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The Sukhana Sedimentary Basin, Siberian Platform: Source Rock Characterization and Direct Evidence of Oil and Gas Presence[1]

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Abstract—Despite the known large natural bitumen accumulations and oil seeps in several kimberlite pipes along the periphery of the Sukhana sedimentary basin, interpreted as direct evidence of petroleum potential, the basin still remains one of the least studied (by geological and geophysical methods) regions of the Siberian Platform. The platform cover of the basin is composed by Riphean, Vendian, and Cambrian clastic (terrigenous) and carbonate deposits reaching 5.5–6 km in thickness in the central part of the basin. The hydrogeological specifics of the basin is largely governed by its location within the northern geocryological zone (Olenek cryoartesian basin) and is expressed as a continuous distribution of permafrost aggraded into the permafrost zone of unique thickness. Direct indicators of ore and gas presence are the East Anabar, Central Olenek, and Siligir–Markha fields of natural bitumen and oil shows in kimberlite pipes of the Daldyn–Alakit region (Udachnaya pipe). The bituminous-carbonate sediments of the Khatyspyt Formation (Vendian, Ediacaran) and the highly carbonaceous carbonate–siliceous–shaly sediments of the Kuonamka Formation (lower–middle Cambrian) are the Sukhana source rock complexes. The geochemically substantiated genetic relationship between the natural bitumen deposits of the East Anabar field and the organic matter of the Vendian Khatyspyt Formation makes it possible to estimate the area of the spread of the latter far to the west, beyond the axial part of the basin. Gammacerane, inherited from the organic matter of the Khatyspyt Formation and ranking as well-preserved and most characteristic biomarker of these bitumens, provides a compelling evidence of their consanguinity. The bitumen and oil of kimberlite pipes in the south of the basin, in the area of reefs of the Siligir–Markha bar, are similar in all geochemical criteria to oils of the Nepa–Botuobiya anteclise. In particular, in primary geochemical characteristics (12- and 13-monomethylalkanes, unique secosteranes, identical carbon isotope composition, etc.) the oils of the Udachnaya pipe are identical to the Irelyakh oils (oil field in the Mirnyi arch). No accumulations of oil or natural bitumen genetically related to the highly carbonaceous Kuonamka Formation have been found within the basin. At the same time, "intraformational" shows of viscous oil, solid bitumen, and allochthonous bitumen (bitumen extracted with chloroform) were documented directly in the sections of the formation, which makes the sedimentary basin a very attractive target for "shale oil" exploration. As for the regional assessment of the petroleum potential of the entire basin, its axial part (Sukhana depression) complicated by local uplifts is of the greatest interest. Both the Khatyspyt and Kuonamka Formations are widespread there, with the thermal maturity of their organic matter corresponding to the oil window. In addition, the regional reservoirs at the Vendian–Cambrian boundary have good petrophysical properties on both the western and the eastern flanks of the basin.

Keywords: natural bitumens, oil shows, source rocks, kimberlite pipes, Proterozoic, lower Paleozoic, Sukhana sedimentary basin

INTRODUCTION

Oil and natural bitumen shows on the surface giving the first clues to oil producing regions are reasonably interpreted as the basis for regional-scale assessment of oil and gas potential of poorly studied sedimentary basins. Incidentally, discoveries of numerous large oil fields and even provinces are known to have been made in the early stages of research by drilling in the proximity to oil seepages on the surface (Uspensky et al., 1964; Levorsen, 1970). Another equally important prerequisite consists in the presence of highly carbonaceous and bituminous sedimentary rocks, with the parameters allowing them to be ranked as prospective oil-source formations. The problem of revealing genetic links between bitumen deposits or oil seeps and Precambrian and Cambrian oil source rocks is one of the pressing challenges to regional assessment of petroleum resource potential of the Siberian Platform.

This paper views the Sukhana sedimentary basin (SSB) as a large negative structure in the northeast of the Siberian

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platform bounded in the west by the slope of the Anabar Shield, and in the north and east by the Lena–Anabar and Fore-Verhoyansk depressions correspondingly. It comprises a series of marginal uplifts (Udzha, Olenek, Kuoika–Daldyn, Muna) of the platform. In the south the basin is bounded by the Syugdzher saddle and the northwestern flank of the Vilyui syneclise (Fig. 1).

GEOLOGY AND HYDROGEOLOGY

The Sukhana sedimentary basin (SSB) remains one of the region of the Siberian Platform that is least studied by geological and geophysical methods, despite the fact that the basin's periphery is noted for large accumulations of natural bitumen and oil shows in kimberlite pipes (Makarov and Kosolapov, 1968; Bazhenova et al., 1979; Antsiferov et al., 1981; Gol'dberg, 1981; Klubov, 1983; Bodunov, 1986; Kashirtsev, 1988). In the geological literature, the central part of the basin is often termed "the Sukhana depression" (Kontorovich et al., 1975; Parfenov et al., 2001).

Judging from the intense alternating magnetic field, in the southeastern part of the basin the crystalline basement is composed of Archean metamorphic rocks, whereas in the northeast the appearing "intermediate" clastic-volcanogenic sequence (Eekit Group) is intensely deformed in isoclinal folds and intruded by granitoids. Judging from the absolute chronology for granitoids (2080–1846 Ma), the group of formations have ages not older than the early Proterozoic (Vinogradov and Krasil'shchikov, 1963). The geographic extent of the Eekit Group in the north of the SSB and within the Olenek uplift is characterized by a "quiet" magnetic field. This area is delimited by the Udzha and Zhigansk transform faults from the west and south. The basement depth reaching maximum (5.5–6 km) in the central SSB, tends to be much lower (about 1 km) on the slopes of marginal uplifts. The Eekit Group crops out on the surface within the Sololi arch of the Olenek uplift (Atlasov, 1953; Erlikh, 1962; Shpunt et al., 1979; Parfenov et al., 2001).

The platform cover of the basin is formed by Riphean, Vendian and Cambrian sediments, with appearing thin Or-

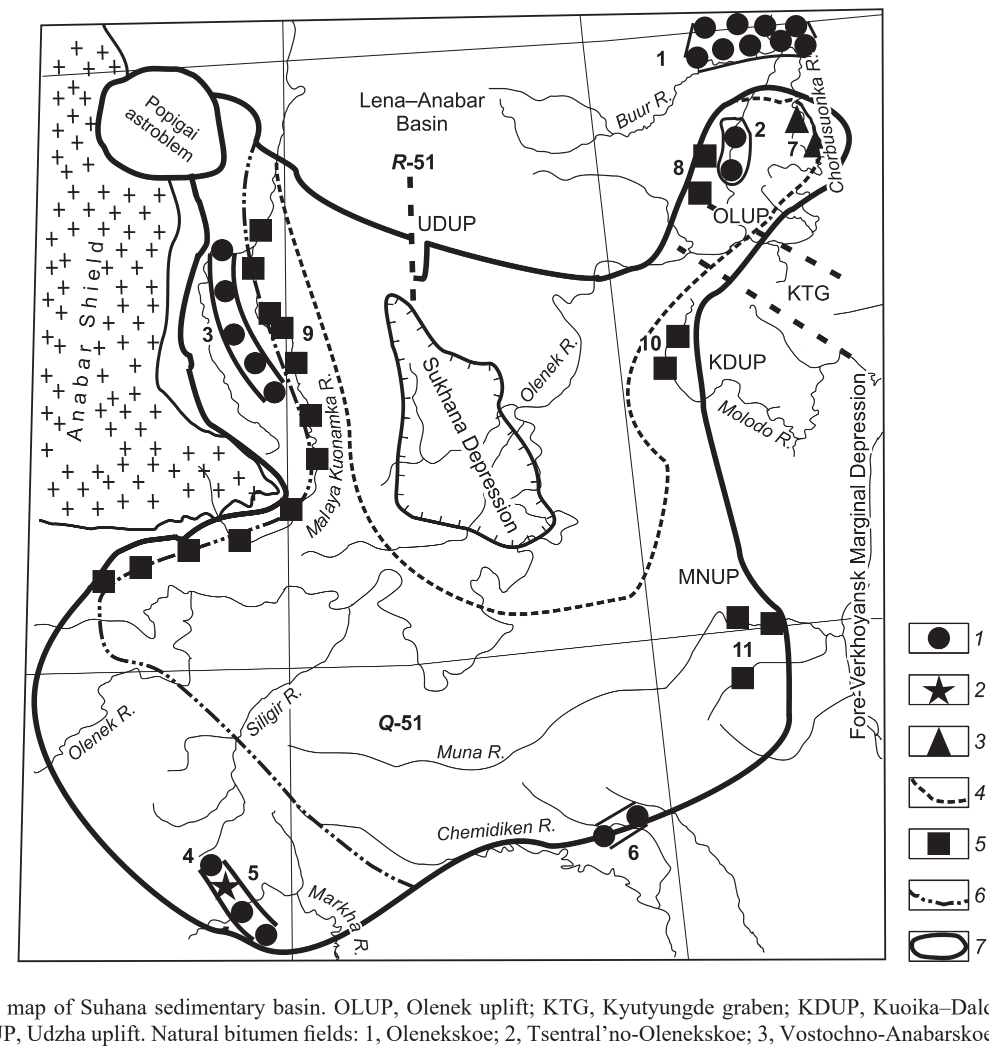

Fig. 1. Schematic map of Suhana sedimentary basin. OLUP, Olenek uplift; KTG, Kyutyungde graben; KDUP, Kuoika–Daldyn uplift; MNUP, Muna uplift; UDUP, Udzha uplift. Natural bitumen fields: 1, Olenekskoe; 2, Tsentral'no-Olenekskoe; 3, Vostochno-Anabarskoe; 4, Siligir-Markhinskoe; 5, Udachnaya pipe, 6, Verkhnemunskoe. Hydrocarbon source rocks outcrops: 7, Khatyspyt Formation (Vendian) on the Khorbusuonka River; 8, Kuonamka Formation (lower–middle Cambrian) on the tributaries of Olenek River; 9, Kuonamka Formation, the southern and eastern slopes of the Anabar Shield; 10, Kuonamka Formation, Molodo River; 11, Kuonamka Formation, Muna and Kulenke Rivers.

dovician and Silurian deposits in the extreme southwest. Its thickness is largely governed by the onset of the deposition of basal platform sediments, i.e., primarily Riphean deposits, inasmuch as thickness of the Vendian–Cambrian part of the section is fairly persistent averaging about 2.5 km.

As was noted above, the SSB geological framework has thus far been largely underexplored, with only few CDP seismic profiles available for its area, whereas it has been scarcely drilled by deep wells. The exception is the southern slope of the Anabar Shield, where along with deep wells and core drilling is complemented by a network of seismic profiles obtained for the Daldyn–Alakit diamondiferous region and the area bordering the Syugdzher saddle. Some of the deep wells penetrated through the entire thickness of Vendian–Cambrian sedimentary cover to depths from 2.5 km (Aikhal'skaya well 703) to 3.1 km (Sokhsolokhskaya well 706). At the base of the sedimentary cover, Vendian deposits unconformably overlie Archean crystalline rocks.

The junction zone of the northern slope of the Olenek uplift and the southern side of the Lena–Anabar trough located in the north, beyond the basin's extent, were studied by acquired set of seismic profiles and several wells drilled, including Burskaya well 3410. The latter is the closest to the basin and penetrated the section of the Mesozoic, upper Paleozoic, Cambrian, upper and middle Riphean deposits to a depth of 3300 m. The stratigraphic scheme of subdivision of the Precambrian and lower Paleozoic sediments of the well at the time, was adopted in accordance with the stratification of the coeval rocks of the Olenek uplift. Later it was substantially revised (Nagovitsin et al., 2015). The whole Precambrian part of the section was attributed to the Neoproterozoic, and split into a number of new formations (Fig. 2).

In this paper, for the western slope of the Olenek uplift and the eastern slope of the Anabar Shield, and therefore for the central part of the basin, we use stratigraphic units that were developed for the geological mapping of the area, taking into account the results of subsequent work (Fig. 2). Post-Cambrian deposits are absent from most of the SSB except for the Kyutyungde graben (KTG, Fig. 1) where the Tournaisian deposits composed of carbonate with gypsum are preserved. However, paleotectonic reconstructions made by F.F. Brachphogel (1984) on the basis of analyzed fauna finds in the xenoliths of kimberlite pipes have shown that the sedimentary cover which existed in the Ordovician, Silurian and Devonian within the entire Anabar Shield and the anteclise adjacent from the east, was at least 1.5–2 km in thickness.

Once the Verkhoyansk passive continental margin began to form, the sedimentary cover gradually became completely eroded. This explains the organic matter thermal maturity level corresponding to the early mesocatagenesis stage in the Precambrian and Cambrian deposits outcropping on the slopes of the Anabar Shield and on marginal uplifts of the Siberian Platform. In the submerged part of the basin, we should expect a more significant transformation of the organic matter of the source rocks, which have realized their potential in the form of oil, and now bitumen field.

According to the hydrogeological zonation of the East Siberian artesian region, the Sukhana basin is subsumed into the Olenek cryoartesian basin (CAB), with the geocryological conditions controlled by the zone of continuous distribution of permafrost composing the cryolithozone having unique thickness (locally reaching 800 m) and low negative sediment temperatures at the base of the layer of zero annual amplitude (Mel'nikov, 1984).

The presence of intra- and subpermafrost cryopegs (natural salt waters and brines having negative temperature) is another feature indicative of permafrost (Tolstikhin, 1971). The specifics of the hydrogeological section of the Olenek cryoartesian basin is dictated primarily by groundwaters of the upper, middle, lower Cambrian and Proterozoic aquifers, and by waterlogged zones of kimberlite pipes and trap intrusions (Bodunov et al., 1986). The aquifers of Vendian–Cambrian deposits localized in the north, near the Sukhana basin border, are characterized by low salinities: 4.5 g/dm^3 in well 50 (Tyumyatinskaya area), and from 12.7 to 17.9 g/dm^3 in well 930 (Khastakhskaya area). In both cases, the water is of sodium chloride composition, with the rNa/rCl coefficient varying from 0.9 to 1.1, and Ca/Cl from 0.01 to 0.05. Incidentally, neither their hydrogeological nor hydrochemical aspects have thus far been studied in the basin's central part.

In the south, subsurface brines in kimberlite pipes (Udachnaya, Aikhal, etc.) within the Daldyn–Alakit region are characterized by a medium degree of metamorphism, with their chemical composition not reaching the stage of gypsum precipitation. The value of their total mineralization (TDS) usually does not exceed 150 g/dm^3. The groundwaters penetrated in kimberlite pipes and trap intrusions are hydraulically connected with the aquifer complexes of the host sedimentary rocks, while their composition and mineralization are largely similar (Alekseev et al., 2017; Alekseeva and Alekseev, 2018).

Brines from the Aikhal, Markha and Sokhsolokh areas and those from the central Nepa–Botuobiya anteclise fall into the same genetic group, with their geochemical evolution having reached the stage of sylvite precipitation, which is also of the case with the subsurface brines of the Mir pipe characterized by the highest degree of metamorphism. The Ca/Cl ratio reaching the value of 0.55–0.63 in the latter, does not exceed 0.36 in the Udachnaya pipe brines, though (Novikov, 2017).

Underground waters of the central part of the Sukhana basin are practically not studied. We can assume that their composition for the Riphean and Vendian–Cambrian parts of the section becomes closer to the coeval horizons of the flank platform of the Lena–Anabar depression rather than Daldyn–Alakit region. The last is already feeling the impact the salt complex behind a reef. In general, low reservoir temperatures can be predicted for potential hydrocarbon deposits and possibly abnormally low reservoir pressures, which may depend on the thickness of permafrost.

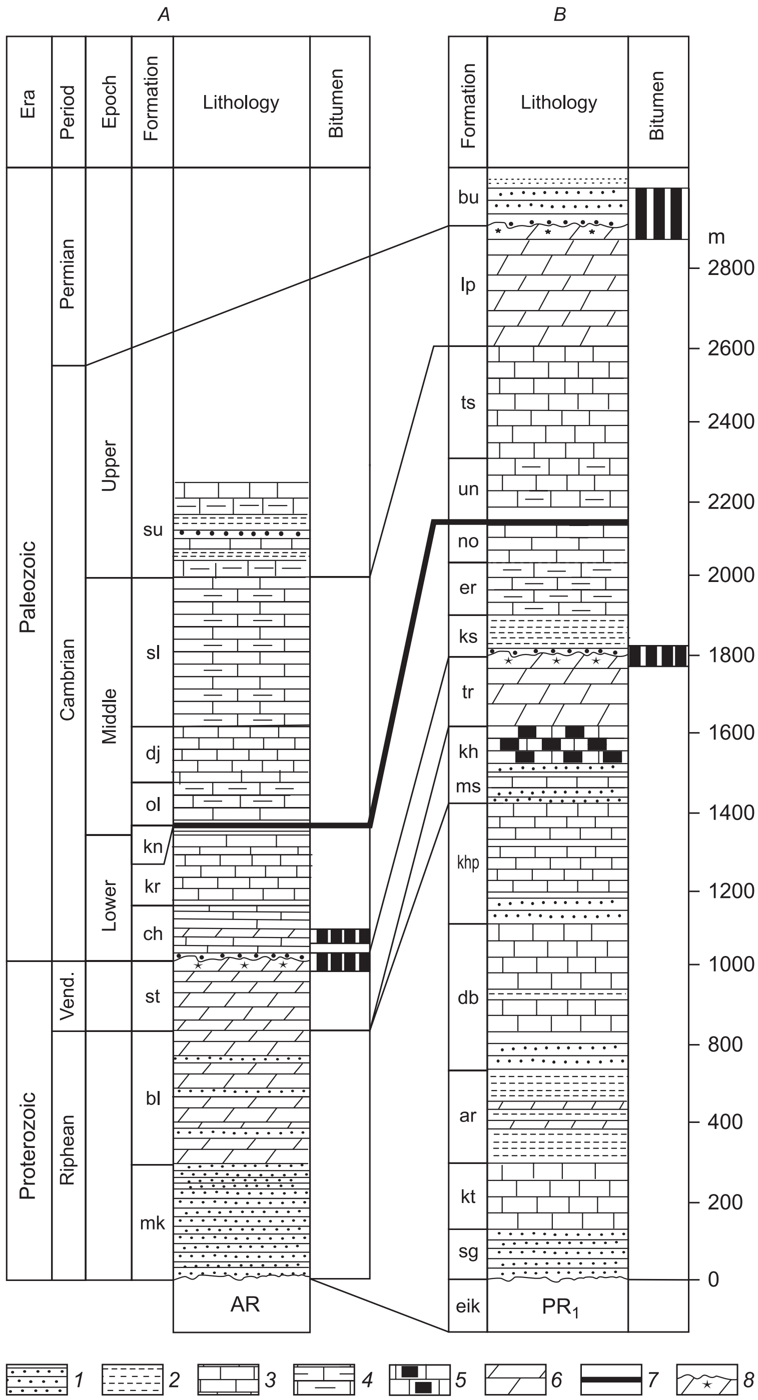

Fig. 2. Lithological and stratigraphic sections of the Eastern slope of the Anabar Shield (*A*) and the northwestern slope of the Olenek uplift (*B*). *1*, sandstones and gravelite; *2*, siltstones and mudstones; *3*, limestone; *4*, marls; *5*, bitumen limestone; *6*, dolomites; *7*, Kuonamka oil shales horizon; *8*, caverns. Local stratigraphic units: mk, Mukun Formation; bl, Biliakh Formation; st, Staraya Rechka Formation; ch, Chabur Horizon; kr, Kuranakh Horizon; kn, Kuonamka Formation (Horizon); ol, Olenek Horizon; dj, Dzhakhtar Horizon; sl, Siligir Horizon; su, Sukhana Formation; eik, Eekit series; sg, Sygynakhtakh Formation; kt, Kyutyungde Formation; ar, Ary-Mas Formation; db, Debengde Formation; khp, Khaipakh Formation; ms, Mastakh Formation; kh, Khatyspyt Formation; tr, Turkut Formation; ks, Kessyuse Formation; er, Erkeket Formation; no, Noui Formation; un, Unkyulyabit-Yuraykh Formation; ts, Tyuesale Formation; lp, Lapar Formation; bu, Buur Formation.

DIRECT INDICATIONS OF PETROLEUM POTENTIAL (BITUMEN ACCUMULATIONS AND OIL SHOWS)

As was mentioned above, the Sukhana sedimentary basin is characterized by widely distributed large bitumen accumulations and oil shows along its periphery both on the eastern slope of the Anabar Shield and on the flanks of the Olenek and Kuoika–Daldyn local uplifts (Bazhenova et al., 1979; Ivanov, 1979; Gol'dberg, 1981; Klubov, 1983; Kashirtsev, 1988, 2003). The southern closure of the basin is remarkable for natural bitumen and oil seeps within the Siligir–Markha rampart and in the nearest kimberlite pipes' sections, including their ore bodies (Makarov and Kosolapov, 1968; Bodunov et al., 1986).

The Olenek bitumen field (point 1 in Fig. 1), not being part of the SSB, due to its origin most likely associated with upper Paleozoic source rocks of the Verkhoyansk passive continental margin (Kabankov, 1954; Ivanov, 1979; Kashirtsev, 1988, 2015).

The Central Olenek bitumen accumulation zone (point 2 in Fig. 1) is located to the west of the Aekit Group outcrops of the early Proterozoic basement, where within the Kersyuke and Khorbusuonka rivers basins, the Khatyspyt Formation is overlain by the Turkut Formation. The latter is composed by stromatolitic dolomites, whose cavernous varieties at the base and top are filled with black tar-like bitumen. While the bulk of bitumen (asphalts and asphaltites) is localized in the basal sandstones and gritstones of the Kessyuse Formation, overlapping with stratigraphic unconformity the cavernous stromatolitic dolomites (Figs. 3, 4). Bitumen content largely governed by reservoir rock properties (porosity and permeability) commonly does not exceed 2%. Even though the zone boundaries are not defined, however within the Olenek uplift alone, the estimated area of the outcropping Vendian–lower Cambrian bitumen-saturated rocks is at least 200 km^2.

The East Anabar bitumen accumulation zone (point 3 in Fig. 1) on the eastern flank of the Anabar arch was traced at a distance of about 200 km along the bitumen-saturated Vendian and lower Cambrian outcrops on the surface in the Malaya Kuonamka and Bol'shaya Kuonamka rivers basin. The Vendian bituminous horizon is confined to dolomites of erosion zone, a product of the Precambrian weathering processes (Staraya Rechka Formation), with thickness ranging from 2 to 17 m. The estimated average porosity of carbonates is 9–13%, while bitumen content in rocks varies from 0.7 to 2.2 % (Klubov, 1983; Kashirtsev, 2003). Several carbonate bituminous horizons totaling 20 m (and more) in thickness and bitumen content up to 3.5% occur on the basal bituminous sandstones and conglomerates (2.5 m) in the section of the Chabur Horizon (lower Cambrian) along the Ulakhan–Tyulen' Creek, a tributary to the Bol'shaya Kuonamka River.

The Siligir–Markha bitumen accumulation zone (point 4 in Fig. 1) was revealed by K.K. Makarov (Makarov and Kosolapov, 1968) in the middle Cambrian Siligir Formation rocks and in upper Cambrian deposits on the southern slope of the Anabar anteclise within the upper reaches of the Siligir and Markha Rivers (Fig. 5). The bitumen accumulations are grouped into a band 40–50 km thick and 210 km long, striking northwest. In the natural outcrops, bitumen develops sinters along the parting planes and numerous cracks, fill the pores and caverns, and intergranular space in limestones (porosity >6–8%). The total bitumen resources of the Siligir–Markha field are estimated at 2 bln tons. In the immediate vicinity of the Siligir–Markha rampart, accumulations of bitumen (from kerites to malthas) and high-viscosity oils confined to the areas of kimberlite pipes (Udachnaya, Leningrad, Flogopitovaya, etc.) occur widely in middle–upper Cambrian sediments.

Oils and bitumen from kimberlites and host rocks of the area of Udachnaya pipe (point 5 in Fig. 1). The most detailed information on geology, hydrogeology and oil shows is provided in (Bodunov et al., 1986). Oil and bitumen seepages in hydrogeological wells drilled within the pipe area were encountered during well tests, as oil ingress of different intensity. Oil commonly arrived from the sub-

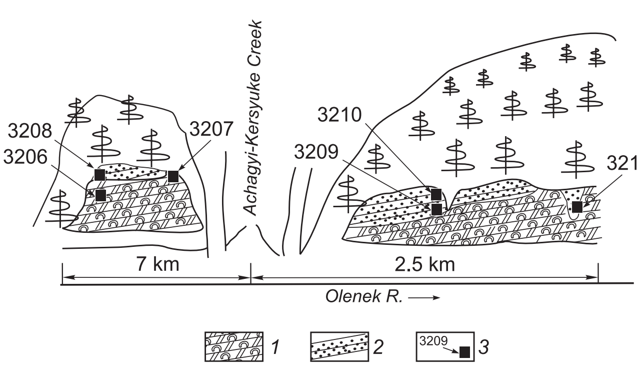

Fig. 3. Central Olenek bitumen field. *1*, algal dolomites of the Turkut Formation with bitumen in caverns; *2*, bitumen saturated sandstones and gravelites of the Kessyuse Formation; *3*, samples (the sketches from Kashirtsev's field diary).

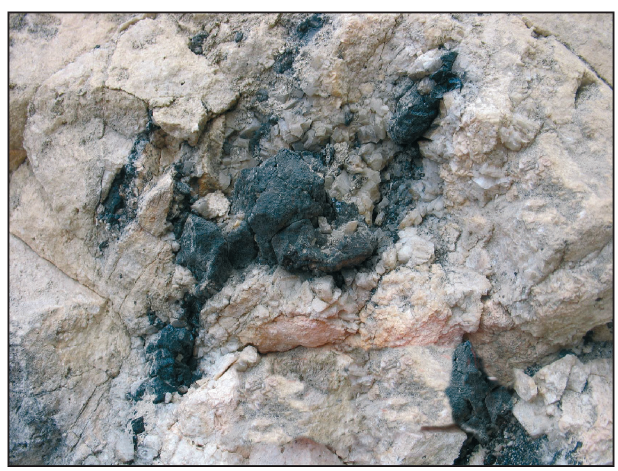

Fig. 4. Natural bitumen in cavern of Turkut's dolomites.

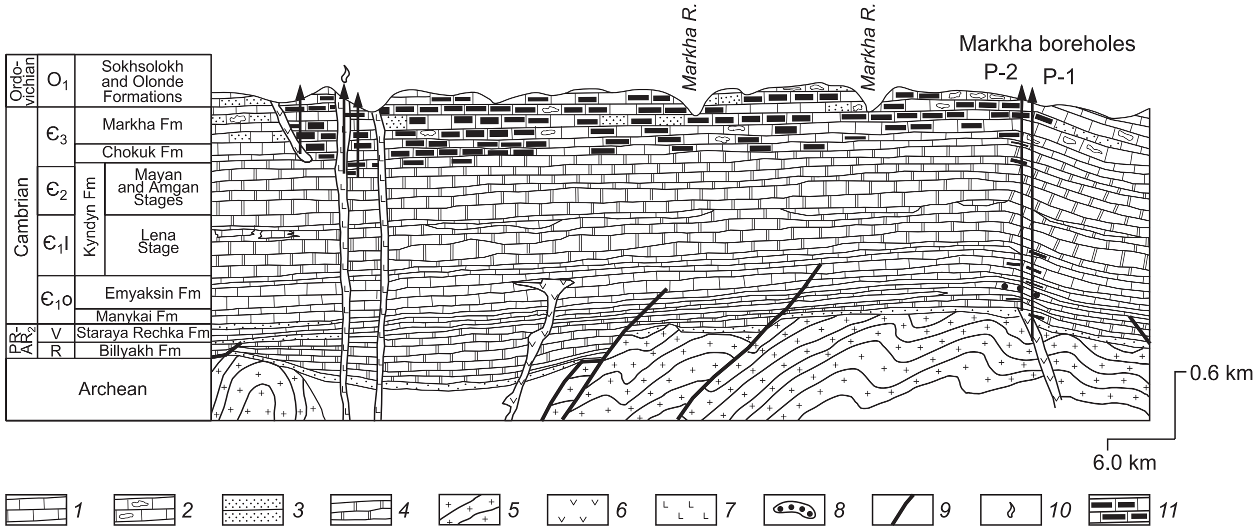

Fig. 5. Schematic lithological-structural profile through Siligir–Markha bitumen field (Makarov and Kosolapov, 1968). *1*, limestones; *2*, intraformational conglomerates; *3*, sandstones; *4*, dolomites; *5*, granite-gneisses; *6*, rocks of trap formation; *7*, kimberlites; *8*, oil seeps; *9*, faults; *10*, gas inflows from the well; *11*, bitumen layers.

permafrost zone in concert with water. Figure 6 provides insights about the stratigraphic confinement of oil accumulations.

Ore bodies of the pipe also abound with oil and bitumen seeps. Bitumen and oil in kimberlite pipes are reported from the fractured and brecciated zones of structures, and also found in calcite veins, caverns, sliding surfaces; the contact zones between the kimberlite bodies and the host rocks are intensely saturated. Oil and bitumen seeps in the western body of the pipe are confined to depths from 300 m and below, down to the bottom-hole zone of wells.

The Verknyaya Muna natural bitumen accumulation (point 6 in Fig. 1) on the eastern slope of the Muna uplift was revealed in basal sandstones (Lower Jurassic) as a result of exploratory drilling for diamonds. The bitumen origin inferred from the integrated geochemical characteristics (heavy carbon isotopic composition, specific distribution of terpenoids, etc.) is associated with Jurassic clayey deposits proper, in the central Fore-Verkhoyansk trough (Kashirtsev, 2003).

SOURCE ROCK COMPLEXES

The SSB source rock complexes are represented by the bituminous carbonate Vendian Khatyspyt Formation and highly carbon carbonaceous-siliceous shales Kuonamka Formation (lower and middle Cambrian).

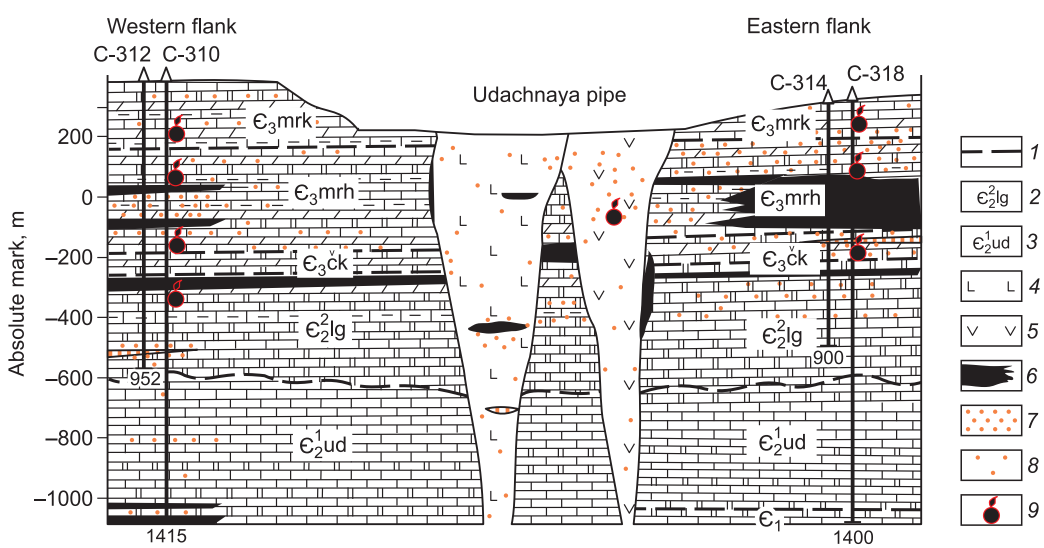

Fig. 6. The geological section of the Udachnaya pipe (Bodunov et al., 1986). *1*, boundaries of stratigraphic units; *2*, laguna-sabkha unit; *3*, reefs-clastic strata; *4*, kimberlites of the Western body pipe; *5*, kimberlites of the Eastern body pipe; *6*, completely oil saturated rocks; *7*, areas of inhomogeneous saturation; *8*, area of weak saturation; *9*, gas shows.

Fig. 7. Outcrop of the Khatyspyt Formation on the Khorbusuonka River (Olenek uplift).

Fig. 8. Outcrop of the Kuonamka Formation on the Molodo River (Kuoika–Daldyn uplift)

The Vendian Khatyspyt Formation (point 7 in Fig. 1) studied on the northwestern slope of the Olenek uplift (Pelechaty et al., 1996; Rogov et al., 2015; Cui et al., 2016) is well exposed in the Khorbusuonka river basin (Fig. 7), with quartz conglomerates, gritstones and sandstones occurring at its base. While the overlying part of the formation (90–100 m) is composed of dark, almost black (odorous) bituminous thin-layered limestones containing lenses of dark, massive, fine-grained limestones and rare interlayers of mudstone.

The content of organic carbon (TOC) hosted by the bituminous limestones ranges from 0.03–4.19%, increasing to 14% in shales (Natapov, 1962; Kashirtsev, 2003; Parfenova et al., 2011a; Cui et al., 2016), while the extent of the formation's distribution within the basin is not known. It appears that the dolomite sequence identified in Burskaya well and labeled as the Khatyspyt Formation, is laterally replacing the "classic" Khatyspyt Formation in the north. The geochemical data provided below allow to infer that the Vendian–Cambrian East Anabar bitumen accumulation owes its origin to hydrocarbon generation from the organic matter of the Khatyspyt Formation. The latter, in this case, should be extending far westwards from the Olenek uplift, beyond the SSB axial part, whereas the extent of the bitumen accumulation zone along the Anabar Shield (>200 km) delineates the equally extensive meridional distribution of the formation (Fig. 1).

The lower and middle Cambrian highly carbonaceous rocks ranked for the first time as the Kuonamka Formation were identified in the Malaya Kuonamka River basin (point 9 in Fig. 1) by K.K. Demokidov (Demokidov and Pervuninskii, 1952). Within the study area, the formation crops out on the surface (points 8–12, Fig. 1) and is well exposed in the western, northern and eastern margins of the basin (Fig. 8). In the extreme southwest of the Daldyn–Alakit area and to the south, on the Syugdzher saddle, coeval sedimentary formations are replaced by reef structures. In the southeast, the formation lies buried beneath Paleozoic–Mesozoic rocks of the Vilyui syneclise and is tending to sink deeper, which unambiguously attests to the presence of the formation in most of the basin.

The Kuonamka Formation interval within the SSB is related to open sea-basin of the Olenek facies region (Savitsky et al., 1972; Antsiferov et al., 1981; Bakhturov et al., 1988; Parfenova et al., 2004). The ubiquitously distributed clay, carbonate and siliceous rocks (25–65 m) are enriched with organic matter, whose content reaches 30% of the rock mass. At the base of the section (Borulakh Horizon) the formation is impregnated with V, Ni, U and phosphates (Gavshin et al., 1984; Zueva et al., 1992).

Results of pyrolysis studies of the organic matter (OM) from the Kuonamka and Khatyspyt Formations have shown that in both the cases it belongs to Type II kerogen (Tissot and Welte, 1981). The OM maturity level in the rocks exposed along the basin's periphery corresponds to early stages of mesocategenesis (Fig. 9).

COMPARATIVE GEOCHEMISTRY OF NAFTIDES AND BITUMOIDS OF SOURCE ROCKS FROM THE SUKHANA SEDIMENTARY BASIN

Geochemical studies of the organic matter of source rocks, crude oils and bitumen were carried out uniformly, according to the commonly accepted procedures at the geochemical laboratories of the two research institutes: IPGG SB RAS and IOGP SB RAS (Kashirtsev, 2009; Parfenova et al., 2004, 2011b, etc.). The analyses were performed on samples of the Khatyspyt bitumoids of carbonate rocks (31); highly carbonaceous Kuonamka shales, carbonates and silicites (36); bitumen collection from Central Olenek and East Anabar fields (23), and the Udachnaya pipe oils (32).

Conventional geochemical parameters (composition and distribution of individual hydrocarbons, including biomarker molecules in aliphatic fractions, benzothiophenes, phenanthrenes and triaromatic steroids in aromatic fractions, TOC and carbon isotopic composition, etc.) were obtained

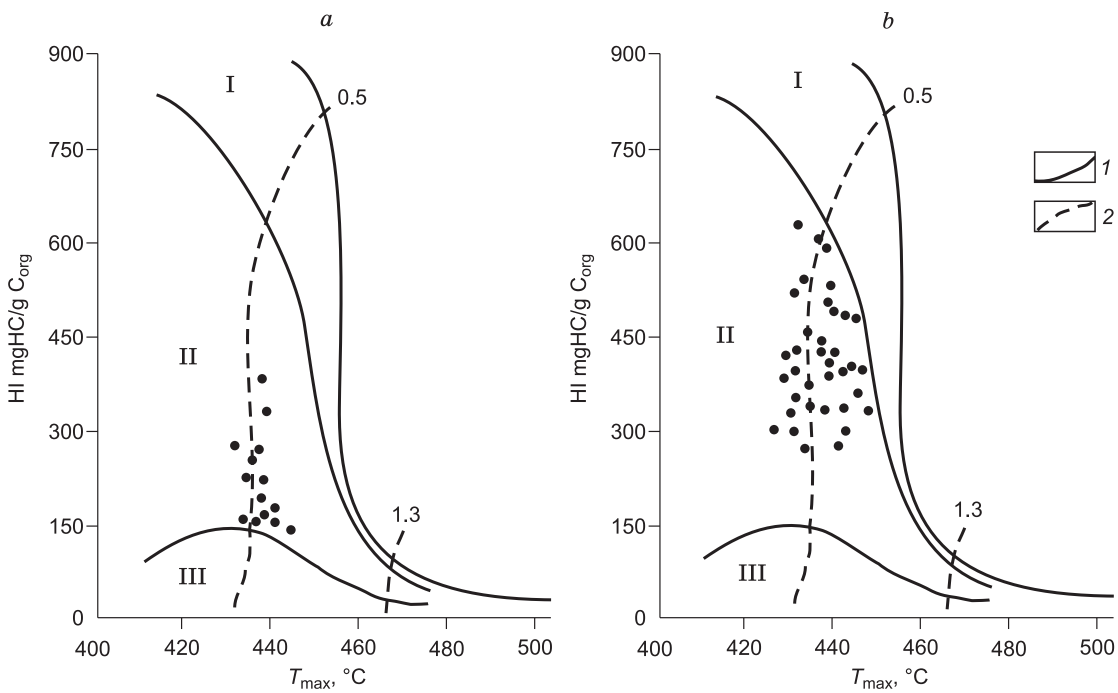

Fig. 9. Diagrams of pyrolytic characteristics of organic matter of Khatyspyt (*a*) and Kuonamka (*b*) Formations. *1*, boundaries of different types of kerogen; *2*, lines corresponding to the vitrinite reflectance.

for almost all of the samples listed above. Additionally, a pyrolysis analysis was applied to clayey and carbonate rocks interpreted as potential source-rocks. In part, these results have been published in the literature (Parfenova et al., 2004, 2011a,b, 2014; Kontorovich et al., 2005; Kashirtsev, 2015). We have highlighted below only the most important geochemical criteria, which, in the authors' opinion, help to distinguish between the source-rock units, while representing the unambiguous genetic correlatives for comparison between the organic matter of source rocks and that of hydrocarbon accumulations.

Since the formation of autochthonous oil reservoirs, natural bitumen from the Central Olenek and East Anabar zones of bitumen accumulation have had a long history associated with their ascending into the hypergenesis zone, the loss of light fractions, followed by chemical and bacterial oxidation (Kashirtsev et al., 2001). At this, gammacerane, the unique biomarker, inherited by the bitumens from the organic matter of the Khatyspyt Formation, is well preserved and definitely serves as the main criterion for determining their genetic affinity (Fig. 10).

Analysis of the specifics of organic geochemistry of oils and source rocks of the ancient carbonate and, specifically, carbonate-evaporite basins (Hindustan, Oman, etc.) showed that elevated concentrations of gammacerane in the source rock extracts are typical of these basins and probably associated with the widely spread ciliated protozoan *Tetrahymena* species that live in the hypersaline conditions of water column stratification (Grosjean et al., 2009; Dutta et al., 2013). As such, evaporate and carbonate formations are often characterized by high concentrations of benzhopanes, with their proposed origin by cyclization and subsequent aromatization of the homohopanoid side chain during early diagenesis (Hussler et al., 1984). While elevated concentrations of gammacerane in bitumoids of the Khatyspyt Formation and mentioned above Vendian–Cambrian bitumens observed in almost all of the studied samples, although variations of gammacerane index GI ($10 \cdot G/G + Hop_{30}$), where G is gammacerane, Hop is hopane) have exhibited a large value spread (GI 0.36 to 3.91), being usually above 1. At this, such GI values never reach even proximity to GI of oils from the Nepa–Botuobiya petroliferous area, where hydrocarbon reservoirs are controlled primarily by salt caprock. Composition and distribution of steranes in the bitumoids of the Khatyspyt Formation in the Olenek and East Anabar natural bitumens are remarkably identical (Fig. 10).

The origin of bitumens of the Central Olenek field interpreted from geological criteria is fairly close to the Khatyspyt Formation as well. Free bitumens (asphalts and asphaltites) begin to occur directly above the source rocks, at the base of the stromatolitic dolomites of the Turkut Formation, and then in its cavernous top (Fig. 4). Their bulk is localized in the overlying basal sandstones and gritstones of the Kessyuse Group. As was mentioned above, the similar stratigraphic levels of the East Anabar and Olenek bitumens occurrence in addition to completely identical biomarker indicators, enable adequate assessment of the Khatyspyt Formation source rock distribution in the SSB. It stands to reason that, in order to allow hydrocarbon fluid migration from oil window (main zone of oil of generation) to the east-

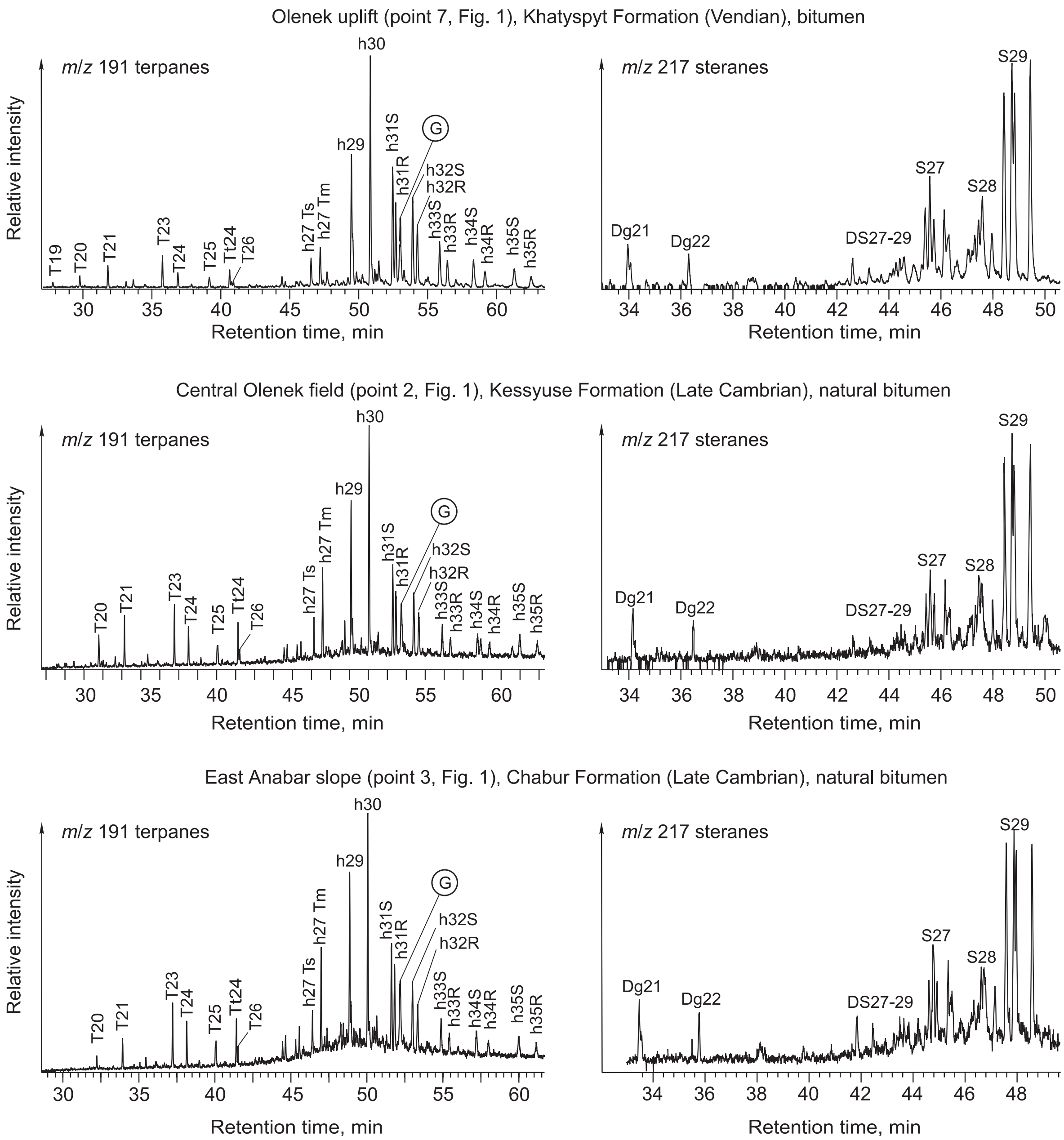

Fig. 10. Mass-chromatograms shows of terpanes (*m/z* 191) and steranes (*m/z* 217) distribution in butumoids and in natural bitumens of Sukhana basin. T, tricyclanes; Tt, tetracyclanes; h, hopanes; G, gammacerane; Dg21, Dg22, diginanes; S27–S29, steranes; DS27–DS29, diasteranes.

ern slope of the Anabar Shield, the formation should at least extend beyond the axial, most subsided, part of the basin (Fig. 1).

According to the chemical and bitumenological data, the most widespread among the naftide shows were documented in the Udachnaya pipe area. However, their geochemical signatures (composition and distribution 12 and 13 monomethylalkanes, terpane and sterane biomarker molecules, carbon isotope composition, etc.) attest to this type being more characteristic of the Nepa–Botuobiya petroliferous region (Kontorovich et al., 1978, 2000; Petrov, 1984; Aref'ev et al., 1993; Kashirtsev et al., 2009). For comparison, results of the study of the Irelyakh oils (Chalaya et al., 2002) are presented herein.

In fractions boiling above 200 °C of the Udachnaya and Irelyakh oils, normal alkanes account for 60–70%, with relatively low molecular weight homologues dominating among them. The distribution maximum is usually associated with n-C_{15}, n-C_{17} or n-C_{19} (Fig. 11).

The odd-numbered carbon chain of normal alkanes distribution (carbon preference index, CPI) is close to 1. The share of isoprenoid hydrocarbons accounts for 10–15% of

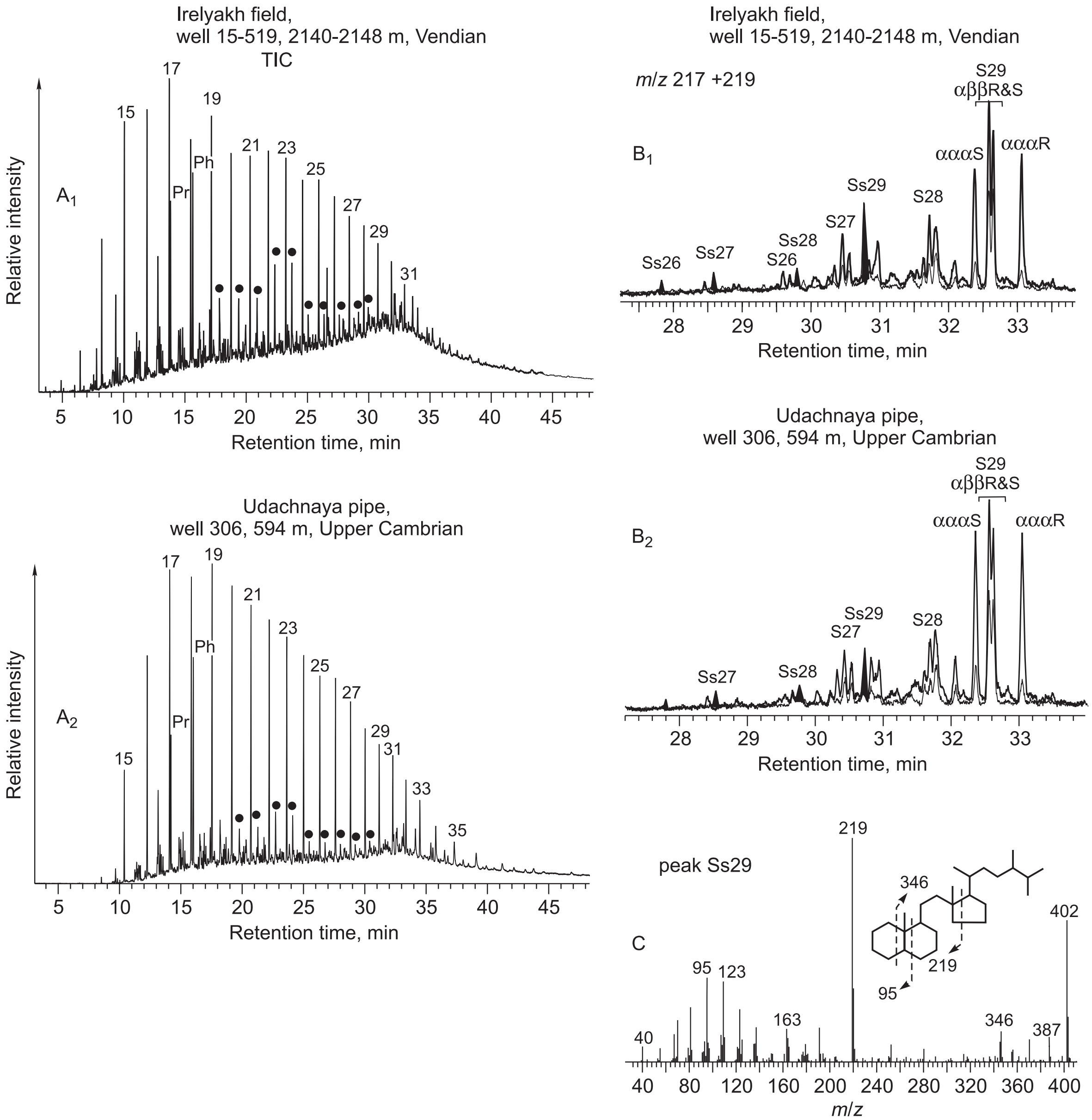

Fig. 11. Mass-chromatograms for total ion current (TIC) shows of distribution of aliphatic hydrocarbons (fractions > 200 °C) from Irelyakh oil field (A_1) and Udachnaya pipe (A_2). B1, B2, Mass-chromatograms of sterane hydrocarbons distribution. C, mass spectrum of secosterane.

the total identified alkanes. Phytane normally prevails over the pristane. The isostructured alkanes in the topped oils are marked by the presence of hydrocarbons of 2-and 3-methyl-alkanes series in the C_{14}–C_{22} range. While in the composition of saturated hydrocarbons, a special place is occupied by "ancient" biomarkers as mid-chain branched alkanes: 12- and 13-methylalkanes (Fig. 11). Their high concentrations, as well as homology, bear a compelling evidence of their relict nature.

Another distinction of these oils consists in the overwhelming dominance of ethylcholestanes (S29 peaks in Fig. 10), whereas diasteranes are almost completely absent from the total balance of sterane hydrocarbons. In the cases of "atypical" steroid structures, several compounds containing no methyl group were located at position C-10 (from *m/z* 203). Besides, the unusual homologous series of tricyclic steroid hydrocarbons was determined from the intense (100%) fragment ion at *m/z* 219.

Molecular-mass ions *m/z* 360, 374, 388 and 402 suggest a tricyclic structure of the homologous series of secosterans C_{26}–C_{29} (Fig. 10). The appearance of two additional hydrogen atoms (*m/z* 219 instead of *m/z* 217) is associated with a broken chain of one of the rings of the sterane skeleton (Kashirtsev et al., 2015).

Judging from the above discussed results, the revealed significant differences between the "Botuobiya type" oil and

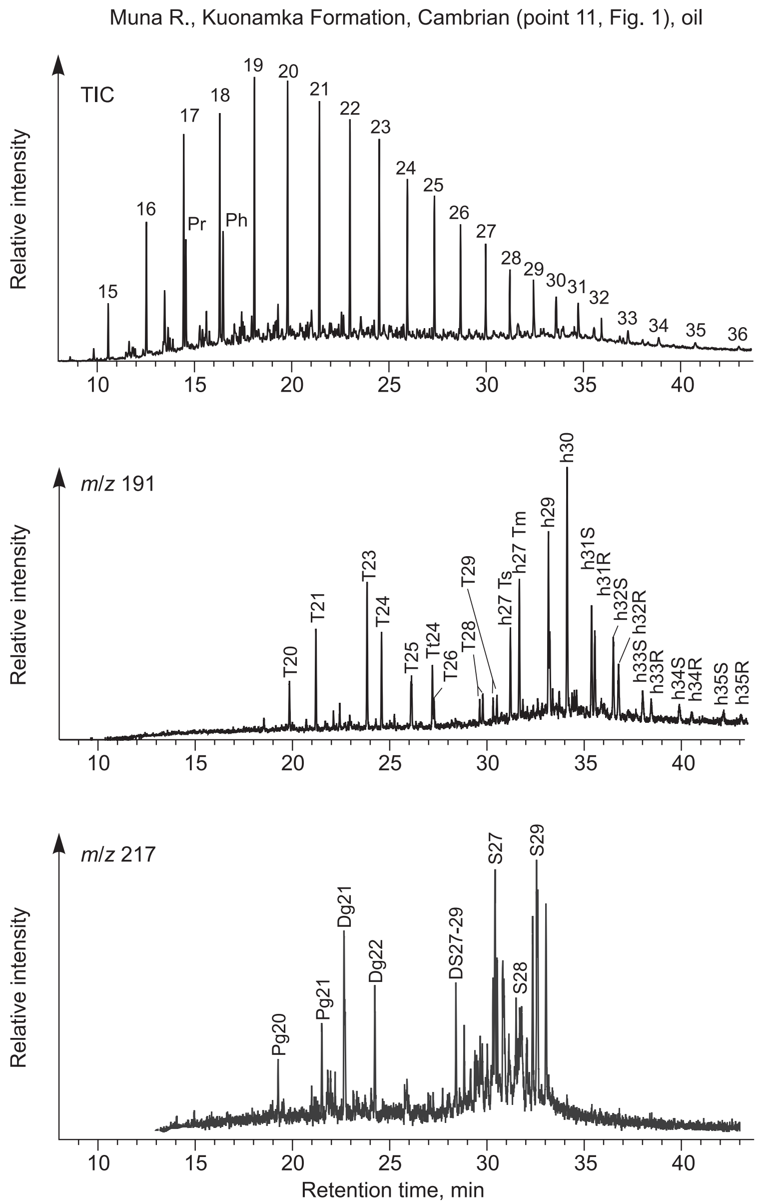

Fig. 12. Mass-chromatogram (TIC) showing distribution of hydrocarbons in the aliphatic fraction of Kuonamka Formation's oil (the Muna River, point 11 in Fig. 1).

the bitumens in the Central Olenek and East Anabar deposits and, obviously, from the Khatyspyt Formation bitumoids, involve a number of parameters. Sadly, this type of oil correlates neither with bitumoids nor crude oils from the Kuonamka rocks. In this respect, geochemical signatures of the viscous oil (Fig. 12) discovered by some authors (Kashirtsev, 2003; Parfenova et al., 2014) in secretory cavities of siderite nodules (the Kuonamka Formation section along Muna River) are particularly interesting.

The most prominent feature distinguishing "the Kuonamka oil" from the Vendian–Cambrian bitumens (eastern slope of the Anabar Shield and Olenek uplift), and from oil accumulations of kimberlite pipes (the Sukhana basin) is a relatively high content of diasteranes (Fig. 12), being characteristic of predominantly clayey source rocks. Whereas diasterane concentrations varying from low to practically nonexistent indicate a greater influence of algal carbonates in the source rocks composition (Moldowan et al., 1985; Peters et al., 2005). The Kuonamka oil and bitumens are distinguished by: vanadyl porphyrin complexes (totally missing in the bitumens and bitumens of the Khatyspyt Formation) and specific distribution patterns of benzothiophenes and triaromatic steroids (Zueva et al., 1992; Kontorovich et al., 2005).

Recently, prospects of searches for and exploration of "shale" oil in Russia have been actively discussed and of geological-engineering evaluation. In our opinion, the highly carbonaceous Kuonamka Formation represents the most promising reservoir rocks in the Sukhana basin. Migrated bitumen (Savitsky et al., 1972; Antsiferov et al., 1981), viscous oils sealed in the siderite nodules cavities (Muna River), and bitumen drips formed in the interplanar spacing of shales (Malaya Kuonamka River) are highly significant indicators of "intraformational" oil bearing potential of this sedimentary complex (Klubov, 1983; Kashirtsev, 2003). Bitumens are observed in the sections of the northeast Siberian Platform on the Molodo, Muna and Kyulenke Rivers in the upper part of the Amydai, Malaya Kuonamka and Maspakyi Horizons (Parfenova et al., 2014). All these data, along with the certain elements concentrations being above the Clarke value, have a strong potential of inviting particular interest from researchers and companies seriously concerned with integrated development of shale formations in Eastern Siberia.

CONCLUSIONS

Direct evidence of oil and gas potential viewed as cumulative contribution of large natural bitumen accumulations on the Sukhana basin's eastern and western slopes, and oil from numerous kimberlite pipes on its southern closure indicate high prospects of this region primarily in terms of searches for oil fields.

The main source-rock complexes of the Sukhana sedimentary basin are: bituminous carbonate Vendian (Ediacaran) Khatyspyt Formation; highly carbonaceous and carbonate-siliceous shaly Kuonamka Formation (lower–middle Cambrian).

The geochemically substantiated genetic link between natural bitumen deposits in the East Anabar/Central Olenek regions and Vendian sediments of the Khatyspyt Formation allowed estimating the area of distribution of the latter far to the west from the Olenek uplift, and beyond the axial part of the basin.

No appreciable accumulations of oil or natural bitumen have been found to be ranked as genetically related to the highly carbonaceous Kuonamka rocks (Formation). At the same time, the "intraformational" (in-situ) evidences of viscous oil, solid bitumen and allochthonous bitumoids in the sections of this complex can serve as sufficiently convincing basis for searches for shale oil in most of the SSB area.

The Siligir–Markha rampart bitumens and oil shows of kimberlite pipes determined from a set of basic geochemical characteristics have shown the closest affinity with the "Botuobiya type" oil of the Mirnyi arch and overwhelmingly likely to owe their origin to the Riphean trough formations on the southern slope of the Anabar anteclise.

We consider that estimates of the basin's petroleum potential on a regional scale should be generally associated with its axial part (Sukhana depression) and the complicating local uplifts (Merchimden rampart, etc.), given that the two major oil source formations (Khatyspyt and Kuonamka), with the organic matter maturity level corresponding to the "oil window zone" are widespread there, while regional reservoirs at the Vendian–Cambrian boundary exhibit good porosity and permeability properties on both the western and eastern slopes of the basin.

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