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Rocks of the Bazhenovo and Abalak Formations, Central Krasnoleninsk Arch, Western Siberia: Composition, Structure, and Formation Conditions

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Abstract—The finding of hydrocarbon accumulations in Upper Jurassic rocks of the Krasnoleninsk Arch, which were previously considered fluid trap and oil source sediments, stimulated us to have a new look at these rocks. The analysis of geophysical data on boreholes revealed that reservoirs in Upper Jurassic rocks are mainly represented by siliceous and carbonate varieties, which were named potentially productive beds. This work presents results of the detailed investigation of the lithology of Upper Jurassic rocks for distinguishing different rock types (including potentially productive beds) with the aim of their correlation and prediction of lateral distribution.

Some areas within the Krasnoleninsk Arch incorporate industrial-scale oil and condensate inflows from rocks of the Bazhenovo and Abalak formations. Based on geophysical data on boreholes, as well as the lithology and petrography of core samples, the inflows are related to siliceous and carbonate beds. The reservoirs were developed as a result of rock alteration and belong to the fracture–cavernous type (Belkin *et al.*, 1988; Zubkov, 1989; Zubkov and Fedorova, 1989; Zubkov and Bondarenko, 1997). They were formed due to the tectonic crushing of solid but fragile carbonate and siliceous lithological rock types. Additionally, the tectonic crushing was accompanied by hydrothermal reworking that stimulated oil generation in Bazhenovo and Abalak rocks, the leaching and redeposition of soluble minerals, and the origination of additional fractures and caverns.

It is evident that hydrocarbons reserves in these rocks are dependent on their thickness and lateral distribution within the study territory. From this standpoint, it seems to be extremely important to restore the formation conditions of siliceous and carbonate rock types with the aim of the prediction of their spatial distribution and well-to-well correlation, because the number of these thin beds in the drilled sequence can reach 15–17(!).

The present work is aimed at a detailed investigation of the mineral rocks composition of the Bazhenovo and Abalak formations in order to reconstruct formation conditions and identify principal lithological rock varieties. These rock varieties can be favorable for the formation of secondary reservoirs that are capable of accumulating hydrocarbon pools.

The investigations were carried out with the use of physical and chemical methods, including optical and electron microscopy, X-ray structural, spectral, and thermobalance analyses. In total, 170 samples taken from five boreholes drilled in the Em-Egovsk (boreholes 1274, 1812, 1817, 1820, and 1333) and Pal'yanov (borehole 12366) areas were analyzed by different methods.

Based on analytical results, specific features of the mineral composition of rocks, and the ratio of clay minerals, we distinguished three zones in the Bazhenovo Formation and six zones in the Abalak Formation. They formed under conditions of two geochemical facies (table).

The deposits under consideration almost completely belong to the Upper Jurassic, with the exception of Lower–Middle Callovian sediments attributed to the topmost part of the Tumen Formation (Fig. 1). It should be noted that the boundary between the Oxfordian and Kimeridgian is provisional, because the definable remains of zonal ammonites are absent in the recovered sequences. The bottom of the Abalak Formation (Zone Ab_5) contains zonal ammonite *Quenstedtoceras (Soaniceras)* sp. ind., which, according to the definition by S.V. Meledina (UIGGM, Siberian Division of the RAS), belongs to the Upper Callovian.

The generalized geological section includes two geochemical (pyrite and chlorite—siderite) facies (table; Fig. 1). Sediments of the Frolov Formation, which overlie bituminous rocks of the Bazhenovo Formation, as well as the middle and lower parts of the Abalak Formation, were deposited under conditions of the chlorite–siderite facies.

The pyrite geochemical facies unambiguously differs from the chlorite–siderite one by the compete absence of chlorite and siderite, while the chlorite–siderite facies sometimes contains abundant pyrite (table). During the accumulation of the pyrite-facies sediments, Mineral composition and structure of the Bazhenovo and Abalak formations in the Krasnoleninsk region

Formation	Geochemical facies	Zone (index)	Thickness of zone, m	Mineral composition, %									Number of analyses
					content of clay minerals, %								
				quartz and feldspars	hydromica	mixed-layer minerals	kaolinite	chlorite	total content of clay minerals	total content of carbonate minerals	pyrite	kerogen	
Frolov	Chlorite–siderite	Fr Il–Kt	–	16–40 29	16–20 18	14–17 16	55–61 58	5–10 8	25–56 49	0–54 11	1.9–5.4 3.9	0.4–8.6 4.9	5
Bazhenovo	Pyrite	Bzh_1 (pyrite) Il–Sm–Kt	6–9	24–46 34	29–33 31	29–40 35	29–42 35	–	16–24 20	<1	24.7–41.6 32.7	8.1–19.0 14.5	9
		$Bzh_{1.1}$ (transitional) Il–Sm–Kt	0–1.0	30–39 35	35	35	30	–	21–29 25	<1	13.1–14.2 5.8	17.9–35.9 26.9	2
		Bzh_2 (carbonate) Il–Sm–Kt	0–3.0	7–18 12	28–35 31	30–36 33	29–40 37	–	4–19 9	20–86 67	1.3–14.2 5.8	1.7–18.8 6.2	6
	Siliceous	Bzh_3 (kaolinite) Kt	9–12	16–51 39	16–27 23	11–30 22	40–73 54	–	12–42 31	0–59 10	6.1–18.3 11.5	3.4–14.0 9.5	34
Abalak		Ab_1 Il–Sm–Kt	3.5–7.0	21–57 41	30–35 33	26–37 32	30–39 35	–	22–39 32	8–40 17	5.8–13.0 9.3	3.4–9.3 5.5	10
		Ab_2 Il–Sm	0–4.5	13–65 42	25–48 36	38–61 53	3–24 9	–	13–44 30	0–85 18	3.3–16.4 10.4	1.1–8.4 3.6	21
		Ab_3 (glauconite) Il–Sm	4.0–6.5	12–47 30	15–33 22	33–66 43	4–26 14	5–25 16	15–56 41	5–72 20	1.3–14.6 9.6	0.7–2.6 1.4	21
	Chlorite–siderite	Ab_4 Kt–Sm	4.0–5.0	5–38 18	10–23 17	35–76 46	10–40 25	4–25 13	7–62 35	0–87 39	2.4–13.0 6.7	0.1–2.5 1.1	18
		Ab_5 Sm–Kt	8.0–12.5	6–31 20	8–18 13	10–33 20	37–67 53	10–21 14	12–82 58	0–79 16	1.9–16.5 6.1	0.3–2.6 1.1	28
		Ab_6 Kt–Sm	0–3.5	34–45 39	13–17 15	30–50 38	26–40 35	11–15 13	12–56 36	5–45 21	3.0–5.0 4.0	–	3

The numerator shows range of values, the denominator presents average value; (–) not detected.

the concentration (activity) of S^- anion was so high that the whole amount of bivalent iron contained in solution and sediment was bound in the form of framboidal pyrite; therefore, other Fe-bearing minerals could not originate under such circumstances.

It seems to be attractive to outline the boundary between the Bazhenovo and underlying Abalak Formation along a facial discontinuity, as was done with respect to the Frolov and Abalak formations (table; Fig. 1). However, sharp changes in the mineral composition, organic matter (kerogen) content, radioactivity, and other properties of sedimentary rocks occur within the pyrite geochemical facies; therefore, the boundary between the Abalak and Bazhenovo formations is drawn inside the pyrite geochemical facies, including the two upper zones of the Abalak Formation.

With the aim of defining the main lithological varieties or rock types in the composition of the Bazhenovo and Abalak formations, we constructed a ternary diagram in which the fields with groups of points corresponding to a single rock type are shown (Fig. 2). In total, nine varieties are defined. The bisector from the vertex of the lithological triangle corresponding to 100% carbonate minerals divides all defined rock types into two groups (Fig. 2). Varieties in the right half of the triangle are characterized by higher total quartz (or biogenic silica) and feldspar contents but lower clay mineral concentrations, relative to rock types situated in the left half of the triangle. It is interesting that practically each rock variety in the right half of the triangle has an almost symmetrical counterpart in the left half (Fig. 2).

Thus, we can distinguish the following lithological varieties or rock types: (1) low-siliceous–carbonate rock with a very low content of clay minerals; (2) siliceous–carbonate rock with low clay content; (3) carbonate–clayey—siliceous rock; (4) clayey—siliceous rock; (5) low-clayey–carbonate rock with a low content of silica; (6) siliceous–clay—carbonate rock; (7) siliceous–carbonate—clayey rock; (8) carbonate–siliceous—clayey rock; and (9) siliceous—clayey rock (Fig. 2).

Let us consider in more detail the mineral composition of each of the distinguished zones, as well as lithological types or rock varieties in their composition.

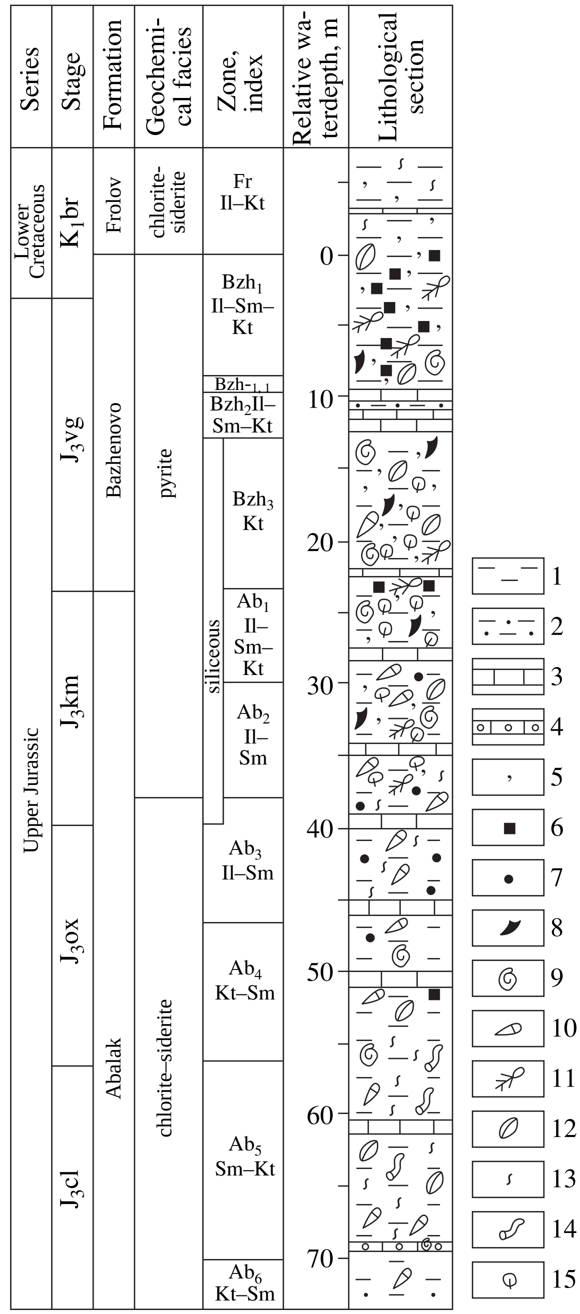

Fig. 1. Composite lithostratigraphic section of the Bazhenovo and Abalak formations in the central Krasnoleninsk Arch. (1) Clay (argillite); (2) siltstone; (3) limestone; (4) oolitic limestone; (5) bituminosity; (6) pyritization; (7) glauconite; (8) onychites of tautides; (9) ammonite imprints; (10) belemnite rostra; (11) ichthyodetritus; (12) bivalve shells; (13) fractures (glide plains); (14) fucoids; (15) silica content.

Frolov Formation

The Frolov (Fr) Formation, more precisely its bottom part, accumulated under conditions of the chlorite–siderite geochemical facies. Based on the predominance of illite and kaolinite in the composition of clay minerals, the Fr field is named the illite–kaolinite (Il–Kt) zone (table; Fig. 1). It consists of siliceous–clayey and siliceous–clayey–carbonate rocks (types 9 and 6, respectively).

The siliceous–clayey variety (Type 9) is represented by rocks of dark brown color caused by numerous microinclusions of fine-dispersed organic matter (kerogen). They are thin-laminated structure, not durable, and easily to split into thin plates parallel to the layering. In addition to detrital kerogen, the rock includes microlenses of brown-red vitrinite, framboidal pyrite microlayers, and more rarely ichthyodetritus frag-

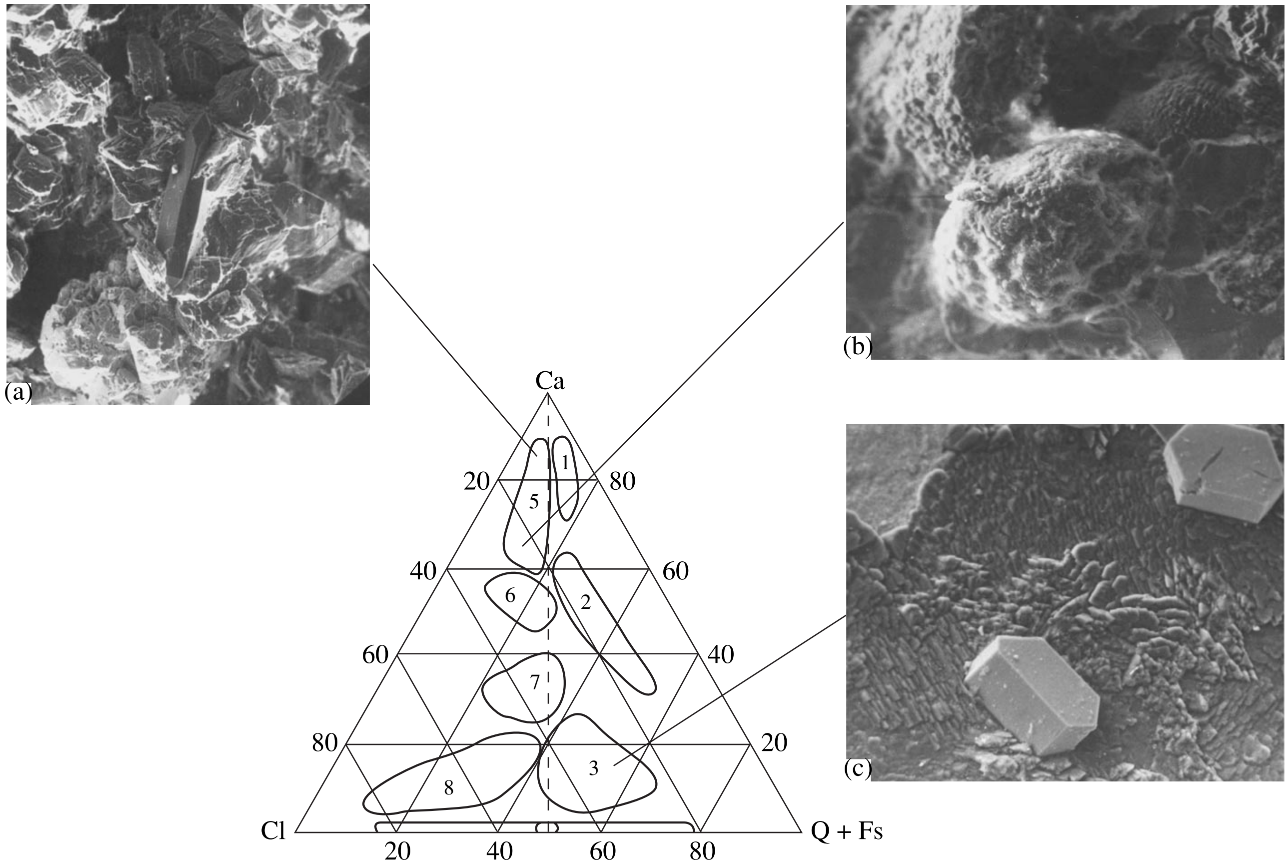

Fig. 2. Lithological rock varieties (types) of the Bazhenovo and Abalak formations in the Krasnoleninsk region.
Rock types: (1) low-siliceous–carbonate with very low clay content (low-siliceous–carbonate), (2) siliceous–carbonate with low clay content (siliceous–carbonate), (3) carbonate–clayey–siliceous, (4) clayey–siliceous, (5) low-clayey–carbonate with low silica content (low-clay–carbonate), (6) siliceous–clayey–carbonate, (7) siliceous–carbonate–clayey, (8) carbonate–siliceous–clayey, (9) siliceous–clayey. (Cl) clay minerals, (Ca) carbonates, (Q + Fs) quartz (biogenic and terrigenous) plus feldspar. SEM photos micrographs: (a) fracture surface covered with small crystals of Mg–Fe calcite (matrix), microcrystalline barite aggregate (bottom left), and elongated quartz crystal (center); magn. 50 (zone Ab_4, Type 5, borehole 1817, the Em-Egovsk area); (b) general view of oolites with an external shell composed of ankerite and siderite and matrix of Ca-rich siderite; magn. 100 (zone Ab_5, Type 5, borehole 12266, the Pal'yanov area); (c) epigenetic apatite crystals formed due to the dissolution of ichthyodetritus on fracture surface covered with a microcrystalline calcite crust; magn. 150 (bottom of zone Bzh_3, Type 3, borehole 1820, the Em-Egovsk area).

ments. Silt-sized clasts of quartz and feldspars and rather numerous laths of hydromica are observed as well. Clayey flakes are commonly subhorizontal and characterized by simultaneous extinction or brightening in polarized light.

The siliceous–clayey–carbonate variety (Type 6) represents a brown, patchy, compact marl with the siderite composition and subconchoidal fracture. The marl is made up of polycrystalline isometric (rounded) and elongated aggregates of brown siderites. The isometric aggregates are 0.02–0.05 mm in size, while the elongated ones are 0.05–0.1 mm along the long axis. The clayey aggregation in the marl has a brown color due to the presence of kerogen and iron hydroxides. Pyrite is represented by cubic and octahedral crystals, in contrast to the framboidal one in the clayey varieties. The distribution of clay and siderite material is irregular.

Bazhenovo Formation

The upper (pyrite) zone (Bzh_1) accumulated under conditions of the pyrite geochemical facies. All clay minerals, which are present in its composition, are contained in approximately equal quantities. Therefore, it is called the illite–smectite–kaolinite (Il–Sm–Kt) zone. This zone has a thickness of about 10 m and is marked by a very high content of fine, parallel-bedded, framboidal pyrite, whose concentration reaches 35–41 wt % (table). Therefore, it is also called the pyrite zone.

Rocks in this zone are only represented by the clayey–siliceous variety (Type 4), i.e., dark gray to black, thin-laminated, quite compact and highly bituminous mudstones with an even cleavage. Numerous, frequently pyritized, ichthyodetritus remains are found. Onychites of teutids and ammonite shells are occasionally encountered. In addition to the high pyrite content, a significant concentration of kerogen (up to 19 wt % or almost 36 vol %) is also noted.

The microscopic study showed that the adjoining pyrite strata are spaced at ~0.02 mm. Since the zone thickness is about 10 m, one can easily estimate the total number of pyrite strata in this zone (~5×10^5). In other words, if we suppose that the bedding has a seasonal nature, the duration of pyrite zone sedimentation can be approximately estimated at 500 ka.

The clay material in the described rock variety is usually finely dispersed and demonstrates an almost simultaneous extinction or brightening under the microscope. Thin, long, brown, vitrinized and gelified seaweed remains are seldom. Sometimes, one can observe silicified biogenic features with a rounded shape. At high magnification, it is well seen that framboidal pyrite aggregates are associated with biogenic silica.

Carbonate minerals are completely absent. They are likely to be unstable in conditions of H_2S contamination in the near-bottom water layer and sediments during their accumulation.

Data points, which represent the mineralogical composition of the clayey–siliceous rock, fall on the ternary diagram base within a range of 50 to 72% of biogenic silica; i.e., these could be assigned to silicites (after Teodorovich, 1935). However, the diagram does not consider the total kerogen and pyrite content, which can reach 48–50%. Because of the high kerogen content, the described rocks lack a sufficient mechanical strength, which is typical of real silicites, and are unfavorable for the development of secondary reservoirs of the fracture or fracture–cavernous type.

The pyrite zone base contains a thin transitional subzone ($Bzh_{1.10}$, about 1.5 m thick, which is marked by a very high kerogen content and can be named the kerogen subzone (table, Fig. 1). In this subzone, the pyrite content is almost two times less than in the pyrite zone, the share of clay minerals slightly increases, and the kerogen concentration is maximum (almost up to 36 wt % or more than 60 vol %).

The kerogen subzone is also composed of Type 4 rocks represented by black, thin-bedded, well-washed and high-bituminous mudstones. Silt-sized particles include quartz fragments and authigenic (biogenic) siliceous particles, which owe their origin probably to radiolarians or other organisms having siliceous shells.

Kerogen is mainly present as small, gelified vitrinite laths, which probably represent alga fragments. Pyrite is subordinate, relative to the content in overlying rocks, and is encountered the form of microlenses.

The second (carbonate) zone of the Bazhenovo Formation (Bzh_2) is also characterized by approximately equal contents of clay minerals, that is why the same index (Il–Sm–Kt) is applied to this zone. It has the least thickness among the distinguished zones (only about 3 m) and a high content of carbonate minerals. Rocks of this zone are represented by two varieties: low-siliceous–carbonate rocks (Type 1) and siliceous–carbonate rocks (Type 2).

Type 1 consists of gray to dark gray (with brown tint), massive rocks with subconchoidal to conchoidal cleavage and are characterized by a low content of kerogen, clay minerals, and biogenic silica. The carbonate mineral in limestone beds within this lithotype is represented by calcite. Dolomite is subordinate.

These rocks often display a microlayered structure and mainly consist of aggregates and grains of carbonate minerals, which probably replaced remains of organisms or their vital activity (pellets?). The dimension of individual grains range from fine silt to sand. Isometric particles are observed together with elongated ones. Kerogen in this rock variety looks as brown gelified vitrinite. The dispersed framboidal pyrite and a small amount of silt clasts are also observed.

Type 2 rocks represent massive, low-clayey, siliceous, microcrystalline limestones of brown color caused by the presence of dispersed kerogen. The latter is associated with a small amount of framboidal pyrite microaggregates. Rare flakes of clay minerals are also encountered. The silt-sized clasts are subordinate, while polycrystalline (biogenic) silica microconcretions are abundant. Sometimes one can observe thin cracks filled with bitumen.

The third (kaolinite) zone (Bhz_3), designated by index Kt, occurs near the bottom the Bazhenovo Formation and differs from the second zone by a noticeable predominance of kaolinite over other clay minerals. The thickness is about 10 m. It includes three lithological varieties: siliceous–carbonate rocks (Type 2), carbonate–clayey–siliceous rocks (Type 3), and clayey–siliceous rocks (Type 4).

Type 2 rocks have been described above. We should only note a higher content of polycrystalline microaggregates of biogenic silica.

Type 3 is represented by dark brown to black, high-bituminous, rather firm rocks with splintery, sometimes tabular, more rarely subconchoidal (in varieties with the highest silica content) cleavage and a characteristic hydrocarbon smell. The cleavage surface reveals numerous onychites of teutids and fragments of bivalve shells. Ammonites remains are found in the lower part of the zone. A coating of white or bright yellow sulfates occasionally appears on chip or cleavage surfaces. The major minerals are clays (~25–30% on average), biogenic, more rarely terrestrial silica (~40–45%), pyrite (10–12%, on the average), and kerogen (~10%).

Biogenic silica is present as microlenses and elongated inclusions or radiolarian shells. The size of microinclusions (small lenses) varies from 0.1–0.2 to 0.4–0.5 mm. At high magnification, it is well seen that these aggregates consist of very small (0.002 to 0.01 mm), acute-angle silica (quartz) fragments. It is possible that these are pellets altered to a variable extent (Zubkov and Mormyshev, 1987).

Only calcite and dolomite are representatives of carbonate minerals in this rock variety. The carbonate mineral content is not high (10–15%, on the average). The microscopic study showed that dolomite is present as small rhombohedral crystals and more rarely as their silt-sized aggregates. Calcite is often observed in shell fragments of different organisms. Sometimes, it substitutes radiolarian shells with the initial siliceous composition.

Type 4 embraces most of the samples. It is represented by almost black, high-bituminous, thin-laminated, clayey–siliceous rocks with a strong hydrocarbon smell and even, more frequently sudconchoidal cleavage, which often show imprints of teutid onychites and bivalve and ammonite shells.

Carbonates are practically absent in this rock variety, and the major components are represented by clays (30–40%, on the average), biogenic silica (50–65%), pyrite (12–15%), and kerogen (7–11%, on the average).

The biogenic authigenic silica is present in the same form as in type 3 rocks. However, it also includes radiolarite, which consists of thin layers, from some millimeters to some centimeters thick, made up of radiolarian shells, altered to a variable extent by secondary processes (sometimes completely or partially pyritized).

Kerogen is represented by metamorphized remains of seaweeds, plankton, and coalified remains of terrestrial plants.

Kaolinite predominates among clay minerals. Its X-ray patterns show rather narrow reflections, testifying that this mineral has a quite high-ordered crystalline structure. Illite (Il) and smectites (Sm) are subordinate (the total content is not more than 40–45% of the total amount of clay minerals). Chlorite is completely absent in this geochemical facies (table).

It should be noted that the upper part of the third zone is dominated by clayey-rich varieties, which are thin-laminated, well-decanted, and enriched in silt-sized particles and dispersed framboidal pyrite. Kerogen is mostly present in the form of dark brown gelified vitrinite.

The lower part of the kaolinite zone consists of silica-rich varieties (silicites or radiolarites). Here, low-carbonate varieties (Type 3) are also present. Usually, these are low-silty, bituminous, clayey silicites with a high share of biogenic siliceous material, whose morphological varieties are described above. Thus, the lower part of the third zone could be named not only kaolinite zone but siliceous zone as well (table, Fig. 1).

In some boreholes, the lowest section of this zone contains a thin (not thicker than 1 m) layer, similar to the pyrite zone (Bzh_1). The pyrite content in it reaches 20–25%, while the kerogen concentration does not exceed 6.5–9.5%. It is characterized by a higher biogenic silica content. Dolomite is occasionally found as small rhombohedral crystals in thin cracks. Numerous ichthyodetritus fragments are frequently replaced by pyrite. Under the influence of secondary processes, phosphates in fish remnants were intensively leached and re-deposited as small apatite crystals with perfect crystallographic facets (Fig. 2c). Because of specific compositional and physical properties (high natural radioactivity and low resistance), this interlayer could serve as a reliable reference unit easily marking the boundary between the Bazhenovo and Abalak formations. It should also be noted that a similar ichthyodetritus-rich pyrite layer was first described by us in borehole 554 section in the Salym oil field (Zubkov and Mormyshev, 1987).

Abalak Formation

The uppermost zone of the Abalak Formation (Ab_1) also belongs to the pyrite geochemical facies. Because the ratio of clay minerals in its composition is approximately equal, this zone is designated by the Il–Sm–Kt index. Its thickness attains 5 m (Fig. 1).

This zone includes the same three rock varieties that are found in the previous zone at the bottom of the Bazhenovo Formation (Fig. 2, types 2, 3, and 4). Therefore, only the most specific features of these rocks are considered below.

Zone Ab_1 is distinguished by significant decrease in the gamma-activity of rocks owing to a sharp reduction of the kerogen content (on the average less almost by half). In addition, the decrease in the relative content of kaolinite (down to 35% of the total content of clay minerals) and, correspondingly, the increase in illite (Il) and smektite (Sm) share is noted (table).

Like the Bzh_3 zone, zone Ab_1 is enriched in biogenic silica (up to 60–65%) and can be named siliceous zone. The fine-dispersed (framboidal) pyrite is usually observed in the form of pseudomorphs of organic remains, more rarely as individual framboids and small crystals.

The lower part of this zone includes a thin unit, where pyrite substitutes numerous radiolarian shells. The layer enriched in pyritized radiolarian shells is encountered almost in all of the studied boreholes that penetrated this unit. Therefore, it can be considered a marker or reference level for the lower part of zone Ab_1.

The second zone (Ab_2), marked by index Il–Sm (i.e., illite and smectite prevail), also belongs to the pyrite geochemical facies. It was found in two boreholes (1820 and 12366), where its thickness reaches 4.5 m. Three rock varieties are distinguished in its composition; however, the bulk of the zone is represented by the clayey–siliceous rock (Type 4), which was described above in detail. Several carbonate–clayey–siliceous rock samples (Type 3) were also found. This zone includes a low-clayey–carbonate variety (Type 5) represented by dark gray (with brownish, sometimes greenish tint due to the presence of glauconite or probably celadonite) low-clayey limestones, more rarely marls.[1] The limestones have micro- or cryptocrystalline structure and numerous small caverns filled with epigenetic kaoline, more rarely with microcrystalline quartz. Hollow caverns, as well as thin fractures filled with brown bitumen are also observed. They enclose pyrite aggregates, which replace mainly radiolarian shells.

Brownish green marls are characterized by a rather high content of coarse (up to medium sand-sized fraction) glauconite grains. Large fragments of bivalve shells and small shells of foraminifers have the predominant calcite composition. The glauconite grains have different colors (yellow-green and brighter bluish green) owing to an inhomogeneous redox potential in the sediment and, correspondingly, different valence conditions of Fe. It should also be noted that glauconite appears in the Abalak Formation at the boundary between the pyrite and chlorite–siderite geochemical facies.

In terms of the lithological composition and of clay minerals ratio, zone Ab_2 is very similar to the third zone Ab_3 encountered in all studied boreholes. The thickness of zone Ab_3 in boreholes recovering zone Ab_2 is small and *vice versa.* Hence, one can suppose that zone Ab_2 essentially is the same zone Ab_3 that was formed in conditions of the H_2S pollution of sediments.

Zone Ab_3 (Il–Sm), as distinct from the previous ones, belongs to the chlorite–siderite geochemical facies, and its thickness attains 5.5 m. Because of the high glauconite content, it can also be named glauconite zone. Rocks in this zone have a characteristic green color or tint, and this sign allows us to consider the zone as a marker facilitating the correlation of sequences drilled by separate boreholes. The zone is made up of the largest number of lithological varieties (six rock types).

(1) The clayey–siliceous variety (Type 4) composes the topmost part. Rare, large, light green glauconite grains, which are absent in the overlying zones, appear in this lithotype.

(2) The zone also includes the low-clayey–carbonate variety (Type 5). Siderite, which is present in addition to calcite and dolomite, becomes the principal carbonate mineral in the lower part of the zone. The limestones are brownish green and frequently fractured and cavernous. Fractures are filled with microcrystalline quartz, calcite, and fine-grained pyrite. Because of the presence of small hydrocarbon inclusions in quartz and calcite crystals, the rocks often have a brownish tint.

Grayish green, almost massive, clayey limestones are encountered at the base of the zone. They have a complex composition dominated by dolomite and calcite. Calcite crystals are quite large (feather-shaped at crossed nicols) and contain fine-dispersed pyrite. Dolomite is lighter owing to a lower content of clay, kerogen, and pyrite. It often divides large glauconite grains into separate blocks. Thin and long crevices in the sample, are filled with microcrystalline calcite, crevices were formed after all other structural features. They often crosscut not only the carbonate matrix but glauconite grains as well. Rare silt-sized particles are present in the carbonate matrix.

(3) Siliceous–clayey–carbonate rocks (Type 6) in this zone can be divided into several varieties, among which the brownish green clayey limestone is of special interest. It is made up of siderite (two types), dolomite, and high-manganese calcite. The high-manganese calcite found here can be considered a zonal marker owing to its specific composition. Siderite and high-manganese calcite are present in the limestone as concretions and oolites (1–2 to 5–8 mm) cemented by clay matrix with an admixture of silt-sized particles. Rhythmic zonal features similar in appearance with biostromes, with a thickness of individual layers of some tenths of millimeter to 1 mm, are also encountered. The principal clay mineral in this limestone is glauconite. Carbonate inclusions (oolites) have cryptocrystalline structure and often show thin hairlike cracks. Pyrite is most common as thin veinlets and has a secondary, more likely hydrothermal origin. One can also observe thin fractures filled with milk-white and water-transparent quartz. Sometimes these fractures are open. In this case, quartz crystals are absolutely transparent and have a perfect crystallographic habit. Their origin can be related to the hydrothermal activity as well. The described rock variety is found in boreholes 1812, 1817, and 1820 of the Em-Egovsk area.

A sample of brownish green color, patchy, clayey limestone consisting of fine-crystalline siderite, glauconite, and admixture of silt-sized particles was taken closer to the bottom of the zone. Glauconite has a yellowish green color. Pyrite fills fractures and forms separate small oolites and their aggregates.

(4) The siliceous–carbonate–clayey variety (Type 7) is represented by grayish green, bedded rocks, which consist of clay minerals (chiefly glauconite) and pellet-like siderite grains with an admixture of fragments of bivalve shells and belemnites having a calcitic composition. The presence of a small amount of silt-sized clasts and dispersed fine-grained pyrite is also a characteristic feature.

(5) The carbonate–siliceous–clayey variety (Type 8) is composed of rather loose, gray (with greenish tint) parallel-bedded rocks made up of predominantly clay minerals (glauconite and illite laths), siderite microconcretions, belemnite (more rarely bivalve shell) fragments, and dispersed fine-grained pyrite.

(6) The siliceous–clayey variety (Type 9) is represented by gray (with greenish tint), thin-laminated, very loose rocks with very rare belemnite rostra. They consist of mainly clay minerals (yellowish green glau-

[1] Because of the absence of the needed analytical equipment, we could not precisely distinguish glauconite and celadonite; therefore, although only glauconite will be mentioned elsewhere in order to avoid repetitions, the possibility of celadonite presence will be implied.

conite and illite). Silt-sized fragments of quartz–feldspar composition are present, and dispersed fine-grained pyrite is also abundant (up to 12–14%). We can also observe the so-called glauconite “sandstone” consisting of numerous large glauconite grains, 0.08–0.2 mm in size, which are cemented by hydromica and fine-grained pyrite. It should be noted that the last two varieties (types 8 and 9) belong to the lower half of the described zone.

The fourth zone (Ab_4) is predominated by kaolinite and smectites and has a thickness of 4–5 m. It can be designated as the (Kt–Sm) zone with three principal rock varieties.

(1) The low-clayey–carbonate rock (Type 5) is represented by several limestone varieties.

A thin (0.8 m) limestone is observed at the top of this zone. It consists of calcite, siderite, and dolomite. The rock is cut by numerous fractures, open surfaces of which are covered with white, small calcite crystals. The microscopic study showed that the bulk of the rock (matrix) is made up of cryptocrystalline calcite containing fine-grained aggregates of dolomite and its individual crystals. In addition, the matrix includes silt-sized particles and pyrite. The latter is noted as tiny cubic crystals and aggregates replacing biogenic detritus or filling fractures. In addition to pyrite and silt particles, the carbonate matrix contains large glauconite grains, which are sometimes broken into blocks by the associated siderite. Open fracture surfaces in this lithotype are covered with epigenetic barite and Mg–Fe calcite crystals. Well-faceted, elongated, small quartz crystals, captured by Mg–Fe calcite, are rare (Fig. 2a).

The lower part of the zone is marked by gray (with brownish tint) massive limestones consisting of microcrystalline calcite and siderite. Rare, large grains of glauconite, broken into blocks by carbonates or including small carbonate crystals, are noted in them. The minor pyrite is dispersed as microinclusions or aggregates. These rocks are encountered in boreholes 1274, 1817, and 1820 of the Em-Egovsk area. Their thickness is 0.8–1.2 m. The limestones can probably be suggested as a zone marker.

In terms of texture, structure, and composition, the microoolitic (probably pelletal) limestone in this zone is similar to the glauconite–siderite marl described in the previous zone. However, the glauconite content is noticeably less (not more than 8–10%). In addition, calcite is present. It is interesting that the largest glauconite grains (0.5–1.0 mm) include numerous small siderite crystals captured during the process of glauconite growth.

Gray (with brownish tint) fractured limestones occur at the base of the zone. They mainly consist of microcrystalline calcite, which is crosscut by cracks, 0.3 to 3–5 mm thick. Glauconite grains with small rhombohedral dolomite crystals are dispersed in the calcite matrix. Silt-sized grains and pyrite are also present. Pyrite is often encountered as small cubic crystals and aggregates replacing dispersed organic detritus. Surfaces of open fractures are covered with white microcrystalline calcite. Rare pyritized burrows are noted.

(2) The carbonate–siliceous–clayey variety (Type 8) is represented by gray, thin-stratified, very loose, bitumen-free micaceous mudstones, which contain rather numerous remnants of bivalve and ammonite shells. Toward the lower part of the zone, the mudstones grow lighter owing to the kerogen depletion in rocks. The microscopic study revealed an increase in the fine-grained siderite concentration in the form of microconcretions and decrease in silt-sized particles. Pyrite is mainly concentrated in microlayers as small cubic and rectangular crystals.

(3) The siliceous–clay variety (Type 9) differs from the previous one by the absence of carbonate material and a much higher degree of the orientation of clay particles in laminae. The clay particles show an almost simultaneous extinction or brightening under the microscope. Note that this rock variety is the richest one in clay minerals (up to 58–62%). Occasional pyritized burrows appear at the bottom of this zone.

The fifth zone (Ab_5) principally differs from the previous one by a noticeable increase in the relative portion of kaolinite and a decrease in the content of smectites (Sm–Kt zone). This is the thickest zone in the Abalak Formation (12.5 m) and includes three lithological rock varieties (Fig. 1, table).

(1) The low-clay–carbonate rock (Type 5) is represented by several limestone varieties.

The top section is composed of a thin limestone layer with a phosphorite interlayer containing a noticeable amount of silt-sized particles and rare glauconite grains. Carbonate minerals are mainly represented by siderite of two polymorphous types differing in the isomorphous admixture content. The microscopic study showed that siderite is present in the form of homogeneous cryptocrystalline mass containing an admixture of silt particles and microcrystalline pyrite. The rock is cut by fractures filled with calcite. The color of the limestone changes from brownish gray to dark brown owing to the distribution of fine-dispersed organic matter, hydroxides, and pyrite. Thin crevices and microcaverns are filled with brown bitumen similar to oil.

The middle section includes a thin layer of gray (with brownish tint) limestone made up mainly of siderite with a small admixture of dolomite, very rare silt-sized clasts, and fine-dispersed pyrite (not more than 2–3%).

The lower section reveals a thin (~0.4 m) layer of brown massive limestone with siderite, dolomite, and a small amount of silt-sized particles (not more than 5–8%). The brown color of this interlayer is related to the presence of iron oxides, hydroxides, and dispersed organic detritus. Pyrite is found as microconcretions, which are more or less uniformly distributed in siderite mass, and as aggregates related to organic remnants.

In clayey oolitic limestone, taken from the bottom of the zone penetrated by Borehole 12366 in the

Pal'yanov area, we found the above-mentional zonal ammonite, presumably of Late Callovian age. It should be noted that similar oolitic limestones were encountered in other boreholes in the bottom of this zone; therefore, the limestone can be used as a zone marker. The oolites have a bi- or trizonal structure. In bizonal oolites, the kaolinite aggregate in the center is surrounded by an ankerite or Ca-bearing siderite film. Trizonal oolites contain one more central zone more frequently represented by fragments of quartz, feldspars, or metamorphic rock. The matrix is generally composed of siderite with rather abundant calcium and manganese admixture (Fig. 2b). Fractures and microcaverns, filled with brown (due to bitumen film) kaolinite, are also found.

(2) The carbonate–siliceous–clayey variety (Type 8) is represented by gray (with brownish tint), thin-stratified, rather loose and friable rocks. Their microlayered structure is related to an inhomogeneous distribution of clay–silt material and kerogen. Numerous burrows, often pyritized, are a characteristic feature of the rock type. Fragments of bivalve and ammonite shells are noted. Pyrite is often present as small concretions (up to 1mm) and larger microlenses (up to few centimeters). Brown, obviously authigenic kaolinite is observed just in the center of pyrite lenses and concretions. Glide planes are formed around the pyrite concretions. Small siderite grains (microconcretions) are constantly present as admixture. The microscopic study showed that a significant portion of silt-sized material (up to 20–25%, sometimes higher) is contained in clayey varieties of the rocks (types 8 and 9). Illite laths are diversely oriented (clay particles do not exhibit simultaneous extinction).

(3) The siliceous–clayey variety (Type 9), which differs from the previous one only by the absence of carbonate material, is commonly represented by bivalve and ammonite shell fragments and siderite microconclusions. It is worth noting that fucoids are constantly observed in rocks of this zone, making this zone easily distinguishable from other zones. Besides, worm tracks testify to the absence of H_2S pollution in near-bottom water and bottom sediment of the Late Jurassic paleosea at that period.

The lowermost zone (Ab_6), designated as the (Kt–Sm) zone, was only recovered by Borehole 1274 in the Em-Egovsk oilfield. Its thickness is about 3 m. Rocks of this zone are characterized by an increase in the relative portion of smectite (table). We can distinguish three lithological varieties.

(1) The siliceous–carbonate–clayey variety (Type 7) is located at the bottom of the zone and consists of gray (with brownish tint), silt-rich marl with numerous interlayers of coalified detritus. Pyrite is observed as concretions and lamellae at intervals enriched in coaly detritus. The carbonate material is mainly represented by concretions of cryptocrystalline siderite and microcrystalline rhombohedral dolomite, as well as fragments of belemnite rostra. The fine (more rarely coarse) silt particles are poorly rounded or angular.

(2) The carbonate–siliceous–clayey variety (Type 8) is represented by gray thin-stratified rocks with rare pyrite concretions and solitary fragments of belemnite rostra. In comparison with clayey varieties from the overlying zones, this variety is distinguished by a high content of silt-sized clasts, large mica laths, and lesser ordering of clay and mica particles. The carbonate material is represented by fragments of marine organism shells and brown microconcretions of siderite.

(3) The siliceous–clayey variety (Type 9), which, like in other zones, differs from the previous variety by the absence of carbonate material.

Based on the analysis of the mineral composition, textures and structures, rocks of the Bazhenovo and Abalak formations accumulated under conditions of gradual seafloor subsidence in an epicontinental basin. The accumulation of Bazhenovo sediments was strongly governed by living organisms, which accomplished the biodifferentiation of clastic material supplied to the basin. They were also directly introduced after dying out into the composition of these sediments (Zubkov, 1989; Zubkov and Mormyshev, 1987). The Bazhenov Formation is enriched in kerogen and biogenic silica, because the latter previously constituted shells of radiolarians and probably diatoms. Carbonate sediments accumulated during short-term shallowing periods in the epicontinental basin probably related to eustatic oscillations of the World Ocean level or changes of paleoclimate from humid to semiarid(?) one.

Of the whole diversity of the distinguished rock varieties, all rocks of types 1, 2, and 5, as well as rock varieties of types 6, 7, 3, and 4 with the highest silica content, can be assigned to potentially productive beds (Fig. 2).

Based on the analysis of the mineral composition of different lithological varieties in six zones, one can define zones Bzh_3 and Ab_1–Ab_3 as the most perspective (in terms of oil potential) borehole section intervals, where secondary reservoirs could form. These zones are most enriched in siliceous and carbonate lithotypes, which can be traced over long distances and, consequently, can contain significant hydrocarbon reserves. Carbonate layers included in other zones of the Abalak Formation are thin (0.5–1.0 m, on the average) and, as a rule, small. Therefore, they cannot contain large oil reserves.

Attention should also be paid to intense epigenetic alterations of rocks in the Bazhenovo and Abalak formations. Fractures and caverns in carbonate and siliceous rocks are filled with vein minerals with well-faceted and highly ordered crystalline structures. These minerals are represented by pyrite, barite, apatite, different types of complex carbonate minerals, quartz, and kaolinite, which often contain oil and bitumen microinclusions (Fig. 2). Hence, one can suggest that hydrotherms, together with neotectonic movements, played a great role in the formation of secondary reservoirs. The hydrotherms, on the one hand, stimulated oil generation in the Bazhenovo and Abalak formations, and, on the other hand, leached carbonate and, to lesser degree, siliceous rocks, leading to the development of fractures and additional caverns.

CONCLUSIONS

(1) In the central part of the Krasnoleninsk Arch, sediments of the Abalak and Bazhenovo formations accumulated in a shallow-water epicontinental basin under conditions of the chlorite–siderite (lower and middle parts of the Abalak Formation) and pyrite (upper part of the Abalak Formation and the whole Bazhenovo Formation) geochemical facies.

(2) Based on the detailed lithological and mineralogical analysis, we can subdivide the Bazhenovo Formation into three zones and the Abalak Formation into six zones differing in the content of major components and ratio of clay minerals.

(3) Both formations include nine rock varieties, which can be provisionally subdivided into siliceous and clayey ones (without the consideration of carbonates). Varieties with the maximal silica content belong to the Bazhenovo Formation (particularly to its bottom part) and compose the upper part of the Abalak Formation as well. The clayey varieties are generally related to middle and lower parts of the Abalak Formation.

(4) Hydrocarbon accumulations in the Bazhenovo and Abalak confined to siliceous and carbonate beds, where secondary reservoirs of the fracture–cavernous type originated under the influence of neotectonic movements accompanied by hydrothermal activity.

(5) Siliceous rock varieties have a biogenic origin. They are widespread over the area and have a considerable thickness.

(6) Carbonate rocks are of a complex (biogenic and chemogenic) nature. They accumulated on uplifted areas of the Late Jurassic paleobasin seafloor (similar to banks). Most of them quickly pinchout, poorly correlate, and have a small thickness. Paleostructural reconstructions based on seismic data must be used for the prediction of their distribution area.

(7) Siliceous and carbonate lithotypes, which are confined to the bottom of the Bazhenovo Formation and the top of the Abalak Formation, have the greatest areal distribution and total thicknesses. The principal hydrocarbon reserves in the Bazhenovo and Abalak rocks are precisely related to these lithotypes.

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