The history of hydrocarbon generation in the Mesozoic-Cenozoic sedimentary cover in the northeast of the Bolshaya Kheta megasyncline

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Abstract. The dynamics of hydrocarbon generation by the Jurassic and Cretaceous source rocks in the northeastern part of the Bolshaya Kheta megasyncline was reconstructed by historical and geological modelling. The amounts of liquid and gaseous hydrocarbons generated by these source rocks were estimated for each time period and catagenetic substage.

1. Introduction
The geology of the northern West Siberian petroleum province has been the focus of extensive research efforts since the 1950s and remains one of the highest priority exploration targets in the Russian Arctic zone. Most of proved reserves in the study area came from Cretaceous reservoirs. Additional exploration efforts are needed to ensure the development of Jurassic reservoirs. To further improve exploration efficiency and predict hydrocarbon potential, a historical-geological modeling has been used to delineate the spatial and temporal distribution of zones of different thermal maturity grades within the main source rock sequences (SRS).

2. The present state of the problem
The genetic methods for evaluating the sedimentary basins for hydrocarbon potential have been developed independently in numerous research papers of Russian [1–10] and Western authors [11–18]. The differences in approaches lie primarily in the methods used to describe the processes of hydrocarbon generation and expulsion. The genetic approach and its modern modifications is based on quantitative modeling of the formation of a sedimentary cover, heat and mass transfer in the rocks, as well as on chemical and kinetic modeling of organic matter transformation. The above became the basis for the development of integrated software packages intended for use with numerical three-dimensional modeling of the evolution of the sedimentary cover and the processes of petroleum generation. This approach has become known as basin modeling in the Western and, partly, Russian scientific literature. Along with this, the terms historic-geological or historical-genetic method coined by Russian authors [4, 19] are widely used.
Basin modeling has been recently widely applied in assessing hydrocarbon potential and restoring the history of hydrocarbon generation in the northern regions of Western Siberia [20–23], South Kara megasyncline [24], Yenisei-Khatanga regional trough [25], Caspian basin [26], northeastern Sakhalin Island shelf [27], etc.

At the same time, basin modeling has been used to solve different problems with respect to the Bolshaya Kheta megasyncline [28].

As regards hydrocarbon potential predictions, the reconstruction of the extent and dynamics of hydrocarbon generation can be of particular interest. In a generalized form, of great importance are the duration of burial, residence of the SRS within the oil window, estimated amounts of hydrocarbons that were generated in each SRS depending on a particular catagenetic grade of source rocks.

3. Problem statement

The section of the Mesozoic-Cenozoic sedimentary cover in the northeastern part of the Bolshaya Kheta megasyncline represents an alternation of shale- and sand-dominated sedimentary sequences. The sedimentary cover reaches a maximum thickness of 9000 m and thins out eastward along the basin periphery.

The tectonic map of the Jurassic [29] shows that the North Taz megadepression is the deepest part acting as the main source kitchen (Figure 1). It is bounded by several plays, such as the Messoyakha inclined ridge in the north, Tagul promontory and a series of large dome-shaped uplifts in the south. Of particular interest is the unique large-size fields of the Vankor group (Suzunskoe, Vankorskoe, Lodochnoe, Tagulskoe) in the east of the region, which were confined to a series of uplifts of the same name within the Togul promontory and Dolgan mesomonocline.

![Figure 1. Tectonic map of the Jurassic structural stage of the Bolshaya Kheta megasyncline [29].](image-url)

Most of identified resources in the study area came from Cretaceous reservoirs, whereas Jurassic reservoirs have been penetrated only by a few wells. The hydrocarbon potential of Jurassic sediments remains poorly explored. In view of the above, the potential Jurassic sources rocks are of particular interest. These include primarily the Bazhenov horizon, the main source rocks of the central and southern West Siberian sedimentary basin. Thus, the following Jurassic SRS were selected as objects of research: Levin, Kiterbyut, Laida, Malyshnev, Bazhenov (including the Bazhenov Formation and upper units of the Yanov Stan and Golchikha Formations). The combined Cretaceous Malaya Kheta-Yakovlev SRS was considered additionally.
Modeling of petroleum generation processes in the main Jurassic and Cretaceous source rock sequences of the northeastern part of the Bolshaya Kheta megasyncline was performed using the most recent geological, geophysical, geothermal and geochemical data, as well as the experience in regional basin modeling gained by the Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Science.

4. 3D model of the sedimentary cover in the northeastern part of the Bolshaya Kheta mega syncline

A three-dimensional model of the Mesozoic-Cenozoic sedimentary cover was generated using the Temis software package (Beicip-Franlab). The study area some 340·360 km in size was structurally and stratigraphically subdivided into 20 layers. The model uses 1 km grid. The model is limited to the structural map for the base of the Triassic sedimentary section. The lithological model of the study area comprises a set of lithofacies maps.

Calibration of the thermal history of sediments is based on vitrinite reflectance measurements on samples from wells and maps of organic matter thermal maturity (catagenesis) for the top of the Jurassic [30–32]. The heat flow through the base of the sedimentary cover was assumed to be constant.

The selection of SRS and justification of the types of organic matter were performed based on geochemical data (Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Science): present-day Corg content of rocks, hydrogen index, T_max, etc.

The following source sequences were selected: Levin (type III kerogen), Kiterbyut (type III kerogen), Laida (type III kerogen), Malshev (mixed type II/III kerogen), Bazhenov horizon (mixed type II/III kerogen), Malaya Kheta-Yakovlev complex (type IV kerogen).

All the types of kerogens were modified in accordance with the modern understanding of the ratios between liquid and gaseous generated hydrocarbons. The calculated volumes of gas generation from the Malaya Kheta-Yakovlev complex in the early stages of catagenesis were corrected for balance models of the change in kerogen compositions [33–35].

The original concentrations of organic matter in each SRS were restored by calculating the degree of kerogen transformation after calibration of the rock thermal history.

5. Results

The results of the historical-geological modeling were used to reconstruct the dynamics of generation of liquid and gaseous hydrocarbons in different time (Figure 2) and different stages of catagenesis [36] (Table 1). Of primary importance are maps showing the time at which each SRS entered the oil/gas window.

5.1. Levin SRS

In the southern part of Messoyakha inclined ridge, the Levin SRS reached the mesocatagenetic substage (MC_1 grade) at 169 Ma in the mid-Bajocian, MC_2 at 160 Ma in the mid-Oxfordian, MC_3 at 139 Ma in the Late Berriasian, MC_4 at 126 Ma in the Late Barremian, MC_5 at 110 Ma in the Early Albian, AC_1 at 89 Ma in the late Turonian, AC_2 at 65 Ma in the early Paleocene. The total hydrocarbon generation from Levin source rocks was 70,889 billion m^3 of gas and 16,589 million t of oil.

5.2. Kiterbyut SRS

In the eastern parts of the Vnutrennyaya and South Messoyakha mesodepressions, the Kiterbyut SRS reached the mesocatagenetic substage (MC_1 grade) at 165 Ma in the early Callovian, MC_2 at 150 Ma in the Tithonian, MC_3 at 134 Ma in the Valanginian, MC_4 at 119 Ma in the mid-Aptian, MC_5 at 101 Ma in the late Albian, AC_1 at 80 Ma in the mid-Campanian, AC_2 at 52 Ma in the early Eocene. The total hydrocarbon generation from this SRS was 188,891 billion m^3 of gas and 166,725 million t of oil. The most intensive hydrocarbon generation took place during MC_2 and MC_3 substages.
5.3. Laida SRS
In the northeastern part of the Bolshaya Kheta megasyneclise and eastern part of the East Antipayut a megadepression, the Laida SRS entered the mesocatagenetic substage (MC1 grade) at 149 Ma in the mid-Tithonian, MC2 at 135 Ma in the mid-Valanginian, MC2 at 116 Ma in the mid-Aptian, MC3 at 91 Ma in the late Turonian, MC3 at 73 Ma in the late Campanian, AC1 at 51 Ma in the early Eocene, AC2 at 3 Ma in the late Neogene. The total hydrocarbon generation from this SRS was 19,990 million t of oil and 25,705 billion m3 of gas. The most intensive hydrocarbon generation took place during MC12 and MC2 substages, at 90-50 Ma, from the late Turonian to the early Eocene.

5.4. Malyshev SRS
In the Antipayuta-Tadebeyakha and Bolshaya Kheta megasyneclises, the Malyshev SRS reached the mesocatagenetic substage (MC1 grade) at 138 Ma in the early Valanginian, MC1 at 127 Ma in the mid-Barremian, MC2 at 99 Ma in the early Cenomanian, MC3 at 74 Ma in the mid-Campanian, MC3 at 55 Ma in the early Eocene, AC1 at 18 Ma in the first half of the Miocene. At present, these rocks have reached the apocatagenetic substage (AC2 grade) in the deepest parts of the North Taz megadepression.

Table 1. Generation potential of different source rock sequences of the northeastern part of the Bolshaya Kheta megasyneclise divided into stages of catagenesis.

| SRS                  | PC1 | PC2 | PC3 | MC11 | MC12 | MC2 | MC31 | MC32 | AC1 | AC2 | Total   |
|----------------------|-----|-----|-----|------|------|-----|------|------|-----|-----|---------|
| Malaya Kheta-Yakovlev| 160 | 151 | 284 | 136  |      |     |      |      |     |     | 695     |
| Bazhenov              | 511 | 109 |     | 53,352| 22,390| 1500| 27   | 1    |     |     | 89,323  |
| Malyshev              | 331 | 11,657| 64,941| 58,936| 8822 | 129 |      |      |     |     | 144,818 |
| Laida                 | 1783| 15,759| 2405 |      | 42   |     |      |      |     |     | 19,990  |
| Kiterbyut             | 2472| 104,645| 51,249| 8128 | 408  |     |      |      |     |     | 166,725 |
| Levin                 | 1206| 13,814| 1517 | 52   |     |     |      |      |     |     | 16,589  |

| SRS                  | Oil (×10^6 t) | Gas (×10^9 m³) |
|----------------------|---------------|---------------|
| Malaya Kheta-Yakovlev| 695           | 24,532        |
| Bazhenov             | 89,323        | 28,122        |
| Malyshev             | 144,818       | 50,169        |
| Laida                 | 19,990        | 25,705        |
| Kiterbyut             | 166,725       | 16,589        |
| Levin                 | 16,589        | 25,705        |

Figure 2. Mean generation rates of liquid (a) and gaseous (b) hydrocarbons in the northeast of the Bolshaya Kheta megasyneclise.
The total hydrocarbon generation from this SRS was 50,169 billion m$^3$ of gas and 144,818 million t of oil. The most intensive hydrocarbon generation took place during MC$_2$ and MC$_3^1$ substages.

5.5. Bazhenov SRS
The Bazhenov SRS reached the MC$_1^1$ grade at 126 Ma in the late Barremian, MC$_2^2$ at 100 Ma in the late Albian, MC$_2^3$ at 71 Ma in the early Maastrichtian, MC$_3^1$ at 36 Ma in the late Eocene. Only the deepest parts of this SRS, within the North Taz megadepression are currently within the MC$_3^2$ and AC$_1$ grades. The total hydrocarbon generation from this SRS was 28,122 billion m$^3$ of gas and 89,323 million t of oil. The most intensive hydrocarbon generation took place during MC$_2^2$ and MC$_2^2$ substages.

5.6. Malaya Kheta-Yakovlev SRS
The Malaya Kheta-Yakovlev SRS reached the PC$_1$ grade at 67 Ma in the late Late Cretaceous, PC$_2$ at 64 Ma in the early Paleocene, PC$_3$ and MC$_1^1$ at 60 Ma in the mid-Paleocene, within the Ust-Porttovaya megasalient, Middle Messoyakha mesoswell, Dolgan mesomonocline, Chaselka megaswell, North Chaselka saddle, Taz and the Zapolynarnoe dome-shaped uplifts these rocks have not yet entered PC$_3$ and MC$_1^1$ grades. The total hydrocarbon generation from this SRS was 695 million t of oil and 24,532 billion m$^3$ of gas. The most intensive hydrocarbon generation took place during PC$_3$ substage.

6. Petroleum systems evolution
An analysis of the evolution of all petroleum systems shows that the process of intense hydrocarbon generation began at 165 Ma in the mid-Callovian. The oil/gas windows were reached at 65–60 Ma in the late Cretaceous—early Paleogene. The total generation of gaseous hydrocarbons from all SRS was 388,308 billion m$^3$. The Kiterbyut SRS account for 49%, Levin and Malyshev SRS for 18% and 13%, respectively. The total generation of liquid hydrocarbons from all SRS was 438,140 million t. The Kiterbyut, Malyshev, Bazhenov, Laida, and Levin SRS account for 38%, 33%, 20%, 5%, and 4%, respectively. The Malaya Kheta-Yakovlev SRS accounts for only 0.2% of total amount of liquid hydrocarbons generated by all SRS.

During the evolution of the sedimentary cover, the Jurassic source rocks have entered the oil window and subsequently gas window. As a result, gaseous hydrocarbons were charged into traps already filled with liquid hydrocarbons, which led to changes in the phase composition of hydrocarbon accumulations. Secondary cracking of hydrocarbons in the deeply buried Lower-Middle Jurassic source rocks also played a role. Under high temperature and pressure conditions, liquid hydrocarbons were decomposed into gaseous components. This process led to inflows of gaseous hydrocarbons into traps, and subsequent expulsion and dissipation of liquid hydrocarbons. The discovery of new large oil fields in the Jurassic part of the section can be regarded as highly unlikely.

7. Conclusions
The historical and geological modeling allowed us to reconstruct the history of hydrocarbon generation from the main Jurassic and Cretaceous source rock sequences and estimate the amounts of gaseous and liquid hydrocarbons generated from these source rocks in a particular period of time and catagenetic substage.

The intense hydrocarbon generation took place during the entire Mesozoic-Cenozoic in the northeastern parts of the Bolshaya Kheta megasyncline in the Jurassic and later in the Cretaceous source rocks.

The Jurassic source rocks reached the oil window and subsequently gas window. The Malaya Kheta-Yakovlev sources rocks reached the early catagenetic stage of gas generation.

In the study area, the main potential for discovering new gas and gas condensate fields is associated with the Jurassic.

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