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The Influence of Clay Minerals Swelling on Reserve Production

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Влияние набухания глинистых минералов на выработку запасов

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reservoir rocks destruction, clay minerals swelling, permeability change, oil reserves, interaction of injected water with rock clay minerals.

During the oil and gas reservoirs development, various processes occur, ranging from varying the physicochemical properties of formation fluids to changing the reservoir properties of productive formations, which leads to their destruction. All these processes can influence the final oil recovery in different ways. Research into the influence of clays on the permeability of sandstones has been conducted for more than 50 years, but the presence of clay minerals in reservoir rocks still poses a problem for oil production. When oil is displaced from productive formations, the injected water interacts with the clay minerals of the rock, which leads to significant changes in the dynamics of oil production in the fields. This parameter can especially change when maintaining reservoir pressure by injecting fresh water, since the composition of the injected water significantly affects the permeability of reservoirs. In addition to the type and spatial distribution of clay minerals, another important component that influences the degree of permeability change is fluid composition. Basically, the reduction in permeability occurs when the injected water is less mineralized than the formation water.

To establish the dependence of swelling on clay minerals, the work analyzed the results of 1007 laboratory samples that were used to study the mineral composition of clay fractions. To identify the dependence of swelling on various clay minerals, a significant number of graphs were constructed and a relationship was established between swelling and mixed-layer formations of the hydromica-montmorillonite series, which made it possible to establish the swelling values for other fields. To determine the effect of swelling on the change in porosity, a coefficient for reducing porosity due to swelling was introduced.

The calculation of oil reserves for the YuV$_1$ layer of 13 fields showed that when taking into account the clay minerals swelling, the value of reserves decreased by an average of 8.6 %. It was shown that the injection of fresh water led to the destruction of reservoir rocks of fields with high swelling and low porosity, which was confirmed by the low production of reserves for other fields characterized by opposite values of swelling and porosity. Freshwater injection did not affect production from initial recoverable reserves.

Ключевые слова:
разрушения пород коллекторов, набухаемость глинистых минералов, изменение проницаемости, запасы нефти, взаимодействие закачиваемой воды с глинистыми минералами породы.

При разработке нефтяных и газовых коллекторов происходят различные процессы, начиная от варьирования физико-химических свойств пластовых флюидов до изменения коллекторских свойств продуктивных пластов, что приводит к их разрушению. Все эти процессы по-разному могут оказывать влияние на конечную нефтеотдачу. Исследования влияния глин на проницаемость песчаников проводятся более 50 лет, но до сих пор присутствие глинистых минералов в породах-коллекторах представляет собой проблему для добычи нефти. При вытеснении нефти из продуктивных пластов происходит взаимодействие закачиваемой воды с глинистыми минералами породы, что приводит к значительным изменениям в динамике добычи нефти по месторождениям. Особенно этот параметр может измениться при поддержании пластового давления закачкой пресной воды, так как состав закачиваемой воды существенно влияет на проницаемость коллекторов. Кроме типа и пространственного распределения глинистых минералов, еще одной важной составляющей, которая влияет на степень изменения проницаемости, является состав флюида. В основном снижение проницаемости происходит, когда закачиваемая вода менее минерализована, чем пластовая.

Для установления зависимости набухаемости от глинистых минералов в работе проведен анализ результатов 1007 лабораторных образцов, которые были использованы для изучения минерального состава глинистых фракций. Для выявления зависимости набухаемости от различных глинистых минералов было построено значительное количество графиков и установлена зависимость между набухаемостью и смешанослойными образованиями гидрослюда-монтмориллонитового ряда, что позволило установить значения величины набухаемости по другим месторождениям. Для определения влияния набухаемости на изменение пористости введён коэффициент снижения пористости за счет набухаемости.

Произведенный расчет запасов нефти по пласту ЮВ$_1$ 13 месторождений показал, что при учете набухаемости глинистых минералов величина запасов снижается в среднем на 8,6 %. Показано, что закачка пресной воды привела к разрушению пород-коллекторов месторождений с высокой набухаемостью и небольшей величиной пористости, что подтверждается низкой выработкой запасов для других месторождений, характеризующихся противоположными значениями набухаемости и пористости. Закачка пресной воды не повлияла на отбор от НИЗ.

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Introduction

There are two types of destruction of reservoir rocks. The first type is associated with the presence of swelling clay particles and their mobilization. The second one arises from specific technological operations and is independent of mineralogy and rock texture. It is important to identify reservoir rocks which will be sensitive to water in order to correctly select a development system for them. The destruction of the reservoir rock of the first type depends on the type of clay minerals, their distribution in the pore space and the composition of the fluid. All clay-water interactions, such as clay swelling and fine migration, occur at the pore level [1].

Clay minerals are very small particles which belong to the group of aluminum hydrosilicates and have a maximum particle size of less than 0.005 mm [2–4]. Kaolinite, smectite and illite are three main groups of clay minerals [5–7]. Montmorillonite accounts for 25 % of all shales in shale-cemented sandstones and is important for sandstones in view of the problem of reservoir quality.

Studies of clays influence on the permeability of sandstones have been carried out for more than 50 years, but until now the presence of clay minerals in reservoir rocks is a problem for oil production. The authors of the publication [8] stated that water-based drilling muds are used more often as the water is more environmentally friendly. However, water causes hydration and swelling of the clay and therefore reduces permeability [9]. Other authors [10] used oil sands to measure air and water permeability, focusing on the type and amount of clay. They showed that the most sensitive to water are sands containing kaolinite, illite and mixed clay (illite-montmorillonite), and the least sensitive are sands with small amounts of kaolinite and illite.

According to [11], one mechanism of the damage for formation is reduced permeability near the wellbore due to smectite swelling or kaolinite deflocculation when these clay minerals come into contact with water-based fluids.

Other authors [12] also noticed that both poorly consolidated and rather dense formations containing a large number of clays filling pores and vulnerable to water-based fluids, such as kaolinite, montmorillonite, chlorite, illite and mixed-layer clays, are similarly susceptible to changes in the permeability of reservoir.

In the paper [13], the possible swelling mechanism of clay particles lining the pores of reservoir rocks was discussed in detail from the point of view of Donnan's osmotic and membrane effects in relation to intra-partial swelling. Swelling of expanding clay mineral particles in contact with relatively fresh water is considered the most common cause of water sensitivity problems encountered in oil production. The swollen particles restrict flow in the pores of the rock, and the smallest expanded plates break off, dispersing in water inside the pore, and further restrict flow when they get stuck in the constrictions of the pores. Grains of non-expanding clay minerals interact specifically with water, but are not able to swell and disintegrate to the same extent as grains containing expandable minerals.

The studies presented in [14] showed that if the reservoir sands contained traces of montmorillonite, water-sensitive changes in reservoir permeability occurred due to dispersion and fine migration: as the water cut increased, the swelling clay plates moved apart and collapsed. In general, under favorable colloidal conditions, non-swelling clays such as kaolinite and illite can be released from the pore surface and these particles then migrate with the fluid flowing through the porous formation. In contrast, swelling clays such as smectite and mixed-layer clays first expand under favorable ionic conditions before disintegrating and migrating. In other words, non-swelling clays can also be said to interact with water, but this interaction is smaller than that of swelling clays.

One of the parameters that also control the degree of change in reservoir permeability is the spatial distribution of clay within the pore structure, which for natural sandstones is associated with clay origin. Both swelling and non-swelling clays can be clastic and authigenic. Clastic or allogeneic clays are a dispersed matrix of clay granules and fragments equal in size to sand particles [2, 15]. Authigenic clays are found in the form of loose grain coatings, pore lining, pore filling, pseudomorphic substitutions and fracture filling and have a significant impact on reservoir quality. Authigenic clays have a greater impact on formation damage due to their direct vulnerability to pore fluids than clastic clays, which are tightly packed in the matrix of the rock. Montmorillonite found in sandstones is of both clastic and authigenic origin and appears as a pore lining. Authigenic kaolinite is the most common clay mineral in sandstone reservoirs and mainly forms scales that fill pores [16, 17].

In addition to the type and spatial distribution of clay minerals, another important component that affects the degree of change in permeability is the composition of the fluid. Most of the permeability decrease occurs when the injected water is less mineralized than the formation water. Change in the chemical composition of the aquatic environment changes the degree of swelling, as well as the type and amount of exchange cations, present between layers of montmorillonite. Since the presence of salt in the water slows down the swelling of the clay [18], in work [19] it was used distilled water without the addition of salts to maximize the swelling of the clay and estimate its maximum effect on the permeability of the sample. Experiments [19] combined core flooding with X-ray μ computed tomography (μ-CT) to study the swelling of clay minerals and its effect on the permeability of a loose porous medium. Clay was added to the balls of soda lime and quartz grains as a coating: swelling (montmorillonite) and non-swelling (kaolinite). Permeability changes in the experiments were monitored as a function of time using pure water. All clay-coated samples showed a 10-40% reduction in permeability, compared to similar data from samples without coating.

In general, permeability decreased with increasing clay content. A 39 % increase in montmorillonite particle volume was observed by CT immediately after saturation of the sample with water, i.e. swelling occurred almost instantaneously after contact of water with clay. In contrast, kaolinite particles had a volume increase of 15 %, which was primarily associated with hydration of clay pellets with water. Calculated porosity reduction attributed to clay swelling ranged from 0.4 to 1.7 %, including samples coated with both montmorillonite and kaolinite. According to the authors [19], such a decrease in porosity leads to a decrease in permeability by only 2–5 %, which is primarily connected with the high initial porosity and permeability of the selected samples. Overall, the study confirmed that fine migration is the primary cause of reduced permeability in a large number of kaolinite-coated samples (non-swelling clay). Growth of swelling clays such as montmorillonite was found to have minimal impact on permeability in high porosity samples (36–40 %). Extension of the model to samples with lower porosity and higher clay content showed that swelling will significantly contribute to a decrease in permeability [19].

According to the author [20], the study of phase permeabilities in the case of combined filtration of oil and fresh water, leading to maximum swelling of clay minerals, is of great interest. But with long-term injection of fresh water, by the effect of of clay particles dispersion, the reservoir is damaged. Also, swelling of the shale component of the reservoir leads to a decrease in effective porosity, which makes it necessary to measure the reservoir saturation taking into account the new effective porosity, which is not an easy task. The change in the structure of the pore space due to the swelling of the clay component affects the filtration of water more significantly than the filtration of the hydrocarbon liquid.

The following conclusion was made by the results of research [20]:

– swelling and deformation of clay particles leading to the restructuring of the porous medium structure are the main factors changing the permeability of the rock and affecting the nature of water filtration in clay-containing reservoirs;

– swelling of clay particles in the reservoir rock has a selective effect on reducing phase mobility. The ratio of ultimate phase permeabilities of oil and water in swollen rock increases compared to the ratio of these parameters in conservative reservoir systems. The effect increases with increasing rock swelling intensity.

Methods of Research

The existing methods for determining the mineral composition of rocks by X-ray diffraction analysis (XRD) make it possible to determine the content of clays of various mineralogical composition, attributed to kaolinite, chlorite, mica-containing particles, etc. Each clay mineral has different swellability and solubility factors and may have different effects on oil displacement capacity during filtration of fresh and mineralized water [21, 22].

Analysis of core material obtained from wells located in the fields of Western Siberia, beds of terrigenous deposits of the Jurassic group (bed YuV_1) shows that kaolinite is the predominant clay mineral (Fig. 1). Kaolinite has a 1:1 layered structure and low base exchange capacity (3.3 meq/100 g for kaolinite). It is a non-swelling clay, but it is easily dispersed and migrates [23, 24].

To establish the dependence of swelling on clay minerals, it was carried the analysis of the results of 1007 laboratory samples, which were used to study mineral composition of clay fractions [25]. Layers of various layered clay minerals are similar to each other and can interbedded. The most common minerals are built by two types of layers (for example, montmorillonite hydromica or hydromica kaolinite). The swelling capacity of mixed-layer minerals may be higher than that of montmorillonite minerals, since the alternation of layers may cause some weakening of the relationship between individual structural units [26].

To detect the dependence of swelling on various clay minerals, a significant number of graphs were constructed. However, the relationship is established only between swelling (S) and mixed-layer formations (MLF) of the mica-montmorillonite series, which is linear in nature. $S = f$ relationships (MLF) were built for 13 fields. The square of the correlation coefficient (R^2) ranges from 0.7735 to 0.9845.

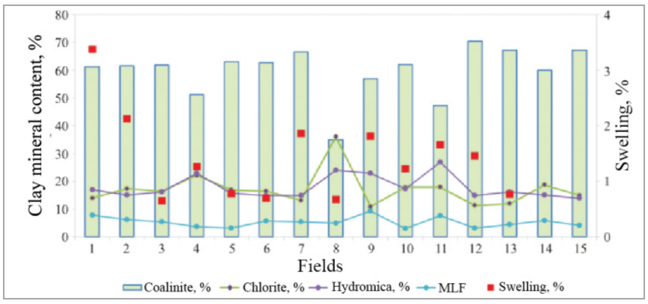
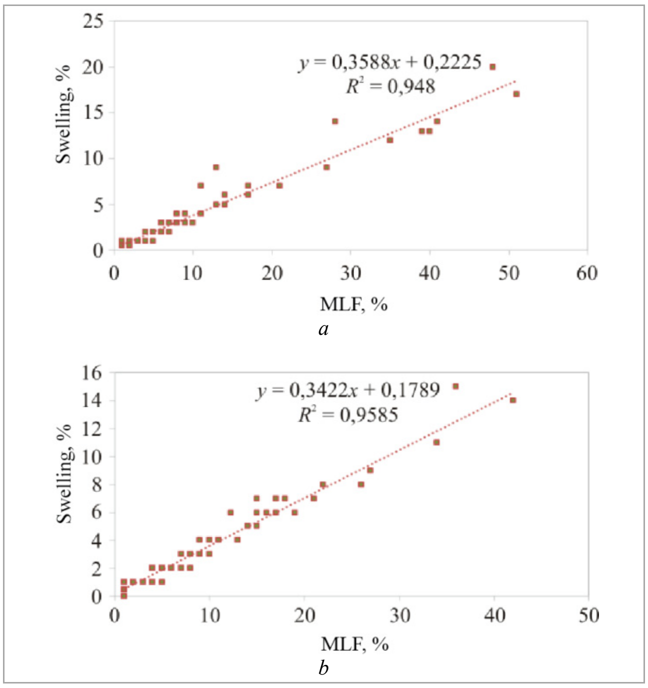


Fig. 1. Distribution of clay mineral content and YuV_1 Reservoir Swelling by Fields



a

b

Fig. 2. Examples of constructing the swelling dependence on MLF by fields: *a* –field 1; *b* – field 2

Examples of field relationships are shown in Fig. 2. By results of construction of dependencies as per 13 fields, it was obtained a generalized relationship (Fig. 3), described by the equation:

$$S = 0{,}3458 \cdot MLF + 0{,}1181. \qquad (1)$$

Thus, the obtained equation was used to determine the swellability values for the field where the MLF data were presented and the swellability values were absent (fields 14 and 15). The table shows the swelling data – actual and calculated values for testing the equation.

In their work [27], the authors drew attention to the fact that the methods for determining porosity factors K_p and oil and gas saturation K_{ogs} of rocks on core samples, which are used in estimating oil and gas reserves and in plotting petrophysical relationships, do not take into account such factors as swelling of clay material, loss of swelling moisture in the process of drying core samples, abnormal density of swelling moisture (interlayer water) and residual water. In the opinion of V.D. Dakhnov [28], swelling moisture volume of clay particles are not taken into account from the volume of open pores of the rock and, accordingly, are excluded when calculating the coefficient of residual water of reservoirs. In laboratory methods, samples are pre-dried at 105–120 °C to determine porosity and residual water content. In this case, some of the interlayer water is removed, which leads to an increase in the amount of residual water and open porosity. Other authors also noted that swelling moisture is removed from clays during heating of samples at temperatures from 70 to 250 °C and with a decrease in initial humidity the rate of bound water removal is higher [29–32]. During drying the samples of average humidity at a temperature not exceeding 105 °C, the swelling moisture loss is about 10 %, while when boiling in toluene in the temperature range 110–120 °C, the moisture loss is not less than 15 % of the total.

Experimental Data

In our opinion, it is important to know the swelling value for each pay zone and take it into account when designing a waterflood system [33], as well as when calculating oil and solution gas reserves, since their value may be overestimated.

To determine the effect of swelling on the change in porosity, we introduce the coefficient of reduction in porosity due to swelling and denote it as K_{ps}.

$$K_{ps} = 1 - \frac{\text{H}}{m}, \qquad (2)$$

where m – porosity, H – swelling.

Initial oil-in-place reserves are calculated by the formula [34–36]:

$$Q_{\text{in}} = F \cdot h_{no} \cdot K_p \cdot K_{os} \cdot \theta \cdot \sigma_o, \qquad (3)$$

where Q_{in} – initial oil-in-place reserves, th.t; F – reservoir area, thousand m^2; h_{no} – net oil thickness, m; K_p – open porosity factor, decimal units.; K_{os} – oil saturation ratio, decimal units; θ – correction factor, considering oil shrinkage, decimal units.; σ_o – oil density at surface conditions, t/m^3.

By addition of K_{ps} to the formula for finding the initial in-place oil reserves, we get (4):

$$Q_{in} = F \cdot h_{no} \cdot K_p \cdot K_{os} \cdot \theta \cdot \sigma_o \cdot K_{ps}. \qquad (4)$$

The calculation of oil reserves for Zone YuV$_1$ of thirteen fields showed that, taking into account the swelling of clay minerals, the value of reserves decreases by an average of 8.6 %. The range of decline ranges from 4.2 to 18.7 %. A significant decrease is observed in reservoirs with high K_{ps}. Figure 4 shows a comparison of the approved oil reserves and reserves calculated with consideration to K_{ps} for the fields.

In order to determine the relationship between the impact of K_{ps} on oil production, we will perform regression analysis [37–39] for the fields and model the recovery from initial recoverable oil reserves using the following parameters: reservoir rock permeability, net oil-saturated thickness of the reservoir, sand content, compartmentalization, sweep and oil saturation factors, porosity. Data on fields with at least 20 years of development were used in regression analysis.

According to the results of regression analysis the normalized R^2 turned out to be negative sign (Fig. 5). Regression coefficient F has a fairly high value of 0.67.

We perform a regression analysis and replace the values of the average porosity for the reservoir with the porosity recalculated with consideration to swelling, and

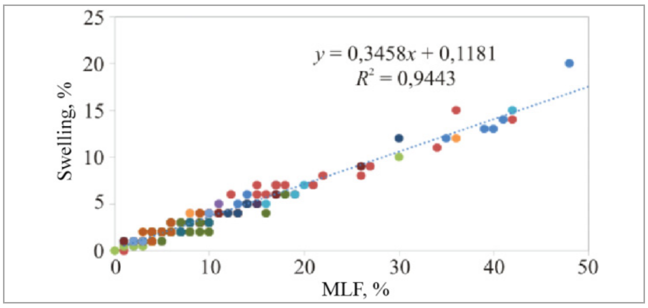


Fig. 3. Swelling dependence on MLF by fields: fields are indicated by different colours

Swelling data by YuV$_1$ reservoir of the fields

Field	Number of studies	Swelling, % (fact)	Swelling, % (calculation)	R^2
1	120	3.4	3.2	0.948
2	222	2.1	2.1	0.9585
3	78	0.7	0.8	0.9147
4	241	1.3	1.3	0.9464
5	85	0.8	0.7	0.8376
6	27	0.7	0.6	0.7819
7	45	1.9	1.9	0.9663
8	43	0.7	0.9	0.7735
9	26	1.8	1.9	0.9681
10	9	1.2	1.1	0.9845
11	31	1.7	1.7	0.9793
12	8	1.5	1.5	0.9715
13	19	0.8	0.9	0.9042
14	19	–	0.9	
15	34	–	0.7	

Remark: * – there were no data on the swelling of clay minerals for the fields.

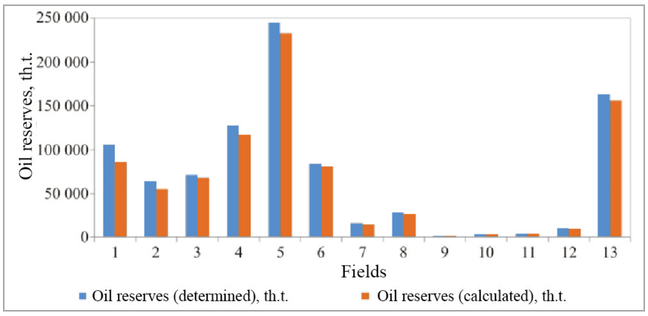
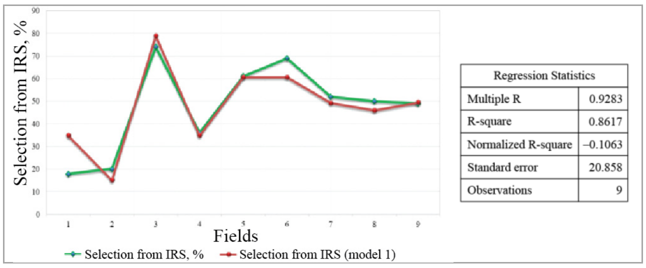
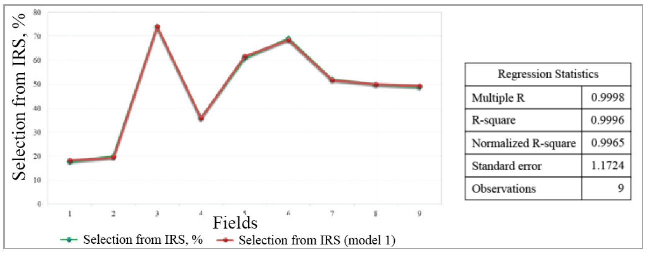


Fig. 4. Comparison of oil reserves by the fields



Regression Statistics	
Multiple R	0.9283
R-square	0.8617
Normalized R-square	–0.1063
Standard error	20.858
Observations	9

Fig. 5. Results of construction the model from initial recoverable reserves (IRS) selection



Regression Statistics	
Multiple R	0.9998
R-square	0.9996
Normalized R-square	0.9965
Standard error	1.1724
Observations	9

Fig. 6. Results of construction the model from initial recoverable reserves (IRS) selection with consideration of K_{pn}

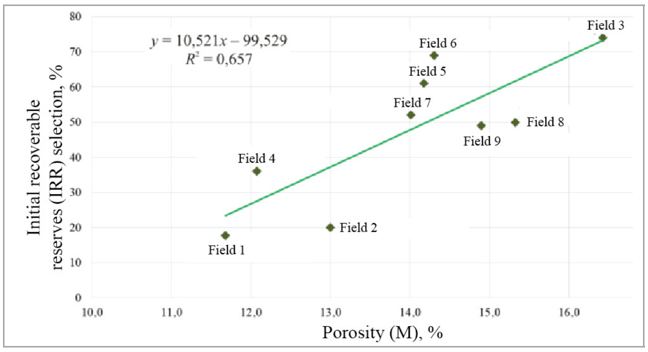


Fig. 7. Dependence of initial recoverable reserves (IRR) selection on porosity M

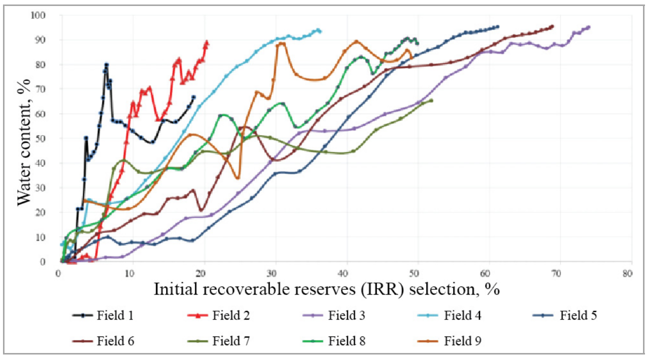


Fig. 8. Displacement characteristics by fields

denote as M. The results of the construction are shown in Fig. 6. The calculation error is 1 %. Normalized R^2 has a sufficiently high value.

Plot the $Q = f(M)$ relationship, the construction results are shown in Fig. 7. The square of the correlation coefficient is 0.657, which indicates a significant relationship between the parameters under consideration.

Thus, it can be concluded that with an increase in swelling, which entails a decrease in the pore space, the withdrawal from the initial recoverable reserves decreases.

When oil is displaced from producing reservoir the injected water interacts with clay rock minerals, which leads to significant changes in oil production dynamics by fields [40–43]. This parameter may change especially when reservoir pressure is maintained by fresh water injection since the composition of injected water significantly affects reservoir permeability [44–49].

Figure 8 shows the displacement characteristics for the fields under consideration with identical development systems and well spacing. Since the beginning of development in fields 1-3 and 8, fresh (river) water has been used for the reservoir pressure maintenance system. Given the high swellability and low porosity, fresh water injection may have resulted in reservoir rock failure, confirming the low depletion of reserves (Fields 1 and 2) and vice versa. For fields 3 and 8 with opposite swellability and porosity, fresh water injection did not affect recovery from initial recoverable reserves.

Conclusion

1. The results of 1007 laboratory samples which were used to study the mineral composition of clay fractions were analyzed.

2. To identify the dependence of swelling on various clay minerals a significant number of graphs were constructed; the relationship between swelling and mixed-layer formations of montmorillonite hydromica, which is linear, was determined. Based on the results of building relationships for 13 fields a generalized relationship was obtained, which made it possible to calculate swelling values for other fields.

3. To determine the effect of swelling on the change in porosity, a coefficient of reduction in porosity due to swelling (K_{ps}) was introduced.

4. The calculation of oil reserves for YuV_1 reservoir of thirteen fields showed that, taking into account the swelling of clay minerals, the amount of reserves decreases by an average of 8.6 %. The range of decline ranges from 4.2 to 18.7 %.

5. Regression analysis was performed to determine the relationship between the impact of K_{ps} on oil production for fields and simulated recovery from initial recoverable oil reserves (initial recoverable reserves). This parameter was found to be very significant in the model. The calculation error is only 1 %, which indicates that with an increase in swelling, which entails a decrease in the pore space, the withdrawal from the initial recoverable reserves decreases.

6. It is shown that fresh water injection led to destruction of reservoir rocks with high swellability and low porosity, as evidenced by low depletion of reserves. For other fields characterized by opposite values of swellability and porosity, fresh water injection did not affect the recovery from initial recoverable reserves.

References

1. Mungan N. Discussion of an overview of formation damage. *J Petrol Technol.*, 1989, vol. 41 (11), 1224 p.
2. Faruk C. Reservoir Formation Damage: Fundamentals, Modeling, Assessment, and Mitigation. *Gulf Professional Publishing*, 2023, 1096 p. DOI: 10.1016/C2020-0-03547-4
3. Hughes R.V. The application of modern clay concepts to oilfield development (Conference Paper). *Drilling and Production Practice*, 1950, pp. 151-167.
4. Meunier A. Why are clay minerals small? *Clay Minerals*, 2006, vol. 41, pp. 551-566. DOI: 10.1180/0009855064120205
5. Grim R.E. Modern concepts of clay minerals. *J Geol.*, 1942, vol. 50 (3), pp. 225-275.
6. Grim R.E. Clay mineralogy Edition: View all formats and editions. Publisher: McGraw-Hill, New York, 1953.
7. Hughes R.V. The application of modern clay concepts to oil field developments API Drilling Prod Pract, 1950, pp. 151-167.
8. Greenwell H.C., Anderson R.L., Ratcliffe I., Williams P.A., Cliffe S., Coveney P.V. Clay swelling - a challenge in the oilfield. *Earth Sci. Rev.*, 2010, vol. 98, pp. 201-216. DOI: 10.1016/J.EARSCIREV.2009.11.003
9. Kacprzak G., Boutin C., Doanh T. Permeability of sand-clay mixtures. Arch Civil Eng, 2010, vol. 56 (4), pp. 299-320. DOI: 10.2478/v.10169-010-0017-6
10. Baptis O.C., Sweeney S.A. The effect of clays on the permeability of reservoir sands to waters of different saline contents. *Pacific Coast Regional Conference on Clays and Clay Technology, June 25-26, 1954.* Berkeley, California, 1954, pp. 505-508. DOI: 10.1346/CCMN.1954.0030141
11. Bishop S.R. The experimental investigation of formation damage due to the induced flocculation of clays within a sandstone pore structure by a high salinity brine. *SPE 38156 paper presented at the SPE European Formation Damage conference, June 2-3 1997.* The Hague, The Netherlands, 1997, pp. 123-143. DOI: 10.2118/38156-Ms
12. Amaefule J.O., Kersey D.G., Norman D.L., Shannon P.M. Advances in formation damage assessment and control strategies. CIM Paper No. 88-39-65. *Proceedings of the 39th annual technical meeting of Petroleum Society of CIM and Canadian Gas Processors Association, June 12-16 1988.* Calgary, Alberta, 1988, 16 p. DOI: 10.2118/88-39-65

13. Dodd C.G., Conley F.R., Barnes P.M. Clay minerals in petroleum reservoir sands and water sensitivity effects. *Clays Clay Miner*, 1954, vol. (1), pp. 221-238. DOI: 10.1346/CCMN.1954.0030118
14. Marfil R., Delgado A., Rossi C., Iglesia A.L., Ramseyer K. Origin and diagenetic evolution of kaolin in reservoir sandstones and associated shales of the Jurassic and Cretaceous, Salam Field, Western Desert (Egypt). *Int. Assoc. Sedimentol. Spec. Publ.*, 2003, vol. 34, pp. 319-342. DOI: 10.1002/9781444304336.CH14
15. Ezzat A.M. Completion Fluids Design Criteria and Current Technology Weaknesses Paper presented at the SPE Formation Damage Control Symposium, Lafayette. Louisiana, February, 1990. Paper Number: SPE-19434-MS. DOI: 10.4043/19434-MS
16. Houseknecht D.W., Pittman E.D. Origin, diagenesis, and petrophysics of clay minerals in sandstones. *SEPM Special Publication*, 1992, vol. 47. DOI: 10.2110/pec.92.47
17. Wilson M.D., Pittman E.D. Authigenic clays in sandstones; recognition and influence on reservoir properties and paleoenvironmental analysis. *Journal of Sedimentary Research*, 1977, vol. 47 (1), pp. 3-31. DOI: 10.1306/212F70E5-2B24-11D7-8648000102C1865D
18. Mohan K.K., Fogler H.S. Colloidally induced smecticic fines migration: existence of microquakes. *AIChE Journal*, 1997, vol. 43 (3), pp. 565-576. DOI: 10.1002/AIC.690430302
19. Aksu I., Bazilevskaya E., Karpyn Z.T. Swelling of clay minerals in unconsolidated porous media and its impact on permeability. *GeoResJ*, 2015, vol. 7, pp. 1-13. DOI: 10.1016/j.grj.2015.02.003
20. Stupochenko V.E. Nauchnoe obosnovanie metodov intensifikatsii razrabotki glinosoderzhashchikh kollektorov i usovershenstvovannykh polimernykh tekhnologii s tsel'iu povysheniia nefteotdachi plasta [Scientific substantiation of methods for intensifying the development of clay-containing reservoirs and improved polymer technologies in order to increase oil recovery]. Doctor's degree dissertation. Moscow: VNIIneft', 2000, 437 p.
21. Krivova N.R., Leont'ev S.A., Zviagin A.A. Izuchenie vliianiia mineralizatsii zakachivaemoi vody na nefteotdachu plastov [Studying the influence of injected water mineralization on oil recovery]. *Neftepromyslovoe delo*, 2023, no. 11 (659), pp. 52-57. DOI: 10.33285/0207-2351-2023-11(659)-52-57.
22. Pupkov N.V., Krivova N.R. Issledovaniia vliianiia zakachivaemoi v plast vody na priemistost' nagnetatel'nykh skvazhin [Research of the effect of water injection into a formation on the water-intake capacity of injection wells]. *Neftepromyslovoe delo*, 2019, no. 7 (607), pp. 18-22. DOI: 10.30713/0207-2351-2019-7(607)-18-22
23. Worden R.H., Morad S. Clay minerals in sandstones: controls on formation, distribution and evolution. *Clay mineral cements in sandstones. International Association of Sedimentologists, International Association of Sedimentologists Special Publication 34*, 2003, pp. 3-41. DOI: 10.1002/9781444304336.ch1
24. Jerez J., Flury M., Shang J., Deng Y. Coating of silica sand with aluminosilicate clay. *J Colloid Interface Sci.*, 2006, vol. 294, pp. 155-164. DOI: 10.1016/j.jcis.2005.07.017
25. Krivova N.R., Belokurova E.V., Leontiev S.A. Clay minerals influence on the process of oil displacement by water in Jurassic reservoirs. *E3S Web of Conferences*, 2023, vol. 462, 03057 p. DOI: 10.1051/e3sconf/202346203057
26. Rynskaia G.O. Razrabotka metodiki ucheta vliianiia nabukhaniia glin na petrofizicheskie svoistva peschano-glinistykh porod [Development of a methodology for taking into account the influence of clay swelling on the petrophysical properties of sandy-clayey rocks] Ph. D. thesis. Moscow: MINKh i GP, 1985, 188 p.
27. Leont'ev E.I., Nefedova N.I. Novyi metodicheskii podkhod k opredeleniiu koeffitsientov poristosti i neftegazonasyshchennosti kollektorov laboratornymi sposobami [A new methodological approach to determining the coefficients of porosity and oil and gas saturation of reservoirs using laboratory methods]. *Geologiia nefti i gaza*, 1982, no. 11.
28. Dakhnov V.N. Vliianie glinistosti kollektorov na tochnost' podscheta zapasov nefti i gaza [The influence of reservoir clayiness on the accuracy of oil and gas reserves calculations]. *Geologiia nefti i gaza*, 1977, no. 9, pp. 58-60.
29. Zaks S.L. Otbor i issledovanie kernov na vodo- i neftenasyshchennost' [Selection and study of cores for water and oil saturation]. *Neftianoe khoziaistvo*, 1947, no. 6, pp. 24-30.
30. Zlochevskaia R.I., Zlochevskii S.I., Kuprina G.A. Issledovanie termicheskoi degidratatsii kation-zameshchennykh obraztsov montmorillonitovoi gliny [Study of thermal dehydration of cation-substituted montmorillonite clay samples]. *Sviazannaia voda v dispersnykh sistemakh*. Moscow, 1972, pp. 195-211.
31. Kul'chitskii L.I., Us'iarov O.G. Fiziko-khimicheskie osnovy formirovaniia svoistv glinistykh porod [Physico-chemical basis for the formation of properties of clayey rocks]. Moscow: Nedra, 1981, 178 p.
32. Chukhrov F.V. Kolloidy v zemnoi kore [Colloids in the earth's crust]. Moscow: Akademiia nauk SSSR, 1955, 673 p.
33. Krivova N.R., Leont'ev S.A. Issledovaniia vliianiia zakachivaemoi v plast vody s tsel'iu PPD na mestorozhdeniiakh Zapadnoi Sibiri [Study of the influence of water injected into the reservoir for the purpose of reservoir pressure maintenance in the fields of Western Siberia]. *Opyt, aktual'nye problemy i perspektivy razvitiia neftegazovogo kompleksa: materialy XIII Mezhdunarodnoi nauchno-prakticheskoi konferentsii obuchaiushchikhsia, aspirantov i uchenykh.* Tiumen', 2023, pp. 118-121.
34. Gutman I.S. Metody podscheta zapasov nefti i gaza [Methods for calculating oil and gas reserves]. Moscow: Nedra, 1985, 223 p.
35. Zhdanov M.A. Neftegazopromyslovaia geologiia i podschet zapasov nefti i gaza [Oil and gas field geology and calculation of oil and gas reserves]. Moscow: Nedra, 1981. 453 p.
36. Petersil'e V.I., Poroskun V.I., Iatsenko G.G. Metodicheskie rekomendatsii po podschetu geologicheskikh zapasov nefti i gaza ob"emnym metodom [Methodological recommendations for calculating geological reserves of oil and gas using the volumetric method]. *NPTs Tver'geofizika*. Moscow-Tver', 2003, 258 p.
37. Dreiper N., Smit G. Prikladnoi regressionnyi analiz [Applied Regression Analysis]. Moscow: Vil'iams, 2016, 912 p.
38. Dougerti K. Vvedenie v ekonometriku [Introduction to Econometrics]. Moscow: INFRA, 2001, 402 p.
39. Dement'ev L.F., Zhdanov M.A., Kirsanov A.N. Primenenie matematicheskoi statistiki v neftepromyslovoi geologii [Application of mathematical statistics in oilfield geology]. Moscow, 1977, 255 p.
40. Khavkin A.Ia., Iusupova Z.S., Gerzha L.I. et al. Osobennosti zavodneniia nizkopronitsaemykh glinosoderzhashchikh plastov raznomineralizovannymi vodami [Features of flooding of low-permeability clay-containing formations with different mineralized waters]. *Neftepromyslovoe delo.* Moscow: NTS VNIIOENG, 1992, no. 8, pp. 14-18.
41. Sokolovskii E.V. Primenenie radioaktivnykh izotopov dlia kontrolia za razrabotkoi neftianykh mestorozhdenii [The use of radioactive isotopes to control the development of oil fields]. Moscow: Nedra, 1968, 180 p.
42. Tabakaeva L.S. Eksperimental'nye issledovaniia osobennostei vozdeistviia na nizkopronitsaemye glinosoderzhashchie neftianye plasty rastvorami polielektrolitov [Experimental studies of the effects of polyelectrolyte solutions on low-permeability clay-containing oil formations]. Ph. D. thesis. Moscow: IPNGRAN, 2007, 174 p.
43. Stupochenko V.E. Vliianie glinistosti kollektora na polnotu vytesneniia nefti vodoi [Influence of reservoir clay content on the completeness of oil displacement by water]. *Geologo-fizicheskie aspekty obosnovaniia koeffitsienta nefteotdachi*. Moscow: VNIGNI, 1981, no. 228, pp. 59-79.
44. Khavkin A.Ia., Tabakaeva L.S. Vliianie mineralizatsii zakachivaemoi vody na proizvoditel'nost' skvazhin [The influence of injected water salinity on well productivity]. *Geologo-fizicheskie faktory effektivnoi razrabotki mestorozhdenii uglevodorodov*. Moscow, 2005, pp. 108-115.
45. Khavkin, A.Ia. Rezul'taty matematicheskogo modelirovaniia protsessa vytesneniia nefti vodoi iz glinosoderzhashchikh plastov [Results of mathematical modeling of the process of displacement of oil by water from clay-containing formations]. *Oprosy izucheniia neftegazonosnosti nedr*. Moscow: IGiRGI, 1981, pp. 99-104.
46. Jones F.O. Influence of Chemical Composition of Water on Clay Blocking of Permeability. *JPT*, 1964, pp. 441-446. DOI: 10.2118/631-pa
47. Khilar K.S., Folger H.S. Water Sensitivity of Sandstones. *SPEJ*, 1983, vol. 2, pp. 55-64. DOI: 10.2118/10103-PA
48. Tang G.Q., Morrow N.R. Salinity, Temperature, Oil Composition, and Oil Recovery by Waterflooding. Text: direct. *SPE Reservoir Engineering (Society of Petroleum Engineers)*, 1997, vol. 4 (12), pp. 269-276. DOI: 10.2118/36680-PA
49. Maul' V.Ia., Krivova N.R., Savel'eva N.N. et al. Tekhnologii neftegazovogo inzhiniringa [Oil and gas engineering technologies]. Tiumen': Tiumenskii industrial'nyi universitet, 2023, part. 1, 167 p.

Библиографический список

1. Mungan, N. Discussion of an overview of formation damage / N. Mungan // J Petrol Technol. – 1989. – Vol. 41 (11). – 1224 p.
2. Faruk, C. Reservoir Formation Damage: Fundamentals, Modeling, Assessment, and Mitigation / C. Faruk // Gulf Professional Publishing. – 2023. – 1096 p. DOI: 10.1016/C2020-0-03547-4
3. Hughes R.V. The application of modern clay concepts to oilfield development (Conference Paper) / R.V. Hughes // Drilling and Production Practice. – 1950. – P. 151–167.
4. Meunier, A. Why are clay minerals small? / A. Meunier // Clay Minerals. – 2006. – Vol. 41. – P. 551–566. DOI: 10.1180/0009855064120205
5. Grim, R.E. Modern concepts of clay minerals / R.E. Grim // J Geol. – 1942. – Vol. 50 (3). – P. 225–275.
6. Grim, R.E. Clay mineralogy Edition: View all formats and editions / R.E. Grim. – Publisher: McGraw-Hill, New York, 1953.
7. Hughes, R.V. The application of modern clay concepts to oil field developments API Drilling Prod Pract / R.V. Hughes. – 1950. – P. 151–167.
8. Clay swelling – a challenge in the oilfield / H.C. Greenwell, R.L. Anderson, I. Ratcliffe, P.A. Williams, S. Cliffe, P.V. Coveney // Earth Sci Rev. – 2010. – Vol. 98. – P. 201–216. DOI: 10.1016/J.EARSCIREV.2009.11.003
9. Kacprzak, G. Permeability of sand–clay mixtures / G. Kacprzak, C. Boutin, T. Doanh // Arch Civil Eng. – 2010. – Vol. 56 (4). – P. 299–320. DOI: 10.2478/v.10169-010-0017-6
10. Baptis, O.C. The effect of clays on the permeability of reservoir sands to waters of different saline contents / O.C. Baptis, S.A. Sweeney // Pacific Coast Regional Conference on Clays and Clay Technology, June 25–26, 1954. – Berkeley, California, 1954. – P. 505–508. DOI: 10.1346/CCMN.1954.0030141
11. Bishop, S.R. The experimental investigation of formation damage due to the induced flocculation of clays within a sandstone pore structure by a high salinity brine / S.R. Bishop // SPE 38156 paper presented at the SPE European Formation Damage conference, June 2–3 1997. – The Hague, The Netherlands, 1997. – P. 123–143. DOI: 10.2118/38156-Ms

12. Advances in formation damage assessment and control strategies. CIM Paper No. 88-39-65 / J.O. Amaefule, D.G. Kersey, D.L. Norman, P.M. Shannon // Proceedings of the 39th annual technical meeting of Petroleum Society of CIM and Canadian Gas Processors Association, June 12–16 1988. – Calgary, Alberta, 1988. – 16 p. DOI: 10.2118/88-39-65
13. Dodd, C.G. Clay minerals in petroleum reservoir sands and water sensitivity effects / C.G. Dodd, F.R. Conley, P.M. Barnes // Clays Clay Miner. – 1954. – Vol. (1). – P. 221–238. DOI: 10.1346/CCMN.1954.0030118
14. Origin and diagenetic evolution of kaolin in reservoir sandstones and associated shales of the Jurassic and Cretaceous, Salam Field, Western Desert (Egypt) / R. Marfil, A. Delgado, C. Rossi, A.L. Iglesia, K. Ramseyer // Int. Assoc. Sedimentol. Spec. Publ. – 2003. – Vol. 34. – P. 319–342. DOI: 10.1002/9781444304336.CH14
15. Ezzat, A.M. Completion Fluids Design Criteria and Current Technology Weaknesses Paper presented at the SPE Formation Damage Control Symposium, Lafayette / A.M. Ezzat. – Louisiana, February, 1990. Paper Number: SPE-19434-MS. DOI: 10.4043/19434-MS
16. Houseknecht, D.W. Origin, diagenesis, and petrophysics of clay minerals in sandstones / D.W. Houseknecht, E.D. Pittman // SEPM Special Publication. – 1992. – Vol. 47. DOI: 10.2110/pec.92.47
17. Wilson, M.D. Authigenic clays in sandstones; recognition and influence on reservoir properties and paleoenvironmental analysis / M.D. Wilson, E.D. Pittman // Journal of Sedimentary Research. – 1977. – Vol. 47 (1). – P. 3–31. DOI: 10.1306/212F70E5-2B24-11D7-8648000102C1865D
18. Mohan, K.K. Colloidally induced smecticic fines migration: existence of microquakes / K.K. Mohan, H.S. Fogler // AIChE Journal. – 1997. – Vol. 43 (3). – P. 565–576. DOI: 10.1002/AIC.690430302
19. Aksu, I. Swelling of clay minerals in unconsolidated porous media and its impact on permeability / I. Aksu, E. Bazilevskaya, Z.T. Karpyn // GeoResJ. – 2015. – Vol. 7. – P. 1–13. DOI: 10.1016/j.grj.2015.02.003
20. Ступоченко, В.Е. Научное обоснование методов интенсификации разработки глиносодержащих коллекторов и усовершенствованных полимерных технологий с целью повышения нефтеотдачи пласта: дис. … д-ра техн. наук / В.Е. Ступоченко. – М.: ВНИИнефть, 2000. – 437 с.
21. Кривова, Н.Р. Изучение влияния минерализации закачиваемой воды на нефтеотдачу пластов / Н.Р. Кривова, С.А. Леонтьев, А.А. Звягин // Нефтепромысловое дело. – 2023. – № 11 (659). – С. 52–57. DOI: 10.33285/0207-2351-2023-11(659)-52-57
22. Пупков, Н.В. Исследования влияния закачиваемой в пласт воды на приемистость нагнетательных скважин / Н.В. Пупков, Н.Р. Кривова // Нефтепромысловое дело. – 2019. – № 7 (607). – С. 18–22. DOI: 10.30713/0207-2351-2019-7(607)-18-22
23. Worden, R.H. Clay minerals in sandstones: controls on formation, distribution and evolution / R.H. Worden, S. Morad // Clay mineral cements in sandstones. International Association of Sedimentologists, International Association of Sedimentologists Special Publication 34. – 2003. – P. 3–41. DOI: 10.1002/9781444304336.ch1
24. Coating of silica sand with aluminosilicate clay / J. Jerez, M. Flury, J. Shang, Y. Deng // J Colloid Interface Sci. – 2006. – Vol. 294. – P. 155–164. DOI: 10.1016/j.jcis.2005.07.017
25. Krivova, N.R. Clay minerals influence on the process of oil displacement by water in Jurassic reservoirs / N.R. Krivova, E.V. Belokurova, S.A. Leontiev // E3S Web of Conferences. – 2023. – Vol. 462. – P. 03057. DOI: 10.1051/e3sconf/202346203057
26. Рынская, Г.О. Разработка методики учета влияния набухания глин на петрофизические свойства песчано-глинистых пород: дис. … канд. геол.-мин. наук / Г.О. Рынская. – М.: МИНХ и ГП, 1985. – 188 с.
27. Леонтьев, Е.И. Новый методический подход к определению коэффициентов пористости и нефтегазонасыщенности коллекторов лабораторными способами / Е.И. Леонтьев, Н.И. Нефедова // Геология нефти и газа. – 1982. – № 11.
28. Дахнов, В.Н. Влияние глинистости коллекторов на точность подсчета запасов нефти и газа / В.Н. Дахнов // Геология нефти и газа. – 1977. – № 9. – С. 58–60.
29. Закс, С.Л. Отбор и исследование кернов на водо- и нефтенасыщенность / С.Л. Закс // Нефтяное хозяйство. – 1947. – № 6. – С. 24–30.
30. Злочевская, Р.И. Исследование термической дегидратации катион-замещенных образцов монтмориллонитовой глины / Р.И. Злочевская, С.И. Злочевский, Г.А. Куприна // Связанная вода в дисперсных системах. – М., 1972. – С. 195–211.
31. Кульчицкий, Л.И. Физико-химические основы формирования свойств глинистых пород / Л.И. Кульчицкий, О.Г. Усьяров. – М.: Недра, 1981. – 178 с.
32. Чухров, Ф.В. Коллоиды в земной коре / Ф.В. Чухров. – М.: Изд. Академии наук СССР, 1955. – 673 с.
33. Кривова, Н.Р. Исследования влияния закачиваемой в пласт воды с целью ППД на месторождениях Западной Сибири / Н.Р. Кривова, С.А. Леонтьев // Опыт, актуальные проблемы и перспективы развития нефтегазового комплекса: материалы XIII Международной научно-практической конференции обучающихся, аспирантов и ученых. – Тюмень, 2023. – С. 118–121.
34. Гутман, И.С. Методы подсчета запасов нефти и газа / И.С. Гутман. – М.: Недра, 1985. – 223 с.
35. Жданов, М.А. Нефтегазопромысловая геология и подсчет запасов нефти и газа / М.А. Жданов. – М.: Недра, 1981. – 453 с.
36. Петерсилье, В.И. Методические рекомендации по подсчету геологических запасов нефти и газа объемным методом / В.И. Петерсилье, В.И. Пороскун, Г.Г. Яценко // НПЦ Тверьгеофизика. – Москва –Тверь, 2003. – 258 с.
37. Дрейпер, Н. Прикладной регрессионный анализ / Н. Дрейпер, Г. Смит. – М.: Вильямс, 2016. – 912 с.
38. Доугерти, К. Введение в эконометрику: пер. с англ. / К. Доугерти. – М.: ИНФРА, 2001. – 402 с.
39. Дементьев, Л.Ф. Применение математической статистики в нефтепромысловой геологии / Л.Ф. Дементьев, М.А. Жданов, А.Н. Кирсанов. – М., 1977. – 255 с.
40. Особенности заводнения низкопроницаемых глиносодержащих пластов разноминерализованными водами / А.Я. Хавкин, З.С. Юсупова, Л.И. Гержа [и др.] // Нефтепромысловое дело. НТС ВНИИОЭНГ. – 1992. – № 8. – С. 14–18.
41. Соколовский, Э.В. Применение радиоактивных изотопов для контроля за разработкой нефтяных месторождений / Э.В. Соколовский. – М.: Недра, 1968. – 180 с.
42. Табакаева, Л.С. Экспериментальные исследования особенностей воздействия на низкопроницаемые глиносодержащие нефтяные пласты растворами полиэлектролитов: дис. … кан. тех. наук / Л.С. Табакаева. – М.: ИПНГРАН, 2007. – 174 с.
43. Ступоченко, В.Е. Влияние глинистости коллектора на полноту вытеснения нефти водой / В.Е. Ступоченко // Геолого-физические аспекты обоснования коэффициента нефтеотдачи. – М.: ВНИГНИ, 1981. – № 228. – С. 59–79.
44. Хавкин, А.Я. Влияние минерализации закачиваемой воды на производительность скважин / А.Я. Хавкин, Л.С. Табакаева // Геолого-физические факторы эффективной разработки месторождений углеводородов. – М., 2005. – С. 108–115.
45. Хавкин, А.Я. Результаты математического моделирования процесса вытеснения нефти водой из глиносодержащих пластов / А.Я. Хавкин // Опросы изучения нефтегазоносности недр. – М.: ИГиРГИ, 1981. – С. 99–104.
46. Jones, F.O. Influence of Chemical Composition of Water on Clay Blocking of Permeability / F.O. Jones // JPT. – 1964. – P. 441–446. DOI: 10.2118/631-pa
47. Khilar, K.S. Water Sensitivity of Sandstones / K.S. Khilar, H.S. Folger // SPEJ. – 1983. – Vol. 2. – P. 55–64. DOI: 10.2118/10103-PA
48. Tang, G.Q. Salinity, Temperature, Oil Composition, and Oil Recovery by Waterflooding / G.Q. Tang, N.R. Morrow. – Text: direct // SPE Reservoir Engineering (Society of Petroleum Engineers). – 1997. – Vol. 4 (12). – P. 269–276. DOI: 10.2118/36680-PA
49. Технологии нефтегазового инжиниринга: монография / В.Я. Мауль, Н.Р. Кривова, Н.Н. Савельева [и др.]. – Тюмень: ТИУ, 2023. – Ч. 1. – 167 с.

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