The influence of lithofacies features of the Permian natural bitumen-saturated reservoir rocks on groundwater formation conditions

R L Ibrahimov¹, E A Korolev¹, A AEskin¹, A N Garaeva¹, E R Barieva²

¹ Institute of geology and petroleum technologies, Kazan Federal University, Kazan, Russia
² Kazan State Power-engineering University, Kazan, Russia

E-mail: ibragimovrl@yandex.ru

Abstract. The reservoirs rocks of natural bitumen deposits of the Lower Permian system and the Kazanian stage of the Tatarstan territory are considered. The relationship of groundwater composition in bitumen reservoirs with lithologic features of water-saturated rocks is shown. Rocks compositions contribute to formation of three water classes in oil deposits: hydrocarbonate, sulfate and chloride. Hydrocarbonate waters lie over erosion downcutting of rivers in the most elevated territory part. Their origin is associated with hydrolysis and carbon-dioxide leaching of the Permian terrigenous rocks. Inland waters of hydrocarbonate-sodium (soda) composition of bitumen deposits are located above local drainage basis. They are formed as a result of sulfate reduction processes in deposits. The inland waters of sulfate composition of calcium and sodium groups are characteristic of deposits located below the drainage basis. Their origin is associated with dissolution of gypsum and anhydrites, as well as with ion exchange reactions between the calcium of the solution and the sodium which absorbed by rock complex. Chloride waters associated within the eastern side of the Melekess Depression, where there is an active hydrodynamic relationship between the Permian system aquifers and chloride-calcium salt brines of the Carboniferous rocks. The nature of the distribution and presence of aquifers in deposits is determined by the lithological features of reservoir formation.

1. Introduction

Groundwater is formed as a result of a complex interaction of geological, physical-geographical, physical-chemical, biological and artificial factors. These factors activate processes that affect the water composition: dissolution, leaching, crystallization (precipitation), hydrolysis, sorption, etc. The direction and intensity of these processes depend on the specific geological and hydrogeological features of the studied hydrogeological system. Also the sources themselves are different. Depending on geological, hydrogeological and hydrodynamic conditions of the territory, such sources are: atmospheric precipitation; gases; rocks and organic substances contained in them; oil; juvenile and sedimentation waters. Moreover, lithological composition of rocks is the main source that determines the groundwater qualitative composition. This effect on groundwater composition is well manifested in presence of water-soluble rocks and minerals (limestone, gypsum, dolomite, calcite, rock-salt).
In the eastern and southeastern regions of the Tatarstan Republic, a very close relationship is found between waters component composition and the lithological features of water-saturated rocks. In the Permian deposits of the Tatarstan Republic, several natural reservoirs are distinguished [1]. It depends on the deposits stratigraphy, the distribution and occurrence of various types of cap rocks and collectors.

The natural reservoir (according to I.O. Brod [2]) is a natural reservoir, bounded by impermeable rocks above and below, inside which fluids can circulate. The collectors are rocks that make up reservoirs and can contain mobile substances (water, oil, gas) and give them. From point of view of bitumen saturation, the most common are the Lower Permian and Kazanian reservoirs. They were formed in various facies and paleogeographic environments during sedimentation.

Using these reservoirs as an example, we show the influence of lithological-facies features of bitumen deposits rocks on conditions for formation of the groundwater chemical composition.

2. Results and Discussion

2.1. The Lower Permian system natural reservoirs

According to the lithological composition of reservoirs and overlapping them cap rocks, two classes deposits are distinguished: carbonate and terrigenous [3, 4].

In the carbonate reservoir complexes structure are carbonate sediments of the Asselian, Sakmarian, Artinskian and Kungurian stages of the Lower Permian system. They are represented by dolomites and limestones with intercalations of anhydrite and gypsum of marine and lagoon-marine origin. Reservoirs cap rocks are dense different dolomites with gypsum and anhydrite inclusions. The predominant type of reservoirs is mixed, fissured-porous-cavernous. These are the most spacious reservoirs which subjected to secondary leaching processes. The intergranular porosity of reservoirs averages 10–12% and sometimes increases to 30% [1]. Bitumen deposits are associated with porous dolomites and calcareous dolomites within the eastern side of the Melekess Depression (MD), the southwestern and southeastern slopes of the South Tatar Arch (STA).

The prevalence and thickness of marine facies is increasing to westerly direction (towards the MD). The thickness of lagoon-marine facies is increases to direction of the southwestern and southeastern slopes of UTS.

In the terrigenous reservoir complexes structure are sediments of the Ufimian stage of the Lower Permian system [5]. They are represented by lacustrine-alluvial facies of continental depositional (accumulation) plain. The reservoirs cap rocks are clays of the Lower Kazanian stage (Nemidian horizon), the so-called "Lingula Shales Member". According to lithological composition, they are divided into two parts: the lower one composed of clay-carbonate gray-colored layers and the upper, represented by red-colored sandstones, clays and siltstones. By pore space nature they belong to porous type.

The main industrial accumulations of bitumen are associated with highly porous sand layers of the Sheshmian horizon of the Ufimian stage. These rocks are beach barrier sand paleo-reefs and looks like brachyanticline [6, 1]. The porosity of sandstones is uneven [7]. In the upper part, it reaches 40%, and in the lower - 14%, an average of 27%.

The nature of distribution and presence of studied reservoirs aquifers is determined by lithological features of deposits formation. In separate, most elevated by geomorphologically and tectonically areas, aquifers are found in almost all geological units. But their number depends on presence of water cap rocks in the considered section. For example, in central parts of the Tatarstan, in the erosion surface of
anhydrite and gypsum-bearing rocks of the Tastubian and Sterlitamakian horizons of the Sakmarian stage, where they acted as local aquifer cap rocks, instead of two aquifers in the Asselian and Sakmarian stage sediments, only one horizon is found. They are associated with fractured, cavernous limestones and less commonly to dolomites. Such reservoirs are characteristic for areas of karst processes distribution. Moreover, karst can cover not only the Sakmarian and Asselian stage sediments, but also rocks of the Artinskian, Kungurian stages of the Lower Permian system and even the Upper Carboniferous system formations. In this case, a single aquifer complex is forming. The areas of fractured-cavernous reservoirs development into surface plan coincide with modern and ancient river valleys [8].

Aquifers identified within the bitumen deposits have their own hydrochemical features associated with their location in the geological section. Some aquifers are in constant contact with reservoir, which certainly affects to waters chemical composition. As a rule, these waters in microcomponent composition contain water-soluble organic matter (OM), sulphuretted hydrogen, an increased amount of ammonium, iodine, and bromine. According to the oilfield classification, these are internal, bottom, and marginal waters which coincide with the same reservoirs as bitumens. Internal or intermediate waters are located inside the deposit itself, the bottom waters underlie deposit below, and the marginal (upper and lower) at edge parts of deposit. Upper and lower waters are also allocated and associated to purely aquifers, which lie above and below the bitumen reservoir. This arrangement of aquifers is associated with the conditions for bitumen deposits formation. It is believed that bitumen-saturated formations were initially completely containing with water. During the formation of deposits, due to their lower density, bitumen fluids migrated to elevated parts of the reservoirs, displacing water from there. One way or another, aquifers formed in the same lithologic-facies conditions as bituminous deposits.

According to prevailing water components of the Lower Permian carbonate reservoirs, they have sulfate-calcium or sulfate-sodium compositions [9]. The predominantly sulfate-calcium composition, with a total salinity of 0.6 to 2.8 g/dm³, is characteristic to upper waters of bitumen deposits located on the western slope of the UTS, above the river water's edge. Water of similar composition was found in the dome part of the UTS and STS. Sulfate-calcium waters with a total salinity of 3.7 to 4.3 g/dm³ are also found on the western slope of the UTS, but at lower absolute elevations. Sulfate-sodium waters are somewhat less common. They are common in the lower part of the Sheshma River and the east side of the MD. The predominance of sodium over calcium in groundwater composition is usually observed at total salinity of 3.9-5, sometimes 8-10 g/dm³. Finally, in areas of significant basin subsidence of the Lower Permian carbonate deposits (east side of the MD, eastern and south-eastern slopes of the UTS), the upper, inner and lower waters acquire a chloride-sodium composition. The total salinity of these waters varies from 13.8 to 77.4 g/dm³ (the Gorskoye deposit).

The water content of terrigenous reservoirs of the Ufimiam stage is associated with weakly cemented the Sheshmian horizon sandstones. Three types of waters are noted according to O.A. Alekin: sulphate-calcium, sulphate-sodium and hydrocarbonate-sodium [10].

The presence of weakly mineralized waters of sulphate-calcium composition is typical for shallow depths and areas with a fairly active connection with the surface. Similar conditions are characteristic for upper waters of bitumen deposits. They have a total salinity of 0.8 to 4.4 g/dm³. Water of the same composition is observed in bitumen deposits edge-water zone and in basins of the Melli and Menzeli Rivers, in valley of the Kama River and in lower part of Ik River. The total salinity of water varies from 0.6-0.8 to 2.7-3.0 g/dm³ [9].

Sulphate-sodium waters are usually associated with terrigenous gypsum-bearing deposits of lagoon-marine origin. They are characteristic for inland waters of bitumen deposits, which lie below drainage
basis of the region main rivers (Karmalinskoye, Vostochno-Sheminskoye, Averyanovskoye, Severo-Ashalchinskoye deposits) [1]. The total salinity of waters varies between 3.98 and 5.0 g/dm³. They noted an increased content of sulphuretted hydrogen (up to 497 mg/dm³), bitumen fraction carbon (up to 2 mg/dm³). Similar water, but without water-soluble OM and sulphuretted hydrogen, are found in valley of the Vyatka and Kama Rivers. Hydrocarbonate-sodium (soda) water is found in all inland waters of bitumen deposits located on the western slope of the UTS in active water regime zone (above water's edge of modern rivers). All studied deposits contain bitumen that is in different stages of oxidation. The depth of their occurrence varies from 60 to 100 m. The total salinity varies from 1.02 to 6.7 g/dm³. The waters are enriched with water-dissolved OM (C_{org} up to 18.49 mg/dm³) and sulphuretted hydrogen up to 640 mg/dm³. An increased content of ammonium (more than 2 mg/dm³) and iodine (more than 1 mg/dm³), bromine (0.7-0.9 mg/dm³) are also noted.

It must be said that all waters in contact with bitumen deposits are distinguished by a high content of water-dissolved OM and sulphuretted hydrogen. The content of total organic carbon, bitumen fraction carbon, organic nitrogen, sulphuretted hydrogen increases as it approaches to deposit.

2.2. The Kazanian stage natural reservoirs

The structure involves carbonate-terrigenous and terrigenous-carbonate classes of reservoirs, represented by sediments of the Lower Kazanian and Upper Kazanian stages of the Permian system. They are characterized by porous, fractured, porous-fissured, porous-cavernous, porous-fissured-cavernous reservoirs [11, 1].

The carbonate-terrigenous class reservoirs are distinguished by development marine and lagoon series formations. These are sediments of the Nemdinskian horizon of the Lower Kazanian stage. Here, the cap rock is clays. For of the Baitugan beds fractured reservoirs, composed of limestones with insignificant thickness and distribution, are typical. In the Kamyshla beds, the presence of highly porous reservoirs is associated with lithofacies of bioclastic and oolitic limestones. The most common are cavernous, porous-fissured, porous-cavernous types of reservoirs with average porosity of which reaches 27-32% or more. For terrigenous formations - porous and fissured-porous types of reservoirs.

The main natural reservoir of the Barbashin beds, composed of porous, fine-grained sandstones, is developed within area of the MD. The reservoir porosity reaches 15%.

The terrigenous-carbonate class reservoirs are distinguished by a more complex structure. They are represented by the Upper Kazanian deposits of the Povolzhian horizon. They contain heterogeneous and lithologically irregular rocks (interlayering of sandstones, siltstones, marls, clays, gypsums, limestones), which also include conglomerate and sedimentary breccia. A particularly significant concentration of these clastic rocks is noted in the "Perekhodnaya" member. Red-colored sandstones and siltstones of the continental facies are prevailing. The role of cap rocks of this reservoir is performed by dense variations of carbonate rocks. The porosity of deposits which associated with lithofacies of bioclastic carbonate rocks averages 13% and sandstones 8-10%.

The distribution of bitumen across the section and over area is uneven. Basically, deposits were identified within the eastern side of the MD. The bituminosity of the Lower Kazanian deposits is associated with the Kamyshla and Barbashin beds, and the Upper Kazanian deposits are associated with terrigenous-carbonate rocks (with members of the “Yadrenyi Kamen” and “Seryi Kamen”, partially with member of “Podluzhnik” and “Perekhodnaya”).

The sediment water content is also associated with these lithofacies.
Three aquifers stand out in carbonate-terrigenous class reservoirs of the Lower Kazanian stage. The most water-saturated is the aquifer, which lies above the lingula shales member and is composed mainly of limestones and dolomites. The second and third aquifers are associated with overlying sandstones and limestones. The groundwater chemical composition is represented by three classes: hydrocarbonate, sulfate and chloride [9].

Hydrocarbonate-calcium (less often magnesium and sodium) and sulfate-hydrocarbonate-calcium waters with total salinity up to 1 g/dm³ are developed in the most elevated slope and dome parts of the UTS. Here, water-saturated sediments are represented by red-colored delta-coastal and shallow-marine sediments (sandstones, clays with thin intercalations of limestone and marl).

Against the background of hydrocarbonate water spreading, abnormal sections of sulfate groundwater of calcium and sodium groups are distinguished. The distribution sites of sulfate waters usually correspond to low absolute elevation of aquifers (river valleys). Their total salinity reaches 4 g/dm³.

Three aquifers are also found in the terrigenous-carbonate class reservoirs of the Upper Kazanian stage. The lowest aquifer is associated with sandstones and siltstones lying at lower part level of the “Sloisty Kamen” pack and upper part of the “Yadrenyi Kamen” member. The overlying aquifer corresponds to packs of the “Shikhany”, “Seryi Kamen”, “Podboi” and is represented by sandstones, siltstones, limestones and dolomites. The next aquifer is presented by sandstones of the “Opoki” member, siltstones, fractured and cavernous limestones, and dolomites of the “Podluzhnik” pack. Fractured carbonate rocks (source flow rates up to 10 l/sec) are water-saturated reservoirs. All waters are artesian.

According chemical composition and predominant components, the water is hydrocarbonate magnesium-calcium or calcium-magnesium and hydrocarbonate-sulfate magnesium-calcium with a total salinity of 0.3-0.7 g/dm³. Such water compositions of reservoirs are characteristic for the slope parts of the UTS.

The waters of bitumen deposits located on the eastern side of the MD are characterized by a different composition. Here, in the context of the Lower Kazanian and Upper Kazanian sediments, not sodium Hydrocarbonate and sulphate deposits, but chloride-sodium salt waters and brines with a total salinity of up to 52 g/dm³ were found.

Summarizing what has been said, it can be noted that studied reservoirs are characterized by unstable and intermittent nature of distribution. This is primarily due to presence in these complexes of various lithofacial types of reservoirs with secondary processes traces in the form of recrystallization, sulfatization and calcification, leaching and fracturing. All this ultimately had a significant impact on groundwater chemical composition which saturated these reservoirs.

The origin of calcium hydrocarbonate, magnesium-calcium sodium-magnesium-calcium waters of the Kazanian depositsis associated with hydrolysis and carbon-dioxide leaching of aluminosilicates, which are one of the Permian terrigenous rocks constituent parts [12]. As a rule, these waters lie above erosion cutting of rivers in the most elevated part of territory.

Among the sulfate class waters, the most widely used waters of sulfate-calcium and sulfate-sodium compositions. The water formation of sulfate-calcium composition is associated with dissolution and leaching of gypsum-bearing rocks, which is confirmed by amount of total salinity (does not exceed 3 g/dm³), which approximately corresponds to gypsum solubility under standard conditions (2.09 g/dm³). Sulphate-sodium waters are more total salinity. They are usually found at depths of 300-400 m. Their appearance at depth of only 100-200 m and above is associated with unloading of underground waters deeper horizons. The water origin is associated with dissolution and leaching of gypsum and subsequent ion exchange reactions between calcium of solution and sodium which absorbed by rock complex.
If the formation of sulphate-calcium and sulphate-sodium waters is practically not in doubt, then the formation of hydrocarbonate-sodium (soda) water is still one of the most difficult and debatable.

The above data show that the most acceptable hypothesis for sodium water formation is biogenic theory of Posokhov [13]. Since all conditions described above coincide with the lithological and hydrogeochemical conditions for such waters formation in studied deposits. According to this hypothesis, sodium water is formed as a result of sulfate reduction under influence of desulfurizer bacteria in presence of organic matter and sulfate ion, which, when in an anaerobic environment, create favorable conditions for these bacteria activity. This process is approximately represented as a chemical reaction:

$$SO_4^{2-} + 2C + 2H_2O = H_2S + 2HCO_3^-$$

According to E.V. Posokhov and S.L. Shvartsev [13], the formation of sodium waters through biochemical desulfatization is possible where water exchange is difficult, which corresponds to conditions of occurrence of inland waters in the Tatarstan bituminous deposits.

The presence of chloride waters within the eastern side of the MD by many researchers is associated with the presence of hydrodynamic connection between considered aquifers and underlying ones.

In is confirmed by increased diversity on this territory and practical lack of reliable cap rocks at below.

3. Conclusions

Thus, based on the foregoing, the following conclusions can be drawn:

1. The presence in the section of studied deposits, reservoirs with unstable and intermittent distribution and bedding, special lithofacial features of formation, led to the formation of three water classes: hydrocarbonate, sulfate and chloride.

2. Hydrocarbonate waters lie above erosion cutting of rivers in the most elevated part of the territory. Their origin is associated with hydrolysis and carbon-dioxide leaching of the Permian terrigenous rocks.

3. Another biochemical environment of formation is waters of hydrocarbonate-sodium (soda) composition, characteristic of inland waters of bitumen deposits located above local drainage basis. They are formed as result of sulfate reduction, under the influence of desulfurizer bacteria in organic matter present (in this case, bitumen) and sulfate ion.

4. In the microcomponent composition of all waters in contact with bitumen deposits appears sulphuretted hydrogen and water-soluble organic matter, the content of which increases as it approaches the deposit.

5. The sulphate waters of calcium and sodium groups with increased total salinity are characteristic for inland waters of the deposits located below drainage basis. They are also found in areas of river valleys and tectonically fractured zones. The origin of the first is associated with dissolution and leaching of widespread gypsum and anhydrite, and the second, with dissolution and leaching and ion exchange reactions between calcium of solution and sodium which absorbed by rock complex.

6. Chloride class waters are noted within the eastern side of the Melekess Depression, where there is an active hydrodynamic connection between aquifers of the Kazanian stage and underlying sediments. For this reason, chloride-calcium brines with increased bromine content are inflowing from below.
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