

Genetic classification of subsurface waters and brines of Arctic regions of Siberia

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Abstract. Specificity of hydrogeological aspects of the Siberian sedimentary basins is most pronounced in their Arctic part where the saltless type the cross section grades into saline type in the direction from the Yamal Peninsula (as part of the West Siberian sedimentary basin), passing through the Yenisei-Khatanga basin as far as the Anabar-Khatanga basin with salt domes in its structure. It has been established that the modern chemistry of groundwaters and brines of petroleum-bearing deposits is a product of long-term geological evolution affected by many geological and hydrogeological factors. Slightly metamorphosed groundwaters and weak brines of sodium chloride, chloride-bicarbonate sodium and sodium bicarbonate-chloride composition, with the TDS value varying from 2 to 63.3 g/dm³ (after S. A. Shchukarev) are widely developed within the West Siberian and the Yenisei-Khatanga basins. Subsurface brines from the areas adjacent to the Anabar-Khatanga basin are found to be dominantly sodium chloride in composition, with TDS value varying from 52.3 to 312.3 g/dm³, while those identified in the adjacent areas of the Siberian platform are strongly metamorphosed, of sodium chloride, sodium-calcium and calcium composition, with the TDS value up to 480 g/dm³. Results of the detailed hydrogeochemistry analysis of petroleum reservoirs and paleohydrological history of Arctic parts of the Siberian sedimentary basins have prompted the presence of three genetic groups of subsurface waters in their section: infiltrogenic, sedimentogenic and condensatogenic. The first group includes modern and ancient infiltrogenic waters and brines resulting from salt domes leaching; the second group is composed of sedimentogenic waters (including brines), lithogenic waters and cryopegs. Comprising condensatogenic waters formed syngenetically with the hydrocarbon pools, the third group represents a special type, since the "water-rock-gas-organic matter" system has largely affected the processes of formation of their chemical composition.

1. Introduction

Given that the Arctic is a region with unique potential hydrocarbon resources, its sedimentary basins has justifiably attracted great scientific interest. The fact that more than 90% of Russia's gas and about 10% of oil is currently produced from the discovered oil and gas fields there [1] attests to the presence of commercial hydrocarbon accumulations in many of its sedimentary basins: the West Siberian, Yenisei-Khatanga, Anabar-Khatanga and others. The uniqueness of Arctic reserves consists in the structural level of hydrocarbon potential comprising deposits with the age spanning from the ancient Precambrian through the Quaternary, across the studied basins [1–6]. The hydrogeological structure of Arctic parts of the sedimentary basins of Siberia is also very complex and is controlled by many factors. It stands to reason that the exploration extent of their hydrogeology is extremely varied, with



the West Siberian sedimentary basin (WSSB) being thus far the best studied [7] (Figure 1). The significant role played by water in the formation of sedimentary rocks and the processes of migration, accumulation and degradation of hydrocarbons is distinctly inferred from the fundamental works of V. I. Vernadskii, V. A. Sulin, G. M. Sukharev, A. A. Kartsev and other scholars.

An enormous pool of factual material reflecting the chemical and gaseous composition of subsurface waters and brines has been accumulated since early days of exploration and prospecting for oil and gas in Arctic parts of the Siberian sedimentary basins. The numerous hydrogeochemistry research were conducted by A.S. Antsiferov, M. B. Bukaty, V.I. Vozhov, G.D. Ginsburg, Yu.G. Zimin, G.A. Ivanova, M.K. Kalinko, A. A. Kartsev, A. E. Kontorovich, N. M. Kruglikov, A. R. Kurchikov, V. M. Matushevich, D. A. Novikov, B. P. Stavitskii, O. N. Yakovlev and others. The specific features of hydrogeological structure and conditions of the North-Alaska, Beaufort-Mackenzie, Sverdrup, West Greenland, East-Canadian, Alberta, Athabasca and the other basins are discussed in the works of H. Baadsgaard, S. Bachu, Z. Chen, C.A. Connolly, K. Dewing, M. Gascoyne, S.E. Grasby, J.S. Hanor, B. Hitchon, Y. Lee, F.J. Longstaffe, J.A. Nunn, C.M. Sauveplane, R.L. Stotler, J.R. Underschultz, L.M. Walter, and others. However, despite the lengthy period of study of the Siberian sedimentary basins, the genetic classification of subsurface waters and brines within them has still been largely overlooked.

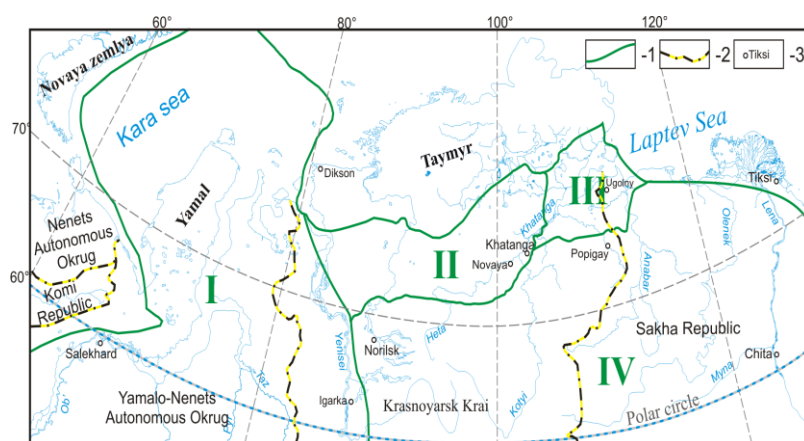


Figure 1. Location of the studied area. Boundaries of: 1 – basins limits, 2 – administrative; 3 – settlements. Sedimentary basins: I – West Siberian, II – Yenisei-Khatanga, III – Anabar-Khatanga, IV – Siberian platform.

In the first half of the last century, hydrogeochemical studies involved a number of classifications of subsurface waters and brines. Suffice it to recall the chemical classification after S. Palmer (1911), M. G. Kurlov (1928), E. Karstens (1932), V. A. Aleksandrov (1932), V. I. Vernadskii (1933), S. A. Shchukarev (1934), V. A. Sulin (1935, 1946), I. I. Chebotarev (1955), H. Schoeller (1955), O. S. Dzhikia (1963), as well as the modified classification by V. A. Sulin L. Bojarski (1970) and others [8–18]. A number of chemical classifications with elements of genetic bias was developed by N. S. Kurnakov-M. G. Valyashko (1917, 1935, 1954), A. M. Ovchinnikov (1954), E. E. Belyakova (1968) and others. Whatever the Earth's hydrosphere origin and evolution, the water was involved in a variety of cycles, which led to the formation of different genetic types of subsurface waters generally understood as types, unified by single source of groundwater recharge, the mechanism of penetration into the subsurface strata and the general direction of water circulation processes [25]. Developing a genetic classification of subsurface waters was dealt with by many scholars, among them E. Suess (Deutsch: Eduard Sueß), R. A. Daly, A. A. Kozyrev, G. N. Kamensky, N. I. Tolstikhin, A. M. Ovchinnikov, E. T., Degens, H. Schoeller, A. A. Kartsev, D. E. White (D. E. White), E. V. Pinneker and others [19–24]. Previously, G.N. Kamenskii [19] identified three genetic cycles of subsurface waters: 1) infiltration, or continental, associated with the infiltration of atmospheric water and a complex of geochemical processes occurring in the uppermost earth's crust. 2) marine, or sedimentational, associated with the burial of marine waters during sedimentation and with their

further metamorphization (metamorphic changes). 3) Metamorphic or magmatic type is associated with the formation of deep waters. Given that it is by far almost impossible to distinguish between magmatic and metamorphic waters, it makes sense to combine the two cycles into one – metamorphogenic-magmatic. Material manifestations of a cycle may not always be distinguished in the pure form, because of the cycles interacting with each other, which leads to the mixing of different genetic types of waters. As such, the interaction between cycles can be illustrated by the sedimentogenic water being displaced by infiltrogenic. It should be noted that the distinguished by many classifications genetic types of waters include such as metamorphic, volcanogenic and others. However, these notions actually imply not genetic types, but mixed waters of different origin.

2. Materials and Methods

Identification of the origin of subsurface waters is one of the key issues in modern hydrogeochemistry. Since the beginning of the 20th century and until now, several classification schemes for genetic types of subsurface waters of sedimentary basins and brines have been developed and used in hydrogeology (V. A. Sulin, A. A. Kartsev, E. V. Pinneker, S. L. Shvartsev and others). According to the classical works authored by S. A. Shchukarev, V. A. Sulin, S. B. Vagin, A. A. Rosin, M. I. Subbota, Ya. A. Khodzhakuliev, A. A. Kartsev, N. M. Kruglikov, V. V. Nelyubin, O. N. Yakovlev, V. M. Matusевич and other researchers, the genetic type of water is established using "genetic" coefficients, reflecting the relationship between different macro- and micro-components in its composition: rNa/rCl , Cl/Br , Ca/Cl , $r(HCO_3+CO_3)/r(Ca+Mg)$, B/Br , $Br/Cl \cdot 10^{-3}$, $Sr/Cl \cdot 10^{-3}$, $rNa/(rCa+rMg)$, $rNa+rMg/rCa$, rCa/rMg , $rSO_4 \cdot 100/rCl$, $rHCO_3 \cdot 100/rCl$, $Br \cdot 10^3/M$, $I \cdot 10^3/M$, $NH_4 \cdot 10^3/M$, Br/I , HCO_3/SO_4 , $(M/H) \cdot 100$, $(rCa/rNa) \cdot 100$, etc. The pool of data that served as the basis for this study is represented by the test results of more than 6200 objects from 437 search area, including 7286 samples of subsurface waters and brines. In this paper, we used the terminology and definitions of genetic types of subsurface waters from the classifications by A. A. Kartsev and S. L. Shvartsev [22, 23, 25], as they are described below.

Sedimentogenic waters (salty waters and brines) imply aqueous solutions arriving to the sedimentary basin during sediment deposition in the marine environments. The same type should include aqueous solutions originating from lakes and lagoons of marine origin, usually saline (salt), sometimes desalinated [22]. Aqueous solutions (usually fresh, brackish, more rarely saline) of atmospheric origin, which penetrated into the sedimentary rocks by infiltration during hypergenesis should be called *ancient (fossil) infiltratogenic waters*. A. A. Kartsev, S. B. Vagin, V. M. Matusевич [22] and other researchers distinguished *lithogenic* type of waters released during thermodehydration of various minerals of sedimentary rocks. In the conditions of Western Siberia, they are found to be developed in Cretaceous and Jurassic reservoirs at depths of more than 2 km [7, 22, 26]. The author supports the viewpoint expressed by V. V. Nelyubin and O. N. Yakovlev [27] elucidating on the mechanism of the formation of *condensatogenic* waters and understands them as formation waters of the background composition and salinity, admixed with fresh (non-saline) condensation water released from the water-carbon mixture during its vertical migration, under the changing thermobaric conditions. The formation and preservation of condensatogenic water fringes are also favored by the formation of hydrocarbon pools through rapid vertical migration of hydrocarbons from petroleum kitchens into traps [28].

3. Results and Discussion

It has thus far been established that Arctic parts of the WSSB are characterized by relatively low TDS of subsurface waters and brines, which are $< 63.3 \text{ g/dm}^3$ in the areas of Izvestinskoye, Komsomolskoye and Gubkinskoye fields in the Nadym-Taz interfluve area [26, 29] and is not greater than 51 g/dm^3 within the Malyginskoye group of fields on the Yamal Peninsula [30]; by sulfate-free, rich in dissolved OM and gas of hydrocarbon composition in subsurface waters of Mesozoic structural level, as well as by variable hydrogeochemical types and salinity of subsurface waters, both over area and in the cross section. At this, each of the Mesozoic confined aquifers (with pressurized waters)

characterized by a number of hydrogeochemical signatures were influenced by the paleohydrogeological history [31] and the subsequent processes of metamorphization of subsurface waters composition, as well as by the waters' vertical migration from the Paleozoic basement to the sedimentary cover in the areas of thinned or missing Triassic volcanic-sedimentary strata [26]. The Yamal Peninsula is features by unique formations developing within the cryogenic strata – cryopegs consisting of high-salinity water and brines with negative temperature up to $-8,5^{\circ}\text{C}$, which formed as a result of cryogenic metamorphization of seawater and are of chloride sodium-magnesium composition and a TDS value up to 150 g/dm^3 [32].

Within Mesozoic complexes of the Yenisei-Khatanga basin, the waters with highest salinity and TDS more than 20 g/dm^3 were revealed in the Pelyatka area (24.8 g/dm^3 , Aptian-Albian-Cenomanian complex), Sukhaya Dudinka area (23.3 g/dm^3 , Lower-Middle Jurassic complex) and the Vankor area ($23,0\text{ g/dm}^3$, Upper Jurassic complex) [33]. Given the specific hydro-geothermal and hydrodynamic conditions in the aquifers within Jurassic and Cretaceous sediments [33], these helped establish general hydrogeochemical patterns: sodium- bicarbonate and sodium-chloride-bicarbonate waters with TDS up to 5 g/dm^3 are commonly distributed along the northeastern border, which are succeeded by sodium-chloride subsurface waters with salinity up to $15\text{-}20\text{ g/dm}^3$ when approaching the central and southwestern parts. The hydrogeochemical picture of subsurface waters indicates the aquifers differentiation within Jurassic and Cretaceous sediments. In the cross section, various types of the vertical hydrogeochemical zonality can be distinguished – from direct, which is dominant within Messoyakha inclined ridge, to the inversed type. The diversity of the subsurface waters composition generally observed in the lower parts of the sedimentary cover declines up the section, while in Aptian-Albian-Cenomanian complex the hydrogeochemical conditions tend to become more even, with levelled off TDS concentrations in underground waters [7].

Further eastwards, the saltless type of the section characteristic of the WSSB and Yenisei-Khatangs basin is replaced by saline type within the Anabar-Khatanga basin, which is immediately reflected in the hydrogeochemical field, affecting also the nature of the vertical hydrogeochemical zoning [7]. This was established earlier by the characterization of the hydrogeological features in the transition type section (from the ancient Siberian platform to the young West Siberian plate), by the example of the Pre-Yenisei sedimentary basin located more southward [34, 35], where salt domes and stock structures typical for many world's salt basins are widely developed [36]. Presently, the brines of the Anabar-Khatanga basin have been identified within the seven aquifer complexes: in Lower-Middle Jurassic, Triassic formations, and in Permian, Carboniferous, Devonian, Vendian-Cambrian and Riphean deposits. The studied brines are of sodium chloride composition with the TDS value varying in a wide range from 52.3 to 312.3 g/dm^3 . The chemical type of high-calcium brines and TDS reaching $54.6 - 144.6\text{ g/dm}^3$ was established within the aquifer complexes of Riphean deposits in the Kostrominka area, within Cambrian deposits in the North-Soulem area and within Permian deposits in the Ulakhan and North-Soulem areas. The two types of vertical hydrogeochemical zoning established in the region include inversion type which is confined to the areas of salt domes distribution on the Yuryung-Tumus Peninsula, within the South Tigyan, Ilyin and other structures. The highest-salinity brines with TDS up to 312.3 g/dm^3 were revealed in aquifer aquifers of Triassic formations [7], which exhibits a significantly declining trend further down the section, though. High-salinity brines identified in the boundary zones of salt diapirs and appear to result from leaching of salts largely facilitated by modern and ancient infiltration waters. The direct (normal) type of vertical hydrogeochemical zoning is established within the structures showing the absence of salt domes. Whereas Cambrian, Vendian and Riphean deposits in the boundary areas of the Siberian platform, adjacent to the study area from the south, contain high-grade metamorphic brines of sodium chloride, sodium-calcium and calcium composition with TDS value up to 480 g/dm^3 .

It has been established that with the increasing degree of metamorphization of subsurface waters and brines, which is basically growing after burial of calcium, bromine and strontium, significantly changing their composition. A comprehensive analysis of hydrogeochemical materials showed that among all the studied subsurface waters and brines, the most metamorphic have proven to be brines

distributed within the Anabar crystalline shield of the Archean-Proterozoic age, which are characterized by a calcium chloride composition and TDS concentrations more than 300 g/dm³. This was corroborated by the analysis of distribution of the main genetic coefficients. The amount of rNa/rCl is 0.2-0.3, Cl/Br ranges from 50 to 150, and the ratio of Ca / Cl exceeds 0.5 (Figure 2). Moderate metamorphization of brines is characteristic of Cambrian, Vendian and Riphean aquifers of the Siberian platform [37, 38]. Subsurface waters and weak brines of Western Siberia [39, 40] and the Yenisei-Khatanga [41] basin with halogen formations absent from their structures are at the earliest stage of metamorphization of their composition, the ratio of Ca/Cl usually does not exceed 0.20, and higher values are correlated with waters of active gas exchange within their limits. The infiltrogenic brines promoting leaching within the salt domes of the Anabar-Khatanga basin show genetic affinity with the modern leaching brines of the Iran-Pakistan basin and others. A natural chain of chemical and genetic types of subsurface waters and brines of the Siberian Arctic is basically built as indicated below. The earliest stage implies waters of variegated chemical composition coming from the zone of active gas-water exchange. This is followed by the subsurface waters of sedimentary basins characterized by the absence of salts in the hydrogeological section, which in turn are replaced by brines of sedimentary basins with halogen formations. The chain is culminated with the maximum degree of metamorphization of brines from crystalline shields of the Archean-Proterozoic age. Ultimately, we can distinguish three genetic groups of waters: 1) infiltrogenic, 2) sedimentogenetic and 3) condensatogenic. The first includes modern and fossil infiltration waters, brines leaching salt dome structures, while sedimentogenetic waters (including brines), lithogenic waters and cryopegs belong to the second group. The third group should be a special type of condensatogenic waters developed syngenetically with hydrocarbon deposits. Modern and fossil infiltratogenic waters are aqueous solutions of atmospheric origin, penetrated into rocks by infiltration during hypergenesis. These are characterized by TDS concentrations up to 20 g/dm³ and are chloride-bicarbonate and bicarbonate- sodium chloride in composition.

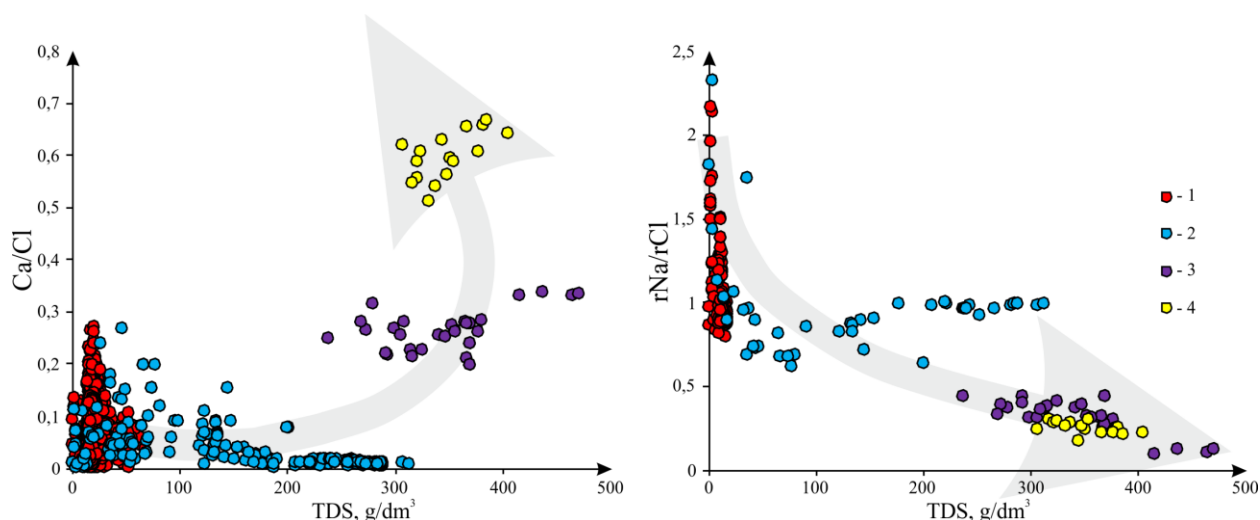


Figure 2. Change in the degree of metamorphism of groundwaters and brines of Arctic regions of Siberian sedimentary basins.

Sedimentary basins: 1 – West Siberian and Yenisei-Khatanga, 2 – Anabar-Khatanga, 3 – IV – Siberian platform, 4 – Anabar shield (southern slope). The arrow shows the direction of metamorphism of groundwaters and brines.

The fossil infiltratogenic waters should also include sodium chloride brines of rock salt leaching, with TDS at levels of 200-315 g / dm³, developed within the salt domes of the Anabar-Khatanga basin. In the Arctic regions of Siberia, sedimentogenetic waters and weak brines are developed within the Jurassic and Cretaceous aquifer complexes of the WSSB and Yenisei-Khatanga basin and are of sodium chloride composition and TDS concentrations from 25 to 63.3 g/dm³. Lithogenic water

released as a result of thermodehydration of mostly clay minerals are widely developed in the Cretaceous and Jurassic horizons at depths greater than 2 km, are characterized by a TDS levels between 5 and 15 g/dm³, and are of chloride-bidrocarbonate and bidrocarbonate- sodium chloride composition. Sedimentogenic brines widely within the aquifers of the Cambrian, Vendian and Riphean of the Siberian platform with the TDS concentrations up to 480 g/dm³, are primarily of sodium chloride, sodium-calcium and calcium composition. cryopegs are widely spread within the Yamal and the Taimyr Peninsulas and found in the sediments of laidas, islands, floodplains in lower reaches of rivers characterized by the marine type of salinization. Cryopegs developed in these areas are characterized by high salinity up to 150 g/dm³ and shallow occurrence depth, from 1 meter. Condensatogenic waters are characterized by the greatest diversity of chemical composition and variation of all genetic coefficients. Besides their low TDS, which is usually 2-10 g/dm³, they are characterized by high gas saturation – to 2.0 L/L and more.

4. Conclusion

A detailed analysis of hydrogeochemical materials resulted in the following inferences: 1) subsurface waters and brines of chloride-bicarbonate sodium, sodium chloride, calcium chloride and other chemical types, with TDS ranging from 0.2 to 480 g/dm³ are commonly developed in Arctic parts of the Siberian sedimentary basins. 2) Hydrogeochemical materials revealed that the subsurface waters of Mesozoic deposits within the West Siberian, Yenisei-Khatanga, Anabar-Khatanga basins are in the early stages of metamorphization of their chemical composition. The brines of the Siberian platform have reached the middle stage of metamorphizations. Most changed are the brines of the Anabar crystalline shield, on account of the processes of interactions between the host rocks and dispersed organic matter. 3) Specific traits of the geochemistry of subsurface waters and brines are largely determined by the composition of the host rocks (the presence or absence of salt-bearing formations), hydrodynamics of pressurized water systems, hydraulic interconnection of aquifers, and paleohydrogeological history. Their modern chemistry is a product of long-term geological evolution of fossil syngenetic waters. The initial composition is formed in the depositional environments. Later, during the stages of diagenesis and catagenesis, the captured waters experience significant changes, since they become involved in a variety of ongoing processes such as sediment compaction, elision water exchange, vertical and lateral migration, thermodehydration of clay minerals and interactions in the "water-rock-gas-OM" system. In this regard, the correct identification of the genetic appearance of subsurface waters and brines along with the composition of the dissolved substances requires a comprehensive study of their isotopic composition. The final classification of aqueous solution to a particular genetic type makes sense only after studying their isotopic composition, primarily distribution of δD , $\delta^{18}O$, 3H , ^{37}Cl , ^{81}Br , $^{87}Sr/^{86}Sr$. 4) The three genetic groups of subsurface waters in the studied area are: infiltrogenic, sedimentogenetic and condensatogenic. The first group includes modern and ancient infiltration waters and salt domes leaching brines, the second comprises sedimentogenetic waters (including brines), lithogenic waters and cryopegs. The third group is designated as specific type of condensatogenic waters formed syngenetically with hydrocarbon deposits.

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