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MECHANICAL PROPERTIES OF OIL-BEARING ROCKS AND STABILITY OF THE BOTTOM HOLE ZONE

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Summary. The paper discusses the relationship between the mechanical properties of oil-saturated reservoirs and stability of the near-wellbore zone during the long-term exploitation of an oil field. The relevance of this task is associated with on one hand the choice of the most rational wellbore design, and on the other – the necessity to consider the mechanisms of rock pressure manifestation, reservoir destruction during fluid movement, etc. These interconnected factors are typically assessed through studies of dynamic petrophysics in the field of oil and gas reservoir development. During the operation of producing wells, a significant decrease is observed in reservoir pressure as a result of the formation of a depression cone in the near-wellbore zone. The most optimal approach is to analyse changes in reservoir pressure over time. The paper provides an example of tracer studies of the averaged filtration parameters of reservoir rocks in the interval between injection and production wells. The paper describes cases of modelling in-reservoir fluid dynamics, where the injection well is located on the flank of the structure, and the production well is at its crest, and vice versa. The paper also presents assessments of mechanical properties (hardness, yield strength, etc.) of core samples at various levels of confining pressure. Terrigenous and volcano-clastic-sedimentary reservoirs with a specific cavernous pore structure were used for testing. The results of these studies allowed the classification of the tested samples according to the criteria of Deere and Miller, as well as the establishment of correlation relationships between individual physiccal and mechanical properties.

Introduction

As is known, in terms of efficiency, the well bottom and adjacent bottom hole part of the productive interval, are fundamentally important during the entire period of active exploitation of deposits (Mirzajanzadeh, Ametov, 1983). Ensuring the required reliability of this part of the well is associated with the necessity to maintain the mechanical stability of the bottom hole zone to damage under the conditions of changing field development. In the practice of oil and gas production, various bottom hole designs were used, however the most rational bottom hole design should consider the mechanisms of rock pressure, reservoir fracture during fluid movement, etc. These interrelated indicators usually evaluated by dynamic petrophysics studies in the area of oil and gas field development (Khristianovich et al., 1957; Baklashov, 2005; Mori, Furmentro, 1994). Thus, in particular, academician S.A.Kristianovich proposed an idea of the geo-discharge method (Khristianovich et al., 1957). Later, specialists and scientists from the Institute of Problems of Mechanics of the Russian Academy of Sciences proposed a method of the directed discharge (drainage) of a reservoir (hydraulic fracturing method - HFM) based on increasing the permeability of the bottom hole zone of the reservoir by creating artificial stresses within the reservoir (Baklashov, 2005; Mori, Furmentro, 1994). The idea of the directional drainage method (DDM) consists of an idea that it is not necessary to restore the permeability of natural filtration channels blocked during drilling and operation of wells, but much better to additionally create a new system of cracks in the rock – filtration channels. At the same time, the permeability of these channels can exceed the natural permeability by tens or even hundreds of times. During hydraulic fracturing method (HFM), high-pressure liquid injected into the existing cracks porous, causing high stresses within these cracks and ensured their further growth (Baklashov, 2005; Mori, Furmentro, 1994). As a result, the rock unevenly released from compressive stresses in different directions occurring tangential stresses, and at a certain value of these stresses, the rock begins to crack (Gasanov et al., 2016). However, unlike rocks tectonic fracturing, which often produces one or more extended cracks, hydraulic fracturing produces multiple cracks within the single formation volume. In the whole, cracking and loosening of the rock carried out due to the release of elastic compression energy accumulated in it by rock pressure.

Theory

In the practice of development oil and gas fields, the methodology to justify the choice of the design of the bottom holes of oil producing wells is well known (RD 39-2-771-82, Krasnodar, VNIIKRNEFT), according to which the stability of rocks in the bottom hole zone of wells is determined on the following cases:

1. Liquid or gas extracted from the reservoir;
2. The liquid injected into the reservoir;
3. There is no any fluid movement.

At the same time, a significant decrease in reservoir pressure is observed during the operation of producing wells as a result of the formation of a depression funnel in the bottom hole zone of the formation (Gladkov, Gladkova, 2008). As a result, the formation, especially in the bottom hole zone, begins to growth additional vertical load leading to deformation of the pore space. In this case, both elastic and plastic, decreases in the capacitance and filtration properties of rocks occur. The extending of such bottom hole deformations can be detected only based on special, rather laborious monitoring, or by theoretical methods to predict the stability of reservoir properties of real sediments at great depths (Gladkov, Gladkova, 2011; Gladkov, 2011). However, the analysis of reservoir pressure changes in area and depth of oil deposits over time could consider being the most optimal (Trofimov et al., 2007). Based on these data, the nature of the variation of reservoir properties in each producing and injection well of the field is estimated, and isobar maps are constructed. Such isobar maps used to calculate the area- and volume-weighted average reservoir pressures within the outer oil-bearing contours or within the testing zone. In addition to isobar maps, maps of the difference in reservoir pressure in the same well are composed of the current date and previous measurement date. Based on the totality of maps compiled, the effectiveness of water injection into the reservoir assessed, as well as the presence of falls, zones of replacement of the porous reservoir with dense impermeable rocks, etc. was revealed.

As an example, tracer studies of the average values of reservoir filtration parameters in the interval between injection and production wells were cited. The mutual arrangement of injection and production wells within the geological structure and the direction of the intra-reservoir fluid flow were commonly modelled. In particular, the results of the study of formation of fluid dynamics were described (Trofimov et al., 2007; Zhang, Rykus, 2015).

a) b)

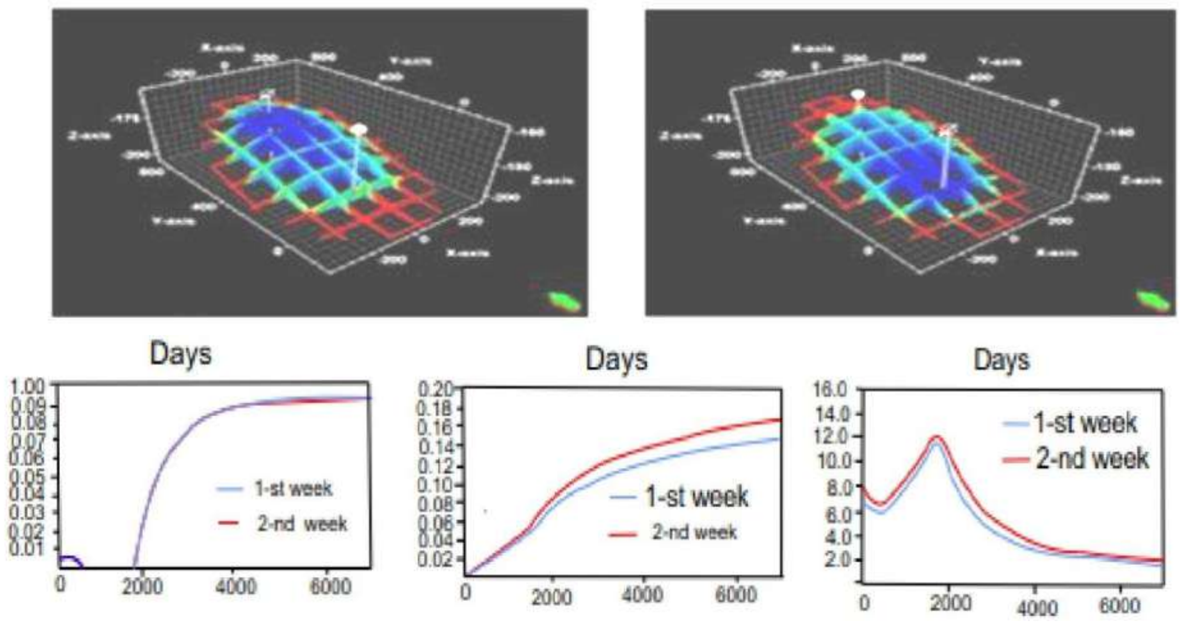

Fig. 1. The results of modelling of the watering, production and flow rates at different positions of injection and production wells (Trofimov et al., 2007)

In this research, two principal locations of the injection and production wells were considered relatively to the overall structure of the field:

1) the injection well is located on the wing of the structure, and the production well is on its roof (Fig. 1a);

2) the injection well is located on the roof of the structure, and the production well is located on its wing (Fig. 1b).

According to the modelling results, it turned out that the location of the injection and production wells relative to the elements of the field structure does not significantly affect the watering availability of wells (Trofimov et al., 2007). In both cases, the first and second, the beginning of reservoir flooding and its steady growth over a long time occurred after 1800 days. Simultaneously, oil production rate under the second model turned out to be slightly higher than under the first one.

Discussions of results

Tracer methods similar as the described above are applicable in any flooding system and any degree of watering of production wells. These methods have found wide application in many oil-producing companies in the study of oil reservoirs, and the resistance of productive reservoirs to secondary deformations that occur during development studied sufficiently in (Imanov, 2001, 2012). These studies provide estimates of the hardness and yield strength of core samples at various values of all-round pressure (Fig. 2). In particular, it is noted that siltstones at pressures up to and including 25 MPa collapsed elastically. In this case, the hardness and yield strength of siltstones under atmospheric conditions are 58.8 and $42.7 \cdot 10^7$ N/m^2, respectively (Hasanov et al., 2022).

Unlike terrigenous reservoirs, volcanogenic-sedimentary reservoirs with a specific cavernous pore structure also differ in the nature of deformation under the influence of an external compressive load. Thus, Table 1 shows the results of a series of tests on the deformation of the pore structure and permeability under uniaxial pressure (Heap et al., 2022, 2024).

A review of the data in Table 1 shows (Teymen, 2018) that the density of dry U_w rocks varies from 1.34 to 2.02 g/sm^3, open porosity P_a – 14.2-37.5%, water saturation W — 7.0 – 27.9%, velocity of propagation of longitudinal waves V_p – 1.25-2.85 km/s, index point load I_s – 1.30-4.69 MPa, compressive strength U_{cs} – 6.6-69.2 MPa. According to the classification of Deere and Miller (Deere, Miller, 1966), among the data given in Table 1, 5 samples belong to moderately strong $U_{cs} \geq$ (110-55MPa), 9 to weakly strong $U_{cs} \geq$ (55.0-27.5 MPa) and 13 to very weakly strong $U_{cs} \geq$ (27.5MPa). The bending strength of the studied samples (F_{ts}) varies from 1.23 to 6.35 MPa, kick strength (D_n) — 2-17 MPa, resistance to abrasive wear (B_{sa}) – 28.3-139.1 sm^3 / 50 sm^2, and hardness (HB) – 1.9-49.2 kg/mm^2.

Their compressive strength, bending strength, kick strength and resistance to abrasive wear were tested to identify correlations between the physical parameters of some samples and their mechanical properties (Table 2) (Heap et al., 2024).

However, it should be noted that the hardness of rocks does not increase indefinitely due to increase of hydrostatic pressure. Thus, the curves of the dependence of hardness on hydrostatic pressure at 200 MPa begin to flatten out (especially noticeable on the curves of sandstone hardness). The observed process illustrates the structural resistance to deformation characteristics of most solids including rocks.

In addition to the above-mentioned geomechanical properties, the stability of the bottom-hole zone of wells is closely related to the initial stress state and structural features of the mountain range as a whole (Gasanov, 2021; Alimzhanov, 1999; Zaalishvili et al., 2023).

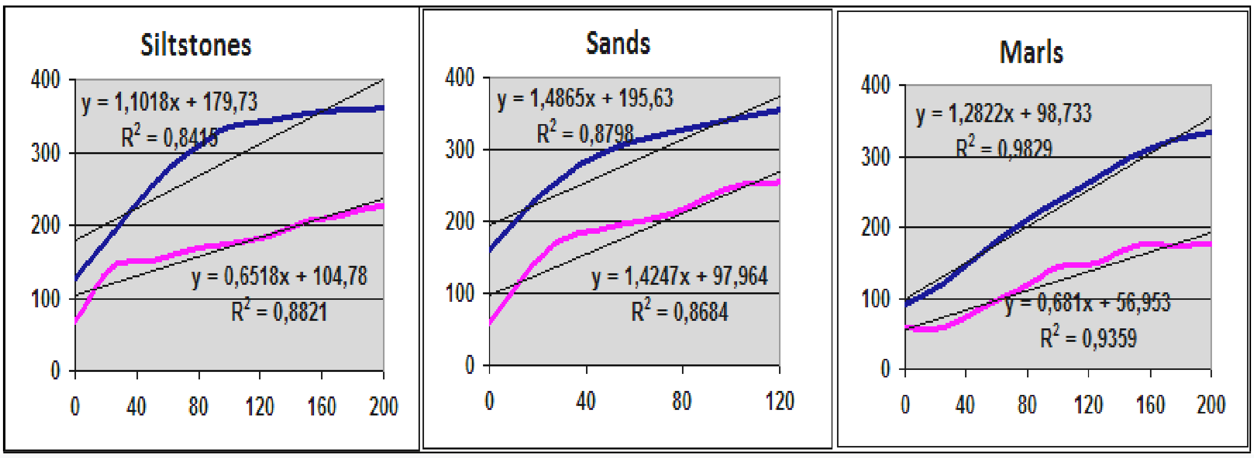

Fig. 2. Different values of confining pressure

Table 1

The test results of tuff samples (average values and standard deviation)

Code Sample	U_{cs}	F_{ts}	D_n	B_{sa}	HB	I_s	V_p	U_w	P_a	W
	MPa			sm³/50sm²	кg/mm²	MPa	кm/s	g/sm³	%	
T-1	69.2±3.9	6.24±0.7	17.0±1.5	27.2±1.6	49.2±3.4	4.69±0.4	2.94±0.1	1.97±0.0	14.5±0.2	7.4±0.0
T-2	59.9±1.2	5.50±0.2	11.8±1.3	28.3±1.1	32.1±1.6	3.60±0.2	2.75±0.2	2.02±0.0	13.9±0.5	6.9±0.2
T-3	54.7±3.0	5.37±0.6	12.0±1.7	34.5±3.1	39.2±3.5	2.97±0.3	2.55±0.1	1.96±0.0	16.7±0.4	8.5±0.3
T-4	61.5±7.4	6.35±0.4	14.4±1.3	29.8±2.4	30.7±1.8	3.74±0.5	2.71±0.0	1.89±0.1	18.7±0.6	9.9±0.2
T-5	55.9±4.9	5.16±0.7	11.8±1.4	30.4±1.5	42.1±4.6	3.34±0.4	2.84±0.4	1.91±0.0	17.9±0.2	9.4±0.1
T-6	43.9±1.2	5.00±0.3	10.3±0.8	41.2±3.7	27.8±2.8	2.86±0.5	2.71±0.3	1.89±0.1	19.8±1.2	10.5±1.0
T-7	40.4±3.8	4.12±0.4	10.6±0.8	43.9±4.4	25.4±2.0	3.02±0.3	2.81±0.1	1.87±0.0	18.7±1.0	10.4±0.6
T-8	39.8±2.8	5.41±0.6	10.3±0.9	52.9±3.8	23.8±1.2	3.25±0.2	2.84±0.3	1.93±0.0	18.5±0.4	9.6±0.1
T-9	32.8±0.5	3.88±0.3	8.2±0.8	58.5±3.5	10.9±0.4	1.90±0.1	1.92±0.0	1.74±0.0	20.7±2.3	11.9±1.6
T-10	31.9±2.6	4.58±0.3	8.9±0.6	54.1±4.3	19.6±1.8	2.29±0.2	2.23±0.0	1.77±0.0	22.4±1.4	12.7±0.8
T-11	26.4±4.8	4.32±0.4	9.4±2.1	41.1±3.7	17.9±2.0	2.45±0.4	2.04±0.2	1.87±0.0	23.5±0.9	12.9±0.4
T-12	26.9±1.0	4.20±0.3	6.6±1.7	52.3±5.2	7.5±0.6	1.97±0.5	2.03±0.0	1.55±0.0	29.5±0.6	18.8±0.3
T-13	26.1±0.7	4.82±0.2	5.9±1.1	57.3±2.9	12.1±0.7	2.55±0.4	2.21±0.2	1.58±0.0	25.8±1.5	16.3±1.1
T-14	20.9±1.1	3.29±0.3	7.4±1.2	56.7±6.2	8.1±1.0	2.11±0.4	2.32±0.1	1.60±0.0	29.2±0.1	18.2±0.1
T-15	16.8±1.1	3.62±0.4	5.9±0.5	86.4±5.2	11.5±0.6	2.17±0.3	2.22±0.3	1.47±0.0	33.2±0.2	23.0±0.5
T-16	7.8±0.5	1.23±0.2	2.0±0.2	122.2±8.6	3.7±0.1	1.32±0.2	1.30±0.2	1.36±0.1	34.4±0.4	25.4±0.4
T-17	15.1±1.0	3.32±0.5	5.9±0.9	94.2±4.7	12.6±1.0	2.14±0.4	2.15±0.2	1.44±0.0	33.4±0.9	24.7±0.7
T-18	25.5±1.7	4.56±0.4	8.8±0.8	56.0±5.0	15.8±1.1	2.42±0.5	2.29±0.2	1.88±0.0	26.7±0.3	12.8±0.1
T-19	6.6±0.9	1.37±0.1	2.0±0.3	139.1±14	1.9±0.2	1.51±0.3	1.36±0.3	1.34±0.0	37.5±0.2	27.9±0.7
T-20	25.1±2.0	4.12±0.3	5.9±0.6	67.0±5.4	7.5±0.4	2.29±0.1	2.53±0.4	1.70±0.1	21.5±0.4	12.6±0.5
T-21	35.7±2.5	4.72±0.4	8.9±1.1	68.3±2.7	16.7±1.0	2.86±0.3	2.85±0.3	1.77±0.0	18.2±0.0	10.3±0.3
T-22	6.7±0.8	1.55±0.2	2.0±0.1	130.0±7.8	2.2±0.2	1.65±0.4	1.25±0.3	1.52±0.1	31.6±0.5	20.8±0.2
T-23	14.6±1.4	2.22±0.1	2.7±0.2	113.1±6.8	2.7±0.2	1.86±0.3	1.85±0.2	1.50±0.0	30.3±0.8	19.5±0.4
T-24	30.3±2.8	3.87±0.2	8.2±0.7	58.6±4.1	22.1±2.2	1.76±0.1	2.28±0.1	1.83±0.0	25.8±0.4	14.2±0.5
T-25	19.4±2.4	3.15±0.1	3.5±0.4	70.2±6.3	6.4±0.6	1.43±0.1	1.55±0.1	1.57±0.0	28.1±0.7	18.0±1.2
T-26	28.8±3.8	4.45±0.4	7.8±0.7	63.7±3.8	15.6±0.6	1.90±0.2	2.78±0.1	1.61±0.0	26.9±1.3	16.6±1.6
T-27	34.2±2.3	4.55±0.3	8.2±0.8	65.6±4.6	12.0±0.8	2.29±0.1	2.23±0.2	1.89±0.0	18.2±0.6	9.7±0.8

Table 2

Correlations between physical properties of the tested samples

No	Interdependent parameters	The optimal regression equation	The correlation coefficient
1	Compressive strength (MPa) and point load index (MPa)	Y = 19.5 (X) - 16.2	R = 0.82
2	Compressive strength (MPa) and open porosity (%)	Y = -56.48 Ln (X) + 209.84	R = 0.84
3	Compressive strength (MPa) and hardness (kg/mm²)	Y = 1.2581 X + 9.6626	R = 0.87
4	Compressive strength (MPa) and longitudinal wave velocity (km /s)	$Y = 4.5314\ X^{2.2296}$	R = 0.68
5	Bending strength (MPa) and point load index (MPa)	Y = 3.7946 Ln (X) + 0.877	R = 0.77
6	Bending strength (MPa) and water saturation in weight proportion (g/cm³)	Y = -0.1948 X + 6.9885	R = 0.73
7	Bending strength (MPa) and hardness (kg/mm²)	Y = 1.3792 Ln (X) + 0.5732	R = 0.82
8	Bending strength (MPa) and longitudinal wave velocity (km/s)	$Y = 1.1068\ X^{1.555}$	R = 0.80
9	Impact resistance (MPa) and point load index (MPa)	Y = 10.965 Ln (X) -1.3277	R = 0.82
10	Impact strength (MPa) and dry rock density (g/cm³)	Y = 16.117 X -19.7	R = 0.76
11	Impact resistance (MPa) and hardness (kg/mm²)	$Y = 1.1068\ X^{0.6394}$	R = 0.90
12	Impact strength (MPa) and longitudinal wave velocity (km/s)	$Y = 1.2375\ X^{2.1686}$	R = 0.81

Possible deformations and subsidence of the Earth's surface during the development of oil and gas deposits are commonly found in the following cases (Alimzhanov, 1999):

– the presence of abnormally high reservoir pressures (AHRP) by the development of productive facilities without maintaining reservoir pressure;
– low strength and deformation characteristics of the reservoir;
– the presence of high porosity of reservoir rocks (up to 30-40%);
– relatively small depth of the developed deposits (up to 2000 m);
– significant total capacity of productive deposits.

Conclusions

A summary of the results of the study of the physical and mechanical properties of a number of terrigenous and sedimentary-volcanogenic rocks showed the presence of a significant relationship between the values of porosity, density and deformation-strength properties. In particular, it was found that the compressive strength U_{cs}, bending F_{ts} and impact toughness D_n decrease logarithmically with increasing open porosity P_a, while abrasive wear resistance B_{sa} nonlinearly increases with increasing open porosity Pa for sedimentary-volcanogenic rocks. Density U_w and water saturation Ware linearly interrelated with the mechanical properties of the rock; compressive strength U_{cs}, bending F_{ts} and impact toughness D_n increase with increasing density U_w. The speed of sound is an important indicator for predicting the mechanical properties of rocks; U_{cs}, F_{ts} and D_n are linearly related to the speed of sound, but the relationship between B_{sa} and V_p is represented by an inverse logarithmic function with a low correlation coefficient R = 0.66. The velocities of longitudinal waves V_p in rocks are determined by lower values of standard deviation than the velocities in porous media. Since the tested samples were highly porous, the correlation coefficients obtained on the longitudinal wave velocity V_p are somewhat lower than on other parameters. The point load index I_s is a very significant parameter in predicting the main mechanical properties of geological media, since the calculation of U_{cs}, F_{ts}, B_{sa} and D_n values is impossible without this characteristic. The higher the point load index, the greater the values of U_{cs}, F_{ts} and D_n. In addition, there is a close correlation between s - cs and I - U, with a correlation coefficient R> 0.80. However, a weak inverse correlation with R = 0.69 was found between B_{sa} and I_s.

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МЕХАНИЧЕСКИЕ СВОЙСТВА НЕФТЕНОСНЫХ ПОРОД И УСТОЙЧИВОСТЬ ПРИЗАБОЙНОЙ ЗОНЫ СКВАЖИН

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Резюме. В статье рассматриваются данные зависимости механических свойств нефтенасыщенных коллекторов и устойчивости призабойной зоны скважин в процессе разработки месторождения. Актуальность данной задачи связана, с одной стороны, с выбором наиболее рациональной конструкции забоя скважины, а с другой – с необходимостью учета механизмов изменения горного давления, разрушения пласта-коллектора при движении флюида и т.п. Эти взаимосвязанные показатели обычно оцениваются методами динамической петрофизики, согласно которым в процессе эксплуатации добывающих скважин в призабойной зоне пласта формируется воронка депрессии и наблюдается значительное снижение пластового давления. При этом наиболее оптимальным считается анализ изменений пластовых давлений нефтяных залежей во времени. Для иллюстрации этого в работе приведены трассерные исследования осредненных значений фильтрационных параметров пластов в интервале между нагнетательной и добывающей скважинами. Описаны случаи моделирования внутрипластовой флюидодинамики, когда нагнетательная скважина находится на крыле структуры, а добывающая скважина – на ее вершине и наоборот. В работе также приведены оценки механических свойств (твердости, предела текучести и т.п.) для проб кернов при различных значениях всестороннего давления. Причем к испытаниям привлекались как терригенные, так и вулканогенно-осадочные коллекторы со специфической – кавернозно-поровой структурой. В частности, установлено, что прочность на сжатие Ucs, изгиб Fts и ударная вязкость Dn логарифмически уменьшаются с ростом открытой пористости Pa, в то время как абразивная износостойкость Bsa нелинейно увеличивается с ростом открытой пористости Pa для осадочно-вулканогенных пород. Плотность Uw и водонасыщенность W линейно взаимосвязаны с механическими свойствами породы; прочность на сжатие Ucs, изгиб Fts и ударная вязкость Dn увеличиваются с ростом плотности Uw. Результаты позволили классифицировать испытанные пробы соответственно критериям Дира и Миллера, а также установить корреляционные связи между отдельными физико-механическими свойствами.

Ключевые слова: *призабойная зона, терригенные коллекторы, механические свойства, всестороннее давление*

NEFTLİ SÜXURLARIN MEXANİKİ XÜSUSİYYƏTLƏRİ VƏ QUYUDİBİ ZONASININ DAYANIQLIĞI

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Xülasə. Məqalədə yatağın işlənməsi zamanı neftlə doymuş süxurların mexaniki xassələrinin və quyu dibi zonasının dayanıqlığının şəraiti haqqında məlumatlar araşdırılır. Bu mövzunun aktuallığı bir tərəfdən quyu dibinin ən səmərəli dizaynının seçilməsi, digər tərəfdən isə lay təzyiqinin dəyişmə mexanizmlərinin, mayenin hərəkəti zamanı kollektorluq xüsusiyyətlərinin dəyişilməsi və s. amillərin nəzərə alınması zərurəti ilə bağlıdır. Bu, bir-biri ilə əlaqəli göstəricilər adətən dinamik petrofizika metodlarından istifadə etməklə qiymətləndirilir. Nəticə etibari ilə, quyu dibinin neft hasilatı zamanı təzyiq depressiyasının formalaşması, eləcə də lay və lay təzyiqinin əhəmiyyətli dərəcədə azalması müşahidə edilməsi mümkün olur. Bu araşdırmalarda ən optimal təhlil neft yataqlarının lay təzyiqinin zamanla dəyişməsi hesab olunur. Məsələnin həlli məqsədilə məqalədə basqı və hasilat quyuları arasındakı intervalda layların filtrasiya parametrlərinin orta qiymətlərini izləyən tədqiqatlar metodu təqdim olunur. Laydaxili maye dinamikasının modelləşdirilməsi halları, basqı quyusunun yataq strukturu qanadında, hasilat quyusu isə onun tağ hissəsində və əksinə olduqda təsvir edilir. Həmçinin, məqalədə məhdudlaşdırıcı təzyiqin müxtəlif dəyərlərində bəzi süxur nümunələri üçün mexaniki xassələrin (sərtlik, məhsuldarlıq və s.) təxminləri təqdim olunur. Bundan başqa, tədqiqatlara spesifik kavernoz-məsaməli struktura malik həm terrigen, həm də vulkanogen-çökmə kollektorlar nümunələri cəlb edilmişdir. Nəticələr sınaqdan keçirilmiş nümunələri Deere və Miller meyarlarına uyğun təsnif etməyə, həmçinin fərdi fiziki və mexaniki xassələr arasında korrelyasiya asılıqlarını təyin etməyə imkan vermişdir.

Açar sözlər: *quyudibi zona, terrigen süxurlar, mexaniki xassələr, qapalı təzyiq*