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Studying the Wellbore Stability Enhancement Mechanism during Drilling through Fractured Argillites

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Исследование механизма повышения стабильности ствола скважины при бурении трещиноватых аргиллитов

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The paper presents the relevance of enhancing wellbore stability by developing and applying efficient drilling fluid compositions for well constructions in fractured argillite. In the process of well constructions, there comes a range of complications associated with instability of rocks forming borehole walls, which sometimes results in lower penetration rates, higher construction costs and well abandonment. Often, drilling problems occur at drilling through mudrocks that account for up to 70 % of field sections. When using water-base drilling fluids, the mudrock swelling due to the contact with the fluid dispersion medium adversely affects the drilling process and can significantly increase well construction costs. The accumulation of wellbore cavings inhibits well circulation, causes landing of drilling tools and may result in tool sticking. An analysis of drilling problems in fractured argillite is presented; the mechanisms affecting open hole stability in the fractured argillite deposits are shown. The use of potassium chloride is recommended to enhance the stability of argillite-formed borehole walls. The results are supported by experimental studies using the Chenevert method, as well as fracture propping tests. When the argillite sample was placed in potassium chloride (KCl) solution, there was a minor fracture expansion and propagation over the entire sample length, which is a positive result. To enhance wellbore stability, further study approaches are proposed: upgrading mud by adding inhibiting compounds, such as salt solutions in combination with high-molecular polymer compositions.

Ключевые слова:
бурение скважин, глинистые породы, аргиллиты, гидратационно-активные глинистые породы, Лабаганское месторождение, осложнения, обвалообразование, лабораторные исследования, диспергирующая способность, устойчивость, буровой раствор, кольматанты, ингибиторы, катионные полимеры, метод Ченеверта.

Отражена актуальность повышения устойчивости ствола скважины за счет разработки и применения рациональных составов буровых растворов для строительства скважин в трещиноватых аргиллитах. В процессе сооружения скважины возникают разнообразные осложнения, сопряженные с неустойчивостью пород, слагающих стенки ствола скважины, что влечет за собой снижение скорости проходки, рост стоимости строительства, а в некоторых случаях приводит к ликвидации скважины. Зачастую осложнения проявляются в интервалах проходки глинистых пород, которые составляют до 70 % разрезов месторождений. При использовании буровых растворов на водной основе набухание глинистых пород вследствие взаимодействия с дисперсионной средой раствора оказывает негативное влияние на процесс бурения и может значительно повысить стоимость строительства скважины. Скопление обрушившейся породы в стволе скважины затрудняет процесс промывки скважины, способствует посадке бурового инструмента и может стать причиной возникновения прихвата. Приведен анализ проблем бурения в трещиноватых аргиллитах, показаны механизмы, влияющие на стабильность открытого ствола скважины в отложениях трещиноватых аргиллитов. Для повышения стабильности аргиллитов, слагающих стенки ствола скважины, рекомендуется применение хлористого калия. Результаты подтверждаются данными экспериментальных исследований, проведенными по методике Ченеверта, а также тестирования на расклинивание трещин. При помещении образца аргиллита в раствор хлористого калия (KCl) наблюдалось незначительное расширение и распространение на всю длину образца трещин, что является положительным результатом. Для повышения стабильности ствола скважины предлагаются пути дальнейшего изучения: повышение качества промывочного раствора путем ввода комплексных ингибирующих добавок, таких, например, как растворы солей в сочетании с высокомолекулярными полимерными композициями.

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Introduction

The recent international practice has proven that almost all wells are complicated by the process-related incompatibility of individual drilling intervals. Therefore, in most cases, multi-string structures and drilling fluids with different technological properties are used. However, even advanced well design and construction technologies cannot solve all the drilling problems that obstruct fast and efficient drilling operations.

Maintaining the gauge hole, which depends on the wall stability, is one of the most challenging tasks when drilling oil and gas wells. Generally, this problem occurs when drilling through low-cohesion lithified sediments represented by argillite, clayey shales and shaly claystones. In their turn, argillite account for approximately 70 % of all wellbore instability-related problems [1-13].

The problem of the borehole wall instability when drilling through mudrocks is widely described in various literature sources, and a range of solution options, which use involving, inhibiting and non-dispersion drilling fluids is provided [2, 3, 10-12, 14-27].

That being said, the issue of fractured argillite instability is not covered. Mainly, possible causes of fractured argillite destabilisation and control measures are described. However, there is no clear insight into reasons of loosing fractured argillite stability and solutions thereto, accordingly [7-9, 28-32].

In case of lost stability of the rocks forming the borehole walls, the major complications arise during drilling. There are different types of borehole wall stability failures, yet all of them are determined by changes in the gauge hole size. The hole enlarges with cavings caused by falling or sloughing rocks, and reduces with rock bulging that can incite both rock slides (rocks falling under gravity towards a well bottom) and bridging (rocks flowing from a well bottom to a well head).

Combating complications that cause gauge hole deviations is crucial when drilling relatively deep wells.

Many engineers and researchers believe that if the drilling fluid density is compatible with the geological and technical conditions, then the loss of borehole wall stability depends on the fluid physical and chemical effect on shale deposits being drilled into. As such, the studies are mainly focused on designing fluid compositions and parameters.

At present, there is a wide range of instrumental procedures for mudrock testing and studying to select a compatible drilling fluid. Most laboratory studies require expensive equipment [33]. Moreover, when constructing wells under difficult geological and technical conditions, many oil and gas companies conduct more detailed studies of shale deposits, including analyses of chemical and mineralogical compositions, losses on ignition, moisture content, density and exchange capacity. These studies are mainly focused on the interaction of mudrock samples with a drilling fluid; the tests for hydration, swelling-induced softening, dispersion, capillary imbibition, osmosis, etc. are conducted. The testing methods are specified in detail in the specialist literature [34].

Many experts believe that the drilling fluid that will ensure the maximum borehole wall stability has to be selected individually for each operation area and geological and technical conditions.

To select the best suited composition and properties of the drilling fluid, it is recommended to perform the following laboratory tests with unstable mudrock samples: X-ray diffraction analysis of rock mineralogical composition using a diffractometer, measurement of cation exchange capacity and detection of reacting cations, building of adsorption isotherms by the Chenevert method, and assessment of dispersion ability [35]. Despite the advanced research and testing methods, the problem of the mudrock stability loss on the borehole walls is yet pending solution, while the effectiveness of the proposed solutions is very low, with split opinions of researchers on this issue.

V.S. Baranov believes that increasing the drilling mud density will not inhibit mudrock caving, while the fluid loss control cannot ensure the borehole wall stability [35]. According to V.D. Gorodnov, the values of drilling fluid loss indicator and mudrock water content under conditions of natural occurrence strongly affect the wellbore stability in shale deposits. Moisture is an essential factor affecting the stability of borehole walls, since low-moisture mudrock tends to lose stability in moisture medium faster than its less moist varieties. V.D. Gorodnov divides mudrock into three classes depending on the change in strength properties subject to moisture degree: highly moistured (high-plasticity, flow rock), moistured (plastic rock) and low-moistured (hydration-active rock) [36].

V.A. Priklonsky states that stability can be estimated by a certain *critical* moisture content characteristic of each type of claystone. When the moisture content of a claystone sample falls below the critical level, the sample is slaking. If the moisture content exceeds the critical level, there is little to no slaking. The increase in the critical moisture content in claystones is directly proportional to the increase in their exchange capacity: for montmorillonite clay, the critical humidity level is about 50 %, and about 25 % for kaolinite clay (37).

According to works of some researchers, the mudrock instability is mainly induced by the joint effect of such factors as the physical and chemical effects of drilling fluid filtrate and the stress state of rocks on borehole walls [38-40].

O.K. Angelopulo believes that it is necessary to set a lower limit of organic agent concentrations for a given filtrate loss value, at which the inhibiting effect is most pronounced [41]. In the analysis of field materials, N.M. Sherstnyov determined that the rock sloughing and falling under continuous exposure to drilling fluid occur in claystone deposits susceptible to tectonic faulting with a steep formation dip [42]. V.S. Voytenko believes that the drilling fluid weight shall be regulated as per claystone pore pressure [43]. A.I. Penkov, at the studies of the water absorption rate in claystone, highlights the advantages of the combined application of acrylic polymers and potassium chloride in drilling muds [44]. This technical solution has proved effective in the Western Siberian fields, yet of no effect in other fields.

In his monograph, V.S. Novikov states that the use of drilling fluids containing claystone swelling inhibitors does not solve the problem of unstable wellbore walls at intervals of argillite deposits [45]. Thus, the method of increasing the mud weight with the minimum filtrate loss rates did not help to slow down the rate of caving formation, while the application of oil-based muds could not fully prevent complications and sticking.

In his studies, V.S. Novikov states that most of the agents used in drilling accelerate the loss of borehole wall stability in claystone and serve to slow down this process only when combined with other agents. The combination of polyacrylamide and potassium chloride ensures the wellbore stabilisation.

M.R. Mavlyutov and N.I. Krysin recommend the use of drilling fluids that include potassium chloride and polyacrylamide [46]. The drilling fluids used by N.I. Krysin at claystone occurrence intervals in Perm Krai have proved to be most effective.

During the well drilling through mudrock in the Achimovian deposits of the Urengoy gas condensate field, V.V. Ippolitov et al. [47] have found that at deviation angles from 42 to 72°, the borehole wall sloughing progresses over time. The borehole wall disintegration rate, when drilling through such shales, may be 2-3 times higher compared to other shale deposits. The borehole walls disintegrate several times more when drilling with polymer drilling fluid with a content of solids of up to 5-7 % compared to drilling with mud-laden fluids containing 20-30 % of the detrital mudrock fraction being drilled out. When the drilling mud weight decreases from 1,190 to 1,100 kg/m^3, the rate of cavings increases by 1.4-1.5 times. When drilling with polymer-mud fluids with a fluid loss rate of 6 cm^3/30 min, the rate of wellbore destabilisation is 20 times higher than that with a fluid loss rate of 2 cm^3/30 min. The use of potassium-based mud by Baroid DF specialists did not prove successful. At the same time, about 49 % of the total well construction time was spent on eliminating complications related to instability of borehole walls. However, this approach would have been sufficiently effective in most parts of Western Siberia.

V.V. Ippolitov recommends using emulsion polymer-mud drilling fluids for drilling through fractured argillites.

L.K. Mukhin in his work suggests to switch to the use of hydrocarbon-based drilling fluids [48]. However, based on the practice, the use of hydrocarbon-based fluids at drilling intervals of unstable shale deposits does not always preclude complications. I.G. Yusupov together with experts of OAO TATNEFT have rationalized the mudrock instability in the fields of Tatarstan using the osmosis theory [49-51]. In his works, S.M. Gamzatov have studied the osmosis effect on the process of borehole wall stability loss in shale deposits [52].

S.V. Vasilchenko, A.G. Potapov and A.N. Gnoyevykh state that in the clay mineral lattice, explosive disturbances may arise resulting from the sharp change in iron ionic radius (transition from the divalent to trivalent state), which results in the wellbore stability loss [33]. When individual mudrock samples were placed in deionised water, it was found that some of the samples disintegrated without swelling. This fact has brought to the conclusion that it is essential to study comprehensively the physical characteristic of shales that determines its propensity to destabilisation when interacting with drilling fluids.

Since the geological and technical conditions of mudrock formation and occurrence vary from case to case, different solutions shall be applied to the issues related to borehole wall stabilisation. It should be noted that the effectiveness of these approaches that are associated with the use of new inhibiting drilling fluids, has not detected any noticeable advantages over existing ones. Moreover, using a new recommended mud often increased losses of mudrock borehole wall stability [52].

A possible reason for the lack of effectiveness in solving the problems with mudrock borehole wall stabilisation using recommended drilling fluids may be the errors made by researchers during laboratory studies and field tests. These errors are mainly caused by an attempt to simplify or speed up experiments or to disregard properties. Laboratory tests are carried out mainly with true shale or with mudrock samples, but, in any case, once the natural structural bonds are broken down, the selected samples are dried and dispersed to a powder state. When placed in identical test liquids, the samples with natural structural bonds and those compression-molded, display entirely different results: the sample with natural bonds remains stable for 30 days in aqueous medium with no signs of softening (Fig. 1, *c*), while the compression-molded sample (Fig. 1, *a*) in the same liquid turns into a powder after 5 minutes (Fig. 1, *b*). In such case, highly stable mudrocks may be mistaken for potentially unstable rocks.

Mudrock swelling is also studied after the sample is dried, dispersed and molded, with liquid interaction from all sides, yet the rocks on the wellbore walls are only moistened by drilling fluids from one side, while on the other three sides the nearwellbore rock is affected by overlying, underlying and lateral rocks. Figure 2 shows visual results of the study of all-sided and one-sided water-base fluid interaction with montmorillonite clay samples. It was visually determined that the rate of sample disintegration and swelling in the container is much higher than that of the compression-molded sample. It can be concluded that, due to incorrect studies, the recommended drilling fluids for maintaining the borehole wall stability in mudrocks have little to no effectiveness.

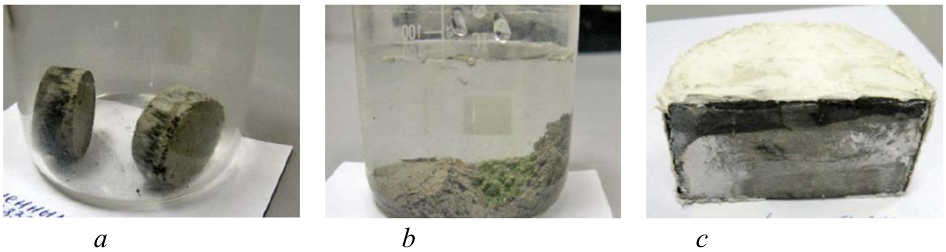

Fig. 1. Laboratory stability study of siltstone in aqueous medium with natural and artificial structural bonds: *a* – compression-molded sample; *b* – sample with artificial structural bonds placed in aqueous medium; *c* – sample with natural structural bonds

Fig. 2. Behaviour study of montmorillonite clay samples at all-sided and one-sided water saturation: *a* – from left to right: compression-molded sample before the test; compression-molded sample after the test, placed in a cell and kept in aqueous medium; compression-molded sample after the test, placed in a glass and kept in aqueous medium; *b* – a cell for compression-molded sample

The studies in Russia and overseas are focused on swelling mudrocks. Many researchers are trying to address the issue of borehole wall instability when drilling through the deposits of shale, argillite and siltstone deposits by transferring the test results obtained with claystones. This idea being incorrect, it entails serious consequences when it comes to field practice, since the claystones, in turn, bear no resemblance to consolidated lithified mudrocks in terms of strength and deformation characteristics. It is known that the inhibitive muds that are effective in drilling plastic clays, are little to no effective in brittle fractured argillaceous rocks [53, 54].

The selection of the composition, properties and technological parameters of a drilling fluid that can successfully maintain the borehole wall stability must be based on the nature of mudrock deformation and disintegration, since it depends on the structure, strength and properties of structural bonds in the rock. Unfortunately, many experts underestimate or simply disregard the impact of this nature of stability loss. It is intended to classify mudrocks by the nature of their disintegration, which is reasonable.

By the strength of the structural bonds that determine stability, mudrocks are divided into rocky, semi-rocky and dispersed rocks. The first two types are characterized by rigid chemical structural bonds with cohesive contacts (found in shale). Mudrocks of the third type have physical, chemical, mechanical, water-colloid structural bonds with coagulation or transition contacts (found in claystones) [52].

The behaviour of externally-affected mudrocks in downhole conditions is driven by composition, structure and strength of structural bonds. There are mechanical models that describe mudrocks by the character of their deformation and disintegration: rocky metamorphic shales, semi-rocky sedimentary argillites and siltstones correspond to the elastoplastic model (brittle disintegration character), while dispersed cohesive sedimentary claystones and their varieties correspond to the plastic model (plastic or viscoplastic disintegration character). The claystones are capable of absorbing and retaining water in bound state; therefore, the claystones on the borehole walls are further plasticised, start flowing, swelling, narrow the gauge hole and collapse down the well. Argillites are not plasticised when exposed to drilling fluids, always remain brittle and do not swell (54). Argillites are destabilised and slough down the well due to fractures: mud filtrate and/or mud itself invades and props microfractures, while the rock particles disintegrate and slough. When mudrocks are classified into plastic claystones and brittle shales (or argillites) by the nature of their disintegration, the mitigation of borehole instability problems by choosing the drilling fluid becomes considerably simpler and easier.

Sloughing of potentially unstable shales at well drilling is largely prevented by increasing the mud weight and inhibiting properties. The increased mud weight affects maintaining the wellbore stability both positively and negatively. A similar result can be achieved with the increase of the mud's inhibiting properties.

Electrolytes, such as sodium, potassium, magnesium, calcium chlorides and others, are used for the drilling mud inhibition, some of them having an ordering effect on water molecules. That is, the water molecule is structured, while the water phase viscosity increases. The rest of the electrolytes provide a destructive effect on the associated water molecules and destroy the system, while the water phase viscosity decreases.

The ongoing likelihood of unstable shale fracturing and sloughing can be reduced by using solid bridging agents of different sizes and natures (hydrophobic, hydrophilic) and hydrophobic liquid bridging agents of different molecular mass and structure. Therefore, to reduce the fracture propping effect, the conventional freshwater solutions or saltwater solutions that structure water molecules containing solid (hydrophobic, hydrophilic) and liquid hydrophobic bridging agents are used. The bridging agent principle is to form a blocking layer to prevent the drilling fluid liquid phase from invading into the fractures, and to bind the shale particles split along the fractures using adhesive forces.

An increase in the concentration of bridging agents (liquid and solid, hydrophobic and hydrophilic) in the drilling fluid increases fracture sealing off and maintains the wellbore stability when drilling through unstable shales.

Maintaining a drilling mode that will eliminate severe dog leg when drilling through shale deposits should be ensured, as well. High mud annular velocity combined with low structural and rheological indicators at drilling create a turbulent flow of the drilling fluid, which induces wellbore shale instability and sloughing.

Therewith, to reduce the turbulent flow impact on borehole walls, the pump rate can be reduced, or it would make more sense to adjust the mud rheological properties, which in turn boosts its lifting capacity and the transition to laminar (plug) flow mode. Pressure pulse in a wellbore while tripping may negatively impact the shale stability, and, accordingly, the speed of pipe running in and out should be minimised.

Thus, drilling through the areas of potentially unstable shales requires the use of freshwater polymer drilling fluids or salt-base solutions that structure water molecules, with an increased concentration of solid and liquid adhesive hydrophobic bridging agents.

In this case, the structural and rheological properties of drilling fluids should be maintained at the highest possible level. Competent management of mud properties and operational parameters boosts technical and economic performance when drilling under conditions of possible borehole wall instability.

When plastic and brittle mudrocks alternate in a lithological section, a drilling fluid that can ensure the stability of both plastic claystones and brittle shales shall be used: a water-base drilling fluid that includes cationic polymers in its formulation, is most effective for such sections.

Fractured Argillites Study Methodology

Fracture propping by drilling fluid invasion and argillite swelling is a probable causative factor that destabilises highly-fractured argillites in borehole walls. Drilling fluid also invades nearwellbore zone or moves out under the variable hydrostatic pressure, associated with the circulating pressure increase and the buildup or loss of equivalent circulating density. In this way, the pressure front propagates deep into the nearwellbore zone of shale formations and causes complications through sloughing, sliding and caving.

To determine the drilling fluid impact on argillites, a range of laboratory studies have been proposed to analyse the processes in the sediments of highly-fractured argillites during drilling. A sample was cored at a depth of 1,385-1,475 m from the deposits pertaining to the Artinskian stage of the Permian system.

The argillite sample has a bedded texture that splits into layers along bedding planes (Fig. 3).

Fig. 3. Argillite sample

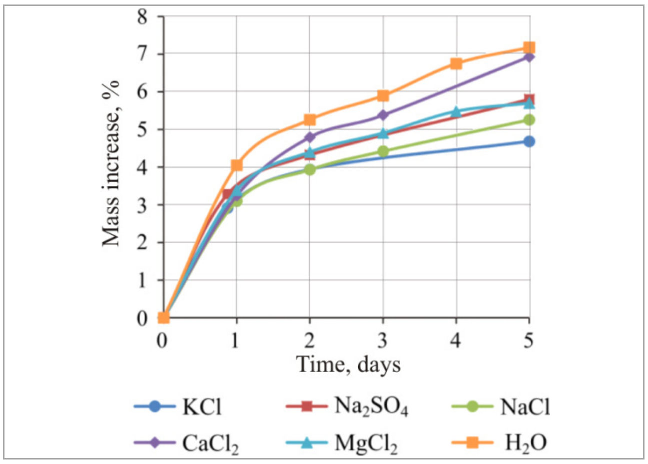

Fig. 4. Dynamics of sample mass percentage increase in vaporous media of saturated solutions

The study of fracturing at interaction with fluids may provide the maximum insight into the stability of shale deposits prone to fracturing when exposed to drilling muds.

The methodology is relatively simple, yet this doesn't negate the study's effectiveness: a rock sample of a near regular shape, with dimensions of 2 × 3 cm, is immersed into the liquid under test at room temperature. The study enables to assess the actual effect of the liquid on the mudrock in the absence of additional exposure to the samples (fluid flow, pressure, temperature and others). Fracturing in the samples is determined visually at set time intervals.

Six argillite samples were prepared for the test and placed in various fluids for 6 hours. The time interval was chosen in the course of the test (the time period after the lapse of which the argillite was fully softened). Pictures of the samples were taken at the start of the test, after 10 minutes and 6 hours later.

Practically, the drilling fluid formulation includes 3 to 7 % of sodium chloride (NaCl) and 5 % to 20 % of potassium chloride (KCl) to inhibit or prevent cleaving of the drilled rock and maintain borehole wall stability.

The use of sodium salts ensures moderate to strong inhibition, while potassium salts induce strong inhibition. Sodium and potassium chloride solutions were proposed as the fracturing test base. The study was also conducted in 5 % solutions of $Na_2(SO)_4$, $CaCl_2$, $MgCl_2$ and pure water.

The Chenevert method allows to evaluate the adsorption forces for various inhibitive compounds. The test procedure consists in placing dried particles of argillite cuttings in a dessicator containing saturated solutions of various salts. Then, water content is determined by the change in the sample mass after certain time intervals, and the dependencies of water content on relative humidity are built [55].

The fluid activity in argillites is determined by the abscissa of isotherm point with the ordinate equal to the argillite humidity value under formation conditions. This parameter can be used to define a potential swelling pressure of fractured argillite that absorbs water from drilling fluid. The lower the water activity under formation conditions, the higher the maximum possible swelling pressure [55].

X-ray crystallography using a diffractometer is mainly used to determine the mineralogical composition of argillite. This method consists in the X-ray diffraction on a space crystal lattice.

The argillite sample was cored at the Labaganskoye field in the Nenets Autonomous District. In the north-east of the area, the mineral composition of argillite is virtually identical and mainly includes illite and kaolinite, only the percentage ratios varying subject to its formation conditions. Following the diffractometer analysis data, the fractured argillites are mainly composed of kaolinite (47-78 %), illite (10-30 %) and authigenic chlorite (3-18 %) [56]. The argillite sample contains a high proportion of kaolinite, which signifies the low cation exchange capacity, swelling ability and water retentivity properties.

Laboratory Results

Figure 4 shows data on mass change of argillite samples in a vaporous medium of saturated 5 % solutions of KCl, $Na_2(SO)_4$, NaCl, $CaCl_2$, $MgCl_2$ and water.

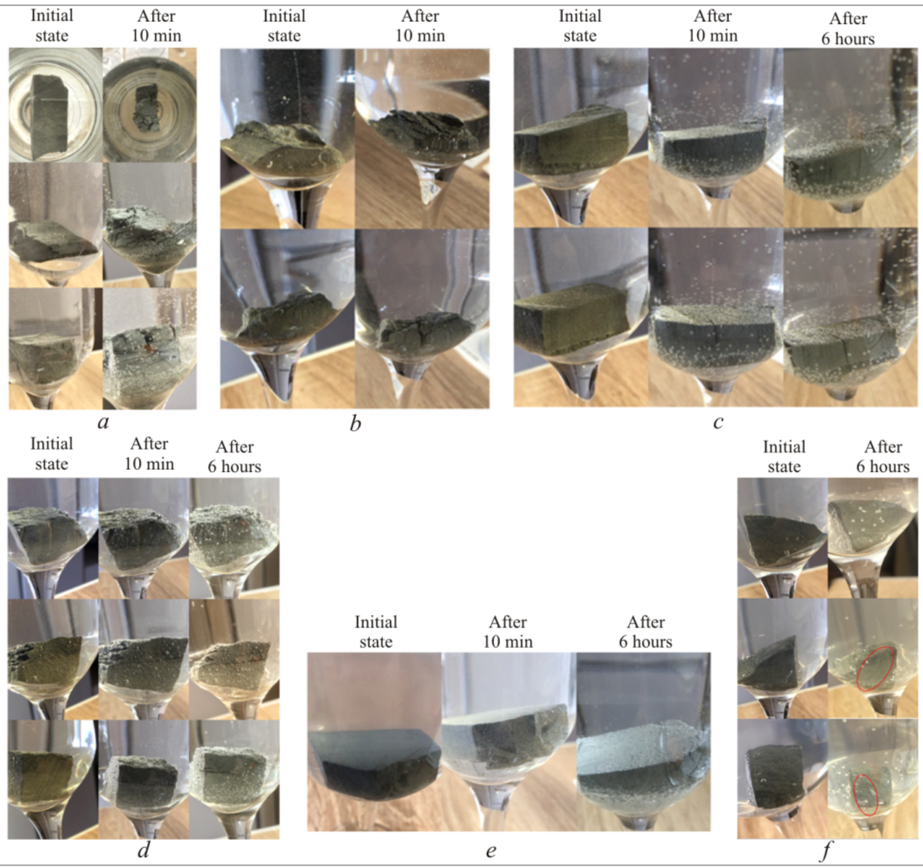

Fig. 5. Argillite sample at interaction with: *a* – water at the start of the test and after 10 min; *b* – NaCl at the start of the test and after 10 min; *c* – Na_2SO_4 at the start of the test, after 10 min and after 6 hours, respectively; *d* – $MgCl_2$ at the start of the test and after 6 hours; *e* – $CaCl_2$ at the start of the test and after 6 hours; *f* – KCl at the start of the test and after 10 min

The minimum increase in the sample mass was observed in the vapours of KCl saturated solution. The most mass increase occurs after the first day of the sample exposure to the solutions vapours, and after the fifth day the mass increase is insignificant, so the recommend test duration is 5 days.

The fracturing test revealed that the effect of water as a reference parameter significantly increases the existing fractures in the argillite sample (Fig. 5, *a*). After 10 minutes of interaction, a complete rock softening is observed, and the sample interaction with a 5 % NaCl solution yielded the same result (Fig. 5, *b*). When argillite interacts with 5 % solutions of $MgCl_2$, Na_2SO_4 and $CaCl_2$, the formation and expansion of fractures along bedding planes with simultaneous rock disintegration is observed over time (after 6 hours) (Fig. 5, *c-e*). When the argillite sample was placed in a 5 % potassium chloride (KCl) solution, minor expansion and propagation of fractures was observed along the entire sample length, which is a positive result (Fig. 5, *f*).

Following the study results, the following conclusions can be drawn: the interaction of water with the fractured argillite has a negative impact on its stability; potassium chloride solution provides more stability to the fractured argillites of the Labaganskoye field; the results with potassium chloride using the Chenevert method and the fracturing test are identical.

Conclusions

Following the study of a fractured argillite sample cored at a depth of 1,385-1,475 m from the deposits pertaining to the Artinskian stage of the Permian system, it was proved that the argillite interaction with the drilling fluid is the primary causative factor leading to its instability.

The Chenevert method was used to determine the swelling potential of argillite samples. The fracturing test clearly demonstrated the drilling fluid ability to prop existing fractures. Potassium chloride salt solution (KCl) ensures greater stability of argillite, which is confirmed by the study involving two test methods.

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