ISSN 2712-8008
Volume / Том 24 №4 2024
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum
and Mining Engineering

UDC 622
Article / Статья
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The migration of Colloids as a Cause of Deterioration of Permeability in Porous Sandstones during Laboratory Investigations

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Миграция коллоидов как причина ухудшения проницаемости пористых песчаников при лабораторных исследованиях

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Received / Получена: 07.05.2024. Accepted / Принята: 30.09.2024. Published / Опубликована: 31.10.2024

Keywords:
colloid migration, porous media, laboratory core tests, core flooding, permeability, permeability hysteresis, effective pressure, well testing.

Rock permeability is not a constant value, it depends on many factors, including the presence of small particles in the fluids and porous medium – colloids that can clog pore channels and reduce permeability. The effect of natural colloids migration, as a rule, is not taken into account when determining the dependencies of permeability on effective pressure, this phenomenon is often ignored by many authors and interpreted as a result of the influence of other factors. The reason for insufficient attention to the fact of mobilization and migration of natural colloids is the difficulty of identifying this phenomenon. It was found that with a change in the effective pressure in the initial period of oil production in real conditions, permeability can decrease more than according to laboratory studies. With a small change in effective pressure, when the probability of a decrease and hysteresis of permeability due to deformation of the porous reservoir is extremely small, the dependencies of permeability on the amount of oil produced were established. This fact confirms the probability of the influence of migration of natural colloids on the decrease in permeability and emphasizes the need to study it. The aim of the work is to study the effect of colloid migration on the permeability of porous sandstones with changes in the fluid injection rate and pore pressure. The article presents the methodology and results of core filtration tests taking into account the decrease in the permeability of the porous medium caused by the migration of natural colloids during fluid injection. The conditions of filtration tests exclude other permeability factors, such as creep and chemical mobilization of colloids. The results obtained demonstrate the dependence of permeability on colloid migration with changes in the fluid injection rate and pore pressure. Filtration studies of core samples using the proposed technique showed that the permeability of the cores decreases only with fluid movement inside the samples, which is direct evidence of pore clogging due to the migration of natural colloids. It was found that a decrease in pore pressure leads to a more intense decrease in permeability during injection, which indicates additional mobilization of colloids. Porous media with higher permeability are less sensitive to colloid migration and changes in pore pressure.

Ключевые слова:
миграция коллоидов, пористая среда, лабораторные исследования керна, заводнение керна, проницаемость, гистерезис проницаемости, эффективное давление, гидродинамические исследования скважин.

Проницаемость горных пород не является постоянной величиной, она зависит от многих факторов, в том числе от наличия в составе флюидов и пористой среды мелких частиц – коллоидов, которые могут закупоривать поровые каналы и снижать проницаемость. Эффект миграции природных коллоидов, как правило, не учитывается при определении зависимостей проницаемости от эффективного давления, это явление часто игнорируется многими авторами и интерпретируется как результат влияния других факторов. Причиной недостаточного внимания к факту мобилизации и миграции природных коллоидов является сложность идентификации данного явления. Выявлено, что при изменении эффективного давления в начальный период добычи нефти в реальных условиях проницаемость может снижаться сильнее, чем по данным лабораторных исследований. При малом изменении эффективного давления, когда вероятность снижения и гистерезиса проницаемости по причине деформации порового коллектора крайне мала, установлены зависимости проницаемости от количества добытой нефти. Данный факт подтверждает вероятность влияния миграции природных коллоидов на снижение проницаемости и подчеркивает необходимость ее изучения. Целью работы является изучение влияния миграции коллоидов на проницаемость пористых песчаников при изменении скорости закачки жидкости и порового давления. В статье представлены методика и результаты фильтрационных испытаний кернов с учетом снижения проницаемости пористой среды, вызванного миграцией природных коллоидов при закачке жидкости. Условия фильтрационных испытаний исключают другие факторы проницаемости, такие как ползучесть и химическая мобилизация коллоидов. Получены результаты, демонстрирующие зависимость проницаемости от миграции коллоидов при изменении скорости закачки жидкости и порового давления. Фильтрационные исследования образцов керна по предложенной методике показали, что проницаемость кернов уменьшается только при движении жидкости внутри образцов, что является прямым доказательством закупорки пор вследствие миграции природных коллоидов. Установлено, что снижение порового давления приводит к более интенсивному снижению проницаемости при закачке, это свидетельствует о дополнительной мобилизации коллоидов. Пористые среды с большей проницаемостью менее чувствительны к миграции коллоидов и изменению порового давления.

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Please cite this article in English as:
Shcherbakova Iu.S., Kozhevnikov E.V., Shcherbakov A.A. The migration of colloids as a cause of deterioration of permeability in porous sandstones during laboratory investigations. *Perm Journal of Petroleum and Mining Engineering*, 2024, vol.24, no.4, pp.219-230. DOI: 10.15593/2712-8008/2024.4.6

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Щербакова, Ю.С. Миграция коллоидов как причина ухудшения проницаемости пористых песчаников при лабораторных исследованиях / Ю.С. Щербакова, Е.В. Кожевников, А.А. Щербаков // Недропользование. – 2024. – Т.24, №4. – С.219–230. DOI: 10.15593/2712-8008/2024.4.6

Introduction

During the development of oil and gas fields the reservoir permeability decreases due to a decrease in reservoir pressure, as which result significant reserves of oil and gas may remain in the reservoir. During the extraction of hydrocarbons or the water injection, the pore pressure and effective pressure change, the reservoirs are deformed and their permeability changes [1–3]. Effective pressure according to K. Terzaghi [4] is the difference between the rock pressure caused by the mass of overlying rocks and the pore pressure.

$$P_{ef} = P_r - P_b, \quad (1)$$

where P_{ef} – effective pressure; P_r – rock (lithostatic) pressure, due to the weight of the overlying rocks; P_b – bed (pore) pressure of liquid in the pores of a productive formation.

Modeling of permeability during reservoir depletion is necessary to determine the timing and completeness of hydrocarbon production. The problem of permeability changes is the subject of a significant number of studies where the sensitivity of rock permeability to effective pressure is mainly determined in laboratory studies of core samples. In addition to laboratory core studies, the sensitivity of permeability to changes in effective pressure can be determined using hydrodynamic well testing (HDWT) data [5–7]. In both cases researchers agree on the general conclusion that permeability is a power-law or exponential function of effective pressure [6, 8–11].

Despite the widespread use of laboratory flooding methods, the results of laboratory studies may be insufficient to describe the properties of real reservoirs. Studies [6, 9] have shown that the sensitivity of rock permeability to effective pressure determined by HDWT is higher than that determined in the laboratory. The main reasons for these differences are as follows:

1. Permeability determination based on well field testing data reflects the integral permeability of the formation taking into account its zonal and layered heterogeneity. A decrease in formation pressure leads to the closure of cracks, separation of individual interlayers, as a result of which the overall permeability of the formation decreases sharply.
2. The selected core material after extraction from the well and natural stress relief undergoes significant changes in the form of volumetric deformations and can no longer reflect the actual properties inherent in the initial conditions of its occurrence.

In work [6], well testing data from fields in the north of Perm Krai were used to compare the results of laboratory studies with real processes in oil formations. Well field testing data were used for the analysis conducted immediately after drilling in the initial period and after some time of operation of production wells. Due to strict selection criteria based on reservoir pressure and water cut of the product, such factors influencing permeability as paraffin and salt precipitation, decrease in phase permeability of oil due to gas or water penetration and also operations to enhance oil recovery of the formation are excluded. For the analysis, dependencies of permeability normalized with respect to initial permeability, on effective pressure are constructed. As a result, it was established that permeability decreases more intensively with increasing effective pressure in real conditions than in laboratory studies. Coefficient analysis of the equations showed that the intensity of permeability decrease also depends on the initial permeability of rocks, namely: more permeable rocks are less sensitive to changes in effective pressure, this correlates with the results of papers [12, 13] which state that larger pores have lower compressibility applying to both terrigenous and carbonate rocks. Thus, in paper [6] it was concluded that low-permeability formations are more sensitive to changes in pore pressure during hydrocarbon production. A detailed study of the pore space structure also confirmed that the main reason for the decrease in the permeability of low-clay rocks in the initial period of production is the migration of natural colloids.

The permeability of fractured rocks depends more on the effective pressure than porous rocks, since the change in permeability is caused by the opening or closing of cracks [14].

With a cyclic change in the effective pressure permeability hysteresis and its incomplete recovery when the effective pressure returns to its original state [9, 15-19] is observed. Permeability hysteresis does not depend on the type of rock, the type of porosity, fracturing, the nature of the change in effective pressure (due to pore or rock pressure) [17, 18].

The generally accepted cause of permeability hysteresis is plastic deformation of the pore space which can occur under loads exceeding the tensile strength of the rock minerals [20-23] or due to creep [24, 25]. These phenomena are well observed in plastic rocks containing a large number of weak, plastic minerals, such as various types of clay. However, in stronger rocks, such as clean sandstones with a low content of clay cement, permeability hysteresis is also observed including with small changes in effective pressure where plastic deformations are unlikely. For example, in work [26] it is indicated that with a decrease in effective pressure by less than 5%, permeability decreases catastrophically.

In weakly clayey porous rocks where microcracks are present, the main decrease in permeability occurs due to the closure of microcracks. According to the computed tomography data, in work [27] it is noted that microcracks close under load, while the size and shape of the pores do not change. It is noted that the compression of microcracks can lead to a decrease in permeability only at large values of the effective pressure change from units to tens of MPa. However, the analysis of oil fields in the Perm Territory [28] showed that permeability hysteresis manifests itself with a smaller fluctuation in reservoir and effective pressures in the initial period of oil production.

In paper [28] an example of permeability hysteresis is given based on the analysis of well testing data.

In the initial period of operation,the decrease in effective pressure in most wells was less than 5 % (in rare wells – 10 %), with such a small change in effective pressure, the probability of deformation of the reservoir in question is extremely small and a decrease in permeability due to narrowing of pores and compression of microcracks is unlikely. At the same time, it was found that permeability has a clear dependence on the amount of oil produced from the well. It should be noted that there are very few studies on changes in the permeability of oil reservoirs with cyclic changes in effective pressure according to well testing data [5–7, 28].

In a laboratory study [29] on strong sandstones, with a significant decrease in pore pressure from 18 to 8 MPa, a decrease in permeability is observed not due to deformations but only during fluid injection.

Thus, a decrease in permeability that is not proportional to the deformations that could occur with a change in effective pressure indicates the presence of some other internal factors. The reasons for a decrease in permeability from effective pressure may be the following: narrowing of pores due to an increase in effective pressure, deposition of organic and inorganic sediments in pores and migration of natural colloids. The criteria for selecting the initial data in the considered works exclude the influence of the first two factors, and a decrease in permeability and its hysteresis are observed only as a result of fluid movement, in connection with which the most likely cause of a decrease in permeability and its hysteresis is assumed to be the migration of natural colloids within the pore space.

Migration of natural colloids in porous media

It has been established that during geological processes of formation and burial of strata, during deformation processes caused by subsidence of strata, changes in pore pressure or tectonic movements, a large number of free particles of colloidal size from several nanometers to 1 μm are formed inside porous media [30–35]. Colloids in rocks can also appear from the outside as a result of filtration of contaminated liquids [36, 37]. As numerous studies have shown, a change in filtration rate leads to the release of colloids [31, 36–51] which can be located on the walls of pores [46], accumulate in the mouths of pores [52], clog interpore channels and form so-called bridge plugs [40, 53] and lie in stagnant zones [47]. The release of colloids is indicated by a change in the concentration of colloids in the effluent washed out of the porous medium [30], a change in the geometry of the pore space [51] and a change in hydraulic conductivity – permeability [43, 54-57, 60].

The migration of colloids inside the porous medium during fluid injection contributes to the blocking of pore channels and a decrease in the permeability of both porous [30, 36, 58] and fractured media [54, 59, 60-61].

Currently, the presence of natural colloids in routine tests during core flooding is often not taken into account and their effect on permeability is simply ignored by many researchers and can be interpreted as a result of the other factors influence. The reason for insufficient attention to the fact of mobilization and migration of natural colloids is the difficulty of identifying this phenomenon [62]. The main evidence supporting the migration of colloids during fluid injection is direct connected with the analysis of colloid concentrations based on effluent data, and indirect describing the analysis of permeability changes during neutral liquid or gas injection [63]. Collection and analysis of effluent during core flooding is performed to assess colloid movement and their effect on permeability [31, 38, 41, 49, 52, 64]. However, experiments are performed under certain limitations: for effluent collection, the sample outlet line must be as short as possible to avoid mixing and errors in measuring the colloid concentration, therefore, in all works where effluent collection is performed, the outlet line pressure is equal to atmospheric pressure [31, 38]. Collecting effluent to determine colloid concentrations in the presence of backpressure is currently technically impossible, therefore, existing studies do not take into account the combined effect of pore pressure changes and colloid migration. The use of filters at the outlet does not show the dynamics of colloid concentration with a change in filtration rate and it is quite difficult to estimate the amount of washed colloidal particles, especially if the colloid sizes are several tens of nanometers.

In some studies computed tomography of rock samples is also used to determine the effect of colloids on permeability. Due to insufficient resolution, computed tomography allows only a significant change in the structure of the pore volume to be estimated at a high concentration of colloids in the fluid. It is impossible to estimate the migration of natural colloids in detail by elements using computed tomography, since the maximum existing tomography resolution exceeds the size of colloids by more than tens and hundreds of times, even at a relatively high resolution of 1.6 μm [52, 53, 64].

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Justification of the methodology

Usually, the permeability of porous and fractured media is determined during long-term injection until the pressure drop or flow rate stabilizes [24, 48, 53, 73, 74]. During this time a large volume of liquid can flow through the sample exceeding several tens or hundreds of pore sample volumes [53, 71] and during this time colloids migrate in the pores or cracks. This approach does not allow us to estimate the contribution of natural colloid migration to the overall decrease in permeability during the initial period of injection after changing filtration conditions or effective pressure [5, 6]. This leads to the fact that many researchers often simply ignore this phenomenon and interpret the decrease in permeability to a greater extent as a result of creep [25]. Despite a large number of studies devoted to permeability degradation, the problem of the combined effect of effective pressure and colloid migration on the permeability of porous media remains poorly understood. Only a few articles have been found that consider the combined effect of pore pressure changes and colloid migration on the hydraulic conductivity of fractured samples.

In papers [49, 54, 56, 57, 60] the filtration of fractured samples was studied under variable pore pressure and constant confining pressure.

The studies established that the hydraulic conductivity of fractures depends on the mobilization and movement of colloids along the fracture.

At a constant fluid flow rate a monotonic decrease in the hydraulic conductivity of the fracture occurs due to clogging with destroyed particles formed during cracking of the sample. Fluctuations in pore pressure lead to an increase in the hydraulic conductivity of the fracture due to unclogging. The greater is the amplitude of the pressure during fluctuations, the greater is the increase in permeability.

In a rock with a fracture the increase in permeability does not depend on the salinity of the filtered water [60]. Fluctuations in confining pressure lead to a decrease in the hydraulic conductivity of the fracture due to gradual compaction [49].

In this paper the authors propose a method and based on it attempt to evaluate the effect of colloid migration on the degradation of porous medium permeability during filtration including with changes in pore pressure. Using sandstone core samples as an example, the results obtained demonstrate the dependence of permeability on colloid migration with changes in the fluid injection rate and pore pressure.

This method allows one to evaluate the degradation of porous media permeability during migration of natural colloids without collecting and analyzing wastewater due to the complexity of accurately sampling the leached liquid at the filter structure. In our case we judge colloid migration by the decrease in sample permeability when injecting clean liquid.

A comparison of the developed method with traditional stationary core flooding was carried out and it was found that the developed method excludes the influence of such factors as chemical reactions and the creep effect on permeability.

Description of the core

The work tested 5 samples of cylindrical core 30 mm in diameter and 30 mm in length. The core was obtained from oil-saturated formations of the Komi Republic field, the porosity of the samples is from 7.85 to 10.31 %, permeability is from 0.98 to 72.25 mD, the initial pore pressure is 27.1 MPa. The core rock is weakly clayey sandstones and siltstones. The properties of the core are shown in Table 1. The essence of this study is to show that permeability is affected not only by the compression of pore channels, but also by the migration of colloids, therefore, in the framework of this study, the nature of the rock is not of particular importance, and the most important thing is that the samples are porous and do not have artificial and natural cracks. The structure of the pore space of the samples was assessed using computed tomography (CT) and a scanning electron microscope (SEM) before and after fluid injection. CT was used to check the absence of cracks and the homogeneity of core properties as well as to compare changes in the pore space structure before and after core flooding. CT showed that the samples were free of cracks but they had a slight layered heterogeneity parallel to the filtration axis and all samples contained a small amount of pyrite. The SEM results showed the presence of colloids on the mineral grains of the sample (Fig. 1). The photograph shows that the colloids are represented by particles of various sizes and shapes, while the colloids are significantly smaller than the pore size. The right side of the photograph (see Fig. 1, *b*) shows the presence of clay mineral plates which can also be a source of colloids. The composition of colloids is usually similar to the composition of mineral grains and cement that makes up the rock and is represented by various types of quartz and clay minerals [30].

From the analysis of SEM photographs the following was obtained:

- in sample 1 (see Fig. 1, *a*) which has the lowest permeability there are no large visible pores and a large number of colloids are present;
- sample of medium permeability 3 (see Fig. 1, *b*) has large visible pores and a large number of colloids of various sizes from large to small;
- in highly permeable sample 5 (see Fig. 1, *c*) large pores are visible, colloids on grains are not observed but there are large fragments of grains.

The obtained information on the structure of the porous medium allowed us to draw a conclusion about the influence of colloid migration on the change in permeability during filtration. The dependences of permeability reduction on the ratio of pore diameters and colloids were not constructed, since: firstly, the samples used have a sufficiently high layered heterogeneity which does not allow an adequate assessment of the effect of the sizes of pore channels and colloids on permeability reduction; secondly, existing tools (including computed tomography) do not allow us to assess the number and size of colloids in the volume of the pore medium in a free state.

Core filtration

The Auto Flood Reservoir Conditions, AFS-300 system by Core Laboratories was used for core flooding (Fig. 2, *a*). The setup allows monitoring the core flooding conditions with simultaneous measurement of flow rate and pressure at the sample inlet and outlet, creates a compression pressure simulating rock pressure, and maintains a certain temperature. The basic diagram of the setup is shown in Fig. 2, *b*.

Before testing the samples were cleaned of formation fluid residues and dried to a constant weight. Deionized water and kerosene were used as liquids. The samples were placed in a core holder at an initial temperature of 25 °C, a confining pressure of 45 MPa and a pore pressure of 18 MPa. The core was flooded parallel to the rock layers. Sample 3 was first filtered with deionized water, then dried and impregnated with kerosene for reverse filtration. Studies [55, 69] have shown that rocks have a stress memory which means that re-application of a lesser or equal load reduces the likelihood of irreversible deformations and creep. In order to relieve stress and minimize the effect of creep on permeability, the samples were maintained at a given pore pressure and confining pressure for 24 hours before injection. The pore pressures and confining pressures of the tests do not exceed the actual conditions of occurrence of the rocks from which the samples were taken also in order to minimize the effect of creep on permeability.

The core flooding was carried out with a cyclic change in the injection rate at a constant confining pressure. The injection rate was changed stepwise from 1 to 5 cm^3/min, at each rate the injection lasted about 5 minutes. The entire injection cycle lasted about 2–3 hours depending on the permeability of the sample. The pore pressure during injection was defined as the average pressure at the inlet and outlet and could change up to 0.4 MPa from the initial value with an increase in the injection rate. This means that the effective pressure changes by less than 1.5 % which is an extremely low value when the formation of microcracks in the rock sample matrix and their effect on permeability are unlikely [54]. A stepwise change in the fluid injection rate is necessary for the mobilization of colloids so several mechanisms are used in the experiment: with an increase in the injection rate, the colloids are mobilized and dispersed in the moving flow [69], at a low injection rate the colloids combine into larger agglomerates and partially clog the pores, a further increase in the injection rate destroys the agglomerates and carries the colloids further into the pore space [69].

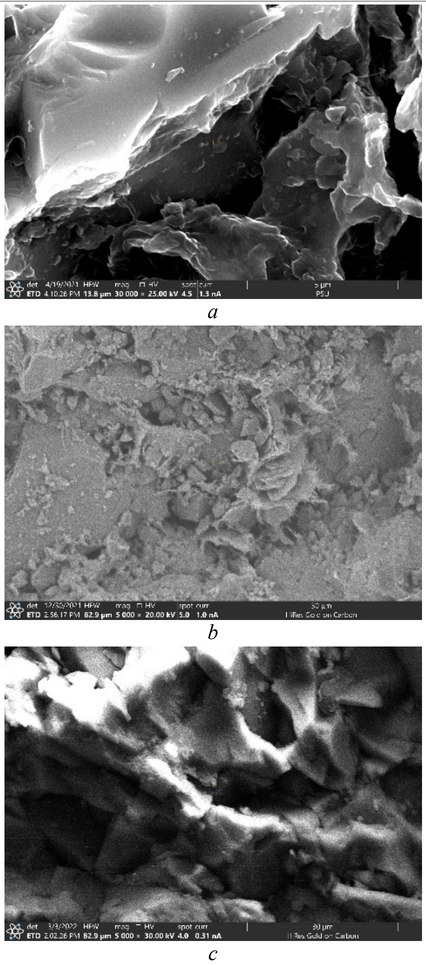

Fig. 1. Sample REM: 1 (*a*), 3 (*b*), 5 (*c*)

Table 1

Properties of core samples

Sample number	Porosity, %	Permeability, mD	Fluid/Flow Direction	Rock
1	7.85	0.98	Water/One Direction	Low clayey siltstone
2	10.16	72.25	Water/One Direction	Cemented clay-free sandstone (clay content less than 2 %)
3	8.33	27.97	Water/One Direction and Kerosene / Reverse	
4	10.31	47.27	Kerosene / One Direction	
5	8.45	52.12	Kerosene / One Direction	

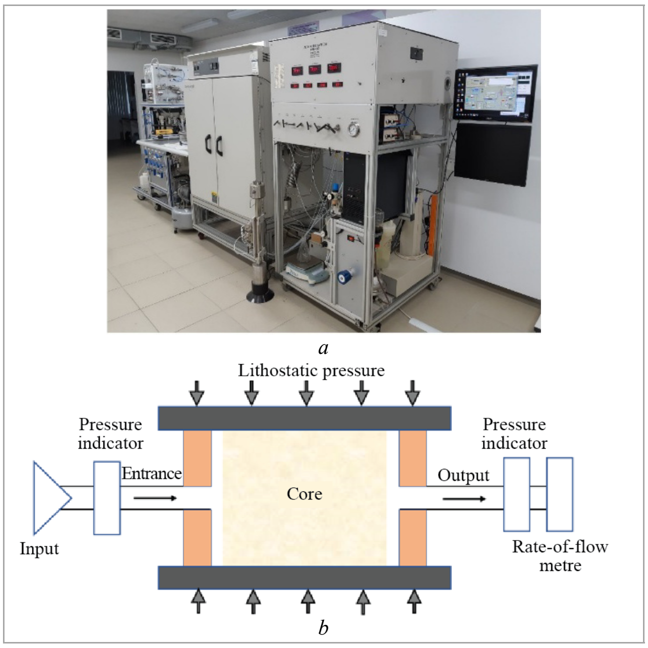

Fig. 2. Photo (*a*) and schematic diagram (*b*) of the core testing setup

In order to ensure that the decrease in permeability is not caused by creep, the fluid injection was also carried out in three cycles. After the first filtration cycle, the sample was kept for 24 h, then filtered under the same conditions; After the second cycle, the pore pressure was reduced from 18 to 13 MPa at a constant confining pressure, the sample was kept for 24 hours and the third injection cycle was carried out.

During the injection the data from the pressure sensors at the inlet and outlet of the sample and from the liquid flow sensors were recorded at a frequency of one measurement per 3 s.

Based on the obtained data on the injection rate, the pressure drop at the inlet and outlet of the sample, based on the viscosity of the liquid and the size of the sample, the instantaneous permeability was determined using the Darcy formula. The calculated values of instantaneous permeability were filtered using the Matlab program, based on the results, graphs were constructed (Fig. 3–5) of the change in relative permeability (k / k_0 where k is the instantaneous permeability, k_0 is the initial permeability) on the volume of the injected liquid, expressed in the number of pore volumes V / V_p, where V is the volume of the injected liquid, V_p is the volume of the pore space of the sample. During injection, the flow rate of the liquid (q) served as a control parameter, and since the samples have different porosity and permeability, the average velocity of the liquid through the core samples (v) was used for comparative evaluation, which was determined by the formula:

$$v = q/(m \cdot S), \tag{2}$$

where m – porosity, S – sample square.

Stage 1. Water injection

At the first stage of the studies deionized water was filtered through samples 1, 2 and 3 after vacuum saturation for one cycle.

As a result, the permeability of the samples decreased from 14 to 50 % (Fig. 3). Despite the practically identical average velocity of liquid movement through the porous samples, the permeability decreases differently. In samples 1 and 2 the permeability changes unevenly while in sample 3 it occurs almost linearly depending on the volume of the pumped liquid. Local pulse changes in permeability on the graphs (see Fig. 3–5), coinciding with the change in the injection rate are associated with transient modes and do not reflect the general change in permeability and can be neglected.

Another important parameter affecting the sensitivity of the permeability between a porous medium and colloid migration is the pressure gradient [52, 65] which is defined as the ratio of the pressure drop at the inlet and outlet of the sample to the length of the sample. In our case all samples have the same length so for ease of comparison we can use the maximum pressure drop at the sample inlet and outlet during the filtration cycle ΔPmax.

The total decrease in permeability of sample 1 was 14 %. The sample has a relatively low permeability; during injection the maximum pressure drop on the sample was 6 MPa which is quite a high value. In addition to the migration of colloids the change in permeability at such a high pressure drop could be influenced by the opening of micro- and macrocracks, as evidenced by the clear dependence of permeability on the change in injection rate (see Fig. 3, *a*). In addition, with such a large pressure drop, there is a high probability of washing out most of the colloids from the pore space [65]. During filtration of samples 2 and 3 the maximum pressure drop was 0.05 and 0.35 MPa, respectively, while the effective pressure changed by less than 1.5 % which is an extremely low value when the formation of microcracks in the matrix of the rock sample and their influence on permeability are unlikely [54].

Sample 2 is characterized by the highest permeability and the lowest pressure drop of 0.05 MPa. The overall permeability decrease was 25 % (see Fig. 3, *b*). Permeability depends on the fluid injection rate which is characterized by a stepwise change; in this case the mechanisms of colloid retention with a decrease in the fluid flow rate prevail over the entrainment of colloids which may be the result of colloid attachment to the pore walls [38]. Sample 3 shows the greatest decrease of up to 50 % in permeability. In this case the main degradation of permeability occurs at the beginning of the filtration cycle, similar to papers [35] then the change in permeability stabilizes and becomes almost linear (see Fig. 3, *c*). It was also found that at high flow rates, permeability decreases less quickly than at low flow rates (see Fig. 4). This suggests that at high flow rates the processes of colloid mobilization and entrainment prevail over retention, in which case the decrease in permeability is not a consequence of bridging but is due to the attachment of colloids to the pore walls. The absence of a bridging mechanism when changing permeability in samples 2 and 3 can also be associated with the large pore size relative to the size of the colloids [72]; in these samples, the decrease in permeability at high fluid velocity is less intense than at lower velocity, similar to work [31]. Another explanation for the fact that at higher injection rates the permeability decreases less is that the filtration program implies a cyclic change in fluid velocity (albeit with a low oscillation frequency) which contributes to the cleaning of pore channels [65] while the pressure gradient in the sample changes cyclically. To test the probability of creep influence on permeability change after the first injection cycle, sample 3 was left in the core holder for 60 h at constant pore pressure and confining pressure; after the holding period more than 100 pore volumes were injected at flow rates of 1 and 2 cm^3/min (see Fig. 3, *c*). The results show that at the beginning of injection after a pause, permeability has a slightly higher value than at the end of the previous injection cycle. This is explained by disturbances and the occurrence of countercurrents inside the sample when filtration stops after the first cycle and the liquid flow is resumed. A similar phenomenon was observed later on other samples while injecting kerosene; it is especially pronounced when the pore pressure changes. Fig. 3, *c* also shows that when injection is resumed, permeability decreases quite intensively at the beginning as in the first cycle but tends to stabilize.

With an increase in the flow rate to 2 cm^3/min, the permeability increased slightly and immediately stabilized. In this case it can be said that conditions have developed while the processes of mobilization and retention of colloids are equivalent to each other or the migration of colloids has completely ceased [65]. The interaction of deionized water with clay particles can lead to their dispersion and migration. The interaction of deionized water with pyrite, its presence in the core was established by the results of CT, can lead to the formation of insoluble colloids of iron (III) hydroxide. Due to the fact that we are only interested in the migration of natural colloids, without the participation of chemical processes and the interaction of clay with water, an inert liquid - kerosene - was chosen for further filtration.

Stage 2. Kerosene injection

The results of pumping pure kerosene through the core samples are shown in Fig. 5. The decrease in the permeability of the core samples ranged from 13 to 46 %.

For sample 4 (see Fig. 5, *a*) the permeability decreased uniformly by 30% during the first and second filtration cycles. After the second cycle, there was a significant change in the filtration conditions due to an emergency release of pore pressure and confining pressure to 0 and 3 MPa, respectively.

After restoring the pore pressure and confining pressure to 13 and 45 MPa, respectively, the sample was kept for another 24 hours before the third filtration cycle. This incident led to dramatic consequences, as a result of which the permeability curve in the third filtration cycle became steeper and more broken, and the decrease in permeability from the amount of pumped liquid was more intense than in the previous filtration cycles. The pressure release could have led to several consequences: a change in the size of the pore channels due to plastic deformations and the release of colloids due to elastic and plastic deformations. However, no narrowing of the channels due to plasti deformations was observed. This conclusion is based on the fact that the decrease in permeability occurred only during fluid injection during a cycle that lasts about 2–3 hours. If the narrowing of the channels had actually occurred, then after a 24-hour pause, the permeability at the beginning would have been less than at the end of the previous cycle, but in our case we observe the opposite. In addition to plastic, elastic deformations can also lead to the appearance of a large number of free colloids in the porous medium [33].

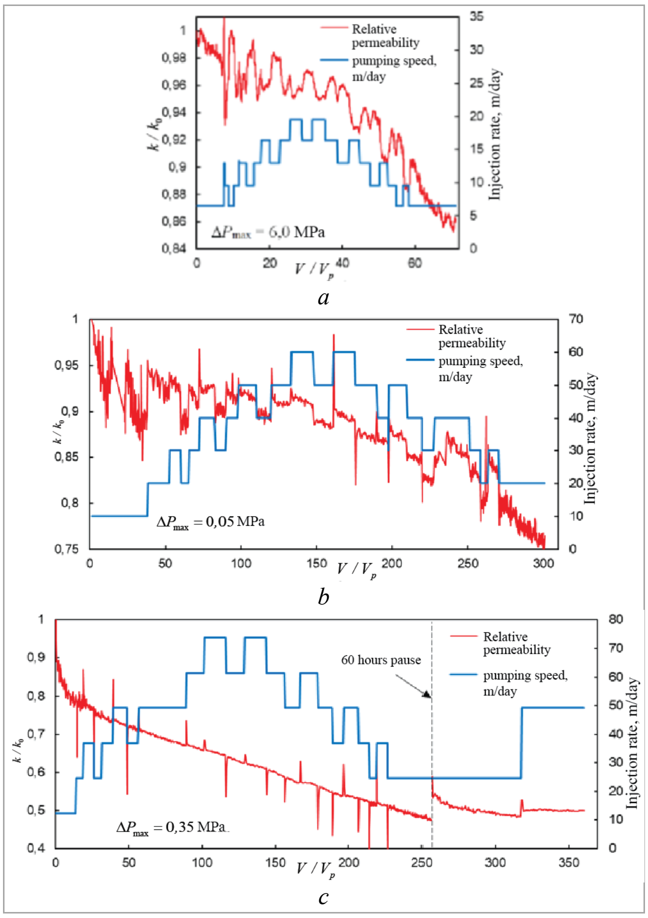

Fig. 3. Change in relative permeability of samples 1 (*a*), 2 (*b*) and 3 (*c*). The confining pressure is 45 MPa, the pore pressure is 18 MPa; in the dashed line there is a 60-hour pause in injection during which the sample was maintained at a constant pore and confining pressure

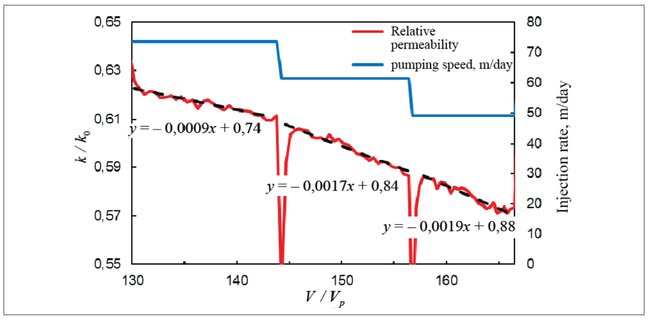

Fig. 4. Change in relative permeability of sample 3 while pumping deionized water. Black dotted lines show linear approximations by equations. The slope of the permeability curve at high fluid velocities is smaller than at lower fluid velocities, this is evident from the coefficient of the linear function: the larger the absolute value of the coefficient, the more intensively the permeability decreases

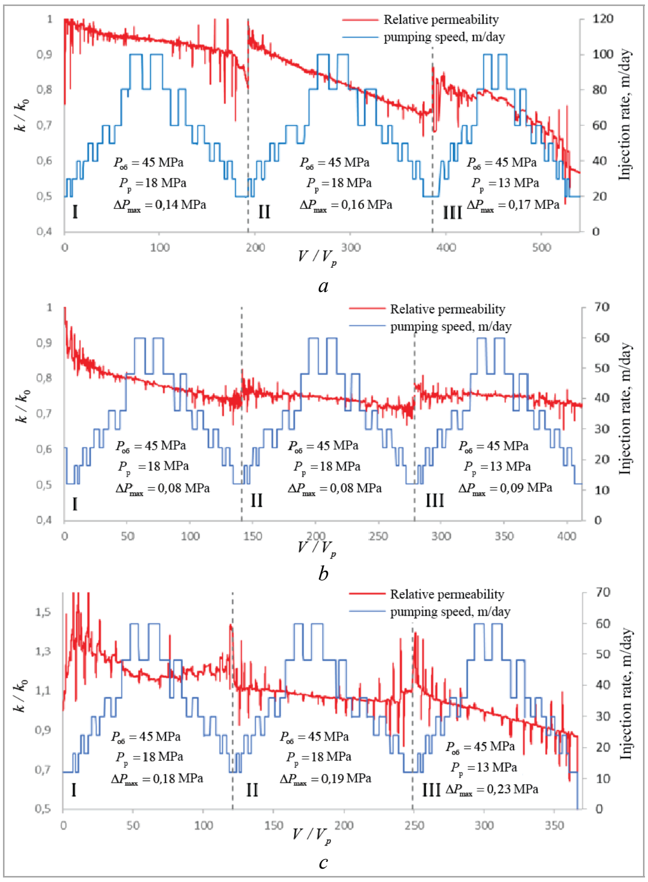

Fig. 5. Dynamics of relative permeability of samples 4 (*a*), 5 (*b*), 3 (*c*) during 3 kerosene injection cycles. Roman numerals indicate the injection cycle. Dashed gray lines show the boundaries between injection cycles – daily pauses, when the sample was maintained at a constant temperature, pore and confining pressure without injection

Most likely, the elastic deformation of the core led to the release of colloids, which was reflected in the change in permeability in the third injection cycle. The overall decrease in permeability was 46 %. In sample 5 (see Fig. 5, *b*), the greatest decrease of about 20 % in permeability occurs while pumping the first 20 pore volumes during the first filtration cycle, then the decrease in permeability occurs smoothly, almost linearly, in each case about 5 %. Such a moderate decrease in permeability is probably due to the high layered heterogeneity of the sample and the presence of highly permeable pore channels parallel to the liquid flow when the migration of colloids does not have such a significant effect [47, 72] which is also confirmed by the relatively small maximum pressure drop of 0.08–0.09 MPa. The overall decrease in permeability was about 28 % while the decrease in pore pressure did not have a significant effect on the change in permeability. Sample 3 was preliminarily injected with deionized water in the forward direction (see Fig. 3, *c*), then the sample was dried, impregnated with kerosene, and injected in the reverse direction (see Fig. 5, *c*). The reverse direction of injection led to erosion of the internal filter cake and mobilization of a large number of colloids, as a result of which in the first cycle of kerosene injection the permeability first increases and then decreases in a similar manner [36].

During massive migration of colloids in the first filtration cycle, the predominant mechanism of permeability reduction is colloid plugging in pore throats. This conclusion can be drawn from the fact that a stepwise increase in filtration flow leads to a decrease in instantaneous permeability, while a decrease in flow, on the contrary, increases permeability, which is consistent with the conclusion that the efficiency of particle retention by colmatation increases with increasing flow velocity [36, 37, 46]. In general, permeability decreases in the first filtration cycle which is due to erosion of the internal filter cake and the transfer of colloids into the sample. Sample 3 demonstrated the maximum permeability decrease in the third injection cycle after a decrease in pore pressure. The permeability curve has a steeper slope, which is probably due to additional mobilization of colloids. At the beginning of the third injection cycle, the permeability of the sample is high but then rapidly decreases during pumping of the first 10 pore volumes. The total permeability decrease based on the results of three cycles was 13 %. Thus, the results of the studies showed that the permeability of the cores decreases only when the fluid moves inside the samples which is direct evidence that pore clogging occurs when the fluid moves and this can only occur due to the presence of natural colloids inside the rock and not because of creep.

Injecting a large volume of fluid at different flow rates can lead not only to the migration of colloids and clogging of pores but also to the cleaning of pores and the washing out of colloids from the rock. When colloids are washed out, permeability is expected to decrease first and then increase [38]. The rate of washing out depends on the injection rate, the size of particles and pore channels as well as the size of the core sample. With high porosity and permeability of the sample, an increase in the fluid flow rate quickly leads to the washing out of free particles and an increase in the permeability of the medium [38]. In low-porosity and low-permeability media, colloids can be washed out over a fairly long time [43]. In our case, the permeability decrease was constant throughout all flooding cycles which indicates a sufficiently large number of colloids and a low velocity of their movement [43, 48].

In all samples, at the beginning of a new filtration cycle a slight increase in permeability is observed relative to the end of the previous cycle, regardless of the pore pressure. This is explained by the occurrence of countercurrents inside the sample while stopping and then resuming injection. The greatest difference in permeability is observed between the end of the 2nd and the beginning of the 3rd injection cycle after a decrease in pore pressure which is also explained by the countercurrent in the samples as a result of the pore pressure release. Flow reversal, even at a small flow rate and volume, can significantly change the permeability of a porous medium.

An increase in effective pressure due to a decrease in pore pressure had a greater effect on the change in permeability of sample 3 (see Fig. 5, *c*) which has the lowest absolute permeability.

To a lesser extent a decrease in pore pressure affected the permeability of sample 5 (see Fig. 5, *b*) which has an average permeability. For sample 4 the change in pore pressure led to a more intense decrease in permeability (see Fig. 5, *a*) but this conclusion is ambiguous due to the emergency pressure release during filtration. In general, it can be concluded that an increase in effective pressure with a decrease in pore pressure leads to a more intense decrease in permeability due to the mobilization of colloids; this decrease is also affected by the gradient of pore pressure in the sample. An assessment of the effect of the average fluid velocity on permeability did not reveal any obvious patterns because of the high heterogeneity of the core samples used.

Conclusion

In this paper, the authors propose a method for assessing the effect of colloid migration on changes in the permeability of a porous medium during filtration including changes in pore pressure. Using sandstone core samples as an example, the results obtained demonstrate the dependence of permeability on colloid migration with changes in the fluid injection rate and pore pressure.

This method allows us to assess changes in the permeability of porous media during migration of natural colloids without collecting and analyzing wastewater. In this case, we judge the migration of colloids by changes in the permeability of samples during injection of pure liquid. Filtration conditions exclude the influence of other factors on permeability, such as creep and chemical mobilization of colloids.

Filtration studies of core samples using the proposed method with variable fluid flow rates showed that core permeability decreases only when fluid moves inside the samples which are direct evidence of pore clogging due to migration of natural colloids.

Flow reversal, even at a small flow rate and volume, contributes to a short-term increase in sample permeability. The pore pressure reduction experiment showed that narrowing of pore channels does not have a significant effect on permeability, since the permeability of all samples at the beginning of the cycle is higher than at the end of the previous filtration cycle.

The pore pressure gradient affects the sensitivity of porous media to colloid migration: the greater the pore pressure gradient becomes the more intense the decrease in permeability appeares.

Samples with higher permeability are less sensitive to colloid migration when pore pressure changes.

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Funding. The work was supported by the Russian Science Foundation grant No. 23-19-00699, https://rscf.ru/project/23-19-00699/.
Conflict of interest. The authors declare no conflict of interest.
The authors' contribution is equivalent.