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CHANGES IN THE SEAM-FILTRATION MODE WITH STRESS REDISTRIBUTION IN COUNTRY ROCK

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A mathematical model for the mechanism of increasing oil output of productive seams is developed. The model involves a deliberate "conversion" of segments of the fault zone of the country rock to a supercritical state, which leads to a local redistribution of stresses in the block massif of rocks and an increase in contour and seam pressures. Based on solving the problem of restricted filtration, it is shown that the use of the proposed mechanism can ensure a relative increase in well production of 5–8%.

Key words: *block medium, filtration, increase in oil output.*

Introduction. According to the estimates of [1], 40 to 60% of explored reserves of hydrocarbons are not actually developed for various reasons, such as inhomogeneity of the seam structure, elevated viscosity of oil, etc. The data of natural observations [2, 3] and laboratory experiments [4, 5] testify that low-amplitude unsteady actions in the range of frequencies of 10–500 Hz lead to an increase in oil production of active wells and, sometimes, to revival of wells out of service. A number of mechanisms explaining these phenomena have been proposed: decrease in fluid viscosity in the dynamic field [5], resonant processes initiated by unsteady actions in a multiphase medium [6] or block structure of the oil seam [7], and an increase in permeability of the reservoir due to intense formation of microcracks [8]. Observations of seismic activity of the rock massifs after quasi-static (filling of water reservoirs [9]) and dynamic (earthquakes [10], massive explosions [11]) actions showed that the amount of energy released (estimated on the basis of the registered acoustic emission) is sometimes significantly greater than the energy due to external sources. This testifies that the potential energy accumulated in the rock massif is set free.

In the present paper, we offer a theoretical substantiation of the mechanism of increasing oil production [12] based on the block structure of the rock massif [13]: an unsteady external action induces a local redistribution of stresses in the country rock, which can increase the pressure in the productive seam and, hence, increase the oil output.

Hypotheses and Formulation of the Problem. Most earthquakes are focused in the vicinity of tectonic faults [14]. This fact can be explained on the basis of the experimental data of [15], which show that the shear strength of interblock contacts is significantly lower than the strength of the blocks themselves. As for tensile stresses, the contacts cannot withstand them at all. Therefore, we can expect that it is at such structural weak points that the equilibrium will be broken under a certain external action.

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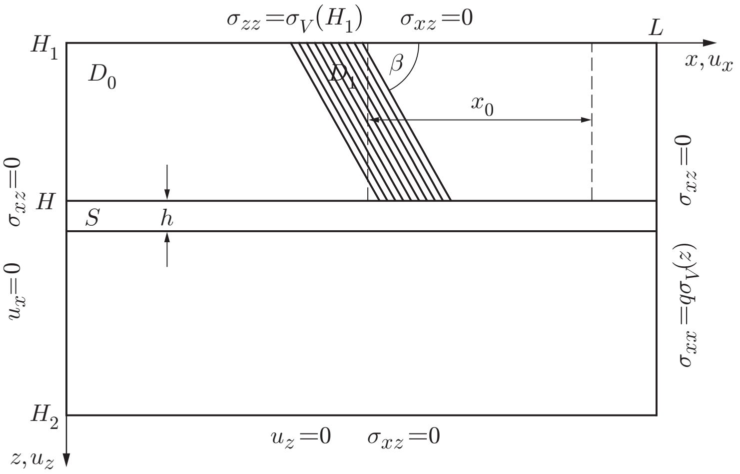

Fig. 1

According to [15], the deformation of interblock contacts in the tangential direction is described by the function

$$\tau(R,\sigma_n)=\begin{cases} K_sR & \text{for} \quad R\leqslant R_p, \\ \tau_p-K_f(R-R_p) & \text{for} \quad R>R_p, \end{cases} \tag{1}$$

where τ and σ_n are the shear and normal stresses, R is the slip of the edges, K_s is the shear rigidity, K_f is the tangent of the angle of inclination of the downward branch, $\tau_p=\sigma_n\tan\varphi+\tau_c$ is the ultimate shear strength, φ is an analog of the internal friction angle, τ_c is the cohesion, and $R_p=\tau_p/K_s$. We assume that the current state of the contact (R_*,τ_*) is close to the limiting state (R_p,τ_p), i.e., $\Delta R/R_p\ll 1$ $(\Delta R=R_p-R_*>0)$. If an external action induces a relative shift of the edges Δu, $R_*+\Delta u>R_p$, then, according to (1), the residual slip is $R_s=(\Delta u-\Delta R)(1+K_f/K_s)$, and a local redistribution of stresses occurs in the medium.

The relative displacements of blocks at distances of the order of kilometers from a nuclear explosion reach 20 mm [16]. Powerful sources of vibrations (with a driver force of 10^6 N) can generate a signal whose amplitude is approximately 0.01 mm at a depth of 2 km [17]. We use this value as Δu. We take a rather typical block structure of the massif and choose the boundary conditions and medium properties so that the proposed mechanism could be implemented.

In a Cartesian coordinate system (x,z) with the z axis directed vertically downward, we consider a rectangular domain D_0 $\{0\leqslant x\leqslant L,\ H_1\leqslant z\leqslant H_2\}$ with a horizontal seam S of thickness h located at a depth H from the daylight $z=0$. Part of the overlying thickness D_1 has an inclined-layered structure with an angle β (Fig. 1). We assume that the medium in D_0 is elastic, tangential deformation of interblock faults in D_1 is described by Eq. (1), and σ_n and normal displacements are continuous.

The domain D_0 obeys the equilibrium conditions

$$\frac{\partial\sigma_{xx}}{\partial x}+\frac{\partial\sigma_{xz}}{\partial z}=\Phi_x, \qquad \frac{\partial\sigma_{xz}}{\partial x}+\frac{\partial\sigma_{zz}}{\partial z}=\Phi_z \tag{2}$$

and Hooke's law

$$\sigma_{xx}=(\lambda+2\mu)\varepsilon_{xx}+\lambda\varepsilon_{zz}, \qquad \sigma_{zz}=\lambda\varepsilon_{xx}+(\lambda+2\mu)\varepsilon_{zz}, \qquad \sigma_{xz}=2\mu\varepsilon_{xz}, \tag{3}$$

where σ_{ij} are the stress-tensor components $(i,j=x,z)$, λ and μ are the Lamé parameters, $\varepsilon_{ij}=0.5(u_{i,j}+u_{j,i})$ are the strain-tensor components, u_i are the displacements, and $\mathbf{\Phi}=(\Phi_x,\Phi_z)$ is the vector of body forces.

We formulate the boundary conditions on ∂D_0 as

$$\begin{gathered} \sigma_{zz}(x,H_1)=\sigma_V(H_1), \quad \sigma_{xz}(x,H_1)=0, \qquad u_z(x,H_2)=0, \quad \sigma_{xz}(x,H_2)=0, \\ u_x(0,z)=0, \quad \sigma_{xz}(0,z)=0, \qquad \sigma_{xx}(L,z)=q\sigma_V(z), \quad \sigma_{xz}(L,z)=0, \end{gathered} \tag{4}$$

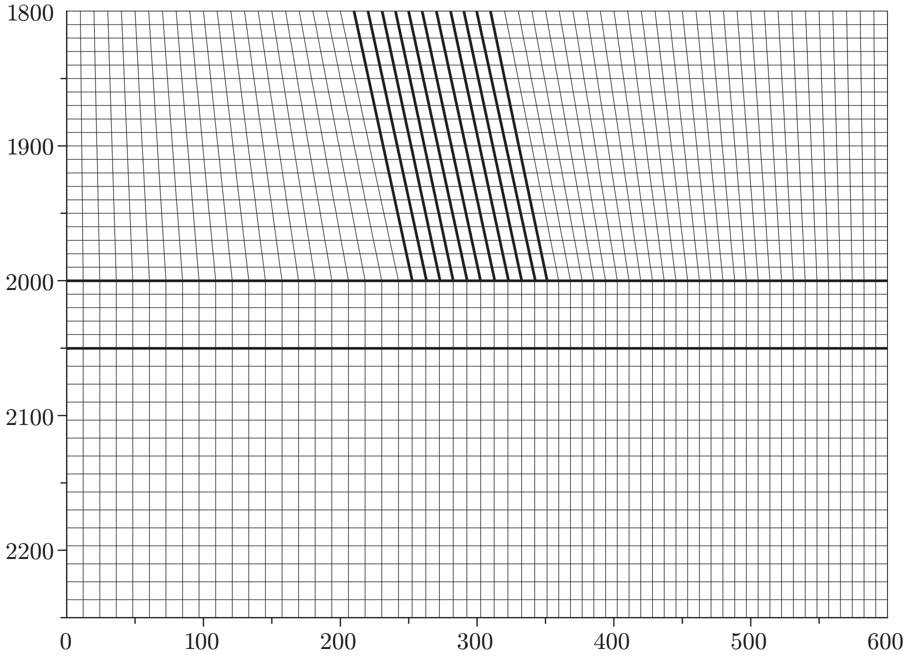

Fig. 2

TABLE 1

Physical Properties of Rocks

Domain	λ, GPa	μ, GPa	ρ, kg/m^3
D_0	7.4	8.0	2500
D_1	6.7	7.2	2500
S	5.2	6.0	2200

where $\sigma_V(z) = \rho g z$ is the lithostatic stress, ρ is the density, g is the acceleration of gravity, and q is the lateral repulse coefficient.

The boundary-value problem (1)–(4) with $\Phi_x = 0$ and $\Phi_z = \rho g$ whose solution determines the initial field of stresses σ_{ij}^0 of the massif is formulated for the model of a planar strain state, which provide an adequate description of the fault ($q < 1$) tectonic mode [18] typical of most oil-bearing regions of West Siberia [19].

System (1)–(4) was solved by the finite-element method by the 2MKÉChK code [20]. Figure 2 shows a fragment of discretization of the computational domain. The following parameters were chosen: $H_1 = 1500$ m, $H_2 = 2500$ m, $H = 2000$ m, $L = 1000$ m, and $h = 50$ m. The domain D_1 located in the middle part of D_0 consists of ten layers (the thickness of each layer is 5 m) separated by discontinuities (see Fig. 1). The physical properties of the rocks are listed in Table 1; for interblock contacts, $K_s = 3$ GPa/m, $K_f = 0.2K_s$, $\varphi = 25°$, and $\tau_c = 0.5$ MPa.

The objective of the numerical experiment is to find the values of q and β such that the value of ΔR along the faults should be of the order of 10^{-5} m. Figures 3a and 3b show the distributions of ΔR on one interblock contact for different values of β for $q = 0.3$ and 0.275, respectively. In the vicinity of the oil seam, the fault zone with $\beta = 78°$ and $q = 0.275$ is in a state close to critical with $\Delta R = 0.05$ mm. This makes it possible to violate equilibrium of the medium with the help of a group of unsteady sources by focusing the signal to a certain area and, thus, produce a redistribution of stresses in the country rock, an increase in pressure in the oil seam, and hence, an increase in well production.

Analysis of the Filtration Process Under a Forced Change in Pressure. Based on the model of unsteady filtration, we qualitatively evaluate the change in well production with a local redistribution of stresses in the massif.

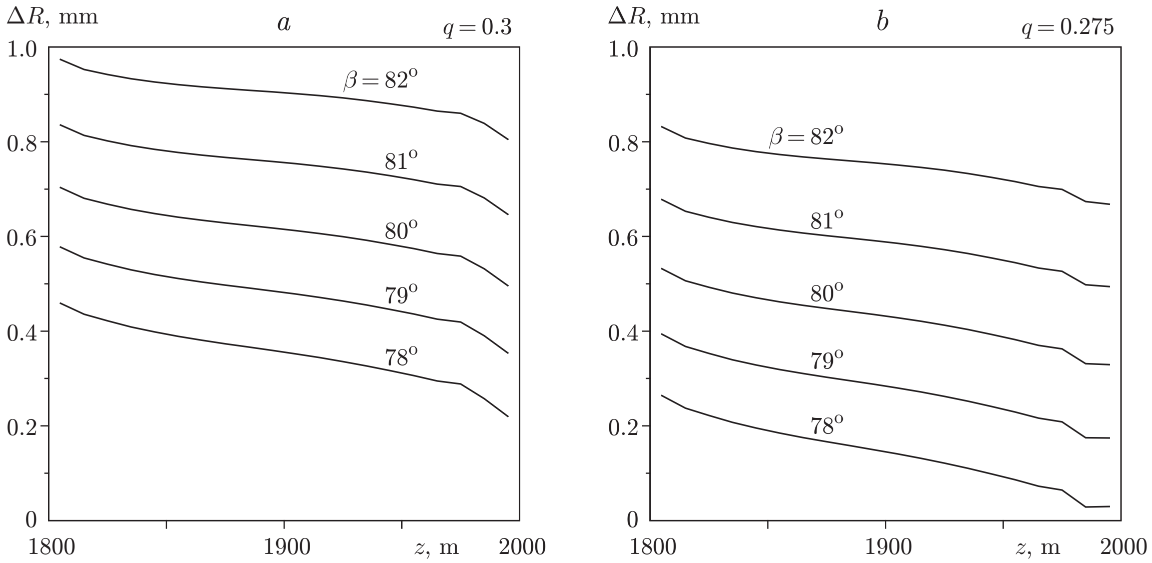

Fig. 3

At the time $t = 0$, the oil seam S (see Fig. 1) is struck by a well located at a distance x_0 from the middle of the fault zone. The motion of the fluid is described by the equation of conservation of mass

$$\frac{\partial (m\gamma)}{\partial t} + \frac{\partial (\gamma w_x)}{\partial x} + \frac{\partial (\gamma w_z)}{\partial z} = 0, \tag{5}$$

equation of state

$$p = p_0 + C(\gamma/\gamma_0 - 1), \tag{6}$$

and the Darcy law

$$w_x = -\frac{k}{\eta}\frac{\partial p}{\partial x}, \qquad w_z = -\frac{k}{\eta}\frac{\partial p}{\partial z}, \tag{7}$$

where w_x and w_z are the velocity components, p is the pressure, k is the permeability, m is the porosity, γ, η, and C are the density, viscosity, and compressibility of the fluid, respectively, p_0 is the atmospheric pressure, and γ_0 is the value of γ for $p = p_0$.

The influence of changes in pressure on the stress-strain state of the oil seam is taken into account by introducing a new vector of body forces into S:

$$\Phi_x = \frac{\partial p}{\partial x}, \qquad \Phi_z = \rho g + \frac{\partial p}{\partial z}.$$

To set the initial distribution of p, we use Khristianovich's hypothesis, which reads that "the fluid pressure in an unstruck seam equals the mean rock pressure" [21]; then, we have

$$p(0, x, z) = (1 + \nu)(\sigma^0_{xx}(x, z) + \sigma^0_{zz}(x, z))/3. \tag{8}$$

Here, we take into account that $\sigma_{yy} = \nu(\sigma_{xx} + \sigma_{zz})$ for planar deformation, where ν is Poisson's coefficient.

We also formulate the boundary conditions for (5)–(7):

$$w_z(t, x, H) = w_z(t, x, H + h) = 0; \tag{9}$$

$$p(t, 0, z) = (1 + \nu)(1 + q)\sigma_V(z)/3; \tag{10}$$

$$p(t, x_0 + L/2, z) = p_0. \tag{11}$$

System (1)–(11) was solved by the technique and codes developed in [22].

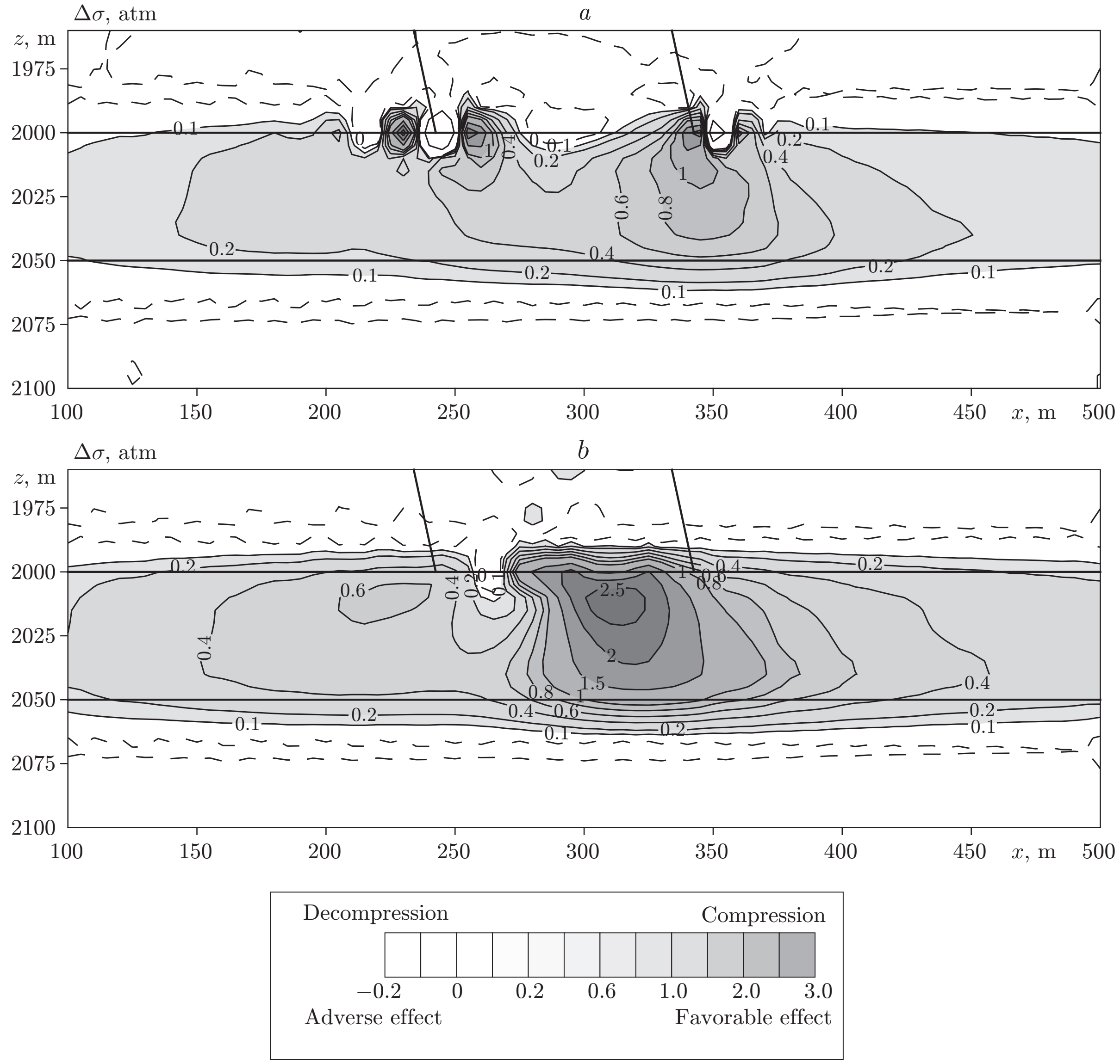

Fig. 4

Let there occur slipping at several segments of fault-zone contacts at $t = t_p$. This causes a redistribution of stresses in the rock massif; the components of the new field of stresses are denoted as σ^1_{ij}. The pressure in the oil seam changes in a jumplike manner:

$$p(t_p, x, z) \to p(t_p, x, z) + \Delta\sigma(x, z).$$

Here $\Delta\sigma = (1 + \nu)(\sigma^1_{xx} - \sigma^0_{xx} + \sigma^1_{zz} - \sigma^0_{zz})/3$ is the increment of the mean stress. The seam permeability also changes: $k = k_0(1 - \Delta\sigma/K)$, $K = (1 - m)K_0 + mC$ is the reservoir compressibility and $K_0 = \lambda + 2\mu/3$ is the bulk compression modulus of the skeleton.

The calculations were performed for the following parameters: $k_0 = 5 \cdot 10^{-14}$ m^2, $\eta = 0.03$ Pa · sec, $m = 0.2$, $p_0 = 0.1$ MPa, $q = 0.275$, $d_0 = 850$ kg/m^3, and $C = 3$ GPa (then, $K_0 = 11.5$ GPa and $K = 9.8$ GPa). Figure 4a shows the isolines of $\Delta\sigma$ for the case of slipping of six contacts in the middle of D_1 with $\Delta u = 0.024$ mm on segments immediately contacting the oil seam. It is seen that the redistribution of stresses generates a noticeable increase in pressure in the oil seam (up to 1.5 atm) in a local zone positioned closer to the confining seam. Figure 4b also shows the lines of equal values of $\Delta\sigma$, but the slipping with $\Delta u = 0.06$ mm is induced at fault segments located at a

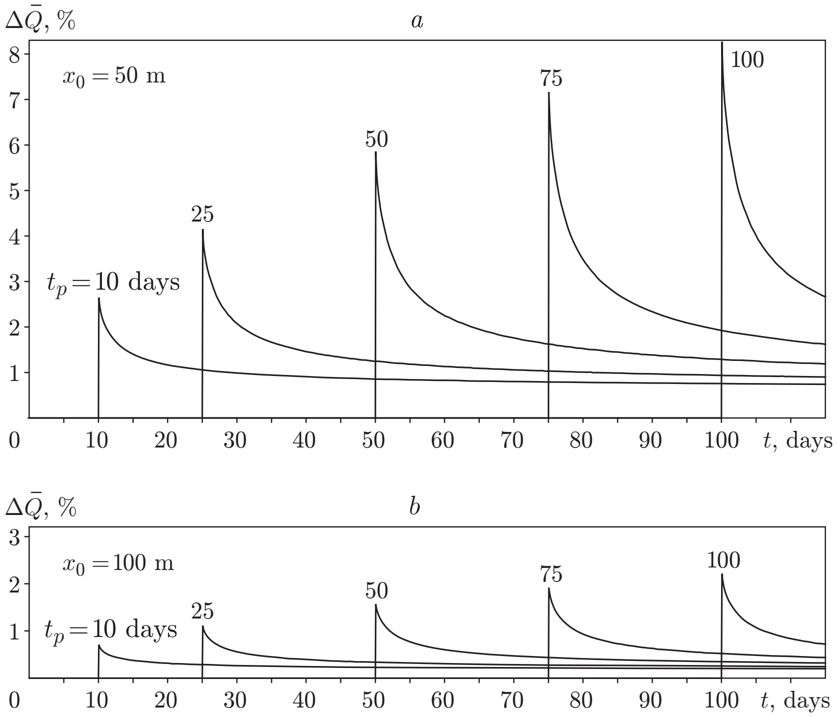

Fig. 5

distance of 20 m from the confining seam. The effect is more pronounced here (the values of $\Delta\sigma$ can reach 3 atm), and the region of elevated pressure is more extended. Nevertheless, it does not seem reasonable to implement the mechanism proposed on powerful seams.

We analyze the change in oil output on the basis of the behavior of the relative increment

$$\Delta\bar{Q}(t) = \frac{Q_p(t) - Q(t_p)}{Q(t) - Q(t_p)} - 1,$$

where

$$Q(t) = \int\limits_0^t \int\limits_H^{H+h} w_z\Big(t, x_0 + \frac{L}{2}, z\Big)\, dz\, dt$$

is the relative flow rate and Q_p is the flow rate after implementation of the mechanism of stress redistribution considered. The time evolution of $\Delta\bar{Q}$ for different values of t_p is shown in Figs. 5a and 5b for $x_0 = 50$ m and $x_0 = 100$ m, respectively. It should be noted that $\Delta\bar{Q}$ decreases with increasing distance between the fault zone and oil well, increases with increasing time period t_p between the beginning of oil exploitation to the moment of contact shear, and rather rapidly tends to a certain steady value, which characterizes the "residual effect" after a forced change in pressure in the oil seam.

Concluding Remarks. Implementation of the mechanism proposed can also produce an adverse effect: the pressure is reduced almost everywhere in the oil seam if slipping of two last contacts is provided in the model considered.

For a thrust-fault tectonic mode characterized by high ($q > 1$) horizontal stresses, the state of the fault zone (for the massif structure and properties specified here) with $\Delta R \sim 0.05$ mm can occur at $\varphi \leqslant 10^\circ$ and $\tau_c \approx 0$. Such values of strength characteristics are inherent in interblock faults filled by clay materials with high humidity.

To determine the possibility and expediency of implementation of the mechanism proposed for increasing pressure in productive seams, the stress-strain state of the massif should be analyzed to find the "weak" zones, and the consequences of making these zones nonequilibrium for the filtration process should be evaluated.

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