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EXPERIMENTAL INVESTIGATION OF THE EFFECT OF EXTERNAL PRESSURE ON THE PERMEABILITY OF OIL-BEARING ROCKS

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In connection with the problem of unsteady filtration and pressure restoration in an oil-bearing formation, it is of interest to carry out an experimental investigation of the nature of the deformation of oil-bearing rocks under the influence of the external pressure p_{ext} of the overlying rocks. When an oil-bearing formation is opened and oil is withdrawn from it, the reservoir pressure p_ℓ falls, while the pressure of the overlying rocks on the roof of the formation, i.e., the external pressure under which the porous medium is situated, remains unchanged. In the process of withdrawing oil from the formation, the pressure under which the porous medium is situated, equal to the difference between the external and reservoir pressures, increases; when withdrawal ceases, it decreases. Studying the influence of external pressure on the volumetric rate of filtration of a liquid in oil-bearing rocks makes it possible to judge the nature of the change in the permeability of these rocks during loading and unloading.

The investigation of filtration was carried out on samples of natural oil-bearing rocks (oil fields of Bashkiria and the Caucasus) with air permeability from 0.2 to 1000 md. The external pressure was created by hydraulic compression of the lateral surface of the sample through a thin lead jacket and was varied within limits up to 600 atm, which corresponds to the range of variation of the pressure of overlying rocks on the roof of an oil-bearing formation. Measurement of the permeability K (experimentally, the pressure drop across the rock sample* was measured at a specified volumetric filtration rate) was carried out on a UIPK-1 apparatus for core studies ([1]). In calculating the permeability, a correction was introduced for the residual deformation of the lead jacket. Nonpolar kerosene was used as the filtering liquid (surface tension at the boundary with water, 46.7 erg/cm^2). Before filtration was begun, an external pressure $p_{\text{ext}} = 100$–150 atm was established, after which the sample was saturated with kerosene under a pressure $p_\ell = 100$ atm. The method of investigation consisted in obtaining curves $K = f(p_{\text{ext}})$ as the external pressure was increased and decreased under conditions of constant reservoir pressure.

As measurements on rock samples of different permeability showed, in all cases without exception the linear law of filtration was obeyed; on its basis the permeability K was calculated at different p_{ext}. The results obtained make it possible to consider that, despite the great variety of types of curves $K = f(p_{\text{ext}})$, differing in details, two main types of these curves were found.

The first type includes curves characterized by the absence of residual deformations in the samples when the external pressure is increased and decreased.

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* The sample length was 2 cm and the diameter 3 cm; the samples were mounted in the core holder in such a way that only the lateral surface was subjected to the action of the external pressure. The dimensions of the samples and the method of mounting them ensured that measurements were carried out under conditions of lateral, but not all-around, compression.

pressure (Fig. 1a, I—the numbers and arrows indicate the sequence of the experiments). The permeability of the sample decreases with increasing external pressure and again rises to its former values when p_{ext} is decreased. Since, when the external pressure is decreased, the permeability at all values of p_{ext} assumes its previous value, it may be considered that the sample deforms reversibly.

The second type includes curves characterizing the presence of residual deformations in samples when the external pressure is increased and decreased. As an example of curves of this type, Fig. 1a, II gives the graph $K = f(p_{\text{ext}})$ for one sample of oil-containing rock. On the return path (decreasing p_{ext}) the permeability is restored slowly, and when the external pressure is reduced to its initial value it proves to be considerably less than its original magnitude. Thus, a peculiar hysteresis of permeability is observed, indicating the presence of residual deformations in the sample.

The irreversible nature of the deformations of various rocks (marbles, sandstones, limestones, etc.) has also been noted earlier in studies of the influence of all-round pressure on porosity ([2–5]). Using the notion of the inelastic character of changes in rock porosity, G. I. Barenblatt and A. P. Krylov solved the problem of unsteady filtration of a liquid in a porous medium ([6]). The notion of the irreversible character of changes in the structure of a porous medium is usually associated with unequal changes in porosity during loading and unloading. However, the filtration properties of rocks are more naturally characterized by permeability than by porosity. Moreover, as follows from the experimental data obtained, the relative change in permeability under the influence of external pressure is considerably greater than the relative change in porosity ([7]).

The study of irreversible deformations under different conditions of repeated cycles of loading and unloading of the rock showed that the nature of the change in permeability during a repeated cycle depends on whether the sample was completely unloaded ($p_{\text{ext}} = 0$) at the end of the return path of the first cycle, or whether the repeated cycle began at the same external pressure at which the first cycle ended. In the first case, the initial value of the sample permeability (at p_{ext} = 100-150 atm) proved to be $K_2 < K < K_1$ (Fig. 1b), whereas

Figure 1: Dependence of permeability on external pressure for various samples of oil-bearing rocks

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in the second case the beginning of the second cycle coincided with the end of the first, the beginning of the third with the end of the second, etc. (Fig. 1c). With repeated cycles of loading and unloading, the permeability in each subsequent cycle proves to be less than in the preceding one; the dependence of permeability on external pressure becomes less and less sharply expressed, and finally the permeability practically ceases to depend on the external pressure (Fig. 1c). For some rock samples, the irreversibility of deformations, detected from the hysteresis of permeability, was observed only at the end of unloading (Fig. 1g).

A study of the dependence $K = f(p_{\text{ext}})$ for samples of various rocks (sandstones, limestones, siltstones, dolomites, etc.) showed that the character of deformation of these samples is different and depends on their mineralogical composition, structure, and the composition of the cementing material. Comparison of the character of the curves $K = f(p_{\text{ext}})$ with the results of mineralogical analysis* of the samples of oil-containing rocks studied shows that the absence of permeability hysteresis is usually observed for fine- and coarse-grained siltstones with a mixed cementing substance filling the pores, and for dolomitized limestones.

The irreversible character of the dependence of permeability on external pressure is observed in most cases for fine-grained sandstones with

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Fig. 1. Dependence of permeability on external pressure for various samples of oil-bearing rocks from the Bashkiria and Caucasus fields.
a: I –Urzhumka; sampling depth 1668-1675 m; coarse-grained aleurolite; $K_{\text{air}} = 0.33$ md; $m = 10.1\%$. II –Baikebash, well No. 2; sampling depth 1925-1929 m; fine-grained aleurolite; $K_{\text{air}} = 0.30$ md; $m = 8.5\%$.
b –Bashkiria, aleurolite; $K_{\text{air}} = 130$ md; $m = 18.6\%$.
c –Baksan River, outcrop; coarse-crystalline limestone; $K_{\text{air}} = 0.57$ md; $m = 3.0\%$.
d –Urukh River, outcrop; dolomite; $K_{\text{air}} = 2.50$ md; $m = 10.6\%$.

with clayey cement; for limestones composed of microgranular calcite; for aleurolites with a mixed cementing material (clayey, contact-type, quartz, and calcite); and for some dolomites. Correlating the character of deformation of oil-bearing rocks with their mineralogical composition requires the further accumulation and refinement of experimental data, in particular data on the influence of external pressure on the filtration properties (permeability) of rocks.

The results obtained make it possible to consider that, contrary to the widespread view that rocks have no residual deformations,

oil-bearing rocks exhibit residual deformations, which can be explained by the manifestation of plastic properties under conditions of lateral compression. In most cases, the manifestation of plastic properties in rocks is apparently connected with their structure and with the plasticity of the cementing substance.

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Note: Figure translations are in progress. See original paper for figures.