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ENHANCING THE RELIABILITY OF CORE ANALYSIS

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ПОВЫШЕНИЕ ДОСТОВЕРНОСТИ РЕЗУЛЬТАТОВ ФИЗИКО-ГИДРОДИНАМИЧЕСКИХ ИССЛЕДОВАНИЙ

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whole core, complex carbonate reservoir, permeability and porosity properties, water flood displacement efficiency, hypothesis statistical check method.

The selection of a representative collection of samples is one of the main problems during the performance of the analysis of core material. Such collection should reflect physical and hydrodynamic processes in the layer in question as accurately as possible. In the case of complex carbonate reservoirs, it is particularly important to cover the maximum range of variation of permeability and porosity properties. It is important to analyze processes occurring in the matrix of rock, as well as in the cavernous and fractured constituent of a rock. The methodology is not sufficiently elaborated; therefore, at the moment of studying a reservoir of a particular field, the task is to develop a method to select a representative collection of samples to perform core analysis. So, using the information obtained on the waterflood displacement efficiency, it is possible to make a sufficiently reliable estimation of reserves and obtain a more accurate oil recovery factor.

Taking the Tedinskoye field as an example, the recommendations have been developed on how to select a representative collection of samples to conduct core analysis, and the need to use a full-diameter core to determine water flood displacement efficiencies has been established.

To evaluate the representativity of a selected collection of samples, a statistical analysis was performed; the hypothesis (statistical criteria) statistical check method was applied based on Student's distribution.

It has been found that the selection of a representative collection of samples for analysis should be made for all types of reservoirs representing a section in question, thus covering a full range of permeability and porosity properties. A collection of samples should include whole core samples, as well as standard size samples, as they help to define the processes occurring in different parts of a formation.

Ключевые слова:
полноразмерный керн, сложнопостроенный карбонатный коллектор, фильтрационно-емкостные свойства, коэффициент вытеснения нефти водой, метод статистической проверки гипотез.

Одной из основных проблем при проведении физико-гидродинамических исследований на керновом материале является подбор представительной коллекции образцов. Такая коллекция должна максимально точно отражать физико-гидродинамические процессы изучаемого пласта. Для сложнопостроенных карбонатных коллекторов особенно важным является охватить максимальный диапазон изменения фильтрационно-емкостных свойств. Оценить не только процессы, проходящие в матрице породы, но и каверно-трещиноватую составляющую породы. Методологические вопросы до конца не проработаны, таким образом, при изучении резервуара конкретного месторождения ставится задача разработать методику по выбору представительной коллекции образцов для проведения физико-гидродинамических исследований. Следовательно, используя полученную информацию по коэффициенту вытеснения нефти водой, с достаточной степенью достоверности можно оценить запасы и получить наиболее точно коэффициент извлечения нефти.

На примере Тэдинского месторождения разработаны методические рекомендации по выбору представительной коллекции образцов для проведения физико-гидродинамических исследований, а также определена необходимость использования керна с сохраненным при выбуривании диаметром для определения коэффициентов вытеснения нефти водой.

Для оценки представительности выбранной коллекции образцов проведен статистический анализ, использовался метод статистической проверки гипотез (статистических критериев), основанный на распределении Стьюдента.

Установлено, что подбор представительной коллекции образцов для исследований необходимо проводить из всех типов коллекторов, которыми представлен изучаемый разрез и по всему диапазону фильтрационно-емкостных свойств. Коллекция образцов должна быть представлена как полноразмерными, так и стандартными образцами, поскольку они определяют процессы, проходящие в разных участках пласта.

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Introduction

In the territory of the Russian Federation, the amount of development objects at complex reservoirs is growing. For instance, oil-saturated reservoirs of a number of the Timan-Pechora Basin are characterized by high fracturing and cavern porosity. At the moment of reserve estimate in projects and reservoir management plans, it is essential to have information about physical and hydrodynamic properties. The reliability of information greatly depends on the selection of a representative collection of core samples for permeability and porosity studies covering a full range of permeability and porosity properties and all reservoir rock types.

A detailed study of physical properties of rocks allows us to predict the locations of oil and gas accumulation, evaluate permeability and porosity properties of a reservoir, and choose the most efficient methods of reservoir drilling and formation fluids extraction. The reliability significantly depends on the availability of petrophysical data [1–3]. There is only one method to obtain such data directly: laboratory core analysis [4].

The purpose of this work is to substantiate the selection of core samples collected for analysis through the example of the Tedinskoye field and to evaluate the need of whole core use in the determination of water flood displacement efficiencies.

Characteristics of the studied object

The Tedinskoye field is located in the central part of the Bolshezemelskaya tundra and, administratively, is included in the Nenets Autonomous Okrug (Figure 1) [5–7]. Tectonically it is located in the western part of the Khoreyver depression within the Kolvavis stage.

Based on lithologic and petrographic researches, the following reservoir rock types have been identified: cyanobiontic microbial-detrital limestone having various structures (lumpy, fragmental, oncolite or nodular, bioherm, and their transient varieties); polyphit limestone; oolitic limestone; detrital-micritic limestone and micritic and thin-layer stromatolite-like limestone. All varieties of microbial-detrital limestone and polyphit limestone are located together and are related to transient types.

The rocks are recrystallized, calcitized, dolomitized, stilolitized, fractured, and porous or cavernous-and-porous to a different extent (Figure 2).

The Development of recommendations on how to select a representative collection of samples for core analysis

The tests conducted in laboratory conditions to determine water flood displacement efficiency and relative permeability with thermodynamic conditions modelling and using core taken from

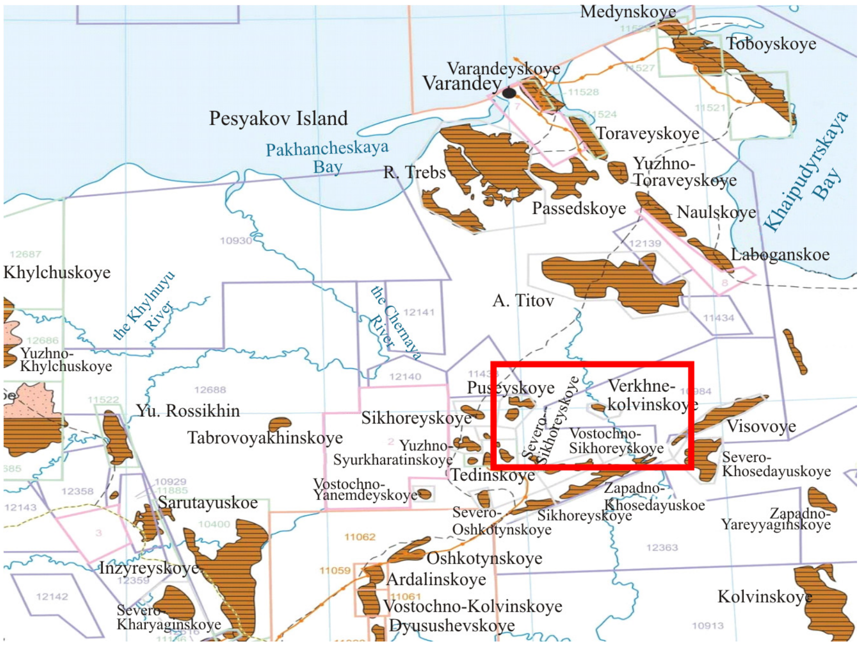
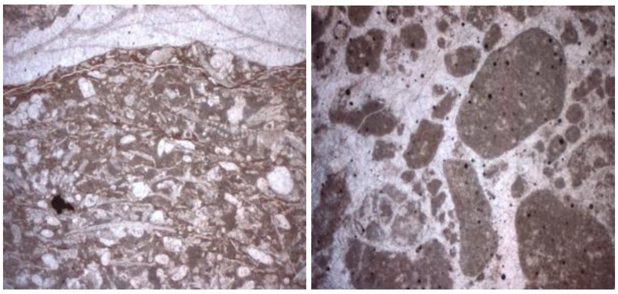


Fig. 1. A fragment of the general map of the northern part of the Timan-Pechora Basin



a *b*

Fig. 2. Thin section image: scaling up ×25: *a* – transmitted light. Organic detritus accumulation in microbial-detrital limestone; *b* – transmitted light. Lumpy fragmental limestone

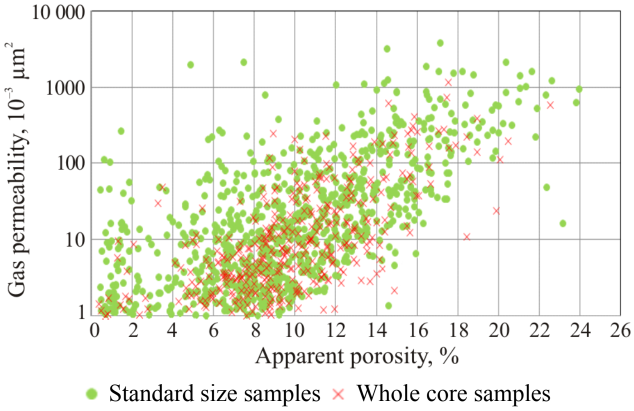


Fig. 3. Dependence of the gas permeability on the porosity

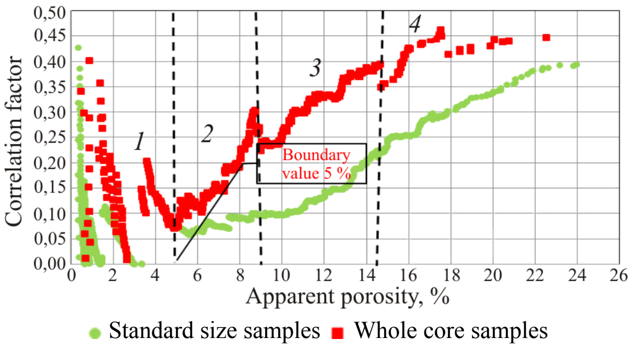


Fig. 4. Correlative accumulation plot for standard size samples and whole core samples

productive intervals are more reliable to demonstrate the hydrodynamic pattern of processes occurring in a reservoir [8–26]. One of the main problems at the moment of analysis of core material is the selection of a representative collection of samples which is to reflect physical and hydrodynamic processes of a formation in question in the most accurate way. In the case of complex carbonate reservoirs, it is important to cover the maximum range of changes in permeability and porosity properties [27]. It is important to analyse processes occurring in the matrix of rock, as well as the cavernosity and fracture porosity of the rock.

To develop recommendations on how to select a representative collection of samples for core analysis, 2075 core samples were used (1532 standard size samples and 543 whole core samples), selected from six wells within D3fm object of the Tedinskoye field (Figure 3). Figure 3 shows that the correlation areas of the two sampling types overlap; however standard size sampling points are more scattered. To make the analysis more informative, it is necessary to enhance research methods and study a scale effect in more detail in a wide range depending on changes in the structure of the pore volume.

This requires the development of new methods for the estimation of the scale effect, the development of methods to select a representative collection of whole core samples in order to perform core flow tests.

At the first stage, an accumulated correlation between the apparent porosity and gas permeability factor was calculated for all samples. Separate correlation plots were created for standard size samples and whole core samples (Figure 4). The accumulative correlation plots characterize the interrelation of the apparent porosity and gas permeability factor in different porosity ranges. Gaps, interruptions, and curvature on plots for whole core and standard size samples show changes in the structure of the pore volume in different ranges. The area between the plots for standard size samples and whole core samples represents a scale effect measure over the entire range of permeability and porosity properties of a field in question. The distance between separate points on the plot within a narrow value of permeability for gas quantifies the scale effect for such range. Such measures for scale effect estimation have been suggested for the first time. Moreover, using such diagram one may estimate boundary values irrespective of calculated values and use them to estimate reserves and identify reservoirs.

Let us study the change in the tilt angle and other effects in more detail on the accumulative correlation plots. In Figure 4, zone *1*, where no effective voids are possible, is highlighted; the increased permeability value is caused here by man-made cracking occurred during the preparation of samples. This is confirmed by the absence of correlations: the samples are located in a nonlinear manner. The figure allows us to clearly define boundary values which agree with the calculated values taken based on the use of correlations between the permeability and apparent porosity.

Therefore, this method allows us to independently determine boundary values to estimate reserves and identify reservoirs. In the porosity range of 5 to 15 % (zone *2–3*), the accumulative correlation grows on both plots, but in whole core samples, in the porosity range of 9 %, there is a surge and a gap caused by the significant contribution of cracks to the effective pore volume (zone *2*). Later, there is a drop and levelling of the accumulative correlation plot, mainly caused by the presence of cavities and pores. The accumulative correlation plot of whole core samples demonstrates a stronger connection with the porosity, but, once the porosity value exceeds 15 %, there is a gap and a surge, which is caused by a dominating role of open pores in the permeability and porosity; this proves reliability and information value (zone *4*). Gaps on the whole core accumulative correlation plot clearly define and fix the boundary lines separating reservoir by types in the presented profile, whereas on standard size samples plots such effect is not clearly seen, and we can only interpret the change in the tilt angles to judge about the effect. A curve characterizing the whole core is located above, and standard size samples' plots are located below, thus demonstrating a scale effect. In general, we can conclude that to evaluate a complex reservoir, a whole core is most representative, whereas standard size samples should be used to determine boundary values.

At the second stage, the results of determining the apparent porosity were compared to absolute gas permeability (Figure 5).

The correlation between the apparent porosity and absolute gas permeability is indicative of the different nature of the relationship between these parameters for complex carbonate reservoirs having different types of the void (see Figure 5).

The main criteria determining a reservoir type is the ability of the rock to let fluid permeate through it, i.e. the permeability. During an experiment performed according to the recommendations on reserves estimation the entire selection was divided into five groups depending on the void types through which fluid filtration prevails. The following three main groups were identified depending on the reservoir types:

1. Fractured reservoir: is characterized by the dominating role of micro-cracks in the permeability and porosity. A so-called crack zone was identified in this group, which is an area where no effective void is possible and increased permeability is due to man-made cracks appeared during the transportation of core material and the preparation of samples.

2. Cracked-porous-cavernous reservoir: consists of rocks having a more complex type of voids due to intensive cavern porosity and fracturing (if the number of caverns is not too big, or if caverns are small, the reservoir type is cracked-cavernous-porous).

3. Cavernous-porous reservoir: is characterized by the dominating role of pore channels in the permeability and porosity, these properties being additionally increased due to caverns. Samples of porous and coarse-porous type voids and samples with single and small size caverns were included in this group.

4–5. Porous reservoir: is characterized by the dominating role of open pores in the permeability and porosity.

The statistical analysis of the apparent porosity distribution for the five selections corresponding to the subdivision shown in Figure 5, was performed separately for standard size samples and whole core samples but demonstrates a similar pattern (Figure 6). However, they differ in maximum values: the maximum value of the whole core is 9%, whereas the maximum value of standard size samples is 6 %. This is indicative of the fact that porosity values are more reliable when a whole core is examined. On the other hand, this value is too low in standard size samples which is an example of a scale effect. In the porosity range of 0 to 5 %, selections for all groups by reservoir type are presented: the ranges are overlapped for standard size samples, as well as for the whole core. From 5 to 15 %, the amount of selection *3* and *4* grows being caused by the contribution of samples through the intensive cavern porosity and by the increase of the number of samples from the porous type reservoir, but as to the whole core, the distribution is more normal, than for standard size samples. Once the porosity value reaches 15 % the number of samples decreases in both

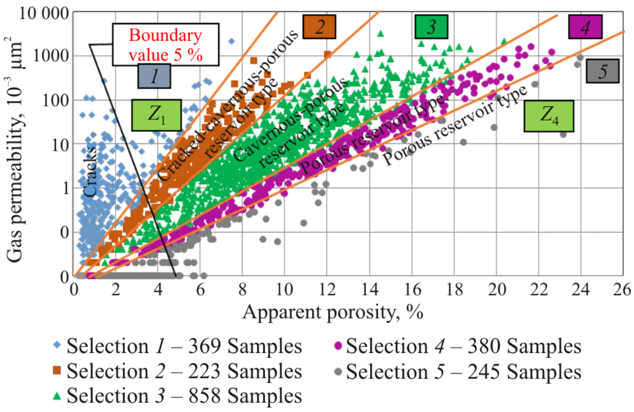


Fig. 5. Dependence of the gas permeability on the porosity in samples distinguished by the type of reservoirs; Z_1, Z_4 indicate linear discriminant functions

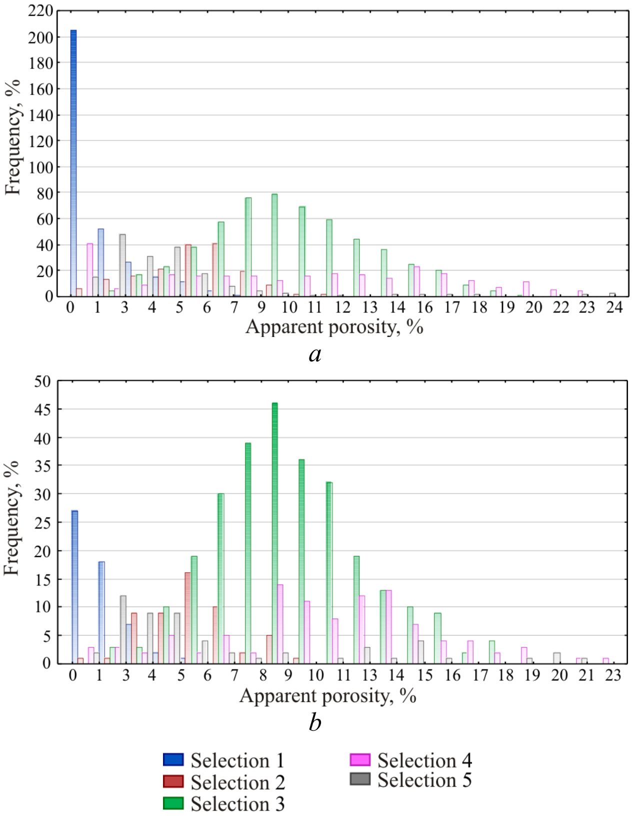


Fig. 6. Distribution of the apparent porosity in standard size samples (*a*) and in whole core samples (*b*)

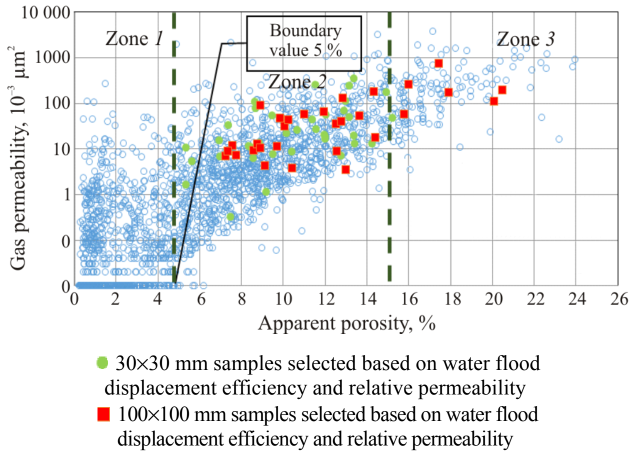


Fig. 7. Dependence of the gas permeability on the porosity (2075 samples in total)

selections. As to the whole core, once 18 % is reached, the amount of samples from selections *3–5* significantly decreases (see Figure 6).

Based on the groups obtained linear discriminant functions are constructed allowing us to divide the area of the correlation field. The classification quality ranges from 92 to 97 %. All obtained linear discriminant functions are statistically significant. They can be used to classify samples in future, and their statistical significance confirms the experimental division into groups.

Linear discriminant functions for D_3fm object of the Tedinskoye field are as follows:

$$Z_1 = 0.919\,(K_{\text{п}}) - 0{,}907\,(\log 10\,(K_{\text{прг}})) - 2.803,$$
$$\text{clas} = 92\ \%;\ F_p/F_t = 215.94,\ p < 0.00001;$$

$$Z_2 = 0.773\,(K_{\text{п}}) - 2.066\,(\log 10\,(K_{\text{прг}})) - 5.043,$$
$$\text{clas} = 93\ \%;\ F_p/F_t = 244.88,\ p < 0.00001;$$

$$Z_3 = 0.776\,(K_{\text{п}}) - 2.940\,(\log 10\,(K_{\text{прг}})) - 5.455,$$
$$\text{clas} = 94\ \%;\ F_p/F_t = 355.63,\ p < 0.00001;$$

$$Z_4 = 0.883\,(K_{\text{п}}) - 4.113\,(\log 10\,(K_{\text{прг}})) - 8.989,$$
$$\text{clas} = 97\ \%;\ F_p/F_t = 168.76,\ p < 0.00001,$$

where $K_{\text{п}}$ is the apparent porosity, %; $K_{\text{прг}}$ is the gas permeability, 10^{-3} μm^2; clas is the correct classification, %; F_p/F_t is the ratio of calculated F-test to theoretic F-test; p is the significance level.

Z_1 and Z_4 linear discriminant functions allow us to distinguish between the area of possible selection of a representative collection of samples and the area of rejected samples for D_3fm object of the Tedinskoye field (see Figure 5).

Applying this method we can identify three zones, where the physical and hydrodynamic pattern of the formation are represented more accurately (Figure 7):

– zone *1* does not have any samples recommended for selection (minimized by the porosity boundary value);

– zone *2* includes mixed samples: standard size samples and full-diameter core samples (whole core);

– zone *3* includes only full-diameter core samples.

Once the permeability and porosity properties were determined under atmospheric conditions and zones recommended for sampling were specified, a selection of 30 whole core samples and 38 standard size samples was made to run tests for waterflood displacement efficiency.

The selected collection of samples was used to conduct penetration tests determining water flood displacement efficiency. Dry samples were weighted at the beginning of the test and then placed in vacuum conditions and saturated with synthetic brine. The gas volumetric method was applied to measure the samples apparent porosity, and then water permeability was measured. The next step was to simulate the residual water saturation of whole core samples was using capillary extraction method. The conditions of this simulation were corresponding or close to values available from experiments on the capillary pressure curve measurements. After that, the samples were additionally saturated with non-polar kerosene [28–29]. The residual water saturation of standard size core samples was simulated using a semi-permeable membrane method. Then, these samples were additionally saturated with non-polar kerosene. Once the pressure in the system was increased, the kerosene was pumped in the amount of 3–4 pore volumes of a sample. Then it was replaced by a model of oil which was pumped in the same amount, thus creating the initial oil saturation in a sample. After that, oil was displaced in a high-pressure burette.

The penetration tests were conducted under the simulated pressure and temperature conditions corresponding to the formation conditions, according to OST (Industrial Standard) 39-195-86 [30].

Analysis of the results

The *t*-statistics analysis was used to evaluate the representativity of the selected collection of samples. The results are shown in table [31–38].

The bar chart (Figure 8, *a*) analysis show that the standard size samples are located towards the left part exhibiting low values of water flood displacement efficiency; whole core samples are located towards the right part with high values of water flood displacement efficiency.

Statistical analysis
of displacement efficiency, unit fraction,
for two selections (t = –3,60558)

Parameter	Standard size sample	Whole core sample
Number of observations	38	30
Average value	0.439	0.534
Standard deviation	0.13285	0.065

Too high values of water flood displacement efficiency are caused by the relatively small size of a sample compared to caverns of big diameter and micro-cracks through which the major part of fluids is filtrated bypassing the matrix of rock. That is why to estimate water flood displacement efficiency of a cracked-cavernous-porous reservoir type, it is recommended to take whole core samples (full diameter samples), as due to their size such samples allow for the scale effect and include micro-cracks, big size caverns, and the matrix of a rock [39–45].

This statement is confirmed by the bar chart of the distribution of values of water flood displacement efficiency in various ranges of gas permeability for D_3fm object of the Tedinskoye field (see Figure 8, *b*). The figure shows that the average values of water flood displacement efficiencies in whole core samples are higher than those in standard size samples.

A comparative analysis of values of water flood displacement efficiency with the use of standard size samples and whole core samples shows that the values obtained on standard size samples are too low and residual oil saturation is too high. The use of data obtained on standard size samples leads to waterflood displacement efficiency error and, as a result, leads to false oil recovery factor values, thus leading to the erroneous estimation of recoverable oil reserves. Therefore, it is important to pay attention to the scale effect in the frame of core flow tests.

Conclusion

Based on the results of the conducted researches, the recommendations concerning the selection of a representative collection of samples for core analysis have been scientifically substantiated.

This is the first time when we have suggested and described a quantitative measure of the scale effect for whole core and standard size samples through a comparison of charts representing accumulated correlations between the permeability and porosity.

Based on the conducted linear discriminant analysis, we have solved the practical problem of the division of productive deposits of D3fm object of the Tedinskoye field depending on the reservoir type.

The suggested recommendations concerning the selection of a representative collection of samples ensures a more accurate selection of samples for core flow tests which will better reflect the physical and hydrodynamic pattern of a formation, and the results will be used during the estimation of reserves and in engineering design documentation. The enhanced methods of research of complex reservoirs with the use of whole core samples improve the reliability of petrophysical data used during reserve estimation (update), in feasibility studies of oil recovery factor, projects, and reservoir management plans.

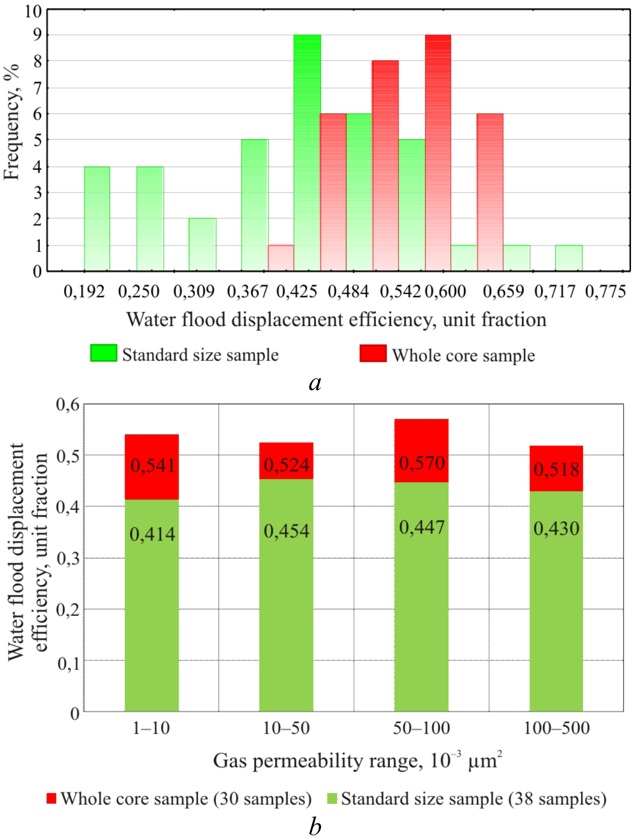


Fig. 8. Distribution of: *a* – water flood displacement efficiency depending on the frequency in the total selection of test values; *b* – average values of water flood displacement efficiency

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