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Geological and mathematical description of the rocks strain during behaviour of the producing solid mass in compression (tension)

A new approach is presented for studying the patterns of structural changes in reservoirs in the process of volumetric strains of a producing solid mass during its compression (behaviour in tension) strain according to the identified lithological types limited to sedimentary rocks of Western Siberia.

Object: The purpose of this study is to develop analytical expressions in the study of volumetric strain of reservoir rocks (the beginning of dilatancy) in accordance with the individual breakdown point of lithological types of the producing solid mass during its compression (behaviour in tension) strain

Methods: The mathematical methods used in this scientific work are presented by the probability theory, and the geo-mechanical features of sedimentary rocks are studied on the basis of the kinetic theory of solids destruction.

Findings: Individual patterns of changes have been revealed in the reservoirs breakdown point during the transition from low-permeability to medium- and high-permeability.

The time of the initial development of volumetric strains (the beginning of dilatancy) in sand shale reservoirs is calculated.

Conclusions: The obtained patterns indicate the fact that low-permeability, medium-permeability and high-permeability rocks should be considered separately when studying the work of the pay zone on tension (this geo-mechanical process will be characteristic of the production wells operation) and on compression (this geo-mechanical process will be characteristic of the injection wells operation).

Keywords: *Strain: Eigenpolarization parameter; sand shale reservoir; producing solid mass; compression and tension of the solid mass; permeability.*

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1.0 Introduction

In the process of studying of the reservoirs breakdown point, the upper permissible limit of critical strains was revealed, after overcoming which the rock structure begins to collapse (disintegration process). Under the conditions of such structural transformations, the value of the revealed breakdown point of reservoirs will be individual for different lithological types under corresponding loads (tension, fault, compression).

Consequently, the result of the breaking of bonds between structural elements (particles) in the crystal lattice of minerals is the initial stage of their volumetric strain (the beginning of dilatancy), the development of which is facilitated by a fracture system formed by accumulations and displacements of vacancies of natural and wave origin (point defects in the rocks structure), as well as by the heterogeneity of the reservoir composition. As a result of the simultaneous predominance of such processes, starting from the parts of rocks structural loosening, the fracture system grows (starting from point defects), the direction of which corresponds to the redistribution of the acting strains to other point defects in the crystal structure, which causes micro-faults leading to the final stage of volumetric strain the limit of which will be the disintegration of local parts of rocks subjected to loads and the formation fluids exposure.

2.0 Materials and methods

To write this scientific work, various approaches were used in the study of the rocks properties, presented in the works of KatanovYu. E., Yagafarov A.K., Zhurkov S.N., Akhiyarov V.Kh., Fedortsov V.K. and other domestic and foreign scientists.

2.1 Literature review

1. Technologies for increasing well productivity and impact on hydrocarbon deposits at the fields of Western Siberia: monograph/Yu. E. Katanov, A. K. Yagafarov, I. P. Popov [and others] (2019): Ministry of Education and Science of the Russian Federation, Industrial University of Tyumen. – Tyumen: Library and Publishing Complex of the Federal State Budgetary Educational Institution of Higher

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In the study of direct and inverse problems of geological and mathematical modelling of large dimensions, a number of computational problems arise. These problems arise in the geological and mathematical model sophistication in real time, which is accompanied by an increase in the amount of initial information transmitted from the entry (initial) level of the research system to its other structural levels, which inevitably leads to the emergence and growth of calculation errors (systematic error). Consequently, it is necessary to identify the optimal compromise between the studied characteristics with respect to each level of geological and mathematical problems.

Any geological and mathematical basis necessary for solving the assigned problems will be adequately formed in two variants: when the parameters under study are independent of each other; when the parameters under study have a certain character of dependence (distinct or not distinct).

Thus, for a multilevel assessment of the geological and mathematical modelling problems, taking into account the potency of their variations uncertainty, an integrated approach is required that will minimize the calculation error. This is on the one hand!

On the other hand, each process is characterized by many characteristics (significant and insignificant for the final results), the consideration of which will be meaningless in their entirety. For the rocks of the producing solid mass JU_1^1 of the Las-Egan oil field (Western Siberia, Russian Federation), a correlation analysis was performed in three main stages: test for multicollinearity, test for the correlation rate, and test of the regression parameters significance (by the p-level, called the level of significance).

As a result, the critical parameter of the system “rock - reservoir destruction probability” was chosen. As this parameter rock permeability was chosen, since the problem of the stress condition of the solid mass is due to various filtration processes through the structure of the reservoirs, which causes their volumetric strain (the beginning of dilatancy) and further structural fall (disintegration).

It should be noted that the main characteristics that determine the filtration properties of the solid mass are the grain size of the rock-forming minerals, the content of the argillaceous ingredient (carbonate component) in the cementing substance, porosity, the values of the geophysical parameter of eigenpolarization α_{ep}, and the interrelation of fluids that saturate the producing solid mass will be directly related to the interstitial surface of reservoir rocks [6,8,11].

If the studied geological and technological characteristics are independent of each other, then designating P_i, as the probability of occurrence of the weakest structural link by i factor; then, for the normal law of distribution of the reservoir rocks strength prorerties, the following can be written:

$$P_i = \frac{1}{\sigma_i \cdot \sqrt{2\pi}} \cdot \int_0^{x_i} e^{\left(-\frac{(x-\mu)^2}{2\sigma_i^2}\right)} dx, \quad \text{... (1)}$$

where μ, σ are the probability distribution parameters, which physically determine specific values and are associated with the measurement scale, while μ determines the average value (mathematical expectation), mode (median) of the distribution corresponding to the shear coefficient; $\sigma_i > 0$ represented by the mean-square deviation, which corresponds to the scale coefficient; x_i is defined as intercept by factor, which corresponds to the current values of the studied parameter.

Involvement of other types of strength parameters distributions is not required, since with an increase in the number of observations within a single set, its distribution always tends to normal.

Then the probability of structural stability retention by factor can be presented as the difference between the probability of the initial structural-deformation stability of the reservoirs and the probability of occurrence of the weakest structural link:

$$r_i = 1 - P_i \quad \text{... (2)}$$

Taking into account the expression for the probability in formula 1, formula 2 can be rewritten as follows:

$$r_i = 1 - \frac{1}{\sigma_i \cdot \sqrt{2\pi}} \cdot \int_0^{x_i} e^{\left(-\frac{(x-\mu)^2}{2\sigma_i^2}\right)} dx. \quad \text{... (3)}$$

Consequently, the composite probability of retention the structural stability of reservoir rocks to possible volumetric strains (the beginning of dilatancy) will be presented as the product of all possible cases in which the structural stability of the reservoirs is retained:

$$r_n = \prod_{i=1}^{n} r_i. \quad \text{... (4)}$$

Taking into account the expression for the probability in formula 3, formula 4 can be rewritten as follows:

$$r_n = \prod_{i=1}^{n} \left[1 - \frac{1}{\sigma_i \cdot \sqrt{2\pi}} \cdot \int_0^{x_i} e^{\left(-\frac{(x-\mu)^2}{2\sigma_i^2}\right)} dx\right]. \quad \text{... (5)}$$

Formula 5 represents the lower (minimum) estimate of the composite probability of structural stability of the reservoir rock, which will be typical for the micro-level of the study. From formulas 4 and 5, the following conclusion can be made: for each strength property of reservoirs, the minimum probability of occurrence of the weakest structural link must be admissible to ensure their structural stability. If this condition is not fulfilled, even for one strength property (from totality), it becomes impossible to ensure the required level of structural stability of the reservoir rock and, as a consequence, the occurrence of volumetric strains in the rock (the beginning of dilatancy). The weakest structural links in the reservoir rock, as a rule, are concentrated in the zones of adsorption weakening, which are formed in the process of the formation fluid impact on the solid mass.

For cases of normal law of vacancies distribution (pinhole structural defects in the rock) in a certain volume of the solid mass V_1, the probability of its volumetric strain will be equal to $P(x)$; on the other hand, the probability of the structural stability of the solid mass during the transition to a volume V that is p several times larger than the volume V_1 (transition from micro- to macro level), taking into account formulas 3-5, can be represented as follows:

$$P^*(x) = 1-P(x))^p, \quad \text{... (6)}$$

where $V = V_1 \cdot p$.

Consequently, the probability of the reservoir volumetric strain $P_p(x)$ can be studied as the difference between its initial structural stability and the probability of structural stability in the transition to the macrolevel:

$$P_p(x) = (1-(1-P(x))^p) \quad \text{... (7)}$$

To understand the physical and geo-mechanical patterns of these processes, it is necessary to form an extended geological and mathematical model of volumetric strain of reservoirs (model of the dilatancy beginning), making a number of assumptions and statements.

Khanin A.A. developed a classification of reservoirs in Western Siberia (Russian Federation), according to which the main lithological types for a given area are feldspars 25-50%, siltstones and polymictic sandstones with quartzitic assays 15-40%, hydromica 10%, shales and others 10-40%. The cementitious agent that binds mineral particles is represented by argillaceous minerals, the percentage of which (within the entire volume of the rock) amounts to 5-40% [11-12].

Taking into account the developed classification, Akhiyarov V.Kh. (1980) determined the intervals of allowed values of lithological types of reservoirs, and oil ones among them will be with values of the geophysical parameters of their eigenpolarization changing within the range of 0.2-0.4.

Further research presented in the scientific works of A.K. Yagafarov (1984), Fedortsov V.K. (1986), Katanov Yu. E. (2018) for the sedimentary cover of the commercially producing play

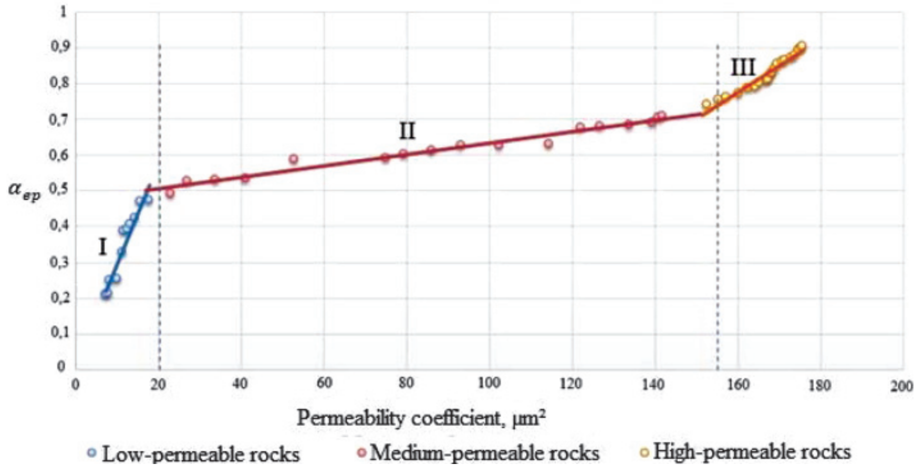

Fig.1 Change in geophysical parameters of eigenpolarization in accordance with lithological differences (the solid mass , the Las-Yegan field, Western Siberia, the Russian Federation)

of Western Siberia showed that a detailed classification into lithological types for each well should be performed separately when interpreting the geophysical well logging data (GIS) [1].

Thus, for the Middle Ob oil and gas-bearing region, for lithological types of oil-saturated rocks, Katanov Yu. E. built approximating patterns for geophysical data of the producing solid mass JU_1^1 of the Las-Egan oil field (Fig.1).

The variety and composition of cementations materials were studied according to the methods of V.A. Valov and B.V. Topychkanov, and the porosity and permeability properties (RQ), shale content, fractional composition according to the methods of I. Leontiev. E., Akhiyarov V. Kh.

It should be noted that α_{ep} is a complex parameter that correlates well with most of the petrophysical parameters of the solid mass.

Based on the identified lithological types (Fig.1) of reservoirs (argillaceous siltstones (I) are low-permeable, siltstones (II) are medium-permeable reservoirs, and polymictic sandstones (III) are highly permeable reservoirs), it follows that with an increase in the argillaceous ingredient in the solid mass volume, as a result, with a decrease in the permeability field values, the correlation between shales and their eigenpolarization parameter α_{ep} will be weaken.

Therefore, the study of the strength parameters of each lithological type of reservoirs must be carried out separately, since their tension (compression) breakdown point will be different.

The further stage of the study proposed to the authors of this scientific work implies the construction of approximating patterns of the tension (compression) breakdown point of reservoirs, taking into account the ideas of the kinetic theory of failure formed by Zhurkov S.N., based on the statement that any fall of the reservoir will not determine the critical state of the geological body, since in any solid body there is a continuous process of structural damage accumulation (diclocation patterns, vacancies travelling), which, ultimately, will lead to the complete destruction of this body.

In the patterns of Zhurkov S.N. (formula 8) a probabilistic nature is constantly traced, depending on the occurrence and further accumulation of inhomogeneities volumes necessary for strain and fracture of the solid. The processes of continuously emerging structural defects in the crystal lattices of minerals will no longer be distributed over a given rock volume, but will accumulate with further transformation into stress raisers, during the development of which first microscopic and then macroscopic conditions of volumetric strain will be formed.

The concept of physical and mechanical work, which is necessary for the reservoir breakdown, clearly contradicts the kinetic resistance theory, since according to the semantic content of this characteristic it is clearly assumed that the process of fracture will proceed in its entire investigated volume, and not in its overstrained area near the fracture (fracture-porous system). This process of the reservoir structure fracturing can be explained as follows: the process of fracturing in the strained reservoir is the result of the gradual accumulation and macromolecules defects development with a systemic, chain structural configuration, which will lead to the impact on other parts of the reservoir, and, as a result, to its fracture. Then the results of studies describing such patterns can be presented by probability theory and mathematical statistics methods with the involvement of rheology and dislocation theories.

$$t_d = t_0 \cdot e^{\left(\frac{U_0 - \sigma_p \cdot \gamma}{R \cdot T}\right)}, \qquad \text{... (8)}$$

where t_d is the time required for the development of the zero stage of volumetric strain (the initial stage of dilatancy) in the reservoir; $t_0 \approx 10^{-13}$ sec. is constant value, independent of the structure and chemical composition of the geological body, which coincides in order with the atomic oscillations period; U_0 is the activation energy of the individual fracturing process (in accordance with the lithological type of the reservoir), which coincides with the heat of sublimation for solid bodies; γ is activation volume of the fracturing process, which depends on the structural features of the geological body and is the structural-sensitive parameter consisting of several atomic volumes; T is the value of the absolute temperature; $R = 8{,}314$ Дж/(моль · К) is the value of the gas constant.

According to the method of Zhurkov S. N., the expression for the breakdown point γ_p can be expressed by the following formula:

$$\sigma_p = \frac{1}{\gamma} \cdot \left(U_0 - R \cdot T \cdot ln\frac{t_0}{t_1}\right), \qquad \text{... (9)}$$

where t_1 is the time constant (in tension or compression), sec.

It should be noted that patterns (8) and (9) represent the atomic nature of the collector fracture process, in accordance with which this process is developing naturally, and the values of the "breakdown point" of various collectors will be conditional if the test duration and temperature are constantly changed.

Thus, for the solid mass JU_1^1 of the Las-Egan field, the authors obtained the dependences of the intervals of allowed values of the reservoirs breakdown point, and also calculated the time required for the volumetric strains initial stage development (the beginning of dilatancy) in the reservoir according to the main lithological types solid mass during its compression (behaviour in tension) strain (Figs.2 and 3). [2-3].

For the solid mass JU_1^1, the mineral composition of shales (cementitious agent) is predominantly hydromicaceous in combination with admixtures of chlorite and kaolinite, mixed lattice minerals.

In accordance with (Fig.3), it can be concluded that the time for the initial stage development of reservoirs volumetric strains varies within the interval 6.5-8 hours (on the time scale, a transition to the natural logarithm of time (sec) was made in hours). These patterns will make it possible to predict the breakdown point of argillaceous reservoirs at various effective stresses.

At permeability values of 85 and higher μm^2, the resulting time required for the initial stage of volumetric strain development (the beginning of dilatancy) is approximately the same, both for the solid mass during its compression strain and its behaviour in tension.

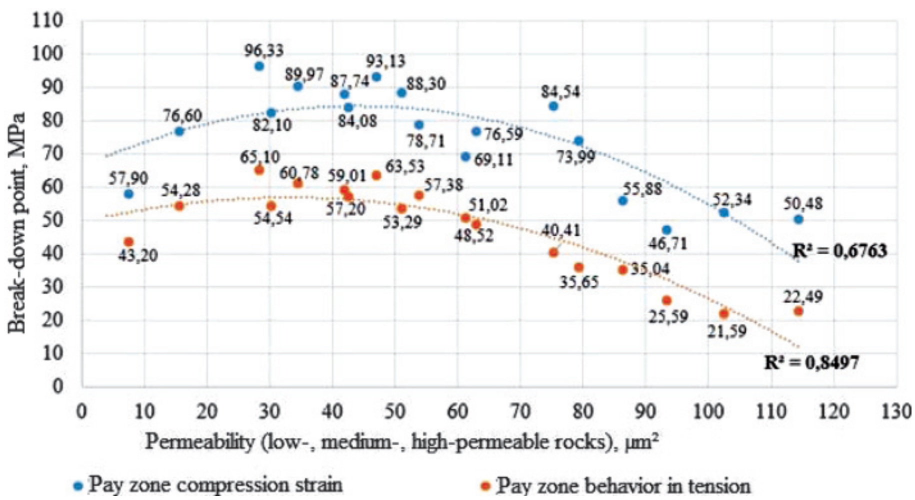

Fig.2 Dependences of the reservoirs breakdown points of the Las-Egan field solid mass with a change in the permeability field of lithological types

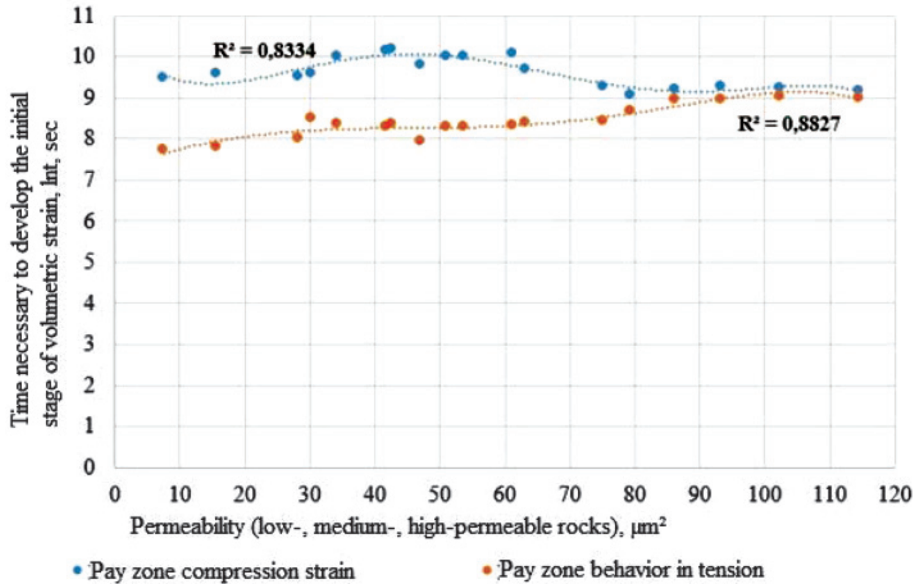

Fig.3 Patterns of changes in the time required for the dilatancy initial stage development at different values of the sand shale reservoirs permeabilities

corresponds to the super limiting stage of the reservoir strain [3].

Consequently, after analyzing Figs.4-9, it can be concluded that under compression the dependence of the reservoir resistance on the volume is weaker than the analogous dependence of the reservoir resistance in tension. This can be explained as follows: some of the vacancies are in a clamped state and do not develop (do not move), forming stress raisers. At the same time, in the effect of tensile force on the reservoir structures, the field of effective stresses will promote the vacancies development [3].

The final stage of this scientific work is the formation of qualitative and quantitative interpretations for

The next stage of the study will probably be the probable statistical estimate of the reservoirs fracture for their previously calculated breakdown point (in compression and tension) and taking into account the developed analytical expressions for each group of lithological types, formed by the producing solid mass permeability value JU_1^1 at the Las-Yegan oil field (Figs.4-9).

The obtained patterns will correspond to the stage of sublimit strain, during which elastic (linear) segments are distinguished, in which overlap (closure) of various structural micro-defects occurs (Figs.4-5). During the transition to medium- and high-permeable reservoirs, microcracks are formed, which corresponds to the stage of reservoir softening (the super-limiting stage of strain) [3].

The transition to the medium-permeable reservoirs (Figs.6-7), in accordance with their individual breakdown point, is a dynamic fracture of the reservoir, which is accompanied by the scattering of its parts – the brittle fracture stage, in which the plastic zone will not be observed.

In accordance with (Figs.8-9) for reservoirs of high-permeable type, the carrying capacity is subjected to a sharp decrease, which forms a scant decrease modulus passing through the conditional breakdown point of the studied reservoir in accordance with the super limiting stage of strain and a brittle fracture modulus (tangent decrease modulus), represented by some tangent parallel on a steeper part of the dependence, which also

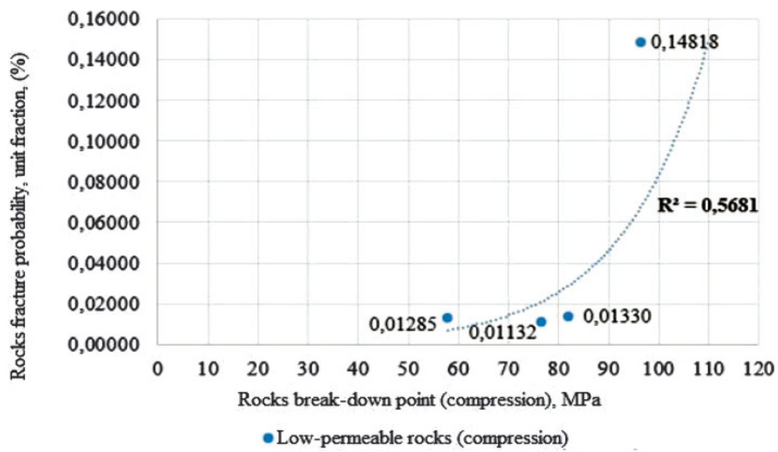

Fig.4 Change in the probability of fracturing of the low-permeable solid mass rocks structure under the conditions of its compression strain

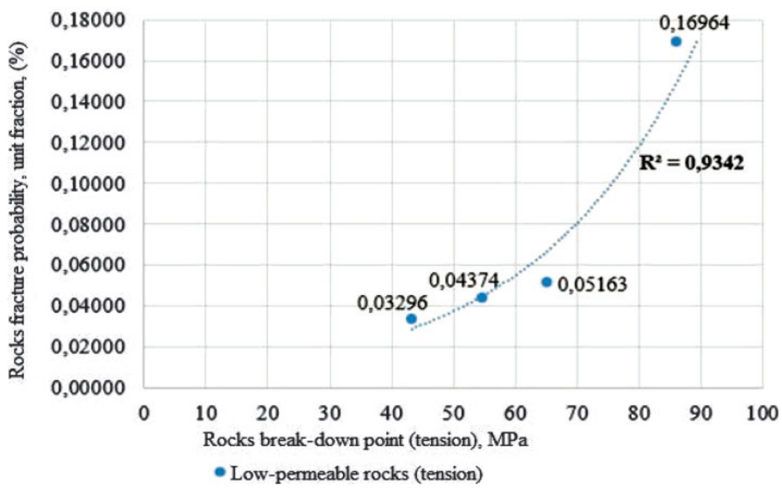

Fig.5 Change in the probability of fracturing of the low-permeable solid mass rocks structure under the conditions of its behaviour in tension

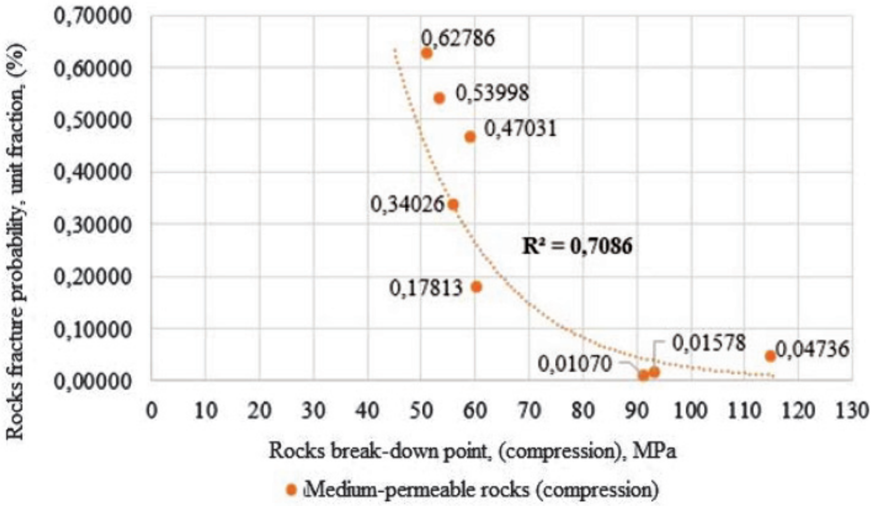

Fig.6 Change in the probability of fracturing of the medium-permeable solid mass rocks structure under the conditions of its compression strain

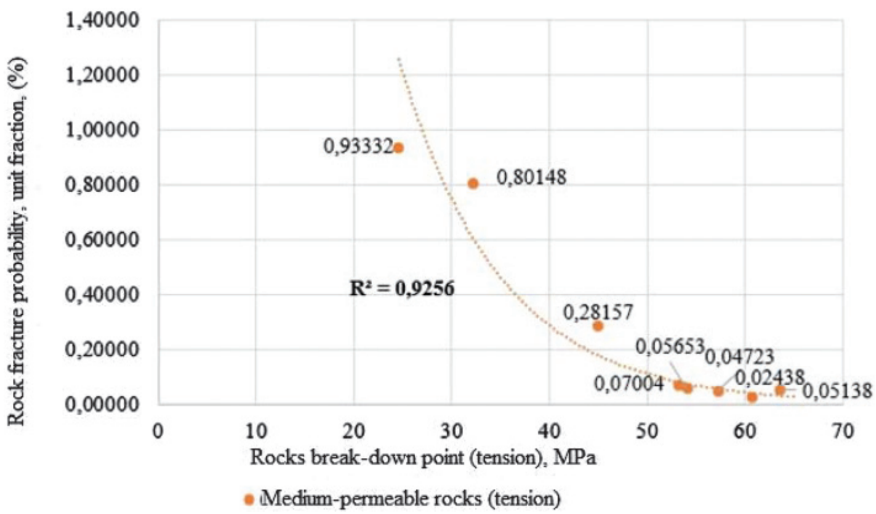

Fig.7 Change in the probability of fracturing of the medium-permeable solid mass rocks structure under the conditions of its behaviour in tension

At the first stage, the pore space of the sandstone is filled with fluid (in particular, water), which increases its moisture content to the level of water saturation; after that, the stage of equilibrium is formed (the second stage), within which there is a stable flow of fluid (water) through the pore space of the sandstone.

The third stage is characterized by a gradual washing-out of the sandstone structure, accompanied by an increase in the hydraulic radius of its pores and intrastratal erosion (subtraction of clay particles). The intensity of such processes of the liquid phase movement through a dispersive porous medium (reservoir) will also be determined by thermodynamic parameters: temperature, fluid pressure gradient, etc. As the porosity field increases, so does the permeability field.

At the stage of activation of the mechanical particles subtraction (third stage), since the intrastratal erosion process prevails, there is a washing-out of the cementitious agent from the reservoir structure, as a result of which its resistance decreases and the process of fracturing of its structure begins. This corresponds to the latent period of sandstone fracturing (Area 3, Fig.10).

Outside this period, volumetric (active) strain of the reservoir takes place in its individual fragments (Area 4, Fig.10). This stage of active strain of sandstone is a the structural and filtration behaviour of polymictic sandstones of the producing solid mass $ЮВ_1^1$ of the Las-Egan oil field (Western Siberia, Russian Federation), Fig.10.

Analysis (Fig.10) shows that the segments (areas) of the curve of change in the sandstones permeability over time have a logical meaning, which is represented by three stages:

- the initial stage of the permeability field development (rapid growth):
- period of the permeability field stabilization;
- a new stage of the permeability field growth.

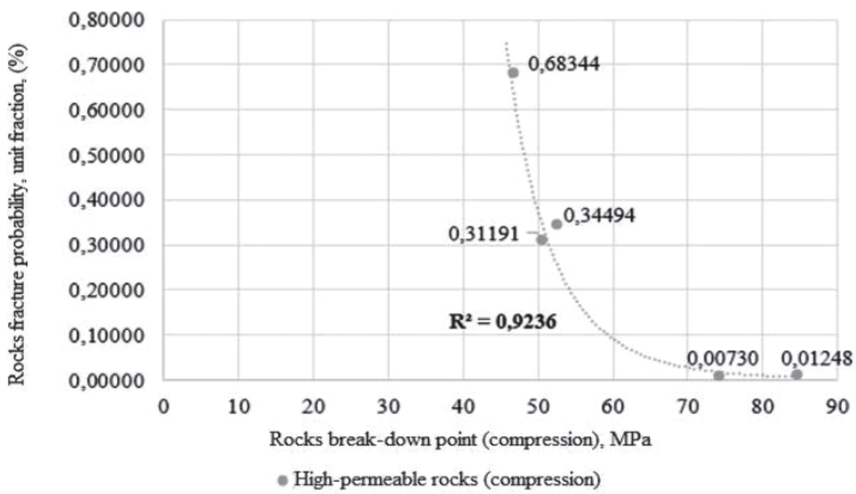

Fig.8 Change in the probability of fracturing of the high-permeable solid mass rocks structure under the conditions of its compression strain

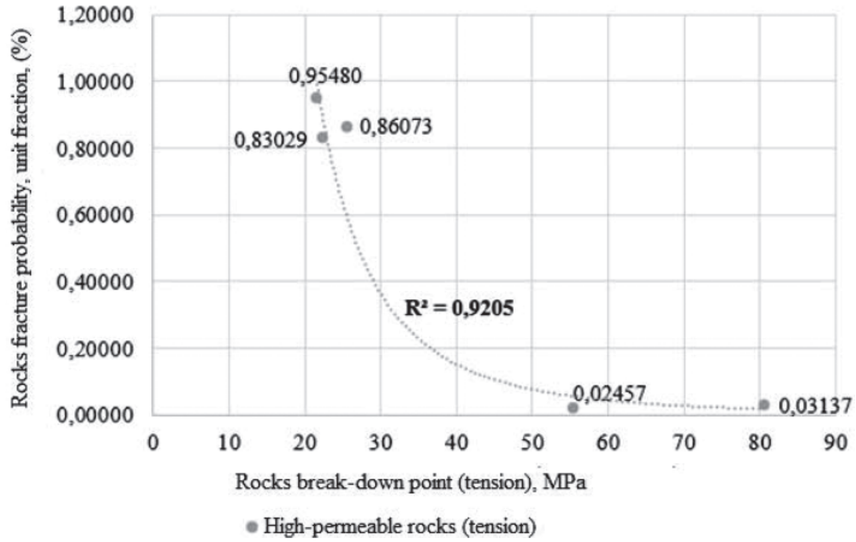

Fig.9 Change in the probability of fracturing of the high-permeable solid mass rocks structure under the conditions of its behaviour in tension

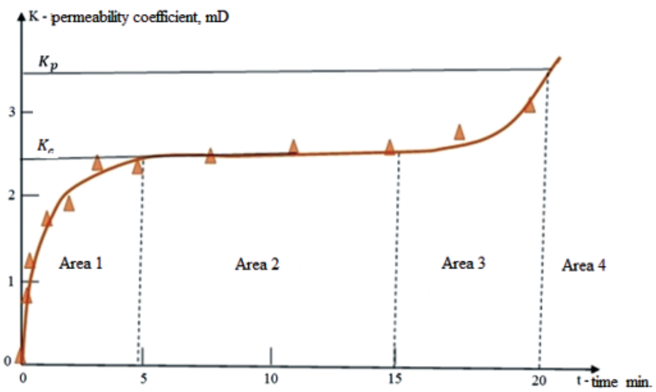

Fig.10 Dependence of the polymictic sandstones permeability coefficient on time; is the sandstone permeability coefficient in a stabilized state; is the sandstone permeability coefficient in the state of the beginning of volumetric strain

prerequisite for such problems as sand ingress and water ingress.

The study of structural and textural polymictic sandstones allowed the authors (Katanov Yu. E., Yagafarov A. K.) to establish the criterion for the beginning of volumetric strain of sandstones [1,4]:

$$\varphi = \frac{K_p}{K_s}, \qquad \text{... (10)}$$

where K_s is the sandstone permeability coefficient in the stabilized state; K_p is the sandstone permeability coefficient in the state of the beginning of volumetric strain (beginning of dilatancy); K_c, K_p is experimentally determined parameters.

The parameter of the sandstones volumetric strain beginning (beginning of dilatancy) will be within the following limits:

$$1,2 < \varphi < 1,5 \qquad \text{... (11)}$$

According to the factor φ, sandstones can be categorized into the following three groups:

- sandstones with low seepage strength (rapidly strained) at values $\varphi < 1,2$;
- sandstones with medium seepage strength (with an average strain rate) at values $1,2 < \varphi < 1,35$;
- sandstones with high seepage strength (slowly strained) with values $\varphi > 1,35$.

For practical calculations of the volumetric strain probability (beginning of dilatancy), it is recommended to take the following value φ:

$$\varphi = 1,35 \qquad \text{... (12)}$$

This value, in essence, will determine the sandstone breakdown point.

If we carry out a geological interpretation of the fluid effect model on the sandstone structure, then it will form a triad of "mineral particles, clay content and liquid (water) phase".

In this case, the proportion of the argillaceous ingredient can be very small (5-10%), but its effect on the sandstone properties is often significant. The works [7, 9, 10, 14-20] provide geological and oilfield data on the filtration coefficient of sandstones that contain sand and an argillaceous ingredient represented by *Na*-montmorillonite.

Based on the processed data, it can be concluded that even at low concentrations of the argillaceous ingredient, there is a sharp decrease in the permeability field of sand shale reservoirs during volumetric strain. The reasons for this performance of sandstones are not obvious and are still poorly known.

As a resultant hypothesis, the following can be logically identified: in the series from "loose reservoir rocks to clays", the adhesion of their structure increases. The adhesion is ensured by the cementitious agents that hold mineral particles in a single space frame. Since argillaceous minerals (hydromica, chlorites, montmorillonite, etc.) often act as a cementitious agent, their content in the total rock volume will determine its adhesion (with an increase in the volume of argillaceous matter, the adhesion of the rock will increase). This is on the one hand!

On the other hand, in addition to the positive effect of the argillaceous ingredient on the rock strength level, an increase in clay content can help block its pore channels, which will inevitably lead to a decrease in the permeability field with an increase in clay concentration.

2.2 Results

The initial time of volumetric strains development of argillaceous sandstones (the beginning of dilatancy) is revealed, which is 6.5-8 hours. The study of the rocks strength characteristics when considering the changes in their structure during the behaviour in tension (compression strain) should be carried out separately, as a result of which it was established:

- for low-, medium- and high-permeability rocks, the values of the probabilities of volumetric deformations (the beginning of dilatancy) during the work of the productive massif in compression (at the transition to the macro level), respectively, are 14.8, 62.7 and 68.3 per cent;

- for low-, medium- and high-permeable rocks, the values of the volumetric strains probabilities (the beginning of dilatancy) during the producing solid mass behaviour in tension (during the transition to the macro level) amount 16.9, 93.3 and 95.4 per cent respectively;
- a qualitative criterion is presented that makes it possible to arrange the volumetric strain rate of polymictic sandstones.

3.0 Discussions

The results are presented at the meetings of the Department of Oil and Gas Fields Development and Operation, Department of Oil and Gas Fields Geology and Applied Geophysics, Industrial University of Tyumen.

4.0 Conclusion

The presented approach to the study of the producing solid mass volumetric strain processes (the beginning of dilatancy) will be effective in the study of the rocks strength characteristics with split-level seepage strength.

Acknowledgements

The authors thank the management of Industrial University of Tyumen (Russian Federation, the city of Tyumen) and the management of OAO KogalymNIPIneft for evaluation of the obtained scientific results.

The scientific work was prepared as part of the state task implementation in the field of science for the performance of scientific projects carried out by the scientific laboratories teams in educational institutions of higher education affiliated to the Ministry of Education and Science of Russia under the project: "Technologies for the production of low-pressure gas of the Cenomanian producing play" (No.0825-2020-0013, 2020-2022).

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