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Influence of Processes of the Formation of Authigenic Clay Minerals of Terrigenous Rocks on Reservoir Properties: Evidence from the Rocks of the Vartov Arch

V. V. Krupskaya[a], G. A. Kalmykov[b], O. V. Khotylev[b], and M. Yu. Revva[c]

[a]*Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 119017 Russia*
e-mail: vi_kru@bk.ru
[b]*All–Russia Research Institute of Geological, Geophysical, and Geochemical Systems, Varshavskoe sh. 6, Moscow, 117105 Russia*
[c]*OAO Nizhnevartovskneftegeofizika, Nizhnevartovsk, ul. Aviatorov 4, Panel 5, a/ya 219, Khanty-Mansiisk Autonomous Region, 628606 Russia*

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Abstract—Filtration–capacity properties of terrigenous reservoir rocks significantly depend on catagenetic transformations of clay minerals. Results of our research revealed the authigenic nature and formation stages of kaolinite and chlorite. The volume and shape of pore space define the morphology of clay particles. Depending on the pore volume, kaolinite crystallizes either as thick tabular aggregates or as fan-shaped intergrowths. The formation of authigenic clays in pores of terrigenous reservoirs decreases filtration–capacity properties of rocks with low permeability and, conversely, increases filtration–capacity properties of rocks with high primary permeability and large pore volume.

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INTRODUCTION

Information on filtration–capacity properties of rocks is of great importance for calculating oil reserves in the deposit and elaborating the optimal technology of its development. The main properties (porosity and permeability) can be estimated from results of the geophysical logging of wells, study of cores, and others. Of crucial importance in this context is the study of composition, degree, and transformation stages of clay material in terrigenous reservoirs.

TECHNIQUE

The aim of this work is to correlate the composition of clay minerals and modes of their occurrences with reservoir properties of the rocks.

The following methods were used.

(1) Lithological description of the core, including its study in boxes and samples taken after its primary description. All core pieces were photographed. The lithological section was constructed based on the description of the core pieces. Their boundaries were outlined based on the core description in boxes and their coordinates were established based on the GIS data. Each sample was cut into two half-cylinders. One part was used for the study of petrophysical properties, while the other part was used for detailed lithological investigations involving grain size, chemical, mineralogical, and other analyses.

(2) Microscopic description of thin sections and their imaging on POLAM and OLYMPUS microscopes using standard techniques accepted in sedimentary petrography (Logvinenko, 1967).

(3) Mineralogical analysis of samples by X-ray methods in accordance with the certified technique developed by Sidorenko and Metlova (1989). Calculation of the relative proportions of clay minerals normalized to 100%. Materials for investigations were placed at our disposal by the Tellus Closed Joint-Stock Association.

(4) Grain size analysis by the wet sieving method (Petelin, 1967) modified by (Alekseeva, 2002). The modified technique made it possible to exclude the strong mechanical influence on the sample. Cretaceous and Jurassic rocks underwent considerable transformations, when feldspars were dissolved and replaced by clay minerals. However, they retained the primary mineral "framework." Strong mechanical action can disturb the integrity of brittle minerals and provoke overestimation of the content of fraction <0.01 mm in the grain size composition. Grinding in mortar by ceramic pestle was avoided during the preparation of samples. The results of sample preparation were examined under optical and electron microscopes.

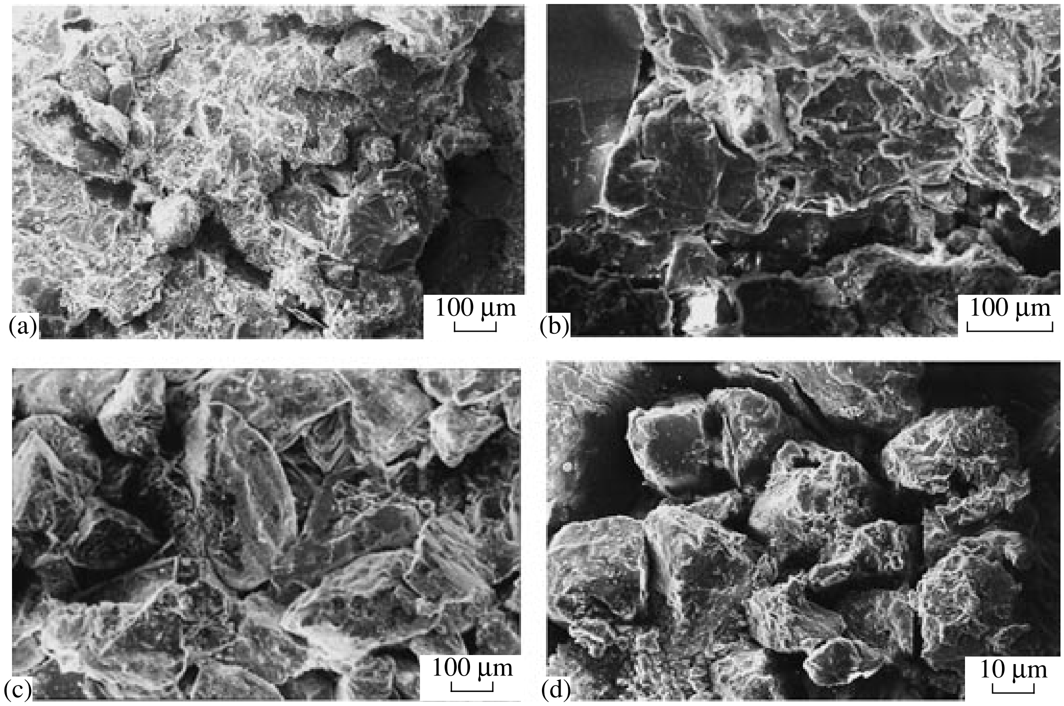

Fig. 1. Scanning electron images of reservoir rocks. (a) Horizon YuV 1-1; (b) horizon BV 16; (c) horizon BV 8-1; (d) horizon PK 19.

(5) X-ray structural studies of clay minerals according to the technique in (Brindley and Brown, 1980) were performed for three pelitic fractions (10–5 μm, 5–1 μm, <1 μm) on DRON 3 and D/MAX-2200 X-ray (Rigaku Co.) diffractometers. Proportions of clay minerals were calculated using the Biscaye method (Biscaye, 1965).

(6) Refinement of kaolinite and chlorite compositions on a KOMEX microprobe using standard methods.

(7) Petrophysical investigations of core material, including the measurements of porosity (drying technique) and permeability (*GOST 26450.2-85…*, 1985).

(8) Geophysical logging of wells carried by the Tellus Closed Joint-Stock Association using standard techniques.

RESULTS

The present communication is devoted to discussion of results of the investigation of rocks from one of the petroleum deposits in the Vartov arch, West Siberia. We consider in detail four sections of the main Upper Jurassic and Lower Cretaceous horizons.

Horizon YuV 1-1 (Lower Jurassic)

Lithology. Jurassic sediments are represented by intercalation of gray vaguely bedded micritic limestones with gray, light gray, and grayish beige fine-grained sandstones and light to brown-gray silty mudstones containing traces of erosion and pyrite inclusions. As compared to other sections, the Jurassic sandstones are enriched in carbonates, clays, and fine intercalation of sandstones and silty mudstones. The cement is composed of the carbonate–clayey (partially, quartz) regenerated material.

Petrophysics. The Lower Jurassic sequence has high porosity and low unstable permeability. One can identify two thin reservoirs with porosity and permeability equal to 17.6% and 38.6 mD, respectively (Table). Host rocks have the average porosity of 7.9% and permeability of 1.2 mD. The reservoirs have small pores with the average size of 23–30 μm (up to 50 μm in some places and up to 90 μm in rare cases) (Fig. 1).

Composition of clay minerals in the cement. As compared to the host rocks, the reservoir rocks are insignificantly enriched in kaolinite and depleted in hydromica (Fig. 2). The studied Jurassic sedimentary sections are located at different distances from the coast (O. V. Yapaskurt, personal communication). Nevertheless, all sections are similar in proportions of clay and nonclay minerals. Hydromica and kaolinite have negative correlation, while other clay minerals do not show any correlation. This fact testifies to different sources of the sedimentary material.

Under electron microscope, one can see feldspar skeletons left after epigenetic processes (weathering) and well-developed crystals of the newly formed quartz. Fibrous hydromica–smectite aggregates are scattered over the entire pore space. Tiny chlorite particles make up thin rims around the grains. Distinct

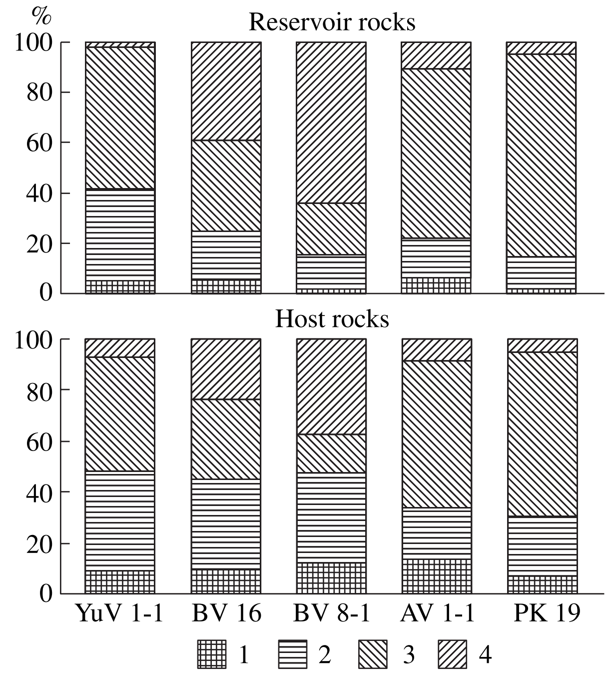

Fig. 2. Proportions of clay minerals in cement of productive and host rocks. (1–4) Clay minerals: (1) smectite and mixed-layer minerals, (2) hydromica, (3) kaolinite, (4) chlorite.

flakes of terrigenous mica are occasional. In some places, kaolinite occurs as aggregates of large particles that completely fill small pores. Relatively large pores contain scarce fan-shaped aggregates of several generations (Fig. 3).

Horizon BV 16 (Lower Cretaceous, Valanginian)

Lithology. The upper part of the studied Valanginian section consists of the intercalation of light gray, beige, and dark brown fine- to very fine-grained sandstones with carbonate cement and gray and dark gray bedded silty mudstones and mixtites. Unlike the other studied horizons, section BV 16 is distinctly divided into three units: upper unit (silty–clayey cap), middle unit (silty–sandy reservoir with oil shows), and lower unit (silty–clayey base). Analysis of the grain size composition revealed that the sediments can be divided into two classes: silty pelites and silty sands (sandy silts).

Petrophysics. The middle sandy oil-bearing unit has the highest porosity and permeability. The average porosity is 19.1% in the reservoir rocks and 9.2% in the host rocks. The average permeability is 19.9 mD and 0.9 mD, respectively. The reservoirs are represented by the 5-m-thick sandy sequence in the central part of the section and two thin sandy siltstone interbeds. The average permeability is lower than that in the Jurassic rocks. However, the pore size is two times more (up to 100 μm, average 50–60 μm).

Composition of clay minerals in the cement. Proportions of clay minerals in the cement correlate well with porosity and permeability. The reservoir rocks are significantly enriched in chlorite and kaolinite and depleted in hydromica and expandable minerals (Fig. 2). Chlorite exhibits wider variations than kaolinite.

Electron microscopic study revealed intricate-fibrous aggregates of smectite–hydromica and fine particles of authigenic chlorite, which form thin rims around terrigenous grains. Kaolinite occurs as aggregates of large hexahedral crystals randomly distributed in the pore space and fan-shaped intergrowths. Kaolinite particles are late formations that fill pores without any contact with the chlorite rim.

X-ray investigations of pelitic fractions showed significant differences in the composition of pelitic minerals between caprocks and reservoir rocks. In particular, fraction <1 μm is abundant in the finely dispersed feldspars and quartz. Based on the shape of reflections, two generations of Fe-chlorites can be distinguished in the X-ray powder diffraction pattern. Microprobe investigations confirmed high Fe and low Mg contents in the chlorites. The second generation of chlorite is presumably authigenic phase. The fine pelitic fraction of the reservoir is significantly depleted (relative to the host rocks) in fragments of minerals, such as quartz and feldspar, and enriched in the authigenic fine-dispersed chlorite. This is confirmed by change of interplanar spacings and shape of basal reflections.

Horizon BV 8-1 (Lower Cretaceous, Valanginian)

Lithology. Lower Valanginian sediments are composed of alternation of gray or light gray fine-grained sandstones with greenish tint, beige siltstones, dark gray graded-bedded mudstones with erosion traces. The sequence also contains dark gray silty mudstones and mudstones with thin sandy interlayers and pyrite inclusions.

Petrophysics. Productive sequences include four sandy horizons with the average porosity of 23.8% and permeability of 211.2 mD. Pores are up to 100–150 μm long. Host rocks have the average porosity of 14.8% and permeability of 2.9 mD.

Composition of clay minerals in the cement. Sediments of horizon BV 8-1 are distinctly enriched in chlorite and depleted in kaolinite in both host and reservoir rocks. The chlorite content in the reservoir is more than 25% higher than that in the host rocks. This is the largest difference among the studied sections. In the Upper Valanginian sequence, the chlorite content (~60%) is higher than the kaolinite content (~20%). The chlorite content generally increases downsection.

Pores are relatively empty with no significant traces of grain dissolution. Most grains are covered by a thin film of authigenic chlorite. Kaolinite develops mainly as small fan-shaped, fairly thick, loose intergrowths in large pores with no contact with chlorite (Table, Fig. 3).

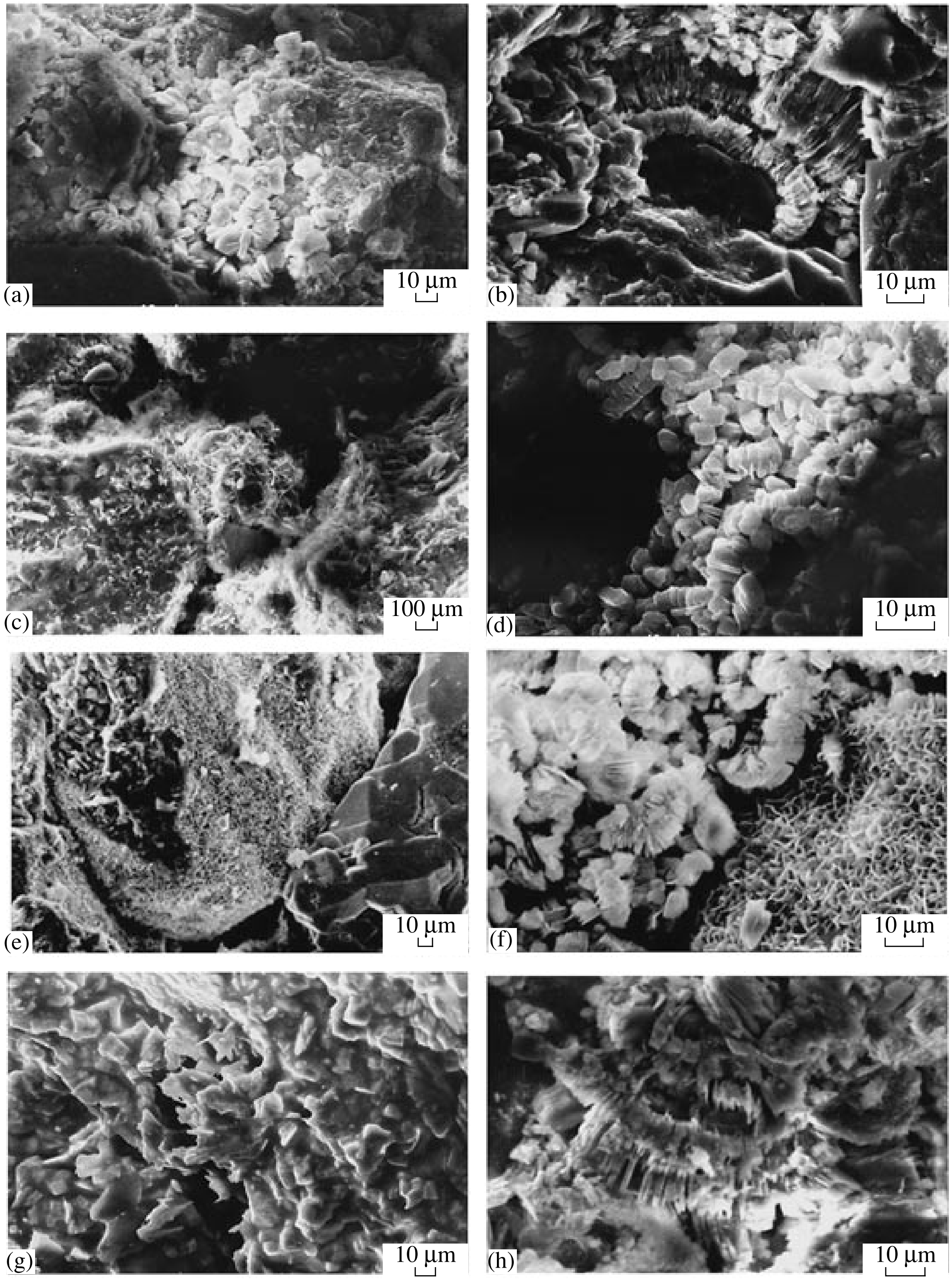

Fig. 3. Photomicrographs of catagenetically altered reservoir rocks from horizons YuV 1-1 (a, b), BV 16 (c, d), BV 8-1 (e, f), and PK 19 (g, h) of the Vartov arch. (a, b) Kaolinite aggregates; (c) crustification chlorite; (d) kaolinite hexahedrons; (e) chlorite rims; (f) chlorite rims on grains and the kaolinite porous cement as fan-shaped intergrowths; (g) dissolution traces of clay cement; and (h) multistage fan-shaped kaolinite aggregates.

Horizon PK 19 (Upper Cretaceous, Cenomanian)

Lithology. Cenomanian rocks are represented by gray fine- and medium-grained sandstones with thin siltstone intercalations in the lower part of the section and two thick interbeds of dark gray to black thin-bedded silty mudstones in the upper part.

Petrophysics. Rocks of horizon PK 19 have high porosity and permeability. The average values are

Correlation between lithological and petrophysical properties, composition of clay minerals and mode of occurrence of kaolinite particles in rocks of the Vartov arch

Horizont		Rocks	Petrophysical characteristics			Clay minerals in cement				Modes of occurrence of kaolinite particles
			C_p, %	C_{perm}, mD	pore size*, μm	hydromica-smectite	hydromica	kaolinite	chlorite	
YuV 1-1	1	Fine-grained sandstones and sandy siltstones	17.6	38.6	25–30, up to 50	4.3	34.4	52.6	2.0	Thick tabular intergrowths, very scarce fan-shaped aggregates
	2	Siltstones, silty mudstones, and calcareous sandstones	7.9	1.2		9.0	43.2	48.1	7.8	
BV 16	1	Sandstones and silty sandstones	19.1	19.9	50–60, up to 100	5.2	19.6	36.2	38.9	Thick tabular loosely cemented
	2	Siltstones and silty mudstones	9.2	0.9		10.5	38.9	35.2	26.6	
BV 8-1	1	Very fine-grained and fine-grained sandstones	23.8	211.2	100–150	1.3	14.2	20.3	64.2	Large and loose fan-shaped aggregates (average, 10 μm)
	2	Silty mudstones	14.8	2.9		11.6	35.8	14.9	37.7	
AV 1-1	1	Very fine-grained and fine-grained sandstones	27.9	225.1	120–180	5.7	15.9	67.2	10.2	Loose fan-shaped aggregates (average, 10 μm)
	2	Silty mudstones	23.2	7.7		12.8	19.8	55.4	8.5	
PK 19	1	Fine-grained and medium-grained sandstones	26.5	1982.5	180–200, up to 500	1.4	12.4	75.3	4.3	Very large (>10 μm) loose multistage fan-shaped aggregates
	2	Silty mudstones and siltstones	16.1	13.1		6.5	23.5	65	5	

Note: (*) Size along long axis; (1) reservoirs, (2) host rocks; (YuV 1-1) Upper Jurassic rocks; (BV 16, BV 10, BV 8-1) Lower Cretaceous (Valanginian) rocks; (PK 19) Upper Cretaceous (Cenomanian Stage, Pokur Formation) rocks; (C_p) porosity coefficient; (C_{perm}) permeability coefficient.

26.5% and 1982.5 mD, respectively, in the reservoir. Sandstones are weakly cemented and fissured. Pores are mainly elongated and large (average 200 μm, up to 500 μm in some places). Secondary intergranular pores are up to 50 μm in size. Cracks are as long as 300 μm. This horizon has the highest permeability (up to 8000 mD) among the studied sediments,

Composition of clay minerals in the cement. Cenomanian rocks have the highest kaolinite content and the lowest hydromica content. Difference in the content of clay minerals is no more than 10–15% in the reservoir and host rocks. The crustification chlorite is almost indiscernible in the photomicrographs. Kaolinite formed in several stages as large and thin fan-shaped intergrowths (Fig. 3). All aggregates are loose and oriented. Therefore, the reservoir properties of rocks should be high. Some images demonstrate distinct traces of dissolution of the clayey cement.

DISCUSSION

The degree of transformation of sediments significantly increases downsection (Fig. 1). For example, relative to Cretaceous (Cenomanian) sediments, Jurassic sediments exhibit intense leaching of feldspars, which is responsible for the secondary increase in the clay content. These processes are more active in the reservoir, where quartz is more rapidly regenerated and feldspar is intensely leached. Consequently, the pelitic fraction (<1 μm) of reservoir rocks is enriched in clay minerals and depleted in feldspar and quartz (no more than 10–20%). The ratio of clay and nonclay minerals in the fine fraction of clay horizons is 1: 1.

Hydromica and mixed-layer hydromica–smectite phases occur together as a homogenous mass. Therefore, it is rather difficult to distinguish these phases. In the Cretaceous rocks, contents of these phases in the reservoir rocks are lower than those in the host sequences. In the Jurassic sediments, this trend is less prominent.

As a whole, the productive sequences are characterized by elevated contents of kaolinite and chlorite. One can see the following regular variations from Upper Jurassic (horizon YuV 1–1) to Late Valanginian (AV 1-1) rocks. Relative to the host rocks, the reservoirs are depleted in mixed-layer minerals, hydromica, and kaolinite. At the same time, they are enriched in chlorite. In the same direction, the host rocks are depleted in chlorite and kaolinite and enriched in hydromica and mixed-layer minerals. From Upper Valanginian (horizon AV 1-1) to Cenomanian (horizon PK 19) rocks, the reservoirs and host sediments show similar compositional variations: decrease in the content of mixed-layer minerals, hydromica, and chlorite is accompanied by increase in the kaolinite content.

Authigenic clay minerals formed in several stages. The catagenetic stage produced chlorite crustification rims owing to the transformation of dark minerals (Chamley, 1989), which were delivered from eastern provenances composed of effusive rocks. This stage was presumably followed by the retrograde epigenesis (Rukhin, 1969; Yapaskurt, 1999) related to the influx of oil fluid into the bed. The tectonic inversion stage (uplift of the basin and rearrangement of hydrodynamic regime) was accompanied by intense dissolution of the chloritic crustification cement and the formation of kaolinite in the liberated pore space. The oil deposit presumably formed at that time. From the base of the Upper Valanginian horizon AV 1-1, the degree of kaolintization grows both upward and downward the section owing to the migration of fluids. In the Upper Valanginian rocks, the high chlorite content is retained and free space in the pores is insufficient for the formation of large fan-shaped particles of authigenic kaolinite. Since Cenomanian rocks are more porous and permeable, they are characterized by the highest degree of kaolinitization among the studied rocks (the kaolinite content is as much as 60–70% or more).

Authigenic chlorite develops on grain surface in fine-grained sandstones and silty sandstones with small pores. Allothigenic chlorite is subordinate. Increase in the chlorite content in reservoir rocks presumably degrades their filtration–capacity properties due to the formation of numerous capillary and subcapillary pores between flakes of crustification chlorite overgrowths on grains (Sarkisyan and Kotel'nikov, 1980). However, the reservoir of horizon BV 8-1 with the highest chlorite content has good filtration–capacity properties. The porosity of rocks decreases. However, the influence of crustification chlorite on the filtration–capacity properties is insignificant.

The content of authigenic kaolinite in the rock cement shows the widest variations (from 20 to 70%). We can distinguish two varieties of this mineral: thick flakes completely filling the pores and loose fan-shaped intergrowths up to 10 μm or more. From Jurassic to Upper Cretaceous rocks, their reservoir properties are significantly improved (increase in porosity, pore size, and permeability).

Aggregates of thick hexahedral kaolinite particles are developed in fine (up to 50 μm long) pores of Jurassic silty–sandy rocks with the high content of pelitic components (average porosity 17.6%, permeability 38.6 mD). They are chaotically distributed in pores. Therefore, the primary permeability and porosity are decreased. Rocks of horizon YuV 1-1 are characterized by the high degree of transformation and the consequent decrease in porosity.

Increase in porosity up to 19.1% in silty–sandy rocks of the Lower Valanginian horizon BV 16 is related to the lower degree of their compaction and postdiagenetic transformation. Their crystalline framework is better preserved, because feldspars are less leached and the newly formed quartz is less abundant.

The amount of authigenic crustification chlorite sharply increases, leading to decrease in permeability to 19.9 mD. With increase in pore size up to 100 μm, kaolinite particles become thinner and larger, but their primary chaotic distribution is retained. Unlike Jurassic rocks, Lower Valanginian rocks virtually lack the fan-shaped aggregates of kaolinite. Therefore, increase in their porosity promotes decrease in permeability.

Reservoirs of the Valanginian horizon BV 8-1 are represented by fine to very fine-grained sandstones with average porosity up to 23.8%. Large (up to 10 μm, on the average) fan-shaped aggregates of small kaolinite particles occur in large pores (up to 100–150 μm long). Despite the high degree of chloritization (64.2% chlorite in the reservoir), the abundance of large intergrowths of kaolinite (20%) leads to a significant increase in permeability (up to 211.2 mD, on the average). Conditions of postdiagenetic transformations sharply changed in the Late Valanginian. Up to this time, kaolinitization regularly decreased and chloritization increased. Beginning from horizon AV 1-1, we observe an opposite trend: kaolinitization is intensified, whereas the relative amount of chlorite in clay minerals decreases, presumably, owing to its intense dissolution.

The Cenomanian sediments have the highest values of porosity (26.5%) and permeability (1982.5 mD). Multistage very large (more than 10 μm) thin and loose fan-shaped kaolinite intergrowths are formed in the free space of large pores. Owing to relatively large sizes of the pores (>200 μm), chlorite was dissolved by oil fluid, as shown by numerous dissolution traces of the clay cement in photomicrographs. The liberated pore space was filled by large intergrowths of kaolinite. The pore size directly correlates with the intensity of washout of the pore space and size of fan-shaped kaolinite aggregates. The postsedimentary pore-hosted kaolinite can serve as a permeable medium (Zaripov et al., 1999). As a result, even an insignificant increase in effective porosity provokes considerable increase in permeability.

The mode of occurrence of kaolinite particles depends on the pore space volume. If the rocks have large pores and high rate of filtration, catagenetic transformations (formation of large fan-shaped kaolinite aggregates) do not lead to the sealing of pores. Consequently, decrease in permeability is proportional to decrease in pore size. If the rocks have small pores filled with hydromica and thick tabular kaolinite flakes, permeability decreases due to the sealing of pores.

CONCLUSIONS

(1) Kaolinite and chlorite are of authigenic origin.

(2) Clay minerals in the cement of terrigenous rocks of the Vartov arch were subjected to multistage catagenetic transformations.

(3) The type of clay formation depends on grain size composition, pore volume, and permeability of rocks.

(4) Chloritization decreases porosity, but this process does not lead to the sealing of pores.

(5) Rocks with small pores are dominated by thick tabular aggregates of kaolinite, while rocks with large pores are filled with fan-shaped loose and large kaolinite intergrowths.

(6) Leaching of chlorite leads to the increase of filtration–capacity properties of rocks.

(7) In host rocks with good filtration–capacity properties and large pores, catagenetic transformations of the oil-bearing terrigenous rocks with the development of new phases of clay minerals do not lead to the sealing of pore space. In rocks with small pores, the authigenic clay formation significantly affects the filtration–capacity properties up to the point of complete sealing of pores.

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