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THE STUDY OF LUMINESCENT-BITUMEN CHARACTERISTICS OF ORGANIC SUBSTANCES OF DOMANIK TYPE DEPOSITS IN THE PERM REGION

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ИЗУЧЕНИЕ ЛЮМИНЕСЦЕНТНО-БИТУМИНОЛОГИЧЕСКИХ ХАРАКТЕРИСТИК ОРГАНИЧЕСКОГО ВЕЩЕСТВА ОТЛОЖЕНИЙ ДОМАНИКОВОГО ТИПА НА ТЕРРИТОРИИ ПЕРМСКОГО КРАЯ

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luminescent-bitumen analysis, domanik type deposits, organic matter, bitumoid ratio, organic carbon content, domanian horizon, statistical characteristics, source deposits, generation potential, Uspensky-Vassoevich graph, allochtonic bitumen, GIS, autochthonous bitumens, correlation coefficient, multivariate statistical models.

The reduction of the resource base of oil and gas in the old oil and gas producing areas, including the Perm region, leads to the need for a detailed study of the processes of generation, migration and accumulation of hydrocarbons. Successful prediction of petroleum potential is impossible without studying the geochemical properties of oil and gas source deposits. Determination of the content of dispersed organic matter in the rock, the degree of bituminousness of the rocks, the composition of the organic matter allow us to estimate the generation potential of the sediments and use it to assess the oil and gas content of the territory.
On the territory of the Perm region the Domanik type deposits are the main source of hydrocarbons for the oil and gas fields.
The deposits of the Domanik type include the Sargayevsky and Domanik horizons of the Middle Frasnian substage, the Mendym horizon and the upper undifferentiated stratum of the Upper Frasnian substage, also the Famennian and Tournaisian layers. These deposits are associated with the development of the Kama-Kinel system of deflections (KKSD).
The article contains a statistical analysis of the chemical and bitumen characteristics of the Domanik type sediments, the relationships between well log data and the results of luminescent bitumen research are considered, multidimensional statistical models for predicting organic carbon content based on GIS data are built, organic carbon content maps for received models are created.
It was found that, within the entire strata, Domanic sediments have very good oil source properties. By the multidimensional statistical modelling and the construction of maps of organic carbon, it was revealed that the highest concentrations of organic matter in the Domanik horizon are observed in the north-east, central and southern parts of the Perm Region.

Ключевые слова:
люминесцентно-битуминологический анализ, отложения доманикового типа, органическое вещество, битумоидный коэффициент, содержание органического углерода, доманиковый горизонт, статистические характеристики, нефтематеринские отложения, генерационный потенциал, график Успенского – Вассоевича, аллохтонные битумоиды, геофизические исследования скважин (ГИС), автохтонные битумоиды, коэффициент корреляции, многомерные статистические модели.

Сокращение ресурсной базы нефти и газа в старых нефтегазодобывающих районах, к числу которых относится и Пермский край, приводит к необходимости детального изучения процессов генерации, миграции и аккумуляции углеводородов. Успешное прогнозирование нефтегазоносности невозможно без изучения геохимических свойств нефтегазоматеринских отложений. Определение содержания рассеянного органического вещества в породе, степени битуминозности пород, компонентного состава органического вещества позволяет оценивать генерационный потенциал отложений и использовать его для прогноза нефтегазоносности территории.
На территории Пермского края к нефтегазоматеринским относятся отложения доманикового типа, которые считаются основным источником углеводородов для нефтегазоносных комплексов Пермского края.
К отложениям доманикового типа (формации) относятся саргаевский и доманиковый горизонты среднефранского подъяруса, мендымский горизонт и верхняя нерасчлененная толща верхнефранского подъяруса, а также фаменский и турнейский ярусы. Данные отложения связаны с развитием Камско-Кинельской системы прогибов.
В статье выполнены статистический анализ химико-битуминологических характеристик отложений доманикового типа, рассмотрены зависимости между данными геофизических исследований скважин (ГИС) и результатами люминесцентно-битуминологических исследований, построены многомерные статистические модели прогноза содержания органического углерода по данным ГИС, построены карты содержания органического углерода по полученным моделям.
В результате проведенных исследований было установлено, что в пределах всей толщи очень хорошими нефтематеринскими свойствами обладают отложения доманикового времени. Благодаря применению многомерных статистических моделей и построению карт содержания органического углерода было выявлено, что повышенные концентрации органического вещества в доманиковом горизонте наблюдаются в северо-восточной, центральной и южной частях Пермского края.

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Introduction

The geochemical characteristics of organic matter are the basis of the sedimentary migration theory of oil formation. A detailed study of the luminescent-bitumen characteristics of organic matter (OM) has made it possible in many petroleum regions, provinces, and provinces to clarify the generation potential of oil source rocks, the features of organic matter migration in petroleum complexes and predict hydrocarbon deposits [1–9]. Therefore, the study of these characteristics for deposits of the Domanik type of the Perm Territory plays an important role.

Domanic type deposits are associated with the development of the Kama-Kinel deflection system (KKSD). Sedimentation occurred from the Sargayevsky to the Early Tournasian time inclusive. The deposits of the Domanik type (formation) include the Sargayevsky and Domanik horizons of the Middle Frasnian substage, the Mendym horizon and the upper undifferentiated stratum of the Upper Frasnian substage, as well as the Famennian and Tournaisian layers.

In general, Domanic deposits are represented by bituminous clayey dark gray, almost black limestone interbedded with marls of the same color, lime – clay – siliceous shales and flints [6–13].

In order to study the geochemical features of the Domanic deposits, the results of luminescent-bitumen analysis of 313 core samples of domanicoid rock formations taken from 88 wells of 75 exploration areas were analyzed.

The main geochemical indicators determined during chemical and bitumen studies are the content in the rock of dispersed organic matter (DOM, %), organic carbon (C_{org}, %), insoluble residue of the rock (IR, %), petroleum ether bitumoide (B_{pe}, %), chloroform bitumoide (B_{hb}, %), alcohol benzol bitumoide (B_{ab}, %), humic acids (G_a, %), as well as the bitumoide coefficient (β, %) [14–20].

Statistical analysis of chemical and bitumen indicators of the Domanic type deposits

Table 1 presents the main statistical characteristics [21–26] of geochemical indicators of the Domanik type deposits for some regions. The table shows that the highest content of organic carbon (C_{org} = 5.59 %) and, therefore, dispersed organic matter (DOM = = 7.08 %) is observed on the territory of the Solikamsk depression.The explanation of this fact is that this territory during the development of the KKSD was mostly located in the area of uncompensated depressions and deflections which are favorable for the accumulation of organic matter. The value of the bitumoid coefficient (β = 15.68 %) with a high content of organic matter (C_{org} = 5.59 %) indicates the presence of migrated bitumoids [17, 27]. The high concentration of chloroform bitumoide (B_{hb} = 1.06 %), as well as the large value of the neutrality coefficient (K_n = 3.44) indicate a significant restoration of bitumoids and their oil character. It is also worth noting the high percentage of the insoluble residue of the rock (IR = 52.44 %), which is the largest among the considered tectonic elements. If accept the fact that the sediments mostly accumulated in the depressive zones of the KKSD, then it can be assumed that the insoluble residue of the rock contains a significant proportion of the pelitic fraction (clay particles). The presence of this fraction favors the adsorption and preservation of organic matter on the surface of the particles.

The lowest content of organic carbon (C_{org} = 3.30 %) and, therefore, dispersed organic matter (DOM = 4.15 %) is observed for the territory of the Bashkir arch. From the Sargayevsky to the Tournaisian age, facial conditions of the shallow shelf and platform lagoons prevailed in this area. The high value of the bitumoide coefficient (β = 39.46 %) confirms the high proportion of epigenetic bitumoide [17, 18]. The high concentration of

chloroformbitumoide (B_{hb} = 1.42 %), as well as the large value of the neutrality coefficient (Kn = 3.23) indicate a significant restoration of bitumoids and their oil character. It is also worth noting the low percentage of the insoluble residue of the rock (IR = 19.98 %), which is the smallest among the considered tectonic elements.

Table 1

The main statistical characteristics of the Domanik type depositsgeochemical indicators

Area	C_{org}, %	DOM, %	B_{pe}, 10^{-2} %	B_{hb}, 10^{-2} %	B_{ab}, 10^{-2} %	Ga, 10^{-2} %	IR, %	β, %	K_n (B_{hb}/B_{ab})
Bashkir arch	3.30 ± 3.02 0.06–12.48	4.15 ± 3.84 0.06–16.60	3.58 ± 5.26 0.00–15.60	141.63 ± 205.43 0.00–500.00	41.74 ± 61.34 1.00–335.00	0.24 ± 0.28 0.00–1.00	19.98 ± 17.59 0.53–57.60	39.46 ± 34.23 0.34–100.00	3.23 ± 5.24 0.10–24.04
Bym-Kungur monocline	4.61 ± 2.82 1.93–17.24	5.60 ± 3.33 2.28–20.34	4.16 ± 3.83 0.12–15.60	140.50 ± 146.04 3.00–500.00	100.99 ± 95.73 8.00–500.00	0.10 ± 0.28 0.00–11.80	37.57 ± 18.17 4.80–97.30	26.63 ± 24.02 0.83–100.00	3.15 ± 5.61 0.25–32.05
Upper Kama depression	4.46 ± 3.23 0.05–17.5	5.92 ± 4.46 0.05–23.28	6.60 ± 14.34 0.00–80.00	94.32 ± 140.70 0.00–500.00	72.54 ± 82.81 0.25–335.00	0.82 ± 2.15 0.00–11.80	48.25 ± 33.01 6.26–98.40	19.84 ± 25.38 0.34–100.00	1.44 ± 2.27 0.19–8.00
Visim monocline	5.26 ± 6.56 0.05–24.33	6.95 ± 8.73 0.05–32.36	1.64 ± 2.23 0.01–8.00	49.32 ± 75.75 1.00–250.00	16.56 ± 8.34 2.00–31.30	1.01 ± 2.34 0.00–8.00	51.70 ± 35.00 0.51–98.72	11.81 ± 14.00 0.48–44.44	2.32 ± 2.97 0.17–10.64
Advanced folds of Urals	4.07 ± 3.39 1.62–16.19	5.27 ± 4.29 1.92–20.24	0.25 ± 0.22 0.01–0.50	15.01 ± 28.08 0.12–125.00	11.39 ± 8.98 0.25–31.30	0.27 ± 0.42 0.00–1.00	50.34 ± 21.76 15.95–89.53	5.23 ± 14.95 0.04–4.99	1.41 ± 1.06 0.48–3.99
Solikamsk depression	5.59 ± 6.38 1.08–46.14	7.08 ± 7.98 1.17–57.68	2.20 ± 3.87 0.00–20.00	105.64 ± 171.22 1.00–500.00	41.61 ± 47.96 2.00–214.00	2.52 ± 6.13 0.00–3.13	52.44 ± 32.51 3.46–99.62	15.68 ± 24.78 0.26–94.58	3.44 ± 6.20 0.19–32.05

N o t e : here and in Table 2 in the numerator – the arithmetic mean ± standard deviation; denominator – scale values (min – max).

To determine the autochthonousness and allochthonousness of bitumoids, the Uspensky-Vassoevich law (schedule) is applied. Figure 1 shows the correlation field betweenβ and C_{org}. Most of the studied rocks samples of the Domanik deposits in the Perm region is characterized by the content of allochthonous bitumoids.

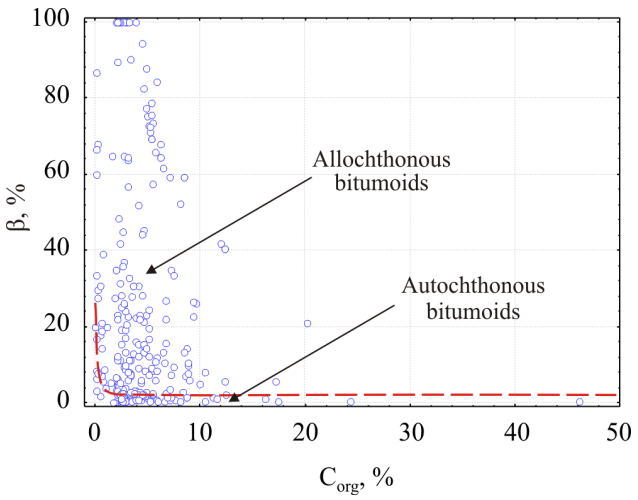

Figure 1.Correlation field between β and C_{org} (for the Domanik type deposits). Dotted line separates allochthonous and autochthonous bitumoids [12]

Table 2 shows the main statistical characteristics of the studied sediments geochemical parameters.

The analysis shows that among all of the studied Domanik type deposits, the Domanik horizon is characterized by maximum average values in almost all geochemical parameters: C_{org} = 5.66 %, B_{pe} = 0.06 %, B_{hb} = 2.11 % B_{ab} = 1.13 %, β = 33.68 %, DOM = 7.11 %. According to the classification of K.F. Rodionova the Domanik horizon belongs to the category of very good source rocks [28].

Determination of statistical relationships between GIS data and the results of bituminous studies of domanic deposits

In this paper, the results of luminescent-bitumen analysis of the domanic sediments were compared with the well logging data of the following methods:

- gamma ray logging (GR);
- neutron gamma logging (NGR);
- gamma-gamma density logging (GGD);
- thermal neutron neutron-neutron logging (TNN), 1 – big probe, 2 – small probe;
- acoustic logging (A).

The possibility of well log methods using for estimating the content of organic carbon is given in [29–38].

Table 2

The main statistical characteristics of the geochemical indicators of Sargayevsky, Domanik and Mendym horizons, the undifferentiated stratum of the Upper Frasnian substage, the Famennian and Tournaisian tiers

Stratigraphic unit	C_{org}, %	IR, %	B_{pe}, 10^{-2} %	B_{hb}, 10^{-2} %	B_{ab}, 10^{-2} %	Ga, 10^{-2} %	β, %	K_n (B_{hb}/B_{ab})	DOM, %
C_1t	3.38 ± 3.05 0.05–17.50	48.64 ± 35.38 0.53–99.50	0.02 ± 0.04 0.00–0.24	0.24 ± 0.65 0.00–5.00	0.25 ± 0.38 0.00–2.14	0.95 ± 2.36 0.00–15.60	11.84 ± 19.92 0.26–86.87	1.30 ± 3.66 0.17–30.83	4.52 ± 4.06 0.05–23.28
D_3fm	4.68 ± 7.24 0.05–46.14	46.76 ± 33.39 0.51–99.62	0.02 ± 0.03 0.00–0.16	0.58 ± 1.22 0.01–5.00	0.20 ± 0.25 0.02–1.48	1.52 ± 5.42 0.00–31.30	17.57 ± 24.72 0.41–100.00	2.65 ± 5.41 0.13–32.05	6.03 ± 9.29 0.05–57.68
D_3f_3	3.29 ± 2.50 0.29–12.48	32.41 ± 20.34 3.02–84.39	0.01 ± 0.01 0.00–0.05	0.35 ± 1.03 0.00–5.00	0.25 ± 0.28 0.00–0.83	0.51 ± 1.69 0.00–8.00	10.06 ± 18.27 0.00–78.76	1.56 ± 4.42 0.00–21.28	4.49 ± 3.40 0.29–16.60
D_3mn	3.63 ± 2.15 0.57–9.92	29.68 ± 20.40 5.35–97.3	0.03 ± 0.08 0.00–0.31	1.19 ± 1.77 0.00–5.00	0.54 ± 0.42 0.00–1.48	0.59 ± 0.13 0.00–11.80	28.38 ± 34.20 0.00–100.00	3.39 ± 6.60 0.25–32.05	4.63 ± 2.68 0.57–12.40
D_3dm	5.66 ± 3.22 0.51–20.25	38.21 ± 20.52 4.41–95.68	0.06 ± 0.10 0.00–0.80	2.11 ± 1.88 0.00–5.00	1.13 ± 1.03 0.04–5.00	0.20 ± 0.51 0.00–4.00	33.68 ± 28.44 0.33–100.00	3.93 ± 5.38 0.25–24.04	7.11 ± 3.78 0.51–23.90
D_3sr	4.90 ± 3.61 0.44–16.19	43.07 ± 29.05 7.71–98.95	0.06 ± 0.06 0.00–0.16	2.08 ± 2.19 0.01–5.00	0.70 ± 1.12 0.06–5.00	0.72 ± 2.55 0.00–11.80	31.79 ± 36.10 0.55–100.00	4.71 ± 5.53 0.13–15.97	6.50 ± 4.79 0.44–20.24

To bring the log curves to a general form and eliminate the influence of units of measurement, different dates of research and different downhole tools, the log data were standardized using the following formula:

$$x_{st} = (x_i - x_{av}) / x_{std},$$

where x_{st} – standardized value of the log data; x_i – i-th indication *of* the log data; x_{av} – average value of the log data throughout the domanicoid formation; x_{std} – standard deviation of the log data for the whole domanicoid formation.

Use of this formula allows reducing the units for each type of logging, since the same logging methods may have different units.

The missing well logs in some wells were calculated using regression analysis [21, 25–26, 39].

In order to determine the links between geochemical indices and log data, a correlation matrix was constructed for the Domanic sediments of the Perm region (Table 3).

According to the Table 3, 23 paired correlation coefficients out of 54 are statistically significant. The highest correlation coefficients are established between the following pairs of indicators: B_{hb} и G_a ($r = 0{,}54$); B_{ab} и GR ($r = 0{,}52$); C_{org}, и GGD ($r = -0{,}50$).

Table 3

Correlation matrix between well log data and geochemical indicators of the Domanik type deposits in the Perm Region

Indicators	C_{org}, %	IR, %	B_{pe}, 10^{-2}%	B_{hb}, 10^{-2}%	B_{ab}, 10^{-2}%	G_a, 10^{-2}%	β, %	K_n (B_{hb}/B_{ab})	DOM, %
GR	0.31*	0.37*	0.47*	0.54*	0.52*	–0.13	0.29*	0.32*	0.42*
NGR	–0.25*	–0.23	–0.38*	–0.46*	–0.40*	0.06	–0.35*	–0.28*	–0.32*
TNN1	–0.45*	0.09	0.21	–0.23	0.10	–0.06	–0.32	–0.35	0.09
TNN2	–0.30*	0.07	0.33	–0.08	0.30	–0.08	–0.21	–0.31	0.08
GGD	–0.50*	0.08	–0.06	0.04	–0.12	–0.02	0.04	0.08	–0.06
A	0.41*	0.23	0.23*	0.38*	0.33*	–0.07	0.22	0.29*	0.23

Note: * – statistically significant correlation coefficients ($p < 0.05$).

Building of multidimensional statistical models for predicting the content of organic carbon (C_{org})

Since the content of organic carbon in the Domanik type deposits is characterized by an exponential distribution, the values of C_{org} were prologized (ln (C_{org})).

As a result of stepwise regression analysis [40] prediction models of ln (C_{org}) for the sediments, as well as for the Domanik horizon, respectively were obtained:

$$\ln(C_{org}) = 0{,}62360 - 1{,}26968\ TNN1 + 0{,}64468\ TNN2 - 0{,}36478\ GGD - 0{,}17218\ GR,\ R^2 = 0{,}497,$$
$$F\ (4{,}468) = 115{,}66,\ p < 10^{-5};$$

$$\ln(C_{org}) = 0{,}94253 - 1{,}20507\ TNN1 + 0{,}45769\ TNN2 - 0{,}22918\ GGD - 0{,}12646\ GR,\ R^2 = 0{,}497,$$
$$F\ (4{,}202) = 49{,}945,\ p < 10^{-5}.$$

From the above multidimensional models, it can be seen that the TNN1 indications characterizing the hydrogen content of rocks have the greatest effect on the ln (C_{org}) forecast [16]. The reduced TNN2 values indicate the presence of voids in the rock and the possibility of accumulation of organic matter in them. A positive angular coefficient in the TNN2 readings arises due to the fact that this method makes a correction to the model (measures the properties of the bottomhole formation zone). The feedback between C_{org} and GGD is explained by the fact that with increasing density of the rock, the volume of voids and, consequently, the amount of organic matter is reduced. The presence of a negative angular coefficient for GR is related to the fact that deposits of the Domanik type are represented mainly by carbonates of varying degrees clay and bituminous.

By well logging curves, using the models obtained, ln (C_{org}) values were calculated, which resulted in true C_{org} values, and then Corg values were averaged over the well section for mapping.

Analysis of changes in the content of organic carbon in the sediments of the Domanik time in the Perm Region

As a result of using multidimensional models, maps of organic carbon content for the Domanic type deposits in general (Fig. 2, *a*) and the Domanik horizon (Fig. 2, *b*) were constructed. As an example, we describe the map of organic carbon content in sediments of the Domanik time.

Analysis of Fig. 2, *b* showed that the Semiluksky deposits are mostly classified as Domanikites (C_{org} > 5%). Plots with a high content of organic carbon are noted: in the southeastern and northeastern parts of the Rakshinskaya saddle in Lysekhinskaya well no. 10 (C_{org} = 16.4 %) and in Dolganovsk well no. 1 (C_{org} = 16.35 %), respectively; in the southern part of the Perm arch in Osinskaya well no. 1 (C_{org} = 14.63 %), confined to the outer sideboard zone of the KKSD, in the northern and southern parts of the Babkin saddle in Turkinsky well no. 53 (C_{org} = 15.3 %) and Kachinskaya well no. 574 (C_{org} = 14.58 %), respectively, confined to the inner sideboard zone of the KKSD; in the southern part of the Bym-Kungur monocline in Dorokhovskoy well no. 1 (C_{org} = 17.3 %), confined to the outer side-zone of the KKSD. On the territory of the Bashkir arch, there are high values in the northern and eastern parts of Chaykinskaya well no. 93 (C_{org} = 15.35 %) and in Shurtan well no. 152 (C_{org} = 17.93 %), respectively, confined to the inner sideboard zone of the KKSD, as well as in the western part of Dubovogorskaya well no. 2 (C_{org} = 17.2 %), confined to the inner sideboard zone of the KKSD.

The minimum content of organic carbon is typical: for the northern and the southern parts of the Upper Kama depression in Ocherskaya well no. 1 (C_{org} = 1.43 %) and Cyril well no. 101 (C_{org} = 1.46 %), respectively; for the central part of the Rakshinsky saddle in Garinsky well no. 62 (C_{org} = 1.56 %).

The map of the average content of organic carbon (see Fig. 2, *a*) in the Domanik type sediments as a whole (C1t-D3sr) is characterized by less differentiation of values, while local peaks of high concentrations of C_{org} were obtained in three wells (in the northern parts of the Babkin saddle and Solikamsk depression).

Conclusions

1. It has been established that, within Perm Region, the best chemical and bitumen indicators of the Domanik type deposits are characteristic of the Solikamsk Depression territory.

2. In the Domanik type sediments, allochthonous bitumoids prevail over autochthonous ones.

3. Within the entire thickness of the Domanik deposits, the Domanik horizon is characterized by the best geochemical indicators and according to the classification of K.F. Rodionova belongs to the category of very good source rocks.

4. Multidimensional statistical models for predicting the content of organic carbon C_{org} of the Domanik type deposits in general and of the Domanik horizon have been constructed.

5. As a result of the use of multidimensional models, maps of average organic carbon content were constructed across the territory of the Perm Region taking into account the well logging data.

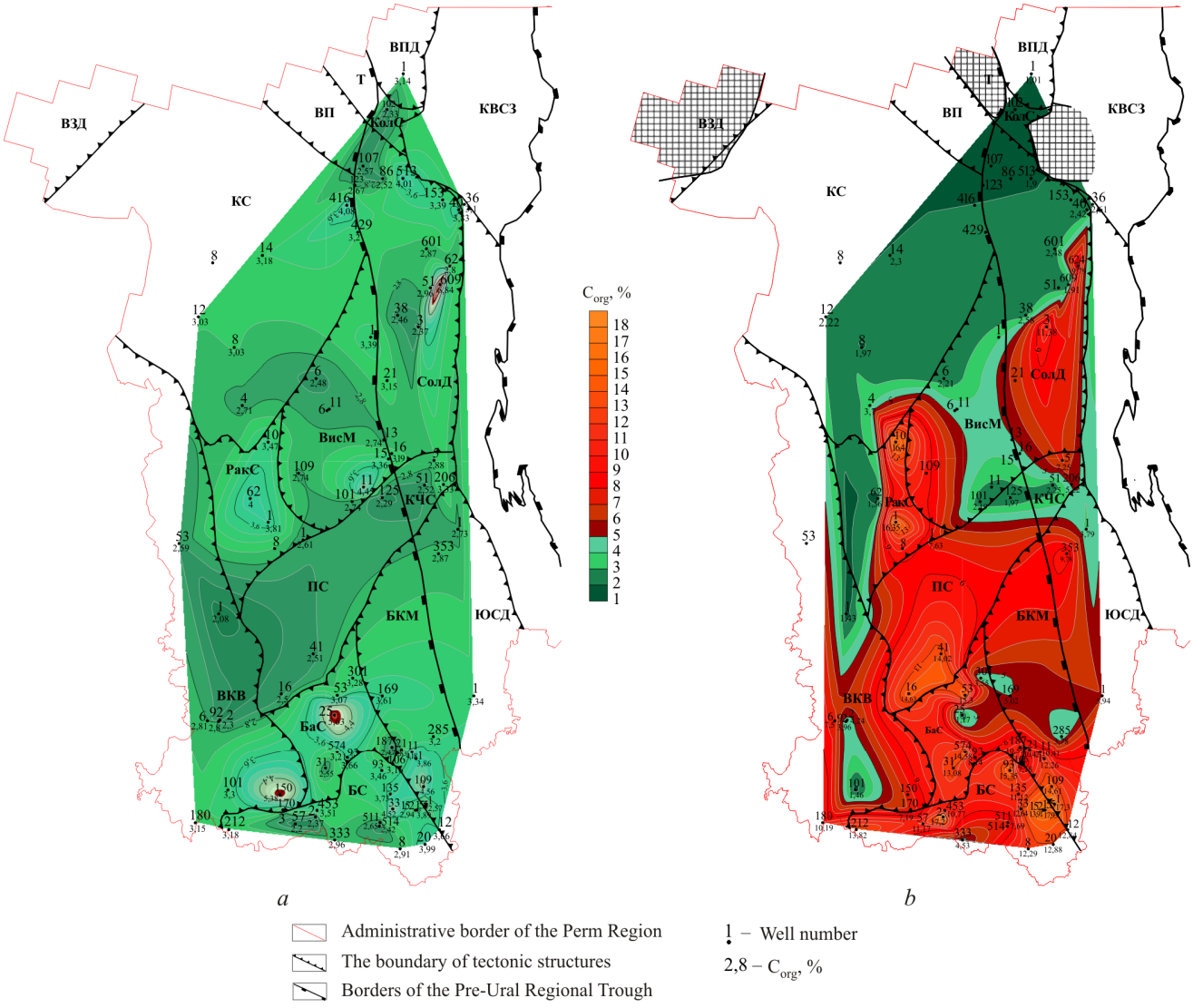

Fig. 2. Map of the average content of organic carbon (C_{org}, %) in the deposits of Domanik type as a whole (C1t-D3sr) (*a*) and Semiluksky (Domanik) time (D3dm) (*b*) in the Perm Region. Tectonic elements: ВЗД – Vyatka Dislocation Zone; ВКВ – Upper Kama depression; Т – Timan ridge; ЦУП – Central Ural uplift; ВП – Vychegodsky deflection; БС – Bashkir dome; ВисМ – Visim monocline; ВПД – Upper Pechersk depression; ЮСД – Yuryuzano-Sylvenskaya depression; КЧС – Kosvinsko-Chusovskaya saddle; КолС – Kolvinskaya saddle; СолД – Solikamsk Depression; КВСЗ – Kozhim-Visherskaya structural zone; ЯЧСЗ – Yazva-Chusovskaya structural zone; КС – Kama arch; БаС – Babkin saddle; БКМ – Bym-Kungur monocline; ПС – Perm arch; РакС – Rakshinskaya saddle

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