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Features of changes in the physico-chemical properties of oils in connection with great depths

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Abstract. A study was made of changes in the physico-chemical properties and occurrence conditions of oils depending on the depth, which made it possible to clarify the quantitative patterns of changes in the physico-chemical properties of oils at different depths and to reveal features of the properties of poorly studied deep-seated oils. The studies used information on more than 21000 oil samples from 167 oil-bearing basins of the world, obtained from the database on the physico-chemical properties of oils. It has been shown that in different oil-bearing basins the density and viscosity of oils decreases with depth. The content of sulfur, resins and asphaltenes also decreases with depth, and the content of light fractions and oil gas increases. The features of the physico-chemical properties of deep-seated oils have been established, which are manifested in a decrease in the density and viscosity of oils, in a decrease in the content of sulfur and asphalt-resinous substances, and in an increase in the content of light fractions and oil gas. The results of geological modeling of changes in the stress state of rocks associated with the displacement of the foundation blocks due to tectonic processes are considered.

It has been shown that at the edges of the downing tectonic blocks at the boundary of the sedimentary cover and the basement, zones of minimum pressure (decompression zones) are formed. The lightest hydrocarbons migrate along the faults into the decompression zones, forming deep-seated hydrocarbon deposits, what can serve as a justification for the features of the properties of deep-seated oils established in the work.

Keywords: deep-seated oils, oil and gas basin, hydrocarbon deposits, database, physico-chemical properties of oil, occurrence conditions, geological modeling, decompression zones

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Introduction

In the coming years, the increase in oil production in our country will be provided mainly by hard-to-recover oils since the reserves of the most easily accessible oils are steadily depleted. It is known that the growth in the production of hard-to-reach oils in recent years makes it necessary to study the qualitative features of hard-to-recover oils. Deep-lying oils (DLO), due to the depletion of their reserves at shallow and medium depths, occupy a special place among hard-to-reach oils (Yashchenko, Polishchuk, 2014a).

The oil deposits located at depths greater than 4500 m are classified as deep-lying oils (Purtova et al., 2011; Ibraev, 2006; Lisovsky, Khalimov, 2009). Insufficient information on the low-permeability oil-reservoir rocks occurring at great depths complicates and slows down the development of resources in deeply buried sediments of oil and gas basins. Geological and geochemical factors for the formation of deep deposits remain the same as for the formation of hydrocarbon deposits in the upper level of rocks at shallow and medium depths, i.e. the presence of a trap, reservoir rocks, fluid seals, and favorable geochemical and hydrogeological characteristics of the section (Punanova, Shuster, 2018). However, the characteristics of these factors change with an increase in the depth of occurrence.

Geological conditions change also with increasing depth. One of the reasons for these drastic changes in geological conditions is a significant compaction of rocks at great depths under the overburden pressure. This leads to changes in the texture of rocks, formation fracturing and, in general, to changes in rock structure. The tectonic activity is increased at great depths, when compared with depths 2000–4000 m, which also determines a considerable difference in the structure of reservoir rocks and fluid seal rocks. Another reason for the significant differences in geological conditions at different depths is the change in the lithological composition of rocks. As a result, the permeability of rocks decreases with

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depth and the nature of the voids changes. Hence, the pore space turns into that pore fractured and then into the fissured-cavernous space. At the same time its open porosity significantly decreases.

Earlier, we have already considered the quality indicators of deep-seated oils (Yashchenko, Polishchuk, 2016b; Yashchenko, Polishchuk, 2019). It was also reported about the analysis of changes in the physicochemical properties of oils depending on the depth (Yashchenko, Polishchuk, 2014b; Polishchuk, Yashchenko, 2001; Yashchenko, 2019). However, their physical properties and characteristics of their chemical composition are understudied, which makes it harder to solve technological problems of both their production and refining under increasing production of deep-lying oils. On the other hand, insufficient information on the physical and chemical properties and conditions for the formation of deposits of such oils makes it difficult to assess the prospects and determine the directions of development of the domestic oil and gas production and petrochemical complexes. Therefore, the purposes of this work are to study the patterns of changes in the physicochemical properties of oils depending on the depth of their occurrence and to analyze the properties and conditions of formation of deep-lying oils.

Materials and Methods

The database (DB) on the physical and chemical properties of oil, developed at the Institute of Petroleum Chemistry SB RAS and described in the works of Yashchenko and Polishchuk served as an information basis for carrying out these studies (Yashchenko, Polishchuk, 2014a; Polishchuk et al., 2001). The distribution of information from the database by depth showed that shallow (up to 2000 m) and medium (2000–4500 m) depths of oil occurrence are represented in the database by samples with the largest sample size (11285 and 9314, respectively), while the number of deep-lying oil samples in the database is only 468 samples, that is, an order of magnitude less.

This tendency to reduction in the amount of information about oils with an increase in the depth of their occurrence is consistent with the well-known pattern of a decrease in oil reserves with depth. Hence, according to Purtova et al., at depths less than 3000 m, the volume of oil deposits is 46 % of oil and gas deposits, at depths deeper than 3000 m it is 37 %, at depths of 3600-4200 m – 30 %, at depths deeper than 4200 m – 18 %, and at depths exceeding 5800 m the volume of oil deposits is only 11 % (Purtova et al., 2011).

In addition, to study the patterns of changes in the physical and chemical properties of oils depending on the depth of their occurrence and to study the specific conditions for the formation of deep-lying oils, the materials on geological modeling of changes in the stress state of rocks due to the displacement of basement blocks resulted from tectonic processes were used (Glukhmanchuk et al., 2014; Yashchenko et al., 2019; Glukhmanchuk et al., 2015). The results of the geological modeling drawing on the example of Western Siberia make it possible to analyze the conditions for the formation of deeply buried deposits.

The results of studies carried out by Glukhmanchuk et al. made it possible to describe the fluid-dynamic model of the oil accumulation in the top of Paleozoic deposits in the following way (Glukhmanchuk et al. (2014). In the course of evolution of oil and gas reservoirs, oil-producing deposits enter the main phase of oil and gas generation, which resulted in the formation of primary hydrocarbon deposits in the sedimentary mantle.

The evolution of subsequent tectonic movements leads to a change in reservoir pressure in rock masses. Geological modeling of the stress state of rocks showed that zones of minimum pressure values, so-called decompression zones, are formed at the boundary of the sedimentary mantle and the basement at the edges of subsiding blocks (Glukhmanchuk et al., 2014). Therefore, the ongoing change in reservoir pressure initiates the movement of fluids, including hydrocarbons, into decompression zones, which could resulted in the creation of conditions for the formation of secondary hydrocarbon deposits in the basement. Further, we will consider this mechanism of the formation of oil deposits at great depths in more detail to discuss the results of the analysis of the physicochemical properties of oils and the conditions of their occurrence.

Results

Analysis of physical and chemical properties of oils of shallow and medium depths

The database used contains 20599 oil samples from 6485 oilfields of 168 oil and gas basins (OGB), occurring at shallow (up to 2000 m) and medium (2000–4500 m) depths (Yashchenko, Polishchuk, 2016). Oils from depths greater than 4500 m are represented in the database by a significantly smaller number of samples (468) from 214 deposits of 26 oil and gas basins. The results of the analysis of the patterns of changes in the physicochemical properties of oils of shallow and medium depths depending on the depth of deposits are given in Table 1.

As you can see from Table 1, the heaviest and most viscous oils occur mainly at depths up to 1000 m. With increasing depth, they tend to exhibit a decrease in the average density to 0.8330 g/cm^3 and in the average viscosity to 66 mm^2/s at depths close to 4500 m. The oils occurring at shallow depths (up to 2000 m), can, on average, be classified as sulphurous, resinous, medium-asphaltene, medium-paraffinic oils, and those with a low gas saturation (Yashchenko, Polishchuk, 2016).

Physical and chemical indicators	Depth of occurrence, m			
	0-1000	1000-2000	2000-3000	3000-4500
Density, g/cm^3	0.9024	0.8660	0.8389	0.8330
Viscosity at 20 °C, mm^2/s	3127.84	318.00	117.31	66.28
Sulfur content, wt%	1.35	1.39	0.71	0.45
Paraffin content, wt%	3.14	4.66	5.43	9.86
Resin content, wt%	15.53	12.91	6.98	6.43
Asphaltene content, wt%	4.40	3.68	1.94	1.93
Fraction, i.b.p. 200 °C, wt%	13.35	23.79	27.30	26.72
Fraction, i.b.p. 300 °C, wt%	30.00	42.62	47.26	48.21
Fraction, i.b.p. 350 °C, wt%	35.39	48.84	55.23	56.14
Gas content, m^3/t	65.10	78.00	124.37	249.68

Table 1. Physical and chemical properties of oils occurring at shallow and medium depths

The content of sulfur, resins, and asphaltenes decreases with increasing depth to 4500 m, while the content of diesel fractions, paraffins, and petroleum gases mainly increases with depth.

The patterns of changes in the properties of oils with an increase in the depth of occurrence were established according to data from Table 1. These patterns are valid both for oils of all oil and gas bearing basins of the world and for oils of individual OGBs. It suffices here to refer to the results of a study of trends to changes in properties of oils of Western Siberia with increasing depth. These results are based on analysis of data on the physical and chemical properties of West Siberian oils occurred at shallow and medium depths (Table 2).

It is seen in Table 2 that similarly to the trends of variation in the global average properties of oils, the density, the viscosity, and the content of sulfur and resins decrease with increasing depth, while the content of paraffin, diesel fractions, and oil gas increases (Table 1). Note that, in contrast to the changes in physicochemical indicators for the global average properties of oils, the tendency for a decrease/increase in the physicochemical indicators of oils of Western Siberia with increasing depth is manifested to a lesser extent. Hence, in passing from shallow depths to medium depths the range of changes in these indicators generally does not exceed 5–10 %.

Analysis of physical and chemical properties of deep-seated oils

An analysis of the peculiarities of the mode of occurrence of oils at different depths was carried out. Table 3 shows data on changes in reservoir temperature and pressure, porosity and permeability of reservoirs at different depths according to data from the database. As you can see from Table 3, the reservoir temperature and pressure, on average, significantly (by several times) increase with depth, while the porosity and permeability of the reservoirs significantly decrease (by 1.6 times and by 2 orders of magnitude, respectively). A decrease in porosity and permeability of rocks under conditions of increased reservoir temperature and pressure suggests the possible problems (technological, environmental, etc.) in the development of deep-lying oil resources (DLO) at great depths exceeding 4500 m.

Figure 1 shows a schematic diagram of the location of oil and gas bearing basins, including the basins with DLO. The most of such oil fields are located in the Perth basin, the Gulf of Mexico basin and in the Tarim OGB. The following fields are distinguished by the deepest wells: Khalakhatang (6640–7070 m), Tuoputai (6400–6750 m) and Aiding (6140–6330 m) of the Tarim Basin, Medicine River (6300–6980 m) and Crossfield (6733 m) of the West Canadian Basin, Shakh Deniz (6500–6688 m) of the South Caspian Basin, Gomes (6050–7022 m), and Linterna (6560 m) of the Permian Basin.

The analysis of the distribution of the deep-seated oils under study by the age of the rocks has been carried out. It has been established that most of the considered DLO sample are Paleozoic oils (more than 53 %), while 1/3 of deep-lying oils are located in Mesozoic sediments and about 14 % – in Cenozoic sediments.

In Russia, hydrocarbon deposits at great depths are typical mainly for the West Siberian and North Caucasian OGBs. In Fig. 2 and 3 are depicted the maps of location of the DLO fields in the West Siberian and North Caucasian oil and gas bearing basins, including 33 and 35 DLO fields, respectively. These are such oilfields as Geologicheskoye (5750 m), Lukyavinskoye (5664 m), Urengoyskoye (5520 m), En-Yakhinskoye (5200–5500 m) and Samburgskoye (5480 m) in the West Siberian oil and gas basin (Fig. 2) and Khankalskoye (5800 m), Novolakskoye (5650 m), Andreevskoye (5600 m), and Samurskoye (5480 m) in the North Caucasian basin (Fig. 3). The wells with the depth interval of 4520–5090 m are drilled in the Vostochno-Sarutayuskoye, Vuktylskoye, and Kozlayuskoye oil fields of the Timan-Pechora basin. In the Volga-Ural oil and gas basin, deep wells are located at the Antipovsko-Balykleyskoye, Zaykinskoye, Zorinskoye,

Physical and chemical indicators	Shallow oils (up to 2000 m)		Medium oils (2000-4500 m)	
	Sample size	Average value	Sample size	Average value
Density, g/cm^3	517	0.8531	2033	0.8373
Viscosity at 20 °C, mm^2/s	163	28.76	764	17.68
Sulfur content, wt%	401	0.52	1694	0.61
Paraffin content, wt%	405	3.58	1480	4.87
Resin content, wt%	365	6.60	1328	5.84
Asphaltene content, wt%	339	1.38	1136	1.48
Fraction, i.b.p. 200 °C, wt%	65	24.46	384	25.41
Fraction, i.b.p. 300 °C, wt%	71	43.14	375	45.82
Fraction, i.b.p. 350 °C, wt%	39	49.91	164	56.07
Gas content, m^3/t	145	113.56	810	120.02

Table 2. Physicochemical properties of West Siberian oils occurring at different depths

and Nagumanovskoye oil fields.

Table 4 shows the results of a comparative analysis of the physical and chemical properties of DLO and oils occurring at shallow and medium depths. As shown in Table 4, the density, viscosity, and contents of sulfur, resins, and asphaltenes in the DLO are significantly reduced, while the content of fractions and oil gas is greatly increased. Classification analysis shows that deep-lying oils are generally characterized by higher quality indicators compared to oils of shallow and medium depths (Yashchenko, Polishchuk, 2016). Thus, according to the classification of oils by Yashchenko and Polishchuk, in terms of quality indicators, DLO can, on average, be classified as paraffinic, low-sulfur, low-resin, low-asphaltene and light oils with high gas and diesel fraction content but with increased viscosity.

It is interesting to compare the physicochemical properties of DLO from different OGBs. Leonov et al. have developed a criterion for choosing the most promising oil and gas basins in Russia and its border areas in order to search for deep-seated hydrocarbon deposits. This criterion was developed on the basis of a set of data on the thickness of the sedimentary cover of the oil and gas basin and the degree of exploration of the upper (2000-4000 m) horizons of the geological section and data on the presence of high-capacity traps and reliable seals (Leonov et al., 2015). Using this criterion, we have established that the Caspian oil and gas basin is the most promising in the search for DLO. It is followed in decreasing order of prospects by the West Siberian, South Caspian, North Caucasian, Barents Sea, Timano-Pechora Okhotsk, Volga-Ural and North-Crimean basins. The Lena-Tunguss and Lena-Vilyui basins complete this list.

Based on information from the database, it has been established that currently 468 hydrocarbon samples are registered at depths below 4500 m. A third of them are Russian oils. Thus, according to the above, only 2.2 % of the information from the world database on the properties of oils relates to deposits at depths of more than 4500 m. This is an indicator of the extremely poor knowledge on hydrocarbon deposits in deeply buried horizons.

In Russia, the most of DLO are concentrated in the North Caucasus (82 % of Russian DLO) and Volga-Ural (12 % of Russian DLO) basins. The presented data show that currently 33 hydrocarbon fields have been proven in Western Siberia at depths of more than 4500 m. However, these are mainly gas and gas condensate deposits. The oil deposits are explored only at Maloichskoye and Samburgskoye fields, which make up less than 10 % of all West Siberian oilfields. Table 5 shows the results of the analysis of physicochemical properties of the oils deep-lying in following oil and gas basins: Pre-Caspian, West Siberian, South Caspian, and North Caucasian. According to the above criterion, these are the most promising basins in Russia and its border areas (Leonov et al., 2015).

As is seen from Table 5, deep-seated oils from different OGBs on average differ in physical and chemical properties. Thus, the oils from West Siberian and North Caucasian basins make the group of DLO

Occurrence depth, m	Reservoir temperature, °C	Reservoir pressure, MPa	Porosity, %	Permeability, mdm^2
0-1000	34.80	7.47	22.72	16.17
1000-2000	50.17	16.33	17.80	2.86
2000-3000	82.54	26.59	16.78	0.24
3000-4500	108.22	41.81	14.97	0.19
More than 4500	134.06	63.09	13.61	0.11

Table 3. Changes in the conditions of oil occurrence and reservoir properties with increasing depth

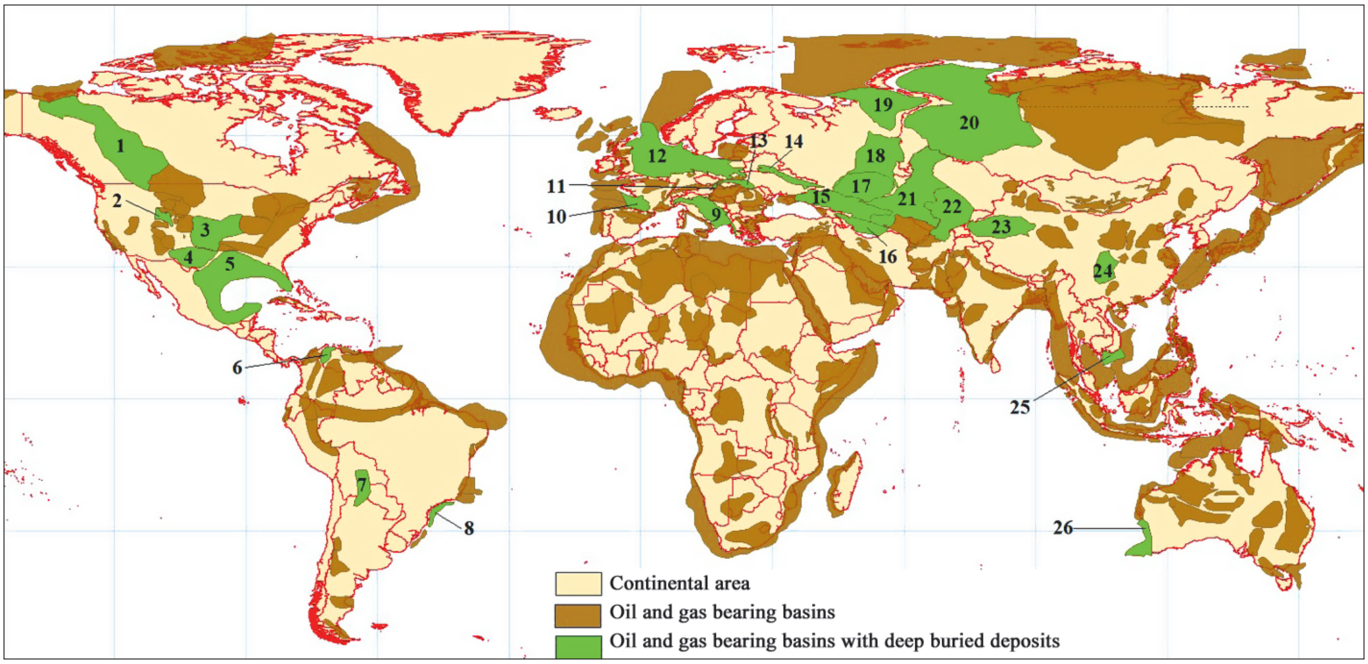

Fig. 1. Distribution of oil and gas bearing basins over the territories of continents Notation: basins with deep-seated oils: Western Canadian, (1); Green River, (2); Western Interior, (3); Permian, (4); Gulf of Mexico, (5); Maracaibo (6); Central Pre-Andean (7); Santos, (8); Adriatic, (9); Aquitanian, (10); Vienna, (11); Central European, (12); Carpathian, (13); Dniepr-Pripyat, (14); North Caucasian, (15); South Caspian, (16); Pre-Caspian, (17); Volga-Ural, (18); Timan-Pechora, (19); West Siberian, (20); Turan, (21); Afghan-Tajik, (22); Tarim, (23); Sichuan, (24); Vung-Tau, (25); Perth, (26).

with high quality properties. Being lightest and low viscous, they have the lowest content of sulfur, resins, and asphaltenes and a high content of all fractions and paraffins. However, the highest quality indicators for the most of physicochemical characteristics are demonstrated by the West Siberian DLO. Hence, they have the lowest density, sulfur and asphaltene content, and the highest content of three fractions. In the group of lower quality DLO, the Caspian oils are the most viscous, while the oils of South Caspian basin exhibit the highest density. As for other characteristics, the oils of these basins are close to those of the oils from the first group.

Discussion of the results

With an increase in the depth of occurrence, a significant compaction of rocks occurs at great depths, which leads to a change in the structure and texture of rocks under the lithostatic pressure and an increase in temperature. The processes of metasomatism and recrystallization of minerals affect the porosity and permeability properties of reservoir rocks, as well as their mineralogical composition. As a result, the rock permeability and reservoir porosity decrease with depth, which is confirmed by the data in Table 3. Since the geological structure of deep horizons is changing dramatically, traditional approaches to predictive resource assessment and to exploration become ineffective. Therefore, the above-established patterns of changes in oil properties depending on the depth of occurrence may be of great importance in the development of new approaches to solving these problems of prospecting and predictive assessment of oil resources.

To explain the obtained results of the analysis of changes in the properties of oils depending on the depth and characteristics of deep-lying oils, we have turned to the results of geological modeling using the example of the deposits of the West Siberian oil and gas basin (Glukhmanchuk et al., 2014). These results make it possible to describe the process of formation of deposits in deeply buried sediments. In the course of evolution of oil and gas reservoirs, oil-and-gas source sediments enter the main phase of oil and gas formation, resulting in the formation of primary hydrocarbon deposits in the sedimentary cover. Subsequent processes of the evolution of tectonic movements lead to a change in over-burden pressure in rock massifs, which initiates the movement of fluids, including hydrocarbons, into decompression zones (Glukhmanchuk et al., 2014). These zones arise at the boundary of the sedimentary cover and basement at the edges of subsiding blocks as regions of minimum pressure values.

Thus, as a result of the described evolution of tectonic movements, conditions arise for the formation of deep-seated secondary deposits characterized by lower viscosity and density of oils and a lower concentration of the main indicators of the chemical composition (sulfur and asphalt-resin substances). Consequently, at depths below 4000–4500 m in rocks passed all stages of lithogenesis and having minimal porosity, the direction of fluid dynamic processes is largely determined by the evolution of their stress-strain state, which can serve as a justification for the above-established patterns of changes in physicochemical properties oils at great depths.

The search for deposits at depths of up to 2.5–3.0 km is based on the model of the upward migration of hydrocarbons, initiated by the processes of compaction of sedimentary rocks. At great depths, the direction of fluid-dynamic processes is largely determined by the evolution of their stress-strain state (Grigoriev et al., 1979). This factor is most significant when considering the processes of migration of hydrocarbons that form deposits in the top part of the basement.

It was found out that in terms of physicochemical and biomarker parameters, the bulk of the oil in the top part of the basement in the West Siberian OGB owes its origin to the Lower-Middle Jurassic source rocks (Kontorovich et al., 1998). The formation of such deposits is described as the process of migration of hydrocarbons from the Jurassic deposits in the zones of their abutment to the edges of the basement protrusions.

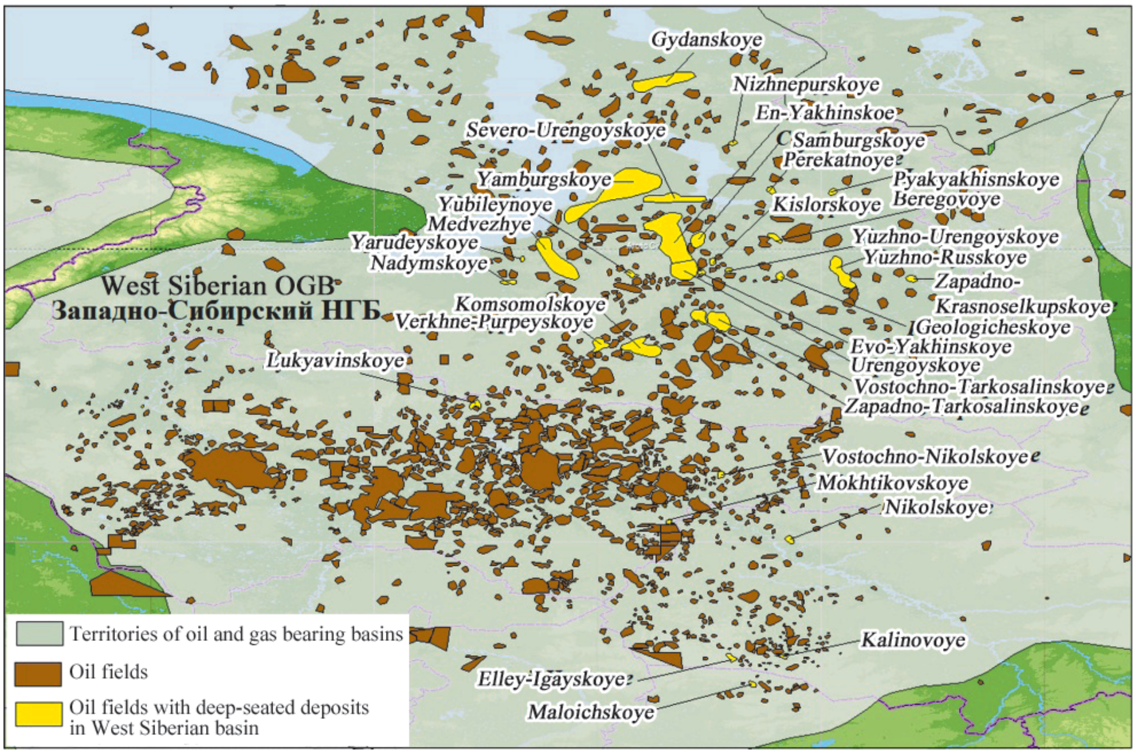

Fig. 2. Distribution of fields with deep-seated deposits over the territory of West Siberian oil and gas bearing basin

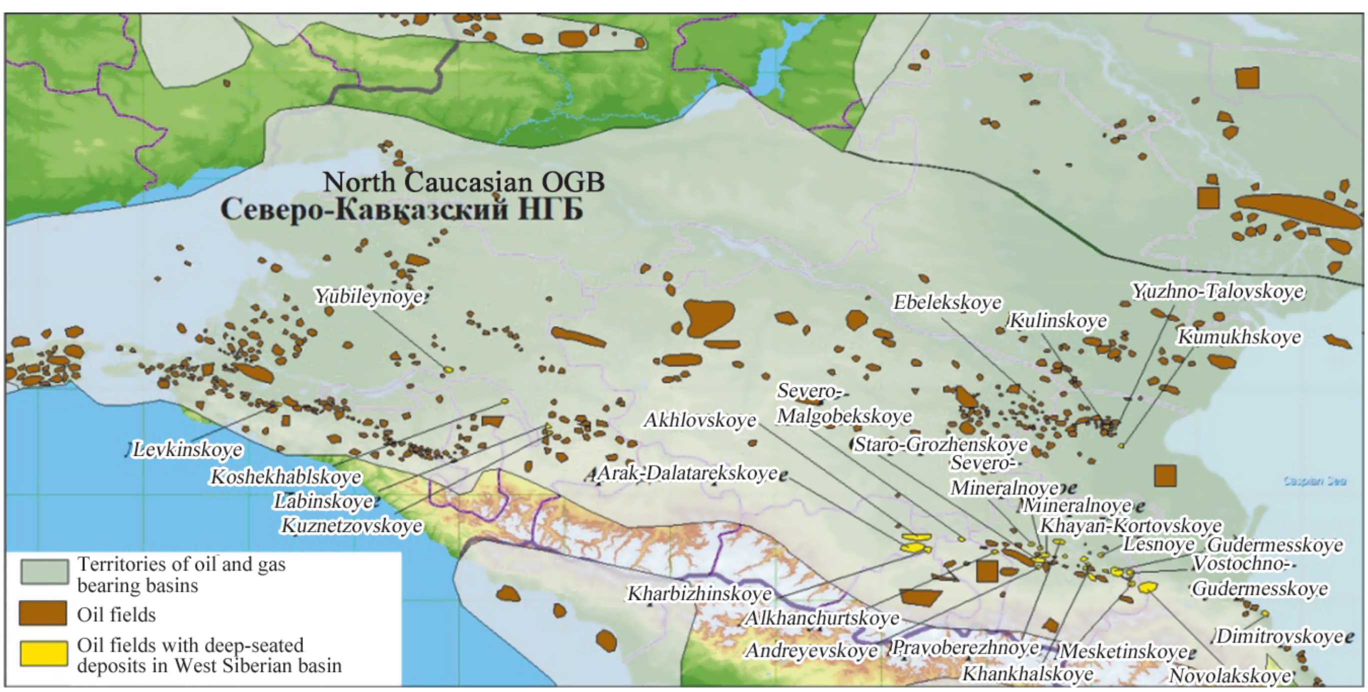

Fig. 3. Distribution of fields with deep-seated deposits over the territory of North Caucasian oil and gas bearing basin

At the same time, the fact that the formation pressure in the basement rocks is higher than in the adjacent Jurassic sediments is usually not discussed. In view of the block structure of the basement, decompression zones (zones of low over-burden pressure) are formed at the bottom of the sedimentary cover and above the edges of the subsiding blocks of the basement, which leads to the downward migration of hydrocarbons through faults in the sedimentary cover (Glukhmanchuk et al., 2014).

Based on the results of the analysis of the data of numerical experiments, the magnitude of the over-burden pressure at different amplitude of the block movement has been calculated and the graphs of the distribution of the over-burden pressure at different amplitude of the block movement have been presented (Glukhmanchuk et al., 2014). The results of these studies allow us to formulate the following conclusions:

- the maximum effect of decompression is observed at the edge of the subsiding block at a distance of up to 200 m from the fault;
- it is advisable to map the boundaries of the subsiding block on the basis of maps of the curvature of horizons corresponding in time of forming to the beginning of the process of oil and gas formation;
- an increase in seismic wave velocities caused by additional compaction of weakly consolidated sediments resulted from the additional compression of rocks above the decompression zone should be expected in the upper part of the sedimentary cover.

Thus, an indicator of the downward migration of hydrocarbons from paleo traps is the subsidence or increased depth of the upper structural beds above them. To illustrate the mechanism of the downward migration of hydrocarbons, in Fig. 4 is shown a diagram of the redistribution of over-burden pressure resulted from the downward displacement of the basement block. The arrows in Fig. 4 show the paths of downward migration into zones of reduced pressure (decompression) in the top part of the basement, formed as a result of block displacement.

The lightest and most mobile hydrocarbons migrate to the decompression zones through the faults in the basement rocks and form deposits in the basement. This can explain the specific physical and chemical properties of the DLO. We have found out that they tend to a decrease in density and viscosity, content of sulfur, resins, and asphaltenes and an increase in the content of light fractions and petroleum gas at depths of more than 4500 m. Note that the above explanation of the mechanism of formation of deeply seated deposits

Physical and chemical indicators	Shallow and medium oils (up to 4500 m)		Deep oils (more than 4500 m)	
	Sample size	Average value	Sample size	Average value
Density, g/cm^3	11602	0.8610	203	0.8368
Viscosity at 20 °C, mm^2/s	4822	827.80	86	145.43
Sulfur content, wt%	7772	1.05	142	0.47
Paraffin content, wt%	5871	5.33	87	6.23
Resin content, wt%	5477	10.25	81	5.99
Asphaltene content, wt%	4958	2.97	77	1.65
Fraction, i.b.p. 200 °C, wt%	1643	24.29	51	31.25
Fraction, i.b.p. 300 °C, wt%	1625	43.64	50	53.27
Fraction, i.b.p. 350 °C, wt%	1038	49.97	26	62.47
Gas content, m^3/t	4058	111.61	38	459.38

Table 4. Comparison of physical and chemical properties of oils occurring at different depths

Physical and chemical indicators	Pre-Caspian basin	West Siberian basin	South Caspian basin	North Caucasian basin
Density, g/cm^3	0.8217	0.8014	0.8415	0.8154
Viscosity at 20 °C, mm^2/s	268.24	6.12	20.66	0.99
Sulfur content, wt%	0.51	0.08	0.19	0.16
Paraffin content, wt%	4.08	7.51	9.10	7.72
Resin content, wt%	5.05	2.48	7.80	2.33
Asphaltene content, wt%	1.07	0.17	1.66	0.38
Fraction, i.b.p. 200 °C, wt%	33.11	34.37	21.36	29.50
Fraction, i.b.p. 300 °C, wt%	51.73	59.45	39.16	59.36
Fraction, i.b.p. 350 °C, wt%	60.80	70.66	57.40	60.44
Gas content, m^3/t	422.76	-	-	398.00

Table 5. Physicochemical properties of deep-seated oil in selected promising oil and gas basins

of lighter oils with improved quality indicators may be insufficient for other deep-lying oil-bearing horizons with different conditions of oil formation and oil accumulation, catagenesis, etc. Hence, in this case, it may be necessary to additionally consider and take into account the conditions of oil generation, the stages of catagenesis, etc.

In the context of the declining oil production in traditional Russian OGBs, the development of hydrocarbon resources of poorly studied deep horizons is an urgent problem today, especially for Western Siberia. As noted above, according to information from the database, no more than 10 % of the oil deposits discovered in the West Siberian oil and gas basin occur in deep-seated formations. In this regard, it is of interest to assess the prospects of searching for DLO in Western Siberia.

The above-mentioned tendencies for the changes in physical and chemical properties with an increase in the depth of occurrence suggest the possibility of discovering of DLO deposits in the West Siberian oil and gas basin, which is also confirmed by the results of geological modeling described above. Indeed, investigations of the downward migration of hydrocarbons in the reference fields of Western Siberia (Verkhne-Tarskoye, Maloichskoye, Khanty-Mansiyskoye, Novoportovskoye, and Vostochnoye fields) with proven oil and gas occurrence of the basement rocks have revealed a complete rearrangement of the upper geological horizons (Glukhmanchuk et al., 2014). According to the results of these investigations, such rearrangements are taken into account in the model of formation of deposits in the top of Paleozoic formations, which provide the downward migration of hydrocarbons from the paleo trap (Fig. 4).

Currently, in the northern regions of Western Siberia, where the main centers for oil and gas production are located, prospecting and exploration operations are concentrated in the depth interval of 3000–4000 m. The industrial development of hydrocarbon resources in this interval of the upper oil saturated layer is technologically difficult, but does not raise questions in scientific and methodological terms. Here, methods and technologies can be applied that have proven themselves in the search and exploration of traditional oil and gas fields.

Deep horizons are a different matter, but the question arises as to whether the risks are justified today? Is it worth investing heavily in the search, exploration and development of commercial oil and gas deposits in Western Siberia at depths of 4500 to 7000 m and deeper, or would it be better to leave this task for the future? If it is the case, what effective methods and technologies for prospecting, exploration and development should be offered to oil and gas companies? Obviously, at great depths, only sufficiently large oil and gas deposits, characterized by a high density of reserves and consistently high production rates of production wells, can be of commercial interest. The extracted commercial product should recoup all investment costs for search, exploration, development and risks.

It is known that there are both geological and environmental risks of developing deeply buried deposits (Korotkov et al., 2010; Zapivalov, 2013). Geological risks include the following factors:

- poor geological and geophysical knowledge on deep horizons, lack of a reliable regional geological model and adequate ideas about the features of oil and gas content of deeply buried horizons;
- unavailability of oil companies to work at great depths in a normal operating cycle in severe conditions of thermobaric and stress-strain state of deep bowels. This results in the high accident rate, long time for well construction, and low quality of sampling and testing;
- imperfection of the known methods of prospecting and exploration of hydrocarbon deposits, not adapted to the conditions of great depths.

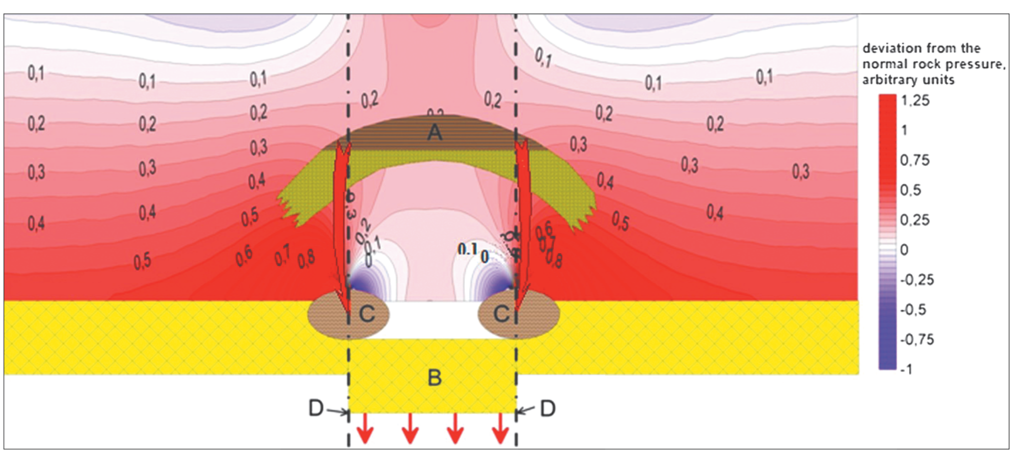

Fig. 4. Model of formation of deposits in the top part of the basement resulted from the downward hydrocarbon migration (Glukhmanchuk et al., 2014). Paleo-deposit (A), downthrown side of basement (B), deposits formed in the basement top as a result of downward migration (C), and fault lines (D). The figures denote the values of the deviation of the over-burden pressure from the normal value of the lithostatic pressure in the stress field.

- routine methodologies and techniques of prospecting and exploration, developed for the traditional conditions of the upper level of oil and gas occurrence, based on the classical sedimentary-migration theory without taking into account the specifics of the structure of deep subsoil. As a result, geological models and predicted hydrocarbon resources of deeply buried deposits are often not confirmed upon drilling.

Environmental risks are caused by the following factors:

- man-made load in the oil-producing areas initiating the manifestation of natural and technogenic geodynamic processes and affects also soils, surface, and ground waters;
- transformations of the earth's crust at great depths, with an intense decrease in reservoir pressure in hydrocarbon deposits causing deformation of the earth's crust and changes of the relief. Geodynamic processes on the surface are manifested as water-logging and flooding of territories;
- the need to develop and implement measures aimed at reducing the technogenic impact of objects and processes of oil and gas production on the state of permafrost. There is much concern about reducing the rate and consequences of the processes of local thawing of permafrost rocks under the prospecting drilling and injection of high-temperature drilling fluids and formation water into the bowels.

At present, about 50 parametric and exploration wells with a depth of more than 4500 m have been drilled on the territory of Western Siberia, which is clearly not enough for the vast territory of the West Siberian megabasin.

Only two super-deep "research" wells were drilled: SG-6 Tyumenskaya (7502 m) and SG-7 En-Yakhinskaya (8250 m), both are located near the Urengoyskoye oilfield. As a result of these works, in the unique oil and gas basin of the world at depths of more than 4500 m, no major oil fields were discovered that would be of industrial importance. According to available data, the main hopes for increasing oil production in the West Siberian basin should be pinned on Paleozoic sediments (Shuster et al., 2015; Trofimov, Masagutov, 2012; Shuster, Dzyublo, 2012; Yashchenko, 2020).

Conclusion

The paper is devoted to the study of the patterns of changes in the physicochemical properties and conditions of oil occurrence, depending on the depth and characteristics of poorly studied deep-lying oils at depths of more than 4500 m.

The results of preliminary studies of quantitative patterns of changes in the physicochemical properties of oils at different depths, presented in the monograph (Yashchenko, Polishchuk, 2014a), are summarized in this paper using a new information obtained in the last decade. The information on 21067 oil samples from 167 oil-bearing basins of the world was used.

It has been found out that in different oil basins the density and viscosity of oils decreases with depth. The content of sulfur, resins, and asphaltenes also decreases with depth, while the content of diesel fractions and oil gas increases. The paraffin content increases to a depth of 3–4 km, and then decreases with increasing depth.

The investigation has found that the features of the physicochemical properties of oils lying at a depth of more than 4.5 km are a lower density and content of sulfur and asphalt-resin substances and increased contents of fractions and petroleum gas. Hence, the oils of great depths have higher quality characteristics as compared to oils from shallow and medium depths.

To explain the obtained patterns, the results of geological modeling of changes in the stress state of rocks caused by the displacement of basement blocks have been used. The displacement of basement blocks was due to the evolution of tectonic movements, leading to the appearance of zones of low over-burden pressure, where deep-seated secondary deposits of lighter oils with increased quality indicators could be formed.

It should be noted that this explanation of the mechanism of formation of deep-seated oils with these properties may be insufficient for other deep-sunken oil-bearing horizons with different conditions of oil formation and oil accumulation, catagenesis, etc. Hence, it may be necessary to consider and take into account also the conditions of oil generation, stages of catagenesis, etc.

Prospects for discovering deep-lying oil deposits in the West Siberian oil and gas basin are considered. Both geological and environmental risks associated with the development of deeply buried deposits are briefly reviewed.

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