Features of the structure and formation of oil deposits in the sediments of the Bashkirian stage of small oil fields on the western slope of the South Tatar arch

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Abstract. Oil-bearing carbonate complexes of the Bashkirian stage of low-amplitude brachianticlinal structures on the western slope of the South Tatar arch are considered. It has been established that the prospects for oil production are associated with the upper parts of the sections, where layers of algal-foraminiferal limestones - packstone occur, overlain by dense clayed mudstone-wackestone limestones. Oil deposits of the dome type, hydrodynamically isolated, are under the pressure of regional or bottom waters. Cap rocks, reservoir rock, water-oil contacts are clearly distinguished in the structure of deposits. The formation of the main elements of oil fields occurred at the stage of sedimentation due to eustatic fluctuations in the level of the epicontinental sea basin. At the stage of transgression, the formation of future reservoir rocks took place, at the stages of regression - cap rocks. The reservoir rocks acquired high capacitive-filtration properties during the period of migration of water-oil fluids. At this time, the dissolution of micritic calcite cement took place, the removal of the dissolved substance outside the reservoir bed, the filling of the void space with oil, and the displacement of residual water to the wings of uplifts. The next stage of transformation of reservoir rocks is associated with the processes of natural waterflooding of oil deposits. The penetration of regional pressure water into the oil reservoir contributed to the formation of local zones of water-oil contacts. Due to the oxidation of hydrocarbons inside the oil deposits in the OWC zone, bituminous and water-bearing subzones were formed. In the first one, intensive leaching of calcite occurred with the simultaneous formation of patchy-banded segregations of calcitized rocks, healing of cavern cavities with diagenetic dolomite and anhydrite. In the second subzone, the process of dissolution of bituminous films on the walls of caverns was going on, accompanied by secondary cementation of pre-existing cavities with diagenetic calcite and chalcedony, which determined the light color of reservoir rocks.

1. Introduction

In recent years, for oil and gas basins, the relevance of replenishing hydrocarbon reserves has become more acute [1-5]. As large fields are developed, the involvement in the development of small and medium-sized oil reserves becomes paramount [6-8]. On territory of the Tatarstan Republic, such objects are concentrated within the western slope of the South Tatar arch and the eastern side of the Melekes depression [9]. They are small brachianticlinal uplifts, in the contours of which reservoir and dome oil deposits are concentrated [10]. The oil-bearing stage covers deposits of the Tournaisian,
Visean, Bashkirian and Moscovian stages of the Carboniferous system [11-13]. Of these, carbonate complexes of the Bashkirian stage are potentially promising [14-16]. Taking this into account, a study of the cores of wells was carried out, which completely uncovered the deposits of the Bashkirian stage within small uplifts. Preference was given to dome uplifts, in which earlier, at the stage of additional exploration, according to geophysical surveys, oil and gas shows were identified, or oil deposits were localized.

2. Materials and methods
The main research methods were optical microscopic, X-ray and differential thermal analyzes. Optical microscopic studies of oil-saturated sandstone samples were carried out using an AXIO Imager polarizing microscope. A2. at various magnifications. Based on the optical constants of the minerals composing the sandstones, the mineral composition of the reservoir rocks and the peculiarities of the relationship of mineral grains were determined.

X-ray diffraction analysis was carried out on a D2 Phaser diffractometer (Bruker, Germany) in order to detail the mineral composition. Analysis mode: X-ray tube voltage - 30 kV, current - 30 mA, scanning step - 0.02°, speed - 1 deg/min. The range of scanning angles in the Bragg-Brentano geometry was from 3 to 40°. Standard powder preparations were used. The qualitative and quantitative mineral composition was determined using the DIFFRAC.EVA and TOPAS software.

3. Results
The study of the cores of the wells that revealed the oil-bearing deposits of the Bashkirian stage showed the prospects of low-amplitude brachianticlinal structures on the western slope of the South Tatar arch. The relatively small thickness of the carbonate complexes of the Bashkirian age predetermined the proximity of the regional oil-water contact to the top of the oil-bearing uplifts. Due to this, most of the lower oil-bearing formations are at various stages of waterflooding. Often, within the brachianticlinal structures, there is only one oil deposit profitable for development, localized in the upper parts of the section of the Bashkirian stage.

The roof, reservoir layers and water-oil contact are well separated into the structure of such deposits (figure 1). The oil deposits are roofed by dense limestones formed at the regressive stage of development of the epicontinental sea basin at the Bashkirian age. The shallow-water conditions of sedimentation contributed to the formation of dense pseudo-brecciated carbonate rocks in the top of the Bashkirian stage section. Macroscopically, they are composed of light gray, less often beige due to iron enrichment in carbonate fragments cemented with greenish gray carbonate clay material (figures 1 and 2). According to optical microscopy, calcareous fragments are cracked mudstone-wackestone limestone fragments according to R.J. Dunham [17]. The rocks are composed of tightly contiguous xenomorphic calcite grains ~0.01 mm in size, which are recrystallized in some areas to a fine-grained structure. The granular mass contains inclusions (5-15%) of organic remains represented by fragments of algae, calcispheres, and ostracod shells. Limestone fragments have an edge of clay material. The similar structure of the rocks determines their low capacitive-filtration properties. According to petrophysical studies, the porosity of pseudobrecciated limestones is 2-3%, the permeability is 0 µm². Due to this, the rocks are good cap for oil-water fluids.

Reservoir rocks in all sections of the roof of the Bashkirian stage are represented by algal-foraminiferal limestone - packstones. Limestones are characterized by uniform vugginess and oil saturation, dark brown color, and massive texture (figures 1 and 2). The rocks are 80-85% composed of organic residues, 15-20% - mineral cementing substance. Organic remains with an average size of 0.1-0.25 mm are represented by whole granular shells of foraminifera (55%), microgranular lumpy aggregates (20%), recrystallized fragments of algae (15%), to a lesser extent, segments of crinoids (5%) and shells of brachiopods (5%). Bioclasts are in close contact with each other, forming a rigid incompressible skeleton with a rhombohedral type of structural packing. The organic remains are cemented with calcite cement. There are two generations of cement: syngenetic (sedimentary) and epigenetic (diagenetic). Sedimentary cement of porous type, microgranular in structure, partially
leached from the intergranular space, often fixed in the form of rims on the periphery of bioclasts. Diagenetic cement of porous type, clear-grained in structure, partially fills previously formed cavernous cavities. According to petrophysical studies, the porosity of the rocks is 15-20%, the permeability is 0.069 µm². The thickness of reservoirs with uniform oil saturation can vary from 2.5 to 4.0 m.

![Figure 1. Lithological section of the Bashkirian stage oil reservoir with photographs of the main sedimentary rocks types.](image-url)

The bottom of the oil deposits of the roof of the Bashkirian stage is set by the position in the sections of the level of water-oil contact (WOC). In most cases, within low-amplitude uplifts, the WOC passes in the bottom part of the reservoir, where oil was previously located. Due to the flow of regional waters into the reservoir rocks, oil in the lower part of the deposit is gradually oxidized, turning into a non-recoverable resource [18]. Thus, the oil-productive interval is limited from below by the area of development of heavy hydrocarbons of oxidized oil. Within the considered oil deposits, the WOC zones have a complex structure. According to the composition of the fluid, they are divided into two subzones: bituminous and aquiferous. The bituminous subzone is located directly at the contact with the oil fluid, separating it from the underlying formation waters. Here, hydrocarbons are mainly represented by bitumen filling the porous-cavernous space of reservoir rocks. The thickness of the bituminous subzone can reach up to 4.0 m. Packstone are characterized by the appearance of dense light gray veinlets consisting of aggregates of clear-grained calcite in a uniformly oil-saturated rock.
According to X-ray analysis, diagenetic dolomite and anhydrite appear in the bituminous subzone. In the aquifer, which reaches a thickness of 2.5 m, packstones in the void-cavernous space contain mainly formation waters. Bitumens form isolated areas in the form of spots and veins. Due to the washing out of rock hydrocarbons, the reservoirs acquire a dominant light gray color (figures 1 and 2). According to X-ray analysis, diagenetic chalcedony appears in the limestones of the aquifer. The study of thin sections shows that the newly formed fine-grained chalcedony metasomatically replaces the calcite of the original rock.

4. Discussion
The results obtained show that within the low-amplitude brachyanticlinal uplifts of the western slope of the South Tatar arch, the most promising for development are the upper parts of the sections of the Bashkirian stage. Oil deposits located in the middle and lower parts of the sections of the Bashkirian carbonate complex have undergone oil oxidation processes due to a regressive shift in the level of the regional WOC. Therefore, when trying to develop them, heavily watered oils are often obtained at the output. Oil-bearing reservoir rocks are algal-foraminiferal packstones that have undergone leaching processes, cap rocks are dense clayed mudstone-wackestone. Thus, the structure of oil deposits is determined by the lithofacies features of carbonate sedimentation in the epicontinental marine basin at the Bashkirian age. Packstones were formed in a relatively deep coastal-shallow part of the sea basin. The presence of algae, microbial lumpy aggregates, foraminifera, and crinoids is characteristic of the photic zone of the epicontinental paleosea with a calm hydrodynamic regime. Under these conditions, carbonate mud sediments formed, consisting of organic residues with an admixture of micrite material. Mudstone-wackestones were formed in shallower water conditions close to lagoonal ones with limited water exchange. Due to the increase in the salinity of sea water, the process of biochemogenic formation of finely dispersed carbonate mud prevailed. The biota was in a depressed state, which predetermined the relatively low content of organic residues in the sediment. Periodically, weakly lithified bottom sediments were subjected to wave action. There was cracking of rocks with washing out of clay material. At some time, carbonate rocks were exposed above the sea level. Under continental conditions, micritic limestones were enriched in iron hydroxides, acquiring a brownish color. The structural features of carbonate rocks acquired at the stage of sedimentogenesis determined their different resistance to the impact of aggressive underground fluids. Packstones, which have better primary permeability, have undergone leaching processes, becoming reservoir rocks. Due to the subcapillary sizes of intergranular pores filled with immobile pore solutions, mudstones-wackestones with clay layers turned out to be more resistant to dissolution, becoming cap rocks.

Fluid lithogenesis of reservoir rocks proceeded in two stages. In the first stage, packstones underwent leaching processes under the action of acidic agents of migrated deep fluids. The leaching was mainly due to the micritic cement calcite, as the most unstable component of the bioclastic carbonate rocks. The leaching of microgranular calcite was accompanied by the removal of the dissolved substance with the formation of communicating pore-caverns. The water-oil fluids that came
later filled the prepared reservoirs, forming oil deposits. In the process of density convection in the dome part of the reservoir, the reservoirs were filled mainly with oil with a small water cut. The main part of the formation water was pushed back to the wings of the brachianclinal structures. A similar distribution of immiscible liquids is observed in the Bashkirian deposits on neighboring higher-amplitude uplifts. The incoming oil stopped all geochemical processes in reservoir rocks for a long time [19-20]. The second stage of fluid lithogenesis is associated with the beginning of natural flooding of oil deposits located at the top of the sections of the Bashkirian stage. Regional formation waters, penetrating into reservoirs, formed local zones of water-oil contacts, which, under hydrostatic pressure, gradually shifted from bottom to top to the roof of oil deposits. At the contacts of water and oil, there were processes of biochemical oxidation of hydrocarbons, accompanied by the accumulation of bitumen. Organic and inorganic acids entering the pore solutions lowered the pH of the medium, increasing its aggressiveness with respect to calcite. As a result, carbonate matter is redistributed in the reservoir rocks of the bituminous subzone. In some local areas, calcite was dissolved, in others it was redeposited. This is how dark brown bituminous limestones with numerous light gray spotty banded segregations of dense calcitized rock were formed. Periodic fluctuations in the partial pressure of carbon dioxide in pore solutions contributed to the formation of small dolomite grains that encrust the walls of caverns. The appearance of anhydrite is associated with the penetration of sulfate ions into the reservoir rocks as part of the aquifer formation waters. In the water-bearing subzone, due to the increased content of carbon dioxide, bituminous deposits on the walls of the pores were dissolved, and the pores were healed by newly formed calcite. Thus, clarification and secondary compaction of carbonate rocks of the cementation zone took place. In the case of the introduction of migratory silica, part of the limestone calcite was replaced by fine-grained chalcedony. Currently, oil deposits in the top of the Bashkirian stage of low-amplitude uplifts are isolated hydrodynamically isolated systems. Oils are under the pressure of regional or bottom water.

5. Conclusion
Considering the above, the following conclusions can be drawn:

- The prospects for the development of oil-bearing carbonate complexes of the Bashkirian stage of low-amplitude uplifts of the western slope of the South Tatar arch are associated with the upper parts of the sections. The volume of oil production will be determined by the thickness of the algae-foraminiferal packstones and the intensity of their leaching. Oil deposits of the dome type, hydrodynamically isolated, are under the pressure of regional or bottom waters.
- The formation of the main elements of oil deposits was carried out at the stage of sidementogenesis due to eustatic fluctuations in the level of the epicontinental sea basin. Reservoir rocks were formed at the transgressive stage of development of the sea basin, seal rocks - at the regressive one. The improvement in the capacity and filtration properties of packstones occurred during the period of migration of water-oil aggressive fluids of the rock.
- Oil deposits in the upper parts of the sections of the Bashkirian stage have a complex structure. Due to the high position of the level of the regional oil-water contact in the reservoirs, the oil reservoir itself and the OWC zones are separated, within which the bituminous leaching subzone and the water-bearing cementation subzone are distinguished.

References
[1] Fadeeva N P, Poludetkina E N, Natitnik I M and Akhunyanov I Kh 2017 Hydrocarbon potential of the Devonian coal formations of the Dnepr-Donetsk trough. Georesources 240-248
[2] Gatiyatullin R N, Vojtovich S E, Sukhov K A and Akhmetshin A Z 2017 Localization of occurrence zones of super-viscous oil resources in poorly studied areas of the Melekesskian depression. Geologiya nefti i gaza 6 83-88
[3] Muslimov R Kh 2016 Modernization of the Russian oil Industry on the way for innovations and Global trends. Georesources 18(4) 246-255
[4] Trofimov V A, Goryunov E Yu and Sabirov I A 2016 Innovative approaches to the solution of searching hydrocarbons in deep horizons of the Volga-Ural oil and gas province. Georesources 19(1) 59-68

[5] Valeeva I F, Anisimov G A, Anisimova L Z and Novikova S P 2016 Geological background of the further exploration of oil in the Nizhnekamsk deflection. Georesources 18(3) 198-206

[6] Muslimov R Kh 2020 The experience of rational development of hydrocarbon resources in the Earth’s interior used in the new paradigm of Academician A.E. Kontorovich – the development of oil and gas complex of Russia. Georesources 22(5) 5-9

[7] Nefyodorov N V, Karpov V B, Kalmykov A V and Nikiforov A I 2014 Features of development and modeling of the small fields dated for massive deposits of carbonate type (on the example of objects of JSC RITEK – Chamber of Commerce and Industry Tatritekneft). Georesources 2(57) 8-12

[8] Kataev O I, Larochkina I A and Reytyukhov K S 2015 Topical issues of the search for new oil fields in the Volga-Ural province. Neftyanoe khozyaystvo - Oil Industry 1 33-37

[9] Petrov M A, Nasibulin I M, Misolina N A, Kolchygin A N, Vafin R F, Kruglov M P and Kazanbaeva O V 2009 The problem of mining highly oils Bashkir time tier east side Melekkessky depression. Georesources 3(31) 38-41

[10] Khusainov R F, Nazimov N A, Gumarev N F, Ganiev B G, Shvydenko M V and Absalyamov R Sh 2015 Development of low permeable Domanic reservoirs using massive hydraulic fracturing on the example of Production Department Almetyevneft PJSC Tatneft. Georesources 4(63) 17-24

[11] Kolchugin A N, Morozov V P, Korolev E A and Eskin A A 2014 Carbonate formation of the Lower Carboniferous in central part of Volga-Ural basin. Current Science 107(12) 2029-2035

[12] Kayukova T P, Kurbsky G P, Yusupova T N, Gabitova R K, Mutalapova I I, Nigmedzyanova L Z, Romanov G V and Mukhametshin R Z 1993 Features of the composition and properties of oils in the section of productive strata in Tatarstan. Geologiya nefti i gaza 5 37-43

[13] Korolev E A, Kolchugin A N, Morozov V P, Nizamutdinov N M and Pronin N V 2014 The reasons of low efficiency of oil extraction from reservoirs of the Vereyskian horizon at Akanskoye oilfield. Neftyanoe khozyaystvo - Oil Industry 10 57-59

[14] Kolchugin A N, Morozov V P, Korolev E A, Eskin A A and Gazeeva FM 2013. Typical sections of Bashkirian carbonate rocks and structure of oil deposits in the southeast part of the Republic of Tatarstan. Neftyanoe khozyaystvo - Oil Industry 11 84-86

[15] Nugmanov I I, Starovoytov A V, Ziganshin E R and Kazakov V V 2018 Geomechanical properties of Bashkirian carbonates from Akanskoye deposit subject to lithogenetic type. Neftyanoe khozyaystvo - Oil Industry 2 30-35

[16] Yusupova T N, Ganeeva Yu M, Tukhvatullina A Z, Romanov G V, Muslimov R Kh and Kruglov M P 2012 Composition of oils in carbonate formations of the Vereya and Bashkir deposits of the Akan field of the Republic Tatarstan. Petroleum chemistry 52(4) 243-248

[17] Dunham R J 1962 Classification of carbonate rocks according to depositional texture: Classification of carbonate rocks. Bull. Amer. Assoc. Petrol. Geol. 1 108-121

[18] Petrova L M, Yusupova T N, Foss T R, Mukhametshin R Z and Romanov G V 2004 Characterization of bitumens from the oil-water contact zone of the Bavlinskoe oil field. Petroleum Chemistry 44(5) 304-310

[19] Gedoliko N M 2010 Evolution of the void space in the zones of water-oil contacts. Bulletin of the Tomsk Polytechnic University 316(1) 99-107

[20] Sakhigareev R S 1989 Secondary changes in reservoirs in the process of formation and destruction of oil deposits (Saint Petersburg: Nedra) 260