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From the Research Laboratories
От изследователските лаборатории

A STUDY ON HOW PERMEABILITY HETEROGENEITY INFLUENCES INITIAL WATER CUT IN UNDERSATURATED OIL FORMATIONS

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Abstract. The exploration of undersaturated oil-bearing, layer-by-layer heterogeneous oil reservoirs has become increasingly important due to the overall depletion of oil reserves. It is associated with non-standard changes in well production and increased values of water cut when these hard-to-recover oil reserves are developed. In its classical understanding, an undersaturated deposit is a conventionally large transitional water-oil zone of the reservoir.

The initial water cut is generally expected to correspond to the high initial water saturation of the formation. However, in some instances, this may not be the case. Predicting the trajectory of water cut during the initial stages of oil field development presents a considerable challenge, ascertaining whether it will increase, stabilize, or decrease. Hence, the primary objective of this study is to identify the key parameter and analyze the range of its variation using statistical methods. This analysis will enable us to make highly accurate predictions regarding the anticipated variations in water cut during the feasibility assessment of new well drilling projects.

In this study, the graphical dependence of the deviation of water cut during the early stages of well operation on the layer-by-layer heterogeneity of the formation was found for the conditions of the selected object, the Vatyogan oil field. The study's findings strongly support the development of innovative technologies for selectively isolating reservoirs. These technologies would enable the reversible restriction of permeability in the low-permeability, low-saturated part of the reservoir. This is a significant advancement considering that current technologies primarily target selective isolation of highly permeable and water-saturated interlayers.

Keywords: permeability heterogeneity; water cut; undersaturated oil formation; water oil zone, OWC

1. Introduction

The initial geological and physical properties of reservoirs and the fluids saturating them largely determine the future performance of oil-producing wells and the oil production facility (Petrakov, Kupavykh & Kupavykh 2020; Yu et al. 2022; Agzamov, et al. 2023; Al-Obaidi & Chang 2024). However, some processes in the bottom hole formation zone of wells that have opened young, unformed oil deposits characterized by low initial oil saturation are not so obvious.

The prevailing assumption is that the initial fluid present in the rock of the prospective oil deposit was water. Microscopic accumulations of hydrocarbons in much smaller volumes after their formation were evenly distributed throughout the entire thickness of sedimentary rocks, the size of which was many times greater than the thickness of the prospective (future) oil reservoir (Zou et al. 2013; He et al. 2023; Zhang et al. 2022; Al-Obaidi, Patkin & Guliaeva 2003). During the prolonged process of oil deposit formation, oil accumulates in geological traps, which are impermeable rock layers shaped like an anticline. The oil rises upwards due to the difference in density between oil and water. This movement happens rapidly in large pores and cracks due to the dominance of gravitational forces over capillary forces. The percentage of oil in the trap increases, and water saturation decreases accordingly. The rate of oil saturation growth over time is uneven, as it is uneven for reservoirs of different permeability and depths. Regardless of the deposit's formation time, hydrocarbons cannot completely replace water (capillary trapping of water in small dead-end pores) (Pentland et al. 2012; Lawrence 2019; Mccarter et al. 2020; Khalaf & Al-Obaidi 2019).

The oil field under study is Vatyogan, a large oil field located in Russia, specifically in the Khanty-Mansi Autonomous Okrug (Vaguet 2013). The proven reserves of the field as of the end of 2004 amount to almost 1.5 billion barrels of oil. Cumulative oil production has exceeded 135 million tons. The deposit is of the layer-arch type and is multilayered. The reservoir is of the terrigenous type. Sandy-clayey deposits of the Quaternary, Neogene, Paleogene, Cretaceous, and Jurassic ages represent the lithological and stratigraphic section of the Vatyogan field (Sharma et al. 2000; Chang, Al-Obaidi & Smirnov 2023).

For example, the oil deposits of the Vatyogan field are characterized by a high initial oil saturation of 98% (formed oil deposit). Low oil saturation can be found only in the transition zones of the formation, in areas where water and oil zones of deposits come into contact (OWC). In this case, the transition zones are relatively small in thickness (conditionally 0.5 – 1 m). In wells that have penetrated such a formation, a prolonged period without water is a frequent event (the transition zone is typically left unperforated)

(Korolev et al. 2023; Wang et al. 2023; Melzer, Koperna & Kuuskraa 2006; Al-Obaidi, Smirnov & Alwan 2021).

The well can produce more than 70-80% of recoverable oil reserves with no more than a 5% water cut. In the drainage area of the well, stagnant, residual waters do not affect the extraction of primary oil reserves.

The primary cause of water flooding is typically water from oil-bearing formations, injection wells, formation water, and breakthroughs due to behind-the-casing flows (Haines et al. 2024; Gambolati & Teatini 2015; Muggeridge et al. 2013; Al-Obaidi 2016). In the first two cases, the water cut of well production increases to 60-70% (breakthrough of remote waters) and stabilizes for production from 5 to 15% of recoverable oil reserves (Rajbongshi & Gogoi 2024; Xue, Liu & Zhang 2023; Jia et al. 2023; Al-Obaidi, Chang & Khalaf 2024). Water is produced from the highly permeable part of the reservoir, but oil continues to flow from the oil-bearing part. In the end, all layers are flooded with water. This process involves a series of water-isolation operations along the well, which gradually increases the coverage of the formation by allowing drainage in the still oil-saturated part of the formation over time (Zhao & Gates 2015; Lee et al. 2023; Katende & Sagala, 2019; Chang, Al-Obaidi & Patkin 2021).

The study examined how permeability heterogeneity within oil reservoirs affects the initial water cut and its subsequent evolution. These factors are crucial in evaluating the viability of new well-drilling projects.

2. Methodology and materials

For oil production objects (facilities) , it is scarce to observe a prolonged initial water-free period in layers characterized by low initial oil saturation ranging from 35 to 70%.These are the so-called young oil production objects with unformed deposits, in which mass exchange processes are still intensive and are far from the final slowdown. The entire oil deposit is one large transition zone (Male 2019; Long 2023). Man-made human intervention (well drilling, creation of differential pressure in the formation, formation of a flow field in the well drainage area) at this stage of the deposit development is accompanied by processes that are not typical for formed deposits with an initial oil saturation of more than 90% and a limited transition zone in the OWC.

Figure 1 depicts a section of the initial oil-saturated formations map for the Vatyogan field, specifically the Aptian stage, AB1-3 formation (southwest), showing accumulated oil and liquid extractions and water injection. This object (AB1-3 formation) is characterized by low (from 33 to 69%) initial oil saturation of productive formations (Fu, Wang & Xiao 2024; Fanchi, Christiansen & Heymans 2002; Guo et al. 2021; Miel, Hameed & Hussein 2022).

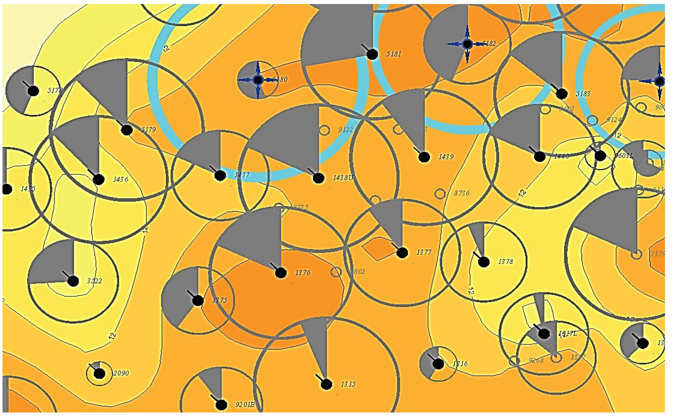

Figure 1. Map of initial oil-saturated formations with accumulated oil and liquid extractions and water injection. Vatyogan field, Aptian stage, AB1-3 reservoir (southwest)

Wells with low initial oil saturation are often associated with high initial water cut due to the phase permeability of fluids for a particular reservoir type (see Fig. 2). However, it is not possible to immediately determine whether the water cut will increase, remain stable, or decrease over time. However, this issue is crucial in the feasibility study for efficiently developing such objects during the drilling stage, where it is necessary to know the starting and typical characteristics of future wells (Wang et al. 2018; Rudyk et al. 2024; Zhang et al. 2019; Smirnov & Al-Obaidi 2008).

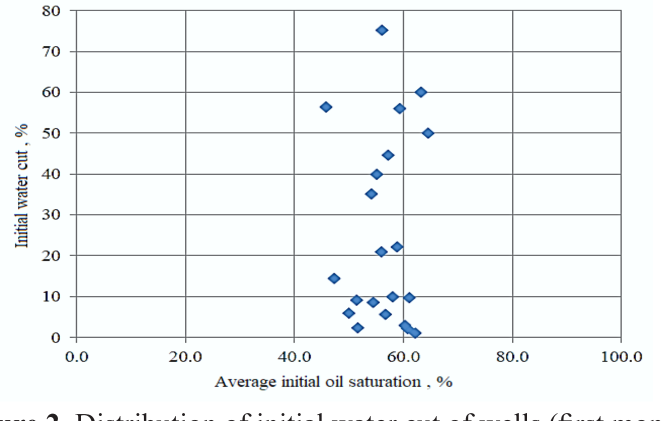

Figure 2. Distribution of initial water cut of wells (first month) and the average initial oil saturation of formations. Vatyogan field, Aptian stage, formation AB1-3 (southwest)

Given the substantial impact of layer-by-layer heterogeneity on the formation of strata, it is reasonable to expect that this factor will also influence the sequence of reservoir saturation during deposit formation (see Fig. 3). As the layers of different permeability in an oil reservoir gradually reach almost equal levels of oil saturation, approaching maximum levels of 97-98%, the permeability plays a crucial role in determining how the oil is displaced. This, in turn, influences the average water cut of the well production during the initial period.

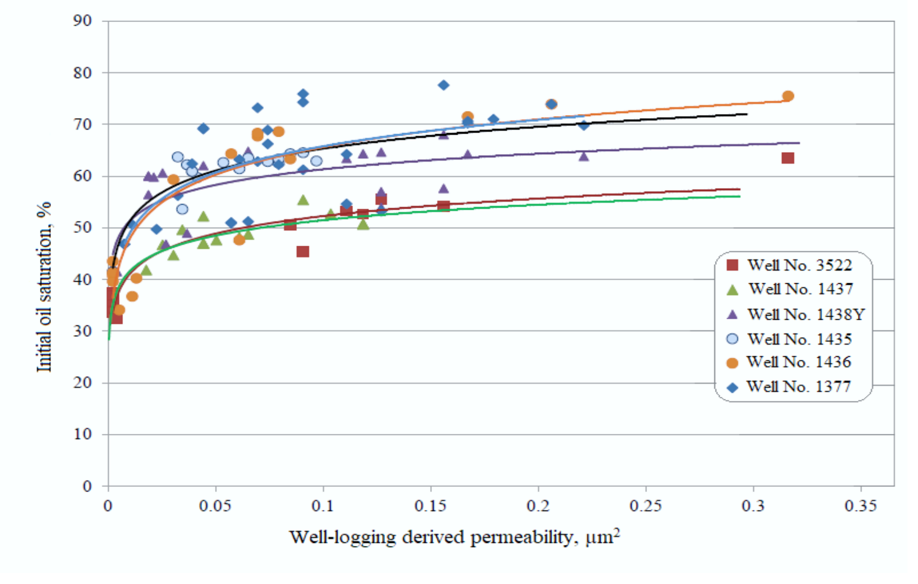

Figure 3. Dependence of the initial oil saturation of interlayers on their permeability within the section of one well. Vatyogan field, Aptian stage, AB1-3 formation (southwest).

In most cases, formation water and injected water have greater mobility than oil and tend to break through highly permeable interlayers, while low-permeability oil-saturated interlayers are gradually deactivated. However, this phenomenon is primarily observed during the late development stage and in the formed deposits.

In the case of the object under study, the deposit's formation process led to advanced saturation (maturation), especially in the highly permeable section of the reservoir (refer to Figure 3). This highlights the heterogeneity of the reservoir's permeability across the section. Next, a study was conducted on the influence of permeability heterogeneity on the initial water cut and its subsequent change, which are the indicators of our interest.

3. Results and discussions

Figures 4 – 9 show the performance indicators of six production wells of the Vatyogan field, operating in the deposit section shown in Figure 1. The initial indicators and the dynamics of water cut in the production of these wells are of interest to our study.The wells were chosen to showcase the wide range of variations in the nature of the initial water flooding. The first three cases (refer to Fig. 4 – 6) are uncommon, while the following three cases are much more typical (refer to Fig. 7 – 9). From the graphs (see Fig. 4-9) it is clear that after the wells are put into operation, after about six months their water cut changes, but not always in a positive direction.

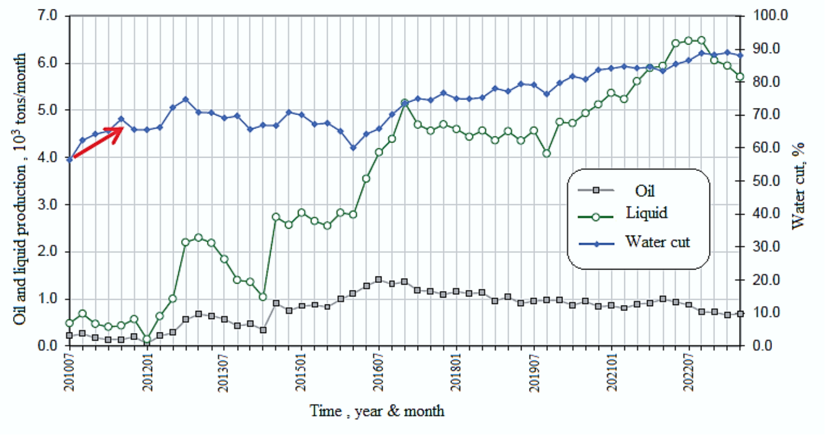

Figure 4. Indicators of well number 3522 of the Vatyogan field

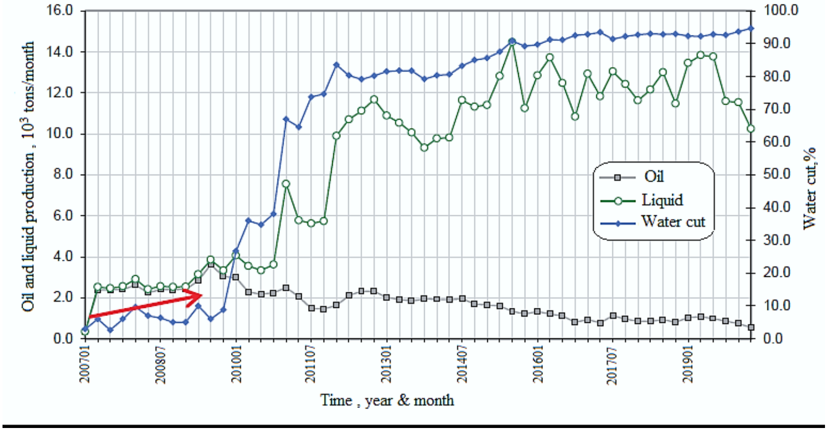

Figure 5. Indicators of well number 1437 of the Vatyogan field

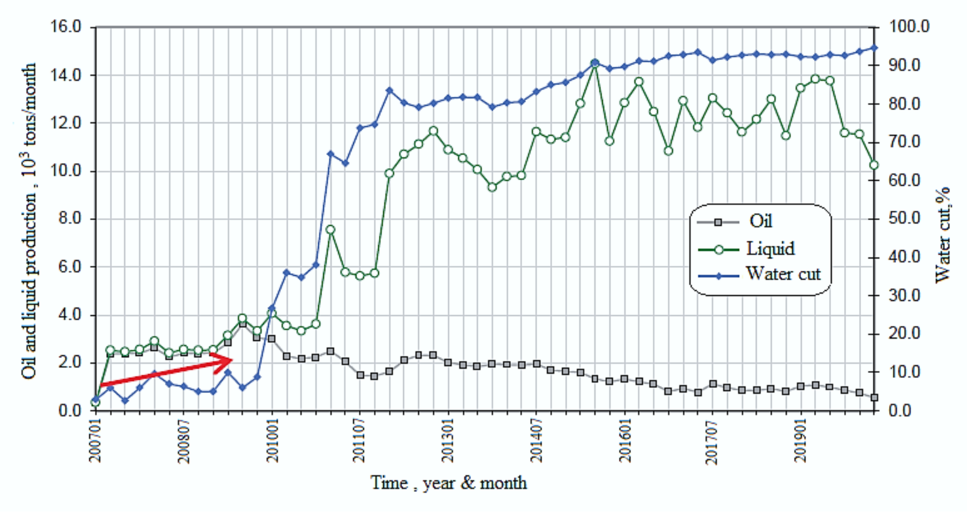

Figure 6. Indicators of well number 1438Y of the Vatyogan field

Figure 7. Indicators of well number 1435 of the Vatyogan field

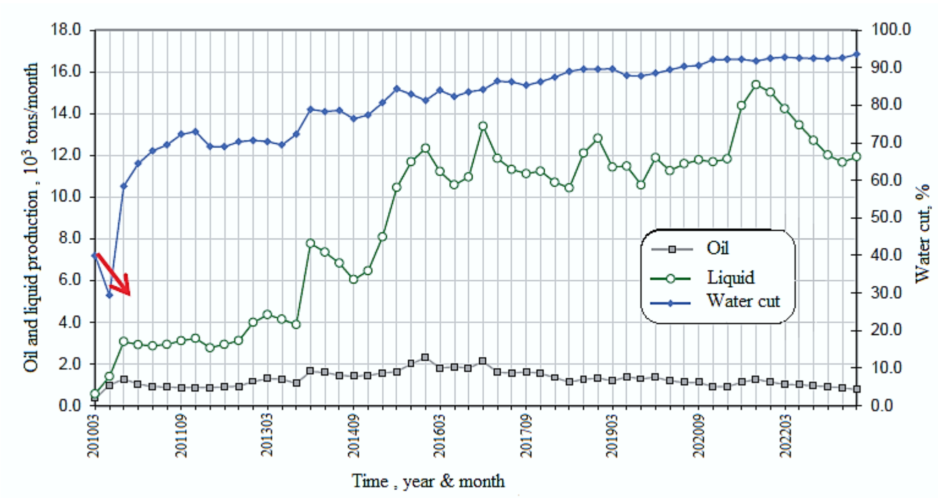

Figure 8. Indicators of well number 1436 of the Vatyogan field

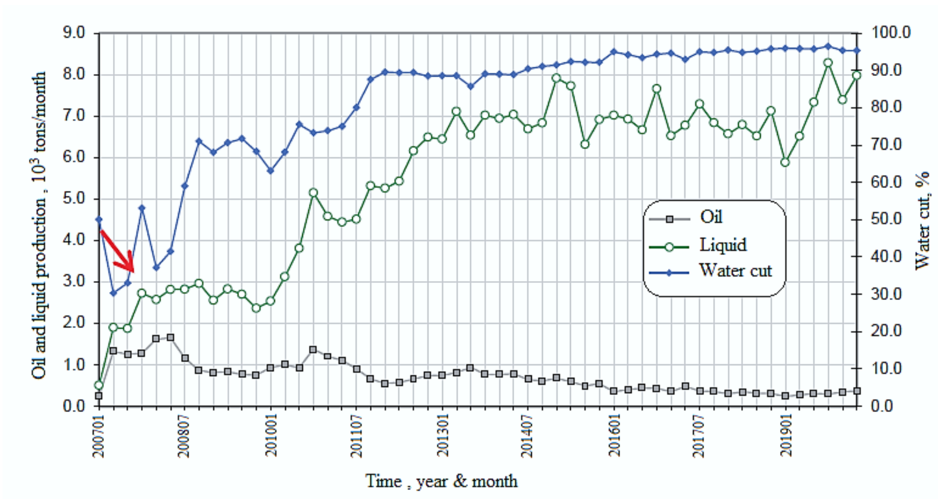

Figure 9. Indicators of well number 1377 of the Vatyogan field

Table 1 displays the main geological and physical characteristics of the productive formations of the wells in the area under consideration. It also illustrates the changes in their initial water cut under low initial oil saturation conditions of the AV1-3 reservoir of the Vatyogan field.

Table 1. Comparison of geological and physical characteristics of heterogeneous productive formations of wells and changes in their initial water cut under conditions of low initial oil saturation of the reservoir AV1-3 of the Vatyogan field

Well No	Oil formation thickness, m	Porosity,%	Oil saturation, %	Permeability, μm^2	Layer-by-layer heterogeneity, rel. unit	Initial water cut, %	Water cut in the first six months of operation, %	Deviation of water cut from the initial level in the initial period, %
5183	15,7	21,7	58,8	0,0852	4,206	22,1	5,31	–16,8
1376	20,4	22,0	56,0	0,1589	7,658	20,9	5,9	–15,0
1375	18,3	22,9	58,1	0,1930	3,908	9,9	2,9	–7,0
1440	13,2	21,3	56,7	0,1008	2,875	5,6	2,3	–3,3
1316	15,1	20,2	47,3	0,0485	4,521	14,4	6,4	–8,0
1435	10,4	20,8	57,2	0,0494	5,898	44,6	24,7	–19,9
5182	19,3	23,0	59,4	0,5524	8,851	56	33	–23,0
1377	18,3	22,0	64,6	0,1032	3,58	50	30,3	–19,7
1439	16,8	22,3	60,8	0,1350	4,648	2,1	1,3	–0,8
1436	8,4	20,6	55,2	0,0665	1,523	39,9	29,4	–10,5
1378	10,8	23,9	61,1	0,4756	2,16	9,7	7,18	–2,5
1315	16,9	22,1	63,3	0,4725	8,281	60	45,2	–14,8
5180	18,6	23,7	54,5	0,4215	4,73	8,5	6,6	–1,9
2090	12,2	20,5	56,1	0,0367	3,105	75,2	84,1	8,9
3522	7,4	21,1	45,8	0,0866	1,726	56,4	68,8	12,4
1317	19,1	19,9	54,2	0,0365	2,291	35,1	46,9	11,8
5178	6,3	21,6	51,5	0,0847	1,685	9,1	16,6	7,5
1438Y	18	21,9	60,3	0,1026	2,346	2,9	6	3,1
1437	14,9	21,8	50,0	0,0690	1,657	5,9	29,6	23,7
5179	16,2	22,1	51,6	0,0778	0,786	2,3	13	10,7
5181	18,9	23,2	62,2	0,2834	2,618	1	13	12,0

The table compares Oil-saturated formations' thicknesses, porosity, oil saturation, permeability, layer-by-layer heterogeneity compared with the initial water content, the water cut in the first six months of operation, and the deviation of the water cut from the initial level in the initial period.

Upon pairwise examination of the parameters, it was found that the initial water cut's graphical dependence on the layer-by-layer heterogeneity of the formation is the most significant (refer to Fig. 10). The deviation of the initial water cut is the deviation from the initial water cut level during the initial period (Yang 2024; Wang et al. 2013).

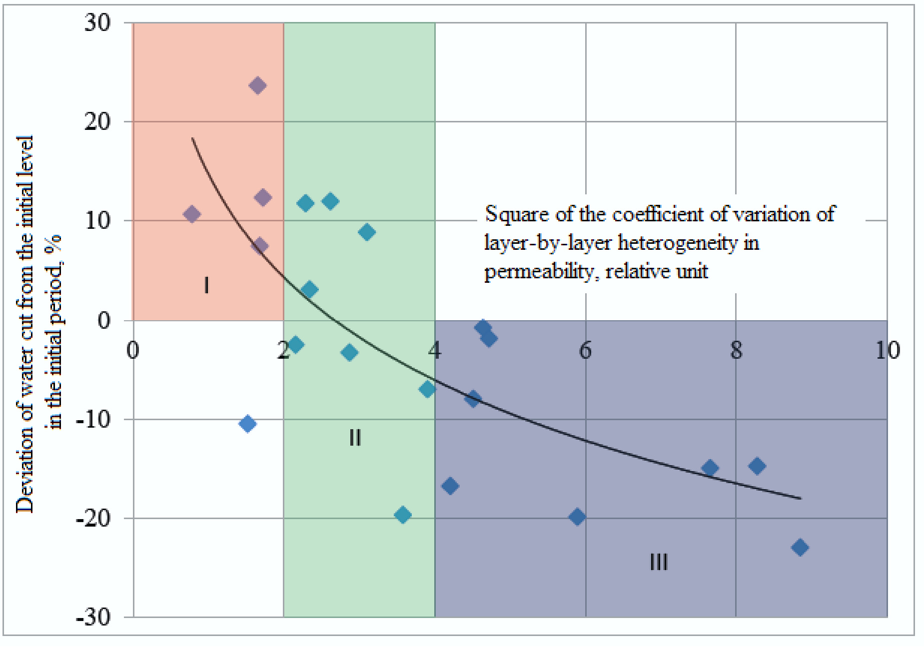

Figure 10. Estimation of the dependence of the deviation of the initial water cut in the initial period on the layer-by-layer heterogeneity for undersaturated oil reservoirs

Three distinct zones (I, II, and III) have been identified within the given construction. These zones reflect varying degrees of layer-by-layer heterogeneity in the formation. Zone I corresponds to the range of 0 to 2, Zone II spans from 2 to 4, and Zone III includes values of 4 or more relative units (see Fig. 10).These zones were selected according to the delimitation principle of areas with stable (in most cases) facts of positive and negative deviations of water cut. The third zone represents both positive and negative values between these zones. The absolute values of the zone boundaries (layer-by-layer heterogeneity) have been rounded to whole numbers. Further investigation involving a larger number of wells will help us to determine the exact value of these boundaries.

4. Conclusions

The research presented in this work was initiated due to unusual initial water cut indicators in several wells of the Vatyogan field of the AV1-3 formation.The graphical dependence of the deviation of the initial water cut on the layer-by-layer heterogeneity of the formation for undersaturated oil reservoirs is the result of the pairwise comparative analysis.

Upon delving into the data from our research, a compelling trend was observed. It turns out that the greater the layer-by-layer heterogeneity of the reservoir formation in terms of permeability (specifically, when the square of the variation coefficient exceeds 4 relative units), the more advantageous it becomes for drilling in that particular section. This insight could have significant implications for drilling operations.

When drilling relatively homogeneous formations (heterogeneity less than 2 relative units), rapid water cut up to 75-85% is predicted with high probability. This is typical for the conditions of the AV1-3 formation of the Vatyogan field. Moreover, it is difficult to make an unambiguous prediction of the initial water cut within the heterogeneity range of 2 to 4 relative units.

Selective reservoir isolation technologies aimed at isolating the waterflooded, highly permeable part of the reservoir are ineffective in such conditions. New solutions are needed that allow reversible limitation of the permeability of the low-permeability, low-saturated part of the reservoir.

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