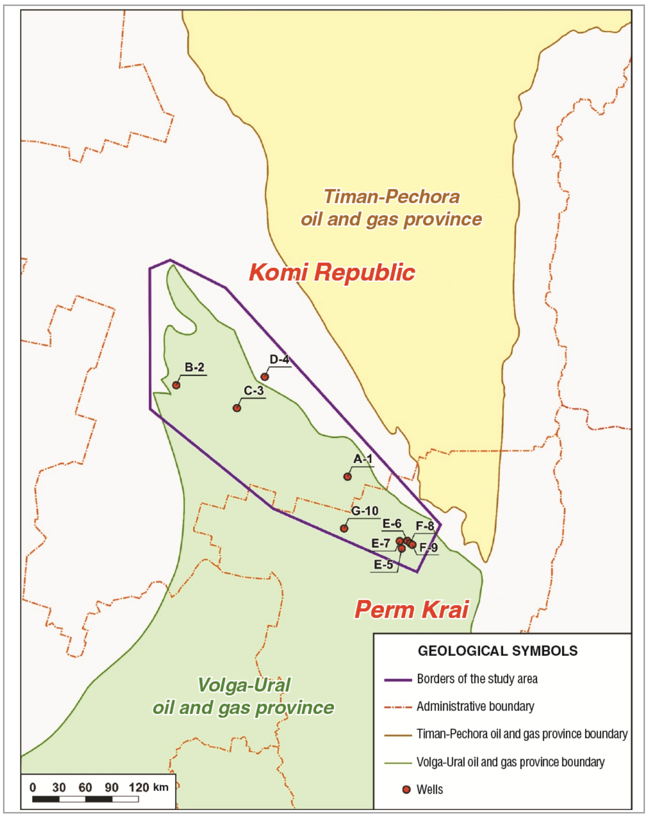

Fig. 1. Overview scheme of the study area

Table 1

Volume of actual pyrolysis data

Well	Number of determinations		
	TOC, %	HI, mg HC/g TOC	T_{max}, °C
A-1	64	29	31
B-2	23	5	5
C-3	31	12	12
D-4	3	3	3
E-4	1	1	1
E-6	5	5	5
E-7	4	4	4
F-8	1	1	1
F-9	7	7	7
G-10	9	-	-
Total	148	67	69

To determine the residual generation potential (S_1 + S_2, mg HC/g rock) of rocks, the results of their pyrolytic studies were analysed. During the analysis, the methodologies of McCarthy et al. [30] and Peters et al. [31, 32] were applied.

Initial values of the main generation characteristics of rocks: initial organic carbon content (TOC^0, %), hydrogen index value (HI^0, mg HC/g TOC) and HC potential (S_2^0, mg HC/g rock) can be calculated in different ways.

Domestic scientists: S.G. Neruchev (1998) [33] and T.K. Bazhenova et al. (1981) [34] developed methods according to which TOC^0 is calculated by multiplying the analytical content of TOC^x by the conversion factor for a given stage of catagenesis (Table 2). To perform the calculation, it is necessary to know the type of organic matter (OM) and to observe the conditions TOC^x > or < 0.50 %.

Table 2

Values of conversion coefficients from residual TOC^x to initial

Catagenesis grades	Methodology			
	Neruchev S.G. (1998)		Bazhenova T.K et al (1981)	
	Saropelic OM	Humus OM	$TOC^x > 0.50$ %	$TOC^x < 0.50$ %
PC_3	$1.03 \cdot TOC^x$	$1.08 \cdot TOC^x$	$1.02 \cdot TOC^x$	$1.05 \cdot TOC^x$
MC_1	$1.14 \cdot TOC^x$	$1.03 \cdot TOC^x$	$1.10–1.30 \cdot TOC^x$	$1.09–1.23 \cdot TOC^x$
MC_2	$1.43 \cdot TOC^x$	$1.10 \cdot TOC^x$	$1.53–1.94 \cdot TOC^x$	$1.44–1.70 \cdot TOC^x$
MC_3	$2.32 \cdot TOC^x$	$1.19 \cdot TOC^x$	$2.35 \cdot TOC^x$	$1.89 \cdot TOC^x$
MC_4	$2.66 \cdot TOC^x$	$1.21 \cdot TOC^x$	$2.43 \cdot TOC^x$	$1.90 \cdot TOC^x$
MC_5	–	$1.22 \cdot TOC^x$	$2.50 \cdot TOC^x$	$1.98 \cdot TOC^x$
AC_1	$3.01 \cdot TOC^x$	$1.23 \cdot TOC^x$	$2.56–2.75 \cdot TOC^x$	$2.00–2.08 \cdot TOC^x$
AC_2	$3.16 \cdot TOC^x$	$1.26 \cdot TOC^x$	″–″ · ″–″	″–″ · ″–″
AC_3	$3.23 \cdot TOC^x$	$1.31 \cdot TOC^x$	″–″ · ″–″	″–″ · ″–″
AC_4	$3.26 \cdot TOC^x$	$1.33 \cdot TOC^x$	″–″ · ″–″	″–″ · ″–″
Graphite	$3.27 \cdot TOC^x$	$1.43 \cdot TOC^x$	$2.85 \cdot TOC^x$	$2.20 \cdot TOC^x$

HI^0 is usually restored using a modified Van Krevelen diagram (HI dependence on T_{max}) – based on the trend depending on the type of organic matter (OM) [35]. In addition, an empirical formula presented in the work of B.Yu. Kerimov et al. (2019) is often used [36].

Among the foreign methods for assessing the initial values of the rock generation parameters, the most widely used are the methods of Peters et al. (1996, 2007) [37, 38], Jarvie et al. (2007, 2012) [39, 40], Chen and Jiang (2016) [41], Pelet (1985) [42], and Banerjee et al. (1998) [43]. Together, their methods include the calculation of TOC^0, HI^0 and S_2^0, as well as the transformation coefficient (TR, fractions of a unit or %), which shows the amount of OM already converted into HC.

In this work, HI^0 was reconstructed using the empirical formula proposed in the work of Kerimov et al. Pyrolytic data are used to calculate the initial value – the analytical value of the hydrogen index (HI^x) and T_{max}. The formula for calculating HI^0 (1) is:

$$HI^0 = HI^x + \frac{HI^x \cdot (T_{max} - 430)}{30}, \qquad (1)$$

where HI^0 is the initial hydrogen index (before the start of the HC generation process), mg HC/g TOC; HI^x is the analytical value of the hydrogen index, mg HC/g TOC; T_{max} is the temperature of the maximum HC yield during kerogen cracking, °C; 430 is the temperature at the start of HC generation, °C.

Several methodologies from previously mentioned were used to restore TOC^0:

1. The restoration of TOC^0 samples for which only the analytical values of total organic carbon (TOC_x) are known from geochemical studies was carried out using the methodology developed by S.G. Neruchev

2. The recovery of TOC^0 samples, for which the entire set of analytical data obtained by the Rock-Eval pyrolysis method is known from the results of geochemical studies, was carried out in two stages:

a) at the first stage, with known HI^x and HI^0, according to the formula Pelet(2), TR was calculated:

$$TR = \frac{(HI^0 - HI^x)}{HI^0} \cdot \frac{1200}{\left(1200 - HI^x\right)}, \qquad (2)$$

where TR (transformation ratio) is the degree to which the oil and gas source rock realizes its initial generation potential, fractions of units; HI^0 is the initial hydrogen index (before the start of HC generation), mg HC/g TOC; HI^x is the analytical value of the hydrogen index, mg HC/g TOC; 1200 is the coefficient with the amount of HC formed per unit mass of organic carbon, mg HC/g TOC;

b) at the second stage, with the obtained value of TR, TOC^0 was determined according to formula (3) developed by C. Peters et al.:

$$TOC^0 = \frac{83{,}33 \cdot HI^0 \cdot TOC^x}{HI^0 \cdot \left(1 - TR\right) \cdot (83{,}33 - TOC^x) + (HI^x \cdot TOC^x)}, \qquad (3)$$

where TOC^0 is the initial TOC content (before the start of HC generation), %; TOC^x is the analytical content of organic carbon, %; HI^0 is the initial hydrogen index, mg HC/g TOC; HI^x is the analytical value of the hydrogen index, mg HC/g TOC; TR (transformation ratio) is the degree to which the oil and gas source rock realizes its initial generation potential, fractions of units; 83.33 is the average percentage content of carbon in the generated hydrocarbons.

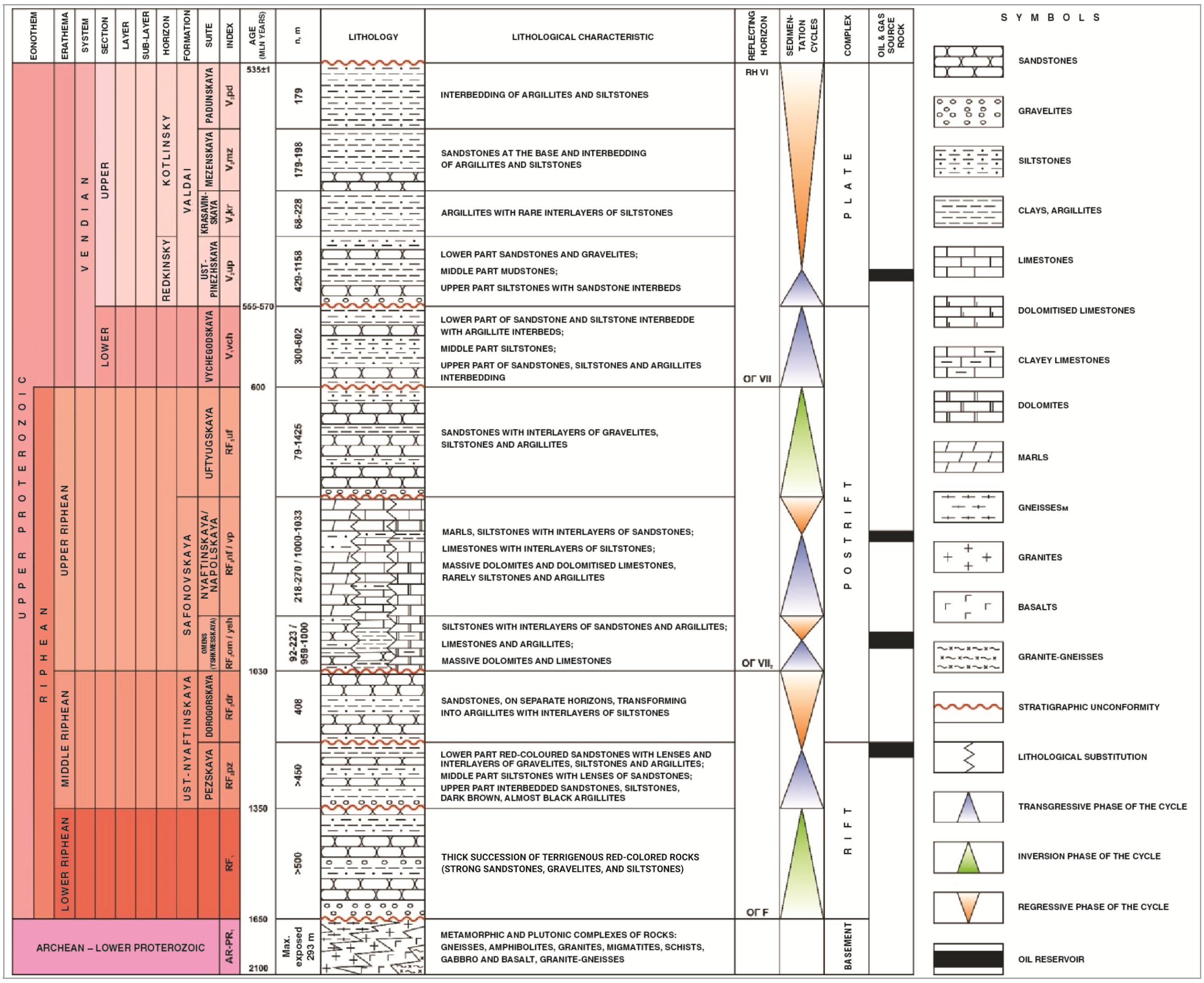

Fig. 2. Composite lithological-stratigraphic section of the Riphean-Vendian deposits of the Vychegda depression

S_2^0 is calculated using formula (4) [44, 45]:

$$S_2^0 = \frac{TOC^0 \cdot HI^0}{100}, \quad (4)$$

where S_2^0 is the initial potential, mg HC/g of rock; TOC^0 – initial organic carbon content, %; HI^0 – initial hydrogen index, mg HC/g TOC.

Oil-bearing formations and their geological-geochemical characteristics

In the Riphean-Vendian complex of the Vychegda depression, a number of oil-producing strata can be observed according to the available geological and geochemical data: the Pezskaya formation RF_2pz, the Omen formation RF_3om, the Nyaftinskaya formation RF_3nf, the Ust-Pinezhskaya formation V_2up (Fig. 2) and the rocks of the Kudymkar series V_2kd.

The Pezskaya formation RF_2pz of the Middle Riphean is formed of a red-gray layer of interbedded argillites, siltstones and sandstones (insoluble residue (IR) – 85.42–95.00 %) with a total thickness of 447 m (well C-3). The lower part of the section is represented by red-colored oligomictic coarse-grained sandstones with lenses and interlayers of angular, rounded gravelstones, transitioning upward into aleurolites and argillites. The cement is predominantly clayey or chlorite-muscovite. The middle part of the formation is formed of siltstones with sandstone lenses. The upper part is represented by interbedded sandstones, siltstones and argillites. Sandstones and siltstones are oligomictic coarse-grained, dark and light gray, and display horizontal, oblique, and lens-like bedding. Argillites are dark grey, brown and black with horizontal and wavy bedded. The cement is clayey.

According to the results of pyrolytic studies of the dark-colored argillites in the upper part of the Pezskaya Formation, the total organic carbon (TOC) ranges from 0.14 % to 0.93 % (with an average of 0.29 %). The organic matter is classified as "mature" to "overmature" (T_{max} – 449–535 °C). The samples exhibit low S_1 (0.02–0.18 mg HC/g rock) and S_2 (0.06–0.50 mg HC/g rock) values, but overall, the rocks have a satisfactory generation potential with $S_1 + S_2$ (0.20–0.54 mg HC/g rock) (Fig. 3, *a*). The hydrogen index (HI) ranges from 35 to 208 mg HC/g TOC, and the productivity index (PI) ranges from 0.09 to 0.43, jointly indicating a complete and/or partial realization of the potential.

The Omen (Yshkmeskaya) formation RF_3om (ysh) of the Upper Riphean with a thickness from 92-223 (wells B-2 and C-3) to 960 m (well A-1) consists of a terrigenous-carbonate strata (IR – 16.00–94.30 %), represented by light gray, dark gray and brownish,

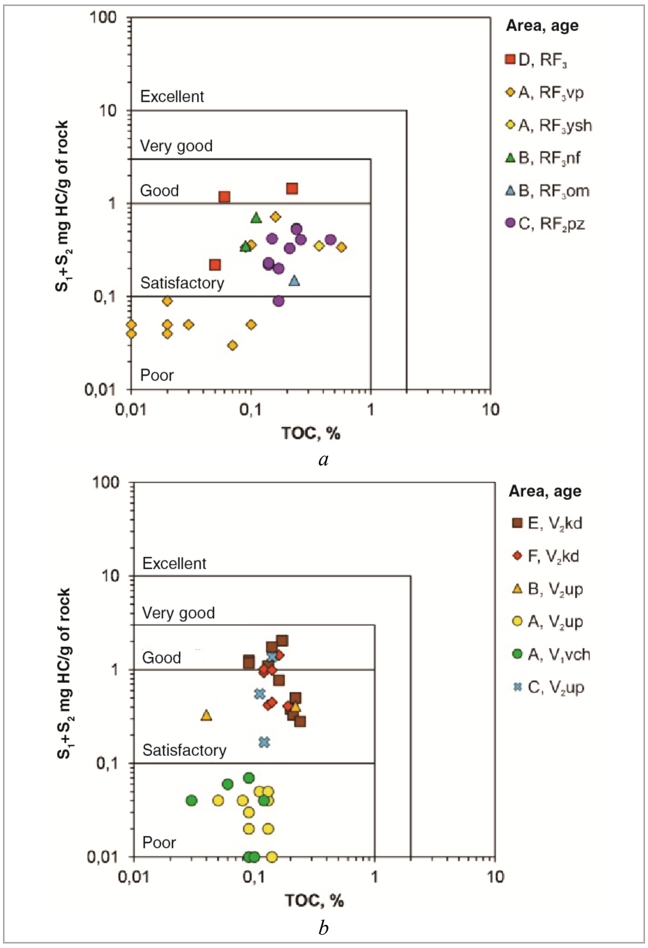

Fig. 3. Residual generation potential of rocks: *a* – Riphean (formations: RF_2pz – Pezskaya, RF_3om – Omen, RF_3nf – Nyaftinskaya, RF*3*ysh – Ishkmeskaya, RF_3vp – Vapolskaya); *b* – Vendian (formations: V_1vch – Vychegodskaya, V_2up – Ust-Pinezhskaya; formations: V_2kd – Kudymkarskaya)

finely crystalline or pelitomorphic layered and microrhythmically layered, medium-coarse-grained dolomites and limestones, sometimes clayey, with thin interlayers of red-dark-colored siltstones, mudstones and sandstones, with inclusions of anhydrite. Sandstones and siltstones are oligomictic, fine-grained, unsorted, calcareous mudstones are dark gray, and almost black. Cement is clayey or carbonate. The textures of the rocks are wavy- and lenticular-layered.

Pyrolytic analysis of argillites and clayey limestones showed that the Omen formation corresponds to TOC contents of 0.02–1.50 % (average 0.28 %) and high transformation of rock OM (T_{max} up to 486 °C). The S_1 and S_2 values are low (0.01–0.09 and 0.3–0.34 mg HC/g of rock) and together indicate significant depletion of the rock potential $S_1 + S_2$ – 0.07–0.35 mg HC/g of rock (see Fig. 3, *a*), which is also confirmed by the extremely low HI values (up to 92 mg HC/g TOC) and high PI (on average 0.56).

The Nyaftinskaya (Vapolskaya) formation RF_3nf (vp) of the Upper Riphean with a thickness from 218–270 (wells B-2 and C-3) to 1033 m (well A-1) is composed of a terrigenous-carbonate sequence (HO – 4.66–63.00 %). Limestones and dolomites are massive stromatolitic crystalline or pelitomorphic from red-colored, light gray to dark gray, dark brown, horizontally-, wavy-layered, weakly clayey, pyritized, with interlayers of schistose marls. Argillites are dark brown micaceous glauconite-containing, siltstones are dark-colored calcareous. Monomictic sandstones are medium- and coarse-grained, gray or light gray with sulfate and carbonate cement.

According to the results of argillites and clayey limestones pyrolysis, the TOC content in the Nyaftinskaya formation varies from 0.01 to 1.50 (average 0.20 %). The organic matter of the rocks is catagenetically "mature" and "overmature" (T_{max} up to 495 °C).

The parameters S_1 and S_2 are low (0.01–0.22 and 0.02–0.62 mg HC/g of rock), but in some units with elevated TOC concentrations, the generation potential of S_1+S_2 is satisfactory (up to 0.72 mg HC/g of rock) (see Fig. 3, *a*). HI – 29–564 mg HC/g TOC and PI – 0.13–0.56 indicate that some rocks have exhausted their potential, while others, with elevated $S_1 + S_2$ and TOC, are capable of generating HC in small quantities.

The Ust'-Pinezhskaya formation V_2up of the Redkinsky horizon of the Upper Vendian is composed of interbedded argillites, siltstones and sandstones (IR – 80.00-95.00 %) with a total thickness of 429-482 (wells A-1, B-2) to 1158 m (well C-3). Argillites are greenish-gray, dark gray, less often dark brown, horizontally layered, thinly platy, calcareous. Siltstones are greenish-gray or brownish, sometimes strongly calcareous. Sandstones are from fine- to coarse-grained, greenish-gray or brownish-gray, horizontally layered, oligomictic or polymictic, with lenticular interlayers of gravelites. Interlayers of basaltic tuffs of greenish-gray color are found. The cement is carbonate or clayey. Sometimes the rocks contain a small amount of authigenic glauconite.

Pyrolytic studies of the Ust-Pinezhskaya fprmation argillites showed that the rocks have TOC contents of 0.02–0.82 % (average 0.14 %) and are located mainly in the "oil window" (T_{max} – 432–466 °C). The S_1 (0.01–0.71 mg HC/g rock) and S_2 (0.01–0.68 mg HC/g rock) values are low, however, the rocks in wells C-3 and B-2 have satisfactory and good potential $S_1 + S_2$ – 0.33–1.39 mg HC/g of rock (see Fig. 3, *b*). The HI values are 100–725 mg HC/g TOC (average 365 mg HC/g TOC) and PI – 0.12–0.51 (on average 0.27) indicate a slight depletion of the potential and ability of rocks to generate hydrocarbons.

In the south-eastern part of the Vychegda Depression according to the results of lithological and petrographic studies of rocks from wells E-4, E-6, E-7, F-8, F-9 and G-10, the Upper Vendian formations are subdivided into the Borodulinskaya V_2br and Kudymkarskaya V_2kd series. The Borodulinskaya series corresponds to the Redkinsky biostratigraphic horizon, the Kudymkarskaya series – to the Kotlinsky one. The rocks are represented by interbedded mudstones, siltstones and sandstones (HO – 84.44–95.60 %) with a total thickness of up to 1500 m. The Borodulinskaya formation is composed of dark gray, greenish-gray, chocolate-brown, micaceous, thin-layered mudstones with numerous interlayers of gray fine-grained calcareous sandstones and siltstones. The Kudymkar series is made up of brownish-green and brownish-gray siltstones and fine-grained sandstones, with interlayers and rare beds of chocolate-brown argillites.

Analysis of the Upper Vendian argillites pyrolysis in the south-eastern Vychegda depression showed that the TOC content varies in the range of 0.09–0.59 % (on average 0.18 %). The rocks are located in the main oil generation zone (MOZ), which is confirmed by the T_{max} value of 433–454 °C. The argillites of this series have higher S_1 (0.03–0.99 mg HC/g rock) and S_2 (0.13–1.51 mg HC/g of rock) values compared to the Ust-Pinezhskaya formation which allows them to be classified as rocks with satisfactory and good potential (S_1 + S_2 – 0.28–2.04 mg HC/g of rock) (see Fig. 3, *b*). HI fluctuates in the range 58–1080 mg HC/g TOC (average 366 mg HC/g TOC), PI – 0.07–0.86 (on average 0.35), which is a characteristic of predominantly incomplete realization of potential. The rocks prove to have generating properties.

Thus, in total, 5 oil-producing levels can be observed in the Riphean-Vendian complex on the territory of the Vychegda depression, of which 3 are in the Riphean and 2 are in the Vendian formations. In general, the rocks have satisfactory and often good residual oil source potential. Restoration of paleogeochemical data will allow us to determine the initial generation potential of the rocks, which is more reliable in oil and gas potential forecast.

Reconstruction results of paleogeochemical data

Based on the methodologies outlined above, results were obtained for the reconstruction of initial values of TOC and HI for the Proterozoic oil-producing formations of the Vychegda depression.

The initial generation potential of the Omen Formation is characterized by a TR of 59–89 %. The rocks at the beginning of their entry into the oil generation zone had TOC^0 values ranging from 0.32 % to 2.56 %. The HI^0 values ranged from 209 to 675 mg HC/g TOC (with an average of 440 mg HC/g TOC), which are typical for sapropelic (Type II) organic matter, a source for liquid hydrocarbons. The initial S_2^0 was found to be between 0.21 and 8.49 mg HC/g rock, corresponding mainly to rocks with good to very good potential.

The transformation degree of the OM in the Omen Formation is TR – 59–71 %. It was possible to establish that the rocks before the onset of hydrocarbon generation had initial TOC^0 – 0.13–3.99 % and HI^0 ~ 300 mg HC/g TOC. The deposits are enriched in sapropelic (II) type of OM and in general, they have a good initial generation potential of S_2^0 – 0.39–3.44 (on average 1.92) mg HC/g of rock (Fig. 4, *a*).

The development degree of the TR potential of the Nyaftinskaya Formation varies from 50 to 100 %. (on average 70 %). Based on the data obtained, the rocks upon entering the MOZ had initial TOC^0 values of 0.14–3.99 % and HI^0 values of 340–730 mg HC/g TOC, which indicates the sapropelic (I/II) type of OM and the ability of sediments to generate liquid HC. S_2^0 is equal to 0.29–5.12 mg HC/g of rock, i.e. the rocks had satisfactory, good and very good initial potential (see Fig. 4, *a*).

The actual realization of the initial oil source potential of the Ust-Pinezhskaya formation is TR = 9–51 %. The paleovalues at the beginning of hydrocarbon generation were TOC^0 – 0.11–0.93 % and HI^0 – 533–785 mg HC/g TOC. The OM of the rocks is represented by the sapropel (I/II) type. The initial potential is low compared

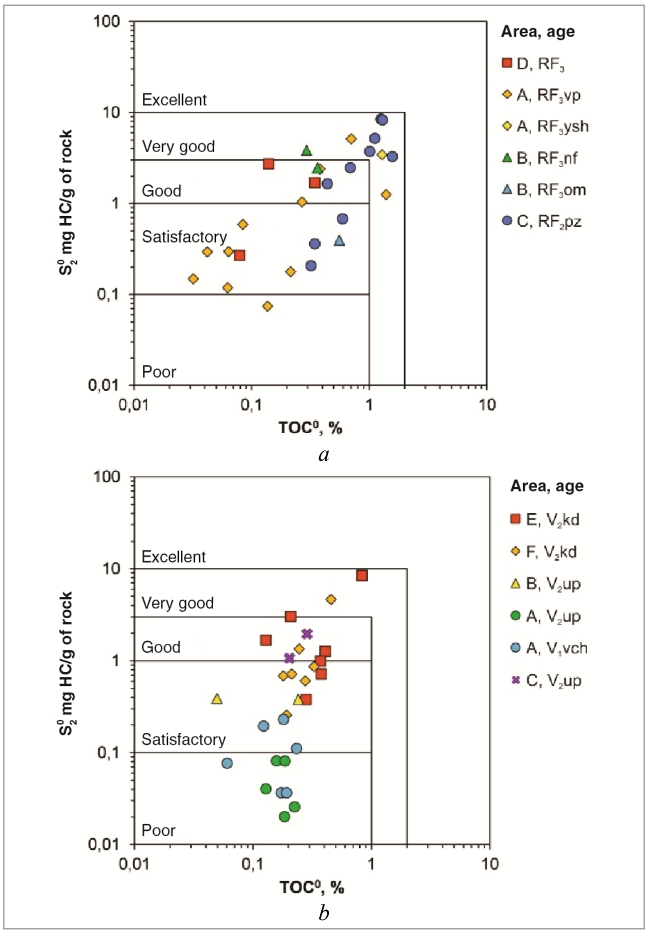

Fig. 4. Initial generation potential of rocks: *a* – Riphean; *b* – Vendian (for the names of the formation see Fig. 3)

to other suites S_2^0 – 0.38–1.98 mg HC/g of rock and is generally satisfactory and good (Fig. 4, *b*).

As for the Upper Vendian formations in the southeastern part of the Vychegda depression, the degree of depletion of their generation potential TR – 10–59 %, initial TOC^0 content – 0.13–0.83 % and initial value of hydrogen index HI^0 ~ 574 mg HC/g TOC are identical to those of Ust-Pinezhskaya Formation. However, most HI^0 values are > 600 mg HC/g TOC, which is typical of type I OM. The deposits have a higher initial oil source potential compared to the Ust-Pinezhskaya Formation. The S_2^0 index is 0.26–8.47 mg HC/g rock, which corresponds mainly to rocks with good and very good potential (see Fig. 4, *b*).

Figures 5-6 present the dependancy of the entire set of calculated paleogeochemical data for TOC^0 and HI^0 on their analytical values, separately for the Riphean and Vendian deposits.

The relationship between TOC^x and TOC^0 for both Riphean and Vendian rocks is reliable, which is confirmed by the correlation coefficients equal to R = 0.9762 and R = 0.8422 respectively. Relationship between HI^x and HI^0 for Riphean and Vendian deposits also strong, as indicated by high correlation coefficients (R = 0.9545 and R = 0.9923).

Thus, with the analytical values of TOC^x and HI^x, one can confidently use the obtained equations to calculate TOC^0 and HI^0 for the Proterozoic rocks of the Vychegda depression.

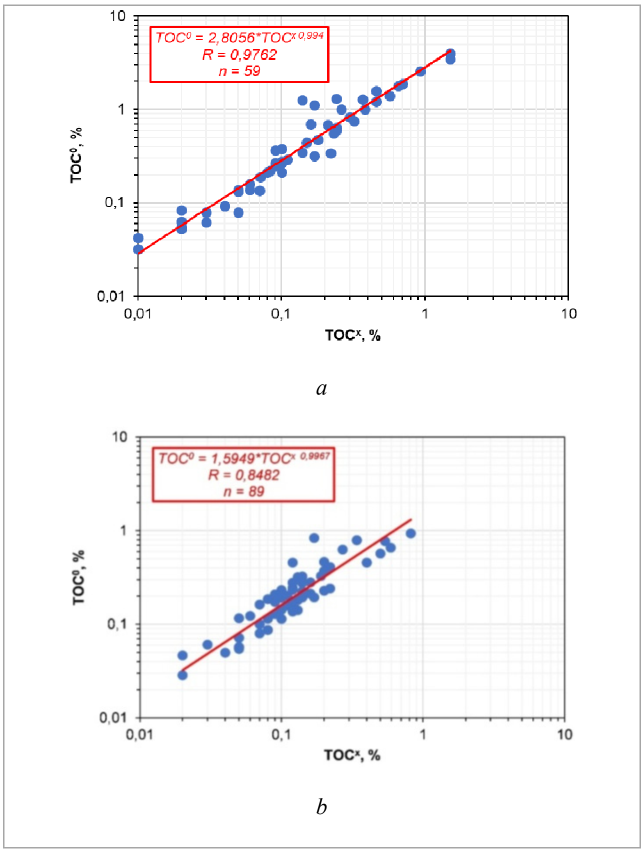

Fig. 5. Relationship between TOC^x and TOC^0 of rocks:
a – Riphean; *b* – Vendian

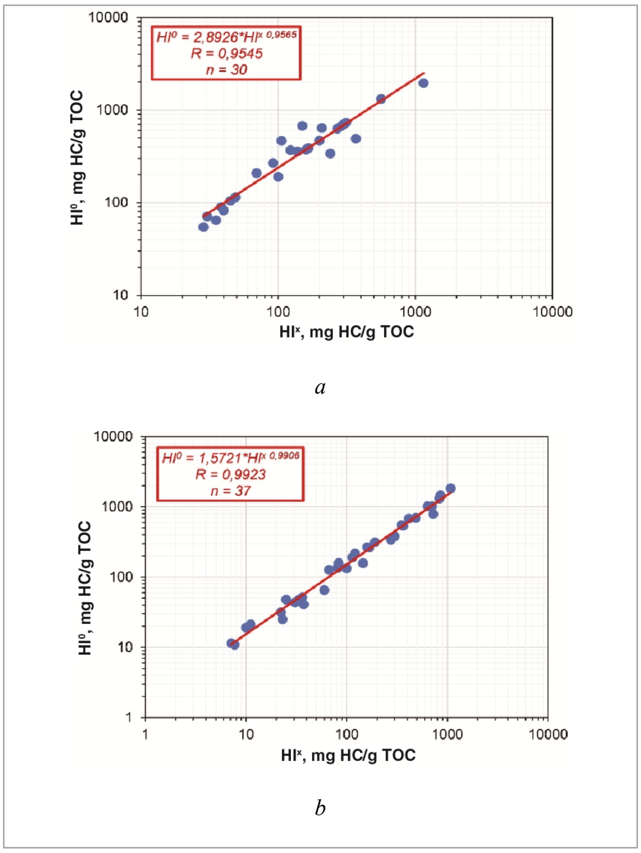

Fig. 6. Relationship between HI^x and HI^0 of rocks:
a – Riphean; *b* – Vendian

Conclusion

Thus, from the analysis of the actual material and the reconstruction of paleogeochemical data for the Riphean-Vendian deposits of the Vychegda depression, the following conclusions can be drawn.

In the study area, five oil-producing levels are identified within the Riphean-Vendian complex: dark-colored argillites of the Pezskaya formation from the Middle Riphean, dark-colored argillites and clayey limestones of the Omen and Nyaftinskaya formation from the Upper Riphean, as well as dark-colored argillites of the Ust-Pinezhskaya formation and the Kudymkar formation from the Upper Vendian. The organic matter (OM) of the oil-generating formation is assessed as "mature" and "overmature," while the residual potential of the rocks is predominantly satisfactory. The oil-generating potential of the Riphean rocks is realized at 50–100 %, while that of the Vendian rocks is at 9–59 %. The restored values of the hydrogen index allowed for the determination of the genetic type of the initial OM in the rocks as sapropelic (I/II). The initial generation potential of the Riphean rocks is predominantly good to very good, while that of the Vendian rocks ranges from satisfactory to very good.

Relationships between the restored values of TOC^0 and HI^0 and their analytical values TOC^x and HI^x have been established, and equations for calculating TOC^0 and HI^0 have been derived separately for Riphean and Vendian oil-generating rocks.

Overall, the relatively large thicknesses of the Riphean-Vendian deposits, high initial concentrations of organic carbon, and values of the hydrogen index suggest significant scales of hydrocarbon generation. The results obtained from the study are crucial in oil and gas potential forecast of the study area using the modern method of basin modeling.

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