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O. M. Karpenko[1],
orcid.org/0000-0002-5780-0418,
V. V. Ohar[1],
orcid.org/0000-0002-7566-3648,
I. O. Karpenko[2],
orcid.org/0000-0001-7753-9010,
I. M. Bezrodna[1],
orcid.org/0000-0002-6835-5276

1 – Taras Shevchenko National University of Kyiv, Kyiv, Ukraine, e-mail: karpenko.geol@gmail.com
2 – National Joint Stock Company Naftogaz of Ukraine, Kyiv, Ukraine

DIFFERENTIATION OF RUDOV BEDS BASED ON THE STATISTICAL METHODS ON GEOLOGICAL AND GEOPHYSICAL DATA

Purpose. To perform the lithological-facies dismemberment of the Rudov Beds using geological and well-logging data to clarify the formation genesis of the hydrocarbon sources deposits within the Yablunivska structure of the Dnieper-Donets basin.

Methodology. Cluster and factor analysis methods were used as well as Q. Passy's method of well logging data interpretation for estimating the content of organic carbon (TOC).

Findings. Regularities of geological structure, lithological heterogeneities, distribution of separate lithotypes and content of organic carbon in the Rudov Beds within Yablunivske oil and gas condensate field are established. The spatial distribution of separate facies types of rocks, thicknesses of their radioactivity layers and content of organic carbon (organic matter) within a single structure of the Dnieper-Donets depression is studied.

Originality. For the first time according to geophysical data with the use of statistical methods, the lithological-facies dismemberment of the petroleum bearing strata, which have a regional distribution within the Dnieper-Donetsk basin, has been performed. It is found that there is no close correlation between natural radioactivity and the content of organic carbon in the Rudov Beds of the Lower Carboniferous. Certain conclusions have been made concerning the confirmation of the hypothesis about the formation of the Rudov beds in the conditions of shallow water desalinated sea gulf.

Practical value. The proposed approach to lithological-facies dismemberment of the Rudov Beds by the well-logging data allows clarifying conditions for petroleum bearing stratum formation in order to assess its real oil and gas generation potential.

Keywords: *Rudov layers, Dnieper-Donets basin, well logging, organic carbon, facial conditions, cluster analysis, radioactivity*

Introduction. The object of research, which has long attracted the attention of the authors of this article, is a very interesting geological formation within the sedimentary strata of the Don-Dnieper trough, which includes the Folded Donets Basin and the Dnieper-Donets depression (DDD).

In the modern stratigraphic scheme [1] the Rudov Beds correspond to the lower part of the Stylian regional horizon. This horizon belongs to the Beyrichoceras-Goniatites ammonite zone (the Upper Visean Substage). In local stratigraphic schemes the Stylian regional horizon combines the Styla Suite (Ve zone) of the Donets Basin and the predominantly argillaceous Solokhiv or carbonate Moshkiv suites of DDD. The Rudov Beds is confined to the lower most part of the Solokhiv or Moshkiv suites. Located with a possible stratigraphic mismatch on the carbonate (mostly)-terigenic stratum of the Yablunivska Suite of the Lower Visean (XIII MFG). This stratigraphic reference corresponds to the Scheme of stratigraphy of the Lower Carboniferous deposits of DDD according to A. M. Vertuh, I. M. Babko, G. I. Vakarchuk, L. P. Kononenko, and others [2, 3].

According to the microfaunistic characteristics (foraminifers), they are referred to the tops of XIII microfaunistic horizon (MFH) and are distinguished as the pay horizon (PH) V-23 [1, 2]. However, this situation of the Rudov Beds and PH V-23 is controversial. Other authors consider it as basal layers of XIIa MFH [4], Fig. 1.

In the central part of the DDD the Rudov Beds unconformably lie on the predominantly limestone of the Yablunivska Suite (Lower Visean Substage, $XIII^{up}$ MFH). They are correlated with the lower part of the Styla Suite (subzone Ve_1) of the Donets Basin. This suite is exposed by quarries in the southern part of the Donets Basin (Fig. 2) and has been well-studied here by Gozhyk, Poletaev, Machulina [1]. According to the results of interregional correlation, this stratigraphic level corresponds to the Lower Tulian regional sub-horizon of the Moscow Basin [1] and is compared with the Cowley Formation of Kansas, USA [5].

The uniqueness of the Rudov Beds and Styla Suite are related to the high content of organic matter, the development of spiculite rocks, widespread distribution within the Dnieper-Donets trough [5, 6] and similarity to gas-shale rocks of known oil and gas fields. Studies by many researchers (Gavtish, Machulina, Babko, Makogon, Ogar, Sachsenhofer) showed that the Rudov Beds have uniquely come to be interpreted as domanicoid deposits (Machulina S. O., Babko I. M. (2004)) that are similar in parameters to the Bazhenov Formation of Western Siberia [6, 8].

Literature review. Significant uncertainty in the judgments of experts relates to the facial conditions in which these organic-rich rocks were formed. S. Machulina and I. Babko [6] believe that these rocks were formed in deep-sea depression. At the same time, Poletaev et al. [9] provide convincing evidence of the shallow genesis of the rocks of the Stylian Regional Horizon as well as the possible influence of desalination and vol-

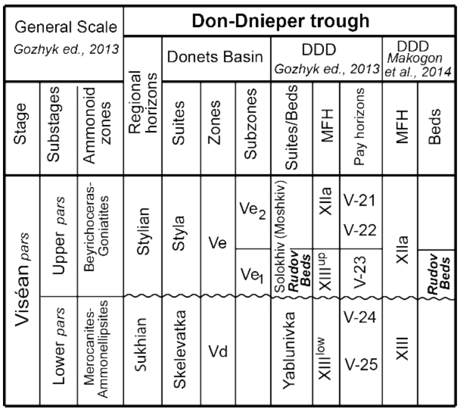


Fig. 1. Stratigraphic position of the Rudov Beds in the DDD

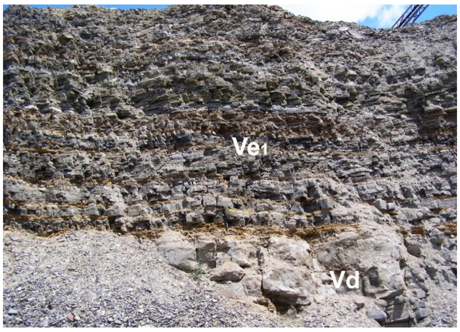


Fig. 2. The "black shale" of the Styla Suite (lowermost part; V_{e1} Subzone) and their contact with massive carbonate rocks of Skelevatska Suite (upper part; Vd zone (Donets Basin, Central Quarry)

canic activity on the chemical composition of waters. The shallow nature of the siliceous rocks of the Styla Suite and the Rudov Beds, which are replaced by continental coal-bearing and bauxite-bearing deposits of the early Tula age, was previously pointed out by one of the author [5]. The work also discussed the main hypotheses regarding the possible causes of the abnormal chemical composition of water at this time. We believe that the Styla (Rudov) time is a special stage of the territory development of the modern Eastern European Platform (EEP), which corresponds to the early Tula maximum of bauxite formation (Mykhailov B. M., Vorontsov V. V., Galitskaya O. I. (1980)). During this phase, unique conditions arose due to the humid climate and the relatively stable tectonic environment. Intensive processes of lateritic weathering and the accumulation of significant amounts of organic matter in lakes and wetland conditions took place on land. Large quantities of organic matter and dissolved silica released during the lateritic weathering were discharged into the coastal zone located on the periphery of the territory of the modern EEP and also included the shallow water of the Dnieper-Donets gulf. As a result, specific siliceous-carbonate and siliceous-clay deposits with high organic matter content are often encountered, which are often considered as source rocks in DDD (Gavrish V. K., Machulina S. A., Kurilenko V. S. (1994)). Thus, the Rudov Beds should have a marked vertical differentiation, which is due to the variability facial coastal conditions. The authors of the paper [3] note the significant variability of the lithological composition of these lateral layers within their distribution within the territory of the DDD. However, they are noted by "fairly stable structure" in sections. Vertical differentiation is noted only by gamma activity and uranium, thorium and potassium content according to laboratory data.

The results of our studies, which will be discussed below, suggest a significant heterogeneity of the Rudov Beds by their physical and lithological characteristics. And according to petrophysical data, the differentiation is observed in all the wells. Each lithotype has a specific arrangement in the section of Rudov Beds and is characterized by lateral distribution.

Methods. We have investigated available geological and petrophysical materials from wells within the structure of the well-known Yablunivske oil and gas condensate field located in the central part of the DDD (Fig. 3). The size of the study area is approximately 6 ×12 km, with 15 wells selected for analysis (Fig. 4).

The wells have a complete set of logging methods, which are typical for prospect and exploration wells. This allowed us to evaluate the lithological and reservoir characteristics of the rocks in the section, to determine the variability of petrophysical parameters and to draw conclusions about certain lithofacial patterns of the Rudov Beds formation. All the wells revealed the sections of the lower and Upper Visean; the borders of the Yablunivka Suite of the carbonate platform and the Rudov Beds are clearly traced everywhere. Depths of beds are from 4371 to 5184 m.

For research, geological interpretation of the results, the following petrophysical data were selected: the diameter of the well Caliper (or Ds); the electrical resistivity by the potential probe PZ; the relative diameter of the well Caliper/Dbit, or Ds/Dn; interval time of acoustic wave DT; GRc gamma radiation exposure dose corrected (adjusted to well conditions); relative hydrogen content (neutron porosity) W; TOC total organic carbon content – as a result of well-logging data interpretation.

TOC estimation was performed using the well-known ΔRLog method by Q. Passey [12]. Adjustment and validation of the interpretation model was performed on the deposits of Rudov layers in the well 2-Rudovska using the results of core material analysis. Missing logging data on some methods were restored using the technology of artificial neural networks [13]. It should be noted that in terms of lithological and petrophysical characteristics, the sections of the Rudov Beds are identical for the Rudivske and Yablunivske oil/gas deposits. Fig. 5 shows a typical example of the well-logging charts in the section of the Rudov Beds.

In the well sections of the Rudov Beds borders, the petrophysical parameters are greatly variable (Fig. 5) vertically, indicating the significant variability of the facial sedimentation conditions. Moreover, in different wells of the Yablunivske field the changes in petrophysical parameters and TOC are significantly different. In Table 1 there are presented general pictures of the statistical distributions of the parameter values probabilities. For forming of representative sampling, the values from logging curves were taken in 0.5 m increments.

Significant differentiation of rocks by petrophysical or physical characteristics suggests that there are several lithotypes or varieties of terrigenous origin in the composition of the Rudov Beds (Table 1).

Literary sources [3] show that the ratio of uranium to thorium content is noticeably different in different parts of the layers.

The authors identify the lower part with the most abnormal radioactivity and the upper part of the Rudov Beds. As can be seen from Fig. 5, the rocks differ in strength: in the upper part of the layers the most fragile rocks (most probably clay) occur, in the lower part they are compacted, as some researchers have noted (Ogar, Babko, Misch, and others) [2, 3, 7] – related to the processes of silicification or increased carbonate content. Increasing the electrical resistivity, decreasing the neutron porosity and reducing the DT when approaching the plantar part of the layers also indicate the presence of compacted types of rocks. All this contradicts the view of some authors about the solid quasi-homogeneity of the Rudov strata.

By far, the best way to investigate the lithological-petrographic features and to identify individual types of rocks in the section is through direct laboratory testing or a description of the rocks. However, it is quite problematic to gather a collection of samples that would evenly characterize the entire thickness of the Rudov Beds. Therefore, well-logging data is the most informative and accessible for analysis here. Moreover, the detailed elaboration of the visible inhomogeneities in the logging curves

Fig. 3. Map of the Dnieper-Donets depression with the location of the Yablunivske oil and gas condensate field

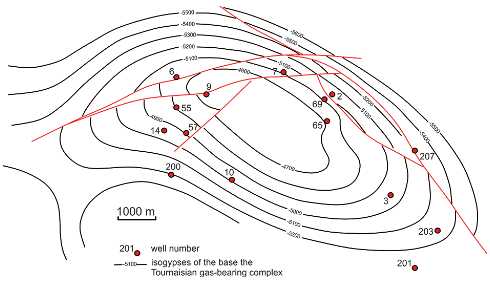


Fig. 4. Structural map of the base of the Tournaisian gas-bearing complex of the Yablunivske field (materials by Holovatski M., Baranovska N., Zyuzkevich M.)

Table 1

Statistical parameters of petrophysical characteristics and TOC of the Rudov Beds rocks in the wells of the Yablunivske field

Parameter	Mean	Min.–Max.	Std. Dev.
Depth, m	4685.3	4371–5184	211.8
DT, mks/m	286.2	166.1–402.3	29.4
Caliper, m	0.282	0.185–0.546	0.063
GRc, mkR/h	20.5	5.2–53	6.1
PZ, Ohm · m	21.1	3.6–64	9
TOC, %	3.1	0.03–5.9	1.1
W	0.3	0.08–0.4	0.04
Caliper/Dbit	1.44	1.0–2.87	0.34

allows us to claim that at least 3 classes of rocks with their physical/petrophysical characteristics are present (Fig. 5). For formal, maximum independent of human factors, the classification procedure of the Rudov Beds rocks, or the allocation of individual classes of lithotypes, effectively use methods of statistical analysis – cluster analysis K-means, or other methods of uncontrolled classification. Generally, using the uncontrolled classification method for a number of petrophysical and geological features, we will be able to estimate the degree of heterogeneity of the Rudov Beds and determine how much they are heterogeneous laterally and vertically, or whether there are certain trends in the distribution of individual lithotypes within this oil and gas reservoir. For a more diverse diagnosis and modeling of the relationships between the individual parameters of the Rudov Beds, a statistical analysis of all available data was performed using the principal component method. The results are shown in Table. 2. The first three factors (major components) control 81 % of the total variance of features.

While interpreting the matrix of the parameters' own loadings for each factor, we can come to the following conclusions. Factor 1 – can uniquely be interpreted as a clay factor, here is a significant effect of the diameter of the well, and the resistivity with another sign, and the relative content of hydrogen. Moreover, various signs of loadings exactly match the ideas

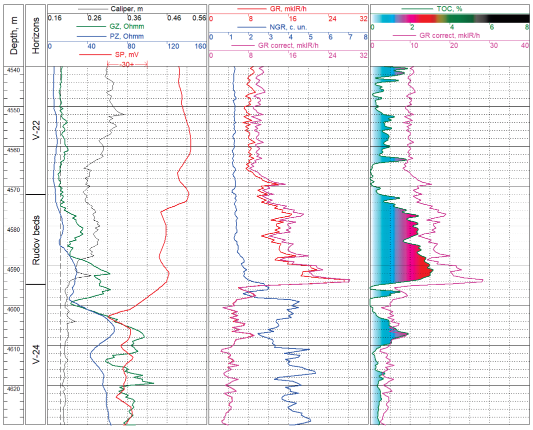


Fig. 5. Well-logging charts and the results of interpretation in the interval of the Rudov Beds occurrence in well 3-Yablunivska

about the behavior of the listed properties while the changing the clayness of rocks.

The second factor is uniquely related to the TOC – organic carbon content. It should be noted that within the Rudov Beds of the Yablunivske oil-gas field this important parameter does not correlate with other characteristics. That is, the specific facial conditions for the organic material accumulation were unlikely to be related to the deposition of clay substance.

The third factor is the natural gamma activity (Table 2). Its variability in the section of the Rudov Beds has its own peculiarities: first of all, a significant increase in the value of GRc is closer to the bottom of the layers, reaching a maximum at the boundary of the layers with the Visean platform. Such elevated anomalies in gamma-ray curves are sometimes observed over the boundaries of erosion surfaces. This characteristic anomaly of the GR in the bottom of the Rudov Beds is known as the regional rapper V3R.

Table 2

Matrix of own loadings (factor coordinates) according to the results of data analysis using the principal component method

Parameter	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
DT	**–0.68**	–0.56	0.07	0.29	0.34
GRc	0.34	–0.07	**–0.86**	0.36	–0.09
PZ	**0.76**	–0.28	–0.24	–0.45	0.24
TOC	0.02	**–0.95**	–0.02	–0.11	–0.23
W	**–0.88**	–0.02	–0.16	–0.27	–0.23
Ds/Dn	**–0.72**	0.21	–0.53	–0.25	0.16

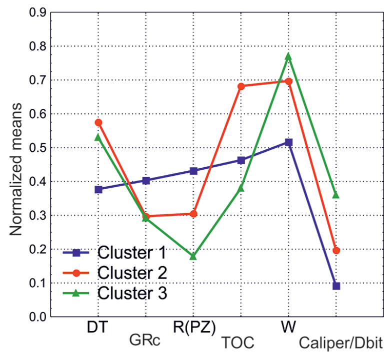


Fig. 6. Distribution of mean normalized values of initial parameters for each lithotype (class) of rocks by the results of cluster analysis

Table 3

Mean values of parameters for each of the obtained classes by the results of cluster analysis. The Rudov Beds, Yablunivske field

Parameter	Claster 1	Claster 2	Claster 3
DT, mks/m	**255.3**	**302.1**	291.3
GRc, mkR/h	**24.4**	19.4	19.1
PZ, Ohm·m	**29.6**	22.0	**14.4**
TOC, %	2.8	**4.1**	2.3
W	**0.246**	0.305	**0.329**
Caliper/Dbit	**1.18**	1.37	**1.68**

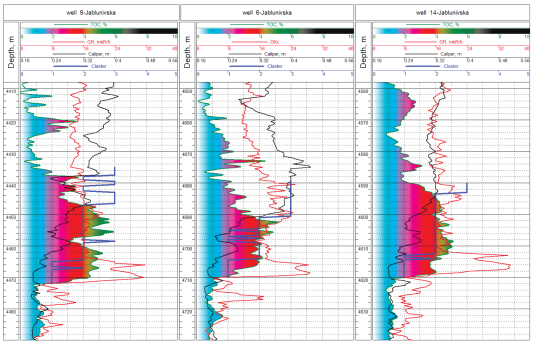


Fig. 7. Distribution of lithotypes (clusters) in the Rudov Beds sections in wells No. 9, 6, 14 of the Yablunivske field. Claster numbers correspond to the values on the blue broken line

After the preliminary procedure of statistical analysis of the whole assemblage of logging data on the Rudov Beds and the identification or confirmation of thoughts about the presence of individual lithofacial groups of rocks, we can proceed directly to the procedure of formal uncontrolled classification.

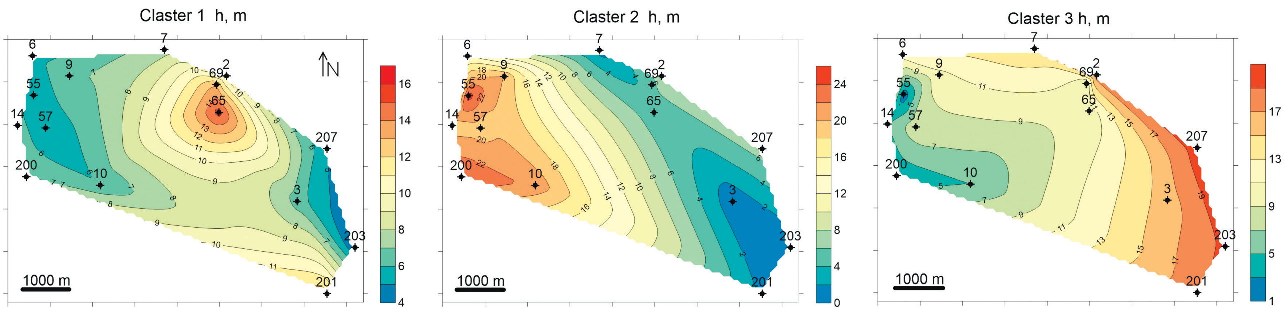
The analysis of the results of cluster analysis with a predetermined number of groups 2, 3, 4, 5 allowed us to choose the optimal number of classes – 3, which we will call as lithotypes of rocks. Confirmation of the correct number of classes for this sample is obtained by histograms of distributions of geological and geophysical parameters, which indicate significant differences in the statistical characteristics of different lithotypes (Fig. 6).

Table 3 shows the mean values of the parameters obtained for each class. These data were used to geologically interpret the classification results and to determine the geologic content and features of each class (lithotype). The mean values of the parameters, which are the most characteristic, "anomalous" relatively to other classes, are determined in bold (Table 3) and specify the individual feature of each lithotype.

Due to such differentiation, each cluster lithotype has a number of features that allow them to be identified as follows:

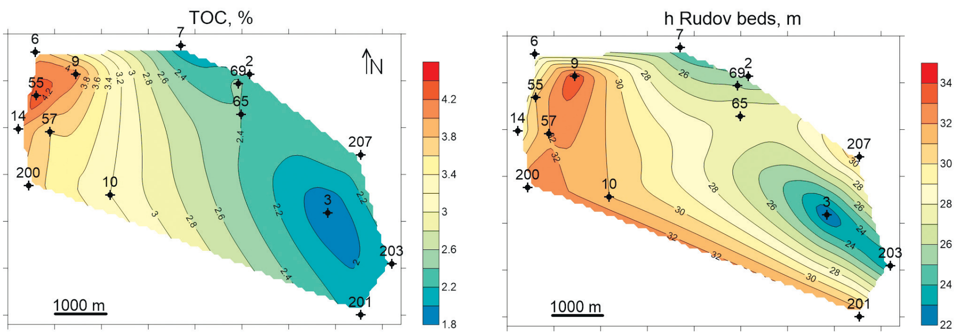
Cluster 1. Lithotype associated with compacted varieties enriched in siliceous and carbonate matter [6, 10]. The compaction is expressed in minimum of the relative diameter of the borehole, the lowest values of the interval time DT and the relative hydrogen content W. That is, the content of the clay component is also minimal here in the Rudov Beds cross. The most characteristic feature is abnormally high radioactivity, with an average of 24.4 μR/h, which is observed, as already noted, in the lower part of the Rudov Beds.

The result is quite unexpected, as most geophysicists and geologists searching for and exploring hydrocarbon deposits in DDD, traditionally believe that the characteristic "hurricane" values of gamma radioactivity in the sole of the Rudov layers are a reflection of the anomalous content of organic matter. However, here, most likely, the high content of uranium and thorium is due to the accumulation of their concentrations in specific paleofacial coastal conditions of the formation of sediments of the lower part of the strata.



a *b* *c*

Fig. 8. Lateral distribution of thickness 1, 2, 3 of lithotypes (clusters) of the Rudov Beds within the Yablunivske oil and gas condensate field:
a – lithotype No. 1; b – lithotype No. 2; c – lithotype No. 3



a *b*

Fig. 9. Lateral distribution of total organic carbon (TOC) and thickness of Rudov Beds at the site of the Yablunivske oil and gas condensate field:
a – TOC distribution, %; b – distribution of thickness, m

Cluster 2. These are mainly clay rocks. However, most petrophysical parameters, their means, are associated with the highest organic matter content. The average TOC values here are 4.1 %, which corresponds to an organic matter concentration of about 10 %. The high organic content significantly raises the average readings on the time interval curve – up to 302.1 µs/m. And at depths more than 4300 m, it is definitely a reflection of the high concentration of kerogen. This lithotype has the greatest oil and gas potential in the composition of the Rudov Beds. It is likely that the maximum amount of shale oil/gas is concentrated in the rocks of the second type. The rocks of this lithotype are inherent in the central part of the layers.

Cluster 3. By all characteristics it is the most argillaceous one with the lowest content of organic matter. The maximum values of the borehole, the relative content of hydrogen, the minimum values of the electrical resistivity are typical signs of clay rocks in the well sections according to the well-logging data. The rocks of this lithotype are mostly found in the upper part of the Rudov Beds.

Fig. 7 shows the distribution of selected lithological types (clusters) of rocks by the well sections of the Yablunivske field in the Rudov Beds (blue broken line). Here, the values on broken line 1, 2, 3 correspond to the cluster numbers marked in the text. A characteristic feature of each lithotype is its specific age and spatial place in the thickness of the Rudov Beds (Fig. 7).

In Fig. 8 in accordance with the results of the cluster analysis and the automated (formal) classification of rocks in the section, a map diagram is presented of the distribution of the total thickness of individual lithological types within the section of the Yablunivske oil and gas condensate field. Interestingly enough, the thicknesses of individual lithotypes undergo significant changes within a relatively small area of 12 km long. This is another confirmation of the shallow water, perhaps lake and lagoon environment during the accumulation of Rudov deposits. In the local area near wells 65, 69, the thickness of the compacted rocks, attributed to 1 lithotype, increases sharply by several times. The log data objectively confirms all the detected spatial inhomogeneities of the layers studied.

The lateral distribution of the organic matter content (or organic carbon – TOC) and the total thickness of the Rudov Beds changes naturally in the southeast-northwest direction (Fig. 9) [14].

Conclusions. The study on the features of the Rudov Beds structure according to well logging at the Yablunivske oil and gas condensate field allows establishing the spatial distribution of the content of organic matter (kerogen, or TOC – organic carbon content) and the total thickness of the rocks. Significant variability of the total thickness and TOC has been established, which is a confirmation of the hypothesis of the shallow water desalinated sea gulf conditions during the period of sediment and organic matter accumulation in the Rudov Beds. The method of cluster analysis identifies three characteristic lithotypes of rocks that have a certain spatial position in the Rudov Beds. The gamma radioactivity of the layers as a whole has almost no significant correlation with the content of organic matter; its magnitude is subject to the specific genetic conditions associated with the accumulation of natural radioactive elements in the thickness of the Rudov Beds.

It should be noted that in the absence of data analysis of rock material, conclusions about the lithological and facial features of the Rudov Beds are based on the results of well-loggind data interpretation. In the near future, it is expected to obtain laboratory studies of the core, which will allow for a deeper and comprehensive assessment of the formation peculiarities of the Rudov deposits.

The method of cluster analysis identified three characteristic lithotypes of rocks that have a certain spatial position in the Rudov Beds. The gamma-radioactivity of the layers as a whole has almost no significant correlation with the content of organic matter; its value is the subject to specific genetic conditions associated with the accumulation of natural radioactive elements in the thickness of the Rudov layers.

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Розчленування рудівських шарів на основі статистичних методів за геолого-геофізичними даними

О. М. Карпенко[1], *В. В. Огар*[1], *І. О. Карпенко*[2], *І. М. Безродна*[1]

1 – Київський національний університет імені Тараса Шевченка, м. Київ, Україна, e-mail: karpenko.geol@gmail.com
2 – Національна акціонерна Компанія «Нафтогаз України», м. Київ, Україна

Мета. Виконати літолого-фаціальне розчленування рудівських шарів із використанням даних геолого-геофізичних досліджень свердловин для уточнення генезису формування нафтогазоматеринської товщі в межах Яблунівської структури Дніпровсько-Донецької западини.

Методика. Були застосовані методи кластерного й факторного аналізу; методика К. Пассі інтерпретації даних геофізичних досліджень для оцінки вмісту органічного вуглецю (TOC).

Результати. Встановлені особливості геологічної будови, літологічних неоднорідностей, поширення окремих літотипів і вмісту органічного вуглецю в рудівських шарах у межах Яблунівського нафтогазоконденсатного родовища. Досліджене просторове поширення окремих фаціальних типів порід, товщина їх шарів радіоактивності та вмісту органічного вуглецю (органічної речовини) у межах окремої структури Дніпровсько-Донецької западини.

Наукова новизна. Уперше за даними геофізичних досліджень свердловин із використанням статистичних методів виконано літолого-фаціальне розчленування нафтогазоматеринської товщі, що має регіональне розповсюдження в межах Дніпровсько-Донецької западини. Встановлена відсутність тісного зв'язку між природною радіоактивністю та вмістом органічного вуглецю в рудівських шарах нижнього карбону. Зроблені певні висновки, що стосуються підтвердження гіпотези про утворення рудівських шарів в умовах мілководної опрісненої морської затоки.

Практична значимість. Запропонований підхід щодо літолого-фаціального розчленування рудівських шарів з використанням даних геофізичних досліджень дозволяє уточними умови формування нафтогазоматеринської товщі з метою оцінки її реального нафтогазогенераційного потенціалу.

Ключові слова: *рудівські шари, Дніпровсько-Донецька западина, геофізичні дослідження, органічний вуглець, фаціальні умови, кластерний аналіз, радіоактивність*

Расчленение рудовских слоев на основе статистических методов по геолого-геофизическим данным

А. Н. Карпенко[1], *В. В. Огарь*[1], *И. А. Карпенко*[2], *И. Н. Безродная*[1]

1 – Киевский национальный университет имени Тараса Шевченко, г. Киев, Украина, e-mail: karpenko.geol@gmail.com
2 – Национальная акционерная Компания «Нафтогаз Украины», г. Киев, Украина

Цель. Выполнить литолого-фациальное расчленение рудовских слоев с использованием данных геолого-геофизических исследований скважин для уточнения генезиса формирования нефтегазоматеринских толщ пределах Яблуновской структуры Днепровско-Донецкой впадины.

Методика. Были применены методы кластерного и факторного анализа; методика К. Пасси интерпретации данных геофизических исследований для оценки содержания органического углерода (TOC).

Результаты. Установлены особенности геологического строения, литологических неоднородностей, распространения отдельных литотипов и содержания органического углерода в рудовских слоях в пределах Яблуновского нефтегазоконденсатного месторождения. Исследовано пространственное распространение отдельных фациальных типов пород, толщина их слоев радиоактивности и содержания органического углерода (органического вещества) в пределах отдельной структуры Днепровско-Донецкой впадины.

Научная новизна. Впервые по данным геофизических исследований скважин с использованием статистических методов выполнено литолого-фациальное расчленение нефтегазоматеринской толщи, имеющей региональное распространение в пределах Днепровско-Донецкой впадины. Установлено отсутствие тесной связи между естественной радиоактивностью и содержанием органического углерода в рудовских слоях нижнего карбона. Сделаны определенные выводы, касающиеся подтверждения гипотезы об образовании рудовских слоев в условиях мелководного опресненного морского залива.

Практическая значимость. Предложенный подход в отношении литолого-фациального расчленения рудовских слоев с использованием данных геофизических исследований позволяет уточнить условия формирования нефтегазоматеринской толщи с целью оценки ее реального нефтегазогенерационного потенциала.

Ключевые слова: *рудовские слои, Днепровско-Донецкая впадина, геофизические исследования, органический углерод, фациальные условия, кластерный анализ, радиоактивность*

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