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Tectonic, Lithofacies, and Geochemical Formation Conditions and Quantitative Estimation of the Petroleum Potential of the Giant Erema–Chona Oil and Gas Accumulation (Siberian Platform)

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Abstract—We present results of research into the tectonic, lithofacies, and geochemical formation conditions of the Erema–Chona oil ans gas accumulation. We characterize present-day structures and their formation history, consider the composition, structure, formation conditions, postdepositional alterations, and porosity–permeability properties of the Osa, Ust'-Kut, Preobrazhenka, Erbogachen, and Upper Chona Horizons, assess the quality of the overlying seals, and describe the technique and results of quantitative estimation of the petroleum potential of pay beds. Modern technologies for the development of oil reserves are also presented, along with geological and economic assessment of hydrocarbon resources of the study object.

Keywords: oil, gas, bed, formation conditions, secondary processes, reservoir, seal, quantitative estimation, economic efficiency, Siberian Platform

INTRODUCTION

The Erema–Chona petroleum accumulation (ECA) is located in the Katanga district of the Irkutsk Region and on the adjacent territory of the Sakha (Yakutia) Republic. Its tectonic affinity is to the central part of the Nepa–Botuobiya anteclise. According to the petroleum zoning, it is located in the center of the petroleum-bearing region of the same name. Its area is 26.5 thous. km^2.

Currently, the entire territory of the ECA is licensed with 17 determined license areas belonging to eight developers. The main ones include OAO NK Rosneft, Gazpromneft-Angara and OAO Surgutneftegaz.

Significant amounts of geologic exploration works have been performed within the contour of the ECA. Its entire territory has been covered by gravimetric survey and most of it—by near-field time-domain electromagnetic sounding. Nearly all of the territory has been studied by the seismic reflection method first by single-fold profiling and beginning with the mid 70s—by multifold CDPM profiling. Deep drilling began in the 70s. At present, close to 200 deep wells have been drilled in 17 areas with a total advance of 321 thous. m. The state of knowledge of the site by deep drilling in general is 12.1 m/km^2 or 7.2 wells/thous. km^2. The eastern half of the site is the most studied by wells and seismic surveys.

Geologic exploration works on the ECA territory discovered 11 oil and gas fields containing 33 deposits including 11 large ones, 18 medium and 4 small in terms of hydrocarbons (HC) reserves. Recoverable reserves of HC as of 01/01/2016 for categories A + B + C_1 + C_2 are equal 1285.6 mln tons of estimated hydrocarbons that include 851.7 mln tons of oil, 428.1 bln m^3 of gas and 5.8 mln tons of condensate.

The main volume of performed geologic exploration on the ECA territory was directed at the search and prospecting of petroleum fields in the Vendian terrigenous complex. The overlying Vendian–lower Cambrian carbonate deposits characterized by higher petroleum potential but more complex structure were usually studied in passing. During drilling and well testing traditional methods were used. Drilling of horizontal well shafts and their testing using hydraulic fracturing was practically not done.

The ECA was first identified and characterized in the framework of the Preobrazhenka Horizon as the Teteya–

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Chona petroleum accumulation zone (Shemin et al., 1991). Then, for 20 years, the structure was specified and the formation conditions of the oil and gas accumulation were determined. The results of these studied were presented in publications by G.G. Shemin (Shemin, 1999, 2000, 2001, 2004, 2007, 2010, 2011; Shemin et al., 2018; etc.).

In recent years, the companies OAO NK Rosneft' and OOO Gazpromneft'-Angara performed significant volumes of seismic surveys and drilling on their license areas. This resulted in a significant growth of hydrocarbon resources reserves not only in the Preobrazhenka Horizon but also in the overlying Ust'-Kut and Osa Horizons. This means commercial petroleum potential was also identified in these carbonate horizons.

Here we present a detailed characterization of tectonic, lithofacies and geochemical formation conditions of the Erema–Chona giant petroleum accumulation. We provide evidence that all identified carbonate and sand beds of the Vendian–Cambrian subsalt complex (B_1, $B_{3–4}$, B_5, $B_{12,13}$, C_{10}, C_{13}) had favorable conditions for the forming of oil and gas deposits. These conditions provided commercial petroleum potential only in this area of the southern part of the Lena–Tunguska petroleum-bearing province. For the first time we describe modern technologies of oil reserves development in carbonate layers of the ECA and the developed concept of geologic-economic evaluation of its oil and gas reserves, showing the cost-effectiveness of developing hydrocarbons in this site. The stratigraphic position of the identified pay beds is shown in Fig. 1.

TECTONIC FORMATION CONDITIONS OF THE EREMA–CHONA OIL AND GAS ACCUMULATION

Tectonic conditions of the formation of the ECA are described in sufficient detail in our publications (Migurskii, 1986, 1997; Shemin, 2007, 2011) and can be summarized in the following. As noted above, the ECA is located in the central, upraised part of the Nepa–Botuobiya anteclise, where it includes the northwestern part of the Nepa arch, modified by the Upper Chona structural peak. In the top of all pay beds listed above, the accumulation is uniformly manifested in the form of a semicircular monocline with layers dipping to the north-northwest and southwest from the high point of the Upper Chona peak (Fig. 2).

The territory of the ECA had quite intense disjunctive tectonics, starkly manifested by seven micrograbens and four main faults that are clearly identifiable on the structural bases of all pay beds (Fig. 2).

Trap magmatism manifested in the ECA on a significantly smaller scale than in the northwest of the Siberian platform. Its rocks compose only 3% of the volume of the sedimentary cover and are represented by mainly sheet intrusive bodies (sills) occurring in the upper part of the sedimentary cover, in the halogen-carbonate Cambrian complex.

The **formation history** of the present-day structural frameworks of the Nepa–Botuobiya anteclise that includes the ECA in its central upraised part is considered in (Shemin, 1986, 2007). The structures were reconstructed based on results of detailed correlation of the Vendian–lower Cambrian deposits, taking into account the factors limiting the use of the thicknesses method (Shemin, 2007).

The structural plan of the Nepa–Botuobiya anteclise and the ECA in the Vendian–early Paleozoic differed from the present-day structures. During this time interval, the northwestern half of the anteclise was the highest point. It composed the southeastern roof part of the largest positive structure—the Katanga paleoanteclise (Tugolesov, 1952). During this period, nearly the entire territory of the accumulation was located within the roof part of the Katanga paleoanteclise. Only the most upraised southeastern part existed in the crestal part of the anteclise (Fig. 3).

The structural plan of the territory under consideration in the middle Paleozoic generally continued this inherited development.

The late Paleozoic–Mesozoic period on the Siberian Platform was characterized by high tectonic activity. At the Permian–Triassic boundary plume tectonics manifested in the formation of rifts and large basins, syneclises, anteclises and the eruption of huge volumes of the Siberian traps (Dobretsov, 1997; Dobretsov and Vernikovsky, 2001). The Yenisei–Khatanga basin formed (Vernikovsky et al., 2018) and the Tunguska syneclise formed and developed (Kontorovich et al., 1981). Its southern part overlapped the Katanga paleoanteclise. As a result, the northwestern slope of the Nepa–Botuobiya anteclise, that is the present-day structural plan of the ECA, was actively forming.

In the post-Triassic time, the present-day structural plan of the Nepa–Botuobiya anteclise and the studied petroleum accumulation on its territory finished forming.

Consequently, the tectonic condition of the formation of the Erema–Chona petroleum accumulation were very favorable, since during the late Precambrian, Phanerozoic and up until the present time, its territory was the most upraised part of the Nepa–Botuobiya anteclise, where hydrocarbons could accumulate nearly without interruptions from the adjacent oil and gas generation zones. The intensely manifested disjunctive tectonics favored the transport of hydrocarbons from the most subsided terrigenous pay beds to the overlying carbonate beds. Trap magmatism within the ECA boundaries only manifested in the upper part of the sedimentary cover and did not have any adverse effects on its petroleum potential.

LITHOFACIES FORMATION CONDITIONS OF THE EREMA–CHONA OIL AND GAS ACCUMULATION

As noted above, seven pay beds have been identified in the Vendian–lower Cambrian petroleum-bearing deposits of

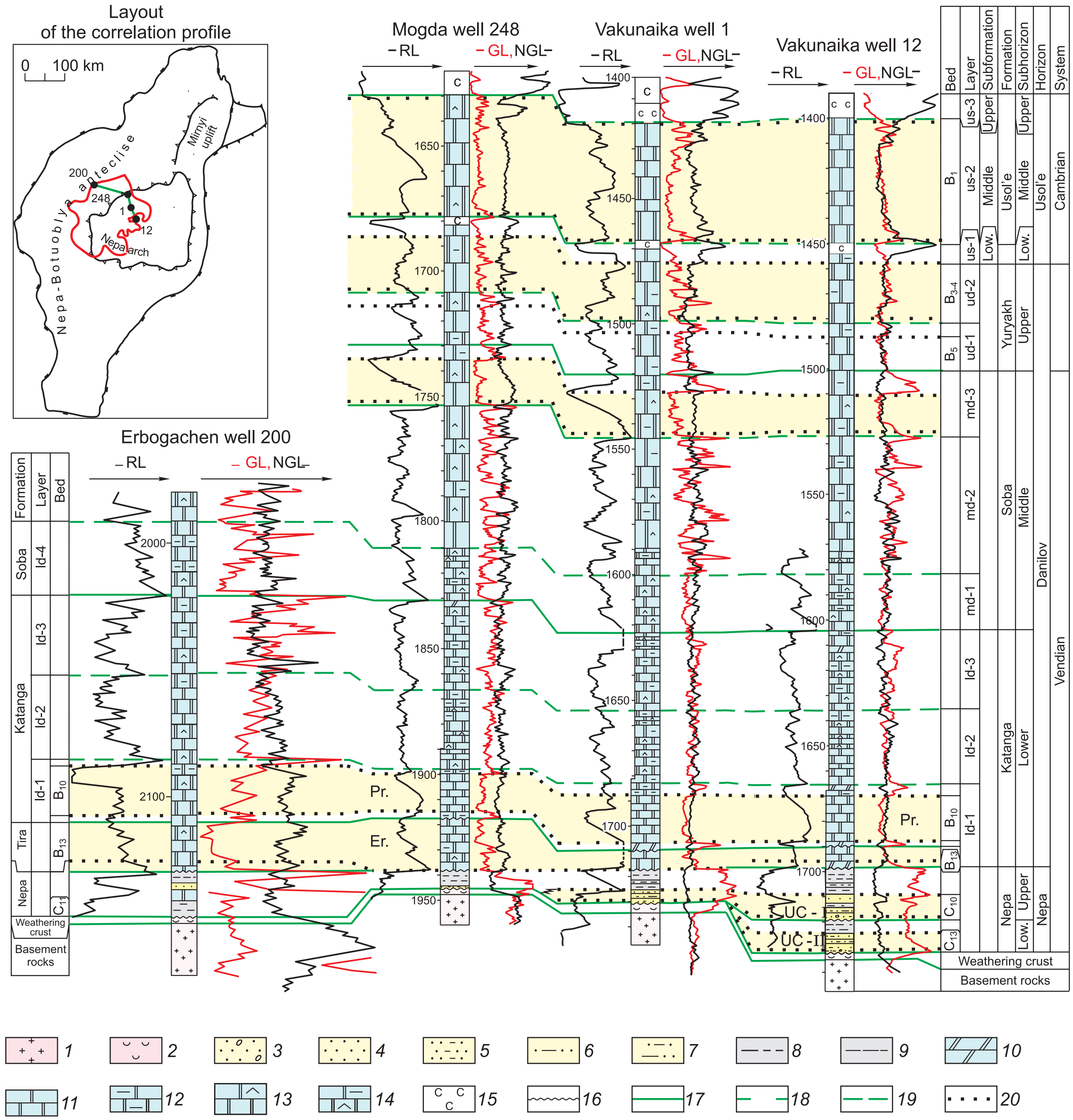

Fig. 1. Stratigraphic position of pay beds in the Vendian–lower Cambrian deposits of the Erema–Chona petroleum accumulation. *1–14*, rocks of: *1*, basement, *2*, weathering crust, *3*, gravelly and gravelite sandstone, *4*, sandstones, *5*, silty sandstone, *6*, clayey sandstone, *7*, silty and clayey sandstone, *8*, clayey siltstones, *9*, silty clays, *10*, marl, *11*, carbonates, *12*, clayey carbonate, *13*, anhydritic carbonate; *14*, clayey and anhydritic carbonate, *15*, rock salt; *16*, gap; *17–20*, boundaries of: *17,* formations (Er., Erema; Pr., Preobrazhenka; UC-I, UC-II, Upper Chona), *18*, subformations, *19*, layers, *20*, pay beds. RL, resistivity log; NGL, neutron gamma-ray log; GL, gamma-ray log. The inset shows the location of the correlation profile.

the ECA: B_1, $B_{3–4}$ B_5, $B_{12–13}$, C_{10}, and C_{13}. Next, we present results of investigation of their lithology, structure, formation conditions, postdepositional alterations, estimation of quality of the reservoirs and overlapping seals.

Pay beds $B_{12, 13}$ are divided by a 5 m thick dolomite break and have the same overlapping seal, so they are one single collector. Therefore, we first present their autonomous lithofacies characteristic, followed by a joined estimation of the quality of their reservoirs and the underlying Tira and overlaying Katanga seals.

Pay bed B_{12} lies in the base of the Katanga Formation and is widespread. Its thickness is usually measured between 18 and 22 m. It is composed mainly of dolomites with three identified genetic types: chemogenic, organogenic (microphytolitic) and organogenic-clastic (Chernova, 1980; Gushina et al., 1991; Shemin et al., 2012).

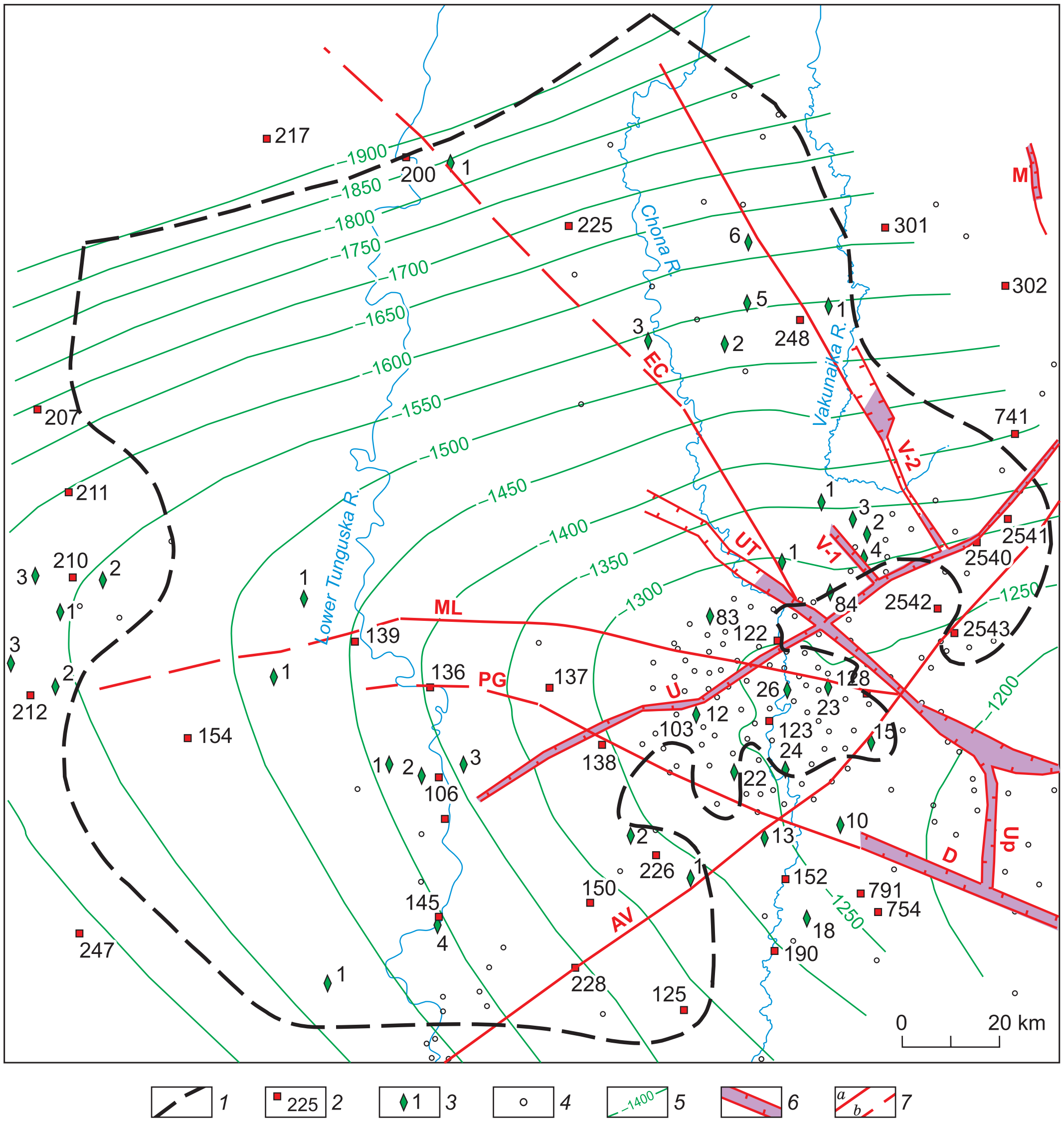

Fig. 2. Structural map for the top of the C_{10} bed of the Erema–Chona petroleum accumulation. *1,* boundary of the Erema–Chona petroleum accumulation; *2–4*, wells: *2*, stratigraphic, *3*, exploration, *4*, appraisal; *5*, isohypses (m) for the top of the C_{10} of the Upper Chona Horizon; *6,* micrograbens: V-1, Vakunaika-1; V-2, Vakunaika-2; Up, Upper Peledui; UT, Upper Chona–Talakan; D, Delinda; M, Mukoka; U, Usol'e; *7*, main faults (*a*, known, b, inferred): EC, Erbogachen–Chuya; ML, Moga–Lena; PG, Preobrazhenka–Gadalin; AV, Angara–Vilyui.

The chemogenic type is widespread in the entire territory and represented by grainy dolomites that compose in average 10–40% of the bed's thickness. A constant admixture of clay material and anhydrite is noted. The microphytolite dolomite type is also widespread on the territory and occupies more of the section (50–70, rarely 70–90%) than the chemogenic type. It is characterized by low content of clay material and anhydrite (up to 2%). The organogenic-clastic type is represented by products of destruction of the chemogenic and organogenic dolomites.

As regards the in-section relationships of these genetic types of dolomites within the ECA, their clay alteration and sulfates contents, they are divided into two types. The first type is mainly represented by microphytolitic (>70%) and organogenic-clastic (15–25%) dolomites, containing a small admixture of clayey and sulfate material. The second is composed mainly of microphytolitic (40–70%) and organogenic-clastic (10–20%) dolomites with a somewhat increased chemogenic component (10–20%).

The determination of formation conditions of pay bed B_{12} sediments was performed following the methodology of V.D. Il'yin and N.K. Fortunatova (1988). The ubiquitous distribution of the first and second section types on the studied accumulation and low content of clayey and sulfate materials in them allowed to conclude that the B_{12} bed sediments on its territory mainly formed in conditions of a shelf shoal and on individual areas in the form of organogenic banks (Shemin, 2011).

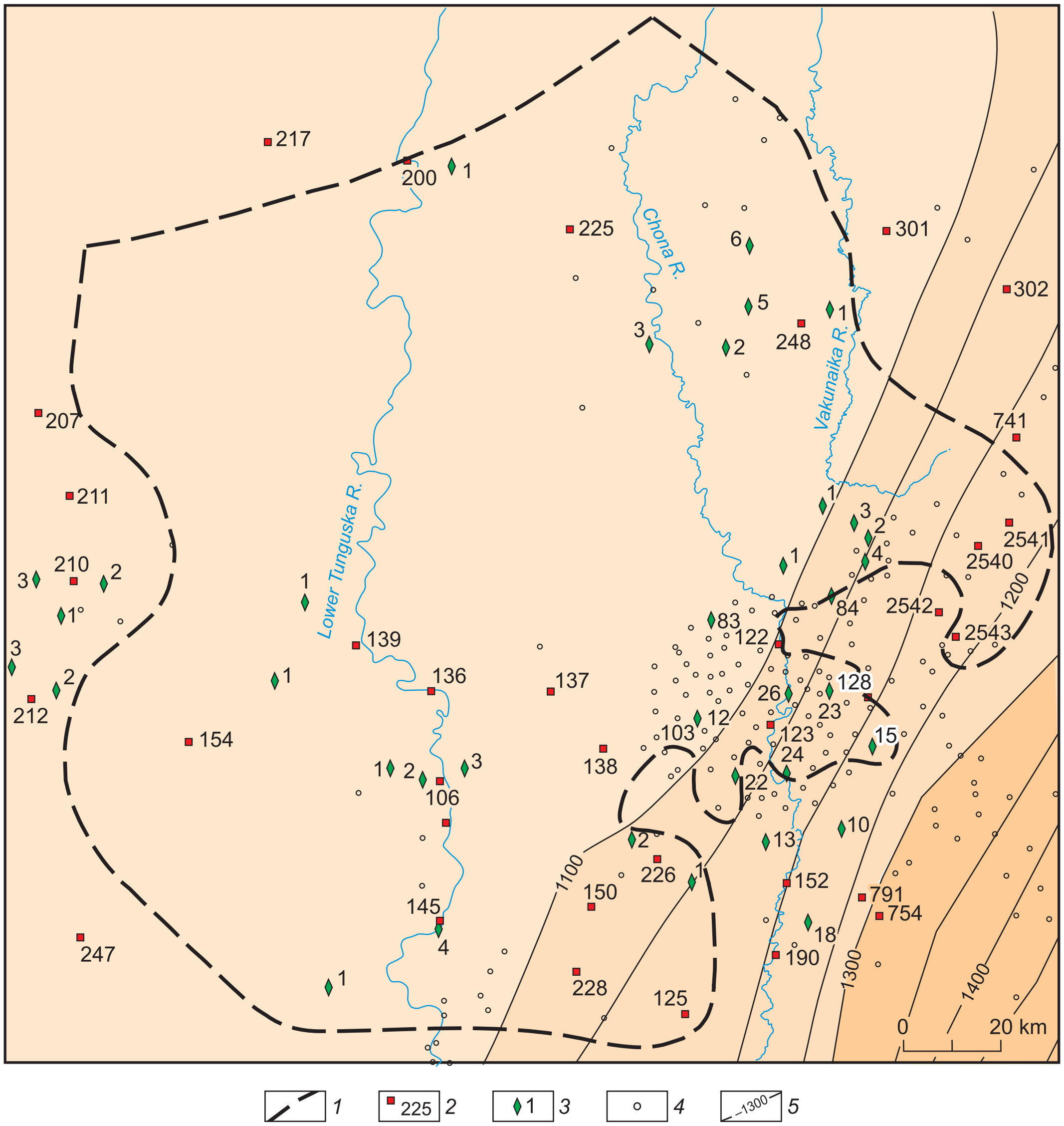

Fig. 3. Paleostructural map of the bottom of the Vendian terrigenous complex for the beginning of formation of the Angara Formation deposits in the Erema–Chona petroleum accumulation. *1,* boundary of the Erema–Chona petroleum accumulation; *2–4*, wells: *2*, stratigraphic, *3*, exploration, *4*, appraisal; *5*, isopachs (m).

On the accumulation's territory the rocks of bed B_{12} have been altered by secondary processes. Among the processes that positively impact porosity and permeability properties (PPP) of reservoirs, the most manifested are recrystallization, fracturing and partly desalination (Fig. 4). They are intensely manifested in the central part of the accumulation, forming a band 40–50 km wide, with a sublatitudinal strike from the Sanarskoe field to the Verkhnechonckoe field. Secondary processes that negatively affect the quality of the B_{12} bed are also present, however to a lesser extent.

Pay bed B_{13} was determined in the much-reduced stratigraphic volume of the Tira Formation that lies directly below the Preobrazhenka Horizon. It occurs only in the northern half of the ECA and was poorly explored by drilling. Its thickness varies between 7–10 and 25 m, with the greatest thickness recorded in the northern part of the accumulation.

The bed is mostly composed of micro- and fine-grained dolomites with alternating layers of anhydritic and magnesite-bearing varieties, fractured with insignificant admixture of clayey material. The lower part of the bed is dominated by chemogenic and biochemogenic dolomites enriched by organogenic clastic material (up to 25% of the rock volume). Upsection they are replaced by stromatolitic dolomites with magnesite-enriched layers. The upper half of the layer is composed of dolomites with layers of microphytolites, clasts, sometimes, clay layers.

Significantly manifested secondary processes are recrystallization, rarely desalination and in very rare cases—sulphatisation, salinization and silification.

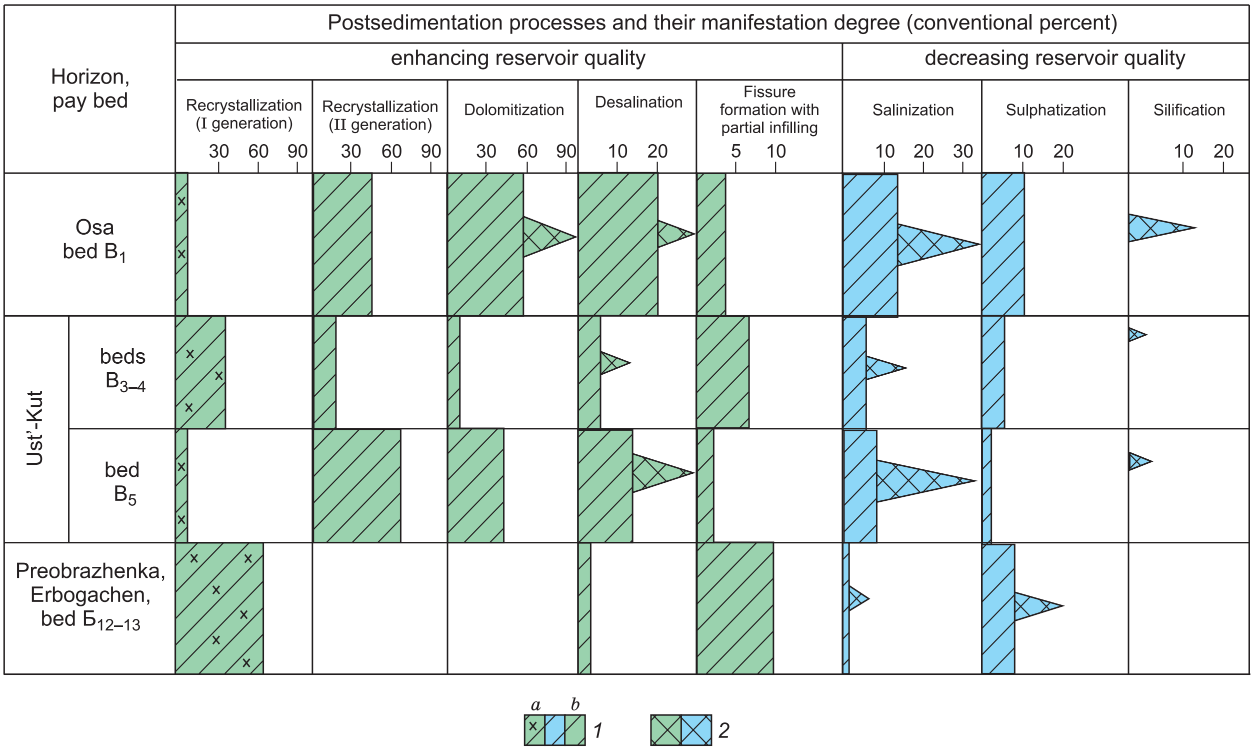

Fig. 4. Principle diagram of the formation of reservoirs of carbonate pay beds of the Erema–Chona petroleum accumulation. *1,* baseline values for processes of: *a*, early diagenesis, *b*, diacatagenesis; *2*, local manifestation as interbeds.

The organogenic composition of rocks from beds $B_{12,13}$ within the ECA and the high level of alteration by postsedimentation processes caused reservoirs to occur nearly everywhere on its territory. Their thickness varies from several to 25 m, but on most of the territory from 10 to 20 m (Table 1).

The PPP of the play reservoirs are characterized by the following indicators. Their effective porosity varies from 7 to 20%, the intergranular permeability is $(0.25–300) \times 10^{-3}$ μm^2. At the same time, the highest values have been detected in the first type of formation section composed of organogenic and organogenic-detrital dolomites containing a small admixture of silty and sulfate material. The distribution of effective porosity and permeability on the area of the ECA is in general similar to that of the reservoir thicknesses. A typical feature of the structure of the pay beds is the regional consistency of their thickness and their PPP on the ECA's area. In general, we judge the quality of the reservoirs of these pay beds as decreased.

The Tira seal embedded stratigraphically below these beds is only partially developed in the ECA. It occurs only in its northeastern part where its sealing properties are low (Shemin, 2007)

The Katanga seal overlapping the beds is widespread everywhere within the accumulation. Its thickness varies between 60 and 75 m. The composition of the seal is clayey-sulfate-carbonate and its quality is usually average.

Pay bed B_5 includes the lower part of the Tetere Formation and is widespread on the ECA's territory. Its thickness varies from 18 to 25 m. The bed is overlain by argillaceous-sulfate-carbonate rocks 5–15 m thick, which separate it from beds $B_{3–4}$ occurring upsection. Pay bed B_5 is mostly represented by dolomites (for 80–90% of its thickness). They are dominated by organogenic variations, with less granular and sporadically-clastic ones.

From a genetic and structural features viewpoint, the sections of the bed are dominated by algae dolomites and have interbeds of microphytolite dolomites. Organogenic rocks occupy 40–50% of the bed's thickness. Granular dolomites are present as interbeds.

In the early Tetere time when the bed B_5 deposits were being formed, sedimentation on the ECA's territory took place in marine environments, in settings of intrashelf shoal and shallow shelf (Shemin, 2007, 2011). In conditions of intrashelf shoal, sediments were deposited in its southwestern and central part with widespread settlement of cyanobacteria. Their habitats were territories of organogenic carbonate rocks formation. In the shallow water shelf settings, sedimentation took place in the northern and northeastern marginal areas of the petroleum accumulation. These were sites of formation of chemogenic, organogenic and organogenic-clastic sediments.

Rocks of pay bed B_5 were affected by postsedimentation processes: recrystallization, dolomitization, desalination and halitization (Gushina et al., 1991; Shemin, 2007) (Fig. 4). Recrystallization manifested quite clearly on the entire territory of the accumulation and dolomitization of the rocks

Table 1. Characteristics of reservoirs and test results of the Osa (bed B_1), Ust'-Kut (beds $B_{3–4}$, B_5), Preobrazhenka, Erbogachen (beds $B_{12,13}$) and Upper Chona (beds B_{10}, B_{13}) of the horizons of the Erema–Chona oil and gas accumulation

Bed	Depth, m	Reservoir thickness, m	Reservoir porosity, %	Reservoir permeability, 10^{-3} μm^2	Reservoir types	Test results: oil, condensate (m^3/day), gas (thous. m^3/day)
B_1	1300–1850, mean 1550	1–2 to 35, mainly 3–5 to 15	7–25, mainly 8–13	0.5–160, mainly 3–20	Vuggy-porous, porous, fissured-vuggy-porous	Oil 0.4–565, mainly 2–10; Gas 1–119, mainly 10–50; Condensate 2–5
$B_{3\text{-}4}$	1350–1900, mean 1600	1–2 to 20, mainly 2–3 to 10	7–20, mainly 8–14	0.5–50, mainly 0.5–10	Porous, vuggy-porous and fissured-vuggy-porous	Oil 0.3–32.7, mainly 2–15; Gas 1–68.2, mainly 3–30; Condensate 0.2–4.7
B_5	1400–1950, mean 1650	1–2 to 15, mainly 2–3 to 7	7–20, mainly 7–14	0.5–30, mainly 0.5–5	Vuggy-porous, porous-fissured-vuggy	Oil 0.8–165, mainly 2–5; Gas 3–173, mainly 5–20; Condensate 0.5–2.1
$B_{12,\ 13}$	1550–2100, mean 1850	2–25, mainly 10–20	7–20, mainly 8–12	0.25–300, mainly 0.25–5	Porous, porous-fissured	Oil 0.2–29.8, mainly 1–10; Gas 1–150, mainly 2–30.4; Condensate 0.2–46.5
B_{10}	1570–1750, mean 1650	2–20, mainly 2–6	8–25, mainly 10–18	5–200, mainly 10–100	Granular	Oil 1.3–200, mainly 5–40; Gas 1.5–450, mainly 20–100; Condensate 1.8–9.2
B_{13}	1570–1770, mean 1670	2–20, mainly 3–10	8–20, mainly 8–15	5–400, mainly 5–50	Granular	Oil 0.2–150, mainly 10–60; Gas 1–150, mainly 2–30; Condensate 2–7.3

Note. Beds were tested without horizontal wellbores and hydraulic fracturing. Note that on the basement uplifts the permeability and porosity parameters of the carbonate layers abruptly increase in quality. In these areas, oil flowrates increase up to several hundred m^3/day. A similar situation has been mapped on the Danilov basement uplift.

took place everywhere and intensely. This process led to the partial (in case of interbeds, complete) destruction of algae structures and to the formation of substitution dolomites. The rocks of the bed were strongly affected by desalination, which his more evenly manifested in algae variations.

Reservoirs of pay bed B_5 on the territory of the ECA occur sporadically. Their thickness varies from 1–2 to 15 m. The greatest thicknesses (7.5–15.0 m) are predicted in three areas of different size. The largest was mapped in the southern part of the accumulation. The average thickness indicators of the bed's reservoirs (5–7 m) are predicted in the central part of the accumulation, and the lowest (less than 5 m) on its borders. The effective porosity of the reservoirs varies from 7 to 20%, permeability (from 0.5 to 30) × 10^{-3} μm^2.

The seal consists of a 7–15 m thick carbonate-argillaceous-anhydrite break separating it from beds $B_{3–4}$ upsection. Its quality is estimated as average and below average.

Pay beds $B_{3–4}$ comprise the upper half of the Tetere Formation, their thickness varying from 20 to 25 m. They are represented by microphytolites, organogenic-oolitic and chemogenic dolomites with thin interlayers of oncolytic-oolitic and algae rocks. The dolomites content in the rocks is 70–95%.

In the late Tetere time, during the formation of pay beds $B_{3–4}$ rocks, sedimentation on the studied territory took place in marine conditions, in an intrashelf shoal. Due to periodic variations of sea level, chemogenic dolomite silt accumulated along with organogenic and organogenic-clastic deposits.

The rocks of beds $B_{3–4}$ underwent recrystallization, desalination, halitization and anhydritization processes. Recrystallization manifested sporadically in the form of spot-like clusters of dolomite grains. Desalination manifested quite unevenly and, in general, insignificantly. In chemogenic dolomites, this process developed mainly in pores and fractures, and in algae and oolitic-oncolytic interlayers—along the entire primary pore space. The halitization process in the pay bed's rocks generally manifested insignificantly and usually evenly in the section. In general, in the rocks of beds $B_{3–4}$, the most significant impact on the formation of reservoir beds was due to recrystallization and desalination processes. The decrease in quality of reservoirs was due both to salinization and sulphatisation.

Pay bed reservoirs of occur sporadically on the ECA and are from 1–2 to 20 m in thickness, but mostly from 2–3 to 10 m. Their highest thicknesses (7.5–20.0 m) are predicted in three areas that coincide in space with the increased reservoir thicknesses of pay bed B_5 described above. The largest is located in the southern part of the accumulation. The other two areas are located in the Mogda and Vakunaika areas. The lowest reservoir thicknesses (less than 2.5 m) are predicted mainly in the marginal areas of the accumulation, and the average ones (5.0–7.5 m) on the remaining, largest part of its territory. The effective porosity of the reservoirs varies from 7 to 20%, permeability (0.5–50) × 10^{-3} μm^2. The highest values are in the microphytolite dolomites.

Pay bed B_1 is defined in the carbonate section of the Middle Usol' Subformation and is widespread on the entire

ECA. Its thickness varies between 40 and 70 m. This bed is overlain by carbonate-halogenic rocks of the Upper Usol'e Subformation, which is a high-quality seal.

The lithological composition and structure of pay bed B_1 are quite diverse. In most well sections its composition is significantly dominated by algae limestones with interlayers of organogenic-clastic, oolitic-oncolytic and chemogenic variations.

The pay bed is uneven in terms of structural features and composition and is usually represented by a one- or two-section structure. In the case of one section it is composed in some cases mainly by limestones (Sanarskaya area), and in others by dolomites (Preobrazhenka and Mogda areas). In the case of a two-section structure, the bed is divided into two layers. In some sections the lower layer is represented by algae limestones with dolomite interlayers and the upper layer—by dolomites often combined with argillaceous limestones. In other sections it is the opposite—the lowers layer is dolomitic and the upper one—limestones.

In the middle Usol'e time, sedimentation on the ECA took place in marine conditions in an intrashelf shoal environment (Shemin et al., 2017) with accumulation of organogenic and organogenic-clastic sediments as well as chemogenic silts.

Rocks of pay bed B_1 underwent intense recrystallization, uneven dolomitization, desalination, salination, local sulphatisation and silicification (Gushina et al., 1991; Shemin, 2007). The most significant positive impact on the formation of the bed was due to desalination, dolomitization and recrystallization processes. The reservoir quality was deceased mainly due to salination, and to a lesser extent—sulphatisation.

The reservoirs of the bed occur locally; their thickness varies from several to 35 m. On most of the area of the accumulation, it is 10–15 m. The PPP of the reservoirs variy in a wide range. Effective porosity varies from 7 to 25%, permeability $(0.5–160) \times 10^{-3}$ μm^2, with the highest values being typical for algae limestones.

The seal for pay bed B_1 is the Upper Usol'e Subformation, composed of halogenic-carbonate rocks 300–600 m thick. The seal is of very high quality.

Pay bed C_{13} includes the lower, mainly sandy part of the Lower Nepa Subformation occurring in the base of the sedimentary cover on the basement rocks. It has a very limited distribution in the ECA, occupying only its southeastern part. The thickness of the bed varies from several to 25 m. The highest thicknesses are in the marginal southeast of the accumulation. In the northwestern direction, they decrease relatively gradually ending with a complete thinning out of the bed.

The bed deposits formed in the early Vendian stage of formation of the Siberian Platform's sedimentary cover. They formed in conditions of coastal plain that was periodically occupied by the sea (Shemin, 2007).

The reservoirs of pay bed B_{13} are developed only in the southeastern part of the accumulation. Their thickness varies from 2 to 20 m, porosity from 8 to 20%, intergranular permeability $(5–400) \times 10^{-3}$ μm^2.

The seal for bed B_{13} consists of argillaceous rocks of the middle and upper part of the Lower Nepa Subformation, which is 5–15 m thick. Its quality is below average and low.

Pay bed C_{10} corresponds to the lower, mainly sandy part of the Upper Nepa Subformation that is widespread everywhere on the ECA. It is composed mainly of sandy deposits. Its thickness in the southeastern part of the accumulation usually varies from 10 to 25 m. On the remaining larger part of the territory, it usually does not exceed 1–3 m. The deposits of pay bed C_{10} formed in conditions of coastal plain that was temporarily occupied by the sea (Shemin, 2007).

Reservoirs of bed C_{10} are widespread only in the southeastern part of the ECA. On this territory, their thickness varies from 2 to 20 m. On the remaining territory, which is significantly larger, the reservoirs occur only locally and their thickness, apparently, does not exceed 1 m. Their porosity varies from 8 to 25%, and permeability $(5–200) \times 10^{-3}$ μm^2.

The seal for pay bed C_{10} is composed of mainly argillaceous deposits of the Upper Nepa Subformation, which occur on the entire territory of the ECA. Its thickness varies from 10 to 30 m. The seal's quality is high and average; in the northwestern marginal part of the accumulation, it is of decreased quality.

Consequently, the lithological-facial formation condition for the Erema–Chona petroleum accumulation were rather favorable, like the tectonic conditions. Firstly, the carbonate pay beds, which contain the main petroleum reservoirs, were formed in similar facial conditions—shallow shelf, intrashelf shoal, organogenic banks—and are mainly represented by organogenic variations. They were altered mainly by processes of recrystallization, dolomitization and desalination, which caused secondary reservoirs to form. Secondly, the lack of the Tira seal overlying the terrigenous pay beds enabled the flow of hydrocarbons from them into the upper carbonate reservoirs, while the mainly lower quality of the seals between these beds caused the migration of HC within the subsalt carbonate complex. Thirdly, the preservation state of hydrocarbon plays in the entire Vendian–lower Cambrian petroleum complex of the ECA was due to the overlying Upper Usol'e high-quality seal.

GEOCHEMICAL FORMATION CONDITIONS OF THE EREMA–CHONA OIL AND GAS ACCUMULATION

Within the Nepa–Botuobiya anteclise, on which the ECA is located, and the adjacent territory of the Fore-Patom regional basin, which is a large zone of oil and gas formation, significant volumes of geochemical research were done on Riphean, Vendian terrigenous and upper Vendian–lower Cambrian carbonate deposits. The research results have been presented in many publications (Bazhenova et al., 1982; Larichev and Chekanov, 1987; Sokolov et al., 1989;

Kontorovich, 2004; etc.) and describe the patterns of organic matter distribution, its catagenic alterations and petroleum generation potential. The authors conclude that the highest petroleum generation potential is typical for Riphean deposits, while the potential of terrigenous Vendian rocks and the subsalt carbonate complex is significantly lower. At the same time, the intensity of migration of fluid bitumoids and of gaseous OM generation manifested rather evenly on the whole area of the region. Their highest indicators were noted in the Fore-Patom regional basin. Notably lower values were in the southeastern slope of the Nepa–Botuobiya anteclise and the lowest—in its central, most uplifted part.

As noted above, the migration of hydrocarbons from these zones to the central, most uplifted part of the anteclise, where the ECA is located, was mainly controlled by the paleostructural framework and the quality of the seals. Three main hydrocarbon migration stages were determined: Vendian–early Paleozoic, middle Paleozoic, and late Paleozoic–Mesozoic (Kontorovich et al., 1981).

During the Vendian–early Paleozoic stage, the period of the most intense hydrocarbons migration from the petroleum-formation zones into zones of oil and gas accumulation, the structural patterns differed from the current ones. The central zone, where the ECA is located, was then a large petroleum accumulation zone, as well as the northwestern part of the Nepa–Botuobiya anteclise. These territories accumulated hydrocarbons that were migrating both from local sources and ones located in the Fore-Patom regional basin. The formation of hydrocarbons plays mainly took place in lithological traps, since the anticlinal uplifts appeared later, and on a limited territory. At the same time, the lithological traps had a different spatial position than their current one (Shemin, 2007).

In addition to this lateral HC migration in the Vendian and early Paleozoic, as well as during subsequent periods, there was a large-scale vertical flow from the Riphean deposits to the Vendian terrigenous collectors, and from these to the overlying subsalt carbonate collectors, since the seals between these formation were either lacking or of low quality.

The flow of hydrocarbons from terrigenous deposits to carbonate ones in large volumes is predicted only in the central and northwestern parts of the Nepa–Botuobiya anteclise. In these parts of the structure, there supposedly was an active hydrocarbon migration limited to oil (Fig. 5).

The structural pattern of the studied territory in the middle Paleozoic stage of hydrocarbon migration generally kept its inherited development. Migration of HC continued from petroleum formation zones—the Fore-Patom regional basin and the adjacent part of the Nepa–Botuobiya anteclise—into zones of petroleum accumulation located in the central and northwestern parts of the latter.

The final late Paleozoic–Mesozoic stage of petroleum formation in the ECA was related to the formation of the Tunguska syneclise. The southern part of this structure overlapped the Katanga paleosyneclise. This resulted in active formation of the northwestern slope of the Nepa–Botuobiya anteclise.

In accordance with the aforementioned tectonic changes, there was an additional HC migration from the southern slope of the Tunguska syneclise into the central, most uplifted part of the Nepa–Botuobiya anteclise, where the ECA was located.

Consequently, during the entire Phanerozoic, there was a lateral and vertical migration of HC from the Fore-Patom regional basin and the adjacent territory of the Nepa–Botuobiya anteclise into the ECA. From the late Paleozoic–Mesozoic the migration originated in the southern part of the Tunguska syneclise. Considering the seals between the pay beds were of low quality, favorable conditions had formed for the generation of HC deposits in them. Their preservation was enabled by the Upper Usol'e high-quality seal that overlies the entire Vendian–lower Cambrian subsalt complex on the entire area.

Thus, during the entire Phanerozoic, the tectonic, lithological-facial and geochemical conditions were favorable for the formation and preservation of hydrocarbon deposits in the Erema–Chona petroleum accumulation. Only within this region of the southern half of the Siberian platform, they provided commercial petroleum potential of all pay beds of the Vendian–lower Cambrian subsalt petroleum complex.

TECHNIQUE AND QUANTITATIVE ESTIMATION RESULTS FOR THE PETROLEUM POTENTIAL OF PAY BEDS OF THE EREMA–CHONA OIL AND GAS ACCUMULATION

Technique of quantitative estimation. When performing a quantitative estimation of petroleum potential of the pay beds of the ECA taking into account the different degree of identified petroleum potential, two methods were used: the volumetric and the geological methods by effective reserves densities for an area unit. Since within the boundaries of the studied petroleum accumulation, beds $B_{12–13}$ are characterized by a nearly ubiquitous development of oil-bearing reservoirs, their petroleum resources potential estimation was determined using the first method. The other pay beds are characterized by sporadic occurrence of petroleum reservoirs. Their traps are predicted as limited in area and their pay bed resources were estimated using the second method.

The volume method is usually used to evaluate oil and gas reserves of identified hydrocarbon plays. When applied to estimations of hydrocarbon resources of pay beds $B_{12,13}$ of the Erema–Chona accumulation, it is used relatively conditionally, because the accumulation includes several not yet delineated hydrocarbons plays, and its area is 26.5 thous. km^2. Nonetheless, we estimated the hydrocarbon resources of these plays using this method because there are no other methods for estimation of hydrocarbon resources of such large objects.

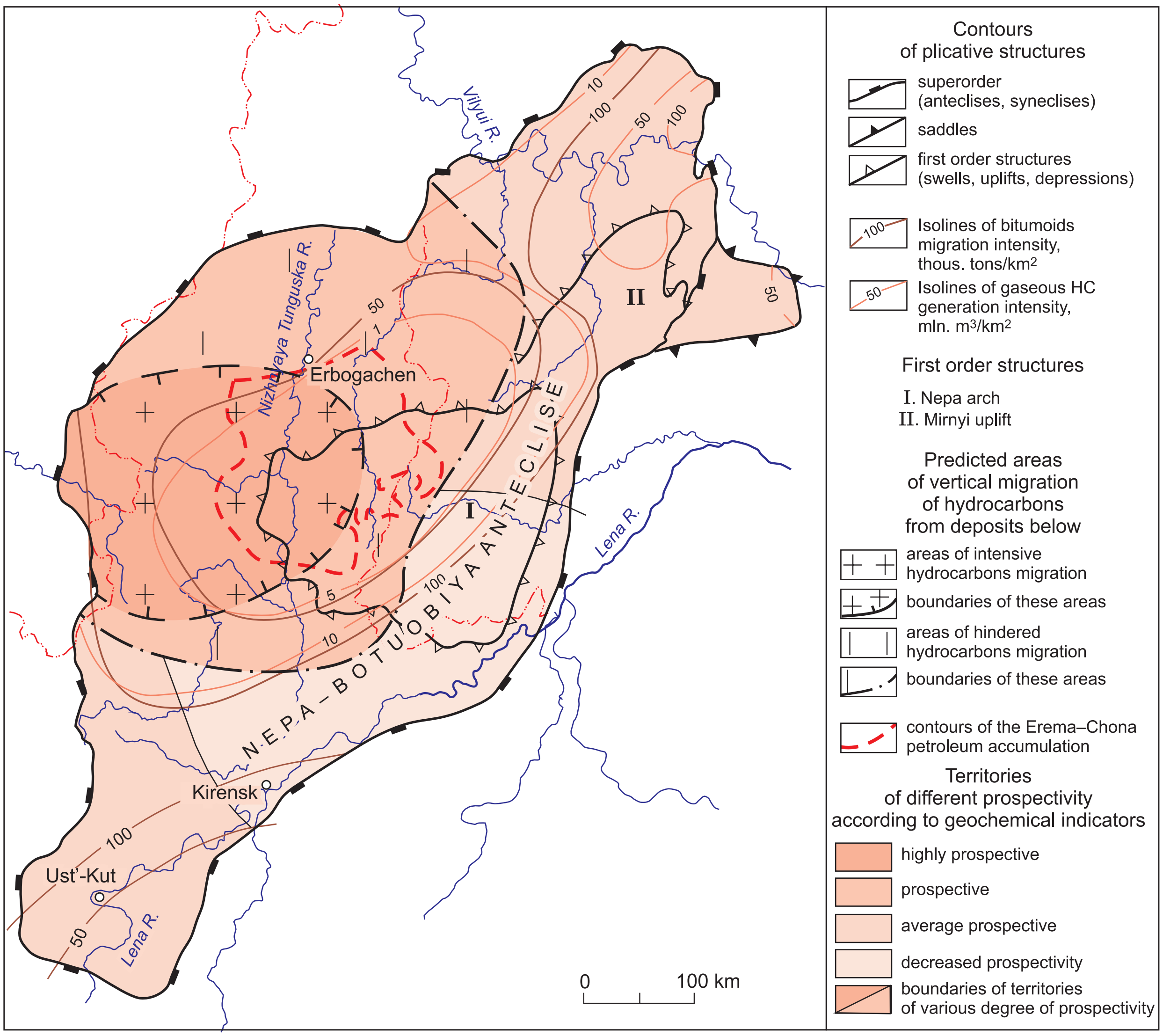

Fig. 5. Estimation of geochemical indicators for petroleum potential of the subsalt Vendian–lower Cambrian carbonate complex of the Nepa–Botuobiya anteclise.

To realize this method the entire territory of the accumulation under study except the areas of identified hydrocarbon plays was divided into 10 calculation regions (conditional plays) based on distributions of oil-saturated reservoir thicknesses and spatial position of regional faults (Fig. 6). The calculation parameters of these "plays" and results of estimation of their oil reserves are given in Table 2.

The geological method by effective densities of hydrocarbon reserves on a unit of area is described in (Methodological guidelines…, 2000). The gist of this procedure is the following. It is a selection of well-studied petroleum-bearing targets that are accepted as reference areas and a transfer of identified hydrocarbon resources densities onto the predicted (calculated) areas using geological parameters that control the petroleum potential.

For the quantitative estimation of petroleum potential of pay beds B_1, B_{3-4}, B_5, C_{10} and C_{13} we used six reference areas: Middle Botuobiya, Talakan (bed B_1), Danilovo (beds B_{3-4}, B_5) and Upper Chona (beds C_{10}, C_{13}). Their complete description is given in (Shemin et al., 2017).

The main geological parameters for translation of hydrocarbon resources densities from reference areas to the calculated areas we used are: hypsometry of the current structure, initial petroleum potential of oil source rocks, seal quality, and reservoir thickness.

Results of quantitative estimation. Total initial hydrocarbon resources (TIR) of the Vendian–lower Cambrian subsalt complex of the ECA are evaluated as 12,890.1 mln tons of conditional hydrocarbon (estimated hydrocarbons, EHC), which corresponds to 49.5% of the last (in 2009) official estimation of EHC resources of the entire territory of the Nepa–Botuobiya petroleum area. These include oil reserves—11,406.0 mln tons (88.5%), gas—1462.9 bln m^3 (11.3%) and condensate—20.7 mln tons (0.2%). Recover-

Table 2. Results of evaluation* of oil reserves by C_2^1 categories of the Erema–Chona oil and gas accumulation in beds $B_{12–13}$

Number of calculation site	Values of calculated parameters									Oil reserves, mln tons	
	F, oil bearing area, thous. m^2	*h*, thickness of effective oil-bearing horizon, m	m_0, porosity coefficient, m^3	$\rho_н$, oil density t/m^3	Θ, formation volume factor	B_s, oil-saturation factor, %	Decreasing coefficient due to possible wedging out of reservoir	η, oil extraction coefficient, %	Oil content on calculation sites, %	Geologic	Recovered
1	1364×10^3	7.0	0.07	0.86	0.85	0.86	0.7	0.11	100	294	32
2	1729×10^3	9.0	0.09	0.86	0.85	0.86	0.8	0.11	100	704	77
3	1004×10^3	6.0	0.07	0.86	0.85	0.86	0.6	0.11	100	159	17
4	6851×10^3	9.0	0.09	0.86	0.85	0.86	0.8	0.11	100	2790	307
5	3092×10^3	7.0	0.07	0.86	0.85	0.86	0.6	0.11	100	571	62
6	1576×10^3	5.0	0.06	0.86	0.85	0.86	0.3	0.11	100	89	9
7	1381×10^3	7.0	0.07	0.86	0.85	0.86	0.6	0.11	80	204	22
8	2501×10^3	9.0	0.09	0.86	0.85	0.86	0.7	0.11	80	713	78
9	520×10^3	8.0	0.08	0.86	0.85	0.86	0.6	0.11	25	31	4
10	2405×10^3	8.0	0.08	0.86	0.85	0.86	0.7	0.11	60	406	44
Σ	–	–	–	–	–	–	–	–	–	5961	662

Note. Locations of calculation sites are given on Fig. 5.
* Our estimate.

able resources of oil, gas and condensate are correspondingly: 1806.5 mln (55.0%); 1462.9 bln m^3 (44.5%) and 15.7 mln tons (0.5%) (Table 3).

Among pay beds the highest HC TIR are in beds $B_{12–13}$—8023.8 mln tons (62.3%), significantly lower are in beds $B_{3–4}$, B_5 and B_1 correspondingly—1615.5; 1094.1 and 996.5 mln tons (12.6, 8.5, 7.7%) and the lowest HC resources are predicted in beds C_{13} and C_{10} correspondingly 677.1 and 482.6 mln tons (5.2, 3.7%).

The accumulated extraction and HC resources of categories A + B + C_1, C_2, C_2' [1] and D_1 of the accumulation are correspondingly equal: 45.8 (0.1%), 798.3 (6.3%), 3632.7 (28.3%), 5961.0 (46.3%) and 2452.3 (19.0%) mln tons of EHC. That is to say, the degree of exploration of its HC resources is 34.7%.

Pay beds $B_{12,13}$ have the highest petroleum potential within the ECA. The HC TIR of these beds are 8023.8 mln tons of EHC, including 7412.1 mln tons of oil (92,4%), 609.3 bln m^3 of gas (7.6%) and 2.4 mln tons of condensate (0.1%). Recoverable oil, gas and condensate resources correspondingly are equal to: 888.3 mln tons (59.3%), 609.3 bln m^3 (40.6%) and 1.8 mln tons (0.1%).

HC reserves and resources of beds $B_{12–13}$ of categories A + B + C_1, C_2 and C_2' are equal to 183.1 (2.3%), 1286.2 (16.0%) and 6554.4 (81.7%) mln tons of EHC, respectively.

The distribution of total initial recoverable[2] HC resources of the beds under consideration on the area of the petroleum accumulation is the following (Fig. 6). Four categories of areas are determined with densities of recoverable hydrocarbon resources respectively: 30–50, 20–30, 10–20 and 5–10 thous. tons of EHC/km^2.

The highest HC TIR densities in the beds are predicted in the central and northeastern parts of the accumulation. On a significantly smaller territory, the petroleum potential of these beds is somewhat lower, in the form of a band encompassing more perspective territories from the northwest and the west.

Even less perspective territories are located in the extreme west and southeast of the accumulation, as well as on the limited area located to the north of the Tympuchikanskoe field. Minimal densities of total initial recoverable HC resources of these beds are predicted on four sites of various sizes (Fig. 6).

Pay bed B_5 has significantly less petroleum potential than those described above. Its TIR of hydrocarbons are estimated as 1094.1 mln tons of EHC, including 1042.2 mln tons of oil (95.2%), 51.4 bln m^3 of gas (4.7%) and 0.4 mln tons of condensate (0.1%). Recoverable oil, gas and condensate resources are correspondingly: 216.2 mln tons (80.7%); 51.4 bln m^3 (19.2%) and 0.4 mln tons (0.1%). HC reserves and resources of the bed of categories A + B + C_1, C_2 and D_1 are: 80.1 (7.3%), 525.7 (48.0%) and 488.2 (44.7%) mln tons of EHC.

The distribution of total initial HC resources of bed B_5 on the area of the ECA is given on Fig. 7. Four categories of territories are determined according to their potential degree with HC TIR densities: 30–50, 20–30, 10–20 and 5–10 thous. tons EHC/km^2, respectively.

The most promising territories are predicted on three areas of several sizes. The largest is located in the southern

[1] Estimation of oil, gas and condensate resources of pay beds $B_{12,13}$ was done by us for category C_2', since these beds have been shown by drilling mapping to be hydrocarbons saturated everywhere on the area.

[2] Because HC resources densities of pay beds $B_{12,13}$ are higher than in the other beds of the accumulation by nearly an order of magnitude, their density values are given as recoverable, and those of other beds as geological.

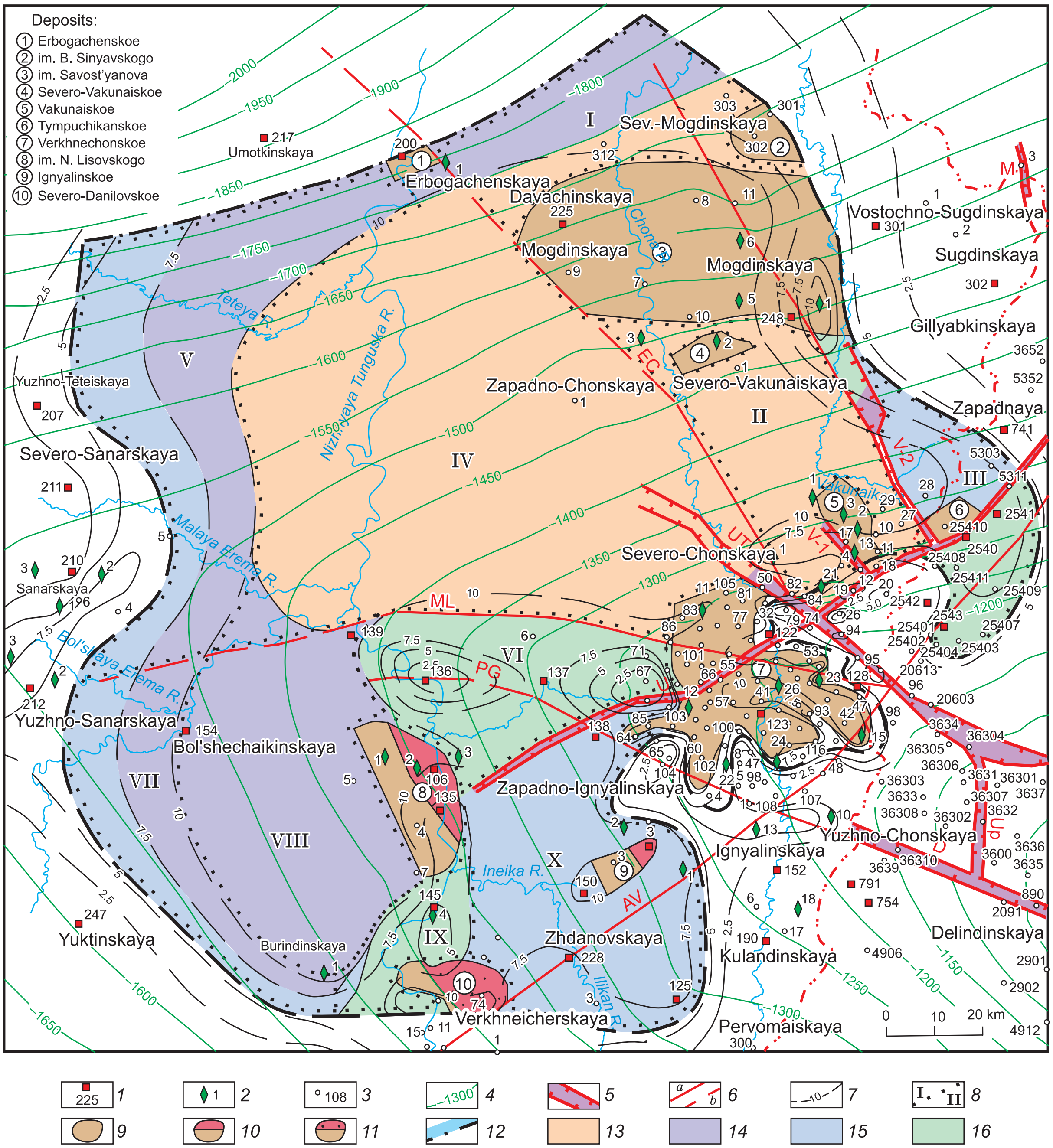

Fig. 6. Evaluation map of densities of recoverable hydrocarbon resources of the Preobrazhenka collector (beds $B_{12,13}$) of the Erema–Chona petroleum accumulation. *1–3*, wells: *1*, stratigraphic, *2*, exploration, *3*, appraisal; *4*, isohypses of the top of the Preobrazhenka pay bed (B_{12}); *5*, micrograbens: V-1, Vakunaika-1; V-2, Vakunaika-2; Up, Upper Peledui; UT, Upper Chona–Talakan; D, Delinda; M, Mukoka; U, Usol'e; *6*, main faults (*a*, known, b, inferred): EC, Erbogachen–Chuya; ML, Moga–Lena; PG, Preobrazhenka-Gadalin; AV, Angara–Vilyui; *7*, reservoir isopachs; *8*, contours of calculation areas; *9–11*, hydrocarbon fields: *9*, oil, *10*, gas-oil, *11*, oil-gas-condensate; *12*, conventional OWC; *13–16*, densities of recoverable hydrocarbon resources (thous. tons/km^2): *13*, 30–50, *14*, 20–30, *15*, 10–20, *16*, 5–10.

part of the accumulation (Fig. 7). The second one, smaller in size, is in the northeastern part and the smallest area includes the Vakunaiskoe deposit. Several less promising areas of this bed are more widespread. They mostly comprise the central part of the accumulation. Even less perspective territories are limited to bands 5–15 km thick around the more promising areas.

Pay beds $B_{3–4}$ is characterized by a somewhat higher petroleum potential than the aforementioned beds. Their HC TIR are estimated as 1615.5 mln tons of EHC, including 1544.0 mln tons of oil (95.6%), 70.1 bln m^3 of gas (4.3%) and 1.4 mln tons of condensate (0.1%). Recoverable oil, gas and condensate resources are respectively equal to: 297.6 mln tons (80.7%), 70.1 bln m^3 (19.0%) and 1.1 mln

Table 3. Oil, gas and condensate resources of the Erema–Chona petroleum accumulation

Pay beds	Oil resources, mln. tons					Gas resources, bln. m^3					Condensate resources, mln. tons					Total mln. tons of EHC				
	Cumulative production	A + B + C_1	C_2	C'_2 (D_1)	Total	Cumulative production	A + B + C_1	C_2	C'_2(D_1)	Total	Cumulative production	A + B + C_1	C_2	C'_2(D_1)	Total	Cumulative production	A + B + C_1	C_2	C'_2 (D_1)	Total EHC
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
B_1	0	3.9	154.3	252.0	410.2	0.1	60.0	135.6	376.9	572.6	0	0.8	2.7	10.2	13.7	0.1	64.7	292.6	639.1	996.5
		0.6	30.6	50.4	81.6							0.6	1.9	7.5	10.0		61.2	168.1	434.8	664.2
$B_{3–4}$	0	21.5	902.0	620.5	1544.0	0	12.0	31.2	26.9	70.1	0	0.5	0.5	0.4	1.4	0	34.0	933.7	647.8	1615.5
		7.3	166.2	124.1	297.6							0.4	0.4	0.3	1.1		19.7	197.8	151.3	368.8
B_5	0.1	75.2	508.6	458.3	1042.2	0	4.8	16.9	29.7	51.4	0	0.1	0.2	0.2	0.5	0.1	80.1	525.7	488.2	1094.1
		25.1	99.4	91.6	216.2							0.1	0.2	0.1	0.4		30.0	116.5	121.4	268.0
$B_{12,13}$	0.1	176.1	1274.9	5961.0	7412.1	0	7.0	11.3	591.0	609.3	0	0	0	2.4	2.4	0.1	183.1	1286.2	6554.4	8023.8
		25.4	200.8	662.0	888.3									1.8	1.8		32.4	212.1	1254.8	1499.4
Σ $B_{1–13}$	0.2	276.7	2839.8	7291.8	10,408.5	0.1	83.8	195.0	1024.5	1303.4	0	1.4	3.4	13.2	18.0	0.3	361.9	3038.2	8329.5	11,729.9
		58.4	497.0	928.1	1483.7							1.1	2.5	9.7	13.3		143.3	694.5	1962.3	2800.4
C_{10}	20.0	260.9	104.2	47.8	432.9	2.5	22.0	18.9	5.4	48.8	0	0.5	0.3	0.1	0.9	22.5	283.4	123.4	53.3	482.6
		86.0	32.7	16.7	155.4							0.4	0.3	0.1	0.8		108.4	51.9	22.2	205.0
C_{13}	20.0	134.5	385.1	25.0	564.6	3.0	18.2	84.6	4.9	110.7	0	0.3	1.4	0.1	1.8	23.0	153.0	471.1	30.0	677.1
		50.5	86.9	10.0	167.4							0.2	1.3	0.1	1.6		68.9	172.8	15.0	279.7
Σ $C_{10}C_{13}$	40.0	395.4	489.3	72.8	997.5	5.5	40.2	103.5	10.3	159.5	0	0.8	1.7	0.2	2.7	45.5	436.4	594.5	83.8	1160.2
		136.5	119.6	26.7	322.8							0.6	1.6	0.2	2.4		177.3	224.7	37.2	484.7
Σ B + C	40.2	672.1	3329.1	7364.6	11,406.0	5.6	124.0	298.5	1034.8	1462.9	0	2.2	5.1	13.4	20.7	45.8	798.3	3632.7	8413.3	12,890.1
		194.9	616.6	954.8	1806.5							1.7	4.1	9.9	15.7		320.6	919.2	1999.5	3285.1

Note. The total estimation of oil, gas and condensate reserves for categories A + B + C_1 and C_2 are given for the following fields: im. B. Sinyavskogo, im. Savostyanova, im. V.B. Mazura, im. N. Lisovskogo, Verkhnechonskoe, Vakunaiskoe, Severovakunaiskoe, Tympuchikanskoe, Inglyanskoe, Severodanilovskoe, and Erbogachenskoe for the state on 01.01.2016. Our estimation of oil, gas and condensate resources for pay beds $B_{12,13}$ is given for the C'_2 category, and for all other pay beds for D_1. Numbers above the trait—oil and condensate resources; below the trait—recoverable hydrocarbon resources.

tons (0.3%). Reserves and resources of category A + B + C_1, C_2 and D_1 of the beds equal: 34.0 (2.1%), 933.7 (57.8%) and 647.8 (40.1%) mln tons of EHC.

The distribution of HC TIR of beds $B_{3–4}$ on the accumulation's territory are the following (Fig. 8). As in the case of the aforementioned beds, there are four categories of areas with the same total initial HC resources densities.

The most perspective areas are almost universally located in the western half of the petroleum accumulation and on the small area in its northeastern part. Less perspective areas are predicted in the northeastern part of the accumulation, where they spread along a northwest striking band from the Erbogachenskoe to the Vakunaiskoe fields. Even less perspective areas are inferred on five areas of various sizes (Fig. 8). Minimal densities of total initial HC resources of the beds are predicted in the southeastern and southwestern parts of the accumulation.

Pay bed B_1 is characterized by the lowest petroleum potential among the carbonate beds of the subsalt complex. Its HC TIR are 996.5 mln tons of EHC, including 410.2 mln tons of oil (41.2%), 572.6 bln m^3 of gas (57.4%) and 13.7 mln tons of condensate (1.4%). Recoverable oil, gas and condensate resources are respectively: 81.6 mln tons (12.3%), 572.6 bln m^3 (86.2%) and 10.0 mln tons (1.5%). HC reserves and resources of A + B + C_1, C_2 and D_1 categories of the bed amount to: 64.7 (5.5%), 292.6 (29.4%) and 639.1 (64.1%) mln tons of EHC.

The distribution of total initial HC resources of the bed on the territory of the ECA is the following (Fig. 9). Like in the case of the beds described above, four categories of areas are determined according to potential degree.

The areas of highest potential are widespread on most of the territory of the petroleum accumulation, comprising its entire central and northwestern parts. The remaining categories of areas are predicted in the northeastern, southeastern and southwestern part of the petroleum accumulation.

Pay bed C_{13} is developed only in the marginal southeastern part of the petroleum accumulation. Its HC TIR are 677.1 mln tons of EHC, including 564.6 mln tons of oil (83.5%), 110.7 bln m^3 of gas (16.4%) and 1.8 mln tons of

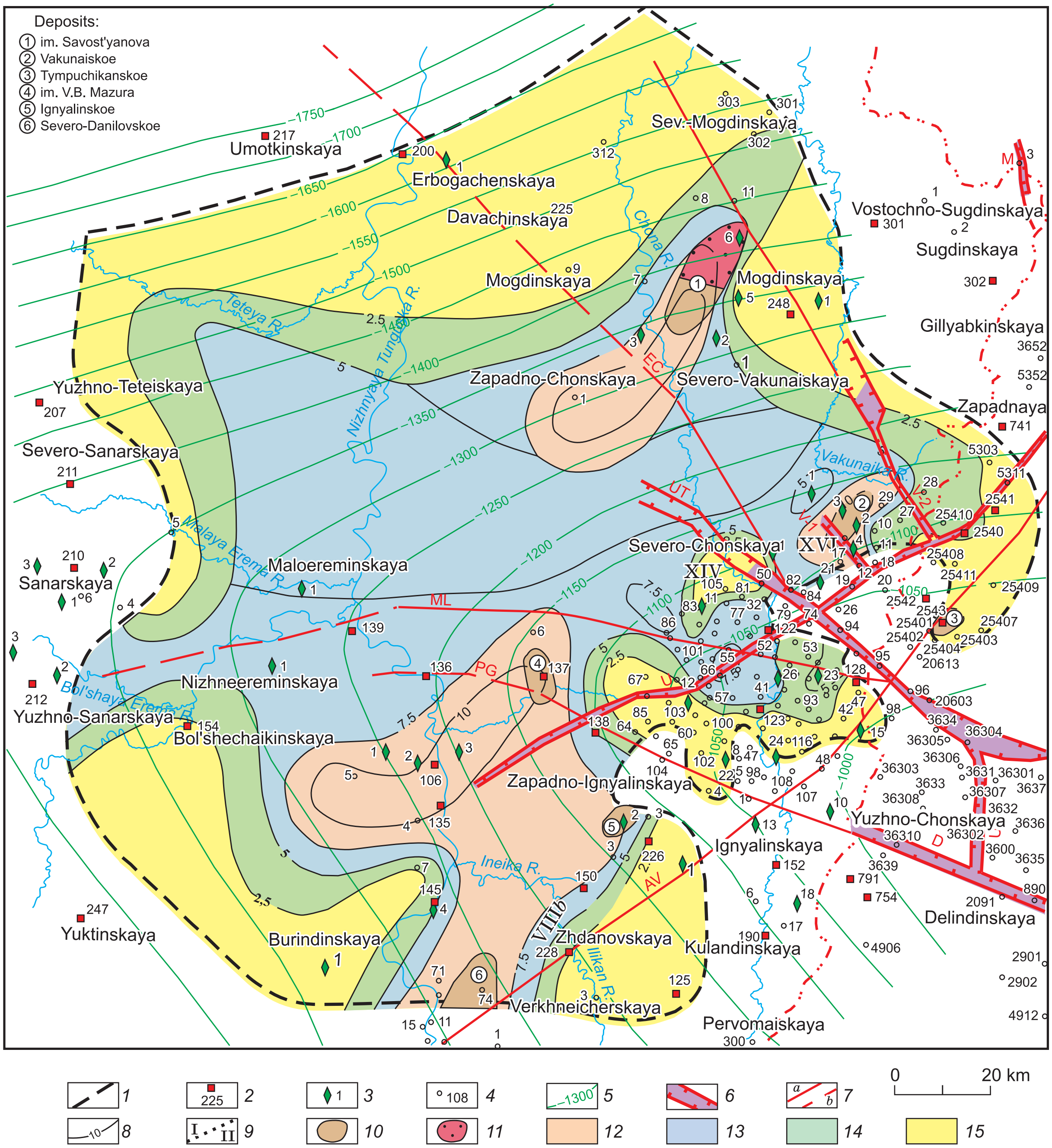

Fig. 7. Prognosis map of densities of total initial hydrocarbon resources of the B_5 pay bed from the Ust'-Kut Horizon in the Erema–Chona petroleum accumulation. *1,* boundary of the Erema–Chona petroleum accumulation; *2–4*, wells: *2*, stratigraphic, *3*, exploration, *4*, appraisal; *5*, isohypses of the top of pay bed B_5 of the Ust'-Kut Horizon; *6*, micrograbens: V-1, Vakunaika-1; V-2, Vakunaika-2; Up, Upper Peledui; UT, Upper Chona–Talakan; D, Delinda; M, Mukoka; U, Usol'e; *7*, main faults (*a*, known, b, inferred): EC, Erbogachen–Chuya; ML, Moga–Lena; PG, Preobrazhenka-Gadalin; AV, Angara–Vilyui; *8*, isopachs of local reservoirs distribution; *9*, contours of calculation areas used in quantitative estimation of petroleum potential of beds; *10–11*, hydrocarbon fields: *10*, oil, *11*, oil-gas-condensate; *12–15*, densities of total initial hydrocarbon resources (thous. tons/km^2): *12*, 30–50, *13*, 20–30, *14*, 10–20, *15*, 5–10.

condensate (0.1%). Recoverable oil, gas and condensate resources respectively equal: 167.4 mln tons (60.3%), 110.7 bln m^3 (39.6%) and 1.6 mln tons (0.1%).

Cumulative extraction, reserves and resources of HC of categories A + B + C_1, C_2 and D_1 of bed C_{13} equal, respectively: 23.0 (3.4%), 153.0 (22.6%), 471.1 (69.6%) and 30.0 (4.4%) mln tons of EHC.

The petroleum potential of the bed for exploration of new oil and gas plays is rather low (Fig. 10). Only in the southern parts of the territory, where the bed occurs and where small

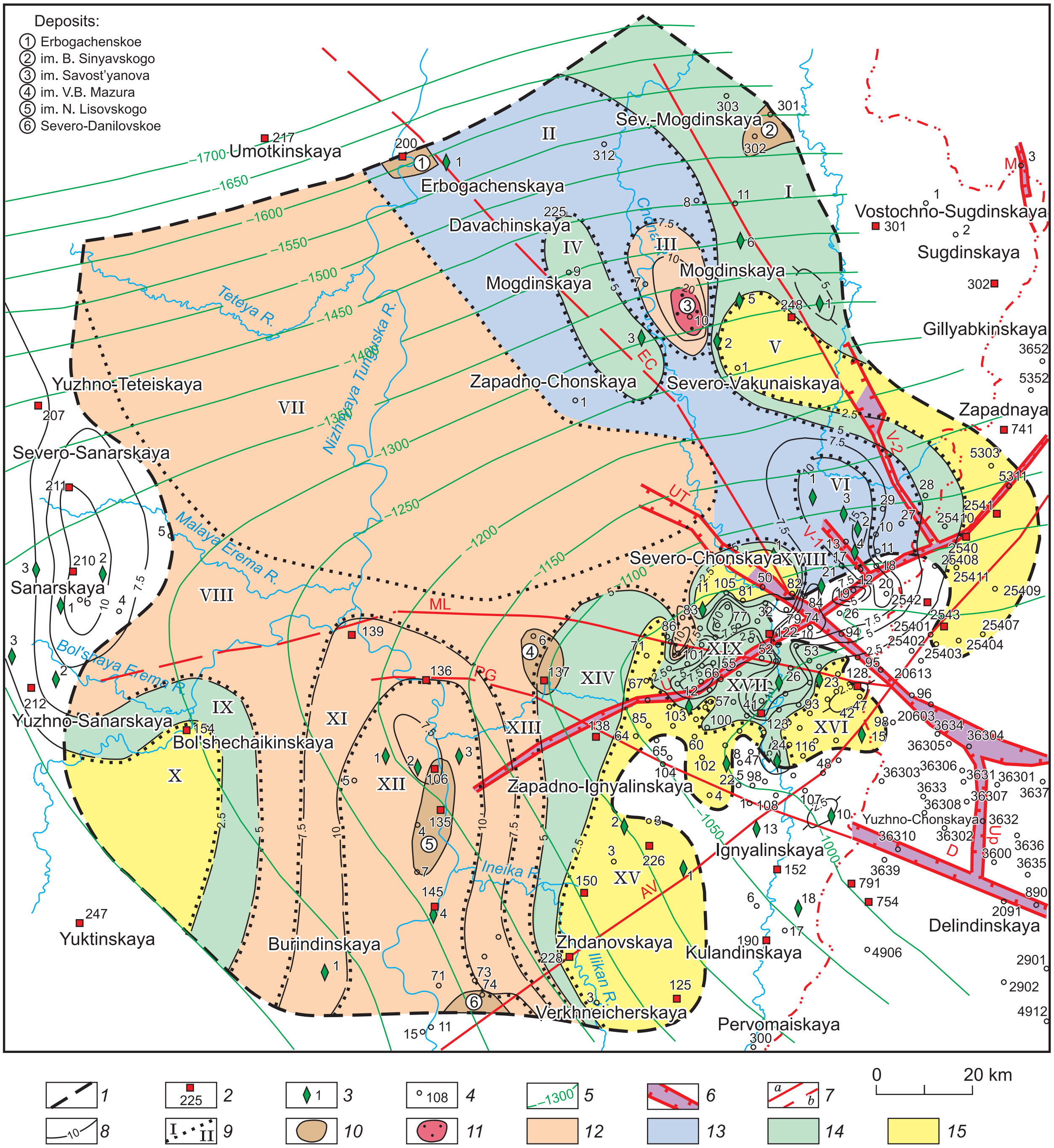

Fig. 8. Prognosis map of densities of total initial hydrocarbon resources of pay beds B_{3-4} from the Ust'-Kut horizon in the Erema–Chona petroleum accumulation. *1,* boundary of the Erema–Chona petroleum accumulation; *2–4*, wells: *2*, stratigraphic, *3*, exploration, *4*, appraisal; *5*, isohypses of the top of pay bed B_3 of the Ust'-Kut horizon; *6*, micrograbens: V-1, Vakunaika-1; V-2, Vakunaika-2; Up, Upper Peledui; UT, Upper Chona–Talakan; D, Delinda; M, Mukoka; U, Usol'e; *7*, main faults (*a*, known, *b*, inferred): EC, Erbogachen–Chuya; ML, Moga–Lena; PG, Preobrazhenka–Gadalin; AV, Angara–Vilyui; *8*, isopachs of local reservoirs distribution; *9*, contours of calculation areas used in quantitative estimation of petroleum potential of beds; *10–11*, hydrocarbon fields: *10*, oil, *11*, gas-condensate; *12–15*, densities of total initial hydrocarbon resources (thous. tons/km^2): *12*, 30–50, *13*, 20–30, *14*, 10–20, *15*, 5–10.

volumes of drilling have been performed, two categories of areas are identified for exploration of HC plays with densities of total initial hydrocarbon resources from 20 to 30 and from 10 to 20 thous. tons of EHC/km^2.

Pay bed C_{10} is characterized by ubiquitous development within the petroleum accumulation, but on most of the territory (except its southeastern part), it is less than 2 m thick. Its HC TIR are 482.6 mln tons of EHC, including 432.9 mln

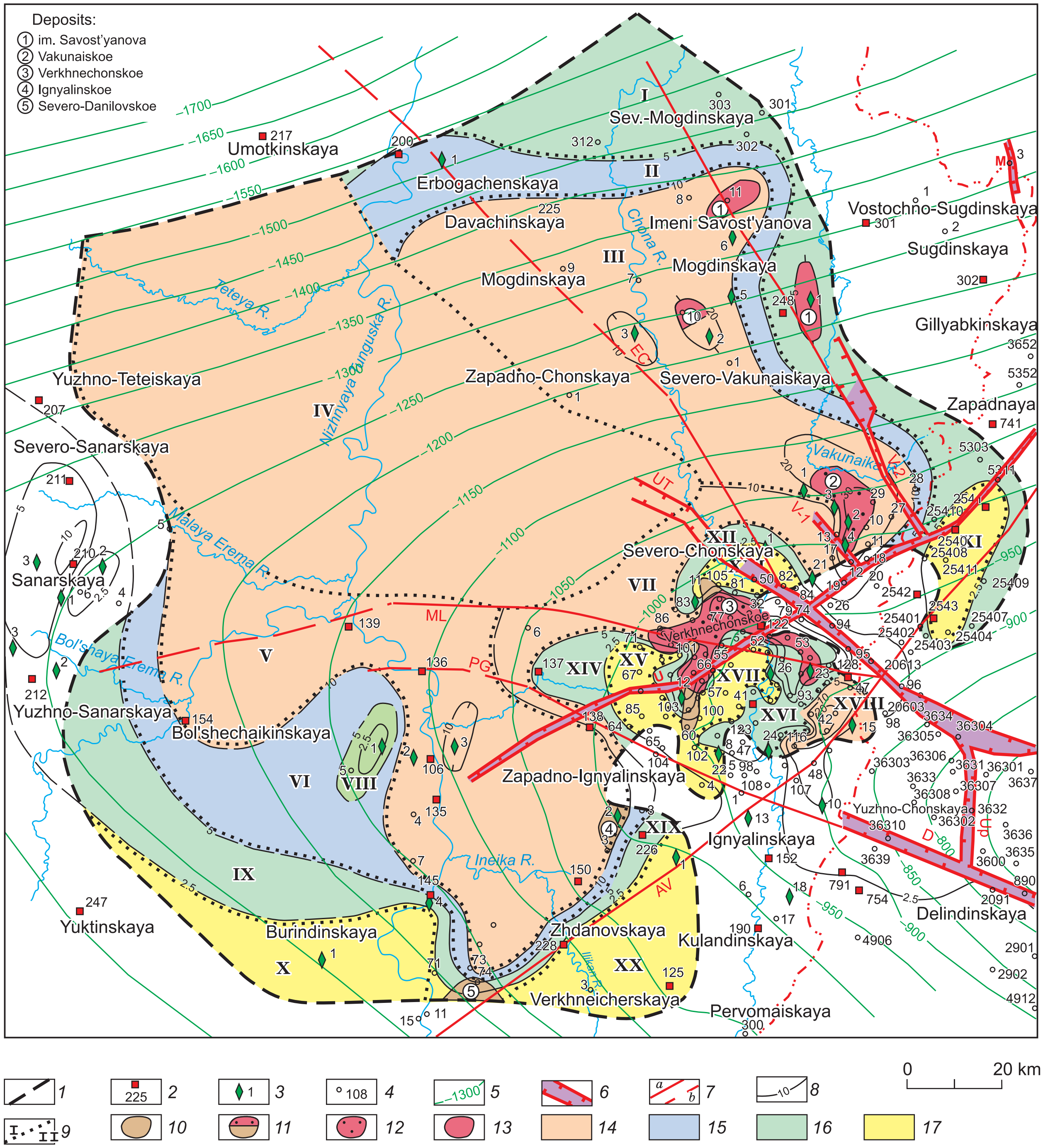

Fig. 9. Prognosis map of densities of total initial hydrocarbon resources of pay bed B_1 from the Osa Horizon in the Erema–Chona petroleum accumulation. *1,* boundary of the Erema–Chona petroleum accumulation; *2–4*, wells: *2*, stratigraphic, *3*, exploration, *4*, appraisal; *5*, isohypses of the top of the Osa pay bed (B_1); *6*, micrograbens: V-1, Vakunaika-1; V-2, Vakunaika-2; Up, Upper Peledui; UT, Upper Chona–Talakan; D, Delinda; M, Mukoka; U, Usol'e; *7*, main faults (*a*, known, b, inferred): EC, Erbogachen–Chuya; ML, Moga–Lena; PG, Preobrazhenka–Gadalin; AV, Angara–Vilyui; *8*, isopachs of local reservoirs distribution; *9*, contours of calculation areas used in quantitative estimation of petroleum potential of bed B_1; *10–13*, hydrocarbon fields: *10*, oil, *11*, oil-gas-condensate, *12*, gas condensate, *13*, gas; *14–17*, densities of total initial hydrocarbon resources (thous. tons/km^2): *14*, 30–50, *15*, 20–30, *16*, 10–20, *17*, 5–10.

tons of oil (89.8%), 48.8 bln m^3 of gas (10.1%) and 0.9 mln tons of condensate (0.1%). Recoverable oil, gas and condensate resources respectively are: 155.4 mln tons (75.8%), 48.8 bln m^3 (23.8%) and 0.8 mln tons (0.4%).

Cumulative HC extraction, reserves and resources of categories A + B + C_1, C_2 and D_1 of bed C_{10} are correspondingly: 22.5 (4.6%), 283.4 (58.7%), 123.4 (25.6%) and 53.3 (11.1%) mln tons of EHC.

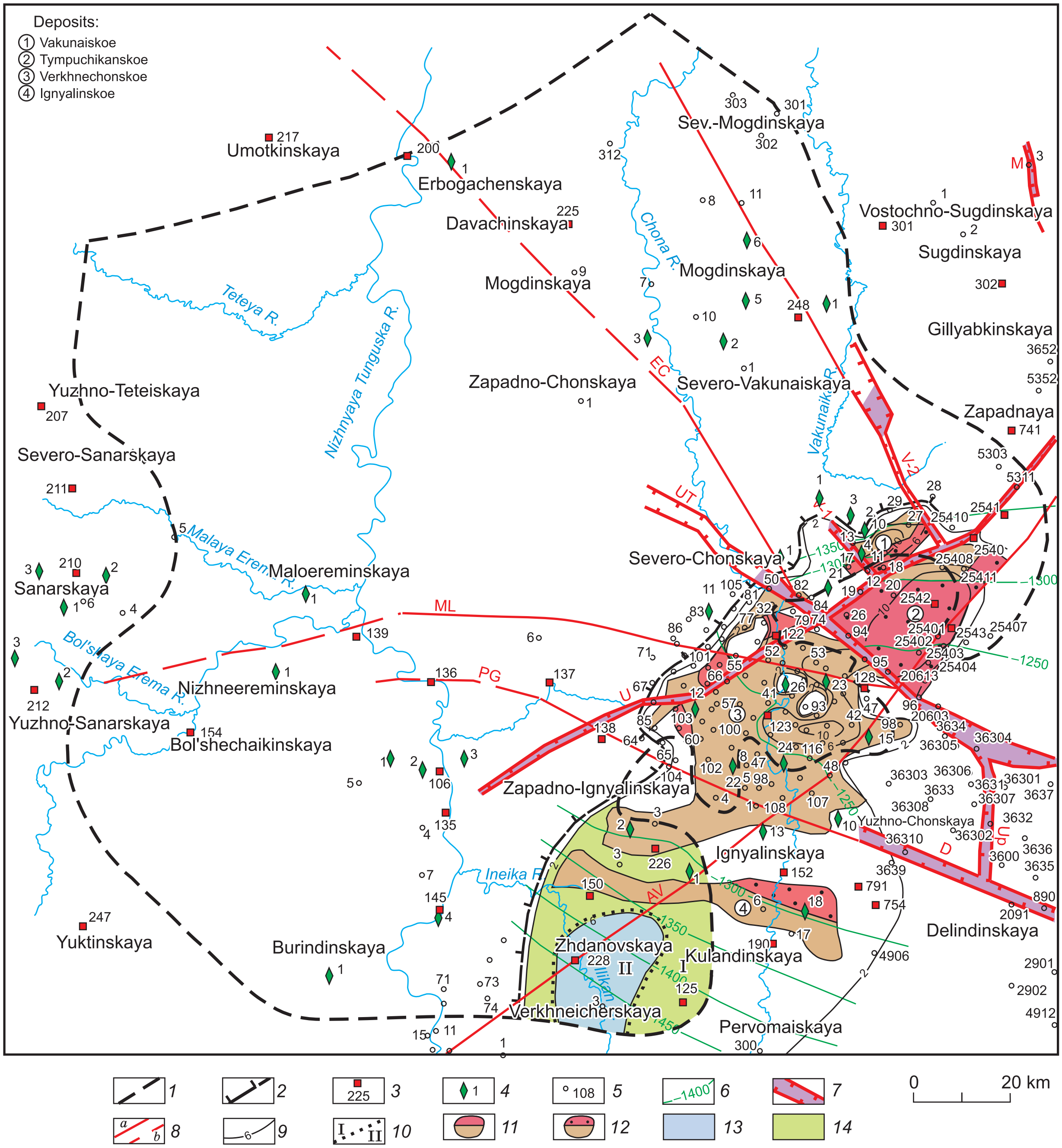

Fig. 10. Prognosis map of densities of total initial hydrocarbon resources of pay bed C_{13} from the Upper Chona Horizon in the Erema–Chona petroleum accumulation. *1, 2,* boundaries of the: *1*, Erema–Chona petroleum accumulation, *2*, reservoir wedging out; *3–5*, wells: *3*, stratigraphic, *4*, exploration, *5*, appraisal; *6*, isohypses of the top of pay bed C_{13} of the Upper Chona Horizon; *7*, micrograbens: V-1, Vakunaika-1; V-2, Vakunaika-2; Up, Upper Peledui; UT, Upper Chona–Talakan; D, Delinda; M, Mukoka; U, Usol'e; *8*, main faults (*a*, known, *b*, inferred): EC, Erbogachen–Chuya; ML, Moga–Lena; PG, Preobrazhenka–Gadalin; AV, Angara–Vilyui; *9*, isopachs of reservoirs; *10*, contours of calculation areas used in quantitative estimation of petroleum potential of the bed; *11, 12*, hydrocarbon fields: *11*, oil, *12*, oil-gas-condensate; *13, 14*, densities of total initial hydrocarbon resources (thous. tons/km^2): *13*, 20–30, *14*, 10–20.

The petroleum potential of bed C_{10} is pretty low, since its reservoirs are also distributed only in the southeastern part of the petroleum accumulation. In this part of its territory, there are three categories of areas with densities of total initial HC resources from 20 to 30, from 10 to 20 and from 5 to 10 thous. tons of EHC/km^2 (Fig. 11).

The most perspective areas, as for bed C_{13}, are predicted on a limited area located close to the southern margin of the petroleum accumulation.

Oil flowrates of the ECA plays vary from several to 200 m^3/day. The highest rates were obtained from the terrigenous C_{10} and C_{13} plays. Oil flowrates from carbonate

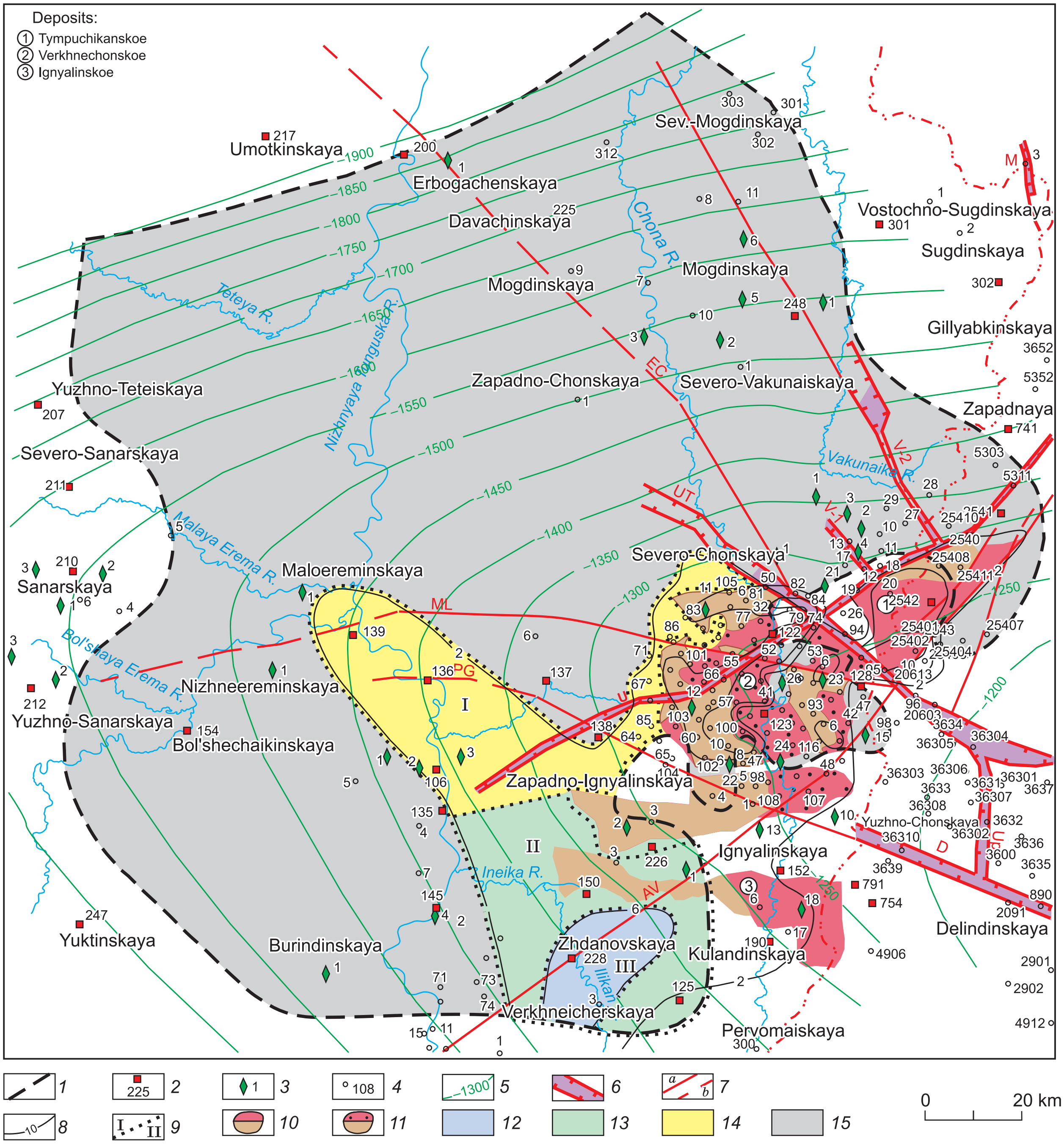

Fig. 11. Prognosis map of densities of total initial hydrocarbon resources of pay bed C_{10} from the Upper Chona Horizon in the Erema–Chona petroleum accumulation. *1*, boundary of the Erema–Chona petroleum accumulation, *2–4*, wells: *2*, stratigraphic, *3*, exploration, *4*, appraisal; *5*, isohypses of the top of pay bed C_{10} of the Upper Chona Horizon; *6*, micrograbens: V-1, Vakunaika-1; V-2, Vakunaika-2; Up, Upper Peledui; UT, Upper Chona–Talakan; D, Delinda; M, Mukoka; U, Usol'e; *7*, main faults (*a*, known, *b*, inferred): EC, Erbogachen–Chuya; ML, Moga–Lena, PG; Preobrazhenka–Gadalin; AV, Angara–Vilyui; *8*, isopachs of reservoirs; *9*, contours of calculation areas used in quantitative estimation of petroleum potential of the bed; *10, 11*, hydrocarbon fields: *10*, oil-gas, *11*, oil-gas-condensate; *12–15*, densities of total initial hydrocarbon resources (thous. tons/km^2): *12*, 20–30, *13*, 10–20, *14*, 5–10, *15*, <5.

beds (B_1, $B_{3–4}$, B_5 and $B_{12–13}$) are lower due to their decreased porosity-permeability properties, usually from several to 20–30 m^3/day. Only in several deposits (Severodanilovskoe, im. Lisovskogo and im. Savost'yanova) from individual wells, which are usually located on basement uplifts, obtained oil flowrates from carbonate plays were commensurable with that from terrigenous Vendian plays. The highest oil flowrate on the ECA was obtained in the Preobrazhenka well no. 9 from the Osa carbonate play—565 m^3/day.

MODERN DEVELOPMENT TECHNOLOGIES OF OIL RESERVES IN CARBONATE RESERVOIRS AND CONCEPT OF GEOLOGIC-ECONOMIC ESTIMATE OF OIL RESERVES IN THE EREMA–CHONA ACCUMULATION

Modern technologies of development of oil reserves in carbonate reservoirs with decreased and low permeability. The wide distribution of carbonate reservoirs with decreased and low permeability but proven oil saturation is the main problem of the commercial development of discovered oil reserves of the ECA. Traditional methods of development with vertical wells are usually estimated as marginally profitable. Therefore, modern methods should be used to solve this problem. Those include: drilling horizontal, long well shafts; drilling horizontally branched wells; and technologies of formation of an artificial filtration environment with selected permeability parameters that unite areas of the play isolated by secondary processes (Batler, 2010). In general, it is a complex of geologic and technical measures – hydraulic formation fracturing (HFF), acid treatment, gas stimulation methods; large volume and deep-penetration HFF, multizonal (MHFF) and acidic HFF (Diyashev et al., 2001; Economides, 2011; Gilaev et al., 2012; Chizhov and Ivanov, 2014). These methods will not only permit to intensify oil flowrates, but also to effectively encompass isolated plays, and will become key elements in technological schemes for the development of deposits.

The idea of HFF was perfected by some hydrocarbon producers for carbonate reservoirs of the Preobrazhenka Horizon (play B_{12}) in several wells (Ignat'ev and Burdakov, 2014). They modeled variants of methods of gas stimulation of plays (Kherliman et al., 2009). However, there has not been any positive result from these methods, apparently, due to technical causes (research results have not yet been published).

In our opinion, modern development of oil reserves in carbonate plays must be based on two provisions: estimation of the possibility of formation of a technically achievable filtration field that simultaneously on a technical level excludes the "joining" of the fracture network in the pressure differential area, while creating depressurization on the oil play (Belonin et al., 2005; Vachromeev et al., 2016). The basis for solving these issues must come from integrated geologic-oilfield results: the geophysical logging complex and core analysis results (hydrodynamic and geomechanics studies of the play), as well as selection and study of deep samples of the play oil (Fuks et al., 1982). Therefore, innovation logging technologies during horizontal wells drilling (LWO) with on-line correction of the directionally drilled well is the first practical step towards HFF design.

The second stage towards projecting and performing large volumes of HFF should be mini-HFF (DataFRAC) (Diyashev et al., 2001). The relatively high cost and technical complexity of large volume hydraulic fracturing imply a significant volume of preliminary tests and investigations. The initial parameters are: play fracturing pressure, fluid efficiency, fluid filtration coefficient, artificial fractures configuration in relation to the profile of horizontal segment of the well shaft and to the parameters of natural fracturing, strain characteristics of reservoirs of the natural collector, formation pressure of the hydrocarbon play system, formation hydraulic conductivity, etc.

Performing salt-acid treatment of carbonate collectors as an additional measure leads to the formation of eroded "arc"-type filtration channels in the bottom-hole zone (BHZ) excluding any deformation of the fracture reservoir in it.

Criteria for target selection, projecting and risk assessment for HFF, MHFF and super-HFF in low permeability carbonate reservoirs with oil and gas saturation were described in the literature. One should note the relatively small HFF experience on HC deposits of the Siberian Platform, which was started by works of G.T. Ovnatanov (1979) on the Atovskoe oil-gas-condensate deposit.

Concept of geologic-economic evaluation of oil reserves in the Erema–Chona accumulation. The geologic-economic evaluation for the ECA was performed using the IPGG-Estimator software developed and adapted to Eastern Siberia in the Center of Economics and Forecasting of Subsoil Oil and Gas Industry of IPGG SB RAS (Eder et al., 2017; Filimonova et al., 2019). Considering the limited volume of this paper, it is described in brief. The target of geologic-economic estimation were oil reserves and resources from plays B_1, $B_{3–4}$, B_5, $B_{12,13}$, C_{10} and C_{13}. The information database was based on real production and financial indicators presented by hydrocarbon producers, and data obtained from reliable open sources, as well as information from IPGG SB RAS databases.

The sequence of performing the geologic-economic estimation was determined by the gradual character of geoprospecting works and the integrated approach in developing the oil and gas territory; the formation of a profile for the production based on the analysis of the structure and quality of the raw materials base; the prediction of technological indicators; the prediction of cost and economic parameters and calculation of criteria of the geologic-economic effectiveness. The period of planning works was 30 conventional years.

Allotments for performing geoprospecting works (including the reinterpretation of data from previous years, 2D and 3D seismic surveys, exploration and appraisal and development drilling) will amount to 318 bln. rub. or approximately 350 rub./ton of added reserves of the C_1 category.

Prognosis of oil extraction from deposits planned for development on the ECA territory was performed taking into account the analysis of the production dynamics of a single well and the technological development layout (including prognosis of the wells introduction dynamics per development year, the well inventory and well network density). The highest oil production level can reach 45–55 mln tons/year. The prognosis includes drilling of inclined directional wells (IDW) with horizontal shafts (HS) and up to 1500 m length using multistage hydraulic formation fracturing (MSHFF) with a 150 m interval.

Capital investments in the development of the ECA include costs of drilling new wells, installation of the production field, as well as costs of external transport infrastructure.

Capital investments in well drilling were determined from the average cost of building one well depending on its type and depth. During the development period, it is planned to drill about 2257 oil production wells. The occurrence depth of the play will be 1550–1670 m, the drilling cost of 1 meter of oil production well is 115 thous. rub., of a drain hole—192 thous. rub., of a water injection well—138 thous. rub.

The probable development layout of the ECA includes costs of installation according to "Methodological recommendations for projecting development of oil and gas-oil fields" (attachment to the Order of the Ministry of Natural Resources of Russia No. 61 of 03/21/2007). Objects of the oil production infrastructure include: the oil-gathering system, high-pressure water lines, high voltage lines, vehicle roads, electricity distribution, installations of oil preparation, compressor and booster pump stations, the rotation village, helicopter pad, service driveways, other objects and expenses. Calculations of complex expense articles used industry norms for average indicators for 1 well. When calculated for summed indicators, building costs amount to 489.3 mln rub./well.

Building costs for the transport infrastructure were calculated assuming the building of oil pipelines up to the trunk line system Eastern Siberia–Pacific Ocean in order to organize oil deliveries to the Asia–Pacific Region countries.

To summarize, the total capital investments into the development of the ECA for the conventional 30 years period will be 3109 bln rub., including geoexploration works—318 mln rub., wells drilling—1282 mln rub., installation—1104 mln rub., transportation—405 mln rub.

Development expenses include material costs, salaries, insurance costs, instruments maintenance costs, scheduled payments for use of the subsoil, depreciation charges, minerals extraction (oil) taxes, costs of oil transportation along the pipeline to the main ESPO pipeline. The oil lifting and sales prime cost of the development of the ECA will be 11,614 rub./ton on average during the period, and the total development costs will be 10,552 bln. rub.

Estimation of the tax burden was done in accordance to the parameters and conditions of the effective taxation system and the budget effectiveness distribution between budgets of various levels. Subsoil operators developing fields on the ECA will be exempt from the oil mineral extraction tax (MET) during 15 years in accordance with current legislation. From 2016 the MET is levied at the standard rate of 919 rub./ton with corrections for the coefficient characterizing the dynamics of world oil prices (K_c) and others. Together with the crude export duty, the MET is 66% of all taxes. Total taxes for the development of the ECA will amount to 14,391 bln rub.

The geologic-economic effectiveness of the development of the ECA was estimated using a system of indicators reflecting the activity of the enterprise in the framework and conditions of the current economics and price parameters (the Ural grade oil costs 58.6 USD/bbl, the USD rate is 63.8 rub.). The dynamics of financial flows was calculated, including taking into account discounting (10%): net present value (NPV) will be 659 bln rub., internal rate of return (IRR)—18.8%, recoupment period—14 years, profitability index—1.5.

According to the calculations performed, in the framework of the accepted technological layout of development, oil transportation and its delivery to final consumers in accepted cost and tax conditions, the development of the ECA is economically cost-effective.

CONCLUSIONS

The Erema–Chona oil and gas accumulation is the only site in the southern part of the Siberian platform, which is the most studied by seismic survey and drilling, and in which commercial petroleum potential has been proven for all pay formations of the Vendian–lower Cambrian subsalt complex. This is due to its favorable tectonic, lithofacies, and geochemical formation conditions.

During the late Precambrian, Phanerozoic and until the present day, this territory was the most uplifted part of the Nepa–Botuobiya anteclise that accumulated hydrocarbons almost continuously during this period from the adjacent oil and gas formation territory—the Fore-Patom regional depression. Its Riphean and Vendian deposits had tremendous oil and gas generation potential.

The migration of hydrocarbons both lateral and vertical on the entire Vendian–lower Cambrian play in the ECA was due to the lack of seals or their low capability. The preservation of formed reservoirs on this territory is due to the existence of the high quality Upper Usol'e seal that overlies the play on the entire area.

Pay formations of the subsalt ECA carbonate complex formed in favorable sedimentation conditions: shallow shelf, intrashelf shoal, and organogenic banks. They have a mostly organogenic composition and contain the most intensely manifested recrystallization, desalination and dolomitization processes that formed secondary reservoirs.

The petroleum potential of the ECA is highest in the Nepa–Botuobiya anteclise. Their TIR for hydrocarbons were estimated to 12,890 mln tons of EHC. Those resources include 11,406 mln tons of oil, 1463 bln m^3 of gas, and 20.7 mln tons of condensate. Recoverable HC resources are correspondingly: 1807 mln tons, 1463 bln m^3, and 15.7 mln tons.

Among pay beds, the highest total HC resources are in beds $B_{12–13}$ (62.3%). Significantly less are held in beds $B_{3–4}$ (12.6%), B_5 (8.5%) and B_1 (7.7%), and minimal HC resources are predicted in beds B_{13} (5.2%) and B_{10} (3.7%).

The TIR distribution for the hydrocarbons of these beds is different on the area of the ECA. The highest densities of hydrocarbons resources of beds $B_{12–13}$ is predicted in the central and northeastern parts of the accumulation; B_5 in areas of different size, the largest being located in the southern part of the accumulation; beds B_{3-4} in the western half of the accumulation; bed B_1 in the central and northwestern part; beds B_{13} and B_{10} in a small area located close to the southern border of the accumulation.

Flowrates of the pay bed in the ECA vary from several to 200 m^3/day. The highest rates were obtained from terrigenous beds. Oil flowrates from carbonate beds are usually between several and 20–30 m^3/day. Only in some fields, individual wells usually located on basement uplifts yielded oil inflows from carbonate beds that were commensurable with terrigenous Vendian beds. Whereas in the Preobrazhenka well No. 9 the Osa carbonate bed yielded he highest oil influx of the ECA—565 m^3/day.

We considered modern technologies of oil development in decreased and low-permeability carbonate reservoirs. Their utilization will not only allow increasing oil inflows and establishing cost-effective development of discovered oil reserves, it also will become a key element in the development of oil plays in carbonate reservoirs of the Eremin-Chona hydrocarbons accumulation.

The geologic-economic evaluation allowed validating the practicability and effectiveness of developing the ECA in the framework of the accepted technological development scheme, oil transportation in accepted cost and tax conditions. The volume of investments needed for an integrated development of the ECA will be 3,109 bln. rub. for a 30 years period, NVP—659 bln rub., IRR—18.8%, recoupment period—14 years, profitability index—1.5.

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