Russian Geology and Geophysics © 2020, V.S. Sobolev IGM, Siberian Branch of the RAS
Vol. 61, No. 4, pp. 412–427, 2020 DOI:10.15372/RGG2019082 *Geologiya i Geofizika*

The Gol'chikha Formation (Upper Bathonian–Lower Boreal Berriasian) of the Yenisei–Khatanga Depression (West of the North Siberian Lowland)

B.L. Nikitenko[a,b,✉], V.P. Devyatov[c], A.P. Rodchenko[a], L.K. Levchuk, E.B. Pestchevitskaya[a], E.A. Fursenko[a,b]

[a] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyga 3, Novosibirsk, 630090, Russia*

[b] *Novosibirsk State University, ul. Pirogova 1, Novosibirsk, 630090, Russia*

[c] *Siberian Research Institute of Geology, Geophysics and Mineral Resources, Krasnyi pr. 67, Novosibirsk, 630091, Russia*

Received 10 December 2018; received in revised form 3 January 2019; accepted 5 February 2019

Abstract—The uppermost Bathonian–lowermost Boreal Berriasian clay horizons (Gol'chikha Formation) of the Yenisei–Khatanga regional depression are regarded as probable oil source strata. Considerable core recovery in the Middle Jurassic to Lower Cretaceous sections from the boreholes drilled in the Paiyakhskaya well site and the presence of oils in the overlying strata of the Shuratovo Formation permit us to carry out integrated stratigraphic (bio-, litho-, chemo-, and seismostratigraphic) and geochemical (organic matter and oils) studies of the entire section of the Gol'chikha Formation and boundary beds, to reveal oil-producing horizons, and to compare the genotype and maturation level of their oils with those of the potentially oil source organic matter (OM) of the rocks. A detailed biostratigraphic zonation of the sections of the Gol'chikha Formation based on microfossils has been carried out. Comparison of $\delta^{13}C_{org}$ variations in the Volgian and in the lower beds of the Boreal Berriasian with those in the Barents Sea shelf and in the northeast of East Siberia provided the basis for more accurate definition of the boundaries of stages and substages in the intervals free of fossils in the Paiyakhskaya area. The studied section of the Gol'chikha Formation has been divided into eight lithologic members calibrated with bio- and seismostratigraphic units. The distinctive features allowing the definition of the upper boundary of the Gol'chikha Formation are proposed using GIS data. Analysis of bio- and chemostratigraphic data allowed the correlation of the seismic reflecting horizons defined in the Gol'chikha Formation and its boundaries with the geologic section and relevant litho- and biostratigraphic units. It has been established that the strata with the highest content of organic matter consist of the upper part of the Gol'chikha Formation (the Upper Volgian and basal Boreal Berriasian). According to the vitrinite reflectance data, the OM catagenesis in the Upper Volgian interval corresponds to the oil window, which is confirmed by pyrolysis data. Thus, these strata can be considered oil-producing. The low $\delta^{13}C_{org}$ values confirm the predominantly marine OM composition. Analysis of oils from the Cretaceous productive strata of the Paiyakhskaya area shows that they formed from the marine OM of the upper part of the Gol'chikha Formation at the same accumulation stage. The comprehensive studies of the Gol'chikha Formation in the Paiyakhskaya well site and complete stratigraphic coverage of the sections confirm that they can be considered a hypostratotype.

Keywords: Jurassic, Cretaceous, stratigraphy, microfossils, geochemistry of organic matter and oil shows, hydrocarbon biomarkers of oil, Arctic, Yenisei–Khatanga depression

INTRODUCTION

Arctic territories of Siberia, including the Yenisei–Khatanga regional depression are of high hydrocarbon potential, but still remain understudied. Upper Jurassic and Cretaceous terrigenous beds are characterized by favorable combinations of reservoirs and seal rocks as well as by concentration of high-carbon formations in the significant part of the Northern Hemisphere. The Gol'chikha Formation is regarded as one of such oil-producing horizons in the Yenisei–Khatanga regional depression and the neighbouring areas of the West Siberian syneclise (Filiptsov et al., 2006; Kim and Rodchenko, 2013). Lately, this formation has been intensively studied based on the materials of drilling, GIS and seismic data (Golovin, 2009; Kontorovich, 2011; Afanasenkov et al., 2016, 2017; Fomin, 2016; Klimova et al., 2018; Kontorovich et al., 2018; Ryzhkova et al., 2018).

The Gol'chikha Formation was introduced into the regional stratigraphic maps of Western Siberia by the Decision of the 5th Interdepartmental Regional Stratigraphic Meeting (IRSM) (Decision…, 1991). The layers in the depth interval of 2937–3312 m from borehole Deryabinskaya 5 was suggested as a stratotype for this formation (Fig. 1, *A*) (Kukushkina and Kislukhin, 1983; Kislukhin, 1986). In the same years (Kartseva et al., 1983), the Deryabinskaya For-

✉ Corresponding author.
E-mail address: NikitenkoBL@ipgg.sbras.ru (B.L. Nikitenko)

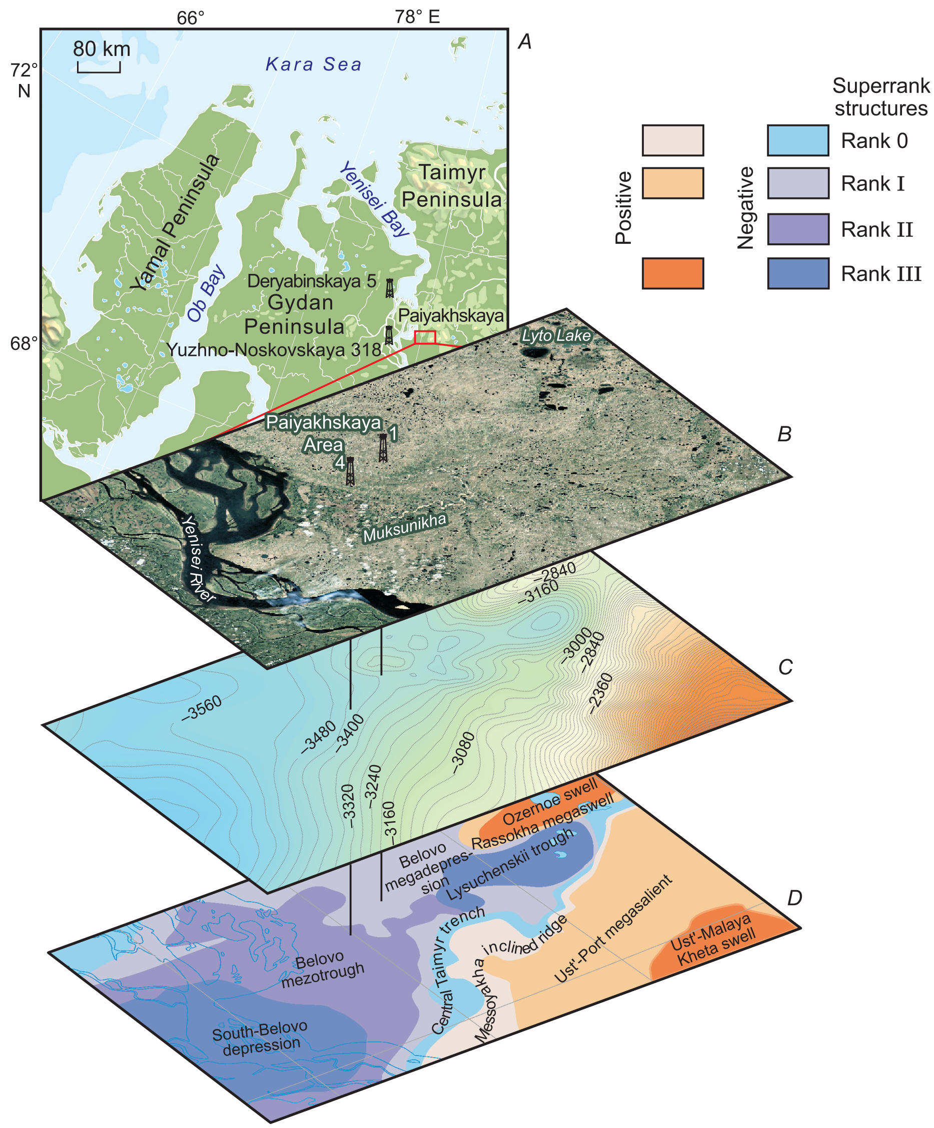

Fig. 1. Location of stratotypic sections of the Gol'chikha Formation in the northeastern part of Western Siberia and the western part of North-Siberian Lowland (A) and the studied sections in the Paiyakhskaya area (B) on the structural map along the top of uppermost Jurassic – lowermost Cretaceous seismogeological mega-unit (B) (Kontorovich, 2011) (C) and the tectonic map of the western part of the Yenisei–Khatanga regional depression (Kontorovich, 2011) (D).

mation was described from the same borehole section and subdivided into the lower (2968–3313 m) and upper (2510–2968 m) subformations. The stratigraphic ranges proposed for these new formations were very close. Nevertheless, it was later shown that the Gol'chikha Formation was approved by IRSM (Decision…, 1991) with nomenclative mistakes ignoring certain recommendations of Stratigraphic Code (Zhamoida, 1992; Shurygin et al., 2000; Russian stratigraphic code, 2006). However, this lithostratigraphic unit was widely applied in geological prospecting and explorations in the northeastern part of Western Siberia and the Yenisei–Khatanga depression. The formation is characterized by significant alterations in its thickness and structure and by a relatively monotonous silty-clay composition.

Note that published biostratigraphic data were incomplete and very schematic. In one case, the Callovian-Volgian (possibly Early Berriasian) age was stated for the Gol'chikha Formation, but the material necessary for this conclusion (taxonomic composition of fossil assemblages) was not demonstrated. In another case (for the Deryabinskaya Formation), the names of the foramimiferal assemblages and some ammonites were indicated, but these fossils were not calibrated with the stratotype section (Kartseva et al., 1983; Kislukhin, 1986).

In 1989, D.P. Kulikov (1989) suggested the 3720–4028 m interval from section of borehole Yuzhno-Noskovskaya 318 as a new stratotype for the Gol'chikha Formation (Fig. 1, *A*) subdividing it into two subformations (lower – 3895–

4028 m, upper – 3720–3895 m). Detailed macro- and micropaleontological data were published for this reference section of the Gol'chikha Formation. However, core data were provided only for the uppermost Bathonian-Callovian interval, and foraminifers of the Upper Oxfordian, Kimmeridgian, Volgian and Lower Cretaceous were identified in the uppermost part of the formation based on the rock cutting material from one interval (3690–3742 m) (Kulikov, 1989). Rare ammonites and foraminiferal assemblages of the Callovian, Upper Oxfordian, Kimmeridgian, Volgian and Boreal Berriasian were revealed in some other sections from the Yenisei–Khatanga depression.

According to the current stratigraphic scheme of Western Siberia (Gurari, 2004), the Gol'chikha Formation is equivalent in age to the Tochino Formation (Upper Bathonian – lower part of the Upper Callovian), Sigovo Formation (uppermost Callovian – lowermost Upper Oxfordian), and Yanovstan Formation (uppermost Oxfordian – lowermost Boreal Berriasian) of the Ust'-Yenisey region. Conformably lying on the Malyshev Formation, the Gol'chikha Formation is overlaid in different areas by the Akhskaya, Shuratovo and Nizhnyaya Kheta formations. However, the upper boundary of the Gol'chikha Formation is hardly recognized from core material in many sections, which is not exclusive due to the gradual changes in the lithological composition of the boundary layers of the Bazhenov and overlaying Kulomzino formations that are similar to those that occur in the eastern part of Western Siberia. Note that the biostratigraphic characteristic of the Gol'chikha Formation does not meet the current requirements in the latest stratigraphic scheme of Western Siberia (Gurari, 2004).

The Paiyakhskaya area (Fig. 1, *B*, *D*) is located in the periclinal zone of the western slope of the Rassokha megaswell and Belovo trough or, according to another tectonic regionalization, in the southwestern part of the East-Noskovskaya depression, constituting quite a steep monoclinal slope along the top of the Upper Jurassic – base of the Lower Cretaceous (Isaev et al., 2010; Kontorovich, 2011) (Fig. 1, *C*). The area is crossed by a number of seismic profiles including such as 3590010 and 0602113, which are laid in sublatitudinal and submeridional directions. In the seismic sections, the Gol'chikha interval produces almost a parallel record of highly dynamic reflections. The Gol'chikha Formation almost reaches its maximum thickness (722 m) in this region with its complete section tapped by a first parametric borehole of 4207 m in total depth that reached the top of the Malyshevka Formation. The core data were collected from this borehole to characterize the lowermost (4000–4029 m) and uppemost (3453–3463 m) parts of the Gol'chikha Formation as well as the lower (3322–3349 m) part of the Shuratovo Formation. The most detailed core data from the middle and upper parts of the Gol'chikha Formation (3890–3900, 3785–3800, 3627–3730, 3463–3564.5 m) come from borehole four reaching its bottom at 3910 m depth that is located within the formation. The oil-saturated and substantially aleurite layer (productive layers HX-IV) lays at the bottom of the Shuratovo Formation.

Significant amount of the core data obtained from the formation sections tapped by the boreholes in the Paiyakhskaya area, and the presence of oil in the Cretaceous parts of these sections provide the basis for combined stratigraphic (bio-, litho-, chemo-, seismostratigraphic) and geochemical (organic matter, oils) studies of the whole section of the Gol'chikha Formation and its boundary layers to detect oil-producing strata and compare the genotype and maturation level of the oils with potentially oil source organic matter (OM) of the rocks. Thus, this formation section can be considered as a hypostratotypic one.

The Gol'chikha Formation is composed of relatively monotonous silty clay strata. According to the results of seismic investigations, its thickness reaches more than 800 m in the submerged part of the Central Taimyr trench and reduces in all directions, reaching the first tens of meters in the edge parts.

Microfauna distribution in the section of the Gol'chikha Formation is not homogeneous in the central part of the western area of the Yenisei–Khatanga depression. Many samples contain no microfossils, which is, probably, due to high sedimentation rate. Nevertheless, the most complete micropaleontological data providing the ground for stratigraphic position of the Gol'chikha Formation are currently obtained from the Paiyakhskaya area, which allows the detailed correlation of unequally distant Middle Jurassic – Lower Cretaceous sections.

Thus, the results of combined (stratigraphic, geophysical and geochemical) studies suggest that the sections of the Gol'chikha Formation from the Paiyakhskaya area can be proposed as a stratotype for the uppermost Bathonian – lowermost Boreal Berriasian in the submerged parts of the Yenisei–Khatanga depression.

MATERIALS AND METHODS

In order to determine the lithostratigraphic composition and boundaries of the Gol'chikha section, the following well-logging data were analyzed: spontaneous-polarization (SP) logging, apparent resistivity (AR) logging, caliper logging, neutron (GR-N) logging, gamma-ray (GR) logging, and acoustic logging. We analyzed the seismic sections crossing the Paiyakhskaya area, calibrated with the section of the highly dynamic seismic reflections assigned to the Gol'chikha Formation and its boundaries, which made it possible to study the spatial changes of the formation morphology and structure.

Micropaleontological analysis was based on the 212 samples from the sections of the Gol'chikha Formation tapped by boreholes Paiyakhskaya 1 and 4. The samples of 200 g in weight were used to study the microfauna. Crushed samples were soaked many times in heated supersaturated solution of sodium hyposulphate for their disintegration that was followed by crystallization of the solution during its cooling. Then, the samples were boiled in water for several days and rinsed through a mesh with a cell diameter of 56 μm. If the samples did not disintegrate completely, the cemented sediments were weighed to recalculate the revealed microfauna for initial 200 g of weight. Following parameters were taken into account during the selection of microfauna: the frequency of occurrence for every species, the ratio of broken and intact tests, the number of adult and juvenile specimens, their mineral composition, grain size, the degree of sediment rounding and sorting, presence/absence of detritus, pyrite, problematics, etc., sediment weight after rinsing and drying.

Thirty four samples from the Upper Jurassic of borehole Paiyakhskaya 4 were used for palynological analysis. Cleaned samples were disintegrated into grains of 2–4 mm in size, dissolved in hydrofluoric acid for several days and then rinsed. The organic and mineral parts were separated using centrifugation in cadmium fluid of specific gravity 2.25. Then, the samples were again soaked in hydrofluoric acid for a day to dissolve residual silicates. After rinsing, the samples were treated by hydrochloric acid for 2–3 hours to remove secondary minerals, rinsed again to be dried and placed in glycerin.

The obtained micropaleontologic and palynologic data were used for biostratigraphic analysis to study the distribution of microfossil zones within the Upper Jurassic – Lower Cretaceous sections and to determine the stratigraphic position of seismic horizon boundaries. To specify the position of stage and substage boundaries in the studied sections, we also applied the chemostratigraphic data obtained from the Upper Jurassic – Lower Cretaceous $\delta^{13}C_{org}$ variations.

Geochemical OM investigation was performed for 67 samples of mudstones and silty mudstones from the Gol'chikha Formation and 13 siltstones samples from the Shuratovo Formation (boreholes Paiyakhskaya 1 and 4). Before the analysis, the samples were crushed into grains of 0.25 mm in size. Organic carbon concentration (C_{org} % in rock) was determined in decarbonized rock after processing a sample in hydrochloric acid (10%) and its burning in oxygen flow at a temperature of 1000–1100 °C using the AN-7529 analyzer. The rock's pyrolytic characteristics (S_1, S_2, T_{max}) were measured with the Rock-Eval version using SourceRockAnalyzer (HumbleInstruments).

OM catagenesis was estimated from vitrinite reflectance (R°_{Vt}) values for 11 samples (analysis performed by A.N. Fomin, Trofimuk Institute of Petroleum Geology and Geophysics) and pyrolytic data analysis.

The studied oil samples were collected at the top of borehole Paiyakhskaya 1 from 3420–3426 m (three samples), 1489–1501 and 1503–1506 (one sample), and of borehole Paiyakhskaya 8 from 3458–3494 m (one sample). Physical and chemical characteristics of the samples (density, fractional composition, sulfur content, hydrocarbon content) were obtained using standard techniques. Gas-liquid chromatography (Agilent Technologies 7820A GC System with HP5 fused silica capillary column) and gas chromatography–mass spectrometry (GC Hewlett Packard 5890 with HP5 fused silica capillary column and Agilent MSD 5972A) methods were applied to detect the hydrocarbon fractions required for geochemical interpretations such as n-alkanes, acyclic isoprenoids, steranes, terpanes and aromatic compounds (DBT, phenanthrenes, mono – and triaromatic steroids). The fractions were obtained through elution liquid chromatography of oil fractions at a boiling point temperature of > 200°C after asphaltene precipitation. The distribution of identified hydrocarbon biomarkers was used to determine the oil genotypes and degree of OM maturity (Petrov, 1984; Peters et al., 2005).

The standard value ($\delta^{13}C_{org}$) deviations of the isotopic signatures of the stable carbon isotopes of non-debituminized carbon-free rock residues was measured at Trofimuk Institute of Petroleum Geology and Geophysics, using a mass spectrometer system comprising a spectrometer Finnigan MAT 253 and an introduction system GasBench II (Thermo Electron Corporation). The $\delta^{13}C$ values were measured using a DELTA V Advantage mass spectrometer (ThermoFisher) in the Tomsk Branch of the Siberian Research Institute of Geology, Geophysics and Mineral Resources. The isotopic signature was characterized as a $^{13}C/^{12}C$ ratio and a $\delta^{13}C_{org}$ (‰) value deviation in relation to the Vienna Pee Dee Belemnite (VPDB) measured as $\delta = ((R_{sample} - R_{standard}) / R_{standart}) \times 1000$, where $R = {}^{13}C/^{12}C$. The error of the obtained $\delta^{13}C_{org}$ values varied as ± 0.1 (for standards) and was less than ± 0.25‰ (for samples). The error for non-debituminized carbon-free rock residues did not exceed 0.3‰, and for oils – 0.5‰.

RESULTS OF STRATIGRAPHIC STUDIES

Biostratigraphy

Microfauna. Microfauna in the Paiyakhskaya section of the Gol'chikha Formation has quite a sporadic distribution, so the sufficient number of samples did not contain any microfauna residues (Fig. 2). The assemblage of the foraminiferal zone Dorothia insperata, Trochammina rostovzevi JF25 having a wide stratigraphic range (uppemost Upper Bathonian – Callovian) is widespread in the lower part of the Gol'chikha Formation (Nikitenko 2009; Nikitenko et al., 2013). The first occurrences of foraminifers from this assemblage (*Trochammina rostovzevi*, *Recurvoides* cf. *scherkalyensis*, *Ammobaculites borealis*, *Haplophragmoides* cf. *magnus*, *Saccammina compacta*) are revealed in argillaceous, dark-grey silstones from borehole Paiyakhskaya 1 (4018 m, Figs. 1, 2). Upper-Callovian ammonites *Longaeviceras novosemelicum* were previously defined slightly above this level (4017.4 m) (Alifirov and Meledina, 2010).

In some cases, the biostratigraphic units on foraminifers characterized by narrower stratigraphic range can be recognized in the lower beds of the Gol'chikha Formation. For example, the assemblages of foraminiferal local zone *Kut-*

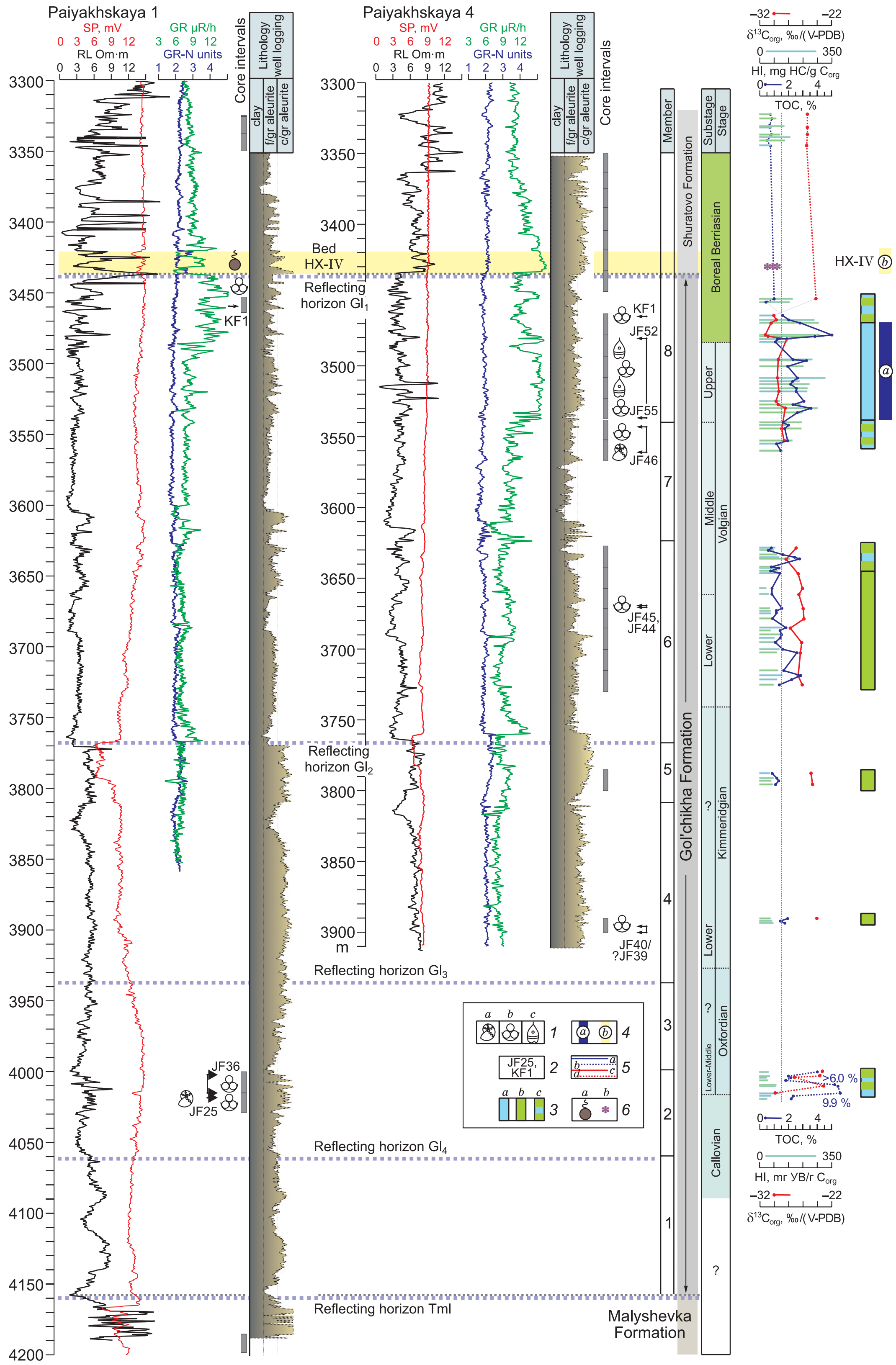

Fig. 2. Bio- and lithostratigraphy in the sections of the Gol'chikha Formation in the Paiyakhskaya area and the positions of main reflecting horizons. Geochemical characteristics of OM and oils. *1*, ammonites (*a*), foraminifers (*b*) and dinocysts (*c*), *2*, indexes of foraminiferal zones (Fig. 3), *3*, OM genotype: aquagenic (*a*), terrigenic (*b*), mixed (*c*), *4*, source rock (*a*), productive horizon HX-IV (*б*), *5*, C_{org} variation curves, %: boreholes Paiyakhskaya 4 (*a*) and Paiyakhskaya 1 (*b*) and $\delta^{13}C_{org}$, ‰ (V-PDB): boreholes Paiyakhskaya 4 (*c*) and Paiyakhskaya 1 (*d*), *6*, oil inflows from productive horizons (*a*) and $\delta^{13}C$ values of the oils (*b*).

sevella memorabilis, *Guttulina tatarensis* JF28 (uppermost Upper Bathonian – lowermost Lower Callovian) are known from the lowermost part of the Gol'chikha Formation in the Ozernaya and Khabeyskaya areas (Kartseva et al., 1983). The foraminiferal zones Ammobaculites igrimensis JF31 and Conorboides taimyrensis JF32 are revealed at higher stratigraphic level in the borehole section drilled in the Kabeyskaya area. Uppermost Bathonian – Lower Callovian ammonites *Cadoceras* sp. juv., *Cadoceratinae* gen. et sp. ind., *Kosmoceras* sp. juv., *Keppleritinae* gen. et sp. ind. are defined in basal layers (4021.2–4032.3 m) of the Gol'chikha Formation in its reference section (borehole Yuzhnoe-Noskovskaya 318). The middle part of the Callovian (4011.9–4016.1 m) is characterized by occurrences of *Rondiceras* sp. juv., *R.* ex gr. *milaschevici*. Upper Callovian *Longaeviceras* spp., Quenstedtoceratinae are identified in the interval 3986.2–4010.7 m (Alifirov and Meledina, 2010). Above this level, no fossils have been revealed in the reference section of the Gol'chikha Formation (Fig. 1). The foraminifers typical for the Kimmeridgian, Volgian and Lower Cretaceous were found only in the cuttings samples from the interval 3690–3742 m (uppermost part of the Gol'chikha Formation and lowermost part of the Nizhnaya Kheta Formation) (Kulikov, 1989).

Another foraminiferal assemblage including *Trochammina* cf. *oxfordiana*, *Glomospira oxfordiana*, *Recurvoides scherkalyensis*, *Ammodiscus thomsi*, *Ammobaculites* cf. *syndascoensis*, *Saracenaria* ex gr. *carzevae* that is typical for foraminiferal zone Trochammina oxfordiana JF36 (Lower Oxfordian – basal part of the Upper Oxfordian), is revealed slightly above this level, in the interval 4000–4015 m of the borehole Paiyakhskaya 1 (Figs. 1, 2) in the dark-gray micaceous and silty (to a different extend) mudstones (Fig. 3) (Nikitenko, 2009; Nikitenko et al., 2013).

The higher levels of the Gol'chikha Formation are characterized based on the micropalaeontological data obtained from the borehole Paiyakhskaya 4 (Figs. 1, 2). Diverse foraminiferal assemblage comprising *Haplophragmoides* ex gr. *canuiformis*, *Trochammina* sp., *Recurvoides* ex gr. *sublustris*, *Lenticulina* cf. *mikhailovi*, *Saracenaria subsuta*, *Pseudonodosaria tutkowskii*, *Dentalina* sp., *Geinitzinita* cf. *praenodulosa* is defined from the interval 3895–3900 m in dark-grey sandy mudstones with glauconite segregations. Such associations are typical for the foraminiferal zone Haplophragmoides canuiformis JF40 (uppermost Upper Oxfordian – Lower Kimmeridgian). However, considering a large number of calcareous forms in this assemblage, we cannot exclude that this level constitutes only to the upper part of this zone (JF39, uppermost Lower Kimmeridgian) (Nikitenko, 2009).

The middle part of the Gol'chikha Formation in the borehole Paiyakhskaya 4 (intervals 3785–3800, 3715–3730, 3700–3715, 3685–3700, 3671–3685, 3657–3671 m) composed of black mudstones with coarse-grained aleuritic interlayers and, sometimes, fragments of bivalve shells and onychites, contain no microfauna (Fig. 2).

The assemblages including *Recurvoides* ex gr. *stschekuriensis*, *Dorothia tortuosa*, *Haplophragmoides* ex gr. *volgensis*, *Kutsevella* cf. *haplophragmoides*, *Lenticulina* ex gr. *sosvaensis*, *Cribrostomoides* sp., *Saracenaria* sp. that are characteristic for the upper half of the foraminiferal zone Kutsevella haplophragmoides JF44 or lower part of the foraminiferal zone Spiroplectammina vicinalis, Dorothia tortuosa JF45 corresponding to the uppermost Lower Volgian, are revealed from the lowermost part of the interval 3657–3671 m of the borehole Paiyakhskaya 4 represented by black mudstones with aleuritic interlayers (Fig. 2) (Nikitenko, 2009; Nikitenko et al., 2013).

The assemblages from the overlaying part of the section in the borehole Paiyakhskaya 4 (intervals 3550–3464 and 3538–3550 m) composed of black mudstones with aleuritic interlayers, contain only agglutinated forms such as *Recurvoides* ex gr. *praeobskiensis*, *Dorothia* cf. *tortuosa*, *Glomospira* sp., *Cribrostomoides* sp. ind., *Haplophragmoides* sp. ind., *Evolutinella* sp. ind. strongly dominating by *Trochammina septentrionalis* that often forms monospecific accumulations. Apart from the foraminifers, the ammonites *Dorsoplanites* sp. are found in this interval. The foraminiferal zone Trochammina septentrionalis JF46 is widespread in Arctic regions of Western and Eastern Siberia (Nikitenko, 2009) and corresponds to the Middle Volgian without its uppermost part (Figs. 2, 3).

The upper part of the Gol'chikha Formation (interval 3478–3538 m) is composed of black mudstones with aleuritic interlayers in the Paiyakhskaya area. Abundant *Ammodiscus veteranus* and rare *Evolutinella* ex gr. *emeljanzevi*, *Trochammina* ex gr. *rosacea*, *Recurvoides praeobskiensis* are revealed from the basal part of this interval. Such assemblage structure and taxonomic composition are typical for the local foraminiferal zone *Ammodiscus veteranus* JF55 (lower part of the foraminiferal zone Evolutinella emeljanzevi JF52) correlated with the uppermost Middle Volgian and lowermost Upper Volgian. The upper part of this interval contains rare *Ammodiscus veteranus*, *Evolutinella emeljanzevi*, *Recurvoides praeobskiensis* suggesting its attribution to the foraminiferal zone JF52 (uppermost Middle Volgian – basal Boreal Berriasian) (Figs. 2, 3) (Nikitenko et al., 2013, 2018).

The uppermost part of the Gol'chikha Formation in the boreholes Paiyakhskaya 4 (3465 m) and 1 (3460 m) composed of black mudstones with sandy aleuritic interlayers having thin horizontal and cross lamination and contains the assemblage of the foraminiferal zone Gaudryina gerkei, Trochammina rosaceaformis KF1 (lower part of the Boreal Berriasian) (Figs. 2, 3) (Nikitenko et al., 2013, 2018). The assemblage includes rare *Trochammina* ex gr. *rosaceaformis*, *Gaudryina* ex gr. *gerkei*, *Cribrostomoides* sp. (ex gr. *volubilis*), *Ammodiscus veteranus, Kutsevella praegoodlandensis*.

Palynomorphs. The samples obtained from the upper part of the Gol'chikha Formation (3564.5–3508 m interval of the borehole Paiyakhskaya 4) (Figs. 1, 2) produced abun-

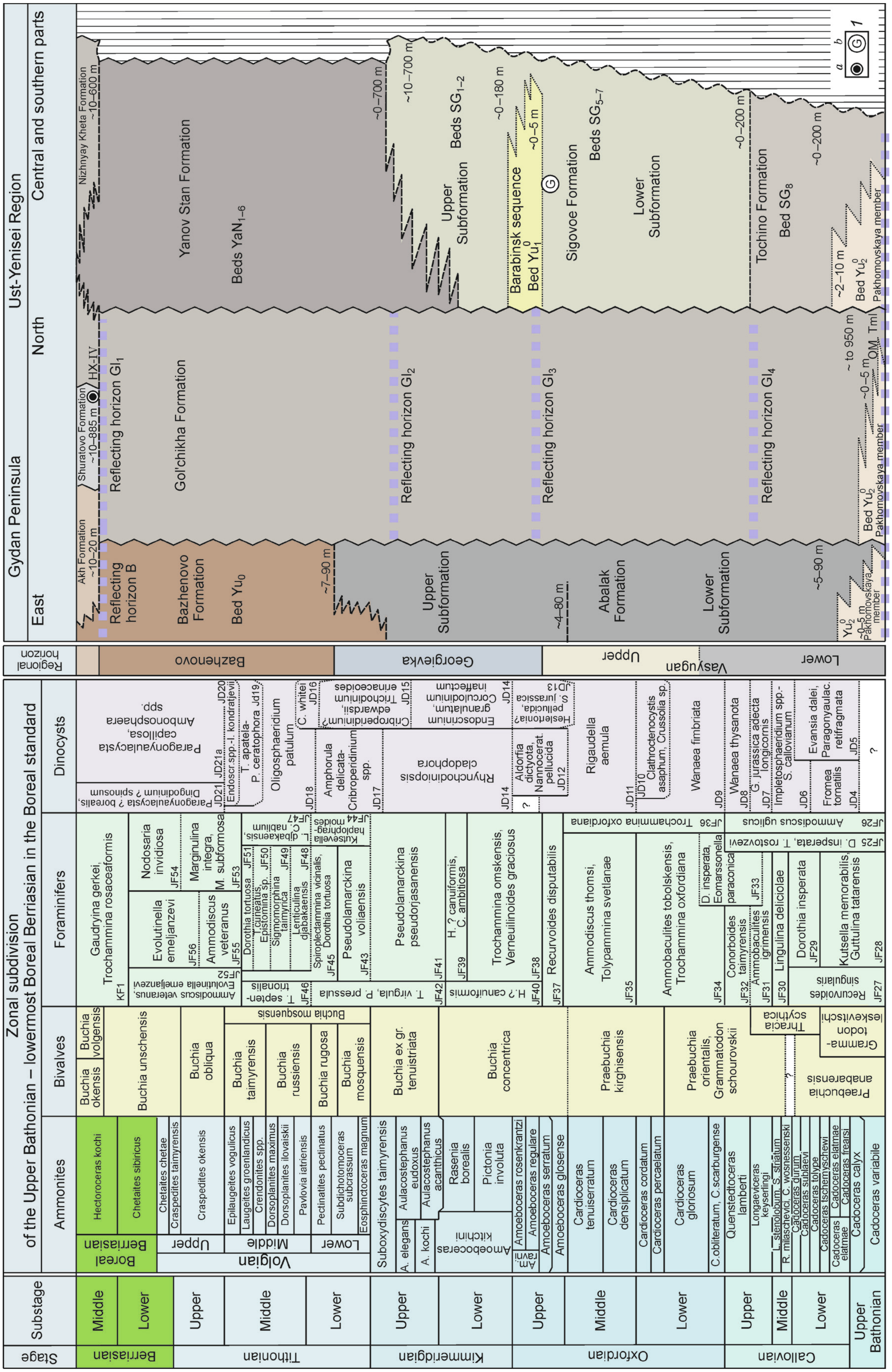

Fig. 3. Stratigraphic chart of the uppermost Bartonian – lowermost Boreal Berriasian of the northeastern part of Western Siberia and the western part of the North-Siberian Depression. *1*, oil (*a*) and gas (*b*) deposits.

dant palynological residue. It is almost completely composed of organic matter, which is strongly altered and reworked up to the pelitic particles, most probably, due to bacteria and detritophages influence. The latter cannot be excluded since some layers are characterized by bioturbation. Palynomorphs are very rare. The associations contain spores and pollen of terrestrial plants as well as vegetative detritus with the preserved structure of plant tissues evidencing the input of continental organic matter. The polymorphs are characterized by no signs of pyritization often considered as a feature of pronounced stagnant conditions and sulfurous contamination, and mainly represented by taxa of wide stratigraphic extend. Striate and granular spores of schizaeaceous ferns of genera *Cicatricosisporites*, *Trilobosporites*/*Concavissimisporites* are rare. These palynomorphs appear in the Upper Oxfordian of Siberia, Australia, North Africa and the northern part of Western Europe (Ilyina, 1985; Batten, 1996; Shurygin et al., 2000; Herngreen et al., 2000; Sajjadi and Playford, 2002; Nikitenko et al., 2015), but they are rare in the Kimmeridgian and Lower Volgian. Their abundance gradually increases in the Upper Volgian and Berriasian. Dinocysts *Gochteodinia mutabilis* (Riley in Fisher et Riley) Fisher et Riley that are typical for the uppermost Kimmeridgian – lowermost Upper Volgian (Powell, 1992; Herngreen et al., 2000) are defined at the depth of 3561.48 m.

The samples obtained from the upper part of the Gol'chikha Formation (interval 3508–3463 m) in the borehole Paiyakhskaya 4 (Figs. 1, 2) contain less abundant organic residue. It is better preserved and not altered unlike the lower layers of studied section. The palynomorphs are strongly dominated by prasinophytes (*Leiosphaeridia* spp.), and *Tasmanites* spp. are rather abundant in the upper part. The abundance of prasinophytes is often regarded to be related to dysoxic and anoxic environments (Tyson, 1995; Jansonius and McGregor, 1996; Ilyina et al., 2005). However, there are no signs of pyritization of the polymorphs considered as a feature of pronounced stagnant conditions and sulfurous contamination. The abundance of prasinophytes can also be related to the increased productivity of a photic zone and input of abundant organic matter to the near-bottom waters that, in turn, is favorable for the bacterial flora development, to be the possible cause of sulfurous contamination (Peters et al., 2005; Kashirtsev et al., 2018). Presence of the spores and pollen of terrestrial plants as well as vegetative detritus having preserved structure of vegetative tissues can be the evidence of continental organic matter input. More abundant occurrences of striate and granular spores of schizaeaceous ferns suggest higher stratigraphic interval that probably corresponds to the Upper Volgian – lower part of the Boreal Berriasian. The dinocysts *Apteodinium maculatum* Eisenack et Cookson are defined at a depth of 3491.05 m. Their lowermost occurrences are known from the uppermost Upper Volgian – lowermost Boreal Berriasian in Northern Siberia and the Russian Platform (Pestchevitskaya et al., 2011).

Chemostratigraphy

The excursion trends of the $\delta^{13}C_{org}$ variation curve obtained for the uppermost Kimmeridgian – lowermost Boreal Berriasian of the Paiyakhskaya area (Figs. 2, 4) are almost identical to those of the Barents Sea shelf (Spitzbergen Is.) and the northwest of Eastern Siberia (Olenek River downstream) despite the differences in absolute values (Hammer et al., 2012; Nikitenko et al., 2018) (Fig. 4, *B*). The outcrops of the Upper Jurassic/Lower Cretaceous of these regions are characterized by well-developed biostratigraphy based on different groups of fossils. Along the correlation of these sections on isotopic-hydrocarbon data, it provides the basis for more accurate definition of stratigraphic positions of stage and substage boundaries in the Paiyakhskaya area for the intervals including no fossils. The comparison of $\delta^{13}C_{org}$ variations from different regions requires proper biostratigraphic control. The combined application of bio- and chemostratigraphic data allows us to improve the accuracy of global correlations.

The highest $\delta^{13}C_{org}$ (–24…–25‰) values are obtained for the Kimmeridgian part of the Paiyakhskaya section, and they gradually reduce in the Lower Volgian to –26.5…–27.9‰. A slight increase of the values is observed near the boundary of the Lower and Middle Volgian (up to – 25.9‰). This level is also characterized by a similar low-amplitude increase of $\delta^{13}C_{org}$ values in the Barents Shelf and Eastern Siberia (Fig. 4) (Hammer et al., 2012, Nikitenko et al., 2018). A negative shift of the $\delta^{13}C_{org}$ value is observed in the middle part of the Middle Volgian, reaching 2‰ and gradually decreasing down to –28.5‰ towards the Upper Volgian. The $\delta^{13}C_{org}$ values reduce down to –29,5‰ in the end of the Volgian and reach their minimum in the basal Boreal Berriasian (–30.0…–31.2‰). The interval with negative excursion is then abruptly replaced by high positive $\delta^{13}C_{org}$ values in the lower part of the Boreal Berriasian reaching 25.3‰ on average (Figs. 2, 4).

Lithostratigraphy

Analysis of well logging materials and the published data (Kartseva et al., 1983, Kislukhin, 1986; Kulikov, 1989) demonstrates that the lower boundary of the Gol'chikha Formation is unambiguously determined when the sandstone with the saw-like configuration of apparent-resistivity curve is replaced by mudstones characterized by low or poorly-differentiated AR values or by an SP anomaly at depth of 4158 m the in borehole Paiyakhskaya 1 (Figs. 1, 2). The boundary between the Shuratovo and Gol'chikha Formations is almost impossible to recognize from the core obtained from the borehole Paiyakhskaya 4. The layers laying both under and above this boundary are composed of black dense argillaceous siltstone, and mudstones are described only at the depth of 3463 m and beneath this level.

Unlike different published variants of stratigraphic position of the formation's top (Zlobina and Rodchenko, 2015;

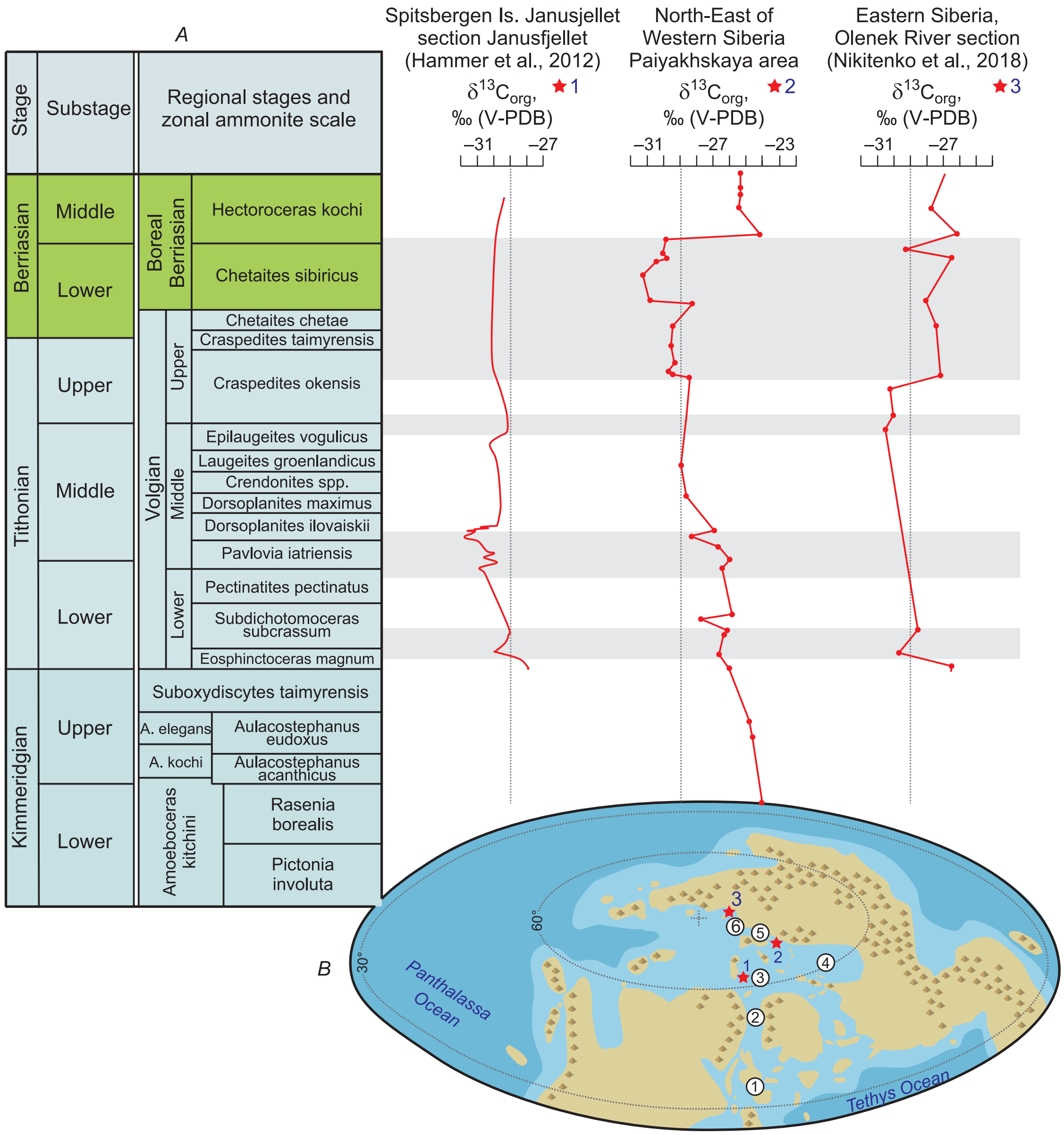

Fig. 4. Comparison of the $\delta^{13}C_{org}$ variations in the sections of the Volgian Regional Stage and lowermost Boreal Berriasian in different regions: Spitsbergen Is. (1), Paiyakhskaya area (2) and Eastern Siberia, the Olenek River (3). (*A*) Global palaeogeography of the Northern Hemisphere in the Late Jurassic – Early Cretaceous (*B*) (palinspastic reconstructions from (Scotese, 2011) with modifications). *B*, encircled numbers: 1, West-European Basin, 2, Vikings' Channel, 3, Barents Sea Basin, 4, West-Siberian Basin, 5, Yenisei–Khatanga Channel, 6, Anabar–Lena Basin.

Klimova et al., 2018), we define it in the base of first high-resistivity bed (oil-saturated in the borehole 1) of the Shuratovo Formation at the depths of 3436 m in the borehole Paiyakhskaya 1 and 3435 m in the borehole Paiyakhskaya 4 (Figs. 1, 2) following the point of view of exploration geologists and the principles of comprehensive evaluation of the upper boundary of the Bazhenov Formation (Ryzhkova et al., 2018).

There is an opinion that the formation consists of two subformations (Kulikov, 1989; Borisov, 2015). While the lower one (Kulikov, 1989) is composed of more coarse-grained sediments, the upper one is considerably argillaceous. Nevertheless, these differences are hardly recognized in lateral distribution. According to the analysis of GIS diagrams from the borehole 1, the formation is characterized by cyclic structure and can be subdivided into eight large members of complex constitution (Fig. 2). The first member is represented by two transgressive-regressive cycles composed of interlaying mudstones and siltstones (re-pro-cyclites according to Yu.N. Karogodin (1980)). The structure of the second one is of regressive character changing from mudstones to siltstone upwards the section.

The specific features of the first and second members correspond to those of the lower subformation as it was de-

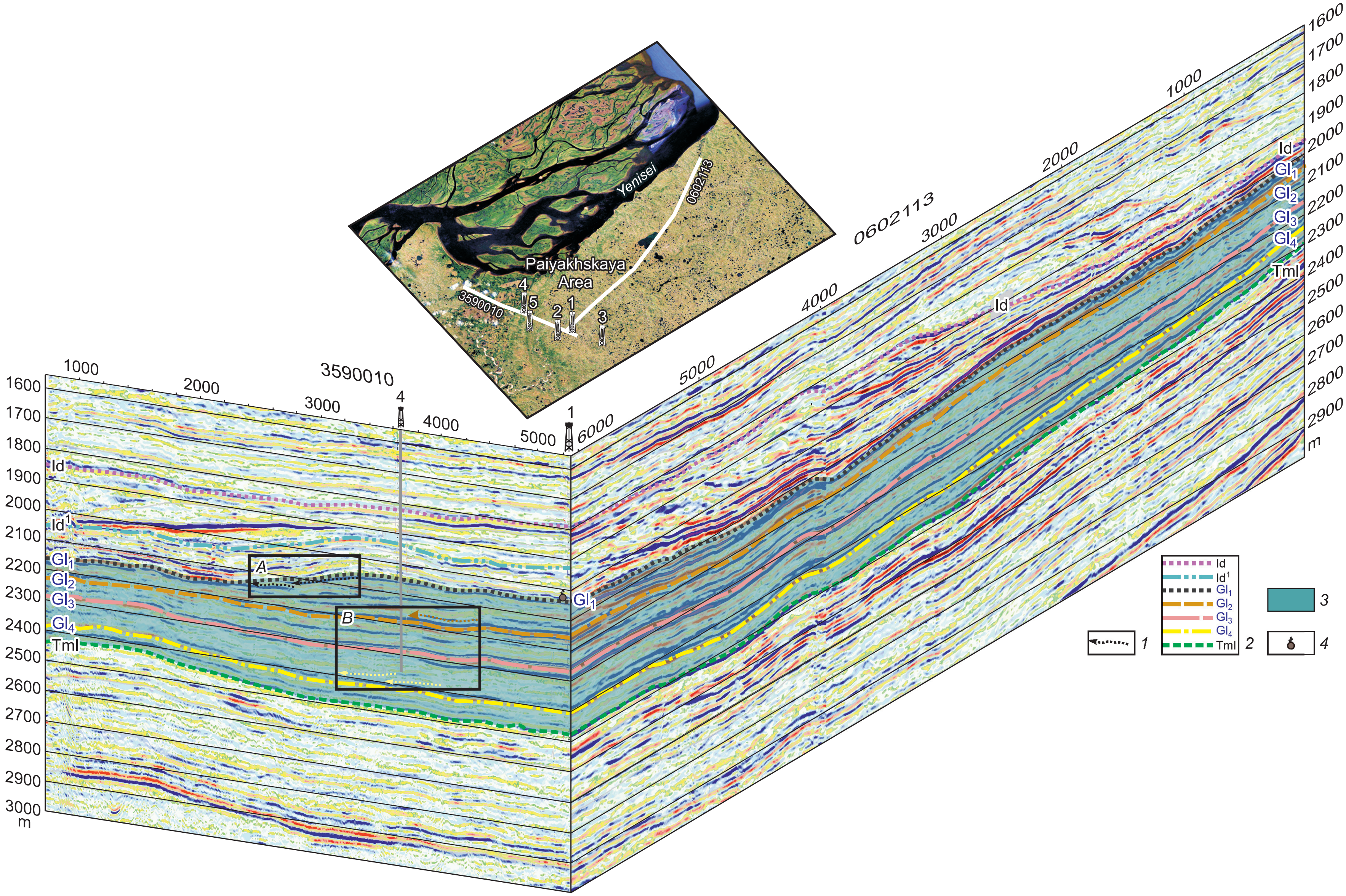

Fig. 5. Fragment of seismic section (profiles 3590010 and 0602113). *1*, examples of downlapping and onlapping of seismic reflections, *2*, reflecting horizons (Figs. 2, 3), *3*, Gol'chikha Formation, *4*, oil inflows. *A*, *B*, see the description in the paper.

scribed by D.P. Kulikov (1989), because they are more coarse-grained than the overlaid strata. Stratigraphic extend of the Lower Subformation was defined as the Callovian – Lower Kimmeridgian. Note that the presence of the Kimmeridgian or Oxfordian in the uppermost part of the subformation is suggested from the occurrences of bivalve shells (*Astarte* sp. juv (cf. *A. extensa*) and *Dacryomya* sp. nov.) in the core the borehole Sredneyarovskaya-3 (3302 + 12.5 m) (Kulikov, 1989) and cannot be regarded as conclusive, because the fossils are defined at generic level. According to our data, the coarse-grained first and second beds are limited to the Callovian – Lower Oxfordian (Fig. 2, foraminiferal zones JF36, JF25 and older).

The composition of third member is also of regressive character dominated by mudstones. The fourth one is composed of mudstones in its upper part and alternation of mudstones and dominated siltstone in its lower part. This member contains the foraminiferal assemblage of the Kimmeridgian zone JF40 (or JF39) (Figs. 2, 3). The fifth member is regarded as a marking one in both sections previously proposed as the hypostratotype of the Gol'chikha Formation (Kislukhin 1986; Kulikov, 1989), and it mainly consists of high-resistivity siltstones with abnormally high GR-N values (in stratotypes and GR) in some other areas on the right bank of the Yenisei River. The composition of the sixth member is of regressive structure, with the siltstone proportion increasing upwards the section. This member contains the assemblage of the Volgian foraminiferal zones JF44, JF45 (Figs. 2, 3). The seventh member is composed of mudstones including fine-dispersed ones with Middle Volgian fossil assemblage in its upper part. The argillaceous rock of the eighth member is characterized by high and stable radioactivity index increasing upwards the section (Upper Volgian – lowermost Boreal Berriasian) (Fig. 2).

The number of members, structure of the section and thickness of the formation change significantly beyond the Paiyakhskaya area (Fig. 1). Facial changes of the formation are determined by rock composition, dissected palaeorelief in the different parts of a source area, the distance from the latter as well as the peculiarities of the formation of the initial members of the Upper Jurassic – Lower Cretaceous clinoform unit. The close borehole sections demonstrate different trends in the logging-curve. The replacement of the Tochino-Sigovo-Yanovstanskaya section type by the Gol'chikha one is of fairly gradual character in the marginal areas of the basin, therefore different variants of section subdivision are often proposed by different researchers in the transitional zone.

Seismostratigraphy

A number of highly dynamic seismic reflections were detected that are associated with the top of undelaying Malyshevka Formation (Tml, uppermost Upper Bathonian) and the top of the Gol'chikha Formation (Gl_1, lowermost Boreal Berriasian) in seismic sections crossing the Paiyakhskaya area in sublatitudinal and submeridional directions (Fig. 5). Apart from this, three reflecting horizons (RH) forming independent seismic sequences are well recognized in the middle part of the Gol'chikha Formation, that we conventionally classified as Gl_2-Gl_4 having a reliable calibration to the geologic section slightly under this level.

The Tml—Gl_4 seismic sequence (Fig. 5) corresponds to the lower part of the Gol'chikha Formation in the studied area characterized by a series of extended continuous reflections. According to well logging data from this region, this part of the section is mainly composed of argillaceous siltstone and consistent with the coarse-grained part of the formation. The Tml seismic horizon is confined to the top part of the Malyshevka Formation containing fossil assemblages of the Upper Bathonian in many sections (Shurygin et al., 2000; Nikitenko, 2009; Nikitenko et al., 2013).

The stratigraphic position of reflecting horizon Gl_4 in the section tapped by the borehole Paiyakhskaya 1 below the foraminiferal zones JF25/JF36 of the Callovian and Oxfordian suggests that this part of the section corresponds to the upper part of the Callovian and, thereby, the seismic sequence is approximately consistent with the Tochino Formation of the southern part of the Yenisei–Khatanga regional depression. The stratigraphic range of this seismic sequence is assumed to be the uppermost Upper Bathonian – upper part of the Callovian (Figs. 2, 3).

The records of the Gl_4—Gl_3 seismic sequence (Fig. 5) are also characterized by a series of continuous dynamic reflections. At the same time, some reflections demonstrate a shingled onlap pattern (Fig. 5, *b*, profile 3590010). In the core of the borehole Paiyakhskaya 1, the lower part of this seismic sequence is consistent with the mainly dark grey and black micaceous mudstones characterized by thin horizontal lamination, which are alternated with argillaceous siltstone and contained marine microfossils and numerous siderite nodules. The Gl_3 reflecting horizon is located between the levels characterized by foraminiferal assemblages of zones JF36 (Lower Oxfordian – basal Upper Oxfordian) and JF40 (uppermost Oxfordian – Lower Kimmeridgian, or JF39 — uppermost Lower Kimmeridgian). According to the micropaleontological data, its stratigraphic position corresponds to the uppermost Oxfordian or lowermost Kimmeridgian that is approximately consistent with the boundary between the Lower and Upper Subformations of the Sigovo Formation (the level of the Barabino Member) in the sections of other facial regions of Western Siberia (Gurari, 2004; Nikitenko, 2009; Nikitenko et al., 2013). The stratigraphic range of this seismic sequence is assumed is to be the upper part of the Callovian – uppermost Oxfordian / base of the Kimmeridgian (Figs. 2, 3).

The Gl_3—Gl_2 seismic sequence (Fig. 5) is represented by a series of extended continuous reflections. In the geologic section, the relevant interval of the Gol'chikha Formation is composed of dark grey mudstones, silty in different extent, with glauconite lenses in its lower part and by black mudstones with silty interlayers in the upper one. The stratigraphic position of the Gl_2 seismic horizon is determined by its position between foraminiferal zones JF40 (uppermost Lower Kimmeridgian) and JF44/JF45 (Lower Volgian) and corresponds to the Upper Kimmeridgian (Nikitenko, 2009; Nikitenko et al., 2013). This level may correspond to the base of the Yanovstanskaya Formation in the northeastern part of Western Siberia along the boundary of Siberian Platform. Thus, the stratigraphic range of this seismic sequence is assumed is to be the uppermost Oxfordian / base of the Kimmeridgian – upper part of the Upper Kimmeridgian (Figs. 2, 3).

The Gl_2—Gl_1 seismic sequence (Fig. 5) differs from those described above by a series of well-defined reflections flowing into the clinoform reflections of the Shuratovo Formation by the type onlap pattern (Fig. 5, *a*, profile 3590010) that may give a false impression of stratigraphic discontinuity. There are the fragments of RH onlap pattern (Fig. 5, *b*) near the base of this sequence. The relevant part of the section is built of mainly black mudstones, sometimes argillaceous, with silty interlayers. The stratigraphic position of the Gl_2 reflection seismic horizon is calibrated with the lower part of the foraminiferal zone KF1 and corresponds to the lowermost Boreal Berriasian (Nikitenko et al., 2013). The stratigraphic range of this seismic sequence is consistent with the upper part of the Upper Kimmeridgian – lowermost Boreal Berriasian (Figs. 2, 3).

GEOCHEMISTRY OF THE ORGANIC MATTER FROM THE GOL'CHIKHA FORMATION AND OILS IN CRETACEOUS SECTIONS OF THE PAIYAKHSKAYA AREA

The studied sediments from the sections of the Gol'chikha Formation and lowermost Shuratovo Formation are potentially oil- and gas-producing and their OM content varies from 0.6 to 9.9% (Fig. 2). To determine OM type in the rocks, we used the results of pyrolysis and estimated $\delta^{13}C_{org}$ values, and their variations along the Oxfordian – lowermost Boreal Berriasian section. The performed data analysis has demonstrated that OM katagenesis in studied boreholes increases with the sampling depth from MK_1^2 to MK_2 according to the A.E. Kontorovich scale (1976), and the vitrinite reflectivity varies within a range of 0.70–1.14%. In general, the estimations of OM maturity from pyrolysis data correspond to those based on coal petrography. Analysis of value dependence of hydrogen index (HI) and pyrolytic temperature T_{max} reflecting the quality of organic matter (kerogen type) and its maturity degree, has also revealed certain regularities (Fig. 6).

The OM content varies in high extent (from 1.8 to 9.9% per rock) in the dark-grey mudstones and siltstones of the lower part of the Gol'chikha Formation (lowermost Oxfordian) from the borehole Paiyakhskaya 1 (uppermost part of member 2). The abnormally high concentrations of C_{org} (6.0–9.9%) for the lowermost Gol'chikha Formation were

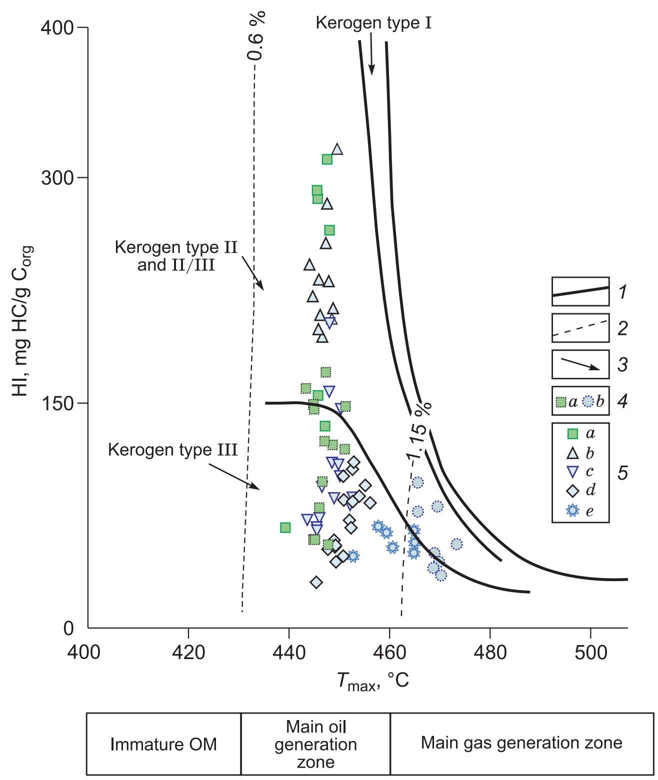

Fig. 6. HI vs. T_{max} dependence for different horizons of the Gol'chikha Formation within the Paiyakhskaya area *1*, lines limiting maximum HI values for three OM types: I, aquagenic, lacustrine type, II, aquagenic, marine type, III, terrigenic, related to higher plants; *2*, vitrinite reflectance isolines (R^o_{Vt}), *3*, direction of HI and T_{max} changes in katagenesis, *4*, samples from the lowermost Boreal Berriasian samples (*a*) and lowermost Oxfordian (*б*), borehole Paiyakhskaya 1, *5*, samples from the lowermost Boreal Berriasian (*a*), Upper Volgian (*b*), Middle Volgian (*c*), Lower Volgian (*d*), and Kimmeridgian (*e*), borehole Paiyakhskaya 4.

obtained from an interval between 4009.0–4015.1 m (Fig. 2), which is due to abundant fine-dispersed carbonaceous plant detritus in the mudstones. The values of C_{org} varied between 1.8–4.1% in other samples from the lowermost Oxfordian. The determination of OM type based on pyrolysis data is problematic, as it is in the main gas generation zone (MGZ) and almost fully depleted its initial hydrocarbon potential (35–97 mg HC/g C_{org}) (Fig. 6). Note that there is some increase in the HI values, up to 77–97 mg HI/g C_{org} that is due to considerable content of fine-dispersed carbonaceous plant detritus. According to the data on carbon isotopic composition, the OM in the studied interval is of mixed terrigenic-marine origin, due to the presence of argillaceous interlayers containing marine or mixed OM with $\delta^{13}C_{org}$ values of –27.2 and –29.9‰ (Fig. 2).

The organic carbon concentrations vary from 0.6 to 2.8% (1.4% on average) in the Kimmeridgian dark-grey and black mudstones from the borehole Paiyakhskaya 4 (members 4 and 5) (Fig. 2). The OM generation potential in the Kimmeridgian part of the Gol'chikha Formation section is also considerably depleted. The HI values vary from 48 to 68 mg

HC/g C_{org}, and the OM maturity corresponds to the end of main oil generation zone (R°_{Vt} = 1.09%, $МК_2$, T_{max} = 453–465 °C) (Fig. 6). The heavy isotopic values ($\delta^{13}C_{org}$ –24.8…–24.0‰) in this part of the section suggest the terrigenic genotype of OM (kerogen type III).

The organic matter from the mudstones in the Lower Volgian and lowermost Middle Volgian (borehole Paiyakhskaya 4, member 6) is of mainly terrigenic type related to terrestrial higher plants. The $\delta^{13}C_{org}$ values in the insoluble constituents of rock are –26.3‰ on average (–26.9…–25.8‰) (Fig. 2). The values of residual generation potential vary from 30 to 110 mg HC/g C_{org} (75 mg HC/g C_{org} in average) in this interval. The HI values increase up to 101 and 146 mg HC/g C_{org} respectively in two samples from the Lower Volgian (3685 m) and lower part of the Middle Volgian (3637 m) that in combination with the results of isotopic signature analysis (–27.7 and –28.3‰) suggests a significant input of marine OM has in the sediments from this part of the section. The R°_{Vt} values (0.87—1.01%) in the Lower Volgian mudstones indicate that the OM maturity corresponds to the level of $МК_2$. No vitrinite reflectance measurements were obtaines from the overlaying Middle Volgian sediments, so determination of the depth corresponding to $МК_1^2/МК_2$ change is problematic. The T_{max} values for the whole interval vary from 444 to 456 °C indicating the OM belongs to the main oil generation zone (Fig. 6).

The mudstones with maximum values of OM saturation (C_{org} varies from 1.0 до 5.0%, 2.5% in average) was revealed in the borehole Paiyakhskaya 4 from the of the uppermost part of the Gol'chikha Formation (Upper Volgian and basal Boreal Berriasian) (Fig. 4). The trend of increasing HI values (from 109 to 203 mg HC/g C_{org}) started in the lower part of the Middle Volgian continues in the upper part of the Middle Volgian (uppermost part of member 7), where OM is of mixed marine-terrigenic type (II/III). Mostly marine OM (kerogen type II and II/III) with HI values exceeding 200 mg HC/g C_{org} is identified in the Upper Volgian (lower half of member 8) (Fig. 6). In the base of the Boreal Berriasian (upper part of member 8), the deposits of the Gol'chikha Formation are characterized by both high (265—312 mg HC/g C_{org}) and low (67.134 and 155 mg HC/g C_{org}) HI values indicating the reduced proportion of marine OM in this interval.

The samples obtained from the uppermost Middle Volginian – basal Boreal Berriasian are characterized by low $\delta^{13}C_{org}$ values (from –31.2 to –28.2‰) that confirms mostly marine OM composition (Fig. 2). In synchronous stratigraphic interval of the section, the $\delta^{13}C_{org}$ values vary from –34.0 to –28.0‰ in the central part of Western Siberia (Bazhenov Formation) (Kontorovich et al., 1986), and from –30.5 to –28.0‰ in the outcrops of the Laptev Seas coast (Pakhsa Formation) (Kashirtsev et al., 2018). The OM katagenesis of the Upper Volgian interval corresponds to the main oil generation zone that is confirmed by both vitrinite reflectance measurements (0.70–0.80%, $МК_1^2$) and the pyrolysis analysis (T_{max} varies from 439 to 450 °C) (Fig. 6).

The C_{org} content in the siltstone from the lowermost part of the Shuratovo Formation (lower part of the Boreal Berriasian) in the borehole Paiyakhskaya 1 varies around the bulk Earth value of 0.9% (Fig. 2) following the classification of N.B. Vassoevich (1973). The OM in most samples from the Shuratovo Formation in the borehole Paiyakhskaya 1 is characterized by kerogen type III mostly related to terrestrial higher plants. The HI values for this interval do not exceed 150 mg HC/g C_{org}. The value of carbon isotopic composition in the insoluble constituents of rock varies from –25.5 to –24.2‰. OM katagenesis in this part of the section corresponds to the $МК_1^2$ level (R°_{Vt} = 0.7%) (Fig. 6).

Oil inflows were obtained from different Cretaceous productive horizons in the test wells of the Paiyakhskaya area (Fig. 1). Oil samples were collected from the wellheads in the borehole 1 (Fig. 2) (test intervals: 3420–3426 m, base of the Shuratovo Formation, 1489–1501 and 1503–1506 m, the Yakovlevo Formation) and borehole 8 (test intervals 3458–3494, the Shuratovo Formation).

The studied oil samples are characterized by low (808.9 kg/m^3) and middle (849.8–868.7 kg/m^3) densities and contain 19–35% of fractions that distil off at a boiling point of 200 °C. Their sulfur content is low (<<0.5%), and their paraffin is high (~ 4.0%). The amount of hydrocarbons (> 85%) in their composition significantly exceeds that of resins (>85%) and, especially, asphaltenes (0.16–0.53%). The amount of saturated hydrocarbons is two times higher than that of aromatic compounds.

The studied oils have light isotopic signature, the $\delta^{13}C$ values vary from –31.3 to –29.7‰ (Fig. 2).

Using GLC, n-alkanes from C_{12} to C_{40} are identified in the saturated fraction having their maximum at C_{17} (8.2–9.4% per total amount of identified *n*-alkanes), which is a typical distribution for hydrocarbon fluids. Among the acyclic isoprenoids (from C_{13} to C_{25}), the pristane concentration is the highest (32.5–37.0% per total amount of identified acyclic isoprenoids), the concentrations of phytane (17.0–20.9% per total sum) and norpristane (16.5–19.4% per total sum) are also high, but much lower in comparison to pristane. The n-alkane/acyclic isoprenoid ratio changes in a narrow range of 5.0–6.5. The other geochemical parameters describing n-alkane and acyclic isoprenoid contents are also characterized by close values: pristane/phytane – 1.7–1.9, pristane/n-C_{17} – 0.6–0.8, phytane/n-C_{18} – 0.4–0.5, CPI – 1.06–1.08, n-C_{27}/ n-C_{17} – 0.3–0.5.

Sterane and terpane concentrations in the saturated oil fractions have been estimated using chromatography-mass spectrometry (CMS).

The C_{27}, C_{28} and C_{29} steranes are characterized by close concentrations (28.7–36.0, 28.0–30.1, 26.9–31.1% per total sum of sterans respectively), while the C_{30} sterane concentrations are much lower (7.6—12.0% per total sum of sterans). Inconsiderable domination of C_{29} homolog over that of C_{27} is determined in two samples, while the analysis of three samples shows slightly higher concentrations of sterane C_{27} in comparison to steran C_{29} values. The ratio of steranes C_{29}/

C_{27} varies from 0.75 to 1.08. The amount of regular structures (αα- and ββ-) exceeds that of diasteranes (βα-) among the isomeric steranes, and ratio βα/(αα + ββ) varies within a range of 0.5–0.8.

Studied oils insignificantly differ in isometric values of their maturity according to the composition of regular steranes: C_{29} ββ (20S+20R)/ αα20R (3.6–5.4) and αα 20S/ αα 20R (1.3–2.3). Among the identified terpanes, it is hopane structures (C_{30} hopane, nor- (C_{27}–C_{29}) and homohopane (C_{31}–C_{35}) that prevail followed, in decreasing order, by tricyclenes (cheilanthanes) (C_{19}–C_{31}, 10.3–24.8%), moretanes (C_{29}–C_{32}, 2.4–4.5%) and tetracyclic terpanes (C_{24}–C_{27}, 0.8–2.0%). The ratio between saturated steroid structures and terpanes varies from 0.5 to 0.7. The ratios calculated from the composition of terpanes have the following values: Ts/Tm (18α(H) 22,29,30– trisnorneohopane / 17α(H) 22,29,30–trisnorhopane) – 1.77–2.37, C_{35} homohopane/C_{34} homohopane – (0.5–0.7), adiantane /hopane C_{30} – 0.30–0.33, Tricyclane index (Itc = $2 \cdot \sum C_{19-20} / \sum C_{23-26}$) – 0.4–0.6. The dibenzothiophenes, phenanthrenes, mono- and triaromatic steroids are identified in the composition of naphthenic-aromatic fraction using chromatography-mass spectrometry (CMS). The phenanthrenes are characterized by maximum concentrations (64.7–84.9% per total sum of identified aromatic compounds). The concentration of triaromatic steroids is much lower (4.9–20.8%), and the values of dibenzothiophene (6.4–9.5%) and monoaromatic steroids (0.7–7.8%) are one order less in comparison to the phenanthrenes. The phenanthrene/ dibenzothiophene ratio varies from 8.8 to 11 and that of tri-/monoaromatic steroids – from 2.6 to 7.1.

The maturation degrees calculated from the composition of identified aromatic structures are of insignificant spread in values: dibenzothiophene index (2- + 3- methyl dibenzothiophene/ dibenzothiophene) – 0.8–1.1, phenanthrene index (2-methyl phenanthrene/phenanthrene) – 0.5–0.6, methyl – phenanthrene index 1 (1.5·(2- + 3- methyl phenanthrene)/(phenanthrene + 9- + 1- methyl phenanthrene)) – 0.03–0.05, R_0(0.6 · MPI 1 + 0.4 %) – 0.42–0.43.

The results of the investigation of oil samples obtained from the Cretaceous productive sediments (Boreal Berriasian, Aptian-Albian) in the Paiyakhskaya area has demonstrated similarities in the chemical properties of oils, $\delta^{13}C$ values, and component composition (hydrocarbons and aromatic compounds) suggest that they were formed at a single accumulation stage and derived from one source area. According to hydrocarbon isotopic composition and genetic parameters of the composition of identified compounds, studied oils can be formed from mostly marine OM accumulated in slightly and/or moderately deoxidizing conditions of shallow water areas due to terrigenous sedimentation (Bray and Evans, 1961; Tisso and Velte, 1981; Petrov, 1984; Kontorovich at al., 1986, 2013; Peters et al., 2005). According to the calculated indexes, the degree of oil maturity corresponds to the main oil generation zone (Petrov, 1984; Peters et al., 2005).

The genotype and maturity degree of the investigated oils most of all correspond to the organic matter of the upper part of the Gol'chikha Formation, according to the results of pyrolysis analysis and $\delta^{13}C_{org}$ data presented above as well as the data on organic geochemistry on the Jurassic and Lower Cretaceous of the Yenisei–Khatanga region (Kim and Rodchenko, 2013; Rodchenko, 2016). This correlation allows us to consider the sediments in the upper part of the Formation (member 8, Upper Volgian – basal Boreal Berriasian) containing mainly marine OM as producing the oil (Fig. 2).

CONCLUSION

The results of comprehensive studies of the sections of the Gol'chikha Formation (Upper Bathonian – lowermost Boreal Berriasian) drilled in the Paiyakhskaya area located in the submerged central part of the western region of the Yenisei–Khatanga depression demonstrate that these sections can be considered as the reference ones. Keeping in mind the insufficient stratigraphic characteristics of the Gol'chikha Formation stratotypes previously suggested in the boreholes Deryabinskaya 5 and Yzhnoe-Noskovskaya 318 (Kukushkina and Kislukhin, 1983; Kislukhin, 1986; Kulikov, 1989; Nesterov, 1991), we suggest the Paiyakhskaya sections as hypostratotypes of this Formation (Figs. 1, 2).

Foraminiferal assemblages of the zones of the Callovian (JF25), the Lower Oxfordian and basal Upper Oxfordian (JF36), the uppermost Oxfordian – lower part of the Lower Kimmeridgian or uppermost Lower Oxfordian (JF40/JF39), the upper part of Lower Volgian (JF44/JF45), the lower part of MiddleVolgian (JF46), the uppermost Middle Volgian – lowermost Upper Volgian (JF55), uppermost Middle Volgian – basal Boreal Berriasian (JF52), and the lowermost Boreal Berriasian (KF1) are defined in the studied intervals of the boreholes Paiyakhskaya 1 and 4 (Nikitenko, 2009; Nikitenko et al., 2013).

The biostratigraphic analysis of the sections from the neighboring territories demonstrates that the boundary between the Gol'chikha and Shuratovo Formations is located within the foraminiferal zone KF1 (lowermost Borelian Berriasian) (Figs. 2, 3). In spite of the unsatisfactory preservation of the palynomorphs and their poor taxonomic composition, we succeed to provide the basis for the definition of the Upper Volgian in the section.

The analysis of the deviations in isotopic signatures of stable carbon isotopes from their standard values ($\delta^{13}C_{org}$) in the upper part of the Gol'chikha Formation and the lower part of the Shuratovo Formation (Volgian – lower part of the Borelian Berriasian) demonstrates that the trends in resulted curve of $\delta^{13}C_{org}$ variations are almost identical to those in the curves from the Barents Sea shelf (Spitzbergen Is.) and the northeastern part of Western Siberia (Olenek River downstream) despite the differences in absolute values (Hammer et al., 2012; Nikitenko et al., 2018). It provides the reliable basis for more accurate definition of the boundaries of stages and substages within the Paiyakhskaya area in the intervals without any fossils (Figs. 2, 4).

According to well logging data, the base of the Gol'chikha Formation is determined by the changes of the sawtooth apparent resistivity curve having small variations as well as the positive anomaly of spontaneous polarization curve demonstrating the change of the sandstones of the Malyshevka Formation by the mudstones of the Gol'chikha Formation (Fig. 2). According to the principles of comprehensive evaluation of the upper boundary of the Bazhenov Formation (Ryzhkova et al., 2018), its upper boundary is defined at the base of the first high-resistivity bed of the Shuratovo Formation (Fig. 2).

The section of the Gol'chikha Formation in the Paiyakhskaya area is subdivided into eight lithological members calibrated with bio- and seismostratigraphic units. The number of members, the structure of the Formation and its thickness change beyond the studied area. The facial heterogeneity of the Gol'chikha Formation precludes its distinct subdivision into subformations in all areas as it was previously suggested (Kulikov, 1989).

A number of highly dynamic seismic reflections confined to the top of the underlaying Malyshevka (Tml) and the top of the Gol'chikha (Gl_1) formations has been defined in the seismic sections crossing the Paiyakhskaya area in sublatitudinal and submeridional directions (Fig. 5) Within the interval of the Gol'chikha Formation, three highly reflecting horizons have been detected forming a separate seismic sequences. An analysis of bio- and chemostratigraphic data allows their calibration with the geologic section.

The OM content in the rock samples from the Gol'chikha Formation and lowermost part of the Shuratovo Formation varies from 0.6 to 9.9% (Fig. 2), demonstrating that these sections are potentially gas – and oil-bearing. It has been shown that sediments contained consistently high values of OM are confined to the upper part of the Gol'chikha Formation (Upper Volgian and basal Borelian Berriasian). The low $\delta^{13}C_{org}$ values confirm the mostly marine composition of OM in this part of the section (Fig. 2). According to the vitrinite reflectivity data, OM katagenesis in the Upper Volgian corresponds to the main oil generation zone that is confirmed by pyrolysis analysis. Thus, these sediments can be considered as those had been producing the oil. According to the pyrolysis of OM, the lower layers of the formation are confined to the beginning of the deep zone of gas generation, indicating that OM has almost depleted its initial hydrocarbon potential (Fig. 6).

The results of analytical investigation of the oils from the Cretaceous productive beds in the Paiyakhskaya area has shown the similarity of their physical and chemical properties, $\delta^{13}C_{org}$ values and component composition (hydrocarbons and aromatic compounds), allowing us to suggest that they were formed at a single accumulation stage and derived from one source area. By their genotype and maturity degree, the studied oils mostly correspond to OM from the upper part of the Gol'chikha Formation (Upper Volgian – basal Boreal Berriasian).

The authors would like to express their gratitude to V.A. Kashirtsev, V.G. Khyazev and N.K. Lebedeva for their valuable recommendations during the preparation of this article.

This study was performed with a financial support of the Russian Scientific Foundation (Project No 18-17-00038) and the Russian Foundation for Basic Research (Project No 18-05-70035).

REFERENCES

Afanasenkov, A.P., Bondarenko, M.T., Kissin, Yu.M., Tarasenko, E.M., Kondratiev, I.K., 2016. Concerning promising oil and gas objects for deep drilling according to the results of regional seismic survey in the Yenisei–Khatanga regional trough. Geologiya nefti i gaza 3, 44–54.

Afanasenkov, A.P., Nikishin, A.M., Unger, A.V., 2017. Mesozoic–Cenozoic geological history of the north of Western and Eastern Siberia based on the seismic data analysis. Geologiya nefti i gaza, 1, 34–40.

Alifirov, A.S., Meledina, S.V., 2010. Callovian ammonites of Western Siberia: chronology and chorology. News of Paleontology and Stratigraphy. Supplement to Geology and Geophysics, Vol. 51 (14), 61–84.

Batten, D.J., 1996. Upper Jurassic and Cretaceous miospores, in: Palynology: principles and applications. Jansonius, J., McGregor, D.C. (Eds.). AASP, Salt Lake City, Vol. 2, pp. 807–831.

Borisov, E.V., 2015. Geological structure of the Gol'chikha Formation in the western part of the the Yenisei–Khatanga regional trough, in: Interexpo GEO-Siberia 2015. XI International Scientific Congress (Novosibirsk, April 13–15, 2015). International Scientific Conference Subsoil Management. Mining. Trends and Technologies for Prospecting and Mining of Ores. Geoecology. Vol. 1, pp. 13–17.

Bray, E.E., Evans, E.D.,1961. Distribution of n-paraffins as a clue to recognition of source beds. Geochim. Cosmochim. Acta 22, 2–15.

Filiptsov, Yu.A., Davydova, I.V., Boldyshevskaya, L.N., Dalilova, V.P., Kostyreva, E.A., Fomin, A.N., 2006. Interrelation of source rock and oils in the Mesozoic deposits of the northeastern part of Western-Siberian Plate from studied carbon biomarkers and organic matter katagenesis. Geologiya, Geofyzika i razrabotka neft'anyh i gazovyh mestorozhdenii, No. 5–6, 52–57.

Fomin, M.A., 2016. Tectonic structure of Mesozoic–Cenozoic deposits of Yenisei–Khatanga regional trough. Geologiya, Geophyzika i razrabotka neft'anyh i gazovyh mestorozhdenii, No. 9, 4–18.

Golovin, S.V., 2009. Classification of Mesozoic hydrocarbon plays of the Yenisei–Khatanga regional depression. Neftegazovaya Geologiya. Teoriya i Praktika 4 (1), 1–21.

Gurari, F.G. (Ed.), 2004. Resolution of the 6th Interdepartmental Regional Stratigraphy Meeting on Specified Stratigraphic Maps of the Mesozoic Sediments of the West-Siberian Plain [in Russian]. Novosibirsk.

Hammer, Ø., Collignon, M., Nakrem, H.A., 2012. Organic carbon isotope chemostratigraphy and cyclostratigraphy in the Volgian of Svalbard. Norwegian Journal of Geology 92, 103–112.

Herngreen, G.F.W., Kerstholt, S.J., Munsterman, D.K., 2000. Callovian-Ryazanian (Upper Jurassic) palynostratigraphy of the Central North Sea Graben and Vlieland Basin, the Netherlands. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO. 63, 1–97.

Ilyina, V.I., 1985. Jurassic Palynology of Siberia [in Russian]. Science, Moscow.

Ilyina, V.I., Nikitenko, B.L., Glinskikh, L.A., 2005. Foraminifera and dinoflagellate cyst zonation and stratigraphy of the Callovian to Volgian reference section in the Tyumenskaya superdeep well (West Siberia, Russia), in: Recent Developments in Applied Biostratigraphy. Powell, A.J., Riding, J.B. (Eds.). The Micropalaeontological Soc., Spec. Issue, 2005, pp. 109–144.

Isaev, A.V., Devyatov, V.P., Karpukhin, S.M., Krinin, V.A., 2010. Oil and gas prospects of Enisei–Khatangsky regional trough. Geologiya nefti i gaza 4, 13–23.

Jansonius, J., McGregor, D.C., 1996. Palynology: principles and application. Publishers Press, Salt Lake City, Vol. 1.

Karogodin, Yu.N., 1980. Sedimentary Cyclicity [in Russian]. Nedra, Moscow.

Kartseva, G.N., Kuznetsov, L.L., Obrazkova, V.P., 1983. New data on Jurassic and Cretaceous deposits in the western part of the Yenisei–Khatanga regional depression, in: Paleozoic and Mesozoic Reference Horizons in the Northern Part of the European USSR and Siberia [in Russian]. VNIGRI, Leningrad, pp. 96–100.

Kashirtsev, V.A., Nikitenko, B.L., Petshevitskaya, E.B., Fursenko, E.A., 2018. Biogeochemistry and microfossils of the Upper Jurassic and Lower Cretaceous, Anabar Bay, Laptev Sea. Russian Geology and Geophysics (Geologiya i Geofizika) 59 (4), 386–404 (481–501).

Kim, N.S., Rodchenko, A.P., 2013. Organic geochemistry and petroleum potential of Jurassic and Cretaceous deposits of the Yenisei–Khatanga regional trough. Russian Geology and Geophysics (Geologiya i Geofizika) 54 (8), 966–979 (1236–1252).

Kislukhin, V.I., 1986. Lithological and regional demarcation of Jurassic and Cretaceous deposits of the north of Western Siberia, in: Hydrocarbon Potential of the North of Western Siberia [in Russian]. ZapSibNIGNI, Tyumen, pp. 13–31.

Klimova, E.N., Kucheryavenko, D.S., Polyakov, A.A., 2018. New data about the reservoir genesis in Pay-Yakha petroleum field and perspectives of their oil potential relating to lower Yenisey province. Neftegazovaya Geologiya. Teoriya i Praktika 13 (1), 1–17.

Kontorovich, V.A., 2011. Tectonics and hydrocarbon potential of the western part of the Yenisei–Khatanga regional depression. Russian Geology and Geophysics (Geologiya i Geofizika) 52 (8), 804–824 (1027–1050).

Kontorovich, A.E., 1976. Geochemical Methods of Quantitative Forecast of Hydrocarbon Potential. Works of SNIIGGiMS [in Russian]. Nedra, Moscow. Issue 229.

Kontorovich, A.E., Kontorovich, V.A., Ryzhkova, S.V., Shurygin, B.N., Vakulenko, L.G., Gaideburova, E.A., Danilova, V.P., Kazanenkov, V.A., Kim, N.S., Kostyreva, E.A., Moskvin, V.I., Yan, P.A., 2013. Jurassic paleography of the West Siberian sedimentary basin. Russian Geology and Geophysics (Geologiya i Geofizika) 54(8) 747–779 (972–1012).

Kontorovich, A.E., Ponomareva, E.V., Burshtein, L.M., Glinskikh, V.N., Kim, N.S., Kostyreva, E.A., Pavlova, M.A., Rodchenko, A.P., Yan, P.A., 2018. Distribution of organic matter in rocks of the Bazenov horizon (West Siberia). Russian Geology and Geophysics (Geologiya i Geofizika) 59 (3), 285–298 (357–371).

Kontorovich, A.E., Verkhovskaya, N.A., Timoshina, I.D., Fomichev, A.S., 1986. Carbon isotope composition of dispersed organic matter and bitumens and some disputed problems of the theory of oil formation. Russian Geology and Geophysics (Geologiya i Geofizika) (5), 1–11 (3–13).

Kukushkina, T.S., Kislukhin, V.I., 1983. Regional and sectional demarcation of Jurassic deposits (Polar regions of Western Siberia). Creative Youth Participation in Boosted Increasing of Daily Production (up to 1 mln tons of oil and 1 bln cubic meter of gas) in the Deposits of Tyumen Region, in: Abstracts of the 6th Scientific and Technical Conference of the Young Scientists and Specialists of ZapSibNIGNI (March 23-24, 1983), Tyumen, pp. 20–21.

Kulikov, D.P., 1989. Stratigraphic subdivision and structural-facial regionalization of Upper Jurassic deposits of the Enisei–Khatanga trough. Russian Geology and Geophysics (Geologiya i Geofizika) 30 (10), 7–14 (10–18).

Nesterov, I.I. (Ed.), 1991. Resolution of the 5th Interdepartmental Regional Stratigraphic Meeting on the Mesozoic of the West Siberian Plain, adopted May 14-18, 1990 and approved by the ISC of the USSR on January 30, 1991 [in Russian]. ZapSibNIGNI, Tyumen.

Nikitenko, B.L., 2009. Stratigraphy, paleobiogeography and biofacies of Jurassic Siberia (foraminifera and ostracods) [in Russian]. Parallel, Novosibirsk.

Nikitenko, B.L., Knyazev, V.G., Peshchevitskaya, E.B., Glinskikh, L.A., Kutygin, R.V., Alifirov, A.S., 2015. High-resolution stratigraphy of the Upper Jurassic section (Laptev Sea coast). Russian Geology and Geophysics (Geologiya i Geofizika) 56 (4), 663–685 (845–872).

Nikitenko, B.L., Pestchevitskaya, E.B., Khafaeva, S.N., 2018. High-resolution stratigraphy and palaeoenvironments of the Volgian–Valanginian in the Olenek key section (Anabar-Lena region, Arctic East Siberia, Russia). Revue de micropaléontologie, doi:org/10.1016/j.revmic.2018.07.001.

Nikitenko, B.L., Shurygin, B.N., Knyazev, V.G., Meledina, S.V., Dzyuba, O.S., Lebedeva, N.K., Peshchevitskaya, E.B., Glinskikh, L.A., Goryacheva, A.A., Khafaeva, S.N., 2013. Jurassic and Cretaceous stratigraphy of the Anabar Area (Arctic Siberia, Laptev Sea coast) and the Boreal zonal standard. Russian Geology and Geophysics (Geologiya i Geofizika) 54 (8), 808–837 (1047–1082).

Pestchevitskaya, E., Lebedeva, N., Rybokon, A., 2011. Uppermost Jurassic and lowermost Cretaceous dinocyst successions of Siberia, the Subarctic Urals and Russian Platform and their interregional correlation. Geologica Carpathica 62 (3), 189–202.

Peters, K.E., Walters, C.C., Moldowan, J.M. The Biomarker Guide. Cambridge University Press, Cambridge.

Petrov, A.A., 1984. Oil Carbons [in Russian]. Science, Moscow.

Powell, A.J. (Ed.), 1992. A Stratigraphic Index of Dinoflagellate Cysts. London.

Rodchenko, A.P., 2016. Organic matter geochemistry of the Upper-Jurassic deposits in the North–East of Western Siberia and cretaceous oil genesis in the region. Geologiya nefti i gaza 6, 107–118.

Russian Stratigraphic Code, 2006. VSEGEI, Saint-Petersburg.

Ryzhkova, S.V., Burshtein, L.M., Ershov, S.V., Kazanenkov, V.A., Kontorovich, A.E., Kontorovich, V.A., Nekhaev, A.Yu., Nikitenko, B.L., Fomin, M.A., Shurygin, B.N., Beizel', A.L., Borisov, E.V., Zolotova, O.V., Kalinina, L.M., Ponomareva, E.V., 2018. The Bazhenov Horizon of West Siberia: structure, correlation, and thickness. Geology and Geophysics (Geologiya i Geophysika) 59 (7), 846–863 (1053–1074).

Sajjadi, F., Playford, G., 2002. Systematic and stratigraphic palynology of Late Jurassic – earliest Cretaceous strata of the Eromanga Basin, Queensland, Australia, Part two. Palaeontographica 261, 99–165.

Scotese, C.R., 2011. Paleogeographic and Paleoclimatic Atlas // AAPG Data Pages. Search and Discovery Article #30192 (2011). http://www.searchanddiscovery.com/pdfz/documents/2011/30192scotese/ndx_scotese.pdf.html.

Shurygin, B.N., Nikitenko, B.L., Devyatov, V.P., Ilyina, V.I., Meledina, S.V., Gaideburova, E.A., Dzyuba, O.S., Kazakov, A.M., Mogucheva, N.K., 2000. Stratigraphy of the oil-bearing basins of Siberia. Jurassic system [in Russian]. Geo, Novosibirsk.

Zhamoida, A.I. (Ed.), 1992. Stratigraphic Code. Second edition with amendments. VSEGEI, Saint-Petersburg.

Tisso, B., Velte, D., 1981. Formation and Dissemination of Petroleum [in Russian]. Mir, Moscow.

Tyson, R.V., 1995. Sedimentary organic matter: organic facies and palynofacies. Chapman and Hall, London.

Vassoevich, N.B., 1973. Key features to characterize the organic matter of modern and fossil sediments, in: Nature of Organic Matter of the Modern and Fossil Sediments [in Russian]. Science, Moscow, pp. 11–59.

Zlobina, O.N., Rodchenko, A.P., 2015. Lithological and geochemical characteristics of the Gol'chikha Formation in the section of the Paiyakhskaya 4 well (Gydan facial area, north of Middle Siberia), in: Interexpo GEO-Sibearia 2015. XI International Scientific Congress (Novosibirsk, April 13-15, 2015). International Scientific Conference Subsoil Management. Mining. Trends and Technologies for Prospecting and Mining of Ores. Geoecology. Vol. 1, pp. 48–53.

Editorial responsibility: V.A. Kashirtsev