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The Influence of Lithologic and Facies Zones on the Efficiency of Cyclic Steam Simulation (as Illustrated by the Permian–Carboniferous Reservoir of Super Viscous Oil of the Usinskoye Oil Field in the Komi Republic)

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Влияние литолого-фациальных зон на эффективность пароциклических обработок (на примере пермокарбонатной залежи сверхвязкой нефти Усинского месторождения Республики Коми)

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The influence of lithologic facies zones on the development of the Permian-Carboniferous reservoir of the Usinskoye oil field was evaluated. To meet the objective, reservoir porosity and permeability of each lithologic facies zone were addressed, the facial zoning influence on the rate of oil extraction in the Permian-Carboniferous reservoir of the Usinskoye oil field was analyzed, and the performance was evaluated after cyclic steam injection. The research deals with the Permian-Carboniferous reservoir of the Usinskoye oil field in the Komi Republic. In accordance with a developed format, a database of core analysis results and a base on cyclic steam simulation efficiency for the period of 5 years were collected. To determine the belonging of facies, we used the classification system for carbonate rocks suggested by Robert J. Dunham with the additions proposed by A.F. Embry and J.E. Klovna (based on the prevalence of structure components in limestone, the grouting agent type, as well as their interrelation in the rock).

Based on the material composition of the rock and on the structural parameter, the following three main facies zones were identified: shallow-water carbonates (internal ramp zone), organogenic buildup (middle ramp zone), shallow-water offshore plain (middle ramp zone, external ramp zone in part). In addition, among the facies, it is possible to single out a moderately deep-water offshore plain (external ramp zone).

In accordance with the research results, curves of the displacement coefficient distribution related to porosity were obtained and guidelines on determining the priority drilling sites within the area were given. As per the core analysis results, in the eastern part of the field, a zone of organogenic buildups was clearly determined; such buildups were formed mainly in the middle and late Carboniferous Period and Early Permian period.

In the north-western part of the field, the existence of an internal ramp with shallow-water carbonate facies was assumed. The location of the priority drilling wells was chosen with regard to the fact that each cluster of development drilling wells is to penetrate facies of organogenic buildups having the best reservoir properties and oil displacement efficiency.

Ключевые слова:

пароциклическая обработка, фильтрационно-емкостные свойства, классификация по Данему, литотип, фациальная зона, коэффициент вытеснения, карбонатная отмель, органогенная постройка, мелководно-шельфовая равнина.

Существует оценка влияния литолого-фациальных зон на процессы разработки пермокарбонатной залежи Усинского месторождения. Для достижения поставленной цели решаются задачи по определению фильтрационно-емкостных характеристик для каждой литолого-фациальной зоны, произведены анализ влияния фациальной зональности на степень извлечения нефти для пермокарбонатной залежи Усинского месторождения, оценка производительности после проведения пароциклических обработок. В качестве объекта исследования выбрана пермокарбонатная залежь Усинского месторождения, расположенного в Республики Коми. По разработанному формату была сформирована база данных по результатам петрофизического анализа керна, база по эффективности пароциклических обработок за пятилетний период. При определении фациальной принадлежности принята классификация карбонатных пород по Р.Х. Данему с дополнениями Эмбри и Кловена (по преобладанию в известняке структурных компонентов, типу цементирующего вещества, а также их взаимоотношению в породе). На основе вещественного состава породы и структурного параметра были выделены три основные фациальные зоны: карбонатная отмель (зона внутреннего рампа); органогенная постройка (зона среднего рампа); мелководно-шельфовая равнина (зона среднего рампа, частично зона внешнего рампа). Дополнительно можно выделить также такую фацию, как умеренно-глубоководная шельфовая равнина (зона внешнего рампа).

В результате проведенных исследований построены графики распределения коэффициента вытеснения от пористости пород, даны рекомендации по определению первоочередных участков бурения по площади. По данным исследования керн в восточной части месторождения хорошо выделяется зона органогенных построек, образование которых происходило преимущественно в средне-позднекаменноугольное и раннепермское время. В северо-западной части месторождения предполагается существование внутреннего рампа с фациями карбонатной отмели. Выбрано размещение скважин первоочередного бурения с тем учетом, что каждый куст эксплуатационного бурения вскрывает фации органогенных построек, обладающих наилучшими фильтрационно-емкостными свойствами и коэффициентом вытеснения нефти.

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General Information about the Subject of the Research

The Permian-Carboniferous reservoir of the Usinskoye oil field is one of the biggest in the Timan-Pechora Basin Province and in Russia. The unique character of geological reserves explains constant interests to the reservoir. Despite all materials accumulated throughout years of the field development, to build a conceptual geological model, the following issues still remain topical: the structural and tectonic model update and detailed understanding of the reservoir structure [1–24].

The Permian-Carboniferous reservoir of the Usinskoye oil field is located at a depth of 1100–1400 m; it consists of carbonate rocks and is characterized by an extensive discontinuity of the cross section and by anisotropy of reservoir properties in vertical and horizontal directions. In the reservoir section with an oil saturated layer of up to 350 m, ten formation members combined into the following three development target zones were singled out: lower, middle, and upper ones. The main reserves (about 90 %) are contained in the upper and middle zones. The oil reservoir contains oil with viscosity ranging from 344 to 2024 mPa·s, low gas-oil ratio of 22–30 m³/t and a saturation pressure of 7.6 MPa. The initial reservoir pressure reaches 14.3 MPa; the initial reservoir temperature is 20–25°C.

Historical research data focusing on the reservoir geological structure resulted in conclusions that within the Usinskoye oil field area, the productive carbonate sediments of the Permian-

Carboniferous age are characterized by a very complex geological structure and variable reservoir properties [1, 25–45].

Lithologic Facies Analysis

To further build a conceptual geological model of the reservoir, a lithologic facies analysis was conducted, which made it possible to describe lithologic types of sediments under research. The material composition of the rock was studied; there was selected the structural and genetic classification of carbonate rocks by R. J. Dunham with the modifications by A.F. Embry and J.E. Klován (based on the prevalence of structural components in limestone, the cementing agent type, as well as their interrelation in the rock).

Following the analysis of the material composition of the rock and structural parameters, nine lithologic types of the rock were identified: mudstone, wackestone, packstone, grainstone, boundstone, floatstone, rudstone, crystalline carbonate (dolomite), and clay-carbonate-siliceous rock.

Based on the obtained lithologic types of rocks and seismic exploration studies, the following three main facies zones were singled out in the section of the Middle Carboniferous and Lower Permian sediments (Fig. 1):

- shallow-water carbonates (internal ramp zone),
- organogenic buildup (middle ramp zone),
- shallow-water offshore plain (middle ramp zone, external ramp zone in part).

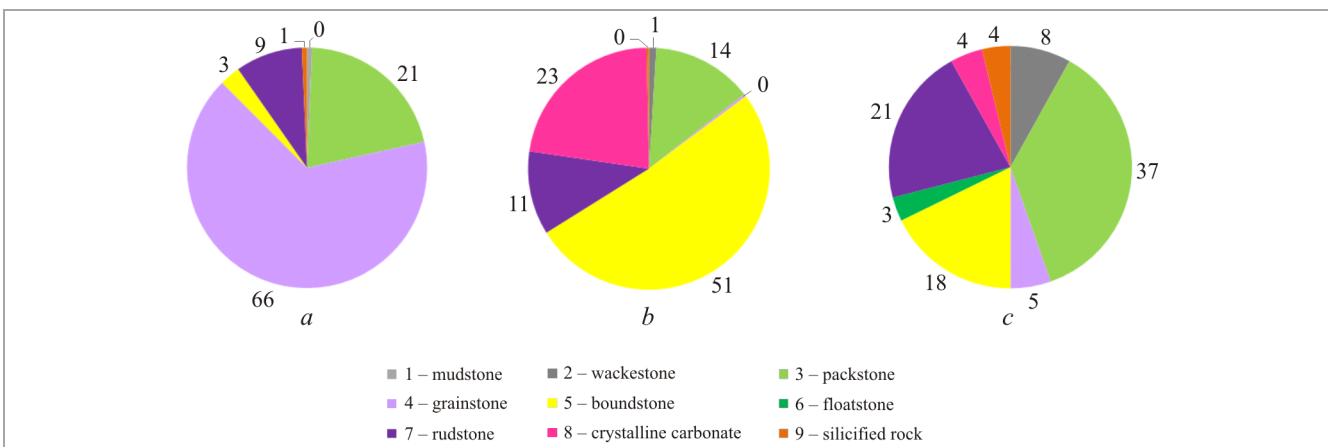


Fig. 1. Most typical distribution (%) of lithologic types in a well for different facies zones: *a* – the facies zone of shallow-water carbonates (internal ramp zone); *b*– the facies zone of organogenic buildup (middle ramp zone); *c* – the facies zone of shallow-water offshore plain (middle ramp zone, external ramp zone in part)

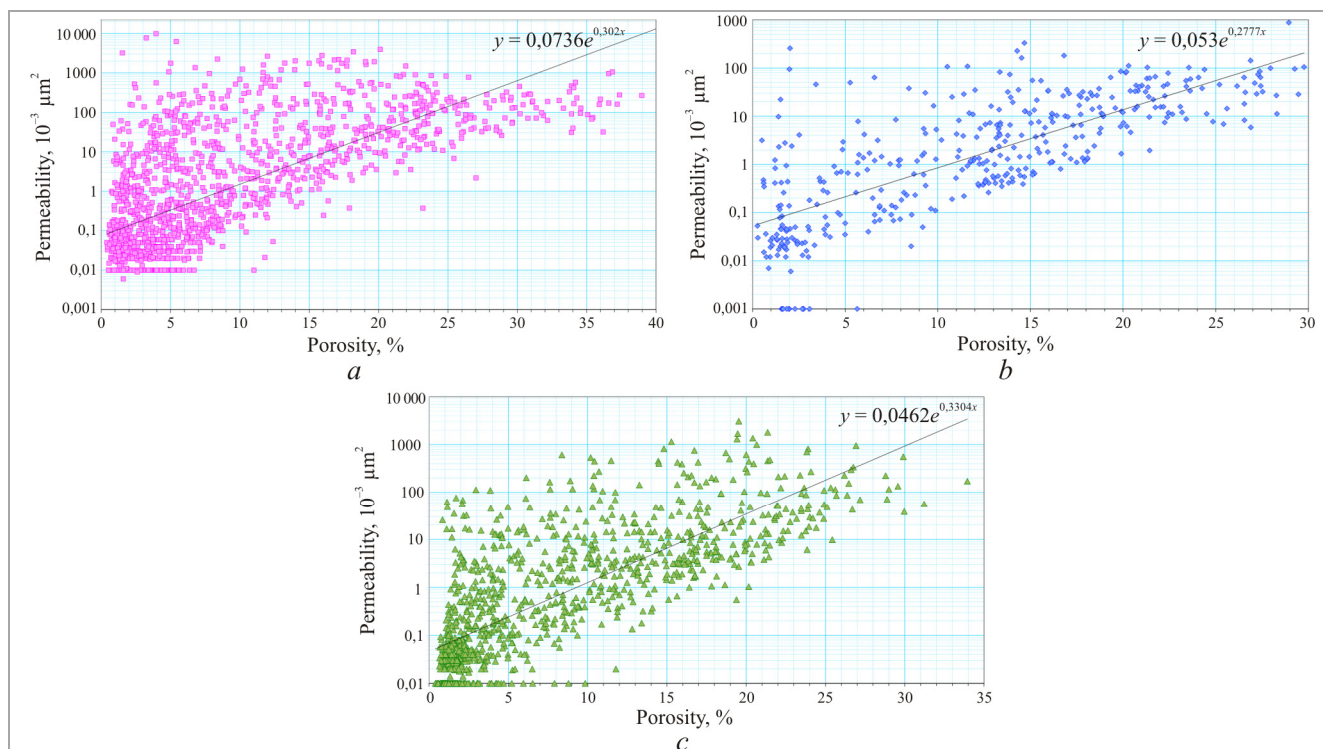


Fig. 2. Variability of permeability ratio with porosity: *a* – organogenic buildup facies; *b* – shallow-water carbonate facies; *c* – shallow-water offshore plain facies

Table 1

Reservoir properties distribution

Facies	Permeability, $10^{-3}\mu\text{m}^2$	Porosity, %	Residual water saturation, unit fractions	Residual oil saturation, unit fractions	Displacement efficiency, unit fractions
Organogenic buildups	$\frac{155.3}{0.01-12573}$	$\frac{7.53}{0.37-27.83}$	0.110	0.593	0.406
Shallow-water carbonates	$\frac{10.01}{0.01-300.5}$	$\frac{4.50}{0.98-21.89}$	0.165	0.656	0.316
Shallow-water offshore plains	$\frac{12.30}{0.01-48.62}$	$\frac{7.17}{1.25-17.59}$	0.169	0.636	0.239

In addition, it is possible to single out a moderately deep-water offshore plain (external ramp zone).

Based on lithologic and petrophysical studies and porosity ratio forecast maps, graphs of permeability variations with porosity were built for each facies zone (Fig. 2).

According to approximating curves for the facies zones obtained as a result of the petrophysical core analysis, it is possible to determine reservoir properties for each zone (Table 1).

A comprehensive analysis of permeability distribution variation with porosity related to

various facies zones made it possible to reveal the following two main facts:

1. Reservoir properties of productive sediments under study depend on the structural and textural features of sediments, which are definitely associated with facial conditions of sedimentation.

2. Irrespective of facies confinement, reservoir properties heavily rely on post-sedimentation processes.

Porosity widely varies in zones of assumed development of sediments in reef shallow-water facies and shallow-water carbonate facies. These are characterized by a mosaic distribution of areas

of better and worse reservoir properties, which is indicative of significant discontinuity of those sediments and various degrees of influence by post-sedimentation transformations. As to areas of sediment developments in shallow-water offshore plains, normally they are characterized by low level reservoir properties. This is obviously due to clay content in these sediments [6]. Therefore, the conducted analysis showed a high degree of variations within the area in terms of macro and micro continuity of rocks penetrated in wells confined to different facies zones. In their turn, the latter play an important role in the efficiency of the development system used for the Permian-Carboniferous reservoir of the Usinskoye oil field.

Water flood displacement efficiency and relative permeability to phase represent two main filtration characteristics of reservoirs and serve as a basis for hydrodynamic calculations of the development parameters [12, 28].

The average effect of the displacement efficiency change was calculated under conditions of the test temperature increase and a general dependence was obtained (Fig. 3):

$$K_{displ} = 0.0419 \cdot \text{Log}(K_{pr}) + 0.0029 \cdot t + 0.0059 \cdot \text{Log}(K_{pr})^2 + 0.0006 \cdot \text{Log}(K_{pr}) \cdot t - 9.278E - 6 \cdot t^2 - 0.0557;$$

$$R^2 = 0.90; Fp/Ft = 512/1.54;$$

$$p < 0.00001.$$

where K_{pr} is the permeability coefficient; t is the time.

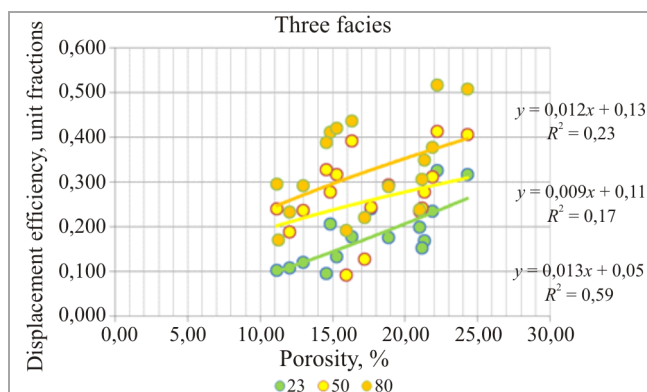


Fig. 3. Variability of the oil displacement efficiency with porosity for facies of organogenic buildups, shallow-water carbonates, and shallow-water offshore plains at the temperature of 23°, 50°, and 80 °C

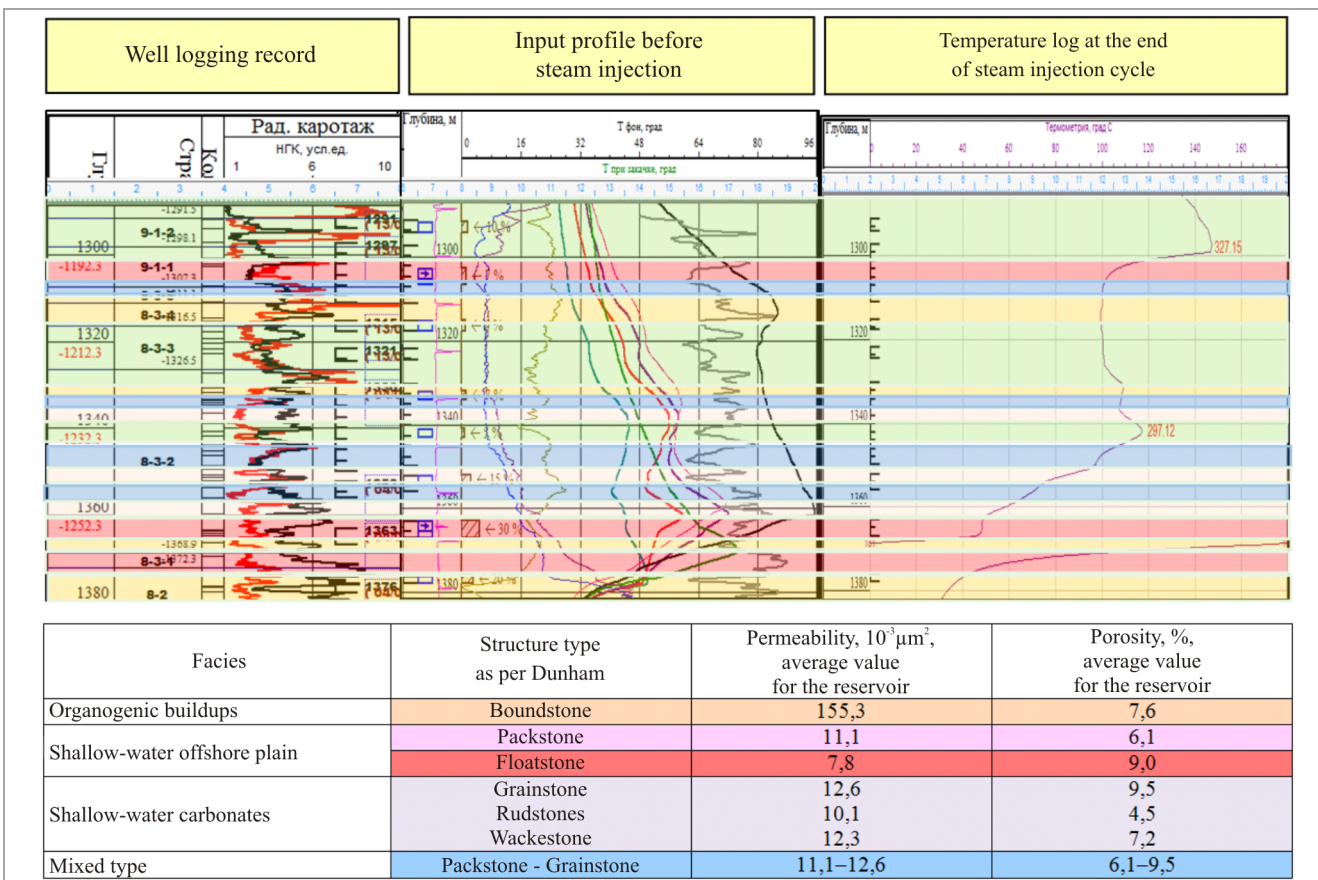


Fig. 4. Comparison of a well log record, input profile, and temperature log

It is known that a formation heating accelerates all oil recovery processes. Temperature increases significantly intensify the reservoir depletion as a result of reduced oil viscosity, expansion of reservoir fluids and decreased gas solubility factor [10]. Results of wells geophysical surveys focused on the fluid influx and temperature logs reveal the influence of macro-pore intervals. As an example, Fig. 4 shows input profiles and temperature logs for a producing well, which penetrated formation members 8 and 9. In the section penetrated by the well, the following facies were found: shallow-water offshore plain, shallow-water carbonates, and organogenic buildups. In March-April 2019, a cyclic steam simulation (CSS) was completed. Thermal log data indicated a temperature anomaly at an interval of 1295.0–1300.0 m (with the maximum temperature of 327.2°C). The interval was earlier marked as a not allowing for input on the input profile. According to the Lithologic, petrographic, and petrophysical core analysis of the Usinskoye oil field well, one of the most permeable intervals is located exactly at that depth.

Well Production Analysis after Cyclic Steam Simulation Subject to a Lithologic Facies Zone

Cyclic steam simulation represents one of the most widely used methods of highly viscous oil developments within the Permian-Carboniferous reservoir of the Usinskoye oil field. In the period from 2017 to 2019, 537 cyclic steam simulations were completed at the reservoir. The overall consumption of steam amounted to 4.7 mt; the incremental oil recovery was assessed as equal to 1.8 mt. The average steam to oil ratio reached 5.4 kt in 2017, 5.9 kt in 2018 and 8.4 kt in 2019. This proves the cyclic steam simulation to be one of the most efficient well interventions performed at the reservoir. High CSS index was mainly driven by the worsening of basic characteristics of developed wells. The main geological and production factors influencing the efficiency of the cyclic steam simulation of wells within the Permian-Carboniferous reservoir include the degree and mechanism of water intrusion as well as the productivity of wells. As the water content goes up and productivity goes down, the CCS efficiency in wells decreases [14].

Given the water content does not exceed 25%, the cyclic steam simulation proves efficient in wells, responding to steam injection, irrespective of their productivity. If the water content of the wells exceeds 25 %, the cyclic steam simulation efficiency depends on the water intrusion mechanism. Hence, normally, the efficiency is higher in medium and high productivity wells rather than in low productivity ones.

Fig. 5 shows the wells productivity on completion of CSS with regard to the wells location and relation to particular lithologic facies zones.

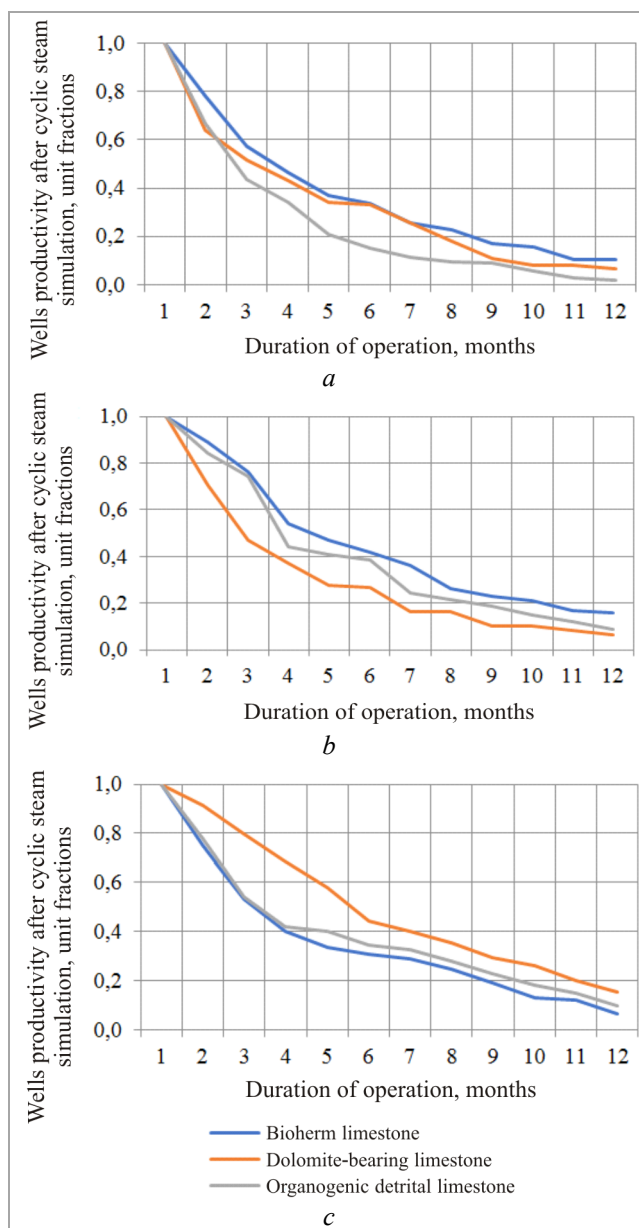


Fig. 5. Decline rate by wells working for: a) target P₁a + S; b) target C₃k + g; c) target C₂m

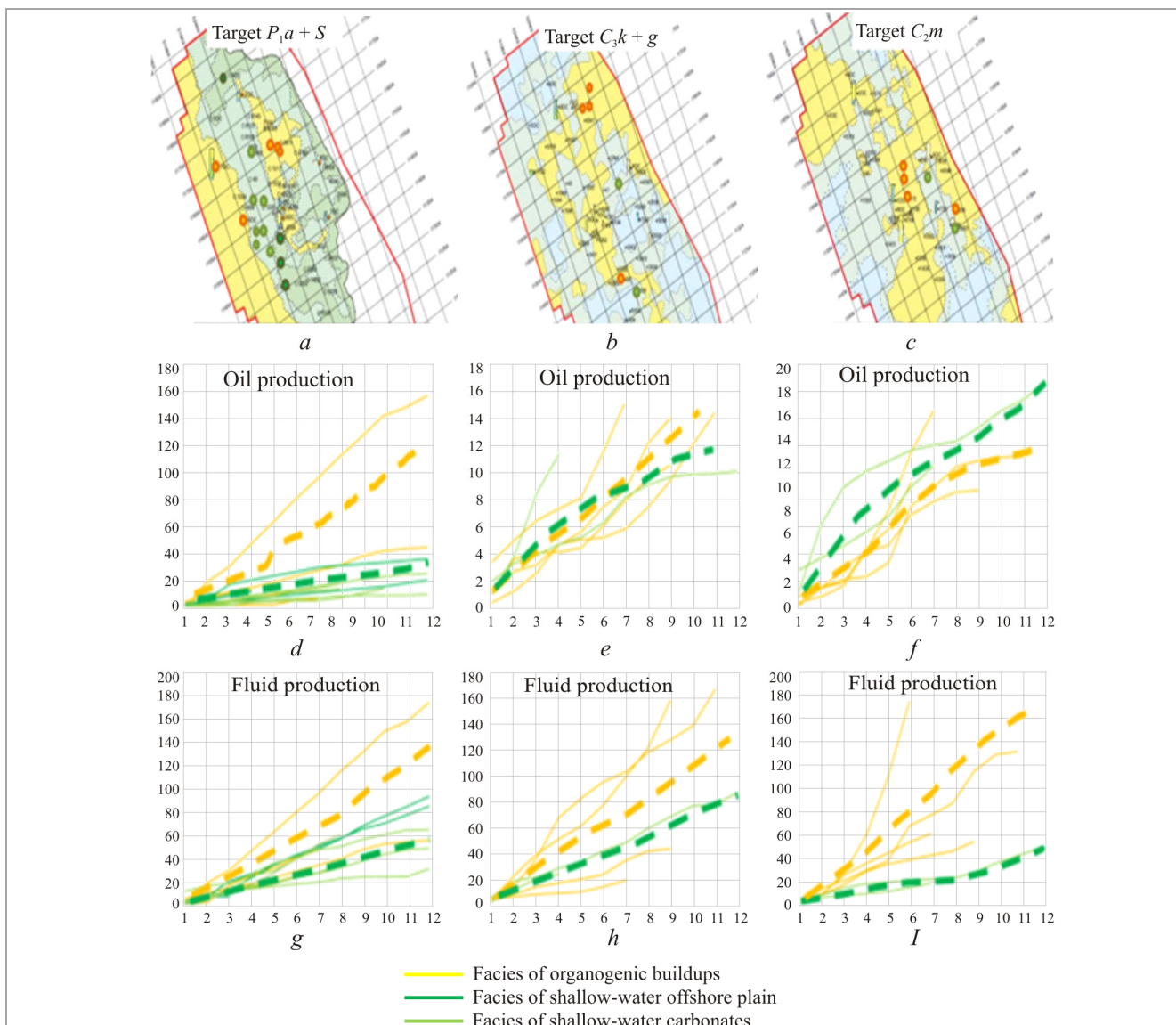


Fig. 6. Fluid and oil production influence depending on different development targets and facies zoning: a) target P_{1a+S} ; b) target C_{3k+g} ; c) target C_{2m} ; d) oil production within target P_{1a+S} ; e) oil production within target C_{3k+g} ; f) oil production within target C_{2m} ; g) fluid production within target P_{1a+S} ; h) fluid production within target C_{3k+g} ; i) fluid production within target C_{2m}

Statistical data given with reference to the wells productivity after the cyclic steam simulation demonstrate that bioherm limestone is characterized by high productivity in formations P_{1a+S} and C_{3k+g} , and has the highest oil production rate.

In the lower part of the cross section (C_{2m}), oil production is lower in bioherm facies vs. organogenic detritus facies, which is probably due to increased fracture porosity leading to the high water content in the wells.

For a further design and development of the Permian-Carboniferous reservoir, it was proposed to locate the wells and complete the priority cyclic steam simulations at the active well stock on the

basis of the information obtained on the reservoir properties within the facies zones.

Fig. 6 (a, b, c) shows the location of the priority drilling wells for formations P_{1a+S} , C_{3k+g} and C_{2m} , respectively.

The wells were located subject to the fact that each production drilling cluster penetrates the facies of the organogenic buildups with the best reservoir properties and oil displacement efficiency (Fig. 7).

Conclusion

The completed analysis demonstrated the high variability of the macro and micro

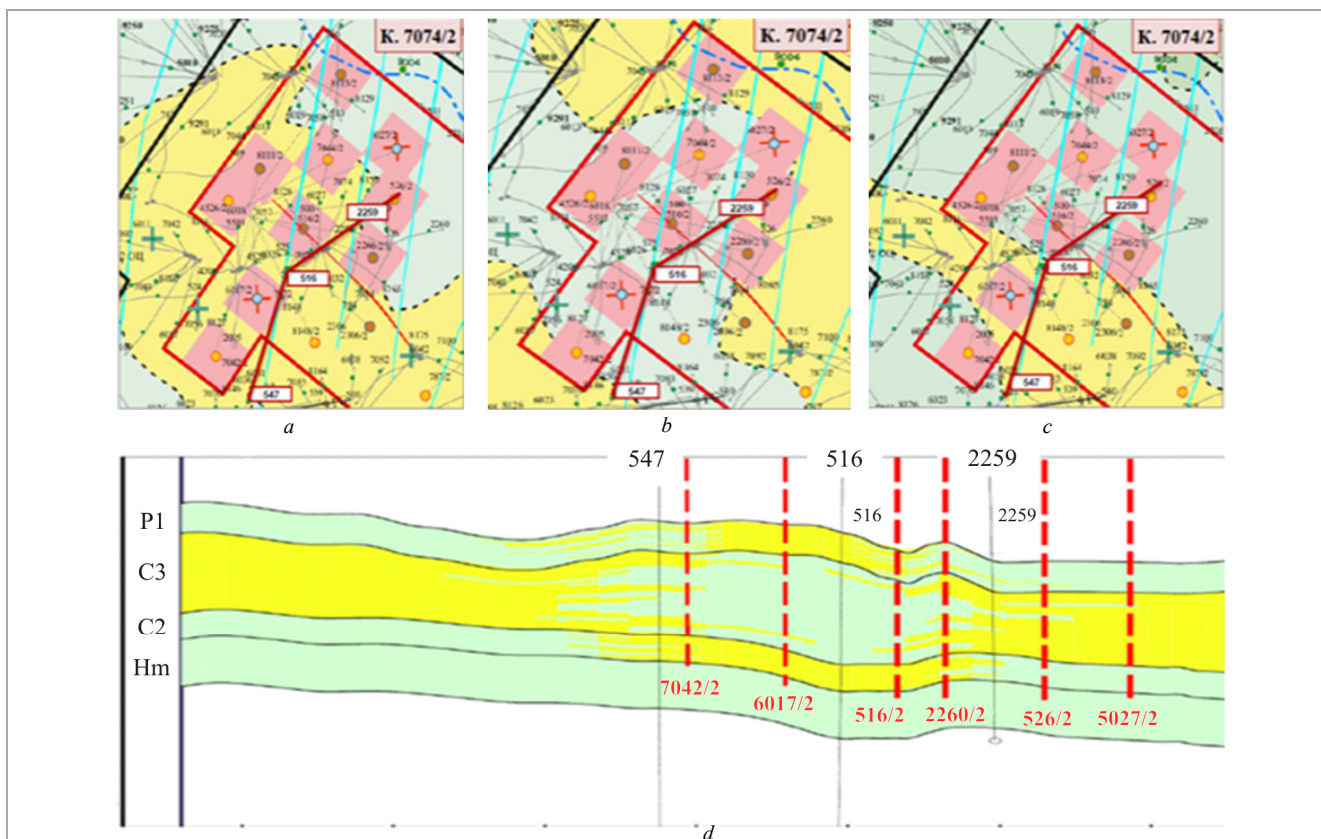


Fig. 7. Identification of lithologic facies zones (illustrated by cluster 7074/2): a) target C_{2m} ; b) target C_{3k+g} ; c) target P_{1a+S} ; d) section view of wells line 547-516-2259

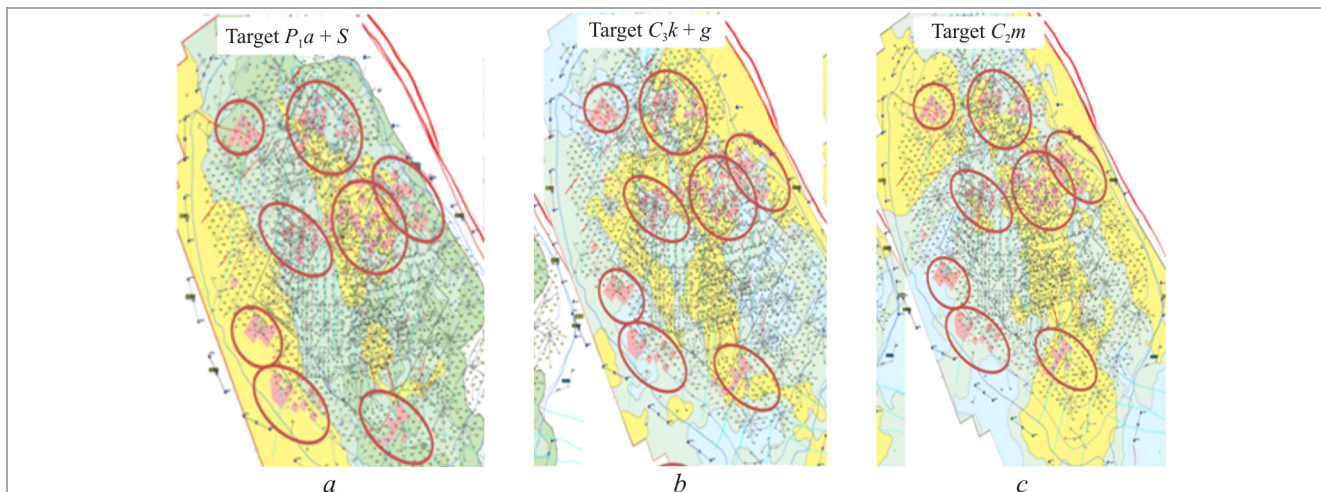


Fig. 8. Location of first-priority wells with regard to the conceptual sedimentation model of the Usinskoye oil field: a) target P_{1a+S} ; b) target C_{3k+g} ; c) target C_{2m}

discontinuity of the wells within different facies zones. Sedimentation conditions and post sedimentation processes determine reservoir properties and different permeability mechanisms. The hydrodynamic displacement is the main mechanism of oil recovery in high permeability reservoirs, while the reservoir fluid expansion and capillary imbibition is the main

mechanism of oil recovery in low permeability reservoirs.

The priority drilling wells were located in line with the conceptual sedimentation model of the Usinskoye oil field subject to the fact that each production drilling cluster penetrates the facies of the organogenic buildups with the best reservoir properties and oil displacement efficiency (Fig. 8).

In order to enhance the efficiency of the Permian-Carboniferous reservoir and ensure the achievement of the designed oil recovery level, it is necessary to consider the lithologic facies zoning for this reservoir.

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