Evaluation of Cretaceous deposits of the Yamal Peninsula for their hydrocarbon potential based on the water-gas equilibria modeling results

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Abstract: Results of the evaluation of petroleum-bearing potential of Yamal’s Cretaceous deposits based on the study of water-gas equilibria are presented. It has been established that the “water-gas” system within them has a complex and unequal pattern. Hydrocarbon accumulations serve as "relics" of antecedent hydrogeological epochs, with groundwater being the most mobile component of this system. The sediments composition is therefore subjected to a slow directional change aimed at establishing an equilibrium, which subsequently results in a qualitatively new state of their geochemical framework. Most of the studied area is characterized by very favorable conditions for persistent preservation of oil and gas accumulations. In northern and central regions of Yamal, there is a slight shift in the water – gas system phase equilibrium, suggesting a potential for discovery of new oil/gas pools and significant hydrocarbon reserves within them. The analysis confirmed the presence of earlier discovered hydrocarbon pools within the studied fields and enabled prediction of new thirteen accumulations. The hydrogeochemical analysis and the water-gas equilibria modeling results have shown that the prospects are significantly lower for new discoveries in SW Yamal.

Key words: prediction of petroleum potential, water-gas system, equilibrium, modeling, Yamal, Western Siberia, the Arctic.

1 Introduction

Gas production from unique Cenomanian deposits (Medvezh’ye, Urengoy and Yamburg gas fields) in Arctic regions of the West Siberian Basin (WSB) is currently declining. This therefore necessitates prospecting and exploration of new hydrocarbon fields and their putting onstream, to maintain production rates at previous levels and provide for their growth, in keeping with Russia’s Energy Strategy and Gazprom development strategy. Total hydrocarbon reserves and resources of all fields in the Yamal Peninsula are ranked as strategic raw material base which can ensure a sustainable level of production for a long period. These include 25 oil/gas/condensate fields with proven reserves amounting to 10.4 trillion cu m (natural gas), 228.3 mln t (condensate), and 291.8 mln t (oil) (Fig. 1) [1]. Significant hydrocarbon reserves have been discovered on the adjacent shelf and the Ob Bay within the Kara Sea offshore area (Leningradskoe, Chugor’yakhinskoe, Obskoe fields, etc.). Pursuant to the "Program for the

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Comprehensive Development of Fields on the Yamal Peninsula and the Adjacent Offshore Areas’

Gazprom’s Yamal onshore fields are assigned to the three production zones designated as the Bovanenkovo, Tambey and Southern. The Bovanenkovo production zone involves three basic fields: Bovanenkovskoe, Kharasaveyskoe and Kruzenshternskoe, which were the first to be put into operation.

**Fig. 1.** Location map of the Yamal Peninsula and overprinted discovered fields

Oil/gas/condensate fields: 1 – Malyginskoe, 2 – Syadorskoe, 3 – North-Tambeyskoe, 4 – Tambeyskoe, 5 – West-Tambeyskoe, 6 - Kharasaveyskoe, 7 – South-Tambeyskoye, 8 – Kruzenshternskoye, 9 – North-Bovanenkovskoe, 10 – Bovanenkovo (Bovanenkovskoe), 11 – East-Bovanenkovskoe, 12 – Verkhne-Tiutey, 13 – West Seyakha, 14 – Nerstinskoe, 15 – Neitinskoe, 16 - Baidaratskoe, 17 – Arkticheskoe, 18 – Ust-Yuribayskoe, 19 – Nurminskoe, 20 – Sredneyamalskoe, 21 – Kambateyskoe, 22 – Maloyamalskoe, 23 – Rostovtsevskoe, 24 – Kamennomysskoe, 25 – Novoportovskoye (Novy Port).

Gas parameters of water-gas mixture representing important hydrogeological criteria the geochemical-prospecting techniques play a critical role in hydrocarbon prospecting. The technological advancement in modeling of hydrogeochemical processes and emergence of most recent physicochemical techniques implemented through sophisticated codes of specialized software products constitute the most valuable approach for forecasting the oil/gas potential and computing future productions. The water-gas system complexity is accounted for its multicomponent structure and multidirectional processes involved, which defies utilization of the previously used methods for calculating the composition of a hypothetical gas phase and its parameters from concentrations of water-dissolved gases (WDG). With this in mind, we used a technique implemented as part of the HG-32 software package [2] allowing to involve all the system parameters in the modeling [3-4].

2 Results and discussion

**Hydrogeological signatures.** According to the accepted hydrogeological stratification, there are five main aquifer complexes in the section of lower hydrogeological storey in this part of WSB (from top downward): Aptian-Albian-Cenomanian, Neocomian, Upper Jurassic, Lower-Middle Jurassic and...
Paleozoic, whose geology and petroleum potential are discussed in detail in [5-6], and groundwater parameters were analyzed in [4, 7-10]. Groundwaters with mineralization (TDS) up to 51 g/dm$^3$ are widespread in the Yamal oil and gas-bearing deposits. These are dominated by groundwaters of Cl-Na, Cl-HCO$_3$-Na and HCO$_3$-Cl-Na types (the classification after Shchukarev). The hydrogeochemical analyses revealed that groundwaters with the highest TDS level belong to Lower-Middle Jurassic deposits. All groundwaters from the lower hydrogeological storey contain WDGs represented by CH$_4$ (> 80 vol.%), its homologues (from 0.5 to 14 vol.%), N$_2$ (up to 6 vol.%), and CO$_2$ (4 vol.%). WDGs in Aptian-Albian-Cenomanian deposits have proven to be explicable drier in composition, with concentrations of methane homologues increasing with depth and peaking in the lower parts of the Neocomian and in horizons of the Lower-Middle Jurassic aquifers. Water saturation also increases depthwards in both the aquifer complexes from 0.3-3.0 L/L (Aptian-Albian-Cenomanian) to 0.9-5.7 L/L (Lower-Middle Jurassic) [4].

Anomalously high formation pressures (AHFP) widespread both in Jurassic and in the overlying (including Neocomian) horizons represent a key hydrodynamic signature of the northern and central Yamal. They should be interpreted as indication of the subsurface confinement, which is characteristic of the pressure-water systems of elision type, where pressure primarily develops at the expense of water expulsion from the compacting sediments and rocks into reservoirs and is often aided by the compaction of the latter due to pore water expulsion, causing its migration through a reservoir rock [11-19]. AHFPs are the most widespread in Jurassic aquifers. This phenomenon is best characterized by the anomaly coefficient (Ka) calculated as the actual reservoir pressure to hydrostatic pressure ratio (taking into account groundwater density in this section). For example, Ka values equal 2.0 (lower parts of the Jurassic interval) for the Bovanenkovskoe, and 1.9 (reservoirs: Yu$_6$-7) for the Malyginskoe fields. Given the basin’s periphery proximity and much thinner sedimentary cover, the southern Yamal regions are characterized by a calmer hydrodynamic regime. The aquifers are generally hydrodynamically partitioned from each other by thick aquicludes. Their isolation is violated only locally, in areas either affected by active faulting and tectonic disturbances or comprising lithological windows [4, 20-24].

The degree of groundwater saturation with gas and the nature of physical-chemical equilibria in the water-gas system. The pattern of gases redistribution between hydrocarbon accumulations and stratal waters was derived from the relationship between individual fugitive emissions of gases calculated for the two systems: HC accumulation-stratal water and stratal water-HC accumulation. The former involved modelling of hypothetical equilibrium composition of WDG using the free gas phase composition, while in modelling the latter the composition of hypothetical gas accumulation was derived from the WDGs concentrations. The established direct relationship between the degree of stratal water saturation with gas (Kg) and the phase composition of HC accumulation revealed that the zone of Kg values spanning from 0.8 to 1.0 comprise primarily gas-condensate accumulations, whereas less saturated waters are associated with oil accumulations. A fairly complicated pattern of the revealed relationships suggests diversity in chemistry and gas compositions of groundwaters, and the presence of groundwaters of different genetic types within the petroleum-bearing interval [7-10, 25].

Analysis of the patterns of gases redistribution between hydrocarbon accumulations and stratal waters showed that the position of HC accumulations is generally unstable with respect to the enclosing groundwaters. Scatter of methane, carbon dioxide, and argon occurs almost from all of the studied HC accumulations, which, given the incoming helium, nitrogen, and varying amounts of methane homologues, is treated as a swapping phenomenon (Table 1). Fugitive emissions of gases increase with depth. Numerous HC accumulations are experiencing reformatory processes towards the weighing of their composition. In terms of their locations, the studied oil/gas fields are distributed among three regions: northern (Malyginskoe, Tasiyskoye, etc.), central (Kruzenshternskoe, Verkhne-Tiutey, Nerstinskoe, etc.) and southern (Nurminskoe, Khambateyskoe, Rostovtsevskoe, etc.). The calculations have shown that the
patterns of interactions between the stratal waters and HC accumulations vary significantly for these areas: methane and carbon dioxide dispersion into the surrounding stratal waters established for HC accumulations is simultaneously compensated by the incoming methane, helium and nitrogen homologues in the northern and central regions, which is not the case in the southern parts of the Yamal Peninsula. The scatter of hydrocarbon components (methane and its homologues) from oil-and-gas and oil accumulations was established in the following reservoirs: TP22 (Nurminskoe field) and NP1, NP2, NP3, NP4, NP7 and NP70 (Rostovtsevskoe field). The diffusion-driven scatter of gas component from HC accumulations is compensated by nitrogen inflow from the stratal waters. Unlike in oil accumulations, the swapping and reformative processes occur most intensely within the gas-condensate and oil-and-gas accumulations.

**Table 1. Patterns of interactions between HC accumulations and stratal waters (from relationships between fugitive emissions of gas in the solution and HC accumulation)**

| Gas    | Malyskinskoe | Tasiyskoe | Kruzenshternskoe | Verkline-Tiutey | Nerstinskoe | Numminskoe | Khamateyskoe | Rostovtsevskoe |
|--------|--------------|-----------|------------------|-----------------|-------------|------------|-------------|----------------|
| H2     | +            | +         | +                | -               | -           | -          | -           | -              |
| CH4    | -            | -         | -                | +               | -           | -          | -           | -              |
| C2H6   | +            | +         | +                | +               | -           | -          | -           | -              |
| C3H8   | +            | +         | +                | -               | +           | -          | -           | -              |
| iC4H10 | +            | +         | +                | *               | -           | +          | +           | +              |
| nC4H10 | +            | +         | +                | +               | *           | -          | +           | -              |
| iC5H12 | +            | +         | +                | +               | *           | -          | +           | -              |
| nC5H12 | +            | +         | +                | +               | *           | -          | +           | -              |
| C6H14  | +            | +         | +                | +               | *           | -          | *           | -              |
| CO2    | -            | -         | -                | -               | -           | -          | -           | -              |
| He     | +            | +         | +                | +               | -           | +          | +           | -              |
| Ar     | -            | +         | +                | -               | +           | -          | -           | -              |
| N2     | +            | +         | +                | +               | +           | +          | +           | +              |

Note: Directions of migration marked by «+» or «-» mean “into” or “from” HC accumulation, respectively; mark «*» means no data available.

**Oil and gas potential evaluation derived from the water-gas equilibria modeling.** In the study area, the HC accumulations quality predicted from the CH4/C5H12/nC4H10 and iC5H12/nC5H12 ratios can be generally divided into two main types represented by a combination of: (1) oil and oil with gas cap, and (2) gas-condensate and gas. In the geological section, these are isolated into two general areas: the top of the section straddling Aptian-Albian-Cenomanian and uppermost Neocomian deposits is dominated by type two (gas and gas-condensate), whereas type one (oil and gas-condensate) of HC accumulations is sitting below. Their analysis confirmed the presence of earlier discovered hydrocarbon accumulations in the PK, KhM, TP and NP reservoir groups and enabled prediction of the discovery of as many as thirteen HC accumulations which were overlooked within the studied oil/gas fields. The most promising discovery of gas accumulations in Aptian-Albian-Cenomanian deposits is thus associated with reservoirs KhM3 (Nerstinskoe field) and PK5 (Tasiyskoe field). While gas-condensate accumulation is anticipated in
reservoir TP7 (Tasiyskoe field). In the Neocomian interval, gas-condensate accumulations are anticipated within the following fields (with indication of respective reservoirs): Malyginskoe (TP16, BYa1, BYa3, BYa4 and BYa5); Tasiyskoe (TP22); Verkne-Tiutey (TP16); on Khambateyskoe (TP16.17 and NP2.3); Rostovtsevskoe (NP4 and NP14). The variation of calculated condensate content in free gas phase (i.e. stable gas condensate) is largely governed by the predicted type of HC accumulations. Unlike most other indicators of gas composition, this one is controlled by thermobaric conditions, rather than by geological and geochemical factors alone. The analysis of the obtained relationship with depth shows that in most of the predicted HC accumulations a high condensate content of free gases exceeds 300 cm³/m³, which appears the value approximated by all of the commercial accumulations discovered in the Yamal Peninsula.

Zonation of the predicted (hypothetical) composition of free gas phase, except for hydrocarbons and non-hydrocarbon gases, is also inferred from the helium-argon ratio distribution with depth, which is directly related to the absolute age of hydrocarbon accumulations. In contrast to the commonly used methods based on helium / argon ratios for groundwater applicable to age-dating of gases and giving very doubtful results, the HG-32 (Hydrogeo) algorithm used in the software package is based on the V.P. Savchenko’s empirical equation for free gases, obtained from the data generalization for a large number of fields all over the globe. Thus, the predicted age of potential accumulations estimated from water-dissolved gases, increases from 20-23 MA (Upper Oligocene) in the uppermost parts of Aptian-Albian-Cenomanian deposits to 40-87 MA (Eocene-Upper Cretaceous) at the lowermost parts of Neocomian deposits. The results show a good agreement with the data obtained by N.N. Nemchenko, A.S. Rovenskaya and M. Shoelle on the isotopic composition of gases from giant gas pools in northern West Siberia [26].

The reported herewith results and findings attest to generally favorable conditions for preservation of oil and gas accumulations in most of the study area. A slight shift in the water-gas equilibrium observed in Yamal’s northern and central regions suggests that new hydrocarbon accumulations and significant reserves are likely to be discovered within them. Whereas the hydrogeochemical analyses and water-gas equilibrium modeling results significantly downgrade the prospects for new discoveries in the southwestern regions of the Yamal Peninsula. We can ascertain that the probability of preserving oil and gas condensate accumulations is ranked low in this area, despite the fact that they formed during antecedent stages of the aquifer system evolution.

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