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Energy Potential Analysis of Facially Heterogeneous Carbonate Reservoirs in the Process of Hydrocarbon Reserves Development

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Анализ энергетического потенциала фациально-неоднородных карбонатных коллекторов в процессе выработки запасов углеводородов

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Analysis of the energy state of a deposit is an integral part of field development monitoring. Now, a significant volume of production in the Perm Krai comes from complex carbonate reservoirs, which are characterized by heterogeneity both vertically and laterally, different filtration and reservoir characteristics, alternation of different types of void space, and a large coefficient of compartmentalization. Under such conditions, the need for constant monitoring of the reservoir energy state, in particular the dynamics of reservoir pressure, increases. In this work, using the example of the T-Fm-Fr carbonate deposit of one oil field located in the Perm Krai in the northern part of the Solikamsk depression, an analysis of changes in reservoir pressure in various lithological-facial zones since the beginning of well commissioning was carried out. The four zones identified as a result of facies analysis are characteristic of fields confined to the reef reservoirs of the Solikamsk Depression and are characterized by different geological structures. It is generally accepted that the filtration and reservoir properties of a reservoir, field reserves and well flow rates can directly depend on lithological-facial zoning. Thus, as a result of the study, it was established that the facies of the upper part of the rear plume of the reef was characterized by the maximum amount of accumulated fluid production and the best filtration and reservoir properties. However, based on the magnitude of changes in reservoir pressure in wells, obtained using artificial intelligence methods in the Data Stream Analytics program, and when calculating statistical criteria, it was established that the features of the facies environment did not significantly affect the magnitude of changes in reservoir pressure from the beginning of putting wells into operation. The calculated criteria confirmed the different amounts of accumulated oil and liquid production by facies and were not statistically significant for the magnitude of changes in reservoir pressure. The results of the study indicated the need to take into account all facial zones as a single development object when choosing the optimal system for maintaining reservoir pressure and selecting well stimulation.

Ключевые слова:
фациальный анализ, динамика пластового давления, статистический анализ, сложнопостроенный карбонатный коллектор, рифовый резервуар, энергетическое состояние залежи.

Анализ энергетического состояния залежи является неотъемлемой частью мониторинга разработки месторождений. В настоящее время значительный объем добычи в Пермском крае приходится на сложнопостроенные карбонатные коллекторы, которые характеризуются неоднородностью как по вертикали, так и по латерали, различными фильтрационно-емкостными характеристиками, чередованием отличающихся типов пустотного пространства, большим коэффициентом расчлененности. В таких условиях возрастает необходимость постоянного мониторинга энергетического состояния залежи, в частности динамики пластового давления. В данной работе на примере карбонатной залежи Т-Фм-Фр одного нефтяного месторождения, расположенного в Пермском крае в северной части Соликамской депрессии, проведен анализ изменения пластового давления по различным литолого-фациальным зонам с начала ввода скважин в эксплуатацию. Выделенные в результате фациального анализа четыре зоны являются характерными для месторождений, приуроченных к рифовым резервуарам Соликамской депрессии, и характеризуются различным геологическим строением. Принято считать, фильтрационно-емкостные свойства коллектора, запасы месторождения и дебиты скважин могут напрямую зависеть от литолого-фациальной зональности. Так, в результате исследования установлено, что фация верхней части тылового шлейфа рифа характеризуется максимальной величиной накопленной добычи жидкости и лучшими фильтрационно-емкостными свойствами. Однако по величине изменения пластового давления в скважинах, полученного с помощью методов искусственного интеллекта в программе Data Stream Analytics, и при расчете статистических критериев установлено, что особенности фациальной обстановки несущественно влияют на величину изменения пластового давления с начала ввода скважин в эксплуатацию. Рассчитанные критерии подтверждают различную величину накопленной добычи нефти и жидкости по фациям и не являются статистически значимыми для величины изменения пластового давления. Результаты исследования указывают на необходимость учета всех фациальных зон как единого объекта разработки при выборе оптимальной системы поддержания пластового давления и подборе геолого-технологических мероприятий на скважинах.

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Introduction

At present, a large volume of production in Perm Krai is related to carbonate deposits confined to organogenic structures. Such reservoirs are most often characterised by complex heterogeneous structure [1, 2]. The heterogeneity is due to the complexity of diagenetic transformations. As a result, the pore size distribution from macropores to pores smaller than 1 μm can be observed [3]. Also, different paleo-geomorphological conditions of sedimentation determine the diverse facies character of sediments. The fact is that the detailed study of rock facies is important for drilling and rational development of hydrocarbon deposits [4–7]. Facies zonation of carbonate reef complexes is an important natural cause of reservoir heterogeneity [8–10]. Thus, the authors [11], after the detailed analysis of selected facies and petrophysical rock typing of the Bangestan reservoir at the Ahvaz oilfield, identified three facies with higher reservoir "quality" and, accordingly, higher values of filtration-capacity properties. Carrasquilla and others [12] pointed out the importance of the facies analyses complexation using different methods and integrating the data obtained with artificial intelligence to better estimate the carbonate reservoir potential in the Campos Basin, Southeastern Brazil. Kakemema and others [13] identified five hydraulic flow units with the best porosity, permeability and capacity values in the Triassic carbonate reservoir in the South Pars field, Persian Gulf basin, based on petrophysical properties, sedimentary facies and their diagenetic modifications. In the following paper [14], on the example of a field in Perm Krai confined to a reef carbonate reservoir, it was noted that rock secondary transformations occur variously in different lithological-facial zones. Consequently, the filtration-capacity properties of the reservoir, field reserves, well flow rates and cumulative oil production may directly depend on the lithological-facial zoning (LFZ) [1, 15–17].

The heterogeneity of carbonate reservoir properties both vertically and laterally, facies variability, complex pore structure and different filtration-capacity properties make it necessary to monitor continuously the reservoir energy state, in particular the reservoir pressure dynamics.

The purpose of this research is to analyse changes of reservoir pressure in wells from their commissioning by different LFZ T-Fm-Fr of the developed object of an oil field in the north of Perm Krai.

Research Subject

The research subject is the T-Fm-Fr deposit of an oil field, which is located in Perm Krai in the northern part of the Solikamsk Depression. The Solikamsk depression is positioned in the area of the large Kama-Kinel trough with wide reef structures of Late Devonian age, which placement is controlled by different tectonic blocks. The T-Fm-Fr deposit under study refers to a reef carbonate massif. The reservoir is represented by biomorphic-detrital and algal lumpy limestones, cavernous and cavernous-porous above, with caverns and cross fractures below, including bitumen.

By facies analysis, four LFZs [18, 19], characterising the development of organogenic-carbonate structure, were identified within the field: the bioherm core (BC), the upper and lower parts of the reef rear plume (UP and LP), and the reef slope (Fig. 1).

The LFZs are typical deposits in the northern part of the Solikamsk Depression [20, 21]. The allocation of these zones is conditioned by certain sedimentation. The facies zones are characterised by different lithological composition, reservoir type and, as a consequence, different filtration-capacity properties and the value of cumulative liquid production (CLP) (Fig. 2).

The differentiation of cumulative liquid production may be due to different stock of production and injection wells, geological and technological conditions of development, drilling rates, type of reservoir tapped, and the efficiency of the applied reservoir pressure maintenance system (RPM). Well stock data and average values of filtration-capacity properties by LFZ are given in Table 1.

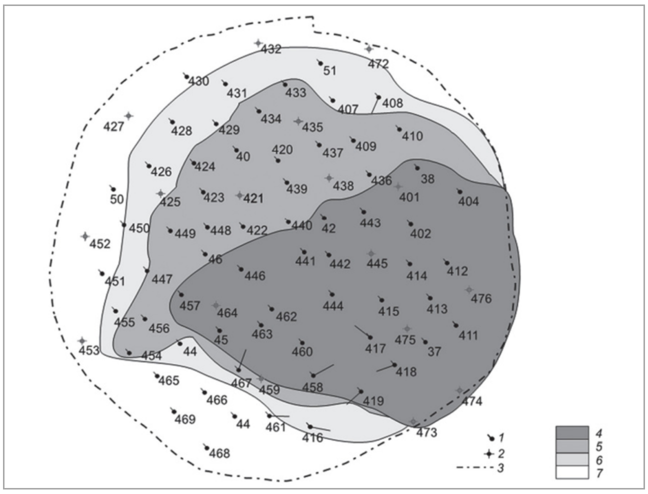

Fig.1. Lithological-facial scheme of the studied field: *1* – production well; *2* – injection well; *3* – outer oil pool outline; *4* – facies zone of the lower part of the reef rear plume; *5* – facies zone of the upper part of the reef rear plume; *6* – facies zone of the bioherm core; *7* – facies zone of the reef slope

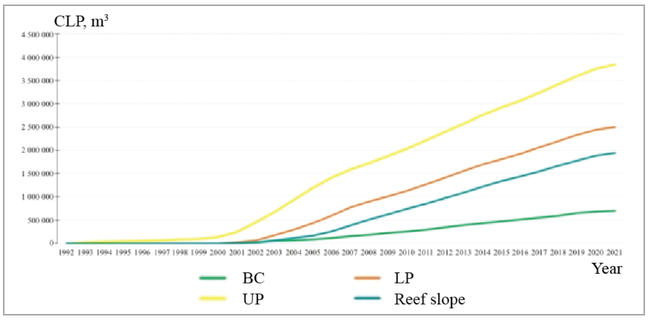

Fig. 2. Graph of cumulative liquid production by LFZ from the beginning of field development

Table 1

Well stock data on LFZ and average values of filtration-capacity properties

LFZ	Number of production wells, units	Number of injection wells, units	$k_{perm, md}$	K_p, %
BC	12	2	8.54	7.92
UP	18	4	73.5	9.3
LP	21	7	41.3	8.91
Reef slope	10	6	6.7	9.71

Filtration-capacity properties of the T-Fm-Fr development object (k_{perm} – permeability coefficient of the formation drainage zone, K_p – porosity coefficient) are given according to the results of production test.

Change Analysis of Reservoir Pressure by LFZ in the Process of Oil-Pool Development

Formation pressure (P_f) is the most important parameter in monitoring the reservoir energy state 22]. The reservoir pressure value is used to forecast hydrocarbon production, development modelling, and well capacity. Often the reservoir pressure is determined as a result of hydrodynamic well testing (HWT). However, it requires a long-term well shutdown, which often leads to fluid underbalance [23–25]. In this case, there is a need to develop indirect methods of reservoir pressure determination, which exclude the long-term well shutdown [26, 27]. Such methods include determination of formation pressure at the stage of drilling or well workover [28], determination of P_f with the material balance method used in reserves estimation [29, 30]. The combination of accumulated well operation data and application of certain mathematical and statistical processing methods also refers to indirect methods of reservoir pressure determination without well shutdown for flow test [31–38].

Artificial intelligence (AI) is widely applied in the oil industry – in exploration, development and production to reduce the cost and time of decision making [39, 40]. In particular, the application of machine learning and AI in assessing the reservoir energy state is considered to be a new trend [41].

In this paper, formation pressure values calculated using artificial intelligence methods are used [23, 41]. The methodology of P_f determination is implemented in the Data Stream Analytics (DSA) software (module "Evaluation and Forecasting of the Reservoir Energy State") [42, 43]. Using the software, with a minimum set of actual initial parameters, it is possible to obtain reliable reservoir pressure values for each well in different periods of reservoir development. The graph of P_f forecast in the DSA programme for one of the production wells in the studied field is shown in Fig. 3.

As can be seen in Fig. 3, the calculated reservoir pressure is characterised by a high degree of correlation (r = 0.89) with spot measurements during well shutdown for flow test. Accordingly, the calculated values can be used to analyse the reservoir energy state during different development periods. The software also allows calculating reservoir pressure values for the future period.

To analyse changes in reservoir pressure during development by different LFZs, a unified database was created for the field under study, containing cumulative liquid production (CLP) and oil production (COP) from the start of well operation and changes in reservoir pressure since well commissioning (ΔP_f). Fig. 4 shows histograms of the studied parameters distribution and statistical characteristics by LFZ.

Analysing Figs. 2, 4 (*a*) it was found that the facies of the upper part of the reef rear plume (LFZ 2) is characterised by the maximum cumulative liquid production. The reservoir is represented by grey, yellowish and dark grey limestones, clotty-detrital and lumpy, cavernous-porous, with thin extended fissures. Due to paleokarst leaching in the rocks

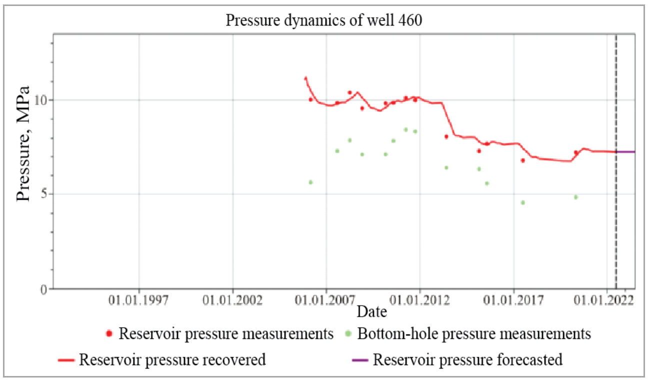

Fig. 3. Example of P_f calculation of well No. 460. Object T-Fm-Fr

of the LFZ, vertical areas of cavern development are formed, passing into sinuous subvertical cavities [21]. The average porosity and permeability coefficients for the facies are 9.3 % and 75.3 mD, respectively. It should be noted that the reservoir of the LFZ is characterised by the maximum average k_{perm} value, mD.

The change of formation pressure in all LFZs is characterised by a normal distribution and approximately the same average value. The reef slope facies stand out from all LFZs, where the range of reservoir pressure varies from –5 to 5 MPa, which indicates a significant amount of reservoir pressure compensation due to the reservoir pressure maintenance system.

After the accumulated data were analysed and combined in STATISTICA software [44, 45], the parametric Student's *t*-test and non-parametric Mann-Whitney *U*-test were used.

The Student's *t*-test is usually used to determine the statistical significance of differences in mean values and can be used both for comparing independent samples and related populations. The larger the *t*-criterion value, the more confidently we can assert that the mean values of reservoir pressure changes by LFZ are different.

As the formula for the *t*-criterion calculation includes mean values, in some cases (with a large number of outliers in the samples) this criterion may give incorrect values. Therefore, in this paper we additionally calculated the non-parametric Mann-Whitney *U*-criterion.

Then, it was determined how small the zone of intersecting values between the two variation series was. The smaller the criterion value, the more likely it is that the differences between the parameter values in the samples are reliable.

Also, to prove the hypothesis that ΔP_f is different across LFZs, the *p*-level of significance was determined for all criteria when comparing the mean values of the studied parameters. A *p*-value greater than 5 % indicates that no significant differences were found among the two samples by LFZ.

The results of mean values comparison of the studied parameters in the LFZ samples, performed by Student's *t*-criterion and Mann-Whitney *U*-criterion are shown in table 2.

The studied lithological-facial zones as a result of pairwise correlation analysis are characterised by statistically significant Student's *t*-criterion for the parameters of cumulative liquid production (CLP) and oil production (COP) from the beginning of exploitation. The Mann-Whitney *U*-criterion also shows

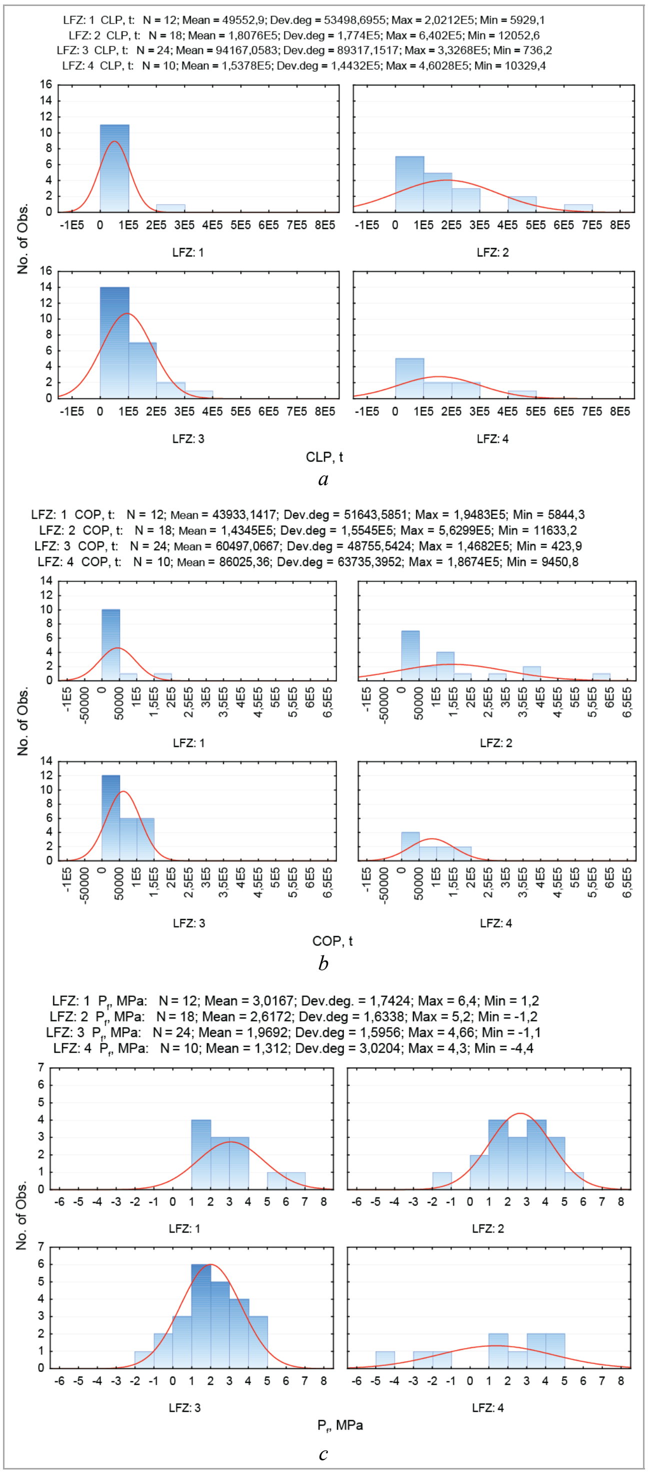

Fig. 4. Distribution histograms: *a* – CLP and statistical characteristics by lithological-facial zones; *b* – COP and statistical characteristics by lithological-facial zones; *в* – ΔP_f and statistical characteristics by lithological-facial zones; *1* – bioherm core; *2* – the upper parts of the reef rear plume; *3* –lower parts of the reef rear plume; *4* – the reef slope

statistically significant differences between LFZs in these parameters. At the same time, the comparison of mean values in the samples for LFZ 3 and 4 revealed that all the studied parameters are not statistically different.

The ΔP_f parameter is not statistically significant in determining both criteria and indicates that in all LFZs, oil reserve recovery is characterised by approximately the same change in reservoir pressure since the well commissioning.

Table 2

Results of analyses on statistical criteria

Parameter	Number of wells		Mean value of parameter		Statistical criteria: *t*-criterion / *p*-level of significance	Statistical criteria: *U*-criterion / *p*-level of significance
	F1	F2	F1	F2	F1–F2	
ΔP_f, MPa			3.02	2.6	0.64 / 0.53	0.14 / 0.88
CLP, t	12	18	49552.90	180757.2	–2.48 / 0.02	–2.31 / 0.02
COP, t			43933.14	143445.7	–2.23 / 0.04	–2.31 / 0.02
	F2	F3	F2	F3	F2–F3	
ΔP_f, MPa			2.6	1.97	1.29 / 0.2	1.35 / 0.17
CLP, t	18	24	180757.2	94167.06	2.07 / 0.04	1.74 / 0.08
COP, t			143445.7	60497.07	2.47 / 0.02	1.69 / 0.09
	F3	F4	F3	F4	F3–F4	
ΔP_f, MPa			1.97	1.3	0.83 / 0.41	0.04 / 0.96
CLP, t	24	10	94167.06	153777.1	–1.47 / 0.15	–1.11 / 0.26
COP, t			60497.07	86025.4	–1.27 / 0.21	–1.15 / 0.25
	F1	F4	F1	F4	F1–F4	
ΔP_f, MPa			3.02	1.3	1.66 / 0.11	0.76 / 0.45
CLP, t	12	10	49552.90	153777.1	–2.33 / 0.03	–2.07 / 0.04
COP, t			43933.14	86025.4	–1.71 / 0.1	–1.68 / 0.09

Note: statistically significant (different) parameters are highlighted in red.

Conclusion

The present article is devoted to statistical analysis of the magnitude of reservoir pressure changes since the beginning of well operation in the zones selected as a result of lithological-facial analysis.

For task solving, we used ΔP_f values calculated with artificial intelligence methods in the Data Stream Analytics software (module "Evaluation and Forecasting of the Reservoir Energy State"). To compare the mean ΔP_f values in lithological-facial zones, the parametric Student's *t*-criterion and non-parametric Mann-Whitney *U*-criterion were calculated in the STATISTICA software.

As a result of the analysis, it was established that the facies peculiarities of the environment do not significantly affect the value of the reservoir pressure change in the conditions of a complexly constructed carbonate reservoir confined to a reef reservoir.

In future, for selecting the maintenance of reservoir pressure system, it is rational to consider all facies zones together as a single development object.

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