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V. V. POPLYGIN[1]*, Dean, Associate Professor, Candidate of Engineering Sciences, poplygin@bk.ru*
S. V. GALKIN[1]*, Dean, Professor, Doctor of Geological and Mineralogical Sciences*
I. V. SAVITCKII[1]*, Assistant*
D. V. POTEKHIN[2]*, Engineer*

[1]*Perm National Research Polytechnic University, Perm, Russia*
[2]*PermNIPIneft Branch of LUKOIL-Engineering LLC, Perm, Russia*

EXPERIMENTAL STUDY OF HYDRAULIC FRACTURES IN CARBONATE ROCKS UNDER TRIAXIAL LOADING

Hydraulic fracturing is one of the ways to increase well production rates. To assess the possibility of successful hydraulic fracturing in rocks, it is necessary to assess the conditions for the formation and development of fractures. The article considers samples of Kashiro-Vereya carbonate deposits in one of the fields in the Perm Region. The samples initially had a different nature of the void space: with the cavernousness, porous, as well as dense rocks. the samples were subject to triaxial loading experiments. As a result, it was found that in permeable samples, with systems of pores and cavities, no cracks form in compression at 20 MPa. In dense samples under pressure more than 10 MPa, intensive development of fractures takes place, and fluid flow is possible in such fractures. The performed studies of rocks allow concluding on the possibility of creating fracture systems for oil production in the Vereya carbonate deposits. The created fractures enable intensive flow of fluids. This will additionally connect large areas of oil-bearing rocks to the production well. Hydraulic fractures enjoy wider spread in denser samples, while permeable samples experience no change in the structure.

Keywords: *triaxial loading, failure angle, stress, strains, bottom-hole pressure*
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Introduction

Oil and gas fields occur at a depth of several hundred to several thousand meters below the earth's surface. During oil and gas extraction from rocks, the reservoir pressure change in the strata, which changes the stress state of rocks and filtration flows. When the stress state changes, the permeation properties and the pore space structure of rocks change [1]. In oil reservoirs, due to the variability of sedimentation conditions, stresses in rocks are anisotropic ($\sigma_1 > \sigma_2 > \sigma_3$) [2]. Complex in-situ processes require attraction of a larger amount of resources for the development of deposits. Therefore, issues related to the dynamics of change in the structure of the pore space are relevant for reliable prediction of fluid flow and forecasting of oil production [3–5].

To increase the production of hydrocarbons from wells, various geotechnical measures are used. One of the most effective technologies is hydraulic fracturing. To design a technology for hydraulic fracturing in wells, it is necessary to understand the dynamics of the mechanical parameters of rocks under loading. One of the most reliable methods for assessing the mechanical parameters and deformation properties of rocks is triaxial loading.

With an increase in the depth of rocks, the difference between the three principal stresses increases [6]. In [7–10], the studies of the mechanical properties of rocks under triaxial loading were carried out, which showed the prime influence of the principal stresses on the values of deformation, strength, permeability and dynamics of destruction of rocks. At a constant value of σ_3, the rock failure mode changed from shear to a mixed type as the intermediate principal stress increased, and the fracture plane angle increased with increasing σ_2. Also, when rock is deformed in the direction of σ_2, expansion occurs at the initial stage, which gradually turns into compression with an increase in σ_2 [11]. The fracture formation threshold stress and the rock tension initiation stress tend to first increase and then decrease with increasing σ_2 [12]. The strength of rocks first increases and then decreases with increasing σ_2 [13].

Research methods

For a complete study of the mechanical properties of rocks, it is necessary to use the methods of triaxial loading, because in experiments with two-dimensional loading, incorrect interpretation of rock behavior is possible [14]. Rocks are a heterogeneous natural material and include areas with reduced strength, which also significantly affects their mechanical properties [15]. When studying rocks under triaxial loading, it is necessary to take into account the presence of these areas in order to reliably determine their parameters.

To predict the strength characteristics of rocks, various criteria are used: the Drucker–Prager criterion [16], the Mogi criterion [17], the Lade criterion [18], the unified strength criterion [19], and others. However, the mechanism of change in the internal structure and permeability of rocks under loading have not yet been fully investigated. In [20], the conditions for the destruction of layered rocks are studied and two possible mechanisms of destruction are considered: along the bedding planes, which are weakening surfaces, or along the planes where stresses exceeding the strength of the rock as a whole are achieved. It is noted that the type of the implemented fracture mechanism depends on the strength criteria and is determined by the direction and magnitude of the principal stresses. To expand the scope of applicability of existing models for changing the permeability and mechanical properties of rocks or to create new, more accurate and universal methods, more experimental data are needed [21].

In this study, experiments were carried out on triaxial independent loading with measurements of deformation characteristics and absolute permeability in order to further use the results in the design of a technology for hydraulic fracturing in wells operating in similar rocks.

Samples of carbonate rocks of the Vereya deposits were taken from a depth of 1116–1120 meters. In sample 1, the presence of unevenly distributed cavernousness was noted. In sample 2, 76% of the volume is represented by porous, 24% – dense rocks. In sample 3, the proportion of permeable rocks is up to 14%, and fracturing has also been established. Sample 4 is completely represented by dense rock.

The tests were carried out for the samples of a cubic shape with a face size of 40 mm. The samples were fabricated on a specially designed stand with high accuracy: the non-parallelism of the faces did not exceed 20 μm (**Fig. 1**).

Permeability is measured by passing compressed air through a sample during loading.

To measure the permeability along one of the axes on the sample faces, parallel to the flow axis, a shell of a polymerizable material is applied (see fig. 1). The shell has a thickness of no more than 50 microns to prevent errors in the measurement results and is able to ensure the tightness of the sample at different stages of deformation.

Fig. 1. Rock samples for triaxial loading

Table 1. Results of loading sample 3

Stress, MPa	$E\cdot10^{-3}$ MPa	ν, Poisson's ratio (unit fractions)	Absolute permeability before loading, mD	Absolute permeability after loading, mD
2.0	21.7	0.20	57.1	52.7
10.0	20.6	0.20	46.1	44.9
20.0	21.7	0.22	42.6	0.00

The reduction in porosity and in pore size in the samples increases with increasing loading rate, and the degree of reduction in porosity depends on the structure and strength of the rocks [1, 22]. Defects in the form of microcracks that exist or appear at the early stages of rock deformation determine the further development of the fracture process [23].

The failure mode is closely related to lithology. Shear zones are commonly found in granite, tensile cracks are the main mode of failure in marble, and sandstone is damaged by compaction zones [24].

Taking into account the above-said, the characteristics of rock failure under triaxial stress conditions have a significant correlation with the loading rate [25], and loading is performed according to the following program:

—the faces are displaced uniformly at a velocity of 1 mV/sec (axial deformation $55\cdot10^{-5}$%/sec);

—the achieved pressure along two axes is maintained constant, and the loading continues along the third axis;

—before and after loading, tomographic studies of the samples are carried out.

The initial pressure for reference is taken to be 2 MPa.

Results and discussion

The samples were subjected to multiaxial loading. As a result of the experiments, it was found that sample 1 remained practically unchanged. In sample 2, fracturing formed at the boundary of the dense and porous sections. Samples 3 and 4 are of the greatest interest from the point of view of involvement in the process of draining oil. In the initial state, they have low permeability without an extensive system of fractures. The study of the process of crack formation will clarify the possibility of hydraulic fracturing in an oil field.

Table 1 and **Fig. 2** give the results of the study of sample 3.

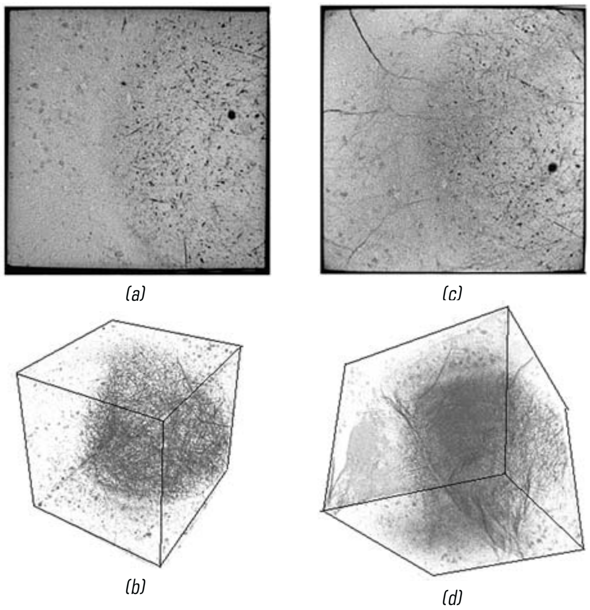
In sample 3, under a load of 10–20 MPa, an extensive system of cracks appeared, associated with previously existing voids. In the previously impermeable part of the sample, after loading, microcracks appeared with an opening of up to 200 μm and at different orientations (see fig. 2). For the initially porous part of the sample, the formed system of microcracks consisted of short channels between microcavities and pores, as well as narrow and extended cracks.

Table 2 and **Fig. 3** describe the results of the study of sample 4.

At a load of 7.5 MPa, a fracture plane with a system of cracks was formed in sample 4. Cracks are parallel structures along the fracture plane. The crack opening reaches 150 μm.

The rock destruction plane angle is 69° for sample 3 and 54° for sample 4.

Under triaxial loading, the fracture planes are approximately parallel to σ_2 and form at a large inclination angle to σ_3, and the fracture angle strongly depends on the stress state [27]. The rock failure parameters in triaxial loading demonstrate the volumetric effect. The cubic specimens are mainly destroyed along one main shear plane [2]. The form of fracture of rocks under true triaxial stress gradually changes from ductile to semi-brittle, and then to ductile with increasing σ_2 [2].



(a) (c)

(b) (d)

Fig. 2. Results of tomographic and microscopic examination of sample 3 before (*a*, *b*) and after (*c*, *d*) loading [26]

To predict the angle of the rock fracture plane under triaxial loading, the following model was proposed in [28, 29]:

$$\Theta = \frac{1}{4}\cdot\frac{\pi}{4} + \frac{1}{2}\arcsin\alpha\,; \tag{1}$$

$$\alpha = \frac{\left(\frac{2}{3}\right)(1+\nu)(\beta+\mu) - \left(\frac{N}{\sqrt{3}}\right)(1-2\nu)}{\sqrt{4-N^2}}\,; \tag{2}$$

$$N = \frac{\sqrt{2}\left(\sigma_2 - \sigma_{oct}\right)}{\sqrt{3}\tau_{oct}}\,; \tag{3}$$

Table 2. Results of loading sample 4

Stress, MPa	$E \cdot 10^{-3}$ MPa	ν, Poisson's ratio (unit fractions)	Absolute permeability before loading, mD	Absolute permeability after loading, mD
2.0	20.0	0.21	—	2.8
7.5	22.9	0.20	9.1	6.8

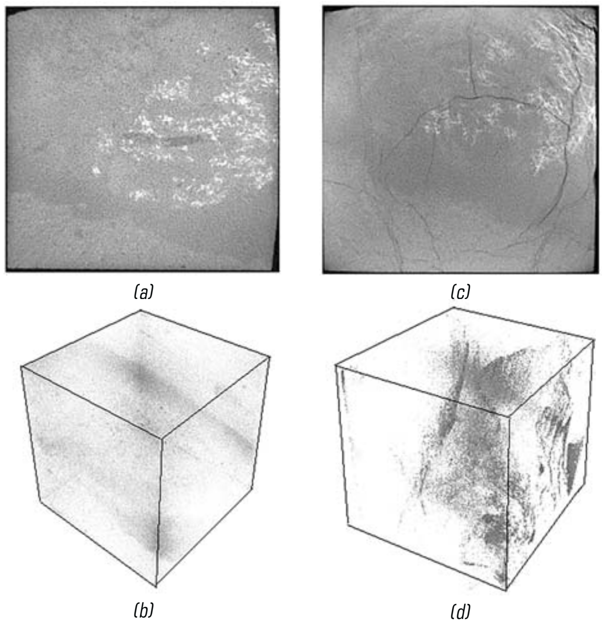


Fig. 3. Results of tomographic and microscopic examination of sample 4 before (*a*, *b*) and after (*c*, *d*) loading [26]

$$\beta+\mu=\frac{3}{2(1+\nu)}\left(\sqrt{4-N^2}\cdot\sin\left(2\Theta-\frac{\pi}{2}\right)+\frac{N}{\sqrt{3}}(1-2\nu)\right), \qquad (4)$$

where Θ is the angle of fracture plane; α is the function of the material parameters; μ is the friction factor; β is the dilatancy factor; σ_2 is the principal stress; σ_{oct} is the octahedral normal stress (or average stress); τ_{oct} is the octahedral shearing stress.

The fracture plane angle predicted by the model agrees well with the experimental results.

In reality, the mechanical parameters of materials, especially the angle of internal friction, are not constant when the stress state changes, and the destruction of rocks often corresponds not to one fracture plane, but to many fracture surfaces.

The most commonly used strength criterion in the geotechnical field is the Mohr–Coulomb criterion which ignores the effect of intermediate principal stress, resulting in a large deviation in the predicted engineering rock strength, which is unacceptable in some designs.

In [30], a three-invariant yield loss function was proposed:

$$F\left(\tau_{oct},\sigma_{oct},\Theta\right)=-\frac{2\sqrt{3}}{9}A\sin(3\Theta)\left(\frac{\tau_{oct}}{\tau_{oct0}}\right)^3+\left(\frac{\tau_{oct}}{\tau_{oct0}}\right)^2-1, \qquad (5)$$

where A and τ_{oct} are the parameters depending on σ_{oct}, A determines the shape of the fracture surface in the deviatoric plane, and σ_{oct0} describes the dependence of τ_{oct} on the average stress in pure deviatoric shear ($\Theta = 0$). The ratio of τ in failure under axisymmetric compression to that under axisymmetric tension increases with increasing A. The shape of the shell in the deviatoric plane changes from a bent triangle at $A = 0.95$ to a circle at $A = 0$, then to an inverted bent triangle for $A = 0.7$ and finally an inverted triangle for $A = 1.0$.

The research results indicate the possibility of creating fracture systems in the low-permeable part of the section of the Vereya carbonate deposits. The orientation of cracks in space reflects the direction of the load and the internal structure of the samples. The formation of extended fractures during hydraulic fracturing with an opening of up to 200 μm will make it possible to involve previously non-drained zones at a distance from the wells in permeation process.

Conclusions

The performed studies of rocks allow drawing conclusions about the possibility of creating fracture systems for the oil production in the Vereya carbonate deposits in the Perm Region. Fractures are formed, through which intensive fluid flow can occur, which will additionally connect significant volumes of oil-bearing rocks to the well operation. In this case, the most spread system of cracks occurs in denser samples, while the rock structure remains practically unchanged in permeable samples. Predicting the angle of the fracture plane in an oil reservoir under additional loading creates the basis for the development of directional fracturing technology. However, due to the complex structure of the rock mass, the accuracy of existing predictive models remains low and further research is needed to improve the accuracy of the models.

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A. Yu. MOTORIN[1,2]*, Junior Researcher, Senior Geophysicist*
S. V. BARANOV[1]*, Chief Researcher, Doctor of Physical and Mathematical Sciences, bars.vl@gmail.com*
P. N. SHEBALIN[2,3]*, Director, Doctor of Physical and Mathematical Sciences, Corresponding Member of RAS*

[1]*Kola Branch of the Geophysical Survey of the Russian Academy of Sciences, Apatity, Russia*
[2]*Kirovsk Branch of Apatit, Kirovsk, Russia*
[3]*Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, Moscow, Russia*

SPATIAL DISTRIBUTION OF BLAST-TRIGGERED SEISMIC EVENTS: A CASE-STUDY OF THE KHIBINY MASSIF

The paper considers spatial distribution of seismic events triggered by blasts during mineral mining in the Khibiny Massif. The subject of the study is the production blasts and seismic events recorded by the seismic monitoring network of Kirovsk Branch of Apatit in 1996–2020. The chains of seismic events triggered by blasts were identified using the nearest-neighbor method. The studies prove that earthquake-to-blast distances averagely obey an exponential distribution independent of the triggering blast magnitudes. The model of the maximal distances from a triggering blast hypocenter to the expected aftershocks with a given probability is constructed in the study. The model agrees with the actual data. The recommendations on using the mode are substantiated from the analysis of the error diagrams.

Keywords: *induced seismicity, production blasts, aftershocks, exponential distribution, aftershock domain, error diagram*
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Introduction

This study continues the research of the authors in the field of time–space patterns of seismic activity in the regions of mineral mining. It is already demonstrated that the number of seismic events triggered by blasting (seismic productivity of blasts) obeys an exponential distribution [1]. It is also found that under conditions of the induced seismicity in the Khibiny Massif, the distances between the seismic events and induced bumps comply with a power-series distribution [2]. A similar result was earlier obtained by the American scientists for the natural seismicity in California [3]. Using the combination of the earthquake productivity law [4], proved for the conditions of the induced seismicity in the