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Fracturing model of the Famennian deposits of the Lekkerskoye oil field

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Модель трещиноватости фаменских отложений Леккерского нефтяного месторождения

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Famennian stage, well, porous reservoir, porous-cavernous-fractured reservoir, fracturing, fracture coverage ratio, subvertical fractures, reservoir pressure, Poisson's ratio, lateral rock pressure.

The analysis of the performed studies – selection and study of oriented core, wave acoustic logging, electromagnetic, ultrasonic scanning of the well wall – made it possible to establish that the oil reservoirs of the Lekkerskoye field consisted of three types of voids: primary pores, karst secondary cavities and flat cracks connecting the entire void space together.

Therefore, the main goal of the work was to establish the most important property of fractured-porous-cavernous reservoirs, which distinguished them from static porous reservoirs and was expressed in the dynamic relationship of the fracturing sweep efficiency with changes in reservoir pressure, which ultimately meant a change in the drainage sweep efficiency of balance oil reserves, located in a low-permeability matrix.

Two specific features of fractured-porous-cavernous formations were established.

Firstly, if in a porous reservoir the effective thickness of the reservoir remained constant with any changes in reservoir pressure, then in a fractured-pore-cavern reservoir, the conditions for the existence of an open fracture thickness changed in any direction depending on the sign of the change in the ratio of lateral rock and reservoir pressures. It was this "hidden" nature of the change in fracture thickness that was still the main obstacle to studying the dynamic properties of fractured-porous-cavernous reservoirs using geological and field methods.

Secondly, the reduction in the sweep factor D_3fm by fracturing and fracture thickness by 10 times with a drop in reservoir pressure not only coincided synchronously with the reduction in the productivity factor, but also caused the destruction of the volumetric fracture network as a system that ensured the hydrodynamic unity of all types of voids of the fracture-pore-cavern collector. In proportion to this, the balance oil reserves of the porous-cavernous matrix, previously covered by a network of fractures, were excluded from drainage.

Ключевые слова:
фаменский ярус, скважина, поровый коллектор, порово-кавернозно-трещинный коллектор, трещиноватость, коэффициент охвата трещиноватостью, субвертикальные трещины, пластовое давление, коэффициент Пуассона, боковое горное давление.

Анализ выполненных исследований – отбор и изучение ориентированного керна, волновой акустический каротаж, электромагнитное, ультразвуковое сканирования стенки скважины – позволили установить, что нефтяные коллекторы Леккерского месторождения состоят из трех видов пустот: первичных пор, закарстованных вторичных полостей и плоских трещин, соединяющих воедино все пустотное пространство.

Поэтому основной целью работы являлось установить самое важное свойство трещинно-порово-каверновых коллекторов, отличающее их от статичных поровых коллекторов и выражающееся в динамической связи коэффициента охвата пласта трещиноватостью с изменениями пластового давления, что в конечном счете означает изменение коэффициента охвата дренированием балансовых запасов нефти, находящихся в низкопроницаемой матрице.

Установлены две специфические особенности трещинно-порово-каверновых пластов.

Во-первых, если в поровом коллекторе эффективная толщина пласта остается постоянной при любых изменениях пластового давления, то в трещинно-порово-каверновом коллекторе условия для существования открытой трещинной толщины изменяются в любую сторону в зависимости от знака изменения соотношения бокового горного и пластового давлений. Именно такой «скрытый» характер изменения трещинной толщины до сих пор является главным препятствием для изучения динамических свойств трещинно-порово-каверновых коллекторов геолого-промысловыми методами.

Во-вторых, сокращение коэффициента охвата пласта D_3fm трещиноватостью и трещинной толщины в 10 раз при падении пластового давления не только синхронно совпадает с сокращением коэффициента продуктивности, но и вызывает разрушение объемной сетки трещин как системы, обеспечивающей гидродинамическое единство всех видов пустот трещинно-порово-кавернового коллектора. Пропорционально этому из дренирования выключаются балансовые запасы нефти порово-кавернозной матрицы, охваченные ранее сеткой трещин.

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Introduction

Tectonically, the Lekkerskoye field is located in the southern part of the Kolvinsky megaswell, which is the most promising area in the Timan-Pechora oil and gas basin (see Fig. 1).

Across all reference horizons (along the roofs of carbonates P_3, C_1, D_3fm), the Lekker structure represents a fault-line asymmetric anticline with northwestern strike, with an amplitude of more than 100 m, a length of about 7 km, and a width of up to 3 km (Fig. 2). Tectonic faulting disjunctive dislocation runs along the northeastern and southwestern limbs of the structure, encircling the fold from both sides. These faults converge to the north at 1 km and diverge to the south at 3 km, dividing the fold area into four longitudinal blocks of different sizes. The main fault running along the northeastern limb has displacement amplitude of up to 50 m with an incidence plane to the southwest. A series of parallel faults on the southwestern limb of the fold is low-amplitude (displacement up to 10 m) with incidence planes to the southeast and southwest (see Fig. 2)

Materials and methods

Active tectonics led not only to the development of a complex system of faults, but also to the repeated breaks in sedimentation. Consequently, it has resulted in stratigraphic inconsistencies, changes in facies and thicknesses, which contributed to the formation of complex reservoirs for the hydrocarbon accumulation within the Lekker structure.

The geological profile of the Lekker field is represented by a thick (up to 4.5 km) sequence of terrigenous and carbonate-terrigenous deposits of the Paleozoic cover. The entire profile has potential for hydrocarbon reserves; however, actual oil-bearing capacity has currently been established only in four stratigraphic productive formations (Table 1).

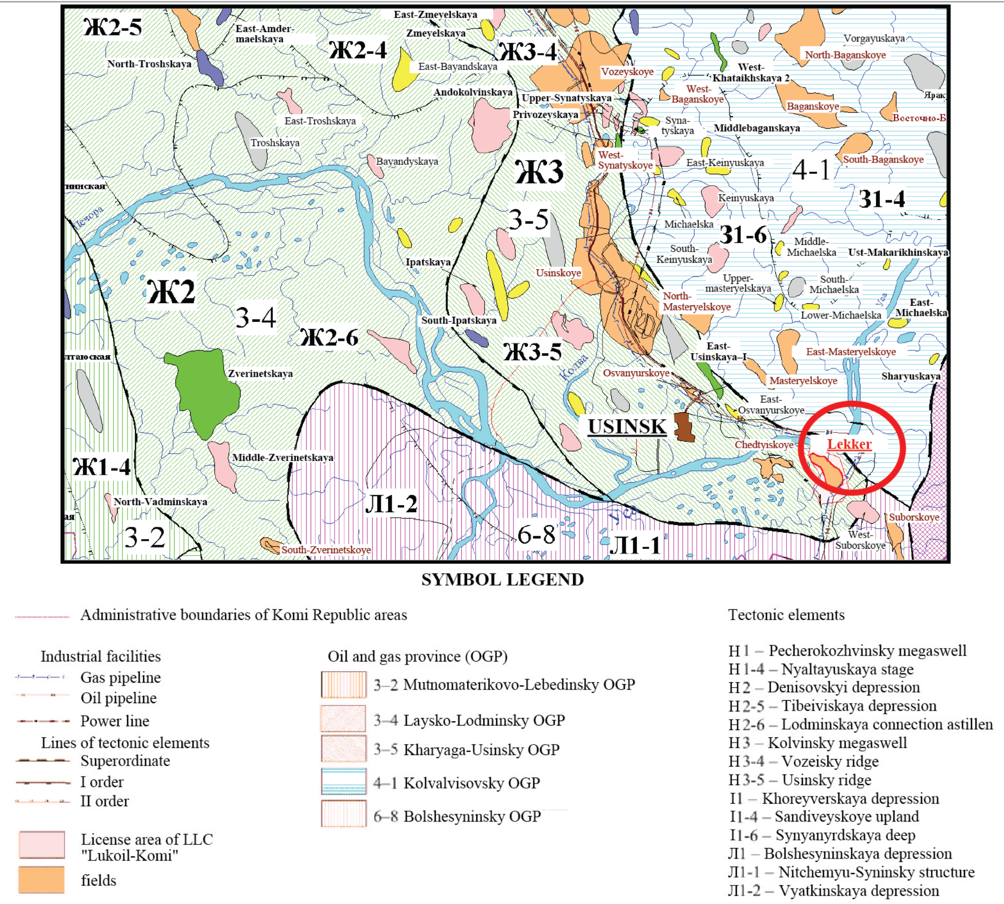

Fig. 1. Extract from the map of tectonic and oil and gas geological zoning Timan-Pechora oil and gas province

Table 1

Brief oil potential characteristics of the Lekker field (as of 01.01.2021)

Stratigraphic unit	Index	Absolute mark of the TVD, m	Reservoir type		Initial recoverable oil reserves A + B_1, million tons	Oil flow rate, t/day
			lithological	capacitive filtration (according to studies using special methods – FMI, SonicScanner, flowmetry results)		
Upper Silurian	S_2	-4183	Carbonate	Porous-cavernous-fractured	0.842	-
Famennian stage	D_3fm	-2801	Carbonate	Porous-cavernous-fractured	3.659	7.7
Visean stage	C_1v	-2801	Terrigenous	Porous	2.779	7.9
Serpukhov horizon	C_1s	-2391	Carbonate	Porous-cavernous-fractured	2.861 (undistributed fund)	-

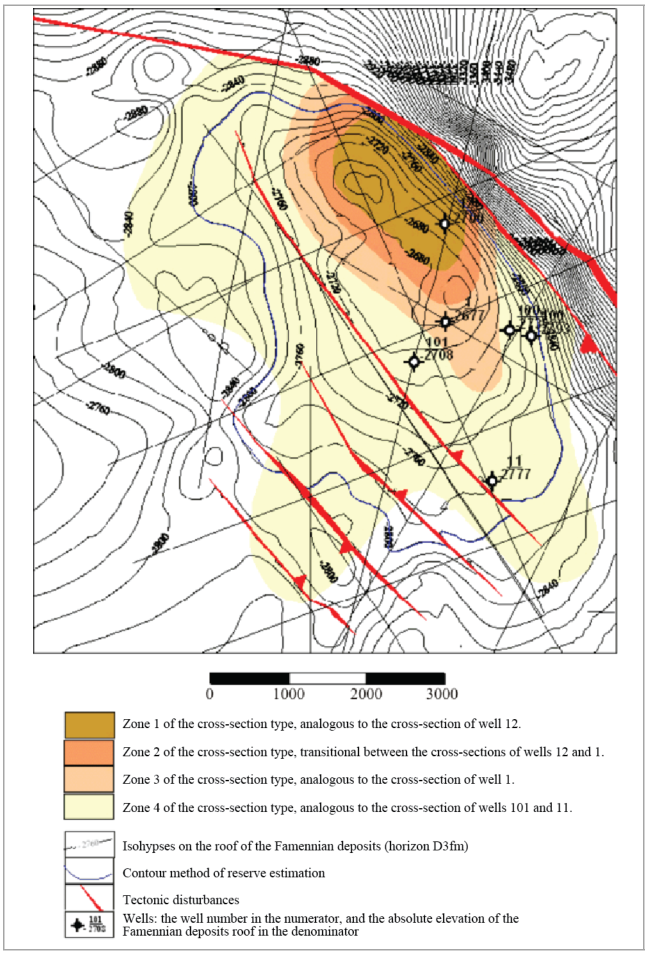

Fig. 2. Structural map of the D_3fm roof layer of Lekker oil field

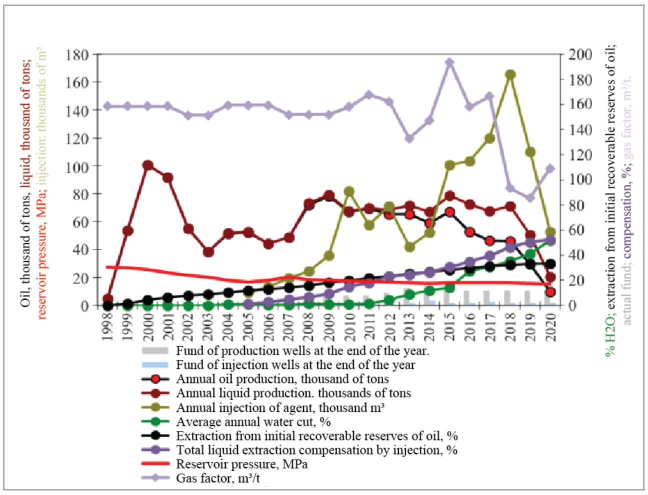

Fig. 3. D_3fm productive formation development schedule of Lekker oil field

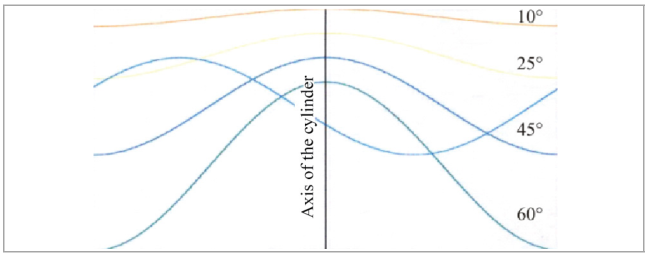

Fig. 4. Schematic layout of the vertical well No. 12 at the Lekker field showing the traces of meso-fractures intersecting the reservoir at different angles to the axis of the wellbore (cylinder)

Research results

Reservoir rocks are characterized by a complex structure of void space, including pore-fracture and porous-cavernous-fractured types [1–5]. The qualitative assessment of the reservoir types is given by all researchers without exception [6–12]. However, until now, no one has conducted a quantitative assessment of each type contribution to the pore space structure (pores, caverns and fractures).

As seen in Table 1, the basic development productive formations are oil deposits in the carbonate formations of the Famenian stage (D_3fm layer) and the terrigenous deposits of the Visean stage (C_1v layer). The development of these objects is being carried out jointly.

In the Famennian stage (D_3fm layer), the reservoirs for oil are the porous-cavernous-fractured dolomites and limestones of the Zelenetskaya (D_3fm-zl) and Ust-Pechora (D_3fm-up) suites. It is believed that the cap rock of D3fm layer is clayey deposits of the Bobrikov horizon. However, there is reason to suggest that the porous terrigenous reservoirs of the Bobrikov horizon lie directly on the eroded surface of the Zelenetskaya suite, and the oil deposit in the terrigenous layer C_1v is hydrodynamically connected through fractures with the oil deposit of the D_3fm-zl layer. The deposit of the D_3fm layer is layer-arched. The water-oil contact is at a depth of –2801 m. Within the D_3fm_4 layer, the deposit height is 109 m, within the D_3fm_5 layer it is 140 m.

According to the laboratory core studies, the D_3fm layer is characterized by extremely low filtration-capacity properties, which do not correspond to the actual initial productivity of the reservoir even with standard values of porosity and permeability (porosity ≥ 3 %, permeability ≤ 0.001 μm^2), accepted when calculating oil reserves (Table 2). Despite all the signs of fracturing, the assessment of oil reserves in the D_3fm layer is produced using methods designed for the porous type reservoir [13, 14].

The initial balance oil reserves of the Famennian deposit in category A + B_1 are 9,996 thousand tons, with the oil recovery factor (ORF) assumed to be 0.366 fraction units. The initial recoverable oil reserves in category A + B_1 amount to 3,659 thousand tons. There is an underexploration of the void space structure, as the actual initial flow rate exceeds the estimated value based on core parameters by 16 to 40 times. The initial oil flow rates in different wells ranged from 12 to 286 tons per day and depended primarily on the pressure in the D_3fm layer at the time of drilling and testing. The lower the current reservoir pressure, the lower the initial flow rate is (Table 3).

This phenomenon is typical for porous-cavernous-fractured carbonate reservoirs, when the commissioning of the first exploratory (prospecting) wells instantly causes a decrease in dynamic reservoir pressure throughout the entire volumetric network of fractures across the entire area of the block (deposit) subjected to drainage [15–24]. As a result, drilling of each new well is accompanied by deep colmatation of fractures, leading to a reduction in both fracture and overall productivity of the D_3fm layer. Additionally, the decrease in reservoir pressure causes compression deformation of the fractures, which further leads to a reduction in fracture and overall productivity of the D_3fm layer. As of January 1, 2021, the reservoir pressure in the D_3fm layer decreased from 30.6 to 17.3 MPa (in the production zones, 15.7 MPa), while bottomhole pressures in the wells dropped from 20–24 to 5–12 MPa, and the reservoir depression decreased from 6.8–9.8 to 1.0–10.2 MPa. If the reservoir is a static porous, then the productivity coefficients remain constant, and oil flow rates decrease only due to the reduction in depression, as shown in Table 4.

The data from Table 4 indicate that the historical oil flow rates of the D_3fm layer at a pressure of 17 MPa are from 2 to 20 times lower than the conditional flow rates calculated without accounting for the compression deformation of fractures in the actual pore-cavernous-fractured type of reservoir.

Table 2

Filtration and capacity properties of the pore matrix (by core) for the D_3fm layer of the Lekker field

Parameter	Unit of measurement	Well		
		1	12	11
Average porosity of the entire section	%	2.35	1.51	3.49
Average permeability of the entire section	μm^2	0.00013	0.00001	0.00076
Average porosity of effective thickness	%	4.9	6.2	5.2
Average permeability of effective thickness	μm^2	0.001	0.001	0.001
Estimated pore matrix oil flow rate	t/day	6.3	7.1	5.5
Actual initial oil flow rate	t/day	137.5	286.0	90.0

Table 3

Exploration and prospecting wells characteristics of the Lekker oil field

Parameter	Unit of measurement	Well					
		1	11	12	100	101	200
		Amplitude, m					
		64.53	67.92	67.82	67.52	67	56
Category	-	Explor.	Explor.	Explor.	Prosp.	Prosp.	Prosp.
Wellbore profile	-	Vert.	Vert.	Incline.	Incline.	Incline.	Vert.
Bottomhole depth	m	4500	4450	3405	3425	3185	2891
Reservoir pressure in D_3fm at the end of well drilling	MPa	30.8	30.8	28.4	25	24	19.5
Maximum initial oil flow rate from D_3fm layer	t/day	137	90	286	20	21	12

Table 4

Comparison of the actual oil production dynamics of a porous-cavernous-fractured reservoir for D_3fm layer with conditional production dynamics under the condition of a porous reservoir type without fractures

Well No.	At P_{init} = 30.6 MPa			At P = 17 MPa					
				Porous collector			Porous-cavernous-fractured reservoir		
	ΔP, MPa	$K_{prod.}$, t/day/ MPa	Q_{sat}, t/day	ΔP, MPa	$K_{prod.}$, t/day/ MPa	Q_{sat}, t/day	ΔP, MPa	$K_{prod.}$, t/day/ MPa	Q_{sat}, t/day
1	6.8	20.2	137.5	3	20.2	60.6	3	9.6	28.9
12	6.8	42	286	4	42.0	168.0	4	18.5	74
200	9.8	11.5	112.7	9	11.5	103.5	9	0.6	5.3

Eventually, it can be stated that due to the decline in reservoir pressure, productivity coefficients have decreased from 11.5–42 to 0.6–18.5 tons/day/MPa, i.e., by 2–19 times, which could not occur in a porous reservoir type without fractures. Since all forecast assessments of oil production from the D_3fm layer were based on the concept of a porous (non-deformable) reservoir, the development of compressive deformation, accompanied by a decline in productivity coefficients and oil flow rates, appeared unexpected and anomalous.

In general, the dynamics of development parameters for the D_3fm layer are shown in Fig. 3. From the data provided, we see that:

- Since the commissioning on January 1, 2021, a total of 1,270 thousand tons of oil have been produced from the D_3fm layer, or 34.7 % of the initial recoverable reserves of category $A+B_1$, equal to 3,659 thousand tons;
- the reservoir pressure decreased from 30.6 to 17.3 MPa, i.e. by 2.4 MPa, or 12 % below the saturation pressure of 19.7 MPa;
- the oil reservoir energy state of the D_3fm layer has transitioned to the dissolved gas mode under filtration properties of the porous-cavernous-fractured reservoir changed by compression deformation;
- due to a decline in reservoir pressure, the average oil flow rate decreased from 141.1 to 7.7 tons/day, with a 40 % reduction due to a decreased pressure differential and a 60 % reduction due to compression deformation of fractures (Table 4);
- the behavior of the reservoir does not fit the expectations of the porous type reservoir for the D_3fm layer, but perfectly matches the characteristics of the porous-cavernous-fractured type [1, 2, 10, 11, 13, 15–17, 19, 21–25].

Thus, the results of the studies indicated the presence of an intensive fracture component in the Famennian stage [26–28]. The standard well logging complex does not reveal the specifics of porous-cavernous-fractured carbonate reservoirs. However, additional sampling and study of oriented core samples [29], wave acoustic logging (WAL), electromagnetic (FMI), ultrasonic (UBI) scanning of the borehole wall, and the Core integration Detail log method made it possible to distinguish traces of microcracks on the wellbore scans, estimate the distance between microfractures and their density, and determine the elastic-mechanical properties of the layers (volume compressibility, Young's modulus, Poisson's ratio) (Fig. 4).

The complex interpretation of laboratory and well data made it possible to determine the fracture parameters (for the entire layer, as well as effective and dense thicknesses):

- lateral stress coefficient – K_s, abs.;
- lateral rock pressure – P_{lat}, MPa;
- fractured layers in the section on the rule;
- the layer has open subvertical fractures if the reservoir pressure in the layer exceeds the lateral rock pressure ($P_{lay} > P_{lat}$);
- coefficient of layer fracture coverage – N_{fr}, abs;
- establish the changes dependency in N_{fr} on the reservoir pressure changes ($N_{fr} = f(P_{lay})$).

The total vertical rock pressure is calculated for the Oil-Water Contact (OWC) depth. In this case, the average calculated bulk density of rocks at a depth of 2,801 m for the carbonate part of the section is 2.65 t/m³, while the average bulk density of rocks for the entire reservoir section is 2.5 t/m³. The calculated expression (MPa) is as follows:

$$P_{rock} = 0.01 \cdot \gamma_{bulk} \cdot H_{owc}. \tag{1}$$

According to the expression (1), the total rock pressure value of the D_3fm layer at the depth of the OWC is 74.2 MPa with an initial formation pressure by fluids filling fractures, pores and caverns equal to 30.6 MPa, or 0.41 of the total rock pressure.

This means that with a lateral thrust coefficient of less than 0.41 and a lateral rock pressure of less than initial reservoir pressure, subvertical fractures remain in an open state and the layer is fractured ($K_s < 0.41$ and $P_{\text{lat}} < 30.6$ MPa).

The lateral stress coefficient (K_s), lateral rock pressure (P_{lat}) and Poisson's ratio (M), the most appropriate parameter for statistical processing of WAL data, have the following relationships [21, 30–32]:

$$P_{\text{lat}} = P_{\text{roc}} K_s;\ K_s = \frac{M}{1-M};\ M = \frac{K_s}{1+K_s}. \qquad (2)$$

For critical values of the lateral stress coefficient and lateral rock pressure, the boundary value of the Poisson ratio separating the fractured and non-fractured beds of the D_3fm layer is 0.3 (with $K_s = 0.41$ and $P_{\text{lat}} = 30.6$ MPa). The Poisson ratio used for calculations, below which layers are classified as fractured, is 0.295 (Fig. 5).

The analysis of the WAL data allows us to establish the most important property of porous-cavernous-fractured reservoirs, which distinguishes them from static porous reservoirs. This property is expressed in the dynamic relationship between the formation fracturing coefficient and changes in reservoir pressure (Fig. 6). As the reservoir pressure decreases from the initial value (set at 29.83 MPa according to WAL, corresponding to a Poisson's ratio of 0.295) to 22 MPa, the fracturing coefficient for the entire section of the D_3fm layer sharply decreases from 0.408 to 0.039. The effective part of the section decreases from 0.563 to 0.054, while the dense part of the section drops from 0.354 to 0 (Fig. 6). Conversely, when the reservoir pressure (along the water injection line into the formation) increases above the initial (hydrostatic) level, an opposite trend is observed – the fracturing coefficient of the D_3fm layer increases rapidly, reaching 0.995 after 36 MPa. According to the studies [1, 2, 33–42], the dynamic relationship between the fracturing coefficient of the D_3fm layer and the decline in reservoir pressure is described by the following expressions for:

- total thickness of the layer

$$N_{\text{fr}} = 0{,}408 \cdot e^{-0{,}3\left(29{,}83 - P_{\text{lay}}\right)}, \qquad (3)$$

- effective thickness

$$N_{\text{fr}} = 0{,}563 \cdot e^{-0{,}3\left(29{,}83 - P_{\text{lay}}\right)}, \qquad (4)$$

- dense thickness

$$N_{\text{fr}} = 0{,}354 \cdot e^{-0{,}3\left(29{,}83 - P_{\text{lay}}\right)}. \qquad (5)$$

The adjustment of the calculated dependency $N_{\text{fr}} = f(P_{\text{lay}})$ to the WAL data for the entire thickness of the D_3fm layer is shown in Fig. 7. It can be observed that, despite the scatter of individual points, the overall trend of decreasing fracturing coverage (especially the moment of sharp decline in N_{fr}) is consistent.

As the reservoir pressure increases above the initial (hydrostatic) level, the expression for determining the fracturing coverage coefficient for the entire thickness of the D_3fm layer takes the following form:

$$N_{\text{fr}} = 0{,}408 \cdot e^{0{,}3\left(P_{\text{lay}} - 29{,}83\right)}. \qquad (6)$$

Thus, the study of the D_3fm layer in well No. 200 using the WAL method reveals two additional specific features of porous-cavernous-fractured reservoirs.

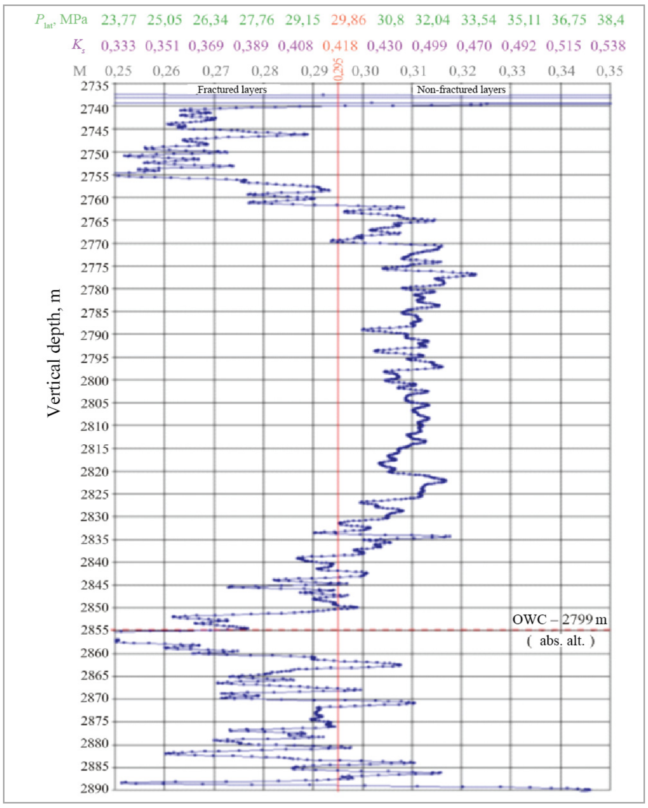

Fig. 5. Distribution of Poisson's ratio (M), lateral stress coefficient (K_s) and lateral rock pressure (P_{lat}) across the D_3fm layer section. Lekker field, well No. 200

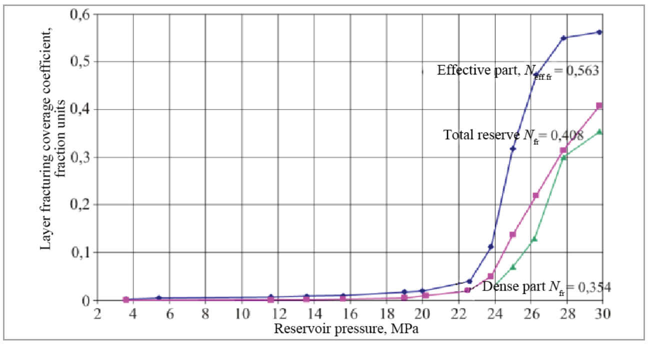

Fig. 6. The fracturing coverage coefficient dependency of D_3fm layer on the changes in reservoir pressure. Lekker field, well No. 200

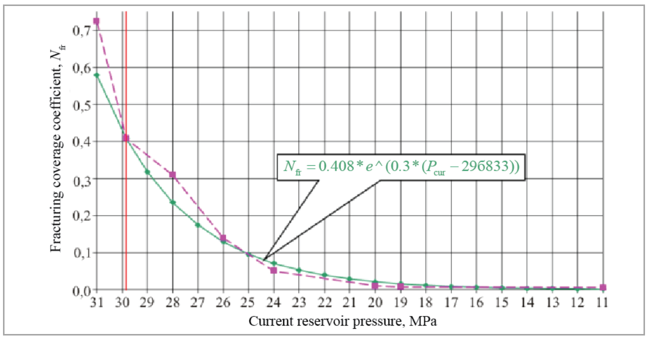

Fig. 7. Adaptation of the calculated curve $N_{\text{fr}} = f(P_{\text{cur}})$ for the entire D_3fm layer section of the Lekker field

Firstly, if in a porous reservoir the effective thickness of the formation remains constant with any changes in the formation pressure, then in a porous-cavernous-fractured reservoir the conditions for the open fracture thickness change in either direction depending on its sign in lateral rock and formation pressures ratio. In particular, for the D_3fm layer the fracture thickness (h_{fr}) decreases according to an exponential law with a drop in formation pressure:

$$h_{\text{fr}} = 64{,}6 \cdot e^{-0{,}3\left(29{,}83 - P_{\text{lay}}\right)}. \qquad (7)$$

As the formation pressure increases above the initial (hydrostatic) pressure, the fracture thickness increases:

$$h_{\text{fr}} = 64{,}6 \cdot e^{0{,}3\left(P_{\text{lay}} - 29{,}83\right)}. \qquad (8)$$

Table 5

Fracture-drained oil reserves dependency of the D_3fm layer at the Lekker field on changes in reservoir fracturing coverage coefficient

Reservoir pressure, MPa	N_{cur} effective thickness	N_{init}–N_{cur} ΔN_{fr}	Fracture-drained oil reserves, thousand tons $Q_{res}{\cdot}N_{cur}$	Losses of fracture-drained oil reserves – $Q_{res}{\cdot}\Delta N_{fr}$	
				thousand tons	% of initial
30.6	0.563	0	5628	0	0
30	0.563	0	5628	0	0
29	0.56	0.003	5598	30	0.3
28	0.55	0,013	5498	130	1.3
27	0.5	0.063	4998	630	6.3
26	0.43	0.133	4298	1329	13.3
25	0.318	0.312	3179	3119	31.2
24	0.113	0.45	1130	4498	45.0
23	0.04	0.523	400	5228	52.3
22	0.035	0.528	350	5278	52.8
21	0.03	0.533	300	5328	53.3
20	0.022	0.541	220	5408	54.1
19	0.02	0.543	200	5428	54.3
18	0,015	0.548	150	5478	54.8
17	0.01	0.553	100	5528	55.3

Note: The initial oil reserves of the D_3fm layer in category $A+B_1$ are 9996 thousand tons. The current reservoir pressure as of 01.01.2021 is 17.3 MPa (in the extraction zones 15.7 MPa).

Table 6

The conditional dynamics comparison of the D_3fm layer parameters for the porous and porous-cavernous-fractured types of reservoirs in well No. 200 at the Lekker field

Pressure, MPa			Porous reservoir				Porous-cavernous-fractured reservoir			
P_{lay}	ΔP	P_{bot}	Permeability, μm^2	Coverage coefficient of drainable oil reserves	Coeff.product .t/day/MPa	Oil flow rate, t/day	Permeability, (specific area) μm^2	Coverage coefficient of drainable oil reserves	Coeff. prod. of bottomhole zone/day/MPa	Oil flow rate, t/day
30	6	24	0.067	0.563	28.1	168	0.067	0.563	15.4	92
29	6	23	0.067	0.563	28.1	168	0.061	0.44	14	84
28	6	22	0.067	0.563	28.1	168	0.055	0.325	12.7	76
27	6	21	0.067	0.563	28.1	168	0.05	0.24	11.5	69
26	6	20	0.067	0.563	28.1	168	0.045	0.179	10.4	62
25	6	19	0.067	0.563	28.1	168	0.041	0.132	9.5	57
24	6	18	0.067	0.563	28.1	168	0.037	0.098	8.6	52
23	6	17	0.067	0.563	28.1	168	0.034	0.072	7.8	47
22	6	16	0.067	0.563	28.1	168	0.031	0.054	7.1	43
21	6	15	0.067	0.563	28.1	168	0.028	0.04	6.5	39
20	6	14	0.067	0.563	28.1	168	0.025	0.029	5.9	35
19	6	13	0.067	0.563	28.1	168	0.024	0.022	5.4	32
18	6	12	0.067	0.563	28.1	168	0.023	0.016	4.9	29
17	6	11	0.067	0.563	28.1	168	0.022	0.012	3.9	27

Note: for a porous reservoir $N_{init} = 0.563$, $N_{cur} = \text{const}$; for a porous-cavernous-fractured reservoir – $N_{init} = 0.563$, $N_{cur} = 0{,}563 \times e^{-0{,}3(P_{init} - P_{cur})}$.

However, it does not mean that such a change in fracture thickness can be observed on the WAL diagram recorded at reduced reservoir pressure, for example, at 22 MPa (see Fig. 7) compared to 30.6 MPa, as in well No. 200. The WAL determines not the actual fracture thickness but the Poisson's ratio, which does not depend on changes in reservoir (effective) pressure strongly enough to detect the change using the WAL method. There are currently no data available to make any judgments about the dependency of lateral rock pressure on changes in reservoir (effective) pressure. The reduction in fracture thickness in studied case should be understood as a reduction in the possibilities (or conditions) for the open sub-vertical fractures, expressed through the calculated change in fracture thickness, the initial value of which is also defined by a calculated method based on static values of Poisson's ratio and lateral rock pressure for the initial (hydrostatic) reservoir pressure according to the rule: $M \leq 0.295$, $K_s < P_{lay}/P_{rock}$, $P_{lat} < P_{lay}$.

It is precisely the "hidden" nature of the change in fracture thickness that remains as the main obstacle to studying the dynamic properties of porous-cavernous-fractured reservoirs using geological and industrial methods.

Secondly, the reduction of the layer coverage coefficient D_3fm due to fracturing and fracture thickness by 10 times, along with the decrease in reservoir pressure from 30.6 to 22 MPa, not only synchronously coincides with the decrease in the fracture productivity coefficient, but also leads to the disruption of the volumetric fracture network as a system that ensures the hydrodynamic unity of all types of voids in the porous-cavernous-fractured reservoir. Consequently, proportionally, oil reserves in the porous-cavernous matrix, previously covered by the fracture network, are excluded from drainage. A clear representation of this can be found in the data presented in Table 5.

$$\Delta Q_{losses} = Q_{res}(N_{init} - N_{cur}). \qquad (9)$$

It follows from Table 5 that as of 01.01.2021, the D_3fm layer has practically lost its fracture component, and only single subvertical fractures with particularly low lateral rock pressure remained in operation, selectively draining the porous-cavernous matrix. According to well testing, the filtration properties of the matrix amount to only 2 % of the initial filtration properties of the entire porous-cavernous-fractured system. It is all quite atypical for porous-cavernous reservoirs (Table 6).

In Table 6, the conditional pore reservoir of the D_3fm layer have the same initial properties (permeability, productivity, coverage of drained balanced oil reserves) as the actual porous-cavernous-fractured reservoir of the D_3fm layer in well No. 200. The situation is quite possible in cases where the mentioned parameters are determined through geological, industrial, and hydrodynamic studies at an early stage of well operation.

A substitution of properties occurs: the parameters of the fractured medium are assigned to the porous medium. Since the porous medium is static, all oil production forecasts are made without taking into account the compression deformation, i.e. the drop in the productivity coefficient and disconnection from the oil reserves drainage contained in the porous-cavernous matrix. Such errors are common in production process and almost always have dramatic consequences [43–45].

In conclusion, we present the main parameters of the D_3fm layer identified by WAL (or related to its interpretation):

– total rock pressure – 74.2 MPa;

– maximum lateral rock pressure – 41.8 MPa;

– initial hydrostatic pressure – 30.6 MPa;

– average lateral rock pressure of fractured layers – 25–27.5 MPa;

– minimum lateral rock pressure of fractured layers – 5–11 MPa;

– the fracturing coverage coefficient ranges from 0.354 to 0.563 and varies according to the following expressions:

$$N_{т} = N_{нач} \cdot e^{-0,3(29,83-P_{пл})} \text{ at } P_{lay} < P_{init}; \qquad (10)$$

$$N_{fr} = N_{init} \cdot e^{0,3(P_{lay}-29,83)} \text{ at } P_{lay} > P_{init}, \qquad (11)$$

where N_{fr}, N_{init} are, respectively, the current and initial fracturing coverage coefficient.

Conclusion

Thus, the use of the WAL results allows us to identify fractured layers, determine the fracturing coverage coefficient of the entire section, as well as for the effective and dense parts of the section. Additionally, it also establishes (in graphical, tabular and partially analytical forms) the dynamic relationship between the fracturing coverage coefficient and changes in the initial reservoir pressure. It ultimately means a change in the drainage coverage coefficient of oil reserves located in a low-permeability matrix.

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