THE INFLUENCE OF ROCK LITHOGENESIS TYPES ON POROSITY AND PERMEABILITY (THE CASE OF PERMO-CARBONIFEROUS DEPOSIT OF THE USINSKOE FIELD)

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Introduction

Porosity and permeability data are essential when preparing an engineering design package, calculating oil and gas reserves, performing geological modelling and planning exploration activities. Based on the Dunham classification, this work offers an in-depth study of how a structure may change porosity and permeability of rock fabrics, including full-size core samples.

A new methodology is developed to differentiate porosity, permeability and petrographic properties depending on facies attributes. A correct estimation of porosity and permeability of reservoirs under development largely depends on sufficiency of the petrophysical basis [1-3]. Only laboratory studies of core samples can serve as a direct way of obtaining such information [4-9].

Laboratory Studies

The paper aims at studying the Perm-Carboniferous deposit of the Usinskoye field. The porosity and permeability properties were analysed for more than 9,000 standard core samples and approximately 1,000 full-size core samples, taking into account the scale factor and including microfractures, large caverns and rock matrix, commensurable with the sample sizes [10-16]. The coverage of the maximum variation range of porosity and permeability is of particular importance for structurally complex carbonate reservoirs [17]. The open porosity ratio for the standard core samples was determined by the fluid saturation method (the Preobrazhensky method) and hydrostatic weighing taking external caverns into account, according to the National Standard GOST 26450.1-85 [18]. While the open porosity ratio for the full-size samples was determined using the MR-ISM-03-OLFI-046-2013 method [19]. As a result of the lithologic, petrographic and petrophysical studies, it is revealed that the rocks of the studied section have heterogeneous but quite good porosity and permeability properties. This fact is associated with the facies attribute, i.e. the distribution of pores, caverns and fractures, as well as their morphological features. The lithological and petrographic data show that the studied rocks (in this section) have undergone a wide range of post-depositional alterations in their geological evolution, e.g. compaction, recrystallization, calcitization, dolomitization, silicification, stylolization, fracturing and leaching. Each of these secondary processes had an unclear effect on the void space formation at various lithogenesis stages. Therefore, their intensity varies in carbonate rocks of different textures.
they are intermittent and formed by the pale fine short-grained calcite or silica in individual cases.

For reservoirs of the second type, the role of fractures as additional flow paths of the bituminous organic matter is of great importance. The rock permeability is determined by secondary and primary pores. The primary pores feature sedimentation and diagenetic recrystallization pores, while the secondary pores feature leached pores, those inherited from the primary pores and those newly formed along the fractures and stylolites. The fractures are not consistent in width; they are extensive and short, tortuous and rectilinear. The fractures are leached in sections. There are multiple filamentary closed fractures.

Reservoirs of the third type feature changes in the porosity and permeability over a wide range. The pores and leached caverns are irregular, elongated and isometric in shape. The pores are interconnected. Some of the fine intergranular pores (dolomitization/ recrystallization pores) are partially or completely filled with the brown bituminous organic matter. Some voids are formed due to leaching of organic remains (dissolution porosity). Locally, the pores are filled with authigenic siliceous material represented by quartz and flabellate chalcedony, which is less common. Compared to Type 2, stylolite occurred less often in Type 3.

Type 4 refers to the porous type of reservoir. The voids are created nonuniformly, mainly in cement, and they are less often in intramatrix cavities of organic residues. The cavities are highly diverse in shape. Individual cavities are partially or completely healed with calcite. Fine pores are sometimes filled with the brown bituminous organic matter. Some pores take the shape of organic remains (moldic porosity). Interparticle and moldic pores sometimes develop near stylolite seams, as well as in stylolite separation films and along mineral and open fractures.

Table 1 shows the distribution of the open porosity ratio and absolute gas permeability depending on the reservoir types. Based on the obtained statistical results, we can conclude that 173 core samples (3.2 %) pertain to the cavernous reservoir; 797 samples (14.7 %) pertain to the fractured cavernous porus reservoir; 1,675 samples (30.9 %) pertain to the cavernous porus reservoir; and 2,782 (51.2 %) pertain to the porus reservoir. Thus, most considered samples belong to the porus type of reservoir, while the least number of the samples belong to the fractured type. The fractured reservoir porosity is up to 2 %, while the permeability reaches the values of up to 10 D (darcy units). The open porosity of the fractured cavernous porus reservoir varies within the range from 0 to 17 %, and the gas permeability exceeds 1 D. For the cavernous porus reservoir, the open porosity lies in the range from 0 to 27 %, while the gas permeability is over 1 D. For the porus reservoir, the open porosity ranges from 0 to 37 %, and the gas permeability is up to 1 D.

### Table 1

| Parameter          | Fractured reservoir | Fractured cavernous porous reservoir | Cavernous porous reservoir | Porous reservoir | Total number, pcs. |
|--------------------|---------------------|-------------------------------------|---------------------------|-----------------|-------------------|
|                    | abs. | %     | abs. | %     | abs. | %     | abs. | %     | Abs. | %     |
| $K_{por}$, %:      |      |       |      |       |      |       |      |       |      |       |
| From 0 to 5 (Zone 1) | 173  | 7.2   | 665  | 27.5  | 714  | 29.5  | 866  | 35.8  | 2418 |
| From 5 to 12 (Zone 2) | 0    | 0.0   | 131  | 10.3  | 595  | 46.6  | 551  | 43.1  | 1277 |
| From 12 to 20 (Zone 3) | 0    | 0.0   | 1    | 0.1   | 339  | 33.9  | 661  | 66.0  | 1001 |
| Over 20 (Zone 4) | 0    | 0.0   | 0    | 0.0   | 27   | 3.7   | 704  | 96.3  | 731  |
| Average value for all zones | 173  | 3.2   | 797  | 14.7  | 1675 | 30.9  | 2782 | 51.2  | 5427 |
| $K_{perm}$, mD:    |      |       |      |       |      |       |      |       |      |       |
| 0.01–1 (Zone 1) | 56   | 2.0   | 450  | 16.1  | 835  | 29.9  | 1448 | 51.9  | 2789 |
| From 1 to 10 (Zone 2) | 64   | 6.1   | 161  | 15.4  | 305  | 29.2  | 513  | 49.2  | 1043 |
| From 10 to 100 (Zone 3) | 39   | 3.8   | 126  | 12.4  | 296  | 29.2  | 552  | 54.5  | 1013 |
| Over 100 (Zone 4) | 14   | 2.4   | 60   | 10.3  | 239  | 41.1  | 269  | 46.2  | 582  |
| Average value for all zones | 173  | 3.2   | 797  | 14.7  | 1675 | 30.9  | 2782 | 51.2  | 5427 |
Analysis of the Obtained Results

Based on the conducted lithological and petrographic studies, we identified the lithogenesis types in the rocks of the Usinskoye field, such as Mudstone, Wackestone, Packstone, Grainstone, Boundstone, Floatstone, Rudstone and Crystalline Carbonate. Table 2 shows the comparison of the texture types (according to the Dunham classification) with their geological and physical parameters. The analysis of average dispersion values and parameter intervals shows that it is impossible to dividing the texture types into geological and geophysical parameters [39-46]. Among all the studied lithogenesis types, Crystalline Carbonate exhibits the best porosity and permeability properties: the average open porosity is 19.51 %, and the average absolute gas permeability is 106.71 mD. Floatstone exhibits the lowest porosity and permeability properties: the average open porosity is 7.65 %, while the average absolute gas permeability is 6.41 mD.

A graph of Pearson’s cumulative correlation against the open porosity ratio was plotted to offer an in-depth study of how the lithological features affect changes in permeability for 5,000 core samples (Fig. 2, a). The discontinuities, interruptions and curvature in the graph reflect changes in the structure of the pore space in different ranges and allow the inhomogeneity areas to be identified. There are four zones, which can be singled out in the graph, depending on the properties of the core samples that belong to different lithogenesis types.

To assess the impact of the different lithogenesis properties on permeability of the samples, we plotted a similar graph of Pearson’s cumulative correlation against the open porosity ratio by using more than 1,000 samples, for which it was possible to identify their attribution to a particular texture as per the Dunham classification (Fig. 2, b). Similarly to Fig. 2, a, four zones can be observed in the graph. Despite the smaller sample array, the nature of the graph is generally identical to that shown in Fig. 2, a. As it can be seen in Fig. 2 (a, b), in the open porosity range of 0 to 5 % in Zone 1, there is a scatter of points across the core samples. In the porosity range of 5 to 20 %, the correlation shows a smooth growth with some correlation discontinuities, which are due to the change in the void space structure and the influence of the rocks of various lithogenesis types. There starts a close-to-complete stabilisation with the porosity of 20 % (Zone 4), since only one lithogenesis type – Crystalline Carbonate – contributes to the void space of the rocks. Table 3 shows the contribution of the Dunham texture to the open porosity distribution over the entire property range for each zone. For the open porosity in the range from 0 to 20 %, the Boundstone contributes the most, while Crystalline Carbonate makes up more than 20 %. Mudstone, Wackestone and Floatstone have the least impacts.

### Table 2

| Texture type as per Dunham | Number of definitions | Permeability, \(10^3 \mu\text{m}^2\) | Porosity, % | Density min., g/cm\(^3\) | Calcite content, % | Dolomite content, % | Insoluble constituent, % |
|---------------------------|-----------------------|-----------------------------------|-------------|--------------------------|--------------------|-----------------------|-------------------------|
| Mudstone                  | 6                     | 152.42 ± 129.17 3.27–227.00       | 10.14 ± 7.18 | 2.68 ± 0.01              | 35.90 ± 28.20     | 3.00 ± 5.25           | 61.00 ± 33.46           |
| Wackestone                | 14                    | 8.08 ± 12.30 0.01–26.01           | 5.35 ± 0.93 3.99–6.00 | 2.70 ± 0.02 2.67–2.72  | 93.10 ± 10.60    | 0.70 ± 1.45          | 6.20 ± 10.95          |
| Packstone                 | 225                   | 9.13 ± 33.47 0.01–257.20          | 6.22 ± 5.84 0.59–27.02 | 2.70 ± 0.02 2.64–2.83  | 86.50 ± 22.16    | 5.20 ± 16.52         | 8.30 ± 15.90          |
| Grainstone                | 190                   | 13.16 ± 35.41 0.01–242.60         | 9.33 ± 6.32 0.51–22.45 | 2.70 ± 0.01 2.66–2.74  | 95.60 ± 7.10     | 0.10 ± 0.61           | 4.40 ± 7.05           |
| Boundstone                | 427                   | 97.85 ± 325.33 0.01–2016.00       | 6.90 ± 5.98 0.37–25.58 | 2.70 ± 0.02 2.64–2.84  | 93.50 ± 11.36    | 1.00 ± 7.68           | 5.40 ± 8.07           |
| Floatstone                | 43                    | 6.41 ± 13.95 0.01–46.97           | 7.65 ± 6.64 0.73–21.91 | 2.73 ± 0.05 2.68–2.88  | 88.20 ± 22.81    | 7.30 ± 21.04          | 4.50 ± 3.80           |
| Rudstone                  | 197                   | 10.87 ± 46.56 0.01–300.50         | 4.50 ± 4.00 0.98–21.89 | 2.69 ± 0.02 2.62–2.78  | 94.10 ± 8.63     | 3.00 ± 7.69           | 2.90 ± 3.57           |
| Crystalline Carbonate     | 148                   | 106.71 ± 200.27 0.01–1055.27      | 19.51 ± 9.73 0.94–37.02 | 2.80 ± 0.04 2.69–2.84  | 18.40 ± 32.87    | 0.00–99.00           | 7.00 ± 6.98           |

**Note:** the gas permeability ratio (mD) is in the numerator; the zone number is in the denominator.
Fig. 2. Graph of Pearson’s correlation coefficient change: a – against the open porosity for all the samples; b – against the open porosity for the samples with the identified Dunham texture; c – against the absolute gas permeability for all the samples; d – against the absolute gas permeability for the samples with the identified Dunham texture. The graphs show standard-size samples.

Table 3

| Parameter                                              | Mudstone     | Wackestone | Packstone | Grainstone | Boundstone | Floatstone | Rudstone | Crystalline Carbonate | Total   |
|--------------------------------------------------------|--------------|-------------|-----------|------------|------------|------------|----------|----------------------|---------|
| Kpor, %:                                               |              |             |           |            |            |            |          |                      |         |
| From 0 to 5 (Zone 1)                                   | 1            | 0.4         | 2         | 0.8        | 60         | 22.6       | 25       | 9.40                 | 95      |
| From 5 to 12 (Zone 2)                                  | –            | –           | 4         | 2.4        | 41         | 24.6       | 19       | 11.4                 | 56      |
| From 12 to 20 (Zone 3)                                 | 2            | 1.4         | 1         | 0.8        | 17         | 12.9       | 38       | 28.8                 | 34      |
| Over 20 (Zone 4)                                       | 1            | 1.4         | 3         | 4.1        | 15         | 20.3       | 7        | 9.5                  | 16      |
| Average value for all zones                            | 4            | 0.6         | 10        | 1.6        | 133        | 20.8       | 89       | 13.9                 | 201     |
| Kperm, mD:                                             |              |             |           |            |            |            |          |                      |         |
| 0.01–1 (Zone 1)                                        | –            | –           | 5         | 1.4        | 86         | 24.7       | 41       | 11.8                 | 110     |
| From 1 to 10 (Zone 2)                                  | 2            | 1.6         | 3         | 2.3        | 22         | 17.1       | 20       | 15.5                 | 38      |
| From 10 to 100 (Zone 3)                                | –            | –           | 2         | 1.7        | 20         | 17.4       | 24       | 20.9                 | 32      |
| Over 100 (Zone 4)                                      | 2            | 4.3         | –         | –          | 5          | 10.6       | 4        | 8.5                  | 21      |
| Average value for all zones                            | 4            | 0.6         | 10        | 1.6        | 133        | 20.8       | 89       | 13.9                 | 201     |
In order to determine how the lithological features change the flow properties of 5,000 core samples, we plotted a graph of Pearson’s cumulative correlation against the absolute gas permeability ratio for all the samples (Fig. 2, c) and for the samples with the identified Dunham texture (Fig. 2, d). The number of zones in the graphs is drawn by analogy with the data given in Figure 2 (a, b), which results from the influence similarity of the lithogenesis type on the porosity and permeability properties of the reservoirs.

For the absolute gas permeability distribution over the entire range of properties, Boundstone contributes the most (Table 3), which indicates their uniform distribution and strong influence over the entire property range. Mudstone, Wackestone and Floatstone have the least impacts.

A pronounced anisotropy of the flow properties is a distinctive feature of the field reservoirs. The permeability of the full-size samples depending on direction varies by 1-2 and sometimes 3 orders of magnitude. In certain cases, the difference reaches 4 orders of magnitude. A comparison of the gas permeability depending on direction is shown in Fig. 3. There are four zones outlined in the graph. It can be seen that different degrees of azimuthal heterogeneity are determined depending on a zone. In Zone 1 and Zone 2, azimuthal anisotropy is not as significant as in Zone 3 and Zone 4.

The gas permeability measured in the direction parallel to bedding varies within the range of $(0.01-15578.66) \times 10^{-3} \mu m^2$ with an average value of $430.20 \times 10^{-3} \mu m^2$, and perpendicular to the bedding within the range of $(<0.01-11467.87) \times 10^{-3} \mu m^2$ with an average value of $222.37 \times 10^{-3} \mu m^2$. The anisotropy ratio (a value expressed by the square root of the quotient of the formation permeability in the horizontal direction by its vertical permeability) was 1.58. It should be noted that the rocks of the Usinskoye field exhibit vertical anisotropy, as well as lateral anisotropy. The ratio of lateral anisotropy is 1.34.

Conclusions

Based on the lithological, petrographic and petrophysical research findings, we studied how various petrotypes/lithotypes change the porosity and permeability of the reservoirs for the Usinskoye field. The authors identified four types of reservoirs and eight different types of lithogenesis, and assessed the geological and physical parameters for each of them. Based on the cumulative correlation plots, we identified four zones of heterogeneity that are subject to the influence of the core samples’ properties of various lithogenesis types. The influence of the structural heterogeneity and lithogenesis type on changes in the porosity and permeability over their entire range was assessed. This is the first time that the full-size core studies with account for the identified zones have been studied, which made it possible to assess the degree of azimuthal anisotropy for each of the zones. The experiments proved that the rocks of the Permo-Carboniferous deposit of the Usinskoye field have extremely heterogeneous permeability properties that vary much. Thus, it is necessary to differentiate the core-to-core petrophysical correlations depending on a fabric of its void space and lithology of rocks.

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