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ANALYSIS OF THE POROSITY PARAMETER USING ELEMENTS OF REGIONAL PETROPHYSICS (ELECTROFACIES) AND CLAYINESS TYPE

The most important calculation parameter, the open porosity ratio (K_p), is generally determined in petrophysical laboratories for the object (stratum) as a whole and without taking into account its regional heterogeneity. A range of the porosity value is taken as a basic criterion for selecting samples to construct the model $R_p = f\left(K_p\right)$ K_p. In this case it is assumed that: the higher ΔK_p is, the higher the validity of the relation $R_p = f\left(K_p\right)$ is. However, in practice such a concept often creates an ambiguity in determining K_p the porosity by electric resistivity of water saturated samples in different wells, even within one field. This phenomenon is caused by underestimating the features of the regional petrophysics object, the facies, which are reflected in the form of well logging curves, including SP, and the element of the general petrophysics object – the clayiness type. The breakdown (classification) of the formation by facies, determination and taking into consideration the type of clayiness, as well as distinguishing and analyzing the petrophysical types of rock based on rock porosity and permeability characteristics within the formation, make it possible to obtain satisfactory relations between electric resistivity and porosity of K_p the rock.

Keywords: open porosity, electric resistivity, facies, clayiness.

INTRODUCTION

The estimated and actual data for calculating the reserves and production of raw hydrocarbons depend, in addition to the quality of sampling and experimental set up, on the degree of approximation of the results of petrophysical studies to the real situation. Frequently, porosity in the comparison planes K_p with R_p and K_p with geophysical well logging data is not differentiated adequately. There are at least two reasons for this discrepancy.

Firstly, in the summary analysis of dependencies of K_p with petrophysical data and geophysical well logging data, regional factors that sometimes have a decisive impact on the petrophysical properties of rocks, are not taken into account by geophysicists (or petrophysicists). First of all, there are such features as: type of clayiness (structured, layered, dispersed), the specific surface of the pore channel, the value of its tortuosity, and shape of the packaging of rock particles, and the "maturity" degree of rocks. All these parameters are not included in the standard set of laboratory studies due to the complexity and lack of time to determine them. Nevertheless, the nature of the flow of fluid and electrical charge in mudded rocks is greatly determined by the combination of these symptoms. The magnitude and variation of these characteristics are defined by the conditions of the sedimentation. Various parts (elements) of the same layer (object) may belong laterally to different geological bodies which were formed in different paleogeographic conditions with their own dynamics of sedimentation, redox, and acid-base environments. A different lithogenesis situation provided the rock with properties that are characteristic only to these sedimentation conditions. Petrophysical characteristics, including electrical, are not an exception.

Secondly, the adequacy between the above parameters is violated for a trivial reason – poor sampling (core) within the stratum (object) section for laboratory research purposes. We can agree that a perfect selection of samples is not possible. However, petrophysicists should draw the attention of experts, using the results of laboratory studies, to the unsystematic sampling and examination of samples.

The objective of this work is an attempt to identify the nature of the variation only of $R_p = f\left(K_p\right)$ dependence that is defined for the homonymic layer on different wells within the same deposit.

General and regional petrophysics. The object and subject of general and regional petrophysics

Before proceeding to the analysis of K_p and R_p, we need to formalize the concepts related to ***the general*** and ***regional petrophysics*** and their objects and subjects. This is due to the fact that in petrophysical literature there is still no clear distinction between objects and subjects of both general and regional petrophysics, which is a consequence of the weak development of a systematic approach in terms of the theoretical framework of petrophysics.

Petrophysics is a geological cycle science. This means that it studies the geological environment (GE), which is determined as an object of petrophysics. The body of knowledge on the object is regarded as the subject of science. In the published materials the term "geological environment" is reduced to the following definition: the GE – is a mineral substance in solid, liquid and gaseous states, and the physical fields inherent to it. The GE is characterized by attributes such as structure, properties, and motion (chemical and physical processes). The GE includes the concept of "rock" as a phase system consisting of solid, liquid and gaseous phases.

It should be noted that geologists understand only the solid phase as the rock [14, 15, 18]. In order to be able to distinguish the concept of the rock in the geological and petrophysical aspects, it is necessary to further formalize this concept. The term "reservoir" is also not suitable for a petrophysical understanding of the rock – it increases, without any doubt, the scope of the concept, but at the same time limits significantly its content.

One of the important features of the GE is its variability over time and space [10]. Variability causes heterogeneity of the object, which is determined by the difference in its properties at different points. G.K. Bondarik [11] writes: "The heterogeneity is detected by comparing the elements of the set with respect to certain properties, by establishing the measures of similarity and relation between elements". For example, it is possible to select the GE heterogeneity based on its different parts (elements) belonging to a different formations (facies) and, as a consequence, to detect the heterogeneity of its physical properties.

Petrophysics, which has GE as its object, studies primarily the (petrophysical) rock, its material composition, structural and textural features, physical, chemical and mechanical properties, and changes in these properties over time (for example, in the process of deposit development).

Following the logic of the system approach, the science of "petrophysics" should be divided into at least two areas: ***general petrophysics*** and ***regional petrophysics*** (there is also general geology and regional geology, general hydrogeology and regional hydrogeology, general soil science and regional soil science, etc.). Each section shall have its own object and system of knowledge (theory, methodology, and application attributes).

From a formal point of view, the basis of ***general petrophysics*** should consist in teaching about the nature and the principles of the formation of the material composition, structural and textural characteristics and properties of (petrophysical) rocks during lithogenesis, and human engineering activities. The system of this science includes the theory and modeling of the formation of the composition, state, structural and textural distinctive features and properties of (petrophysical) rocks. Although the GE is an object of general petrophysics, it is regarded as *a system of attributes*, which has neither physical volume, nor fixed coordinates in geological space (for example, classification of rocks by permeability, density, Young's modulus).

Often, when analyzing this petrophysical characteristic, it is generally considered within the entire stratum without regard to heterogeneity of the stratum itself (belonging of different parts of strata to the different facies). The analysis results using such an approach are often contradictory and ambiguous.

The above difficulties can be overcome (or minimized) if the properties of the (petrophysical) rocks are analyzed using the knowledge system ***of regional petrophysics***. Following on from G.K. Bondarik (1981) who developed a general theoretical foundation for engineering geology, we believe that the basis of the subject of regional petrophysics should be a system of knowledge on the principles of spatial distribution of (petrophysical) rocks, on the principles of spatial variability of their composition, state and properties, and on the nature of the formation of spatial patterns. In contrast to general petrophysics, regional petrophysics should represent the rock not only in the attribute space, but also in geological space. It should consider the rock as a geological body occupying a fixed position in geological space. The object of regional petrophysics are *the geological bodies* selected by a real factor. The geological bodies, their structure, material composition and properties are the result of the interaction of physical fields of a specific dynamic system. Therefore, the properties of geological bodies formed in different paleogeographic conditions reflect the characteristic inherited features that are unique to these conditions.

Separating general petrophysics from the regional framework leads to a measuring technique for rock parameters that is only used in statistical calculations. Calculations are aimed mainly at obtaining a high degree of reliability of approximation of the compared parameters, therefore projected and actual results are often difficult to explain.

K_p and R_p were analyzed taking into account the features of the attribute and geological spaces. In the attribute space, in addition to porosity, the clayiness type is considered, as well as in integral form – a specific surface of the pore channels, their tortuosity, the form of packing of structural rock-forming elements and in the geological form – the facies. The division of the GE by material composition and formation conditions in the aspect of regional petrophysics presents certain difficulties in terms of methodology and requires considerable material and financial costs. Therefore, on the basis of practical tasks, the geological bodies were selected based on the facies, which, in turn, were diagnosed with the use of SP (spontaneous potentials) curves. The technique of determining the facies with SP data (hereinafter – electro-facies) for solving geological issues is given in detail in the well-known monograph from V.S. Muromtsev [19].

Research methods and results

$R_p = f\left(K_p\right)$ was analyzed for Yu2 stratum on the 215, 318, 417, 613 and 1610 wells of Vyngapurovsky deposit.

Sediments of Yu2 reservoir formation within well 215 are presented by light gray, sometimes with a brownish color tone, fine-grained silt and silty sandstone with clay and carbonate-clay cement. The structure is predominantly massive. Thin interlayers of carbonaceous-micaceous and clay material occur, concretions of siderite, carbonaceous plant detritus and pyrite inclusions are noted.

Yu2 reservoir formation near the well 215 consists of light gray and brownish-gray fine-grained and moderately fine-grained silt and silty sandstone with clay and carbonate-clay cement. Interlayers and lenticules of carbonaceous-micaceous and clay material occur. The structure is massive, discontinuous and undulated, gently sloping undulated and lenticular. Alluviations of carbonaceous-micaceous material, siderite

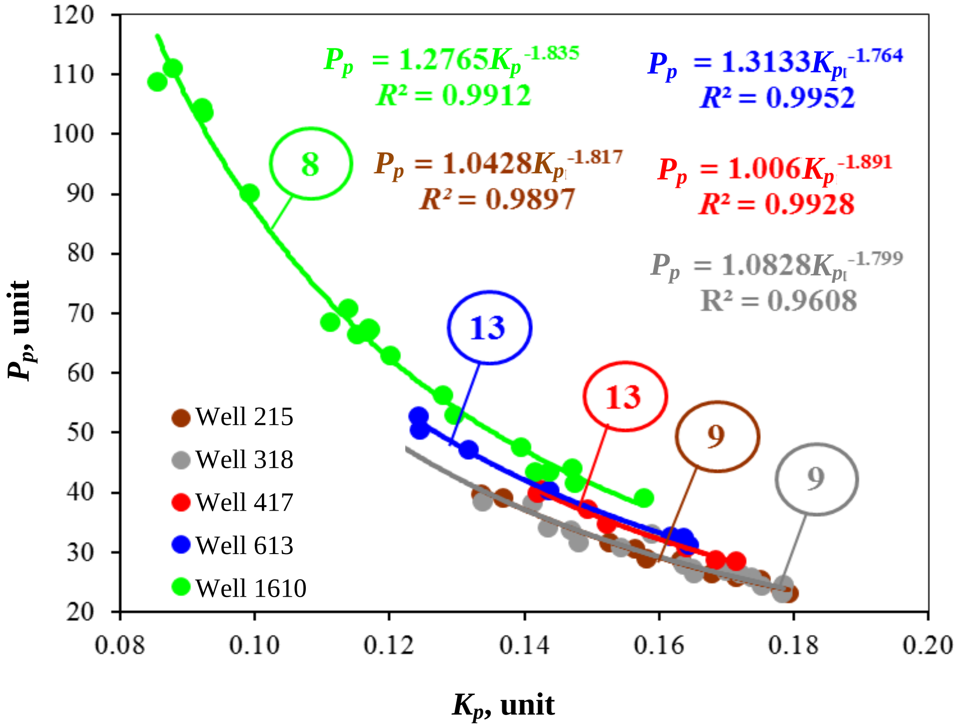


Fig. 1. Comparison of the porosity parameter (P_p) and open porosity (K_p) for the rocks of Yu2 layer of Vyngapurovsky deposit.

concretions and debris of coalified wood are noted.

The rocks of Yu2 reservoir formation exposed by well 417 represent a gray fine-grained silt and silty sandstone with uneven clay interlayers, sometimes changing into a fine- and coarse-grained sand siltstone with clay cement. The structure is mainly microlaminated.

Alluviations of carbonaceous-micaceous material and dark gray silty argillite interlayers are noted in thicknesses of 1 mm to 2 cm. Siderite is developed largely on alluviations. Traces of burrowing organisms are observed.

The collector of Yu2 layer in the well section 613 is composed of light gray fine-grained silt sandstone with clay and clay-carbonate cement, and light-gray fine-coarse-grained siltstone with a clay cement. Carbonaceous plant detritus and carbonaceous-micaceous material, thin slices and lenticules of clay matter are found in the sandstone, the passage ways of burrowing organisms made by clay matter are marked. Numerous slices and lenticules of clay material and carbonaceous plant detritus and aggregates of pyrite and siderite concretions occur in the siltstone.

Sediments of Yu2 reservoir formation exposed by well 1610 represent a light gray fine-grained silt sandstone with carbonate-argillaceous and argillaceous carbonate cements with occasional thin slices of micaceous-carbonaceous material, accentuating the parallel horizontal flazer bedding. Carbonaceous plant detritus is noted.

The composition and shape of Yu2 reservoir rocks imply that the sedimentation paleoenvironment in areas of dislocation of wells 215, 318, 417, 613 and 1610 are, to some extent, different from each other. At first glance, it could be assumed that the difference in the environment of GE formation predetermined the heterogeneity of the petrophysical properties of rocks.

Fig.1 presents a comparison of K_p and R_p by 5 wells (to make it easier to read, graphics data are not presented in a logarithmic scale). It can be seen that the points representing K_p and R_p do not belong to the single curve, but are divided into three groups: 1st group – wells 215 and 318; 2nd – wells 417 and 613; 3rd – well 1610.

We will try to understand why the relation between K_p and R_p is so different within the same reservoir in terms of laterality.

Reason No. 1 − external. SP data indicate that the shape of the curves within the studied formation differs significantly from well to well. Numerous domestic and foreign published materials show that the shape of the SP diagram is closely related to the sedimentation environment and the different geological parameters [2–9, 12, 13, 16, 17, 18, 20, 21, 23, 24]. After completing analysis of the SP waveforms according to Muromtsev [19] for this formation, we managed to identify 3 electrofacies (Figure 2): 8 shores (well 1610), 9 – coastal banks (wells 215 and 318), 13 headers of rip flows (wells 417 and 613).

It is also known that the clay type, and the quantity and composition of clay often have a decisive importance on the value of the electrical resistance of rocks. Unfortunately, to date, there has been no comprehensive study of the clayiness of oil deposit rocks.

Fig. 3 shows the result of the mass determination of the type of distribution of clayiness of Yu2 reservoir of wells J2 215, 318, 417, 613 and 1610. The algorithm for establishing the type of clay is very clear from the figure. In the layered distribution, the clay particles replace the sandstone grains and fill the pore space; for diffused dissemination the clay particles fill only the pore space and in the structural – clay minerals replace only the sandstone grains (Fig. 4).

With the same clayiness index (K_{cl}), the capacitive properties of rocks are defined as follows: in laminated clay volume $K_p = K_{cl}^{\max}\left(1 - K_{cl}\right)$, in dispersed – $K_p = K_{cl}^{\max} - K_{cl}$, in structural – $K_p = K_{cl}^{\max}$ [22]. Fig. 3 also shows that dispersed clay predominates in wells 215, 318, 417, 613 and 1610. Clay minerals dispersed in the pore space can occur in the form of individual particles, coatings of sandstone grains (this promotes the appearance of fused clay crystalline coatings on the grains) and crystalline streaks or bridges of clay minerals within the rock pore space (Fig. 5). For all these types of clay distribution in the pore space of rocks, the specific and extremely strong influence of clays on the permeability of the formation is characteristic (Fig. 6). For example, with the same porosity, the clay streaks in the pore space are characteristic mainly for dense rocks (with less than 1 mD permeability). Clay coatings on the surface of the sandstone grains have rocks with permeability of 1 to 200 mD. In the presence at the pore space of discrete clay particles, permeability increases significantly and reaches 100 ... 1000 mD that is inherent in clean rocks. In other words, the permeability of the reservoir is highly dependent on the type of distribution of clay minerals in the pore space [22].

For analysis of resistance, porosity and permeability of the Yu2 formation J2, petrophysical types of rocks are selected (Fig. 6). For this purpose, the theoretical and empirical findings of Poiseuille, Darcy, Kozeny and Karman are used explaining the dependence of permeability on porosity:

$$K_{perm} = \frac{K_p^3}{(1-K_p)^2} \times \frac{1}{F_s \tau^2 S_{gv}^2}, \qquad (1)$$

where F_s is the coefficient depending on particle packing shape, τ^2 is pore tortuosity, $F_s\tau^2$ is the Kozeny constant, S_{gv}^2 is the surface area of particles in the rock unit volume minus pore space [1].

Transforming the equation (1), we obtain:

$$0,0314\sqrt{\frac{K_{perm}}{K_p}} = \frac{K_p}{1-K_p} \times \frac{1}{\sqrt{F_s}\,\tau \cdot S_{gv}} \qquad (2)$$

where 0.0314 constant is the conversion factor from square micrometer to mD.

In the formula (2) the expression $1/\left(\sqrt{F_s}\,\tau \cdot S_{gv}\right)$ is a hardly determinable parameter. Let us denote it as FZI (F_{zi}) – flow zone position indicator. Ratio $\left(K_{perm}/K_p\right)^{0,5} - RQI$ is the index

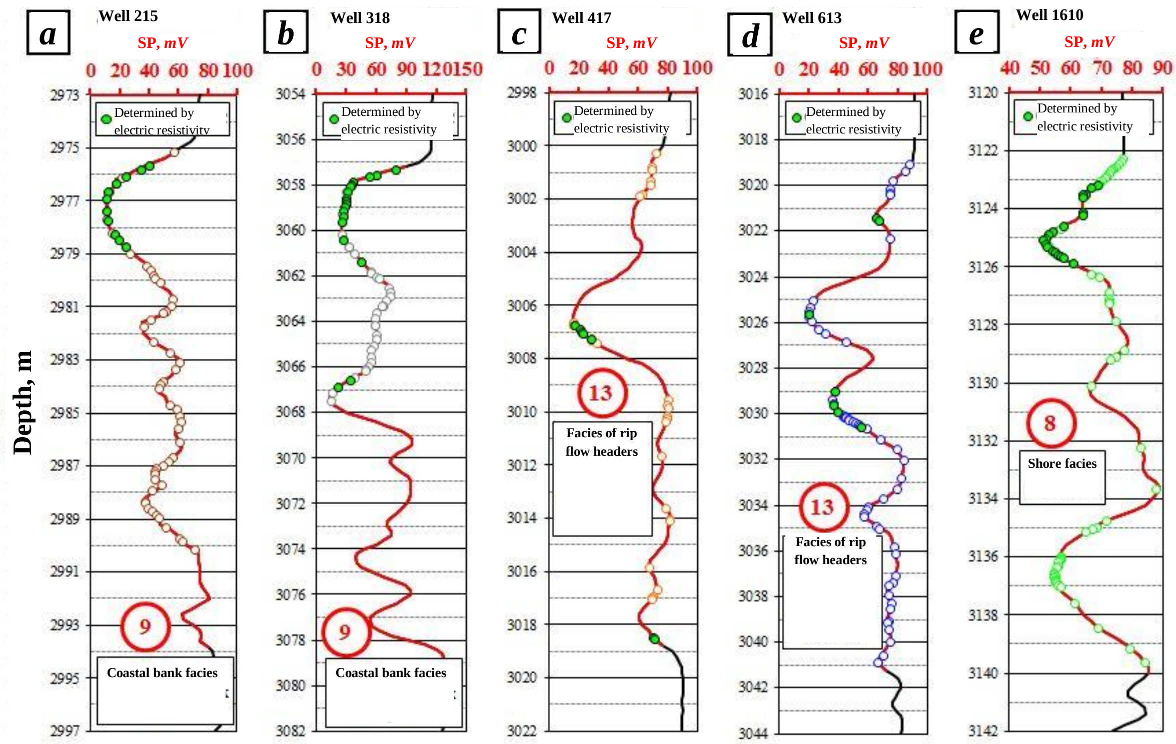


Fig. 2. SP data for Yu2 reservoir formation of wells 215 (*a*), 318(*b*), 417 (*c*), 613 (*d*) and 1610 (*e*) of Vyngapurovsky deposit.

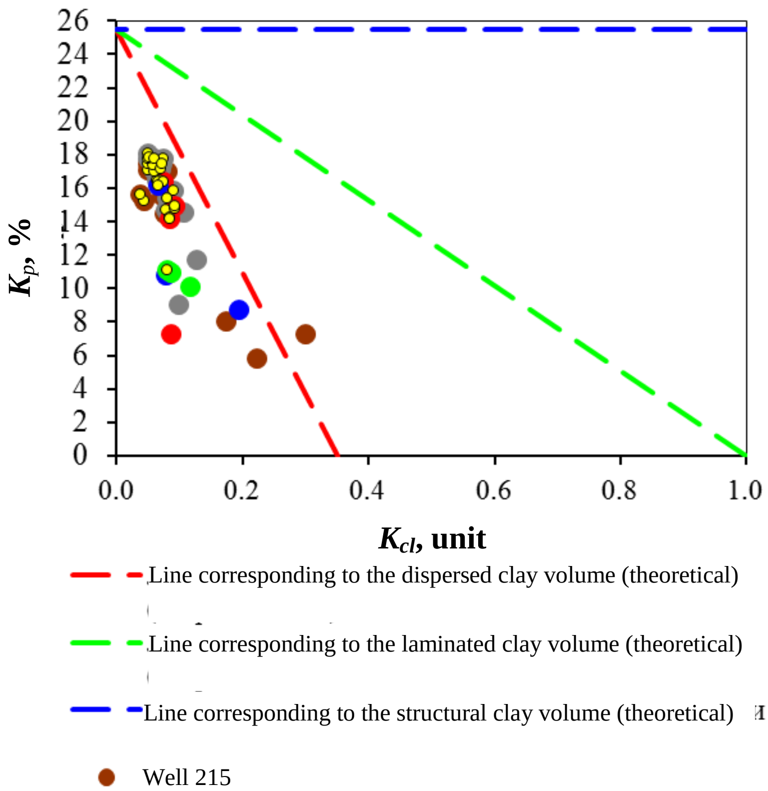


Fig. 3. Comparison of clay volume (K_{cl}) and open porosity (K_p)) for rocks of Yu2 reservoir formation of Vyngapurovsky deposit.

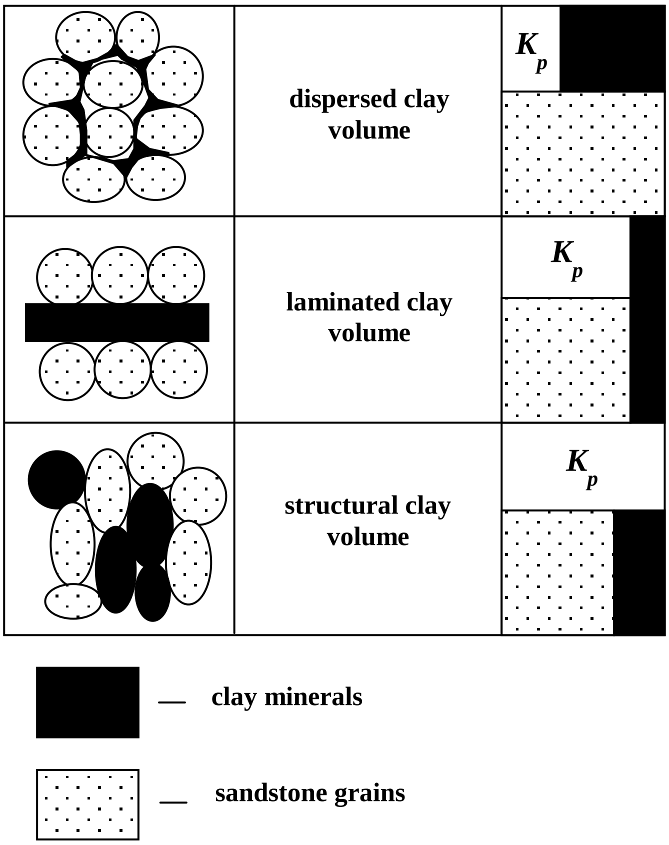


Fig. 4. Types of clay distribution in the clayey sandstone and their influence on porosity [3].

(indicator) of reservoir quality or I_{rq}.

Then, equation (2) will take on the following form;

$$I_{rq} = K_z F_{zi}, \quad (3)$$

where $K_z = K_p/(1 - K_p)$.

These conversions are required in order to evaluate, firstly, the reservoir quality, and, secondly, the values F_s, τ^2 and S_{gv}^2, on which the permeability and electrical resistivity of rocks largely depend [1].

Fig. 6 shows that in the rock samples of Yu2 reservoir formation where electrical resistivity is determined, dispersed clay covering grains mainly predominated (wells 215 and 318). The rocks of the same formation of wells 417 and 613 are distinctive, in that clay forming streaks predominate in the pore space. In the rocks of well 1610 there are two above types of clay distribution. With equal capacitive properties, rock with dispersed clay covering the grains transmits better electrical charges than rocks with dispersed type of clay in the pore space, forming streaks. This is confirmed by the graphs in Fig. 1. The exceptions are the rocks of well 1610, in which the high content of clay and carbonates exerts a decisive influence on the value of electric resistance of rocks (Fig. 7).

This inadequacy between electrical resistance, permeability and porosity is primarily due to unequal conditions of sedimentation in different parts of the Yu2 formation and subsequent lithogenetic transformations. The difference in sedimentation environment, in turn, has determined the regional heterogeneity of petrophysical properties within the reservoir under consideration. The consequence of this is a high variation in ratio R_p and K_p in comparison with different parts of the formation.

Reason No.2 – internal and external. An important point distorting the interpretation results of data R_p and K_p is often a lack of

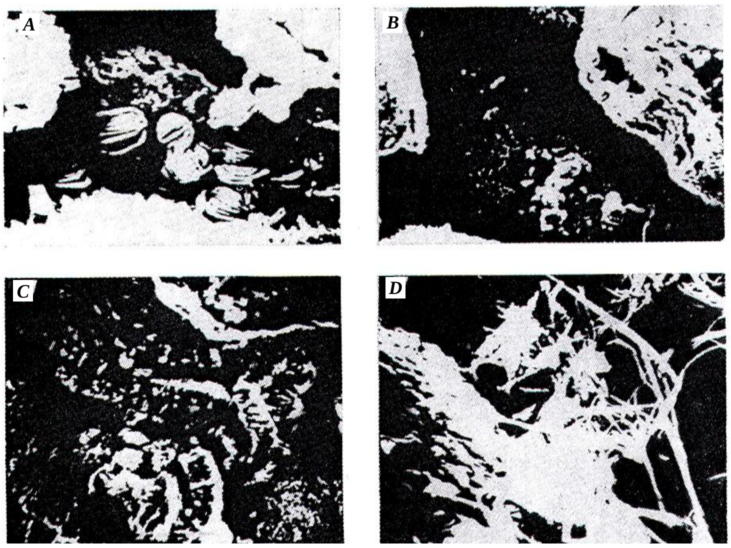


Fig. 5. Examples of distribution of clay minerals occurring in the pore space in the rocks in dispersed form according to V.H. Fertlu:

A – partial filling of the pore space by autologous kaolinite crystals; *B* – smectite film on the surface of the sandstone grains; *C* – authigenic chloride covers the surface of the grains and fills the pore space of rocks; *D* – filling the pore space of rocks by authigenic illite

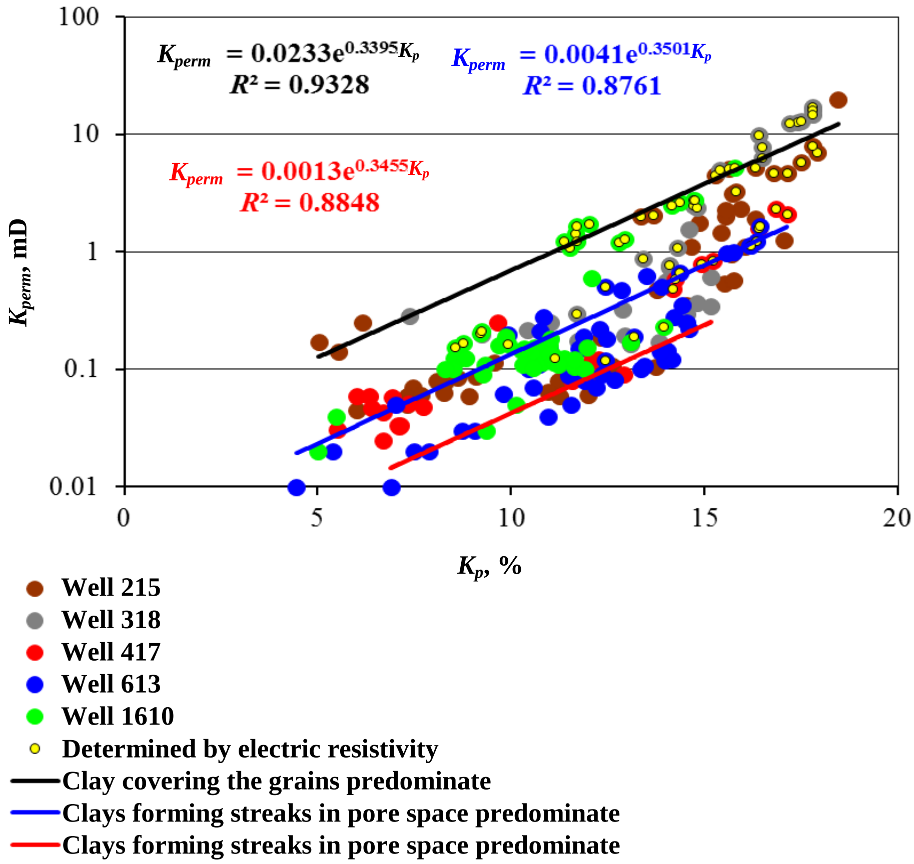


Fig. 6. Dependence between open porosity (K_p) and gas permeability (K_{perm}) for rocks of Yu2 formation of Vyngapurovsky deposit.

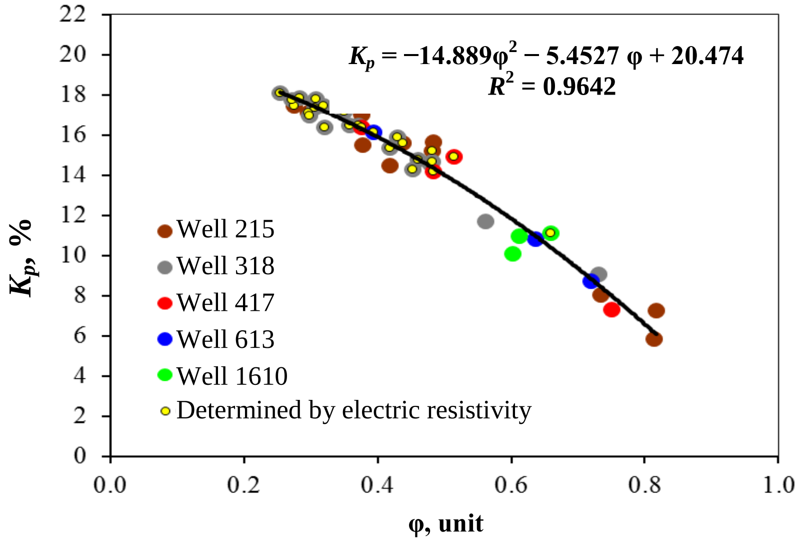
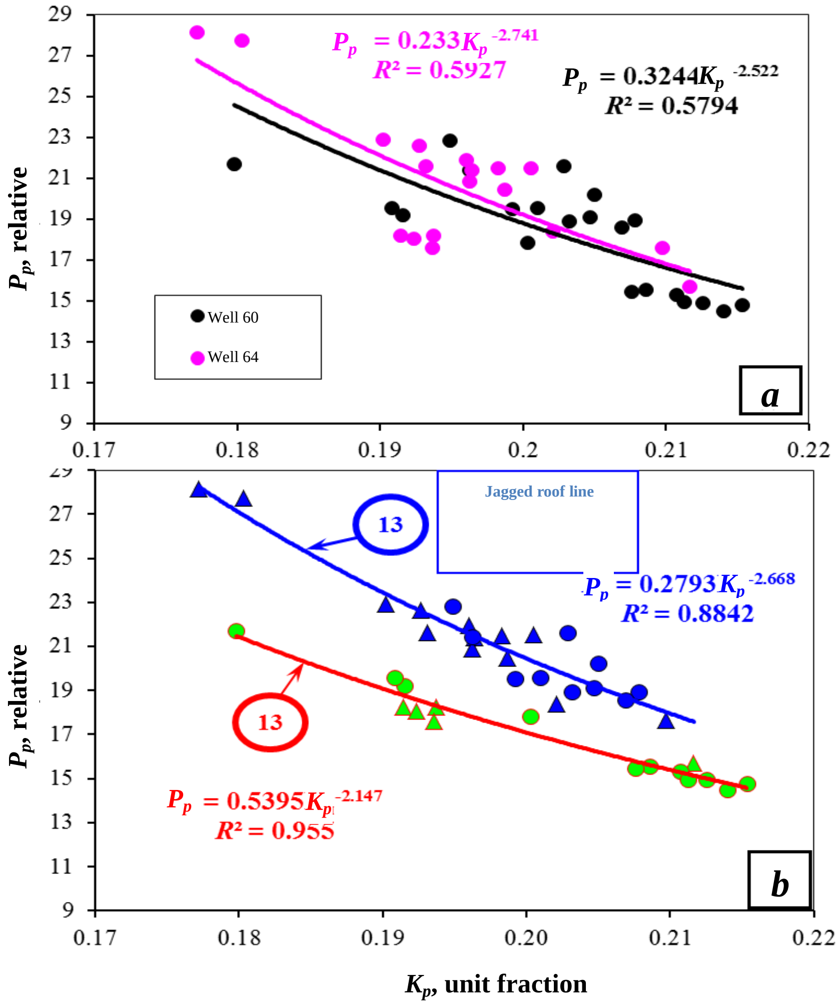


Fig. 7. Comparison of relative clay-carbonate content (φ) and open porosity (K_p) for rocks of Yu2 formation of Vyngapurovsky deposit.



▲ **In Fig. (*b*) – Well 64, clays covering grains and forming streaks in the pore space predominate**

▲ **In Fig. (*b*) – Well 64, clays in the form of discrete particles predominate**

● **In Fig. (*b*) – Well 60, clays covering grains and forming streaks in the pore space predominate**

● **In Fig. (*b*) – Well 60, clays in the form of discrete particles predominate**

Fig. 8. Comparison of the parameter of porosity (P_p) and open porosity (K_p): *a* – before and *b* – after analysis (Yaraynerskoe deposit, wells 64 and 60, formation BV6)

sampling system for the formation section for laboratory studies. Fig. 8 shows joint and separate comparison of R_p and K_p of BV6 formation of wells 60 and 64 of Yaraynerskoe deposit. Referring to Fig. 9, we can see that BV6 layer is represented by one geological body (GB) – facies of rip flow headers.

However, the samples selected for the study are not representative for well 60 or for well 64 – in the first well samples are taken generally from the area of maximum anomalies of SP and in the second from the average and minimum area. Areas in the minimum area of SP anomalies in both wells are characterized by different shapes, and that indicates the difference in the properties of rocks making up the formation. Although different parts of the reservoir were attributed to one facie, upon closer inspection it can be seen that in the final phase the sedimentation conditions of this facie often changed.

The upper part of the formation of deposits (serrate roof line) is characterized by a high content of clay and carbonate material (Fig. 10), which has a significant impact on the electrical conductivity of rocks. For formation BV 6 the definition of the type of distribution of clayiness of wells 60 and 64 was also determined (Fig. 11). It can be seen from Fig. 11 that dispersed clay predominates in BV6 formation. Fig. 12 shows that in the rock samples of upper part of BV6 formation (jagged roof line) where the electrical resistivity is determined, dispersed clay coating grains predominate, and in the middle part of the formation – clay in the form of discrete particles.

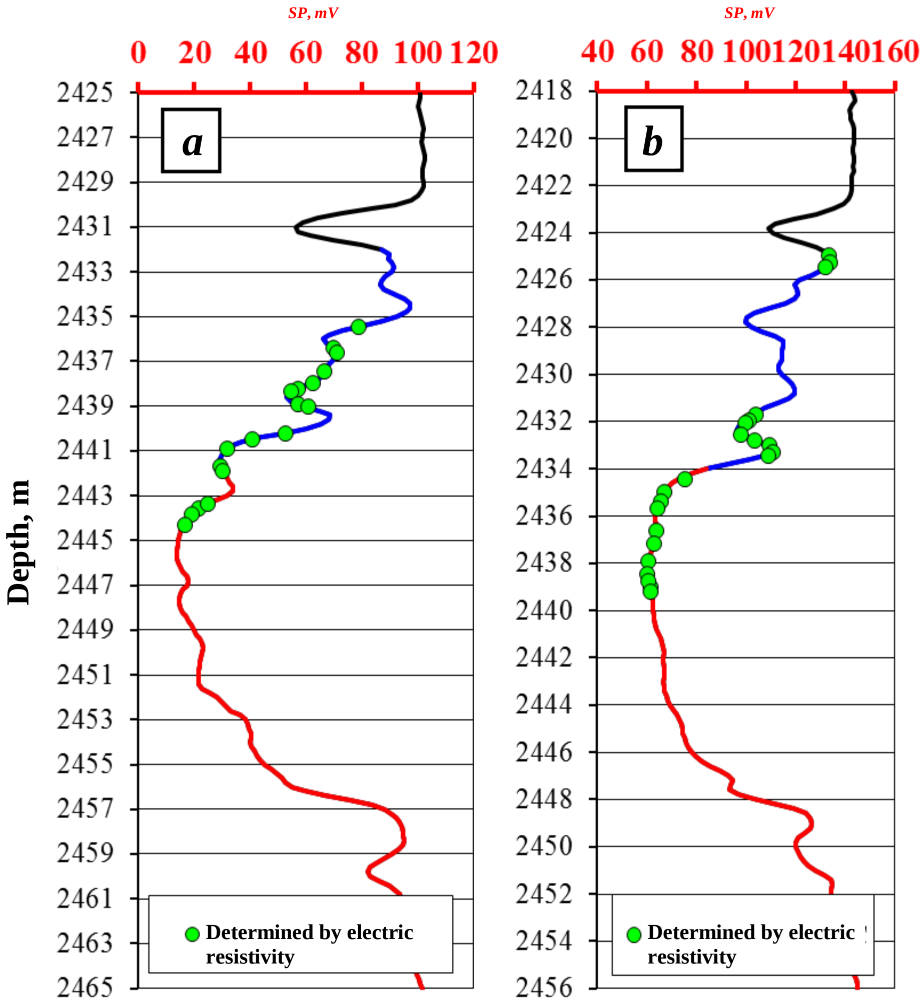


Fig. 9. SP data for rocks of BV6 formation of wells 64 (*a*) and 60 (*b*) of Yaraynerskoe deposit

With equal capacitive properties, rock with dispersed clay volume in the form of discrete particles has a better ability to pass electric charges compared with rock with dispersed clay volume covering the grains, as shown by the graphs in Fig. 8. In this case, we believe that the inadequacy of the relation between R_p and K_p has two causes:

1) absence of a representative set of samples (core);

2) neglecting the features (relationships) of formation forming conditions.

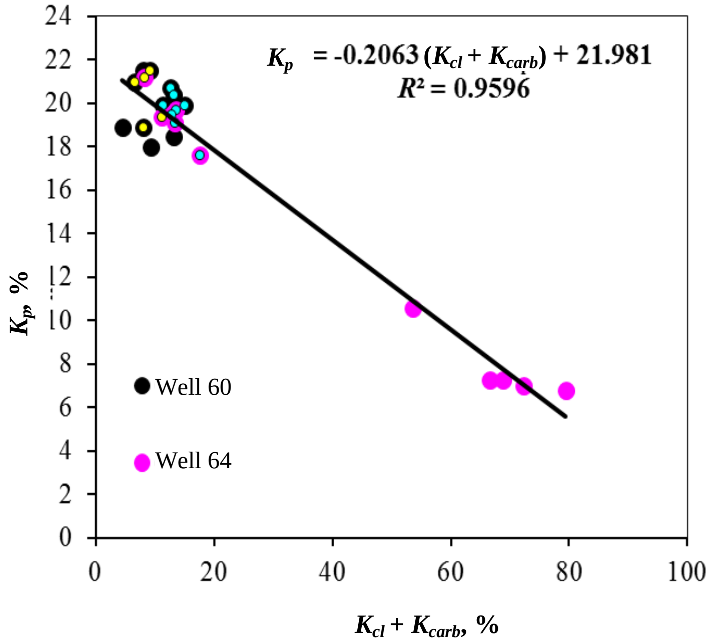


Fig. 10. A comparison of the total value of clay volume and carbonate content (K_{cl} + K_{carb}) with open porosity (K_p) for rocks of BV6 formation of Yaraynerskoe deposit.

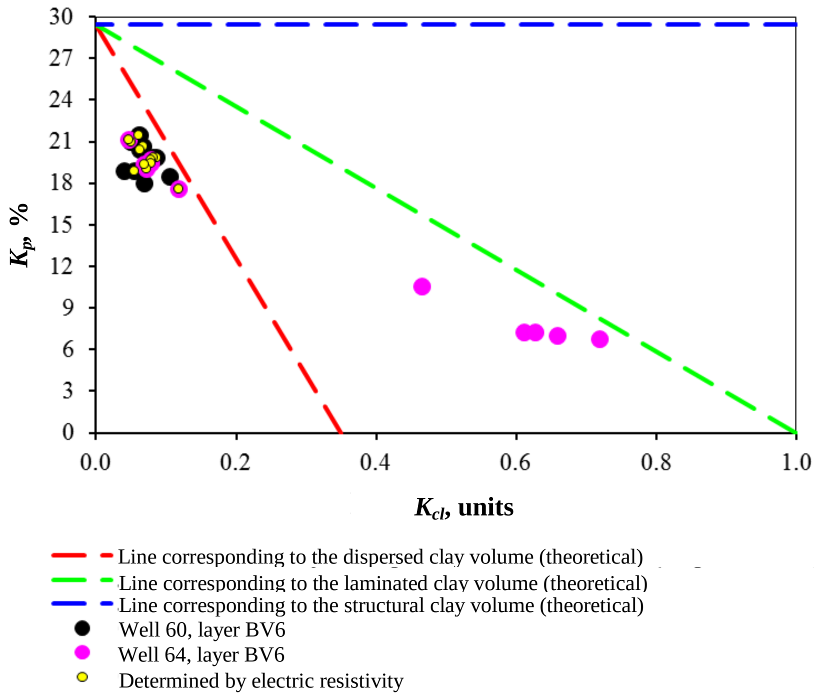


Fig. 11. Comparison of clay volume (K_{cl}) and open porosity for wells 60 and 64 of Yaraynerskoe deposit.

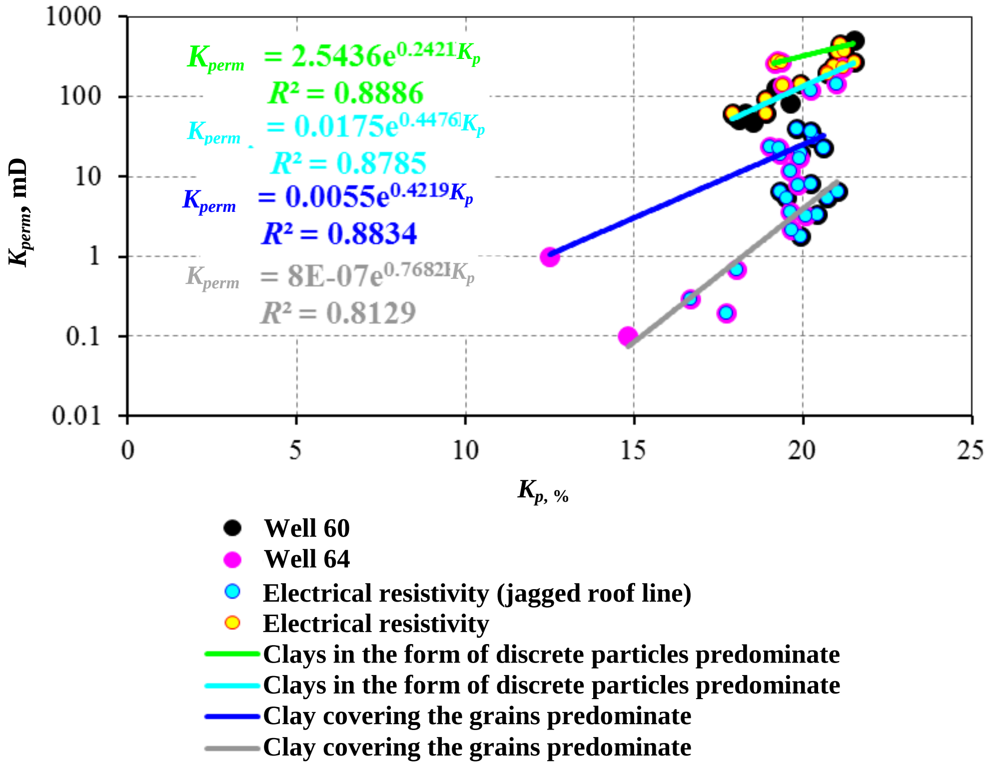


Fig. 12. Dependence between open porosity (K_p) and gas permeability (K_{perm}) of rocks of BV6 formation

CONCLUSION

On the basis of numerous data analyses of K_p, R_p and geophysical well logging we can conclude that it is inappropriate to process together petrophysical data and well logging data which were obtained in the GE representing different facies – geological bodies. It is clearly necessary to focus on where, on what basis and how to allocate the geological body (GB), i.e. to classify the GB – the geographical demarcation. It is reasonable to perform petrophysical modeling within the selected areas. In solving theoretical and practical problems of geophysics and petrophysics we cannot use only such information which only characterizes the object of general petrophysics. With a view to improve the reliability of the analysis results of petrophysical and geophysical data, it is necessary to make the best use of regional petrophysics attributes. It is necessary to develop a theoretical foundation for petrophysics, to form a systematic approach for solving various problems.

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"Gornye nauki i tehnologii"/ "Mining science and technology", 2016, No. 2, pp. 46-58	
Title:	**Analysis of the porosity parameter using elements of regional petrophysics (electrofacies) and clayiness type**
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Abstract:	The most important calculation parameter, the open porosity ratio (K_p) is generally determined in petrophysical laboratories for the object (stratum) as a whole and without taking into account its regional heterogeneity. A range of the porosity value is taken as a basic criterion for selecting samples to construct the model $R_p = f(K_p)$. In this case it is assumed that the higher ΔK_p is, the higher the validity of the relation $R_p = f(K_p)$ is. However, in practice such a concept often creates an ambiguity in determining the porosity by electric resistivity of water saturated samples in different wells, even within one field. This phenomenon is caused by underestimating the features of the regional petrophysics object, the facies, which are reflected in the form of well logging curves, including SP, and the element of the general petrophysics object – the clayiness type. The breakdown (classification) of the formation by facies, determination and taking into consideration the type of clayiness, as well as distinguishing and analyzing the petrophysical types of rock based on rock porosity and permeability characteristics within the formation, make it possible to obtain satisfactory relations between electric resistivity and porosity of the rock.
Keywords:	open porosity, electric resistivity, facies, clayiness
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