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Lithologic, Geochemical and Geophysical Characteristics of the Boundary Strata of the Bazhenov and Kulomza Horizons (*Lower Cretaceous Base)* in the Central Regions of the West Siberia

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Abstract—The gradual transition of the Bazhenov Formation top into the overlying deposits makes it difficult to establish its upper boundary. The problem is aggravated by the lack of core material when the formation is recognized according to the results of geophysical well studies. A comprehensive analysis of geochemical and lithological data and the results of geophysical well surveys enabled us not only to determine the specific structure of the transitional zone from the Bazhenov Formation top to the rocks of the sub-Achimov member, but also to propose the criteria for delineating the upper boundary in the central regions of the West Siberian sedimentary basin within the Khentei hemianteclise, the South Nadym megamonoclise and the Mansi syneclise. Four members are distinguished in the transitional zone of the studied well sections (from bottom to top), which differ in lithological, geochemical and geophysical characteristics: (I) the "coccolithic" upper part of the Bazhenov Formation; (II) transitional member from the upper part of the Bazhenov Formation to the bottom of the sub-Achimov member; (III) transitional member from the bottom of the sub-Achimov member to its lower part; and (IV) the lower part of the sub-Achimov member. Member II is virtually not distinguished within the Khentei hemianteclise and the South Nadym megamonoclise. Member III contains the boundary between zones with different redox conditions. In case member II is distinguished, the upper boundary of the Bazhenov Formation corresponds to its top. To recognize the Bazhenov Formation top, it is necessary to use the integrated analysis results of the lithological and geochemical studies of the well core, and logging data (gamma-ray logging, neutron gamma-ray logging and its variations, lateral logging, and induction logging) when focusing attention mainly on radioactivity.

Keywords: Upper Jurassic–Lower Cretaceous, lithology, geochemistry, organic matter, geographical parameters, upper boundary of the Bazhenov Formation, West Siberia

INTRODUCTION

A fundamental investigation has been undertaken in recent years that resulted in a number of papers devoted primarily to the studies of the lithological composition, the thickness of the distinguished members, distribution and composition of organic matter (OM), and other characteristics of the Bazhenov Formation (BF) in the whole territory of the West Siberian sedimentary basin (WSB). A similar analysis is required to solve problems arising under investigations, during surveys, and production of such a complex, "non-traditional" reservoir as the Bazhenov Formation targeted at hydrocarbons extraction. The problem of delineating the upper and lower boundaries of the formation is still controversial. Researchers focus greater attention on the study of the Abalak Formation transition into the BF (Zubkov, 2001a; Balushkina et al., 2013; Yurchenko et al., 2015; Panchenko and Nemova, 2015), rather than on the upper boundary of the Bazhenov Formation with its overlapping rocks of the sub-Achimov member of the Kulomza horizon with the Lower Cretaceous base. The authors have not found any detailed and integrated analysis of the above-mentioned zone characteristics in literature.

Being biogenic in nature, the Bazhenov Formation is a kerogen–carbonate–argillaceous–siliceous sequence, whose formation dates back mainly to the Volgian Age of the sea transgression within the West Siberian basin (Bulynnikova et al., 1978; Braduchan et al., 1986; Gurari et al., 1988; Kontorovich et al., 2013, 2016). Its basic rock-forming constituents are considered to be: biogenic silicon oxide, carbonate material, argillaceous substance, kerogen, and pyrite, which appeared as a result of diagenesis. The thickness of the formation varies from 20 m to 40 m in the central re-

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gions (Nesterov, 1970; Ryzhkova et al., 2018). The term "kerogen" is used in the present study in compliance with the standard international classification (Uspenskii et al., 1958; Tissot and Welte, 1978; Vandenbroucke, 2003; Bogorodskaya et al., 2005), where it designates all the organic matter of the rock. As mentioned above, the Bazhenov Formation is overlapped (in the absence of unconformity) with the deposits of the Neocomian clinoform complex, such as argillaceous rocks of the sub-Achimov member and the lower parts of the Akhsk and the Sortym formations (Naumov, 1977; Zhamoida and Petrov, 2008). The width of these deposits varies over a wide range in value from complete absence to 80 m (Karogodin et al., 2000; Kiselev et al., 2007). Their formation is referred to the starting stages of the regressive West Siberian paleobasin evolution (Bulynnikova et al., 1978; Naumov et al., 1979; Kontorovich et al., 2014).

The main objective of the present study was to determine lithological, geochemical and geophysical characteristics and formation conditions of the BF transitional zone to the sub-Achimov member rocks. Based on the results of a comprehensive analysis of lithological, geochemical and well-logging data, we also aim at defining the criteria of the upper boundary delineation for the Bazhenov Formation in the central regions of the West Siberian sedimentary basin.

The present work does not consider the issues of the stratigraphic position of the BF top and its compliance with the General Stratigraphic Chart of Russia and the International Stratigraphic Chart, because biostratigraphic methods were not applied to study the sections. The stratigraphic characteristic of the studied section is determined in accordance with (Zhamoida and Petrov, 2008).

The deposits of the WSB transitional zone accumulated mostly during the Early Cretaceous (Kontorovich et al., 1975, 2013). The "coccolithic" BF member has been previously dated from the Berriasian Age (Yasovich and Poplavskaya, 1975; Panchenko et al., 2015). The detailed lithological-geochemical analysis will allow us to define more accurately the changes in the WSB sedimentation conditions in the Early Cretaceous, within the interval of the transition between transgressive and regressive cycles. It also contributes to better understanding of the accumulation mechanism for sea carbonate sediments at final stages. A sharp increase of estimates of apparent resistivity and gamma-ray logging (compared with overlying rocks) can serve as a main criterion for establishing the BF upper boundary in the central region of the WSB based on well-logging data (Khabarov et al., 1980; Braduchan et al., 1986; Gurari et al., 1988). However, well-logging done in the peripheric areas of the central part of the basin give evidence of the fact that this criterion could not be always taken as a basis, because an increase of values for both parameters does not occur simultaneously in some sections (Rodionov et al., 1976; Gaideburova, 1982). The Bazhenov Formation is distinguished by a special lithological structure and distribution of organic matter in different structural-facial regions (Yasovich and Poplavskaya, 1975; Kontorovich et al., 1975, 2018b; Gurari et al., 1988; Polyakova et al., 2002; Eder, 2006; Predtechenskaya et al., 2012; Eder et al., 2015a,b; Sapyanik et al., 2017). Consequently, similar integrated analysis of refining the criteria of delineating the foundation boundaries should be separately conducted in each structural-facial region of the WSB, and it should be followed by the accuracy improvement for its thickness definition, and formation conditions identification in the zone of BF transition into overlying deposits. In such a way, the present study appears to be the first stage of a series of similar studies.

Seven sections of the Bazhenov Formation and the lower part of the sub-Achimov member in the central region of the WSB were chosen as an exploration target. These objects are located within the Mansi syneclise (Salymskaya, Severo-Salymskaya, Chupal'skaya and Malobalykskaya areas), the Khentei hemianteclise (Yuzhno-Yagunskaya and Druzhnaya areas), and the South Nadym megamonoclise (Povkhovskaya area) (Fig. 1). Most surveyed wells are characterized by 100% core recovery from the interval under study.

RESEARCH METHODS

The techniques involved detailed lithological description of core and rock sections with the use of an Olympus BX-59B microscope, sample observation – with a MIRA3 TESCAN scanning electron microscope (SEM), and chemical analyses of rocks. Main rock-forming elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, MnO, K_2O, Na_2O, P_2O_5, BaO and others) were detected by X-ray fluorescence analysis with an ARL-9900-XP spectrometer (Thermo Electron Corporation). DRON-3 and DRON-4 diffractometers were used to study mineralogical composition of the clay fraction (<0.002 mm) and bulk samples of the Bazhenov rocks by the X-ray diffraction technique. The content of sulfur (total, sulphidic and sulphate) and CO_2 was estimated by classical chemical methods (Strakhov, 1957). Geochemical analyses were carried out to determine lithological composition of the reservoir and organic substance at the laboratories of Institute of Geology and Mineralogy and Institute of Petroleum Geology and Geophysics. The names of the rocks (mainly, mudstones) are given according to the classification of Lasar et al. (2015).

The content of total organic carbon (TOC or C_{org}) was determined by the weight semi-micro method with an AN-7529 express-analyzer; a TPH/TOC Source Rock Analyzer (SRA) (Weatherford Laboratory, Instr. Division) was used to define pyrolitic characteristics; group composition was specified from chloroform extracts of the rocks (bitumoids) by column chromatography; hydrocarbon composition was analyzed by gas-liquid chromatography and chromatomass spectrometry (Uspenskii, 1966; Kontorovich, 1973; Kontorovich et al., 1999, 2018a). According to the obtained results (content of rock-forming oxides, C_{org}, sulphide sulphur), the chemical composition of rocks was recalculated in terms of their mineral composition based on O.M. Rosen and coauthors' method (2000) proposed in the amended MINLITH

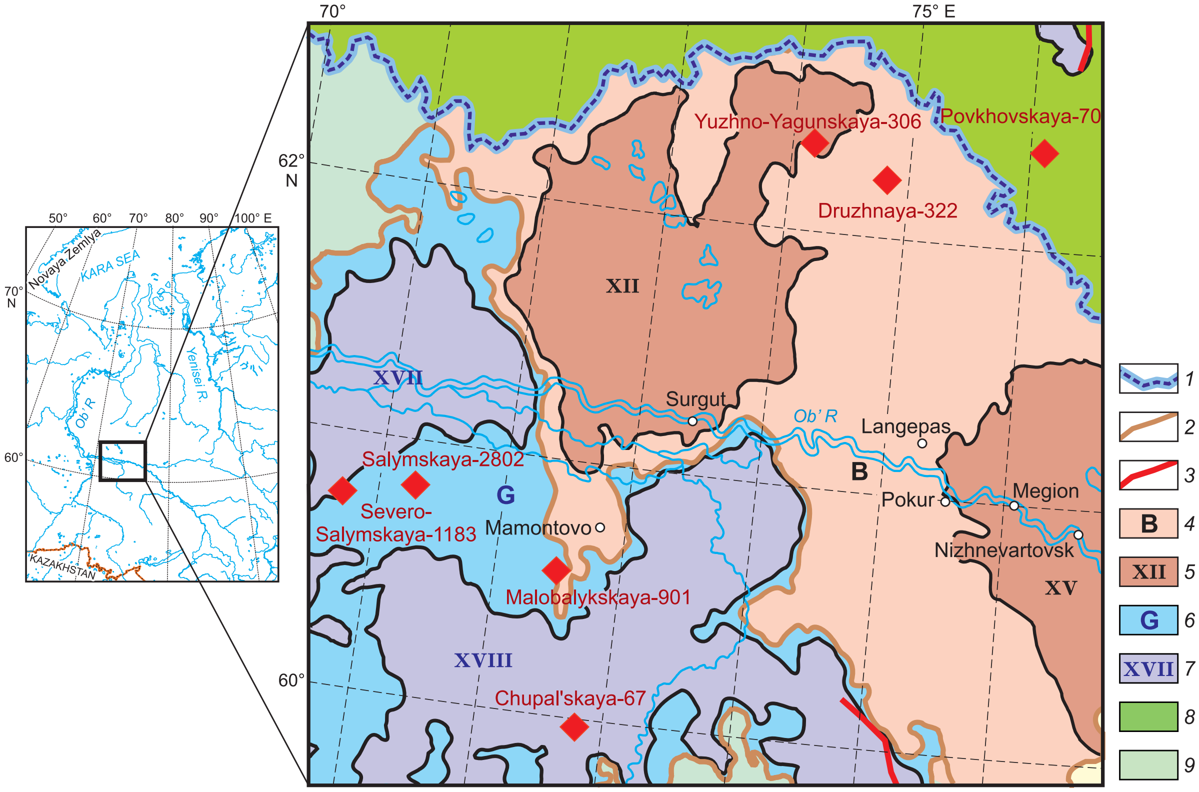

Fig. 1. Position of the studied wells on the tectonic map of the Jurassic structural stage in the petroleum province of West Siberia, from (Kontorovich et al., 2001). Boundaries: *1*, the Internal region and the External belt, *2*, structures of 0 order; *3*, faults; tectonic elements: positive: *4*, 0 order (B, Khantei hemianteclise), *5*, I order (XII , the Surgut arch, XV, the Nizhnevartovsk arch); negative: *6*, 0 order (G, the Mansi syneclise), *7*, I order (XVII, the Tudrinskaya Megadepression, XVIII, the Yugansk Megadepression); intermediate: *8*, South-Nadym megamonoclise of the Yamalo-Kara Depression, *9*, the Krasnoleninsk megamonoclise.

software. Based on the conversion outcome (mineral composition analysis data), each sample was given a lithological name in compliance with the accepted classification (Kontorovich et al., 2016). The curves of the considered constituents distribution and the diagrams of iron pyritization degrees (PD = Fe pyritic/(Fe pyritic + Fe soluble in HCl) were plotted for each section to elucidate: the laws of the vertical pyrite distribution, distribution patterns for total organic carbon and radioactive elements (U, Th, K), pyrolytic characteristics (S_1, S_2, hydrogen index ($HI = S_2/C_{org}\cdot 100$)), and a change in redox conditions in diagenesis (Strakhov and Zalmanzon, 1955; Raiswell et al.,1988). To find a relation of a biochemogenic component to a terrigenic one, the following ratio was used: $(SiO_2 + CaO)/Al_2O_3$. Usually, the content of fine silt size material did not exceed 5% in the deposits under study. Thus, both siliceous and carbonic material of the BF were considered to be much more biochemogenic, but argillaceous material is mostly referred to terrigenous origin.

Then, the results of core studies were compared with well logging data. At the first stage of the research, the core and well-logging data were correlated based on the results of gamma-spectrometric logging. Since geophysical surveys had not been done in all the wells, gamma spectrometry analysis data of core samples were used for the core – well logging correlation and compared with gamma-ray logging data.

To locate the formation's top, detailed lithological columns of the core were analyzed along with various well-logging such as: electrical logging (probes of resistivity logging (RL), induction logging (IL), high frequency induction logging with isoparametric sounding (HFILIS), lateral logging (LL), microprobes (MP)), caliper log (CL), acoustic logging (AL), radioactive logging (gamma-ray logging (GL), spectral gamma-ray logging (SGL), neutron gamma-ray logging (NGL), thermal-decay-time logging (TDT)).

RL, IL, LL and GL techniques were selected as being the most demonstrative and indicative of the most notable difference of geochemical characteristic for the Bazhenov Formation and the lower part of the sub-Achimov member. It should be noted that resistivity logs are traditionally used (RL, A2M0.5N probe) to establish the boundaries of formations. The results of the lithological and geochemical analysis of the core and well-logging materials, brought us to the conclusion that LL data (electrical logging) should be used to delineate the BF boundaries, because lateral logging offers higher resolution at allocating separate types of rocks which are 30 cm in width.

The results of BF sections typification were also taken into consideration; the study had been previously carried out based on the analysis of lithological composition and/or well logging data in the whole territory of West Siberia or its

Fig. 2. Comparison diagrams of the delineated transitional zones of the Bazhenov Formation to the sub-Achimov member based on lithology, OM geochemistry and GWS data. *1*, core interval (with visual homogeneity of the rocks); *2*, specified section intervals: *a*, sub-Achimov member, *b*, transitional interval of the sub-Achimov member, *c*, Bazhenov Formation, *d*, transitional interval of the Bazhenov Formation, *e*, transitional interval according to GWS data; *3*, depth of a section interval, (m); *4*, the boundary between the Bazhenov Formation and the sub-Achimov member (*a*) and its characteristics: *b*, depth (m), *c*, LL values at the boundary (Ohm·m), *d*, GL values at the boundary (microroentgen/ h).

large regions (Ushatinskii, 1981; Gaideburova, 1982; Polyakova et al., 2002; Eder, 2006; Eder et al., 2015a). Anomalous sections of the Bazhenov Formation were not considered.

There exist two main approaches to distinguishing the BF top in practice: by RL and GL anomalies. The upper boundary of the GL anomaly is recognized to pass much higher compared with the upper boundary of the RL anomaly (Rodionov et al., 1976; Gaideburova, 1982; Lapkovsky et al., 2018). Having analyzed all the approaches to the BF top delineation based on well-logging data, the limiting values were estimated for the section interval, within which the boundary can be traced. It is characterized by the gamma-ray logging values of 15 μR/h and more, but the values of apparent resistivity are less than 30 Ohm·m. According to well-logging data, the indicated interval is assumed to be transitional between the sub-Achimov member and the Bazhenov Formation (Fig. 2).

The transitional interval is considered to be a part of a section with all the distinctive features, which are characteristic of overlying (the sub-Achimov member) and underlying (the Bazhenov Formation) deposits. According to well-logging data, the transitional interval covers similar intervals selected by the results of geochemical and lithological studies (Fig. 2). The member boundaries, whose description is given below, were delineated in the well sections based on the analysis of data obtained by three investigation techniques.

It was predetermined (Eder et al., 2016) that the BF thicknesses are controlled by a paleorelief factor in the central regions of the WSB. Consequently, the morphology of the studied interval was specified in relation to tectonic elements of the Jurassic layer within the West-Siberian syneclise (Kontorovich et al., 2001).

RESULTS

Based on lithological-geochemical composition, geophysical characteristics of the rocks, and geochemistry of organic matter in the section interval corresponding to the zone of transition from the BF to the sub-Achimov member, four members are distinguished in the wells of the studied territory from bottom to top (Fig. 2; Table 1):

1) member I ("coccolithic") – the upper part of the Bazhenov Formation;

Table 1. Lithological, geochemical and geophysical characteristics of the members distinguished in the transitional zone of the Bazhenov Formation to the sub-Achimov member

	Parameters	Member I	Member II	Member III	Member IV
Lithology	Type of rocks	Mudstone (kerogen – siliceous-carbonate, kerogen-carbonate, carbonate)	Mudstone (kerogen – argillaceous, argillaceous)	Mudstone (argillaceous, argillite)	Mudstone (silty-argillaceous)
	Thickness, m	1.5–6	0.1–3.1	0.5–5	Not determined
	Color	Dark-brown	Brownish-dark-reddish	Light brown	Dark-grey, grey
	$(SiO_2+CaO)/Al_2O_3$	5–30	3.0–3.5	3.0–3.4	2.9–3.2
	Calcite, %	10–70	0–2	1–4	0–3
	Dolomite, %	7–16	3–7	2–4	2–4
	Argillaceous material, %	15–25	30–35	40–45	45–70
	Albite, %	1–11	7–15	9–20	10–24
	TiO_2, %	0.1–0.5	0.40–0.75	0.6–0.8	0.5–1.0
	U, ppm	17–90	10–40	5–30	3–13
	Th, ppm	<5	3.8–10.0	4–11	3–15
	K, %	<1.5	0.7–2.0	1.6–3.0	1–3
	Pyrite, %	9–25	11–13	8–11	2–3
	Pyritization degree	0.90–0.96	0.83–0.93	0.73–0.85	0.20–0.55
OM geochemistry	C_{org}, % per rock	9–15	5–7	<5	≤3
	S_1, mg HC/g rock	4–9	2.5–6.5	0.6–4.0	0.1–0.9
	S_2, mg HC/g rock	40–70	20–30	1–27	0.2–16.0
	$β_{хл}$ b_{chl}, % per rock	1.0–2.5	0.7–1.8	0.1–0.7	≤0.1
	Dibenzothiophenes (in % per ∑arom. comp.	≤ 50	25–40	10–40	≤25
	Phenanthrenes/ Dibenzothiophenes	≤2.0	1.0–2.2	1.5–4.5	2.5–7.0
GWL	Apparent resistivity, Ohm·m (LL)	25–4325	10.8–30.7	6.7–14.2	4.6–18.6
	Conductivity, mS/m (IL)	9.4–70.1	67.9–97.8	95.9–136.2	96.1–178.6
	Speed of waves propagation, μs/m (AL)	392–551	353–394	419–525	366–486
	NGL, c. u.	2.4–3.9	2.6–3.3	3.4–4.1	3.6–6.1
	Gamma-activity, mcR/h (GL)	32–64	24.9–43.2	15.2–23.7	10.9–19.7

2) member II – transitional from the upper part of the Bazhenov Formation to the bottom of the sub-Achimov member;

3) member III – transitional from the bottom of the sub-Achimov member to its lower part;

4) member IV – the lower part of the sub-Achimov member.

Thus, the transition zone is composed of the upper part of the Bazhenov Formation, a transitional interval (members II and III) and the lower part of the sub-Achimov member.

The boundary between the BF and the sub-Achimov member corresponds to the boundary between members II and III determined in the present study.

According to the macro-description of the core, there is no obvious difference between three lower members (I–III) except for the occurrence of abundant carbonate concretions in "coccolithic" member I, predominantly in the territory of the Khentei hemianteclise and the South Nadym megamonoclise (Eder et al., 2016). The members are reddish black in color with a shade of brown. The rocks color changes to dark-grey and grey, and a shade of brown disappears in the transition from three lower members (I–III) to upper member IV (the lower part of the sub-Achimov member). Despite the macro-description, we sometimes fail to establish the boundary between the above-mentioned members, because at first sight they all seem to be a homogeneous rocks without noticeable changes in composition.

Lithographical, geochemical and geophysical data on four specified members are given below (Figs. 3–6; Table 1). Average values of seven studied wells are used for geochemical characteristics.

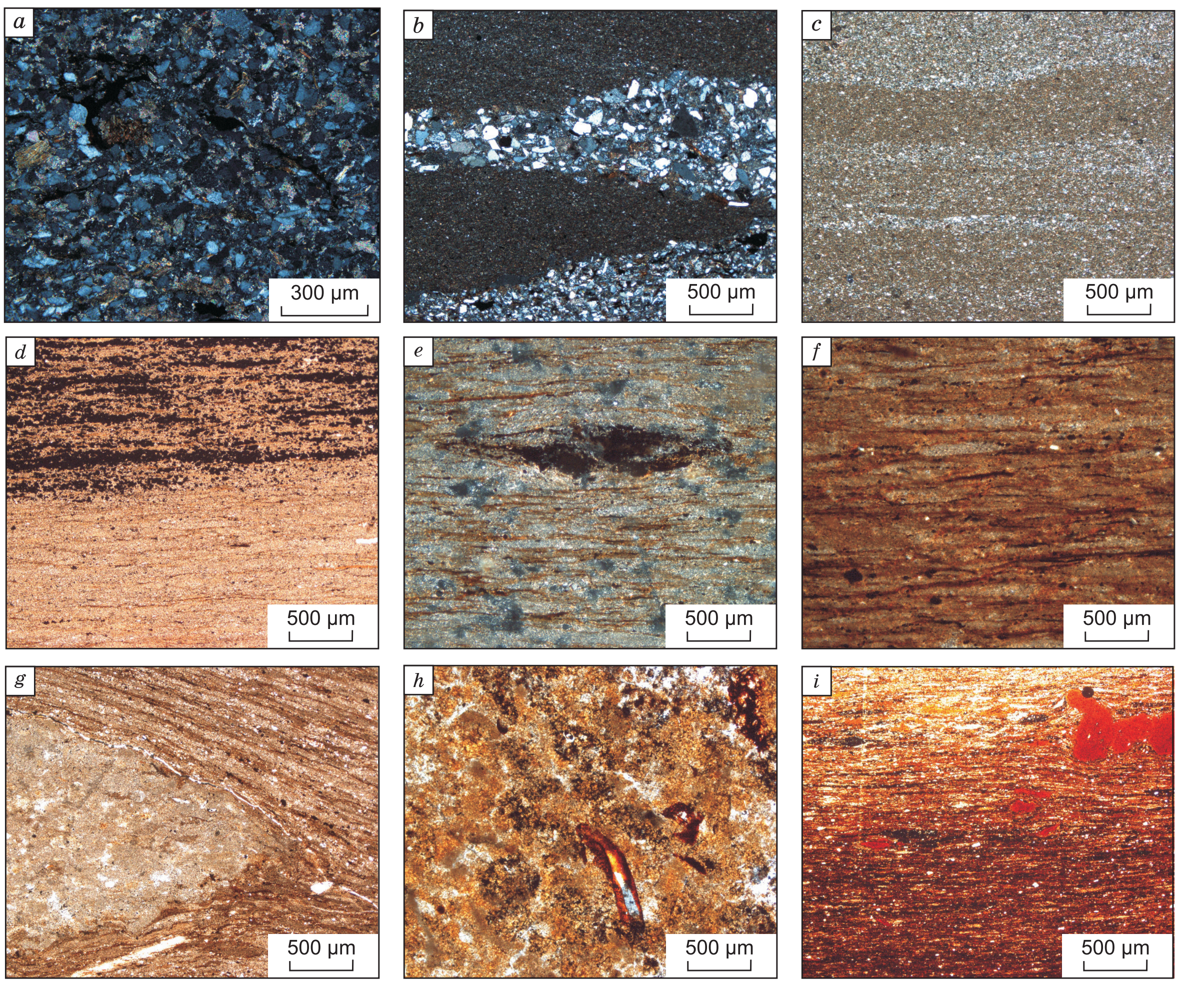

Fig. 3. The rocks of the transitional zone of the Bazhenov Formation to the sub-Achimov member. *a—f*, lower part of the sub-Achimov member (IV): *a*, Fine-grained aleurolite, feldspathic–lithoclastic quartz containing carbonate porous cement, massive, form. Dr.-322-176 (depth – 2844.12 m), crossed Nicols ×; *b*, contact of fine-grained aleurolite with silty-argillaceous mudstone, form. Dr.-322-176 (depth – 2844.12 m), crossed Nicols ×; *c*, silty-argillaceous mudstone, rock microtexture is horizontally-laminated due to uneven distribution of fine-grained aleuritic material, form. Dr.-322-177 (depth – 2844.48 m); *d*, pyritized interbeds in argillite, form. Dr.-322-179a (depth – 2844.78 m); *e*, argillite is organic matter in the shape of elongated lenses, form. Dr.-322-179b (depth – 2844.78 m); *f*, mudstone (siliceous-argillaceous), organic matter is observed both in the microdispersed form and in the shape of lenses, form. Dr.-322-183 (depth – 2846.25 m), crossed Nicols ×; *g*, a transitional zone of the sub-Achimov member (III), siliceous-argillaceous mudstone with baryte lenses, form. Dr.-322-186 (depth – 2846.89 m); *h*, *i*, the upper part of the Bazhenov Formation (I): *h*, micritic limestone, form. Dr.-322-192a (depth – 2848.05 m); *i,* kerogenic mudstone, rock microtexture is horizontally-lenticular-laminated due to uneven distribution of pyrite, argillaceous material and kerogen, form. Dr.-322-192b (depth – 2848.05 m).

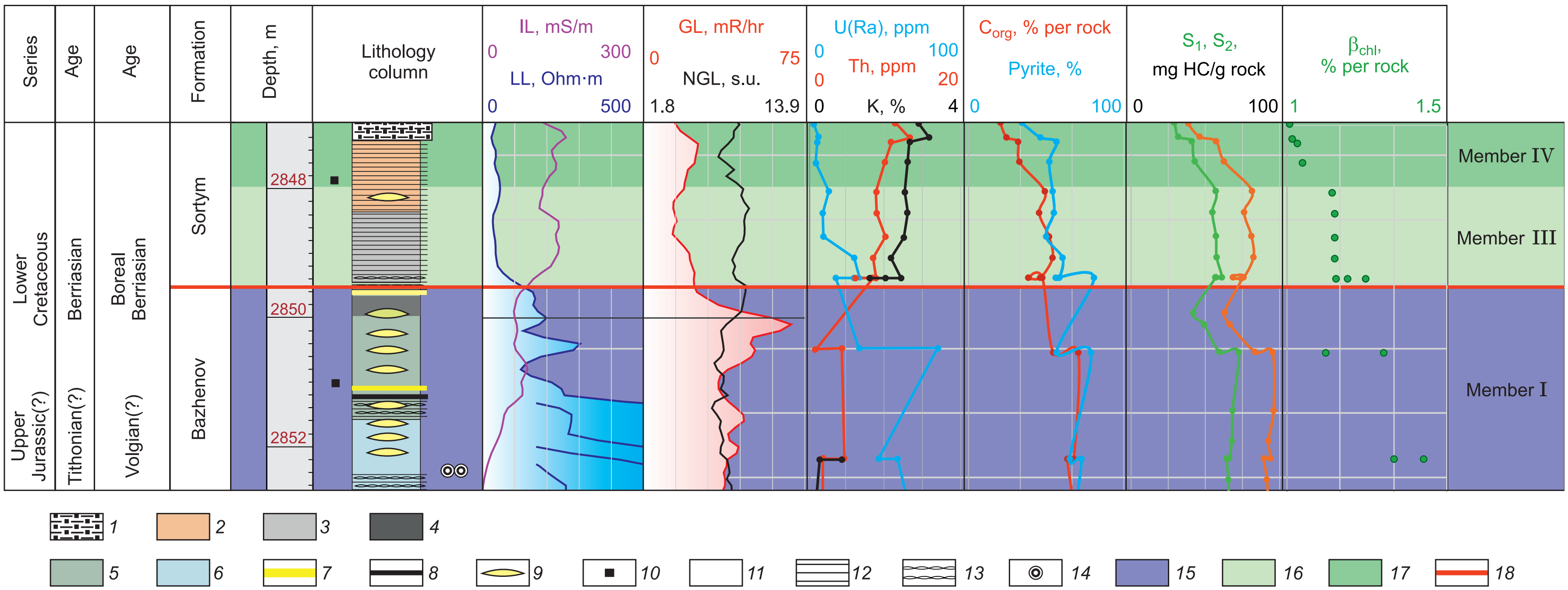

Fig. 4. Geological and geophysical section of the transitional zone of the Bazhenov Formation to the sub-Achimov member, for the well Druzhnaya–322. Types of rocks: *1*, aleurolite, *2*, argillite, *3*, mudstone: argillaceous, siliceous-argillaceous, *4*, kerogenic mudstone (content of pyrite 20–25%), *5*, mudstone: kerogen–carbonate, kerogen–siliceous–carbonate, *6*, kerogensiliceous mudstone, *7*, interbeds of carbonized rocks, *8*, pyritized interbeds; authigenic minerals: *9*, a calcareous lens, *10,* pyrite content from 5 to 10%; textures (the colour matches the type of the rock): *11*, massive, *12*, horizontally-laminated, *13*, lenticular-laminated; organic residues: *14*, coccolithophora; the section interval defined by the results of the complex studies: *15*, upper part of the Bazhenov Formation, *16,* transitional from the bottom of the sub-Achimov member to its lower part, *17,* lower part of the sub-Achimov member; *18,* the roof of the Bazhenov Formation, as accepted in the study.

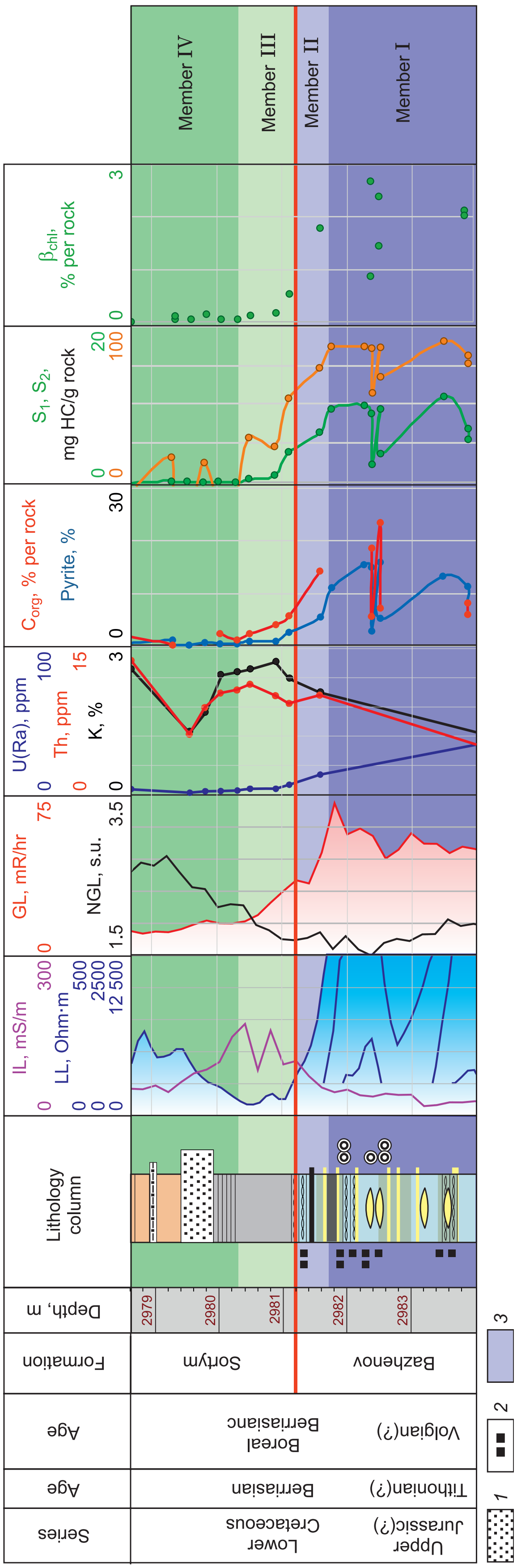

Fig. 5. Geological-geophysical section of the transitional zone of the Bazhenov Formation to the sub-Achimov member, for the well Povkhovskaya–70. The types of rocks: *1*, sandstone; authigenic minerals: *2*, pyrite concentration exceeds 10%; the sections intervals are defined based on the results of the complex studies: *3*, transitional from the bottom of the sub-Achimov member to its lower part. See Fig. 4 for the rest conventional designations.

Member I ("coccolithic") is represented by mudstones (kerogen-siliceous-carbonate, kerogen-carbonate). Its thickness reaches 1.5–3.0 m in the sections of the Bazhenov Formation within the Khentei hemianteclise and the South Nadym megamonoclise, and it equals 4–6 m within the Mansi syneclise. The groundmass is dark-brownish or black in color; that is explained by considerable quantities of microdispersed organic matter, which is evenly distributed in the rock (Fig. 3*i*). The rock microtexture is thin-lenticular-laminated, that is characteristic of the deposit accumulation under conditions of slow background sedimentation. The member is characterized by the occurrence of round- or ring-shape coccolithophorid relicts (Eder et al., 2017), which are 10 µm in diameter. The algae relicts are mostly concentrated in thin (0.02–0.03 µm) microlenses along the rock bedding.

Compared with members II–IV, Member I differs in higher content of biogenic carbonate material (10–70% calcite, 7–16% dolomite) and in the lowest content of argillaceous material (15–20%, 25% in separate cases) (Table 1). The content of thorium does not usually exceed 5 ppm; the content of potassium is not higher than 1% and it rarely reaches 1.5%. These figures are much lower compared with other members; that can be explained by their genetic relation to terrigenous material. The lower content of argillaceous material indicates minimum input of terrigenous material, and a dilution factor for the organic matter was also the smallest. The ratio values of $(SiO_2 + CaO)/Al_2O_3$ in the rocks of the "coccolithic" member are the highest (5–30) compared with other members, that is indicative of significant input into composition of rocks composed of biochemogenic siliceous and carbonic material.

The rocks of Member I are distinguished by the highest content of uranium (17–90 ppm). Average content of pyrite varies from 9 to 12% for this member in different sections of the BF, but in isolated cases it reaches 25%. Pyritization degree equals 0.9–0.96, that is characteristic of high reduction conditions in the rock-forming period of lithogenesis.

The total organic carbon content is high (9–15% per rock) in most samples of this member. However, its content (HO ≤ 50% per rock) in carbonate interbeds is comparable to the values of C_{org} for members III and IV (< 5%). The content reaches maximum values only in very few samples from the studied sections of the BF (Malobalykskaya, Chupal'skaya and Yuzhno-Yagunskaya areas), where C_{org} concentration accounts for 15–24% per rock. Pyrolytic parameters (S_1 and S_2) and bitumoids yield depend on the content of organic carbon. S_1 is equal to 4–9 mg HC/g rock for 78% of samples, but it tends to reduce up to 0.5–3.0 mg HC/g in carbonate rocks. This parameter reaches 10–11 mg HC/g rock in a few samples. S_2 is equal to 40–70 mg

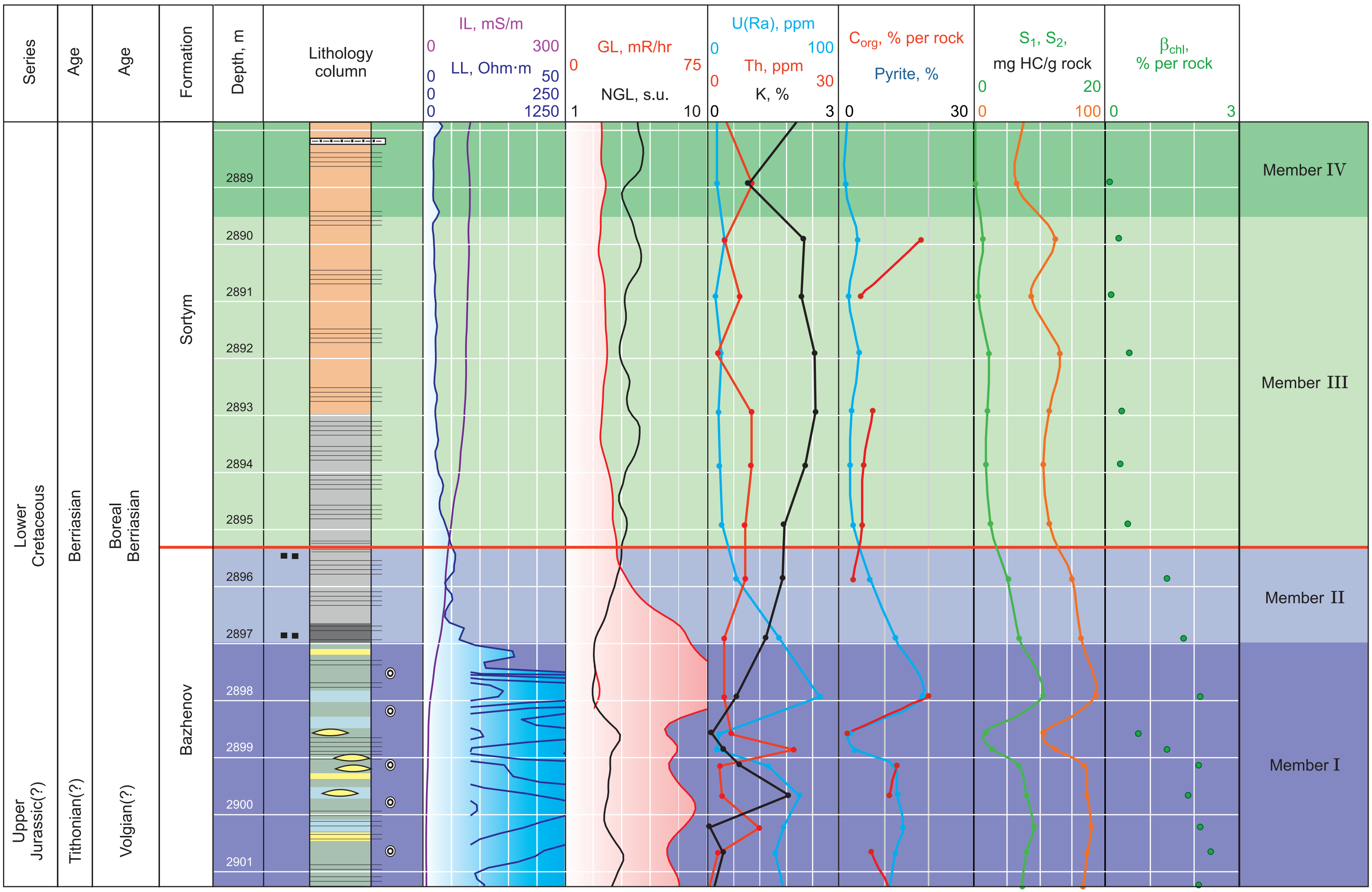

Fig. 6. Geological-geophysical section of the transition zone of the Bazhenov Formation to the sub-Achimov member, for the well Malobalykskaya–901.

HC/g rock for the most of the samples. This value tends to reduce up to 12–40 mg HC/g rock, but it reaches the minimum value (3–12 mg HC/g rock) in carbonate rocks of the Salymskaya area. S_2 increases up to 80–122 mg HC/g in the very few samples from the Chupal'skaya and Yuzhno-Yagunskaya areas. The Hydrogen Index (HI) varies from 350 to 550 mg HC/g C_{org} in the BF top, and its lower values (140–170 mg HC/g C_{org}) were determined only in the Salymskaya area that can be explained by a higher degree of the organic matter (OM) maturity (Kontorovich et al., 2009). The content of bitumoids is high in this member; it equals 1.0–2.5% at the average value of 1.68% per rock. Bitumoids concentrations account for 0.28–1.40% at the average value of 0.81% per rock. The aromatic fraction of bitumoids is characterized by high content of sulfur compounds — dibenzothiophenes up to 50% per amount of identified compounds (phenanthrenes, dibenzothiophenes, mono- and triaromatic steroids) (Kontorovich et al., 2004). The ratio of phenanthrenes to dibenzothiophenes is not higher than 2. The studied area of the BF was apparently located in the zone of hydrosulfuric contamination, where the organic matter was enriched with sulfur.

Geophysical parameters of Member I reach their maximum (apparent resistivity, gamma-ray activity) or minimum (conductivity) in comparison with other selected members. Apparent resistivity of the rocks from Member I varies over a wide range in value from 25 to 4325 Ohm·m (Table 1). The highest values are characteristic of the Mansi syneclise. They do not exceed 2500 Ohm·m in the territory of the Khentei hemianteclise. Apparent electric conductivity of the rocks also varies over a wide range in value not exceeding 70 mS/m in particular wells of the Mansi syneclise and the Khentei hemianteclise. This parameter can reach 120 mS/m for the Khentei hemianteclise. Member I is characterized by high gamma-ray activity values of the rocks, which vary within the range of 32–64 mcR/h owing to high content of C_{org}. Apparent resistivity drops sharply in the vicinity of the top although gamma-ray activity remains stable.

Member II (transitional from the upper part of the Bazhenov Formation to the bottom of the sub-Achimov member*)* is composed of kerogen-agrillaceous and argillaceous mudstones. The thicknesses of Member II increase within the Mansi syneclise and vary between 1.7 and 3.1 m. However, this member is practically missing in the territories of the Khentei hemianteclise (Druzhnaya area) and the South-Nadym megamonoclise (Povkhovskaya area), where its thickness hardly exceeds 0.1–0.3 m. Member II is characterized by increased thickness (2.5 m) in the Yuzhno-Yagunskaya area of the Khentei hemianteclise that is comparable with the parameters of the Mansi syneclise.

The mudstones of Member II are dark-brown, and their microtexture is thin-lenticular-laminated. Kerogen distribution is of lenticular type, i.e., in the form of thin microlenses and interbeds. A sharp decrease of biogenic carbonate material content is registered in the transitional zone between members I and II, i.e., calcite (up to 0–2%) and dolomite (3–7%). On the contrary, a rise in the content of clay material (up to 30–35%) is observed here. Thus, the above-described change in the kerogen occurrence form in the studied rocks agrees with an increase of the argillaceous material content. A rise in the content of albite (up to 7–15%), thorium (up to 3.8–10.0 ppm), potassium (up to 0.7–2.0%) is observed simultaneously. The ratio values of $(SiO_2 + CaO)/Al_2O_3$ tend to drop up to 3.0–3.5, that indicates a reduction in the volume fraction of biogenic siliceous and carbonate rock constituents. The content of uranium ranges in value from 10 to 40 ppm. The average content of pyrite amounts to 11–13%. Rock pyritization degree ranges between 0.83 and 0.93 that is indicative of high reduction conditions.

Based on the organic matter geochemistry, Member II is distinguished only in the Povkhovskaya, Yuzhno-Yagunskaya and Malobalykskaya areas. The content of total organic carbon in Member II is lower than in Member I and varies from 5 to 7% per rock. Compared with Member I, the values of pyrolytic parameters (S_1 and S_2) tend to decrease up to 2.5–6.5 and 20–30 mg HC/g per rock, respectively. On the contrary, HI values remain high (371–511 mg HC/g C_{org}). The content of bitumoids varies from 0.7 to 1.8% per rock at the average value of 1.06%. The content of sulfur compounds (dibenzothiophenes) is reduced by 40% per amount of identified compounds (phenanthrenes, dibenzothiophenes, mono- and triaromatic steroids) in the aromatic fraction of bitumoids. The ratio of phenanthrenes to dibenzothiophenes varies from 1.0 to 2.2.

Member II is characterized by reduction in apparent resistivity of the rocks compared with the underlying member, but not less than 10 Ohm·m (Table 1). The values of apparent electric conductivity tend to increase up to 98 mS/m. Moreover, the Khentei hemianteclise is characterized by a gradual variation in this parameter. Gamma-ray activity drops suddenly, when changing in the interval of 24.9–43.2 mcR/h. NGL estimates are low and comparable for both members of the Bazhenov Formation: "coccolithic" (I) and transitional (II).

Member III (transitional from the bottom of the sub-Achimov member to its lower part) is composed of argillaceous mudstones. However, the Malobalykskaya area is an exception, where this member is represented by argillites and silty-argillaceous mudstones. Its thickness equals 0.5 m in the Khentei hemianteclise and varies from 0.5 to 5.0 m in the Mansi syneclise. In accord with lithological parameters, this interval is missing within the South-Nadym megamonoclise.

The rocks of members III and IV differ in greater bleaching extent of the basic mass down to light-brownish and then to light-grey; concentration of kerogen lenses decreases (Fig. 3). The rocks microtexture is lenticular-laminated.

A noticeable increase of the argillaceous material content (up to 40–45%), albite (up to 9–20%), potassium (up to 1.6–3.0%) is observed in the transition of the BF member into Member III (transitional to the sub-Achimov member). The content of thorium in some rock interbeds reaches 13%. The ratio values of $(SiO_2 + CaO)/Al_2O_3$ do not vary significantly and range in value from 3.0 to 3.4 in the member rocks compared with the preceding one. Compared to the preceding member, the average values of calcite and dolomite tend to decrease at a greater extent and reach 1–4% and 2–4%, respectively. Based on the results of the study obtained by the thin rock sections, we come to conclusion that the volume fraction of fine silt size material tends to increase, that is confirmed by a rise in albite content. Consequently, siliceous material of Member III rocks is terrigenous by origin, but it is originally biochemical in the rocks of member II. The content of pyrite varies from 8 to 11%; the ion pyritization degree is in the range of 0.73–0.85. The latter figure is lower compared with the rocks of the preceding member and conforms to high reduction conditions of diagenesis.

Concentration of total organic carbon does not exceed 5% in Member III for all studied territories. Compared with members I and II, S_1 and S_2 continue to decrease up to 0.6–4.0 and 1–27 mg HC/g rock, respectively. On the contrary, HI rises up to 605 mg HC/g C_{org}. The lowest values of S_2 and HI were recorded in member III within the Salymskaya area (up to 9 mg HC/g and 123–224 mg HC/g C_{org}, respectively); as noticed above, it is explained by the high degree of OM maturity (Kontorovich et al., 2009). The bitumoids content varies from 0.1 to 0.7% per rock at the average value of 0.45% per rock; that is two times lower than in Member II. The content of dibenzothiophenes varies over a wide range from 10 to 40% per amount of identified compounds (phenanthrenes, dibenzothiophenes, mono- and triaromatic steroids) in the aromatic fraction of bitumoids. The ratio of phenanthrenes to dibenzothiophenes varies from 1.5 to 4.5. An extensive spread of geochemical parameters is characteristic of this member.

Compared to Member II, Member III is characterized by lower values of apparent resistivity and gamma-ray activity, which vary from 6.7 to 14.2 Ohm·m and from 15.2 to 23.7 mcR/h, respectively. The values of apparent electric conductivity tend to rise and range in value from 95.9 to 136.2 mS/m. The highest speeds of wave propagation (up to 525 μs/m) in the studied interval are characteristic of member III. Member III considerably differs from underlying member II by NGL data. In the first case, the values vary from 2.3 to 3.5 c.u., and in the second case – from 3.0 to 5.5 c.u. Moreover, the estimates are lower for the Mansi syneclise compared with the Khentei hemianteclise in members II and III.

Member IV (the lower part of the sub-Achimov member) is commonly represented by mudstones (argillaceous, siliceous-argillaceous (less frequently)). The range of thicknesses variation was not determined, because core samples were not collected above 3 m across studied sections. The apparent thickness ranges from 0.8 to 3.0 m.

The content of fine silt fraction impurities apparently increases, because the rock microtexture becomes more lamellar and massive due to its uneven distribution (Fig. 3*a–f*). Argillaceous mudstones are characterized by millimeter intercalations with the abundance of fine silt size material at their base. The content of this material tends to decrease towards their upper part that finally results in complete disappearance. As already noted (O'Brien and Slatt, 1990; Wignall, 1994), such textures are typical for sediments deposited from low-density turbidite flows.

The rocks of the lower Member (IV) of the sub-Achimov member are characterized by high content of argillaceous material (45–70%), that leads to rise in albite concentration (up to 10–24%). Consequently, that gives evidence of an increase of the terrigenous material fraction in the rocks. The content of potassium is equal to 1–3%; the content of thorium is 3–15 ppm. Microbeds of fine silt material appear in the rocks. The rocks become more silty and convert into silty mudstones (up to 20–25%) in the interval of 1.0–2.5 m intercepted from the bottom of the member and up the section. In contrast to Member III, interbeds of intrinsic mudstones (the content of clay material is more than 50%) are found within the interval; these rocks are not common to the BF. The content of kerogen in the rocks ranges in value from 0.3–4.0%. Compared with Member III, the interbeds containing kerogen (not less than 1%) are a frequent occurrence. The content of uranium varies from 3 to 13 ppm. It significantly increases (about 30 ppm) at the boundary with Member III. The average content of calcite is 0–3%; the average content of dolomite — 2–4%.

The content of pyrite is prominently reduced (up to 2–3%) in most studied sections of the rocks belonging to the lower part of the sub-Achimov member. The extent of pyritization decreases considerably (0.2–0.5) and conforms to oxic and sub-oxic conditions of formation in diagenesis. The sections of the Salymskaya area make an exception, where the pyrite content remains in the interval of 2–5 m within the range of 9–20%. The values of pyritization degree vary from 0.8 to 0.9.

Compared with members I and II, sharp decrease of C_{org} content (not more than 3% per rock) is observed in the sub-Achimov member, as already noted by I.V. Goncharov et al. (2016). On average, the content of C_{org} in Member IV is higher within the Mansi syneclise than in the Khentei hemianteclise and the South-Nadym megamonoclise (1.5 against 0.7% per rock). Pyrolytic parameters (S_1 and S_2) are the lowest (0.06–0.70 and 0.2–3.1 mg HC/g rock, respectively) in the studied sections within the Khentei hemianteclise and the South-Nadym megamonoclise. HI does not exceed 329 mg HC/g C_{org}. These parameters are higher (0.3–0.9 and 4.0–16.0 mg HC/ rock, respectively) in the Malobalykskaya and Chupal'skaya areas of the Mansi syneclise. The bitumoids content of is the lowest and does not exceed 0.1% per rock. The content of dibenzothiophenes is reduced to 25% per amount of identified compounds (phenanthrenes, dibenzothiophenes, mono- and triaromatic steroids) in the aromatic fraction of bitumoids. The ratio of phenanthrenes to dibenzothiophenes rises up to 7.0.

The clay rocks of the sub-Achimov member are characterized by low values of apparent resistivity. They do not exceed 10 Ohm·m within the Mansi syneclise, and 15 Ohm·m – within the South-Nadym megamonoclise.

Some extreme values (up to 30 Ohm·m) are associated with a rise in silt content. The member's rocks are characterized by the highest estimates of apparent electric conductivity reaching 178.6 mS/m (Table 1). The values of gamma-ray activity do not exceed, on average, 15 mcR/h. Some extreme values of a rise in gamma-ray activity are registered in the section of Member IV, ranging from the South-Nadym megamonoclise to the Mansi syneclise, and vary from 16 to 25 mcR/h, respectively. In the latter case, these extreme values are associated with the content of C_{org}, which amounts to ≈ 4%. Higher values of gamma-ray activity agree with a significant increase of potassium and thorium concentrations in the rocks within the South-Nadym megamonoclise and the Khentei hemianteclise.

RESULTS AND DICUSSION

Upper boundary of the Bazhenov Formation

The analysis of lithological composition of the rocks and geochemical characteristics of the organic matter at the upper boundary of the Bazhenov Formation confirms the fact that it becomes more abrupt in the territories of the Khentei hemianteclise and the South-Nadym megamonoclise. Member II is virtually missing in these regions. The rocks are observed to change in color owing to a sharp decrease of C_{org} content (up to 1–3% per rock within the Khentei hemianteclise and South-Nadym megamonoclise, and up to 2–5% per rock within the Mansi syneclise). Since uranium is genetically related to organic substance (Pluman, 1971; Neruchev, 1982; Zubkov, 2001b; Zanin et al., 2016; and others), we also observe a significant reduction in the content of this element. Concentration of fine silt fraction impurities rises from 1–2% to 5–7%, and the content of the clay material increases from 20% to 40–70%. Thus, concentrations of potassium, thorium and albite tend to increase considerably with the occurrence of microtextures, which are characteristic of distal slow low-density decaying turbidite flows. Thorium and potassium are known to be the elements genetically related to terrigenous argillaceous material (Smyslov, 1974). Consequently, a sharp increase of their concentration at the boundary between the BF and the lower member of the sub-Achimov member provides supporting evidence of a rise in the input of terrigenous material in this period.

A change in genesis of the siliceous material also occurs in the rocks at the boundary under study. It is predominantly biochemogenous in "coccolithic" Member I and terrigenous in members II–IV. A sharp decrease of a biogeneous component fraction in members II–IV is confirmed by analysis of $(SiO_2 + CaO)/Al_2O_3$ indicator. It is over 5 in the BF, but it is equal to ≈ 3 in members II–IV.

A sharp decrease of iron pyritization degrees is registered. It indicates a change in reduction conditions to suboxic in diagenesis and presumably to oxic in sedimentogenesis. Member II is thicker (2–6 m) within the Mansi syneclise compared with the Khentei hemianteclise and the South-Nadym megamonoclise. Therefore, there is no abrupt change of the rock composition and a variation in argillaceous material content ranges from 35 to 40–45%. Concentration of organic carbon in the BF top varies from 9 to 15% per rock for most samples, and this value is less than 5% per rock in carbonate interbeds.

The occurrence of pyrite microbeds in members II and III is characteristic of pyrite distribution. Within the BF top, higher pyrite concentrations in the rocks are well-correlated with higher concentrations in the rocks of organic carbon. This relation is not found in the rocks of the sub-Achimov member; higher pyrite concentrations are registered in the rocks with relatively low content of carbon (less than 2%). The evidence of high pyrite concentrations in low-carbon sediments is also given in the following studies (Strakhov, 1962; Gavrilov, 2010), where they are associated with the migration of ion-containing solutions in diagenesis and sulfide precipitation at the boundary of reducing and oxic environments in sediments. Therefore, the pyritization zone in low-carbon sediments of the sub-Achimov member described in (Zubkov, 2001b, 2016; Panchenko et al., 2016) can serve as a benchmark of a change in redox conditions being indicative of a geochemical barrier in the deposit. As mentioned above, a variation in redox conditions is caused by a change in water drive in the investigated territory. According to the analysis of iron pyritization degrees, sedimentation conditions for the BF rocks embedded in its top were highly reduced, and the bottom of the sub-Achimov member was transitional between anoxic and oxic. All the above confirms the existence of a redox barrier at the boundary of the studied sediments.

The analysis of the carbonate material (calcareous and dolomitic) distribution within the examined transitional zone confirms that interbeds of secondary carbonates, whose thickness ranges from 0.5 to 1.0 m, are found in the upper part of Member I in the studied BF sections. They are observed at the boundaries between members III and IV, and members II and III within the Mansi syneclise. Deposition of these carbonates is also associated with the substance precipitation from the solutions on the geochemical barriers.

S_1 and S_2 vary slightly from 4–9 to 40–70 mg HC/g rock in most samples from the BF (Member I), and to 0.1–4.0 and 0.2–20.0 mg HC/g rock in the lower part of the sub-Achimov member (members III-IV), respectively. Moreover, there is a slight decrease of HI values (from 350–550 to 330–500 mg HC/g C_{org}.). The highest values of bitumoids concentrations (up to 2.5% per rock) are characteristic of the BF in the Mesozoic section of the WSB. The content of bitumoids is much lower in the sub-Achimov member and does not exceed 0.7% per rock. On the whole, the trends of a variation in organic matter and rock composition remain unchanged.

The ratio of phenanthrenes to dibenzothiophenes rises up to 7 in the aromatic fraction of the sub-Achimov member bitumoids in comparison with the BF, where it is not higher than 2; that also gives evidence of a change in redox conditions of sediments. The increase of dibenzothiophenes content in the Bazhenov Formation can be explained by their accumulation as a result of diagenetic reconversion of the aquatic organic substance in the deposits of salty water bodies with hydrosulfuric contamination, or by deficit of oxygen in the bottom waters (Kontorovich et al., 2004).

It should be stressed that sometimes there is no coincidence between the boundaries of the transitional members delineated based on lithological parameters, on the one hand, and geochemistry of the organic substance, on the other hand (Fig. 2). It is explained by the fact that a relatively slight variation in sedimentation conditions influences primarily the sediments composition, but a change of the OM composition occurs a little later. In most cases after a change of the rock composition (e.g. an increase of the clay material content by 5–10%), a variation in OM content is observed in the interval of 1–2 m up the section. The boundary between the BF transitional member (II) and the transitional member (III) of the sub-Achimov member is an exception. Being delineated based on lithology and OM geochemistry data, the boundaries between these members tend to coincide in all studied sections. It might be explained by an abrupt change in sedimentation conditions (mainly from biochemogenic to allothigenic) in this period. Comparison of the member boundaries established by the above-stated characteristics is given in Fig. 2.

According to the results of the study, the well-logging survey complex (GL, NGL, LL, IL) should be applied to establish the BF top by well-logging. A similar complex is proposed by (Khabarov et al., 1981; Balushkina, 2011; Pavlova et al., 2012) for lithological identification of the Bazhenov Formation. As opposed to the technique of the BF upper boundary delineation by resistivity anomaly (RL), the use of the above-mentioned complex allows taking account of a transitional zone in the BF structure from its upper part to the bottom of the sub-Achimov member (Member II).

It is impossible to establish the boundaries of the members by well-logging parameters due to divergence of values in separate wells (Fig. 2). Recognition of the BF top by the integrated analysis of lithological, geochemical and geophysical parameters enabled us to obtain qualitative characteristic of the boundary. The following characteristics correspond to the BF top location: minimum apparent resistivity estimates followed by their sharp increase; a sharp rise in gamma-ray activity; low NGL parameters; a sharp reduction in induction conductivity (Figs. 4–6). Average values of geophysical parameters of the surveyed wells are equal to: 17 Ohm·m (LL), 24 mcR/h (GL), 3.6 c.u. (NGL), 90.7 mS/m (IL). The deviation (1.5 times) from average values in separate wells could be associated, in particular, with the use of different standards for setting radioactive logging devices, and with the log data interpretation neglecting the width of the invasion zone and drill mud composition for electrical logging.

Conditions of formation. The "coccolithic" Member (I) formed in conditions of lower migration of terrigenous material, or in conditions of a "starving" basin, where biogenic sedimentation predominated. Coccolithophoridous algae and radiolarians were the main producers of the organic substance and rock-forming organisms in that period. According to the extent of deposits pyritization, conditions in diagenesis were highly reduced. Owing to high bio-productivity and slack bottom waters, this period was the most favorable for accumulation of large amount of organic matter (at present, it accounts for 25% in separate samples). Sedimentation period of the material from Member (II) was characterized by high input of argillaceous material in connection with the regression onset and coastline progradation towards the central region of the WSB. As already noted, its concentration tends to increase from 15–20 to 35% in Member II. A rise in input of the terrigenous material might have caused muddiness of the water that created unfavorable conditions for fauna. It was the period when coccolithophorid algae disappeared and the quantity of radiolarians reduced. A decline of kerogen accumulation was also observed. As a result, sedimentation volume of biogenic carbonate and siliceous materials shrank dramatically. An insignificant variation in redox conditions was observed in diagenesis. However, it was a reduction in volume of the buried organic matter that might have led to the drop in reducibility of the sedimentation environment.

The next stage of rock material deposition in Member III (transitional from the lower part of the sub-Achimov member) was marked by much greater input of clay material. 40% content of the argillaceous material was a threshold value, at which the volume of kerogen accumulation reduced up to 2–4%. This variation in the sedimentation regime probably aggravated burial conditions for the organic matter. On the one hand, an increased amount of supplied clay material led to dilution of buried organic remains in sediments, on the other hand, water flows started to reach the central part of the basin and brought argillaceous material being a cause of disturbance in the standing bottom water. That was confirmed by a decrease of iron pyritization degree (PD) (up to 0.7–0.8) in diagenesis. As noted earlier (Zanin et al., 2005), the extent of deposits pyritization represents environments in diagenesis, so they were usually more oxic in sedimentogenesis. Consequently, sedimentogenesis conditions are supposed to be sub-oxic (PD is less than 0.7). Compared with the preceding period, the volume of accumulated organic matter reduced significantly due to worsening of its burial conditions, dilution with the argillaceous material and the sub-oxic conditions.

In the period of rocks formation in Member IV (the lower part of the sub-Achimov member), a considerable rise in the volume of terrigenous argillaceous material was observed (up to 45–70%), concentration of kerogen in the rocks reduced up to 0.5–2.0%, and the input of fine silt size material also increased (5–10%). OM burial conditions changed up to oxic–sub-oxic; probably, they were oxic in sedimentogenesis.

A rise in thicknesses of members II–III from east to west is correlated with the well position in relation to positive and negative tectonic elements of 0 order (paleo-landscape), and distance from the provenance area. The highest values of thicknesses are characteristic for the section within the Mansi syneclise. The thickness of the transitional interval (by well logging) reaches 19 m in separate sections. It is probably referred to the confinement to the slope of the Mansi syneclise from the side of the Khentei hemianteclise. The problem is not still resolved, and further surveillance is required. In the first instance, we have to increase the number of observation sites.

CONCLUSIONS

1. Four members are distinguished in the studied sections of the central regions belonging to the West Siberian sedimentary basin. They are marked by lithological, geochemical and geophysical characteristics: I – a "coccolithic" member of the Bazhenov Formation; II – an upper transitional member of the Bazhenov Formation; III – a transitional member of the sub-Achimov member; IV – a lower member of the sub-Achimov member.

2. The upper boundary of the Bazhenov Formation (between the transitional members of the Bazhenov Formation and the sub-Achimov member) is characterized by a change of the lithological composition of rocks and geochemistry of the organic matter. The boundary appears to be more abrupt in the BF sections of the Khentei hemianteclise and the South-Nadym megamonoclise, because of almost complete absence of the BF transitional member, but more gradual within the Mansi syneclise. In both cases, a change in the rocks composition points at restructuring of the sedimentation system being a cause of a substantial reduction in accumulation volume of the organic matter in sediments.

3. The transitional part in the sub-Achimov member is distinguished by the pyritization zone, predominantly at the geochemical barrier – a boundary where redox conditions change. The change is confirmed by the analyses of the iron pyritization degree and the organic matter indicators.

4. To delineate the BF top, it is necessary to use the results of the integrated analysis of lithological and geochemical studies of the well core and well logging (GL, NGL and its variations, LL and IL). For the analysis of logging data, it is radioactivity that should be taken into consideration, rather than the values of electric resistance. In this case, the section should include kerogen-argillaceous and argillaceous mudstones of Member II, which are characterized by higher radioactivity. The BF top has the following qualitative characteristics (the description is given from top to bottom) as minimum apparent resistivity values followed their sudden increase, a sharp rise in gamma-activity, lower NGL estimates, and a sharp reduction of induction conductivity. The average values of geochemical parameters are 17 Ohm·m (LL), 24 mcR/h (GL), 3.6 c.u. (NGL), 90.7 mS/m (IL). The 1.5 times deviation from average values in separate wells could be associated with adjustments of measurement equipment and technological characteristics of well-drilling.

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