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Deep-buried Lower Paleozoic oil and gas systems in eastern Siberian Platform: geological and geophysical characteristics, estimation of hydrocarbon resources

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Abstract. The study of deep-buried oil and gas systems is a promising trend in the preparation of hydrocarbon resources. The study of the factors determining oil and gas potential is extremely important. The Lena-Vilyui sedimentary basin in the eastern Siberian Platform has a potential for the discovery of large oil and gas fields in deep-buried Cambrian deposits. The use of original methodological approaches to the analysis of black shale and overlying deposits, generalization of the results of lithological, biostratigraphic and geochemical studies of Cambrian deposits in territories adjoining the study area, modern interpretation of geophysical data showed that siliceous, carbonate, mixed rocks (kerogen-mixtite) of the Kuonamka complex and clastic clinoform-built Mayan deposits are most interesting in terms of oil and gas potential. Oil and gas producing rocks of the Lower and Middle Cambrian Kuonamka complex subsided to the depths of 14 km. The interpretation of modern seismic surveying data confirms the hypothesis of a limited occurrence of the Upper Devonian Vilyui rift system. Based on generalization of geological, geophysical and geochemical archival and new materials on the Lower Paleozoic deposits of the eastern Siberian Platform, a probabilistic estimation of geological hydrocarbon resources of the Cambrian and younger Paleozoic complexes in the Lena-Vilyui sedimentary basin was performed. Based on basin modelling results it was concluded that the resources were mainly represented by gas. It is presumed that oil resources can be discovered in traps of the barrier reef system as well as on the Anabar and Aldan slopes of the Vilyui Hemisyneclise. With a confidence probability of 0.9, it can be stated that total initial resources of oil and gas (within the boundaries of the Vilyui Hemisyneclise) exceed 5 billion t of conventional hydrocarbons. The recommended extremely cautious estimate of resources of the pre-Permian complexes is 2.2 billion t of conventional hydrocarbons. In the study area, it is necessary to implement a program of deep and super-deep parametric drilling without which it is impossible to determine the oil and gas potential of the Lower Paleozoic.

***Keywords*:** geological structure; source rocks; Kuonamka complex; oil and gas system; oil and gas potential; quantitative estimation; hydrocarbon resources; Cambrian; Lower Paleozoic; Lena-Vilyui sedimentary basin; Siberian Platform

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Introduction. The current period of economic development is noted for a rapid growth of power engineering and energy consumption. Undoubtedly, renewable energy sources and hydrogen will play the leading role in energy supply of mankind in future. However, the estimates by the IPGG SB RAS and other world experts show that these energy sources will not provide the necessary increase in energy resources in the long term. Natural gas will play the key role in global energy as an energy resource. It is expected that by 2035-2040, natural gas consumption in the world will exceed 8 billion t o.e., i.e., it will double. This trend will persist until the 70s of the XXI century.

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In the coming years, the main importers of gas will be: China – to 300 billion m^3, Japan – to 120 billion m^3, OECD countries – to 360 billion m^3. Significant volumes will be exported to the EU countries. Russia will remain one of the largest exporters of pipeline and liquefied natural gas in the world. Thus, preparation of a large additional source of natural gas supplies to the world markets, primarily to the Asia-Pacific Region, which can be the Cambrian in the Lena-Vilyui Basin, is an extremely important task for the Russian economy.

The study of deep-buried Precambrian and Paleozoic oil and gas systems is a promising trend for the preparation of hydrocarbon (HC) resources. Study of the factors determining oil and gas potential, prospecting and exploration of HC fields at depths below 4-5 km is extremely relevant. Geological exploration of deep-buried sedimentary complexes was carried out in Russia and the USSR from the 1960s and 1970s. Oil and gas fields were discovered in the pre-Mesozoic of the Cis-Ural Trough (Russia, Akobinskoe condensate field), in the Caspian Depression (Kazakhstan, Karachaganakskoe oil and gas condensate field, Tengiz oil and gas field, occurrences at depths to 5.4 km), in Transcaucasia (Azerbaijan, Shah-Deniz and Bakhar gas condensate fields, occurrences at depths to 6.5 km), etc.

Deep-buried resources are also developed abroad. Over the last 10-15 years, oil-and-gas-bearing horizons occurring at great depths in sedimentary basins of Asia, etc., were investigated. Based on the study of microstructure, reflectivity and pyrolysis of reservoir bitumen occurring in the Upper Proterozoic and Early Cambrian deposits at depths to 5,000 m, it was ascertained that temperature evolution of the oil system in the South Oman Basin occurred in several stages. It was shown that the source of bitumen are the underlying carbonate oil-producing rocks [1]. Geochemical study of chemofossils of oils and oil source rocks in the Lower Paleozoic Tarim Basin in China, restoration of the subsidence history and reconstruction of paleotemperatures of sedimentary complexes allowed to conclude that the Cambrian and Ordovician deposits subsided to the depth of 10,000 m. It was ascertained that oils from the Ordovician reservoirs at depths of 5,038.0-5,801.4 m are mature; their source was the Cambrian and Ordovician oil source strata [2, 3].

For the Lower Cambrian Qiongzhusi Formation in the South Sichuan Basin, estimations of the generation potential of high-carbon mature oil source rocks and gas formation volumes were made [4]. It was determined that the black shale formation has the potential for shale gas production at depths to 3,000 m. Based on the study of isotope-molecular composition of HC gases in the Sichuan Basin sampled at depths from 4,500 to 6,000 m, it was revealed that gas from the Precambrian and Cambrian sedimentary complexes formed by two processes: oil cracking and HC generation by the Cambrian oil source rocks [5]. A giant accumulation of natural gas was discovered in reservoirs of the Neoproterozoic Dengjin Formation in the Sichuan Basin in southwest China [6]. The study of sedimentary rocks, investigation of HC generation processes and their migration allowed the researchers to consider five potential Neoproterozoic and Cambrian oil and gas source complexes. The assumption that the Lower Cambrian black shale rocks in the Sichuan Basin are the main source of hydrocarbon gases was substantiated [6].

Commercial condensate and gas were discovered in a deep (~6,900 m) exploratory well drilled on the Tazhong Uplift of the Tarim Basin (China) [7]. This led to resumption of the studies of the Cambrian oil source rocks in the Basin. Based on modelling of these rocks enriched in organic matter (OM), it was shown that gas composition and carbon isotopes from the well were similar to the products forming at the stage of thermal evolution corresponding to the vitrinite reflectivity coefficient of 2.2-2.5 % (catagenetic stages $АК_1$-$АК_2$ on A.E.Kontorovich scale). It was revealed that the Cambrian dolomite reservoirs in combination with a salt cap create favourable geological conditions for large-scale accumulation of HC.

PetroChina drilled Luntan-1 exploration well to a depth of 8,882 m [8] on the Tabei Uplift in the Tarim Basin. This well produced a significant oil and gas inflow from the Cambrian deposits in the

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interval of 8,203-8,260 m. This is the deepest oil inflow from the Lower Paleozoic reservoir in in the world. Pressure in this interval is 90.8 MPa, formation temperature in oil-bearing strata is 170 °C. The reservoir of HC accumulation is sandy bioclastic dolomites, oolitic limestones about 60 m thick. Porosity of the reservoir varies within 1.6-5.0 % averaging at 2.55 %. The Middle Cambrian evaporite rocks are the fluid seal for this reservoir. The produced Cambrian oil has a density of 0.82 g/cm^3, contains 0.26 % sulfur, 11.3 % paraffins, 0.20 % resins, and 0.06 % asphaltenes. Gas produced from well LT1 contains 77 % methane, 8 % ethane, 2 % propane, 4 % CO_2, 3 % N_2, 1,590-1,730 mg/m^3 H_2S. In well LT1 at the base of the Cambrian section, in the 8,665-8,688 m interval, a horizon of oil-producing mudstones and siliceous mudstones with organic carbon (C_{org}) content of 2.1 to 29.8 % and an average content of 11.3 % was recorded. $\delta^{13}C$ values of kerogen vary from –30.5 to –28.1 ‰, which points to the aquatic nature of OM. Pyrolytic parameter T_{max} = 470-485 °C, which corresponds to vitrinite reflectivity of 1.4-1.7 % (MK_3^1-MK_3^2). A unit of high-carbon rocks is clearly visible on the time seismic sections. According to basin reconstructions by the researchers, the main phase of oil formation and emplacement of deposits was recorded in the Permian and ended in the Early Triassic.

In the Lower Paleozoic section in the southern Khalakhatang region of the same Basin, a giant oil accumulation was recently discovered at depths of 7,000 to 8,000 m [9]. It was ascertained that oil was contained in the Ordovician reservoirs. Oil accumulation is a well-preserved part of an ancient oil and gas system. By the geochemical characteristics of oil and gas, crude oil can be classified as mature originating from the mixed marine organofacies of shales, marls and carbonates. Despite very high modern reservoir temperatures, cracking of oil did not occur due to a relatively short-term effect of high temperatures on it. Analysis of crude oil from superdeep wells was made, chemical compounds were studied, pyrolytic experiments and kinetic calculations were accomplished [10]. The authors suggest that cracking temperatures of oil are in the range of 210-220 °C. The deepest limit of liquid oil occurrence in the Tarim Basin, according to the estimates [10] can be at the level of 9,000 m. Based on the data on molecular and isotopic composition, the origin of deep-buried occurrences of light oil in the Ordovician carbonate reservoirs in the northern Tarim Basin is still discussed [4, 11].

The above brief review shows that as a result of integrated geological-geophysical and geochemical studies of deep-buried Upper Proterozoic and Lower Paleozoic oil and gas systems commercial hydrocarbon occurrences can be discovered in them. The Lena-Vilyui sedimentary basin has a potential for the discovery of large oil and gas fields in the Cambrian deposits in the eastern Siberian Platform. It comprises the Vilyui Hemisyneclise and the Pre-Verkhoyansk Foredeep (Fig.1).

The purpose of this work is to provide a quantitative estimation of hydrocarbon resources in the Kuonamka complex and the associated Lower Paleozoic oil and gas systems (OGS), for which it is a source of hydrocarbons, using the results of studies on the structure and characteristics of the sedimentary filling of the Lena-Vilyui Basin.

Research object. Analysis, generalization of new and archival geological-geophysical and geochemical materials. The Vilyui Hemisyneclise was first identified in 1932 by N.S.Shatsky. He called it the Vilyuiskaya Depression. In the 60-80s of the last century, in the papers edited by V.G.Vasilev, A.A.Trofimuk, G.S.Fradkin, N.V.Cherskii, the term “syneclise” was used to name this structure, although many researchers noted that the “syneclise” did not have the eastern slope and formed a single subsidence zone with the Pre-Verkhoyansk Trough. The term “hemisyneclise” was first proposed in the late 1970s by K.I.Mikulenko and used in the work “Geology of Oil and Gas of the Siberian Platform”[1].

Reference drilling and the first geophysical investigations allowed determining that the Vilyui Hemisyneclise was a deep depression filled with thick Lower Paleozoic, Upper Paleozoic and Mesozoic strata. Total thickness of sedimentary formations in the most subsided parts of the

[1] Geology of Oil and Gas of the Siberian Platform / Ed. by A.E.Kontorovich, V.S.Surkov, A.A.Trofimuk. Moscow: Nedra, 1981, p. 552.

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Hemisyneclise, according to deep seismic sounding data, reaches 14,000 m. Modern features of geological structure of the Vilyui Hemisyneclise began to form in the Jurassic period and were clearly manifested at the end of the Early Cretaceous. By that time, the largest structures that also exist today formed – the Linden and the Lungkha-Kelin depressions and the Khapchagai Megaswell. In the east, the Hemisyneclise was closed by the Verkhoyanskaya fold system (Fig.1).

The Vilyui Hemisyneclise and the adjacent part of the Pre-Verkhoyansk Trough can be considered as an autonomous sedimentary (sedimentary rock) basin, the boundaries of which coincide in plan with those of the occurrence area of the Jurassic-Cretaceous complexes. Deep drilling meterage in the Lena-Vilyui sedimentary basin is 850,000 m including more than 280 reference, parametric, prospecting and exploratory wells. Almost all gas and gas condensate fields discovered to date are confined to terrigenous deposits of the Upper Permian, Lower Triassic and Lower Jurassic pays [12-14]. The source of gas in these fields were mainly Upper Paleozoic rocks enriched in terrigenous (humic) OM. More than 50 % of explored gas reserves in the fields are concentrated in the Lower Triassic of the Srednevilyuiskoe and Srednetyungskoe fields. The volumes of gas production by now amount to about 15 billion m^3.

Research work in the last three decades of the XX century and the first decades of the XXI century allows a more grounded approach to estimating the prospects of oil and gas presence in the Lower Paleozoic complex, although some issues remain unclear.

According to the researchers, another source of HC within the Lena-Vilyui Basin could be the OM-enriched rocks of the Kuonamka Formation and its age and facies equivalents of Lower and Middle Cambrian [15-17]. Oil-producing strata which determine the prospects of oil and gas presence

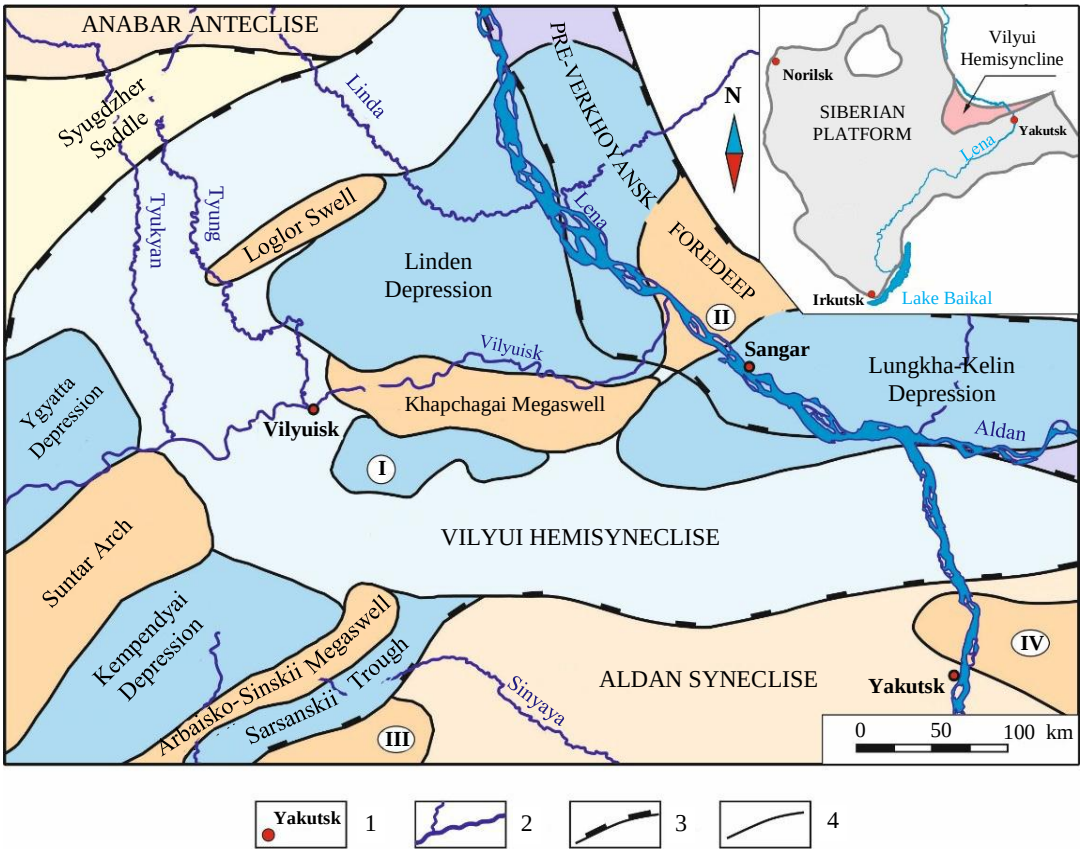


Fig.1. Fragment of structural tectonic map of oil and gas-bearing areas in the Republic of Sakha (Yakutia) (based on materials of OAO Yakutskgeofizika, 2015 with supplements and amendments)

1 – residential place; 2 – hydrographic network; 3 – boundaries of supra-order tectonic elements; 4 – boundaries of superorder tectonic elements: I – Tangnarynskaya Depression; II – Kitchanskii Projection; III – Namaninskii Projection; IV – Yakutskii Arch

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in the Lower Paleozoic (Cambrian) complex comprise the Kuonamka and Inikan formations (Botomian and Toyonian (Lower Cambrian) – Amginian and the first zone of Mayan (Middle Cambrian) occurring under the Upper Paleozoic-Mesozoic-Cenozoic sedimentary cover of the Hemisyneclise [18-20].

Commonly, rocks of the Kuonamka complex in the southeastern Siberian Platform have C_{org} content less than 5-10 %. In the eastern Siberian Platform, organic carbon content in rocks of the Kuonamka complex reaches 36.6 %. Oil shales, mudstones, clay-siliceous rocks are enriched to the maximum in OM (C_{org}> 10 %). Limestones and black cherts, as a rule, contain to 5 % C_{org} in rock. Minimum concentrations of C_{org} to 0.1-0.5 % are recorded in bioclastic limestones. In the areas adjacent to the Vilyui Hemisyneclise, high-carbon rocks of the Kuonamka complex are common in sections on the slopes of the Anabar Anteclise. On the northern slope of the Aldan Anteclise, oil shales have so far been identified only in sections of the Lena and Sinyaya rivers (limestones with C_{org} 17-18 % (K.K.Zelenov, 1957, F.G.Gurari et al., 1984), and the Yudoma River (S.F.Bakhturov et al., 1988).

New studies showed that in the areas adjoining the Vilyui Hemisyneclise in the northeastern Siberian Platform, the content of organic carbon in rocks of the Kuonamka complex is within 1-21% (Fig.2). Abnormally high contents of C_{org} 10 % and higher were determined in clay-siliceous and clay-siliceous-carbonate rocks from exposures in the Molodo and Kyulenke river basins, and boreholes Serkinskaya VII-5 and Serkinskaya VII-10. In the southeastern Siberian Platform, C_{org} content in rocks of the Kuonamka complex (Sinskaya and Inikan formations) from exposures in the Sinyaya and Yudoma River basins and boreholes Khotochu N 7, Krasnyi Ruchei N 5, Tit-Ebya N 6 in the Lena-Amga Interfluve does not exceed 10 %, varying mainly from 0.5 to 8 % (Fig.2) [17, 21]. In clay-siliceous-carbonate rocks and silicites, C_{org} values do not exceed 2 %. Elevated C_{org} contents of 5 % and higher are recorded in rocks of mixed composition.

The estimation of OM potential of oil-producing deposits was made using the results of pyrolysis (Fig.2), the dependence of generation potential of rocks on C_{org} content, and the analysis of HI and

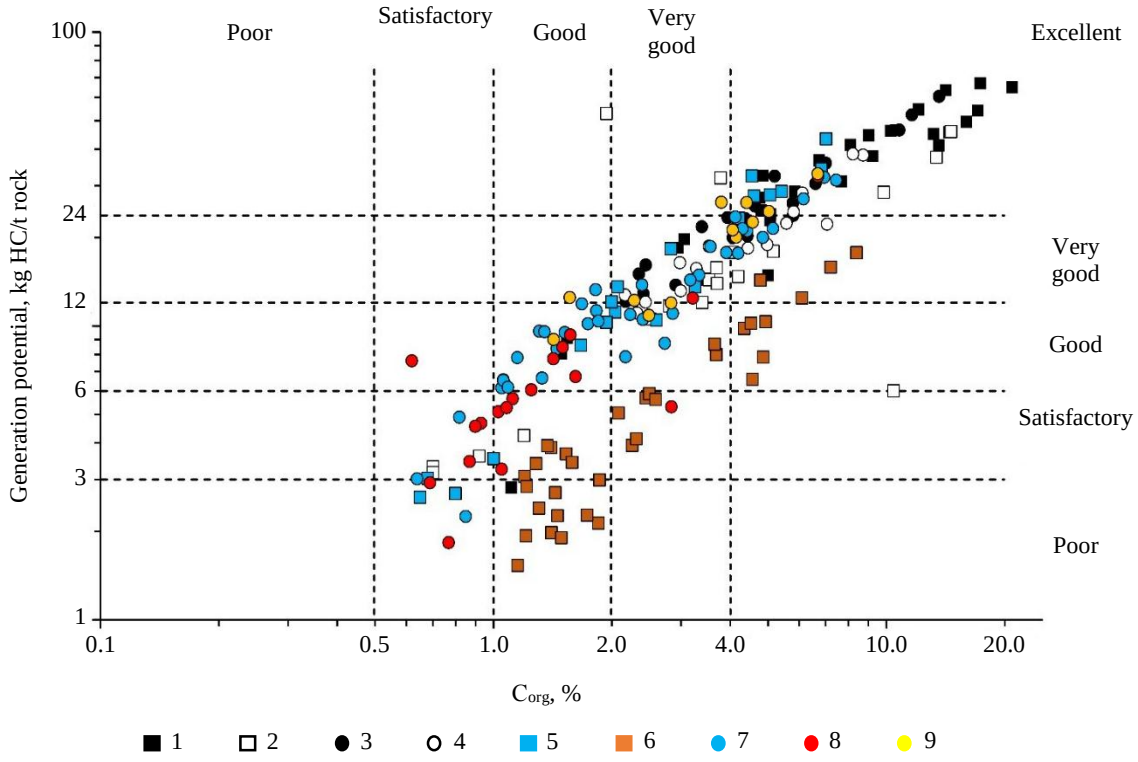


Fig.2. Dependences of generation potential of the Kuonamka complex rocks on the content of organic carbon

Studied sections: 1 – Molodo River; 2 – Kyulenke River; 3 – Serkinskaya Borehole N 5/VII; 4 – Serkinskaya Borehole N 10/VII; 5 – Sinyaya River; 6 – Yudoma River; 7 – Khotochu Borehole N 7; 8 – Krasnyi Ruchei Borehole N 5; 9 – Tit-Ebya Borehole N 6

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T_{max} (HI is hydrogen index, T_{max}, temperature of the maximum HC yield). Current state of OM shows that rocks of the Kuonamka complex are mainly characterized by aquatic marine, less frequently "lacustrine" type of OM tending to generate oil of good, very good and excellent quality.

T_{max} values of rocks in the studied collections from the slopes of the Anabar and Aldan anteclises range from 426 to 455 °C (average value 438 °C), HI – from 107 to 798 mg HC/g C_{org} (average value 410 mg HC/g C_{org}). This mainly points to the initial stage of OM mesocatagenesis. The results of pyrolysis indicate, as a rule, a weak manifestation of the high generation potential of oil source rocks in the Kuonamka complex. The maximum manifestation is recorded for OM of rocks of the Inikan Formation from the collection from the Yudoma River in the southeastern Siberian Platform, for which systematically increased T_{max} values (average value 445 °C) and decreased HI (average value180 mg HC/g C_{org}) are recorded.

Potential regional reservoirs in the Cambrian of the Vilyui Hemisyneclise were partially identified earlier (Geology…, 1981, V.E.Savitskii et al., 1972, V.E.Savitskii, V.A.Astashkin, 1978). High-carbon deposits of the Kuonamka and Inikan formations (Botomian-Amginian-Early Mayan complex, Bazhenov type of reservoir) as well as low-permeability carbonate horizons in these formations can act as reservoirs [21-23]. Along with these spatially isolated probable high-potential accumulations of Cambrian oil and gas, in the Vilyui Hemisyneclise one should also consider rocks of the Mayan complex filling the depression of uncompensated sedimentation of the Botomian-Amginian-Early Mayan paleosea. The age of reservoirs of this complex corresponds mainly to the Mayan (Middle Cambrian). It has a clinoform structure, which was noted by N.V.Umperovich et al. (1982) based on geophysical data, and by V.A.Astashkin et al. (1984) based on geological observations, studying the structure of the reef zone of Yakutia.

Drilling results confirm the potentials of the Cambrian deposits in the Vilyui Hemisyneclise. During testing of the Ust-Markhinskaya parametric and Uordakhskaya exploratory wells, signs of gas presence in the Lower and Middle Cambrian were recorded. In Srednekononchanskaya-1 Well, sampling of 3,359.4-3,411.5 m interval made it possible to obtain carbonated liquid at a flow rate of 828 m^3/day from the Udachninskaya Formation. In Sinskaya-1 boreholes, liquid bitumen was discovered in the core from the Kumakhskaya sequence which is a facies equivalent of the Kuonamka Formation [19]. In the west of the Hemisyneclise, reef organogenic and pre-reef organogenic clastic formations could also be the reservoirs (V.A.Astashkin et al., 1984, N.V.Umperovich et al., 1989, V.E.Savitskii, V.A.Astashkin, 1978, A.E.Ekhanin et al., 1990, etc.).

In Mayan (Middle Cambrian) deposits overlying the Kuonamka complex, fracturing, high porosity (to 18 %), rock bituminousity and oil staining were recorded. In the Tyukyan-Tyungskaya-1 Well, gas inflows were obtained from the Ordovician, the source of which could be the Cambrian deposits.

It is presumed that the regional fluid seal could be the Upper Cambrian formations composed of rocks with a significant concentration of clay fraction – clay dolomites, marls, and mudstones. This regional fluid seal for the Cambrian reservoirs in Western Yakutia was pointed out by V.E.Savitskii, V.A.Astashkin, A.E.Ekhanin, N.V.Umperovich and others (1978-1990). Partial absence of a regional screen directly above the reef strata and local occurrence of caprock are a serious obstacle to an optimistic forecast of oil and gas potential. However, modern researchers note a high oil and gas potential of reef deposits in the Vilyui Hemisyneclise and highlight the need to carry on the investigations of this formation [24-26].

Modern model of geological structure of the Lena-Vilyui sedimentary basin is based on results of an integrated processing of geological and geophysical materials (well history, well logging, structural constructions, seismic logging investigations, results of deep seismic sounding interpretation, etc.). Methodological approaches to the analysis of the Vilyui Hemisyneclise deposits poorly covered by seismic surveying, correlation of horizons, study of changes in thicknesses of sedimentary complexes along the lateral, construction of seismogeological sections and compilation of maps are presented in the works [19, 27]. Identification of tectonic elements is based on

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results of structural constructions for the main reflectors (R) and the analysis of thicknesses between them.

In time sections of the Vilyui Hemisyneclise, a number of stable reflectors are traditionally distinguished in the Mesozoic and Upper Paleozoic interval. The marker reflector is indexed as TP. It is confined to the surface of a regional unconformity. In central areas of the Hemisyneclise, it corresponds to the base of Triassic; at flanks, to the base of Jurassic. In modern high-fold sections the reflectors associated with the Middle-Lower Paleozoic and Precambrian are stratified. Thus, within the Kempendyai and Ygyatta depressions, DK reflection is traced corresponding to the eroded surface of the Cambrian, which underlies the Devonian deposits, and within the Yudoma-Olenek facies zone, K reflector appears, the negative phase of which is confined to the roof of the Inikan (Kuonamka) Formation. Below, KV reflectors are distinguished – the roof of the Lower Byukskaya Subformation of the Vendian terrigenous complex, B – basement surface. Seismogeological conditions and structural characteristics of sedimentary cover of the Vilyui Hemisyneclise and adjacent areas were discussed earlier [27].

Stratigraphic research in combination with seismofacies analysis provided new insights into the structure of Cambrian deposits in the eastern Siberian Platform [19]. In particular, the occurrence of abnormally OM-enriched Kuonamka Formation and its age and facies equivalents (Kuonamka complex) was investigated. It was revealed that the Kuonamka complex formed in two stages. The first corresponds to the Botomian, and the second one to the Toyonian and Early Mayan. The Toyonian-Early Mayan deposits are overlain by clinoform (cross-bedded) Mayan deposits, the structure of which is confirmed by the interpretation of modern seismic data (Fig.3).

Since the 1980s, the existence of a rift system developed under the Upper Paleozoic-Mesozoic sedimentary cover of the Vilyui Syneclise was generally recognized. According to the current notions, it extends northeast from the Kempendyaiskaya-Suntarskaya-Ygyattinskaya zone and, by the three-beam junction scheme is connected with the Verkhoyanskaya rift system in the area of the Kitchanskii projection. It was presumed (K.K.Levashov, 1975, V.V.Gaiduk, 1988, Tectonics…, 2001[2]) [28-30] that the Vilyui rift had a length of about 800 km and a width to 450 km. By analogy with the Kempendyaiskaya zone, it should be filled with volcanogenic sedimentary strata with participation of evaporites. Thickness of the Middle Devonian-Lower Carboniferous deposits that form the rift,

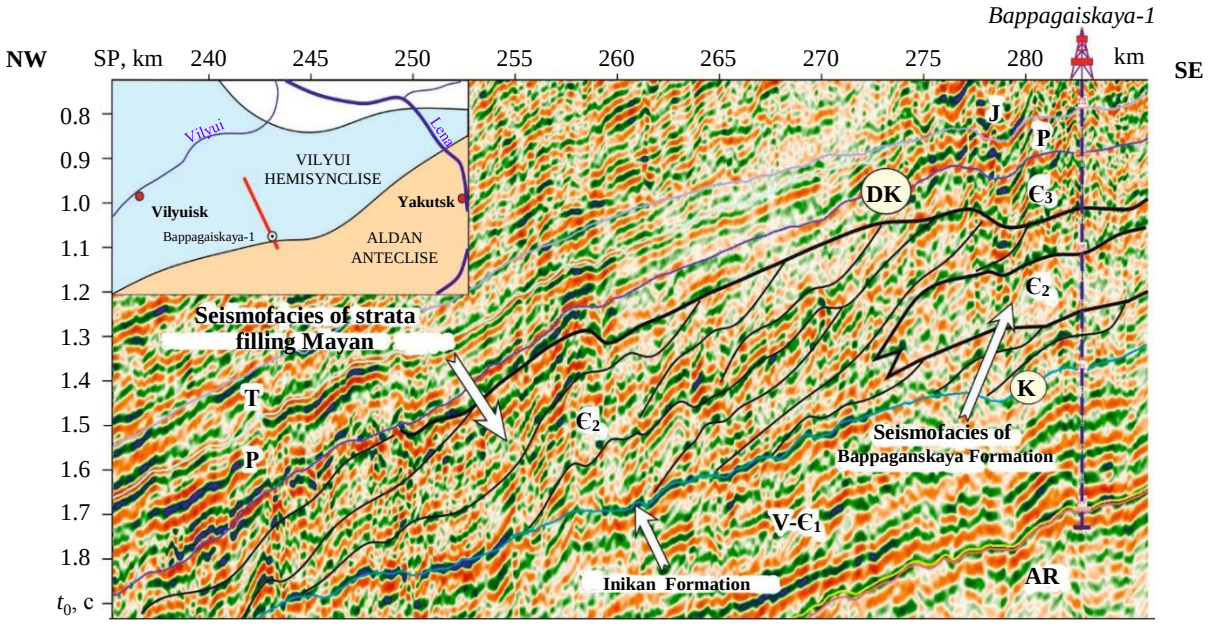


Fig.3. Fragment of time seismogeological section along line N 160807
(West Vilyui area) (according to [31] with supplements)

[2] Tectonics, geodynamics and metallogeny of Sakha Republic (Yakutia) / Publishing Editors L.M.Parfenov, M.I.Kuzmin. Moscow: Nauka/Interperiodica, 2001, p. 571 (in Russian).

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according to the researchers who adhere to this hypothesis, reaches 5-7 km. If this hypothesis is correct, the continuity of occurrence of the Kuonamka complex of oil and gas-producing rocks in the Vilyui Hemisyneclise should be disrupted by rifting and, thus, the probability of discovering large accumulations of hydrocarbons in the Cambrian deposits is extremely low.

Regional seismic surveying in the last 10-12 years allowed to make progress in resolving the problem of existence of the Devonian rift in inner areas of the Vilyui Hemisyneclise. Interpretation of the materials of modern seismic surveying and the constructions accomplished by the authors allow assuming that, with the exception of the Suntar Arch, the Yakutskii Arch and the Kitchanskii projection, the Cambrian deposits occur in the sedimentary cover over most of the Vilyui Hemisyneclise. Their continuous occurrence was not disturbed by the Devonian rifting to the extent that was previously assumed.

Seismostratigraphic and structural reconstructions allowed drawing the conclusion about a limited occurrence of the Devonian complex of volcanogenic sedimentary deposits which accumulated mainly within large negative paleostructures. In time sections, deposits of the rift complex are characterized by the variable-amplitude, irregular seismic recording, and a steep seismic event dip [32, 33]. In the area of the Kempendyai Depression, time thickness of the seismic complex corresponding to these deposits is about 5 s (section along line I-I in Fig.4), whereas in the composite seismic line northeast of it, this thickness is already reduced to 2 s (section along line II-II in Fig.4). Further northeast, the Cambrian deposits penetrated by wells in the Severo-Sinskaya, Bappagaiskaya, and Andreevskaya areas on the southern flank of the Hemisyneclise along the line crossing the axis of the supposed rift, are traced without a break in continuity to the Khapchagai Megaswell and the Linden Depression (section along line III-III in Fig.4). Consequently, according to seismic evidence, there are no grounds for distinguishing the rift zone in central areas of the Vilyui Hemisyneclise.

Research methodology. The purpose of this work is a quantitative estimation of the prospects for oil and gas presence in the Lower Paleozoic stratigraphic complex. When choosing the method of a quantitative estimation of oil potential of the Lower Paleozoic complex in the Vilyui Hemisyneclise one should proceed from the following. Considering that there are no discovered fields or even inflows of oil and gas in the Lower Paleozoic of the Vilyui Hemisyneclise, the resources of the complex can only be estimated by category D_2.

Since there are no standards in this complex in the estimated area, such estimation can be made as envisaged by the Methodological Guidelines[3], only using the method of external geological analogies. Estimations of the Upper Permian, Lower Triassic and Lower Jurassic oil and gas complexes (OGC) were obtained by a comparatively more accurate method of internal geological analogies (IAM). For the remaining OGC, the estimation can be performed using the residual principle. This means that the IAM estimation of comparatively better studied OGC should be subtracted from the total estimation of the basin hydrocarbon resources. The remainder can be differentiated between the remaining OGC in accordance with a specific geological model of the basin. This approach was used to estimate the hydrocarbon resources of poorly studied areas in the Lena-Tunguska oil and gas province in the course of public estimations of oil and gas potential in 1979-1983.

The estimation by the external analogies method was performed for all basins and the Lena-Tunguska province as a whole. At the time of estimation, the exploration maturity of the Nepa-Botuoba, Baikit and Angara-Lena areas allowed selecting the standards and perform estimations by the IAM method for their territories. After that, total estimation of unexplored or poorly explored oil and gas regions was obtained from the difference. The estimation of poorly explored oil and gas areas obtained in this way was expertly divided between the Severnaya Tunguska, Yuzhnaya Tunguska, Katanga and Pre-Sayany-Enisei oil and gas areas taking into account the current ideas about their geological structure. For the Severnaya Tunguska and Yuzhnaya-Tunguska oil- and- gas-bearing areas, corrections to the estimations were expertly introduced towards decreasing due to a probable destruction of deposits by trap intrusions.

[3] Methodological Guidelines for quantitative and economic assessment of oil, gas and condensate resources in Russia. Moscow: VNIGNI, 2000, p. 189.

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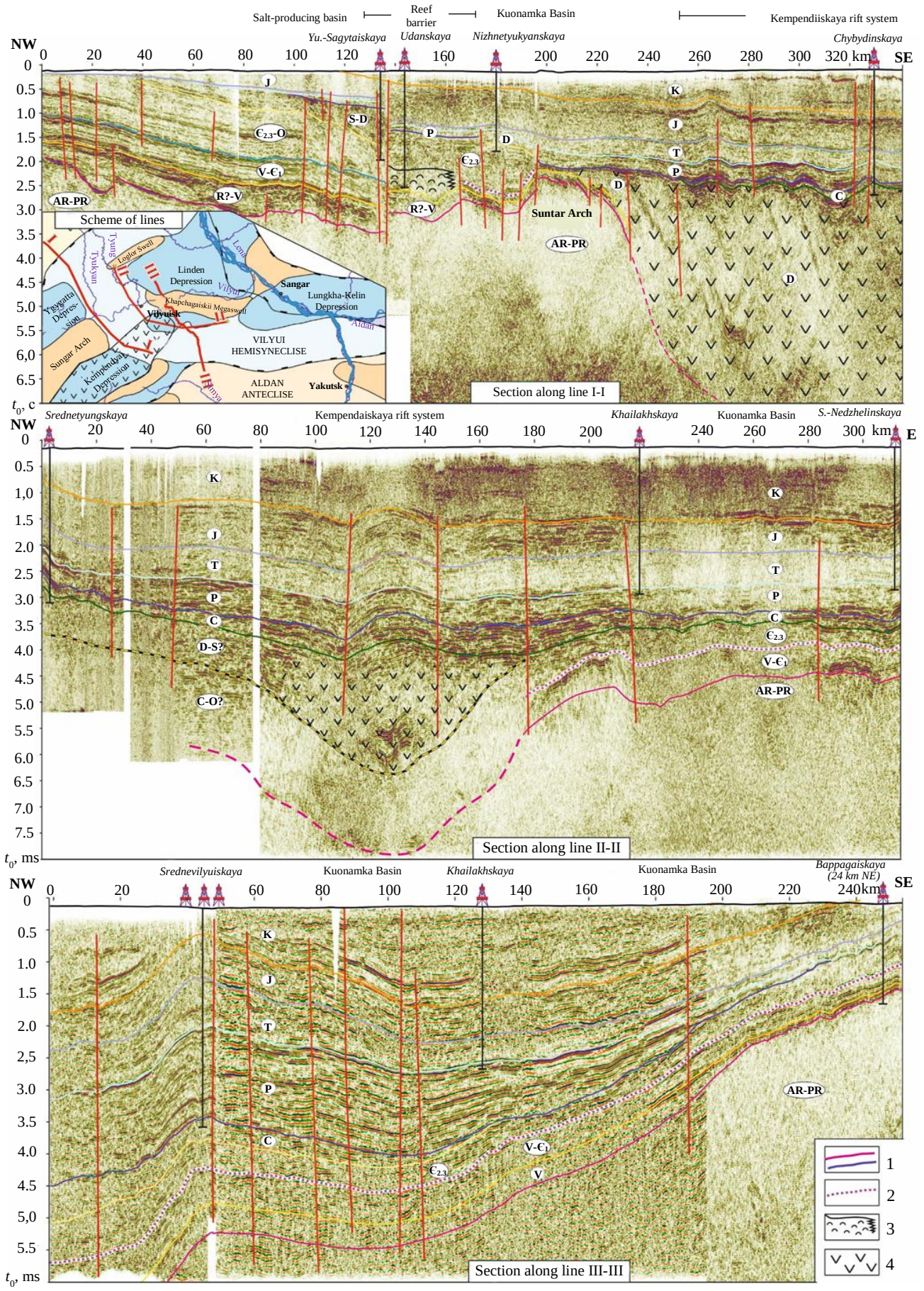


Fig.4. Time composite seismogeological sections of the Vilyui Hemisyncline

1 – reflectors; 2 – reflector confined to the Kuonamka complex; 3 – Zapadno-Yakutdlii barrier-reef complex ($Є_{1-2}$); 4 – presumed occurrence zone of the Upper Devonian rift complex

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In cases where the object of estimation is poorly studied, and only general information is available on its geological structure, it is advisable to use maximally simple and statistically stable dependencies, including sufficiently reliably determined parameters, to estimate the initial geological resources of HC (IGR HC). A group of methods based on the proved stochastic relationships between the IGR HC value and sedimentary filling characteristics was created to estimate poorly studied sedimentary basins. As a rule, a sample of relatively well-studied oil and gas basins is formed to construct the prognostic models for this group, and the corresponding empirical prognostic models are created on its basis.

L.G.Weeks (1949, 1950) was the first to use this approach to estimate the size of oil resources. For well-drilled areas in North America, he estimated the range of changes in the volume density of oil resources (from 200 to 6.500 t/km^3) and indicated 2,800 t/km^3 as the world average. He used this characteristic to estimate oil resources in some areas of the USA and the world as a whole.

The corresponding estimates of average volumetric density of HC resources and its dependence on characteristics of the sedimentary filling are given in the works of M.F.Dvali, T.P.Dmitrieva (1976), I.I.Nesterov, V.V.Poteryaeva, F.K.Salmanov (1971, 1975), V.D.Nalivkin et al. (1970), A.A.Arbatov, A.V.Kondakov (1977), A.E.Kontorovich et al. (1979-1981, 1986), V.S.Reznik (1981), etc. Sedimentary basins were first considered as an estimation object by M.F.Dvali and T.P.Dmitrieva (1976). They also introduced the term "volume-statistical method" (VSM). A detailed criticism of this approach can be found in the works of H.D.Hedberg (1978).

Various modifications of the volume-statistical method were repeatedly used in the course of quantitative estimations and were substantiated in detail, for example, in the following papers (Burshtein L.M. et al., 2000, Methodological Guidelines…, 2000). In the present work, refined versions of the VSM (Burshtein L.M. et al., 2000) were used. For a sample of 59 basins with predominantly Mesozoic or Paleozoic sedimentary filling, the following prognostic equations were found:

$$\ln Q = 1.069 \cdot \ln H + 0.943 \cdot \ln V, R^2 = 0.853, \sigma = 0.690; \quad (1)$$

$$\ln Q = 3.163 + 0.947 \cdot \ln V_{ef}, R^2 = 0.858, \sigma = 0.679, \quad (2)$$

where Q is the OGR, million t of conventional hydrocarbons (CHC); V, volume of sedimentary filling, thousand km^3; H, the thickness of sedimentary cover, km; V_{ef}, effective volume of sedimentary filling, thousand km^3, with the thickness of the ineffective layer 2.8 km; R^2, determination coefficient; σ, standard residual deviation of ln Q value.

The obtained ratios (1) and (2) are statistically very close. For the probabilistic forecast of IGR HC in the Lena-Vilyui Basin and construction of an estimate of resources in the Cambrian complex, equation (2) is further used.

One of the tasks of quantitative forecasting of oil and gas presence is differentiation of estimation by area. Below, we present the accepted procedure of such differentiation.

In the Phanerozoic of the Lena-Vilyui sedimentary basin there were two oil and gas systems: Lower Paleozoic and Upper Paleozoic-Mesozoic. Oil-producing formations in the first of them were marine rocks of the Kuonamka and Inikan formations enriched in aquatic OM (Botomian and Toyonian (Lower Cambrian) – Amginian and the first zone of Mayan (Middle Cambrian), and in the second one – coal-bearing and subcoal-bearing lacustrine-bog and lacustrine-alluvial Permian deposits and, possibly, Upper Carboniferous (V.V.Kazarinov et al., 1967, A.E.Kontorovich et al., 1967, 1971, V.M.Evtushenko, A.E.Kontorovich, 1972, Geology…, 1981).

Lower Paleozoic oil and gas system comprised, in addition to the oil-producing complex, reservoirs in which migrating HC accumulated. The first of them is the Kuonamka and Inikan formations proper with two types of reservoirs: secondary reservoirs in high-carbon rocks forming as a result of destruction of polymer-lipid kerogen and fractured cavernous rocks in carbonate layers of these formations [21, 22, 34]. The best-known example of the second type of reservoir is the repeatedly described Malokuonamka Horizon [16].

In the Lower Paleozoic oil and gas system, two other regional reservoirs are distinguished. The first is reefogenic, reef proper, organogenic and pre-reef organogenic clastic formations (Botomian, Toyonian,

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Amginian, Mayan of Lower – Middle Cambrian) in the western Vilyui Hemisyneclise (age equivalents of the Udachninskaya Formation and strata of algal, granular limestones). The second one is organogenic clastic, carbonate clinoform formations of Mayan and Ayusokkanian (age equivalents of the Tankhaiskaya, Ust-Botomskaya, Ust-Mayskaya, Chaiskaya, Bappagapskaya, Bordonskaya formations). Regional fluid seal of all these reservoirs is the overlying mudstones and clay dolomites of the Upper Cambrian (age equivalents of the upper part of the Dzhuktinskaya, Chargol'skaya and lower part of the Balyktakhskaya formations in the Vilyui Hemisyneclise).

The described structure of the Lower Paleozoic oil and gas system in the Lena-Vilyui oil and gas Basin allows distinguishing several subsystems within it: Tsentral'no-Vilyuiskaya Kuonamka, Zapadno-Yakutskaya reefogenic, Yuzhno-Anabarskaya, Severo-Aldanskaya, Postkuonamka, clinoform. The occurrence areas of individual subsystems are shown in Fig.5.

Differentiation of the obtained estimate by phase composition and between oil-and-gas subsystems was performed taking into account the results of basin modelling [35]. It was determined that over most of the Vilyui Hemisyneclise the main phase of oil formation in the Lower Cambrian complex was 360-300 Ma ago (in the Carboniferous). The late meso-apocatagenic (deep) phase of gas formation mainly due to thermal cracking of forming oil occurred 300-245 Ma ago (in Permian and Early Triassic).

Density of resources in the Tsentral'no-Vilyuiskaya zone (Fig.5) at the time of oil accumulation in the main phase of oil formation and without taking into account lateral migration to the slopes of the Anabar, Aldan anteclises and to the Zapadno-Yakutskaya reef zone was taken as the maximum. The ratio between hydrocarbon resources in the Kuonamka-Inikan and Mayan clinoform complexes was taken as 50 to 50 %.

Oil migration from the Tsentral'no-Vilyuiskii generation centre to the slopes of anteclises (Anabar and Aldan) is confirmed by extensive occurrence of naphthides on their slopes throughout the Cambrian section. Their genetic assopciation with oil-producing rocks of the Kuonamka complex was confirmed back in the 1980s by the high concentration of vanadyl porphyrins in bitumoids of oil-producing rocks and naphthides. Thus, a correction was made for oil migration from the Tsentral'no-Vilyuiskii centre to the peripheral zones of the Vilyui Hemisyneclise. A certain share of oil resources of Tsentral'no-Vilyuiskaya zone (two options were considered – 25 and 50 %) was redistributed in the following proportion: Zapadno-Vilyuiskaya reef zone – 25%, Yuzhno-Anabarskaya – 40 %,

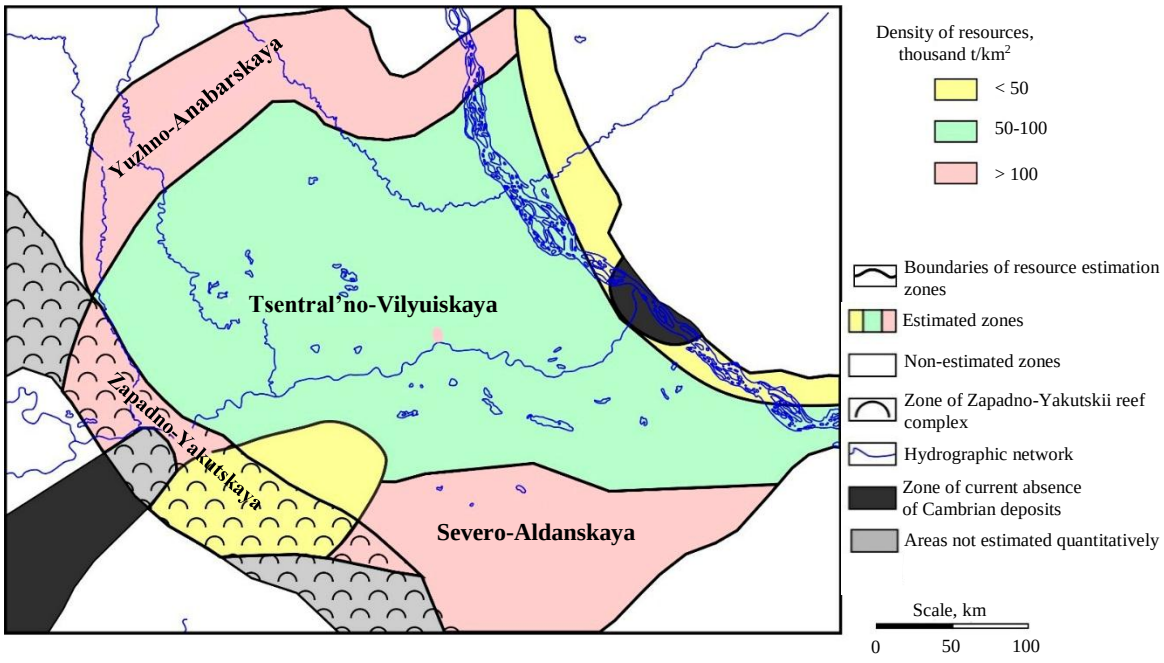


Fig.5. Scheme of zoning and oil and gas potential of the Cambrian complex in the Leno-Vilyui sedimentary basin and adjacent areas

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Severo-Aldanskaya – 35 %. Relative values of the estimate of migration redistribution of resources were adopted taking into account the results of basin modelling of oil formation processes in the Kuonamka complex in different parts of the Tsentral'no-Vilyuiskaya zone.

Undoubtedly, part of oil fields was destroyed by the upwarping processes and weathering, and hypergenic oxidation of oils caused by these tectonic movements. For the peripheral zones, it was assumed that 50 % of oil accumulated in the field was then subjected to weathering and oxidation with formation of malthas, asphalts, asphaltites and other hypergenic naphthides.

Finally, the estimation took into account that oil in the Cambrian reservoirs of the Tsentral'no-Vilyuiskaya zone, during their further subsidence and heating due to thermal cracking, broke down into methane, carbonized residue – an anthracite-like substance in the former pore space of rocks and a certain amount of H_2O, N_2, H_2S, and a part of hydrogen sulfide should break into simple substances. The initial elemental composition of oil is taken as follows: C – 84.5 %, H – 13.3 %, N+S+O – 2.2 %. Then, the mass of methane – a product of oil cracking – is about 23% of its initial mass.

Results. Let us give a brief chronology of quantitative estimations of oil and gas potential of the Vilyui Hemisyneclise, in particular, of the Cambrian deposits. In the Soviet Union, the official quantitative estimate of oil and gas potential of the Siberian Platform including the Vilyui Hemisyneclise, was made every five years since 1960 – as of the beginning of 1965, 1970, 1975, 1985, and 1990. The first two estimates were made at VNIGRI, the next three at SNIIGGiMS. The estimations performed at VNIGRI provided a forecast of HC resources only for the Mesozoic complex. In the estimations accomplished at SNIIGGiMS (A.E.Kontorovich, V.S.Surkov, A.A.Trofimuk, L.M.Burshtein, V.V.Grebenyuk, V.I.Demin, N.V.Melnikov, V.E.Savitskii, V.S.Staroseltsev and others), a forecast was given for the HC resources of not only Permian-Mesozoic, but also of Cambrian complexes.

In accordance with the adopted methodology, the estimation of the Lower Paleozoic complexes was obtained as a difference between the general estimation of the Basin using the EA method (VSM) and total estimation of the Upper Permian, Lower Triassic and Lower Jurassic OGC obtained using a comparatively more precise method of internal geological analogies.

According to the State Register of the Russian Federation, the initial oil-in-place reserves (cumulative production plus reserves of categories $A+B+C_1+C_2$) in the Mesozoic and Upper Permian reservoirs of the Vilyui and Pre-Verkhoyansk OGR amount to 745.5 million t of CHC including gas reserves of 704.7 billion m^3. Total initial oil-in-place resources of the Mesozoic and Upper Permian reservoirs, according to the estimation adopted by the State Expertise as of 01.01.2019, amount to about 2.87 billion t of CHC.

Boundaries of the Lena-Vilyui sedimentary basin can be drawn with some conventionality around the zone of increased thicknesses of sedimentary cover of the Vilyui Hemisyneclise and the Pre-Verkhoyansk Trough. The basin is a formation with sedimentary filling with a large thickness (13.7 km), area (160 thousand km^2) and volume (1,141 thousand km^3), but is relatively poorly studied (Fig.6).

Below are the results of estimating oil-in-place resources of the Lena-Vilyui sedimentary basin using the volume-statistical method: predominant age of the sedimentary filling in basins in the standard sample is Mesozoic and Paleozoic; the number of prognostic equation is 1; 2; the number of basins in the standard sample is 59; modal estimation is 12.5; 12.2 billion t of CHC; the minimum estimation (P = 0.9) is 5.1; the maximum estimation (P = 0.9) is 30.7; 29.4. The results of probabilistic estimates using equations (1), (2) are close and statistically indistinguishable. Any of them can be taken as the base one. Fig.7 shows the calculated (equation (2) integral probability distribution function of the value of the initial geological HC resources inf this basin.

The estimates obtained by the volume-statistical method significantly exceed the estimates of the Upper Paleozoic-Mesozoic oil and gas system in the Lena-Vilyui oil and gas basin according to the IA method. This is natural, since only the Upper Permian, Triassic and Jurassic reservoirs were estimated using the IA method.

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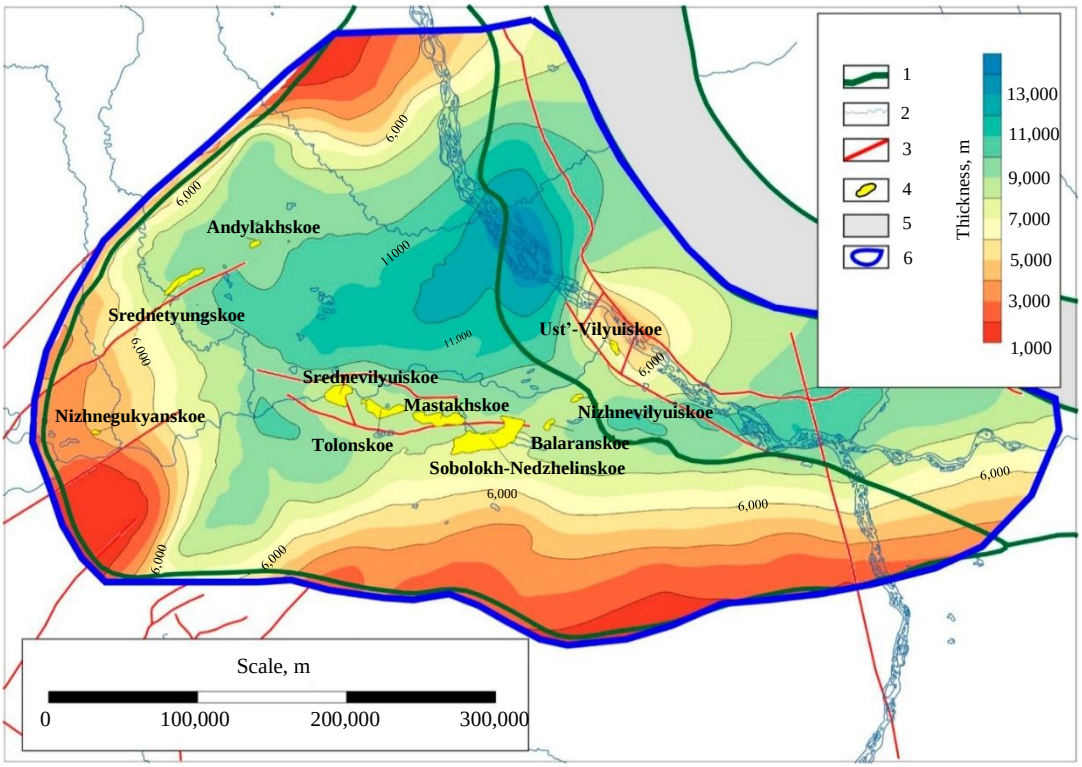


Fig.6. Sketch map of sedimentary cover thickness in Lena-Vilyui Basin
1 – boundaries of OGR; 2 – hydrographic network; 3 – regional faults; 4 – fields;
5 – occurrence zone of Verkhoyanskii fold-and-thrust belt; 6 – boundaries of sedimentary basin

Resources of the Cambrian complex can be obtained from the difference between the estimation of the basin as a whole and the estimation of the Upper Permian-Mesozoic complex. In this case, the initial geological resources of the Cambrian complex with a confidence probability of 0.9 can be estimated as follows: minimum – 2.2, modal – 9.3, maximum – 26.4 billion t of CHC.

Taking into account the estimation performed, it can be stated with a high probability that a giant gas field can be discovered in Cambrian deposits of the Vilyui Hemisyneclise, and oil fields, among them medium and large ones, can be found on the slopes of anteclises and in traps of the Yakutskii barrier reef.

Taking into account the presented approach, the obtained modal estimation was differentiated by oil and gas subsystems. The assessments obtained using this algorithm are illustrated in the Table and the sketch map of oil and gas potential (see Fig.5).

Modal estimate of OGR HC reserves in the Cambrian complexes of the Lena-Vilyui Basin is 9.3 billion t of CHC reserves including oil from 4.8 to 6.6 billion t, and free gas from 2.4 to 4.3 trillion m^3. According to this estimate, recoverable oil resources range from 1.4 to 2.0 billion t.

From the viewpoint of spatial distribution of resources, peripheral zones of the Basin – Zapadno-Yakutskaya reef, Yuzhno-Anabarskaya, Severo-Aldanskaya – seem to be more promising for oil, and the Tsentral'no-Vilyuiskaya Kuonamka – for gas. It is not possible to give more localized estimates of HC resources in the Cambrian of the Lena-Vilyui sedimentary basin at the current stage of investigations.

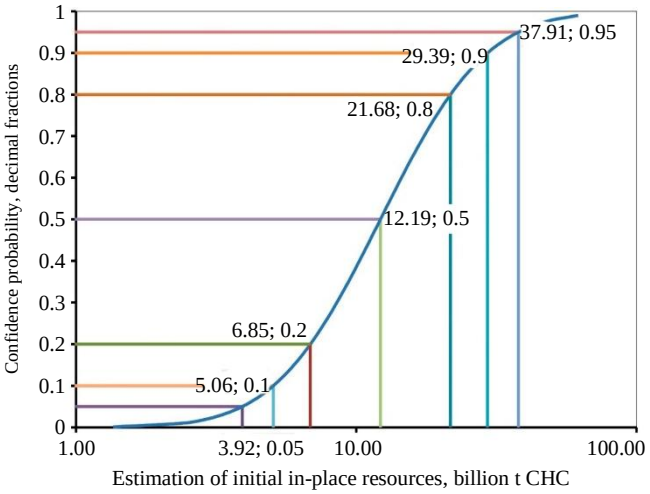


Fig.7. Integral distribution function of estimates of OGR HC in the Lena-Vilyui Basin (equation (2)

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Estimation of in-place and recoverable category D_2 oil and gas resources in the Cambrian complex of the Lena-Vilyui oil and gas basin (share of oil migrating from the generation source 25/50 %)

Zone	Pay complex	Oil, mln t	Dissolved gas, billion m^3	Free gas, billion m^3	Resources, mln t CHC
Tsentralno-Vilyuiskaya Kuonamka	Kuonamka	0.0/0.0	0.0/0.0	2,169.7/1,206.5	2,169.7/1,206.5
		0.0/0.0	0.0/0.0	2,169.7/1,206.5	2,169.7/1,206.5
	Mayan	0.0/0.0	0.0/0.0	2,169.7/1,206.5	2,169.7/1,206.5
		0.0/0.0	0.0/0.0	2,169.7/1,206.5	2,169.7/1,206.5
	Total	0.0/0.0	0.0/0.0	4,339.5/2,413.0	4,339.5/2,413.0
		0.0/0.0	0.0/0.0	4,339.5/2,413.0	4,339.5/2,413.0
Zapadno-Yakutskaya reef	Reef	1,092.5/1,532.9	42.2/60.8	0.0/0.0	1,134.7/1,593.7
		329.7/460.8	11.5/19.2	0.0/0.0	341.2/480.0
	Total	1,092.5/1,532.9	42.2/60.8	0.0/0.0	1,134.7/1,593.7
		329.7/460.8	11.5/19.2	0.0/0.0	341.2/480.0
Yuzhno-Anabarskaya	Kuonamka	973.7/1,356.9	38.3/54.4	0.0/0.0	1,012.0/1,411.3
		291.3/406.4	11.5/16.0	0.0/0.0	302.8/422.4
	Mayan	973.7/1,356.9	38.3/54.4	0.0/0.0	1,012.0/1,411.3
		291.3/406.4	11.5/16.0	0.0/0.0	302.8/422.4
	Total	1,947.4/2,713.8	76.7/108.8	0.0/0.0	2,024.1/2.822.6
		582.7/812.9	23.0/32.0	0.0/0.0	605.7/844.9
Severo-Aldanskaya	Kuonamka	866.4/1,187.3	34.5/48.0	0.0/0.0	900.9/1235.3
		260.7/355.2	11.5/12.8	0.0/0.0	272.2/368.0
	Mayan	866.4/1.187.3	34.5/48.0	0.0/0.0	900.9/1235.3
		260.7/355.2	11.5/12.8	0.0/0.0	272.2/368.0
	Total	1,732.7/2,374.6	69.0/96.0	0.0/0.0	1,801.7/2,470.6
		521.4/710.5	19.2/28.8	0.0/0.0	540.5/739.3
Total	Kuonamka	1,840.1/2,544.2	72.8/102.4	2,169.7/1,206.5	4,082.6/3,853.1
		552.0/761.7	23.0/28.8	2,169.7/1,206.5	2,744.8/1,997.0
	Mayan	1,840.1/2,544.2	72.8/102.4	2,169.7/1,206.5	4,082.6/3,853.1
		552.0/761.7	23.0/28.8	2,169.7/1,206.5	2,744.8/1,997.0
	Reef	1,092.5/1,532.9	42.2/60.8	0.0/0.0	1,134.7/1,593.7
		329.7/460.8	11.5/19.2	0.0/0.0	341.2/480.0
	Total	4,772.7/6,621.4	187.8/265.6	4,339.5/2,413.0	9,300.0/9,300.0
		1,433.7/1,984.2	57.5/76.8	4,339.5/2,413.0	5,830.7/4,474.0

Conclusion. The geological prerequisites for the prospects of discovering giant gas fields in the Cambrian deposits of the Vilyui Hemisyneclise are the unique concentration of marine aquatic organic matter in rocks of the Kuonamka complex and enormous thicknesses of the deposits overlying the Cambrian (high catagenesis of OM).

A new generalization of the results of lithological, biostratigraphic and geochemical studies of Cambrian deposits in the areas adjacent to the Vilyui Hemisyneclise, a modern interpretation of geophysical data and structural constructions showed that of primary interest in terms of oil and gas potential are the siliceous, carbonate, mixed-composition rocks (kerogen-mixtite) of the Kuonamka complex and clastic clinoform-built Mayan deposits. The Mayan sedimentary strata are underlain by the oil and gas source Kuonamka complex and are covered by a regional fluid seal – the Upper Cambrian clay-carbonate deposits.

According to geological, geophysical and geochemical materials, geological environment in the Cambrian in the Lena-Vilyui and Tarim basins [36, 37] is similar in many respects. This allows an

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optimistic estimation of oil and gas potential of the Cambrian complex in the Lena-Vilyui sedimentary basin. A significant advantage of the Tarim Basin is a high quality of the evaporite seal. It should be taken into account that the ancient age of oil and gas-bearing deposits, great occurrence depths of reservoirs, low reservoir properties of pays, and high current formation temperatures cannot serve as a basis for underestimating the prospects for oil and gas presence. This conclusion is supported by the results of studies of high-carbon ancient formations in other basins of the world and Russia [38-40 etc.].

As a result of this study, a probabilistic estimation of gas resources was given for the first time using a set of methods for poorly studied OM-enriched and depleted Cambrian and younger sedimentary complexes of the Lower Paleozoic in the Vilyui OGR. A probabilistic nature of the estimation will allow a more objective assessment of resource development risks. Due to an extremely low exploration maturity, the probabilistic estimation could only be constructed for the area as a whole.

The refined geological model of the Lena-Vilyui sedimentary basin served as the basis for a probabilistic quantitative estimation of oil and gas potential of the Cambrian and younger sedimentary complexes of the Lower Paleozoic. With a confidence level of 0.9, it can be stated that total initial HC resources in the Vilyui Hemisyneclise exceed 5 billion t of CHC. Modal estimate of the initial in-place resources is about 12 billion t of CHC. The recommended extremely cautious estimate of resources of the pre-Permian complexes is 2.2 billion t of CHC. Due to apocatagenesis of OM, these resources should be represented by gas. Oil accumulations in this complex can be found in traps of the barrier reef system and on the Anabar and Aldan slopes of the Vilyui Hemisyneclise. Were the conditions favourable for preservation of HC occurrences is a question that requires special study.

The accomplished resource estimates can be regarded as cautious. In reality, they may be 1.5-2.0 times higher.

It is necessary to implement a program of deep and super-deep parametric drilling in the Vilyui Hemisyneclise, without which it is impossible to resolve the problems of oil and gas potential of the Lower Paleozoic. The implementation of such a program is difficult in the conditions of active and, from our point of view, premature transfer of large areas in central parts of the Hemisyneclise to the distributed subsoil reserves without restrictions in the stratigraphic interval prior to completion of the stage of regional geological exploration.

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