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Nature of Hydrocarbon Fluids at the Fields in the North of Western Siberia: the Geochemical Aspect

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Abstract—The paper presents original results of comprehensive geochemical studies of samples of oils, condensates, gases, core, and cuttings from wells drilled in the north of Western Siberia. The studies involved chromatographic and mass spectrometric determinations of the molecular and isotopic composition of the oils, gases, condensates, and rock extracts. Analysis of the results, considered together with literature data, made it possible to draw conclusions regarding the source of the hydrocarbons and the mechanism of formation of their accumulations. Information on the molecular and isotopic composition of the fluids and the distribution of their accumulations and fields in the sedimentary cover shows that most of them are of polychronic and polygenic origin. Features of the molecular and isotopic composition of the fluids make it possible to evaluate the contribution of various sources to the formation of hydrocarbon accumulations. The composition of their liquid component was formed as a result of the generation of hydrocarbons by the organic matter of Jurassic source rocks. The Lower and Middle Jurassic rocks with non-marine organic matter also made a significant contribution to the formation of the gas component of deposits in the north of Western Siberia, whereas the Cretaceous rocks generated only dry gas and were likely the main source of gas for the giant fields, whose methane has a light carbon isotope composition. The use of the isotopic composition of carbon in combination with molecular parameters makes it possible to clarify the conditions under which a particular field was formed and to elucidate the migration pathways and distances of hydrocarbon fluids to their accumulation sites.

Keywords: oil, natural gas, source rock, molecular composition, stable isotope, Western Siberia, Bazhenov horizon, microbial gas, thermogenic gas, biodegradation

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INTRODUCTION

The north of Western Siberia hosts uniquely large hydrocarbon resources and reserves. Although thousands of publications have been devoted to this territory, the mechanisms that produced the hydrocarbon accumulations and fields are still largely uncertain. However many hypotheses have been put forth, the truth is only one, and it can be approached the closer, the more information is available. The information must be comprehensive because the conclusions and implications derived from results of even the most detailed studies may still be inaccurate and/or erroneous. In view of this, not only geological information is needed but also that from a broad circle of fields of knowledge: geology, chemistry, physics, thermodynamics, biology, etc. This information should adequately reflect the courses of natural processes resulting in the accumulations of hydrocarbons at various levels of knowledge: nuclear (isotope data), atomic (concentrations and ratios of chemical elements), molecular (composition and concentrations of compounds that make up the hydrocarbon fluids), and planetary (climatic variations and tectonics). When analyzed collectively, this information should provide an internally consistent scenario for the origin of the hydrocarbon accumulations and fields, i.e., explain from which source materials, where, when, why, how much, and of which composition hydrocarbons were formed that are found in a certain trap. Understanding these processes and phenomena is important not only to gain an insight into the genesis of the hydrocarbons but should also significantly reduce the risks of the exploration operations aimed at searches for new hydrocarbon accumulations and fields and should facilitate the optimization of expenses for the production of the hydrocarbons and the development of the fields.

In the late 20th and early 21st centuries, many studies were published that dealt with various aspects of the geochemistry of hydrocarbons in the northern part of Western Siberia. Some of these papers pre-

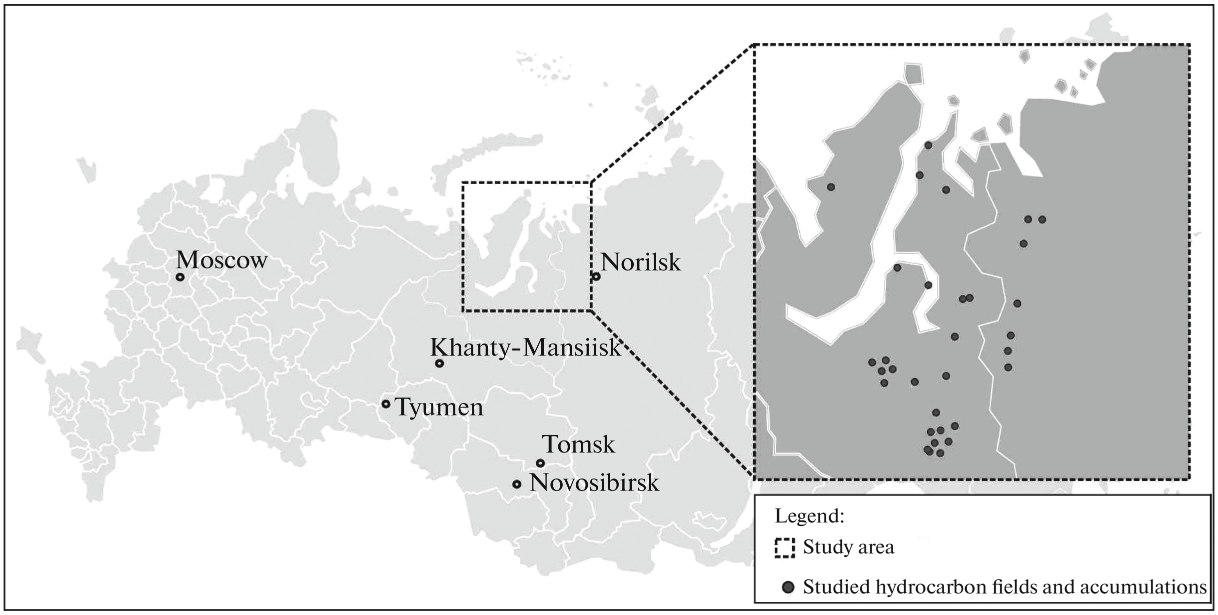

Fig. 1. Location map of the study area.

sented models for the generation of hydrocarbons in the various source rocks (Astakhov, 2015; Nemchenko-Rovenskaya et al., 2011; Kontorovich et al., 2013a; Stupakova et al., 2014). The generated amounts of hydrocarbons were evaluated for both various complexes as a whole (Lower to Middle Jurassic, Upper Jurassic, and Lower to Upper Cretaceous) and some individual formations in them. These results should, however, be viewed cautiously, because they were derived with several assumptions involved in the software and, unfortunately, cannot be verified because of the absence of verification tools. To prove that such modeling results are reasonably accurate, one should provide molecular- and isotope-level proofs that the fluids accumulated in the traps were genetically related to the source rocks, in which the thermal evolution of organic matter resulted in these accumulations (Goncharov et al., 2021).

Recent decades were marked by a tremendous progress in geochemical studies due to, on the one hand, the progress in the sampling techniques (MDT, isotubes, degassing of cuttings) and, on the other, by the principal improvements in the analytical techniques (GC–MS, GC–MS (Q TOF), IRMS pyrolysis), which notably widened the capabilities of geochemistry to acquire more detailed information and eliminated some uncertainties in the interpretations. The authors of this publication were able to use these techniques at laboratories of TomskNIPIneft and NR TPU in Tomsk, and results obtained by studying samples of core material, cuttings, oil, condensate, and gas from dozens of hydrocarbon fields and oil production areas provided us with unique information on the composition of these materials and their genesis. This publication presents some results of these studies. The nature of gas and oil potential of the northern part of Western Siberia shows some differences from and common features with that of Western Siberia as a whole (in the Latitudinal Ob area and the southern and southeastern parts). Herein we use the term *north* as a collective name for the vast territory north of the Siberian Uvals (hills): the Nadym–Pur and Pur–Taz oil- and gas-bearing territories, western part of the Yenisei–Khatanga territory, Yamal, Gydan, Taimyr, and the Kara Sea (Fig. 1).

PREEXISTING HYPOTHESES

In the wake of the discoveries of giant hydrocarbon fields in the north of Western Siberia in the second half of the 20th century, two publications of researchers at SNIIGIMS and VNIGRI came off the press in 1967 (Gurari et al., 1967; *Formation Conditions*, 1967). Then-available information led the authors to the conclusion that the hydrocarbon accumulations were formed by the vertical migration of fluids from the Jurassic rocks. Note that in spite of some difference in the interpretations provided by these authors, none of them did consider the Cretaceous rocks as the source. Simultaneously a paper was published by a research team at ZapSIBNIGNI (Boyarskikh et al., 1967), in which the authors distinguished six oil- and gas-bearing reservoir complexes in the geological section: Lower to Middle Jurassic, Upper Jurassic, Valanginian, Hauterivian–Barremian, Aptian–Cenomanian, and Upper Cretaceous. These authors believed that the hydrocarbons were generated and formed accumulations at their lateral migrations within each of the complexes.

The authors of a series of papers published next year (Bagrintseva et al., 1968; Velikovskii et al., 1968; Nemchenko and Rovenskaya, 1968) argued that the gas- and oil-generating processes involved the organic matter of non-marine genesis, including that in the Middle and UpperCretaceous rocks. Collectively, these papers presented all interpretations of the nature of oil and gas accumulations in the territory that have been put forth as of now. It should be mentioned that all of the publications utilized the same information on the geology of the territory and then-scarce data on the composition and properties of the obtained liquid and gaseous fluids, and all the conclusions were drawn then from this information, with regard to general geological interpretations.

The next step was taken in the 1970s through 1980s, when information became available on the carbon isotope composition of gases from the various fields (Ermakov et al., 1970; Vasil'ev et al., 1970; Nesterov et al., 1981). It was found out that $\delta^{13}C$ of the sum of the gaseous hydrocarbons varies from –34.3 to –64.7‰. The gases of the Cenomanian rocks were proved to have a generally isotopically lighter composition than that of the gases of the Jurassic and Valanginian rocks, which was interpreted as direct evidence that the hydrocarbons came from more than a single source. For example, it was claimed (Vasil'ev et al., 1970) that "the dominant source of gas for the gas fields in northern part of Western Siberia was the coal organic matter of the Pokurskii Group affected by initial metamorphism". In 1981, it has been demonstrated that in spite of the fact that the gas of the Cenomanian rocks has a similarly dry composition, the isotope composition of the methane varies very broadly (within 16‰), within 10‰ in the Cenomanian rocks of the Urengoi field (Nesterov et al., 1981).

GEOLOGY AND STRATIGRAPHY

The geological section of northern part of Western Siberia differs from that of the southern regions in that the thicknesses of the Jurassic–Cretaceous complex in the former are much greater. Oil and gas accumulations are found in the former territory within a very broad range of depths and stratigraphic units: these accumulations occur at depths of 750 to >4500 m, and the reservoir rocks range from Middle Jurassic through Cenomanian–Turonian inclusive. The thicknesses of the Mesozoic rocks also widely varies: it increases at tectonically subsided territories and notably decreases at structures. The geological section consists of alternating rocks of different lithology because of tectonic processes that caused variations in the depth of the sedimentation basin. During transgressions (Fig. 2), clay rocks were accumulated in marine environments, whereas rocks enriched in sandy facies were accumulated in littoral facies during regressions (Shemin et al., 2019).

The stratigraphic section comprises a number of hydrocarbon reservoir complexes: Lower–Middle Jurassic, Upper Jurassic, Neocomian, Barremian–Aptian, and Albian–Cenomanian. The Lower–Middle Jurassic complex (Shemin et al., 2019) is dominated by alluvial–deltaic, lacustrine, and littoral rocks, whose thickness amounts to 2 km and more.

The Lower Jurassic rocks comprise the Zimnii, Levinskiy, Sharapov, Kitebyut, and Nadoyach horizons. The Middle Jurassic sequence includes the Malyshev, Leont'ev and Vym horizons. The Upper Jurassic rocks include the Vasyugan, Georgiev, and Bazhenov horizons (Fig. 2). In various parts of the territory, the Bazhenovhorizon is included in different formations: Bazhenov, Gol'chikhin, and Yanovstan (Ryzhkova et al., 2018), which are constrained to territories with the maximum transgression of the sedimentation basin in the Upper Jurassic and Lower Cretaceous (J_3tt–K_1b). All of the formations show some common features of sedimentation, which predetermined the type of their organic matter and, hence, the composition and properties of the generated fluids. The Bazhenov horizon rests on Yu_1 unit. The underlying Middle and Lower Jurassic rocks include Yu_2, Yu_3, Yu_4, etc. units.

The Bazhenov horizon is overlain by rocks of the Berriasian–Aptian complex, whose bottom part is clays of the Podachimov unit and sands of the Achimovunit, which were formed during the attenuating Upper Jurassic transgression. The geological section is dominated by mudstones and sandstones and to a lesser extent coaly rocks. BT, Byu, Bya, Ach, and Nkh units host the bulk of the liquid hydrocarbon resources. Farther up the stratigraphic section, the Aptian–Albian–Cenomanian rocks (Tanopchin and Yakovlev formations) contain more rocks accumulated in littoral facies. These are intercalating siltstone, sandstone, and coal beds, to which most of the gas accumulations are constrained: the giant gas fields of northern Western Siberia.

SAMPLES AND METHODS

Nowadays our collection of studied oil, condensate and gas samples from fields in northern part of Western Siberia is one of the most representative (Fig. 1). This publication presents our results obtained by studying 97 oil samples and 320 samples of accompanying-gas and free-gas samples from gas caps and gas accumulations at 32 fields. Some of our results are not presented in the tables but are shown in the figures. In addition to gas samples acquired during well tests and production, we also studied gas samples obtained at the degassing of the drill mud, which was sampled in the course of drilling, and gas released from the core material of the source rocks that was released when the core was transported in hermetically sealed tubes.

The oil, condensate, and rock extracts were divided into fractions. Asphaltenes were precipitated from the samples by petroleum ether. The deasphaltenizates

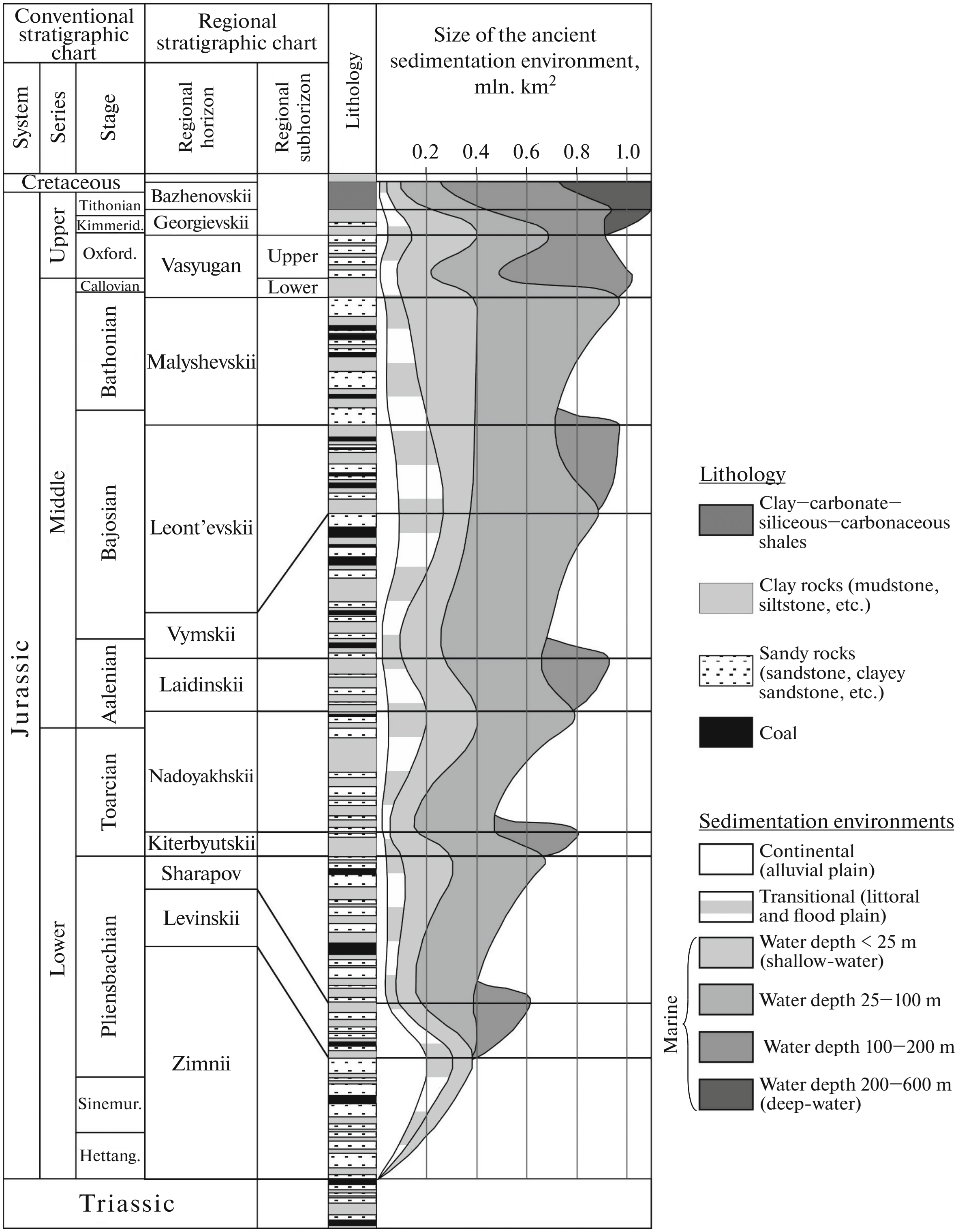

Fig. 2. Lithostratigraphy and Jurassic sedimentation conditions in the northern part of Western Siberian basin (modified after Shemin et al., 2019).

were divided by liquid-adsorption chromatography on silica gel into fractions of saturated hydrocarbons, aromatic hydrocarbons, and resins, which were eluated by the following solvents: petroleum ether, petroleum ether/toluene (6 : 1 by volume), and toluene/ethanol (1 : 1 by volume), respectively.

Carbon isotope composition ($\delta^{13}C$) was determined in samples of oils, condensates, extracts from rocks, and fractions from them on a DELTA V ADVANTAGE Thermo Fisher Scientific mass spectrometer coupled to a Flash 2000 element analyzer.

The carbon isotope composition of the C_1–C_5 gas compounds was measured on the same mass spectrometer but with the application of another sample preparation system: it was a Trace GC Ultra gas chromatograph equipped with an GC Isolink system. Components were separated in a PoraPlot Q (52.5 m × 0.32 mm × 10 μm) capillary column in a programmed-temperature regime. The isotope ratios are reported below in ‰ relative to the VPDB international standard.

The results of replicate $\delta^{13}C$ measurements with the application of a Flash 2000 element analyzer as the sampling tool were mutually consistent within ±0.15‰ (on average), and were consistent within no more than ±0.25‰ if Trace GC Ultra + GC Isolink were used.

The molecular composition of oils, condensates, and extracts from rocks was studied by gas chromatography–mass spectroscopy (GC–MS) on a Hewlett Packard 6890 gas chromatograph coupled to a 5973 mass selective detector. The chromatographic study was conducted using an HP-1-MS (30 m × 0.25 mm) column, with linearly programmed temperature variations: 3 min at 45°C, heating to 310°C at a rate of 3°C/min, thermostatting for 20 min.

Samples of the source rocks mentioned in this publication were studied by pyrolitic technique on a Rock-Eval 6 Turbo (Behar et al., 2001). We have evaluated the residual generation potential of the rocks (S_2, mg HC/g rock and HI, mgHC/gTOC), content of organic carbon (total organic carbon, TOC, wt %), and the temperature of the maximum yield of the S_2 peak (T_{max}, °C).

RESULTS AND DISCUSSION

Source Rocks

The properties of the rocks as a source and their grades of catagenesis broadly vary over the study area, although some common general tendencies and relations are discernible in all of them (Lopatin and Emets, 1999a; Larichev et al., 2003; Filiptsov et al., 2006; Rodchenko, 2016; Afanasenkov et al., 2018, 2019; Fursenko et al. 2021). The Lower Jurassic rocks are the poorest in organic matter, and their organic matter is mostly strongly modified thermally. At most of the territory, this organic matter occurs outside the oil window and is able to generate only small amounts of dry gas (Fomin, 2011; Bogoyavlenskii and Polyakova, 2012). The catagenesis (according to the vitrinite reflectance, R_0) is above 1.5–2% (Fomin, 2011), and hence, the residual generation potential of the organic matter (HI) is <100, and is < 10 mg HC/g TOC in the lowest horizons (Lopatin and Emets, 1999b).

The Middle Jurassic rocks contain much more organic matter, but it contains a large proportion of coals and coaly mudstones. However, some of the mudstone beds contain organic matter of mixed genesis. Most of these rocks occur at the end of the main oil window and onset of the main gas window. In spite of that their generation potential has been largely converted, their HI reaches 300 mg HC/g TOC. It should be borne in mind that the hydrocarbons generated by organic matter of this type are dominated by gaseous component. The best generation parameters in the study territory and Western Siberia as a whole are typical of the rocks of the Bazhenov horizon. They commonly contain 2–6% TOC, and its content occasionally reaches 10% and more (Kontorovich et al., 2018; Lopatin and Emets, 1999a). The initial HI values are as high as 500 mg HC/g TOC and more in the vicinities of the Vankor field (Goncharov et al., 2009a). The organic matter occurs in the active oil window in most of the rocks and has retained its original potential only in the peripheries, in the most uplifted parts of the basin. It is thought that organic matter has entered the gas window in the most buried parts (Fomin, 2011).

The Lower Cretaceous rocks (Akh and Tanopchin formations) contain 1–2% TOC, and the coaly mudstones contain up to 15% TOC. The generation potential of the mudstones OM is usually relatively low (HI = 70–250 mg HC/g TOC) but reaches 350–450 mg HC/g TOC in the coaly mudstones and coals.

Extensive studies have demonstrated that the organic matter of the Cretaceous rocks at most of the territory has not reached maturity sufficient for the beginning of generation of liquid and gaseous hydrocarbons. Only in the most buried parts did it reach the necessary maturity, sufficient to start the generation of liquid hydrocarbons. We have studied in much detail the geochemistry of the core, cuttings, and extracts from rocks of appraisal well Gydanskaya-130, which has been drilled throughout the whole Mesozoic complex (Fig. 3). The vitrinite reflectance R_c calculated for the Lower Cretaceous rocks is 0.55–0.60%, and T_{max} (according to Rock-Eval pyrolysis data) is 430–435°C. At the same time, T_{max} of the Lower Jurassic rocks (Zimnii and Levin horizons) exceeds 500°C, and R_c > 1.8%. Figure 3 also shows that the Aptian–Albian and Middle–Upper Jurassic rocks are rich in TOC, and the current generation potential of the organic matter is >400 mg HC/g TOC. A set of molecular and pyrolitic parameters of catagenesis indicate that the organic matter of the Jurassic rocks is in the hydrocarbon window. Concentrations of organic matter in the Cretaceous and Lower–Middle Jurassic complex, which is made up of coal and coaly shales, are much higher than in the rocks of the Bazhenov horizon. The total thickness of the coaly rocks with high concentrations of organic matter is much greater. The base surface of the Sharapov horizon has T_{max} up

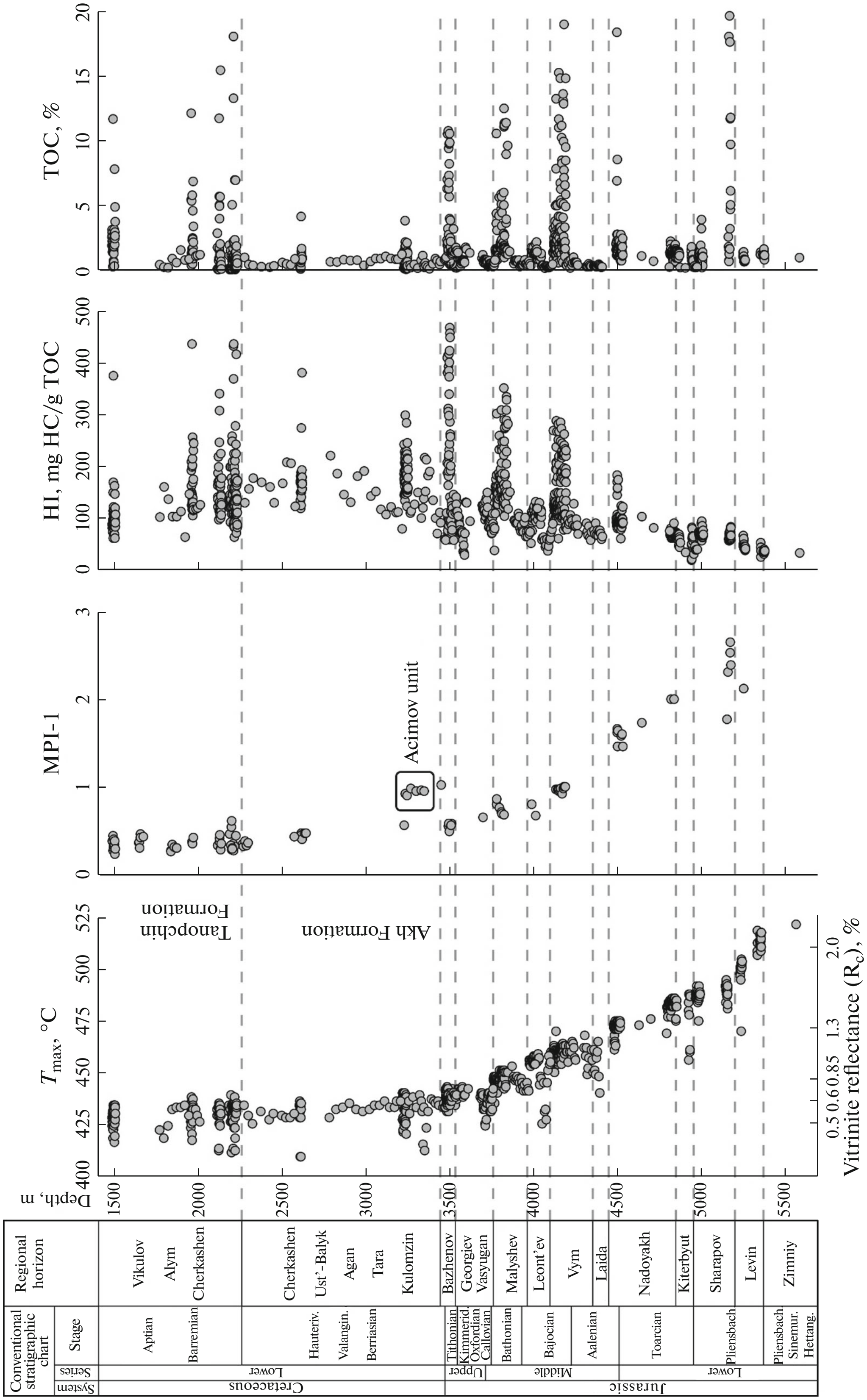

Fig. 3. Variations in some geochemical parameters with depth along Well Gydanskaya-130 (the diagram of TOC show samples with values no lower than 20%; the Methylphenanthrene index-1 or MPI-1 = 1.5 × (2-MP + 3-MP)/((P × 0.69) + 1-MP + 9-MP), where MP are methylphenanthrene isomers, P is phenanthrene, R_c is vitrinite reflectance, calculated as $R_c = 0.018 \times T_{max} - 7.16$ (Jarvie et al., 2001).

to 500°C and HI < 80 mg HC/g TOC. Such organic matter is able to generate only dry gas.

Oils and Condensates

The composition of formation fluid depends on several factors: the genesis of the organic matter, catagenesis, migration, biodegradation, retrograde processes, etc. Table 1 lists fields from which liquid samples have been analyzed. This list includes hydrocarbon accumulations in reservoirs from the Middle Jurassic to the UpperCretaceous. Their composition and properties broadly vary, which was mentioned many times in the literature (Stasova et al., 1981; Fursenko et al., 2021). It is enough to mention that their density lies within the range of 0.750 to 0.960 g/cm^3. The principal molecular parameters listed in this table are the ratio of the isoprenoid hydrocarbons of pristane and phytane (Pr/Ph) and the ratio of the sum of their concentration with C_{17} and C_{18} *n*-alkanes [isoprenoid coefficient: $K_i = (Pr + Ph)/(n\text{-}C_{17} + n\text{-}C_{18})$]. The Pr/Ph ratio is conventionally and widely used and as a readily determinable facies–genetic parameter of oils and condensates. It is principally important that this genetic signature, which is inherited by oil from the organic matter of the source rock, is not modified in the course of catagenesis and migration but can be modified at biodegradation and phase transitions. Phase transitions can be taken into account by merely introducing a correction (Goncharov and Lebedeva, 1985) with regard to the condensate distribution of the sample (if this is condensate). The parameter Pr/pH reflects the redox conditions under which the source organic matter was buried in the sedimentation basin. During the maximal Volgian–Valanginian transgression in central Western Siberia, the sediments of the Bazhenov horizon were accumulated at H_2S contamination of the bottom waters in strongly reducing environments. These rocks served as the source ones for all giant fields in the Latitudinal Ob area. The Pr/Ph ratio of these oils lies within the range of 0.6–1.2. From the central part to peripheries of the basin, its depth decreased, and the probability of biomass oxidation in the course of sedimentation simultaneously increased, which is reflected in the elevated Pr/pH values of extracts from the rocks of the Bazhenov unit (Goncharov, 1987) (Bazhenov, Golchikhin, and Yanovstan formations) and the oils generated by these rocks. In the territories of the Yamal, Gydan, and Taimyr peninsulas, as well as the rest of the Yamal–Nenets Autonomous Territory, the Pr/pH ratio of oils and extracts from the source rocks of the Bazhenov horizon broadly varies from 1.3 to 2.1. We attributed the oils generated by these rocks to the Bazhenov type, by analogy with the southeastern part of Western Siberia (Goncharov et al., 2003, 2012). Data in Table 1 imply that most of these oils are hosted in Cretaceous traps and much less in the stratigraphically lower Upper Jurassic reservoirs (bed Yu_1 at the Kharampurskoe and Vostochno-Urengojjskoe).

An antipode of the Bazhenov-type oils is oils generated by the organic matter of pre-Bazhenov Lowerto Middle Jurassic rocks, which we refer to as the Togur type (Goncharov et al., 2003, 2012). These oils were generated by organic matter that was produced mostly by non-marine bioproducers and was buried under relatively oxidizing conditions, which occurred mostly in lacustrine–paludal and littoral environments. As a consequence of this, extracts from these rocks and the genetically related oils display the highest Pr/Ph (3–5 and higher), which makes these oils readily and reliably discernable from the Bazhenov oils. Practically no accumulations of Togur-type oils have ever been found in the Latitudinal Ob area, but much of these oils occur in southeastern Western Siberia. These oils occur there as accumulations hosted mostly in Middle and Upper Jurassic reservoirs, and also sometime in Cretaceous rocks, if the circumstances were favorable (Festivalnoe and Yuzhno-Myldzhinskoe fields) (Goncharov et al., 2012). The involvement of fluids of this genetic type in producing the oil and gas potential of northern part of Western Siberia has been repeatedly stressed in the literature (Vorob'eva et al., 1992; Skorobogatov et al., 2003, 2006; Soboleva et al., 2019; Goncharov et al., 2022; Chakhmakhchev et al., 1994; Katz et al., 2003; Liu et al., 2016; Fursenko and Kim, 2019; Leushina et al., 2021).

Another important parameter, K_i (Table 1), reflects catagenesis, i.e., the destruction stages (sequences) of the organic matter when oil was generated. The very first fluid portions (extracts from the source rock) generated by the organic matter have $K_i > 1.0$. The further thermal evolution of the organic matter is associated with a continuous decrease in K_i to 0.2 and lower (Goncharov et al., 2004).In contrast to the Pr/pH ratio, the value of K_i very strongly depends on the process of biodegradation, i.e., the microbial oxidation of oil. This parameter is one of the most susceptible criteria of how much the fluid is affected by biochemical degradation in the formation (Goncharov, 1987). However, biodegradation can proceed in a formation only at temperatures below 70°C, and if the formation had got good reservoir properties. The latter is no less important than the reservoir temperature, and biodegradation within a single hydrocarbon accumulation is controlled primarily by the reservoir properties. We have demonstrated this by the example of horizon Nkh_{3-4} at the Vankor field (Oblasov et al., 2018), where this parameters was applied in a modified form. The situation seems to be analogous at some other fields. For example, K_i in horizon RK_{19} at the Beregovoe field varies from 0.38 to 10 and higher. Because of this, if a value of K_i in Table 1 is greater than 0.8, it is highly probable that the oil is biodegraded, and such samples should be very cautiously used in genetic interpretations. In Table 1, oils (condensates) of the Togur-type definitely comprise samples with Pr/Ph > 3.0 and $K_i < 0.4$.

Table 1. Oils and condensates: values of the molecular parameters calculated from the GC–MS data, carbon isotope composition ($\delta^{13}C$) of the oil and its fractions (SatHC—saturated hydrocarbons, ArHC—aromatic hydrocarbons, Re—resins, Asp—asphaltenes)

No.	Field, area	Reservoir age	Horizon	Pr/Ph	K_i	$\delta^{13}C$ oil, ‰	$\delta^{13}C$ SatHC, ‰	$\delta^{13}C$, ArHC, ‰	$\delta^{13}C$ Re, ‰	$\delta^{13}C$ Asp, ‰
1	Bajkalovskoe	Lower Cretaceous	Bk_0	3.40	**1.31**	−30.4	–	–	–	–
2	Bajkalovskoe	Lower Cretaceous	Bk_3	3.17	**10.1**	−30.5	–	–	–	–
3	Bajkalovskoe	Lower Cretaceous	Nsk-VI	1.56–2.13	0.61–**10.7**	−31.6	−32.0	−30.5	−30.6	−30.1
4	Bajkalovskoe	Lower Cretaceous	Nsk-VIII ?	1.53	0.73	–	–	–	–	–
5	Bajkalovskoe	Lower Cretaceous	Nsk-IX	1.99	0.61	−31.2	–	–	–	–
6	Bajkalovskoe	Lower Cretaceous	Nsk-XIII	1.45	0.57	−31.3	−32.3	−31.1	−30.8	−31.1
7	Bajkalovskoe	Lower Cretaceous	Nsk-XIV	1.51	0.58	−32.3	−32.3	−31.2	−31.0	−31.0
8	Bajkalovskoe	Lower Cretaceous	Nsk-XV	1.47	0.57	−32.5	−32.5	−31.5	−31.2	−32.5
9	Beregovoe	Aptian	RK_{19}	2.10–5.42	0.38–**3.92**	−28.3 to −27.1	–	–	–	–
10	Beregovoe	Lower Cretaceous	$A_{7\text{-}8}$	2.60	0.41	−28.4	–	–	–	–
11	Beregovoe	Lower Cretaceous	Ach_1	1.59	0.64	−32.3	−33.0	−32.0	−31.3	−30.6
12	Beregovoe	Lower Cretaceous	$BT_{5\text{-}4}$	2.82	0.37	−28.3	–	–	–	–
13	Beregovoe	Lower Cretaceous	BT_{10}	1,66	0.56	−31.3	–	–	–	–
14	Beregovoe	Upper Jurassic	Yu_1^4, Yu_1^3	3.53	0.33	−27.2	–	–	–	–
15	Beregovoe	Middle Jurassic	Yu_2	3.25	0.31	−26.6	−27.7	−25.1	−25.9	–
16	Bovanenkovskoe	Aptian	TP_{14}	2.15–2.78	**10.9–3.57**	−29.8 to −29.0	–	–	–	–
17	Bovanenkovskoe	Barremian	TP_{15-16}	1.86	**0.89**	−29.2	–	–	–	–
18	Bovanenkovskoe	Barremian	TP_{17}^{I}	1.69	0.46	−30.3	–	–	–	–
19	Bovanenkovskoe	Hauterivian	BYa_1	1.60	0.38	−29.9	–	–	–	–
20	Bovanenkovskoe	Hauterivian	BYa_2	1.55	0.30	29.4	–	–	–	–
21	Bovanenkovskoe	Hauterivian	BYa_4	1.56–1.77	0.30–0.26	−29.0 to −28.4	–	–	–	–
22	Vankor	Aptian-Albian	$Yak_{3\text{-}7}$	1.30–2.13	**0.85–3.70**	−30.53	−30.9	−29.4	−29.8	−30.1
23	Vankor	Valanginian-Hauterivian	Sd_9	1.94	**7.32**	–	–	–	–	–
24	Vankor	Berriasian-Valanginian	Nkh_1	1.93–2.01	0.57–**1.42**	–	–	–	–	–
25	Vankor	Berriasian-Valanginian	$Nkh_{3\text{-}4}$	1.61–1.94	0.56–0.77 **(15.1)**	−31.7	−32.0	−30.8	−30.9	−30.7
26	Vankor	Berriasian-Valanginian	Nkh_4	1.96–2.10	**2.14–12.2**	−31.6	−31.8	−30.9	−30.9	−30.7
27	Verkhnekubinskii LA	Lower Cretaceous	Sd_6	1.44	**1.20**	−28.9	−29.7	−27.6	–	–
28	Verkhnekubinskii LA	Lower Cretaceous	$Sd_{7\text{-}8}$	1.37	**0.69**	−28.7	−29.5	−27.7	–	–
29	Verkhnekubinskii LA	Lower Cretaceous	Sd_8	2.61	0.70	−28.3	−29.1	−26.9	–	–
30	Verkhnekubinskii LA	Lower Cretaceous	Sd_9	2.06	0.52	−28.5	−29.4	−26.7	–	–
31	Verkhnekubinskii LA	Lower Cretaceous	Sd_{11}	1.76	**0.79**	−28.5	−29.5	−27.6	–	–
32	Verkhnekubinskii LA	Lower Cretaceous	Sd_{13}	2.49	**1.13**	−28.5	−28.7	−27.0	–	–
33	Vostochno-Messojakhskoe	Cenomanian	$RK_{1\text{-}3}$	1.85	**3.53**	−29.2	−29.7	−28.7	−30.2	−29.7
34	Vostochno-Messojakhskoe	Aptian	$Mkh_{8\text{-}9}$	1.85	**2.80**	−30.9	−31.2	−30.1	−30.2	−29.9
35	Vostochno-Messojakhskoe	Hauterivian	BU_8	1.81	0.93	−31.0	−31.4	−30.4	−30.6	−29.9

Table 1. (Contd.)

No.	Field, area	Reservoir age	Horizon	Pr/Ph	K_i	δ13C oil, ‰	δ13C SatHC, ‰	δ13C, ArHC, ‰	δ13C Re, ‰	δ13C Asp, ‰
36	Vostochno-Messojakhskoe	Valanginian	BU_{13}^1	1.80	0.59	−31.2	−31.4	−30.4	−30.7	−30.1
37	Vostochno-Urengoy LA	Lower Cretaceous	Ach_5^{2-3}	3.26	0.36	−25.8	−28.2	−26.2	−28.2	–
38	Vostochno-Urengoy LA	Lower Cretaceous	Ach_6	2.58	0.35	−26.3	−26.7	−24.8	−27.0	–
39	Vostochno-Urengoy LA	Upper Jurassic	YuK_0	1.73	0.67	−30.3	–	–	–	–
40	Vostochno-Urengoy LA	Middle Jurassic	Yug_2	1.92	0.44	−30.0	–	–	–	–
41	Vostochno-Urengoy LA	Middle Jurassic	Yug_3	3.39	0.24	−26.3	−26.7	−24.8	−27.0	–
42	Vyngajakhinskoe	Lower Cretaceous	BP_{17}	1.50	0.66	−31.6	–	–	–	–
43	Gorchinskiy LA	Middle Jurassic	Yu_2	4.05	0.33	−26.0	–	–	–	––
44	Gydanskoe	Lower Cretaceous	Ach	2.28	0.61	−29.4	−30.4	−29.2	−29.7	−30.9
45	Zapadno-Irkinskiy LA	Berriasian-Valanginian	Nkh_{4-5}	1.71	0.48	−31.8	–	–	–	–
46	Zapadno-Lodochnoe	Middle Jurassic	Maly-shevskaya Formation	4.37	0.32	−28.4	–	–	–	–
47	Ichemminskaya	Lower Cretaceous	SD_2	2.54	0.36	−29.6	–	–	–	–
48	Ichemminskaya	Berriasian-Valanginian	Nkh_{3-4}	2.60	0.44	−30.6	–	–	–	–
49	Ichemminskaya	Middle Jurassic	Maly-shevskaya Formation	3.39	0.34	−27.1	–	–	–	–
50	Kynskoe	Upper Jurassic	Yu_1^4	3.35	0.31	−27.0	–	–	–	–
51	Lodochnoe	Aptian-Albian	Yak_5	1.46	**3.62**	−30.2	–	–	–	–
52	Lodochnoe	Berriasian-Valanginian	Nkh_1	1.78	0.79	−31.3	–	–	–	–
53	Lodochnoe	Berriasian-Valanginian	Nkh_3	1.85–1.96	0.51–**2.36**	–	–	–	–	–
54	Mangazejjskoe	Upper Jurassic	$Yu_1^2 + Yu_1^3$	3.23	0.33	−27.9	−28.3	−25.9	−28.3	−28.3
55	Novo-Urengoy LA	Lower Cretaceous	Ach_{3-4}	3.21–3.64	0.26–0.35	−27.6 to −25.3	–	–	–	–
56	Novo-Chasel'skii LA	Upper Jurassic	Yu_1^2	4.58	0.24	−26.4	–	–	–	–
57	Pajjyakhskoe	Berriasian-Valanginian	Nkh_4^{1-3}	1.77	0.71	−32,4	−32.5	−31.3	−31.1	−31.6
58	Peljatkinskoe	Valanginian-Hauterivian	Sd_8	3.56	**0.72**	−30.2	–	–	–	–
59	Rogozinskaja (western dome)	Lower Jurassic	–	3.00	0.21	−29.7	−28.8	−27.6	−28.7	–
60	Russkoe	Albian	RK_3	–	–	−30.1	−30.2	−29.4	−29.7	−29.4
61	Russkoe	Albian	$RK_4 + RK_5$	–	–	−30.0	−30.5	−29.5	−30.2	−29.4
62	Russkoe	Albian	RK_6	2.63	0.43	−30.0	−30.4	−29.3	−29.9	–
63	Russkoe	Barremian	Mkh_8	–	–	−30.5	−31.3	−30.5	−30.3	−29.9
64	Russkoe	Lower Cretaceous	BT_2^1	2.05	0.49	−30.8	−31.1	−30.1	−30.1	−29.5
65	Russkoe	Lower Cretaceous	Bt_4	2.14	**0.87**	−30.9	−31.4	−30.7	−30.3	−30.1
66	Russkoe	Middle Jurassic	Yu_2	3.79	0.26	−26.5	−28.0	−25.2	−27.3	–
67	Russko-Rechenskoe	Valanginian	BT_{14}	1.98	0.55	−31.4	−31.7	−30.9	−30.3	–

Table 1. (Contd.)

No.	Field, area	Reservoir age	Horizon	Pr/Ph	K_i	δ13C oil, ‰	δ13C SatHC, ‰	δ13C, ArHC, ‰	δ13C Re, ‰	δ13C Asp, ‰
68	Russko-Rechenskoe	Middle Jurassic	$Yu_3^1 + Yu_3^2 + Yu_4$	4.58	0.34	−27.2	−28.7	−26.3	−27.1	–
69	Salmanovskoe	Aptian	TP_1	6.64	**4.35**	−28.6	–	–	–	–
70	Salmanovskoe	Aptian	TP_{12}	6.09	**1.64**	–	–	–	–	–
71	Salmanovskoe	Aptian	TP_{14}	2.41	**0.62**	−28.5	–	–	–	–
72	Salmanovskoe	Barremian	TP_{16}^2	2.83	0.40	–	–	–	–	–
73	Salmanovskoe	Barremian	TP_{17}	2.78	0.42	−28.7	–	–	–	–
74	Salmanovskoe	Barremian	TP_{18}	3.39	0.32	−28.3	–	–	–	–
75	Salmanovskoe	Barremian	TP_{21}^1	2.57	0.43	−28.7	–	–	–	–
76	Salmanovskoe	Barremian	TP_{22}	2.67	0.32	−27.1	−29.3	−27.1	−27.8	−28.5
77	Salmanovskoe	Barremian	TP_{25}^1	2.10	0.46	−28.9	−30.0	−28.1	−30.7	−29.9
78	Salmanovskoe	Barremian	TP_{27}^2	2.42	0.39	−27.0	−28.3	−26.4	−30.9	–
79	Samburgskoe	Lower Cretaceous	Ach_3	1.81	0.67	−29.7	–	–	–	–
80	Samburgskoe	Lower Cretaceous	Ach_5	1.95–2.82	0.41–0.63	−30.7 to −28.6	–	–	–	–
81	Samburgskoe	Lower Cretaceous	Ach_6^1, Ach_6^{0-2}	2.88	0.39	−28.3	–	–	–	–
82	Samburgskoe	Middle Jurassic	Yu_2, Yu_4, Yu_5	3.44	0.37	−27.1	–	–	–	–
83	Severo-Komsomol'skoe	Upper Cretaceous	RK_1	–	–	−30.3	–	–	–	–
84	Severo-Russkoe	Upper Cretaceous	RK_{19}	5.23	**8.02**	−27.4	–	–	–	–
85	Severo-Russkoe	Lower Cretaceous	BT_{11}	1.61–1.99	0.40–0.58	−30.3	–	–	–	–
86	Severo-Russkoe	Lower Cretaceous	BT_{12}	1.33–1.58	0.48–0.62	−31.2 to −30.1	−31.4	−29.8	−30.8	–
87	Severo-Russkoe	Middle Jurassic	Yu_2^1	3.25	0.33	−24.7	−27.1	−29.6	−26.4	–
88	Tul'skoe	Lower Cretaceous	$vYak_1$	–	–	−30.9	−31.1	−30.6	−30.6	−30.2
89	Suzunskoe	Berriasian-Valanginian	Nkh_1	2.01	0.54	−31.3	–	–	–	–
90	Suzunskoe	Berriasian-Valanginian	Nkh_3	2.03	0.55	–	–	–	–	–
91	Urengojjskoe	Lower Cretaceous	BU_8	2.26	0.64	−32.1	–	–	–	–
92	Khadyr'jakhinskii LA	Aptian	RK_{20}^3	1.96–3.71	0.47–**2.08**	−28.2	−28.7	−30.5	–	–
93	Khadyr'jakhinskii LA	Valanginian	Bt_{14}	1.58	0.55	−32.1	−32.6	−31.8	−31.2	−30.0
94	Khadyr'jakhinskii LA	Upper Jurassic	Yu_1^4, Yu_1^2	1.25	0.55	−29.9	−30.4	−28.2	−29.5	−28.9
95	Kharampurskoe	Aptian	RK_{20}	–	–	−30.7	−31.6	−30.3	−30.1	−29.5
96	Kharampurskoe	Upper Jurassic	Yu_1	1.83	0.41	−31.2	−31.6	−30.8	−30.6	−29.8

Pr/Ph is the ratio of the pristane concentration to that of phytane; $K_i = (Pr + Ph)/(n\text{-}C_{17} + n\text{-}C_{18})$ is the isoprene coefficient. For samples with a condensate distribution, values are corrected according to (Goncharov and Lebedeva, 1985).

K_i values printed in bold pertain to biodegraded samples.

Figure 4 shows some dependences illustrating relations between molecular and isotope parameters of hydrocarbon in the samples. Their analysis provides information on the genesis of the fluids listed in Table 1. A decrease in K_i is definitely correlated with an increase in Pr/Ph (Fig. 4a). Oils from rocks of the Bazhenov unit plot in the top left-hand corner of the diagrams. Their source organic matter was buried

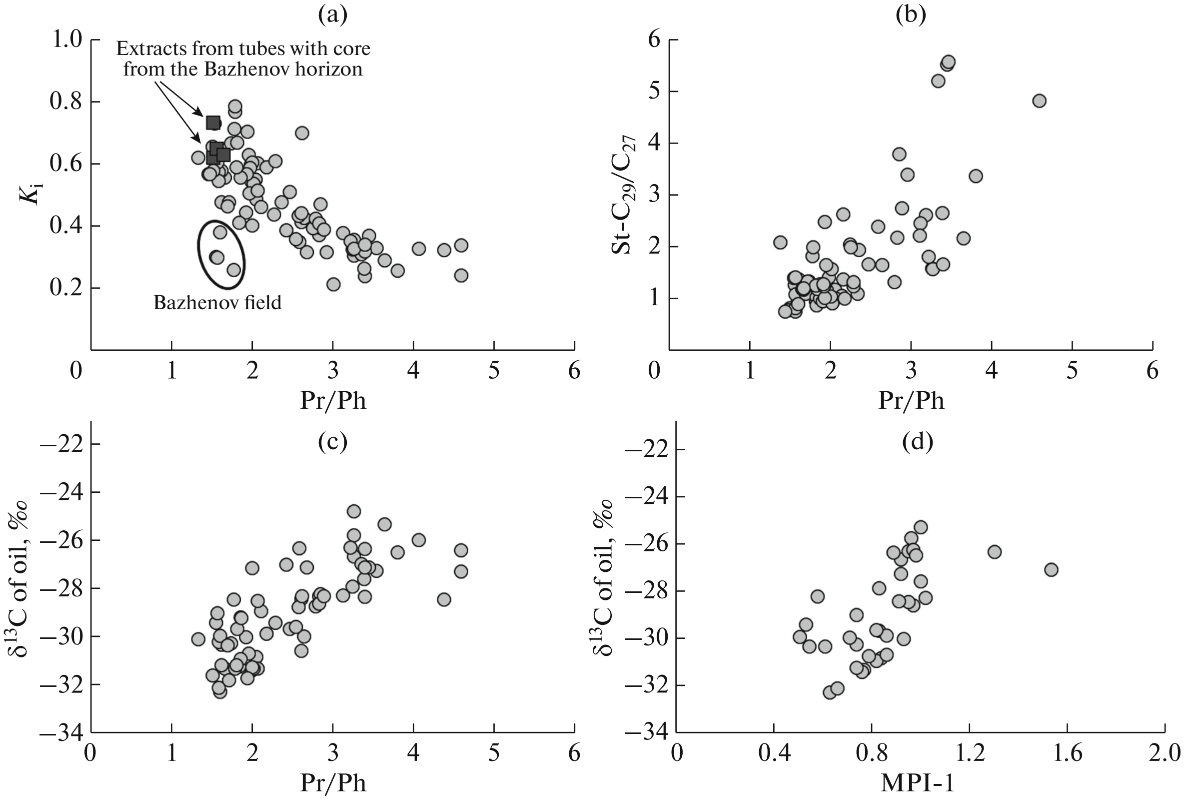

Fig. 4. Correlations between the molecular composition of the hydrocarbons and their carbon isotope composition for the studied oil and condensate samples.

under more reducing conditions (low Pr/Ph values) at low catagenesis (higher K_i values). Conversely, oils in the bottom right-hand corner from the pre-Bazhenov rocks are characterized by more oxidizing conditions (higher Pr/Ph) and higher grades of catagenesis (lower K_i values). This provides grounds to suggest that the reasons for the above trends are that the territory in question includes oil accumulations of both purely Bazhenov and purely Togurtypes, as well as their mixtures. Note that K_i values in Fig. 4a are widely scattered at Pr/Ph values within the range of 1.5–2.0. This is explained by the wide variations in the grade of catagenesis of the rocks of the Bazhenov Formation that was generated the fluids. Samples from the Bovanenkovskoe field differ from the general trend in Fig. 4a in having lower K_i values. Such values are typical of samples of the pre-Bazhenov fluids (Table 1). However, low Pr/Ph values (<2) and light $\delta^{13}C$ suggest relatively reducing sedimentation conditions, which is atypical of the rocks of this age. We found oil samples with such values (0.32–0.40), which are genetically related to rocks of the Bazhenov Formation, only at fields of "Bolshoi Salym" (Lempin field, reservoir temperature 138°C). The grade of catagenesis of the rocks of the Bazhenov Formation in the area of the Bovanenkovskoe field is notably lower than at Salym (Fomin, 2011), however, the South Kara megadepression north of the field is predicted to be characterized by the highest catagenesis grade (AC_1) of the Upper Jurassic rocks. They were likely the dominant source that generated fluid for this field. We have demonstrated that fluid can migrate for such a long distance (150–200 km) with reference for hydrocarbon fields in the southern Tyumen area (Goncharov et al., 2021).

Figure 4b show how the parameter Pr/Ph correlates with the ratio of C_{29} and C_{27} steranes. It is known that oils generated by marine organic matter have values of steranes St-C_{29}/C_{27} close to 1, whereas non-marine organic matter generates oil with two to three (or more) times higher values of this parameter, depending on the bioproducers. With an increase in the Pr/Ph ratio, i.e., an increase in the fraction of oil generated by non-marine organic matter of the pre-Bazhenov rocks, it shows an increase in St-C_{29}/C_{27}. The significant scatter in the St-C_{29}/C_{27} values (up to 5 and more) after Pr/Ph above 2.5 seems to reflect the instability of the facies of lacustrine–paludal and littoral sedimentation environments with the various involvement of higher (terrestrial plants) and lower (algae and phytoplankton) organisms.

The origin of the oils from two distinct groups of source rocks obviously follows not only from molecular parameters but also from the carbon isotope com-

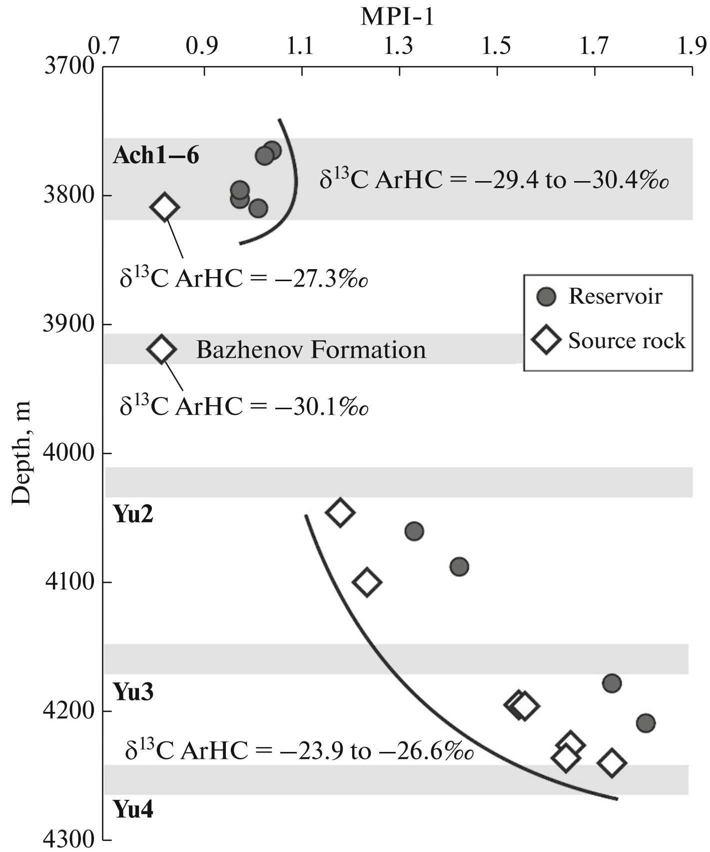

Fig. 5. Variations in the molecular parameter MPI-1 of oils and extracts from rocks with depth down a well drilled at the Urengojjskoe field.

position. It is known (Kodina and Galimov, 1984; Goncharov 1987) that organic matter accumulated under oxidizing conditions is enriched in the heavy carbon isotope, whereas organic matter in reducing environments and, correspondingly, oils generated from this organic matter, contain more light carbon isotope. Definitely, the $\delta^{13}C$ of the unseparated fluid in Table 1 lies between –27.5 and –26‰, the source material was that in the pre-Bazhenov rocks, and conversely, if $\delta^{13}C$ = –32 to –30‰, then the fluid was generated by the organic matter of the Bazhenov horizon. These relations between Pr/Ph, a parameter that reflects the degree of anaerobic oxidation of the organic matter at sedimentogenesis and diagenesis, and $\delta^{13}C$ of the fluid are systematically and reasonably reliably identified (Fig. 4c). The more oxidized organic matter of the lacustrine–paludal and littoral facies of the pre-Bazhenov rocks generated oils and condensates enriched in the "organic" ^{13}C carbon isotope. Because these fluids were generated by more mature organic matter, the relations between the $\delta^{13}C$ and MPI-1, which is one of the most widely applied criterions of catagenesis, seem to be quite logical (Fig. 4d). High Pr/Ph ratios are genetically related to the organic matter of more mature pre-Bazhenov rocks, which generated fluid with high MPI-1 values. It has been demonstrated (Goncharov et al., 2015) that the parameter MPI-1 is unsusceptible to variations in the thermal maturity of the organic matter of the Bazhenov Formation. Even in the Salym oils, whose reservoir temperatures reach 138°C and whose organic matter has 90% exhausted its generation potential, the values of this ratio are no higher than 1.0. At the same time, this parameter is a reliable criterion for estimating the maturity of non-marine organic matter (Radke, 1988). This is convincingly proved by its strong correlation with the vitrinite reflectance and with the pyrolitic parameter T_{max} in the vertical section of Well Gydanska-130 (Fig. 3). This figure also obviously demonstrates that MPI-1 increases in the Achimov reservoirs, which indicates that the fluids saturating them contain pre- Bazhenov hydrocarbons. Analogous relations (an increase in MPI-1 values in the Achimov deposits) was also found at the Urengojskoe field (Fig. 5). It is worth mentioning that extracts from the Middle Jurassic reservoirs have this parameter notably and systematically higher than that in extracts from the coaly mudstones from the same depth. This fact indicates that fluids in the reservoirs are not syngenetic with the host rocks but were generated by more

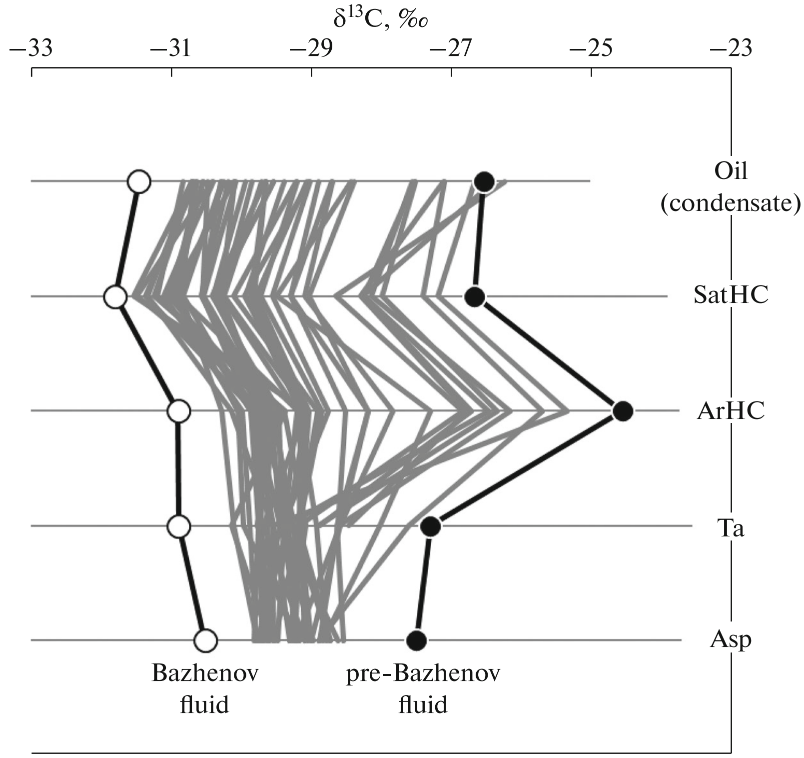

Fig. 6. Carbon isotope composition ($\delta^{13}C$) of oils and condensates from the Bolshoy Urengoy fields and fractions from them: SatHC—saturated hydrocarbons; ArHC—aromatic hydrocarbons; Re—resins; and Asp—asphaltenes.

mature organic matter in underlying rocks. Assuming that heat flows at the Urengojjskoe field and Well Gydanskoe-130 were similar, the values of MPI-1 can be used to roughly estimate the depth and age of the source rocks.

Correlations between the molecular and isotope compositions of the fluids are discernible regionally, at some individual accumulations within a single field, and also often within a single formation. A good example is the Achimov deposits at the fields in the eastern part of Bol'shoi Uregnoy: the Vostochno-Urengoy and Novyi-Urengoy license areas, the Samburgskoe field, etc. (Table 1, Fig. 6). The figure definitely shows that the $\delta^{13}C$ of the total liquid constituent (hydrocarbons, resins, and asphaltenes) of the fluid of the Achimov deposits broadly vary (the scatter of its values is more than 4‰). These variations are within the range of the $\delta^{13}C$ values of fluid samples from the pre-Bazhenov rocks (the rightmost curve in Fig. 6) and the Bazhenov Formation itself (the leftmost curve in Fig. 6). Inasmuch as $\delta\ ^{13}C$ is an additive parameter (whereas the molecular parameters are not), it can be readily utilized to evaluate the contributions of the Bazhenov and pre-Bazhenov fluids to some or other of the hydrocarbon accumulations. In the eastern part of the Urengojjskoe field (the Novo-Urengoy and Vostochno-Urengoy leases) license areas), the content of the pre-Bazhenov fluid generally increases from north to south (Reinblat et al., 2021).

Numerous samples from various wells in the study area are often referred to the same horizon, which is now regarded as a single development and production formation. However, data on their molecular and carbon isotope composition indicate that this is not always the case. A good example in this context is horizon RK_{19} at the Beregovoe field. One of the exploratory wells was drilled at this field and were recovered oil samples with $\delta^{13}C = -26.6$‰ from the Middle Jurassic rocks (horizon Yu_3) and with $\delta^{13}C = -32.3$‰ from the Lower Cretaceous ones (horizon Ach_1) (Table 1). The $\delta^{13}C$ values of these rocks are typical of fluids generated by the organic matter in the pre-Bazhenov rocks and the organic matter of the Bazhenov horizon itself, respectively. The $\delta^{13}C$ of samples recovered from 20 exploratory wells from the formation PK_{19} varies from −27.8 to −31.5‰, which implies that samples from various wells cannot be attributed to a single development target. As a matter of fact, this accumulation can not necessarily be a single continuous object but rather a system of isolated zones (lenses) that are not hydrodynamically interrelated. It is worth mentioning that the $\delta^{13}C$ of some samples from wells spaced 500 m apart from one another may differ by as much as 2% and more.

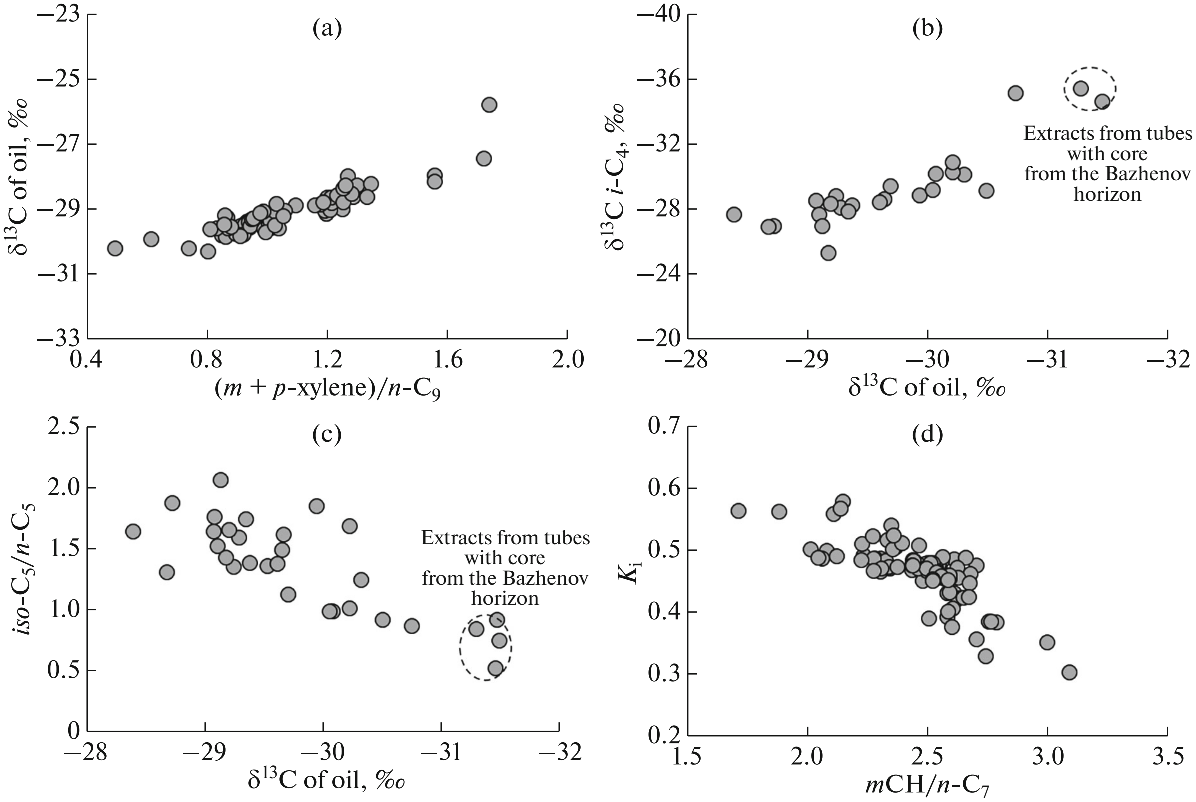

Fig. 7. Correlations between the molecular and carbon isotope compositions of gases, carbon isotope composition of oils and condensates, and molecular composition of the gasoline fraction (mCH/n-C_7 is the ratio of the concentration of methylcyclohexane to that of n-heptane).

The aforementioned relations in the molecular and carbon isotope composition of the hydrocarbons of the intermediate- (pristane and phytane) and high-boiling (steranes and hopanes) fractions are also discernible in the hydrocarbons of the low-boiling fractions and gases. Some of them are displayed in Fig. 7. It has been demonstrated (Goncharov, 1987) that gasoline fractions of oils with high Pr/Ph ratios typically contain elevated concentrations of aromatic and naphthene hydrocarbons relative to the proportion of alkanes and compounds with geminally substituted carbon atoms in both the alkanes and the naphthenes. Figure 7 shows that an increase in the content of the heavy carbon isotope in oils is correlated with an increase in the relative concentrations of aromatic hydrocarbons (Fig. 7a) relative to alkanes, the $\delta^{13}C$ of the *iso*-butane becomes heavier (Fig. 7b), and the ratio of *iso*-pentane to n-pentane increases (Fig. 7c). A decrease in K_i correlates with an increase in the ratio of methylcyclohexane to n-heptane (Fig. 7d), i.e., the content of naphthene hydrocarbons increases relative to that of alkanes.

The relations identified in the changes in the molecular and isotope compositions of the liquid hydrocarbons and their correlations with the composition of the gas thus indicate that the reservoir system in the Cretaceous rocks was formed by filling the traps with either products generated by organic matter in the Lower and Middle Jurassic non-marine source rocks or by organic matter in the Bazhenov horizon. Many of the hydrocarbon accumulations contain mixtures of these fluids. Information on their molecular and isotope compositions provides keys for evaluating the contributions of each of the sources. For example, it follows from Table 1 that most oil and gas-condensate samples from the Aptian–Albian–Cenomanian gas–oil and gas condensate accumulations have lighter $\delta^{13}C < -30‰$ of oils and condensates, which suggests that their liquid constituents were formed at a dominant contribution of products generated by the organic matter of the Bazhenov horizon.

Gases

In contrast to the liquid hydrocarbons, the gases possess much less parameters able to shed light onto the genesis of these gases. One of the most widely employed parameters is the ratios of homologues of normal and iso structure for C_4 and C_5. It is well known (Zor'kin et al., 1984b; Goncharov et al., 2012) that gases accompanying coal and non-marine organic matter are always enriched in branched iso-

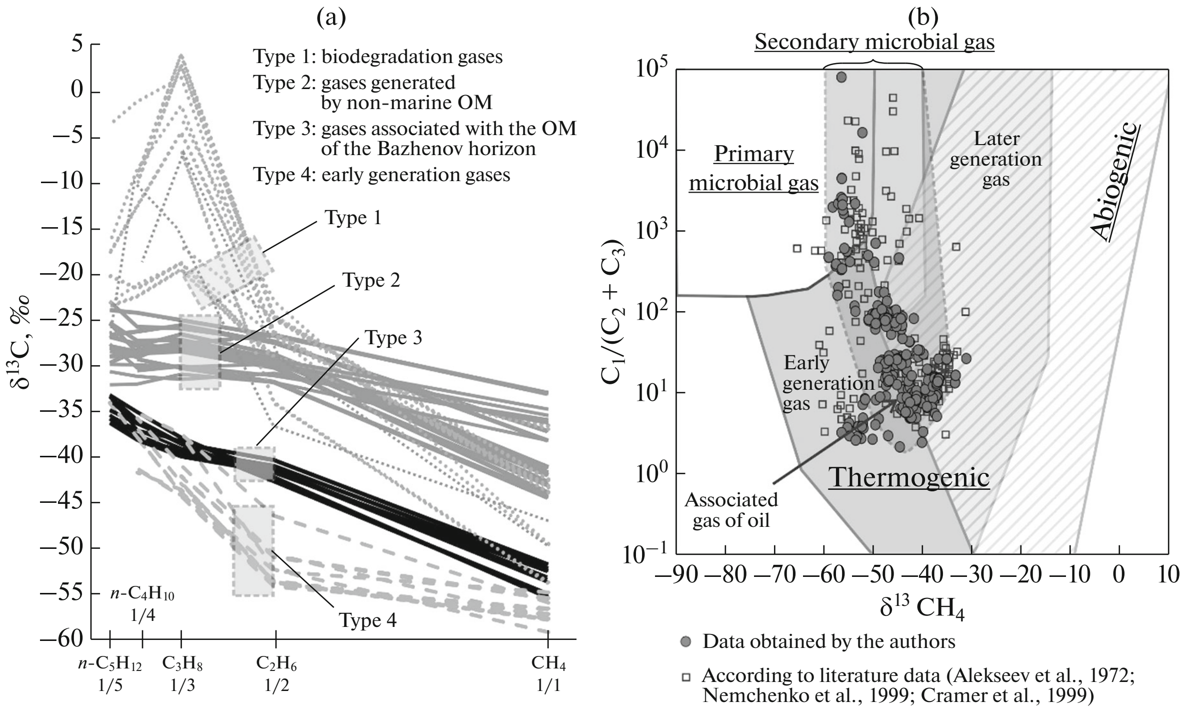

Fig. 8. Carbon isotope composition of gas components: (a) in Chung's diagram for natural gas and (b) in the Bernard–Milkov diagram.

mers. However, the absence of C_4 and C_5 hydrocarbons in the dry gases and the strong correlation of the ratio of iso- and normal homologues with the degree of biochemical degradation in the hydrocarbon accumulation significantly limit the possibility of their application. It has been established (Goncharov et al., 2015) that gas (both dissolved and free) in hydrocarbons in northern part of Western Siberia is often dominated by the homologues with *iso*-structure. Another widely known fact is that the $\delta^{13}C$ of methane in gases in Western Siberia becomes heavier with depth (Ermakov et al., 1970; Vasil'ev et al., 1970; Nesterov et al., 1981; Prasolov, 1990). Also, it has been found out (Goncharov et al., 2005) that methane homologues in oils generated by non-marine oxidized organic matter also have heavier carbon isotope composition than that in "marine" OM. Because of this, the molecular–isotope composition of gases is the main tool applied to identify the genesis of the gases. Genetic diagrams of various type have been worked out in the 20th century for solving applied problems (Bernard et al., 1976; Whiticar, 1999). Extensive data acquired and accumulated lately made it possible to distinguish additional fields in these diagrams subdividing microbacterial gases into primary and secondary (i.e., formed at biodegradation) microbial types, and to differentiate thermogenic gases into those of early generation (i.e., formed at late diagenesis to early catagenesis), gas associated with oil, and gas of late generation stages (Milkov and Etiope, 2018).

Extensive literature is devoted to studies of gases in northern part of Western Siberia, including mass-spectrometric data (Prasolov, 1990; Nemchenko et al., 1999; Goncharov et al., 1983; Milkov, 2010). However, most papers report only the values of $\delta^{13}C$ of methane and sometimes also of its higher homologues. The obtained results provide unique information and a key for understanding the nature of the gases. It has been demonstrated (Chung, 1988) that C_1–C_5 hydrocarbons generated by the same organic matter should form a sublinear curve in the coordinates of $\delta^{13}C$–$1/n$ (where n is the number of carbon atoms in the molecule) on the diagram, named the *natural gas plot* by the author. Many gases studied in hydrocarbon accumulations in northern part of Western Siberia do not comply with this rule (irrespective of the phase state of these gases), and this may suggest that the gases are of polygenic nature. However, many other samples display distributions close to Chung's law, i.e., their distributions are sublinear (Fig. 8a). Based on the arrangement of the lines in the $\delta^{13}C$–$1/n$ diagram and the magnitude of the values of some gas components, four gas types are distinguished in the territory.

One of them is constrained mostly to Cretaceous (from Neocomian to Cenomanian) oil accumulations with gas caps (Bajkalovskoe, Beregovoe, Bovanenkovskoe, Vankor, Vostochno-Messojakhskoe, Lodochnoe, Russkoe, Tagul'skoe, Salmanovskoe, Severo-Komsomol'skoe, Severo-Russkoe, Peljatkonskoe, and some other fields), at which fluid was strongly microbially affected at reservoir temperatures below 70°C. Therewith the microorganisms selectively consumed molecules of normal structure (especially, those of propane), enriched in the light carbon isotope (Goncharov et al., 1983; Goncharov et al., 2013; Goncharov and Oblasov, 2015; Veklich et al., 2021). As a result, the ratio of *iso*- to *n*-structure of homologues increased, and the carbon isotope composition of the propane and *n*-butane became heavier (up to positive $\delta^{13}C$ = +5 to +7‰). These gases may have been genetically related to both the organic matter of the Bazhenov horizon and the older source rocks. Accumulations with gas of such composition are associated withbiodegraded oils or condensates. They are readily discernible in Table 1 based on the K_i values (0.8 and higher) and/or the isotopically heavier composition of the propane in Table 2. The chromatograms of the oils, condensates, and extracts from the reservoir rocks of these accumulations usually contains no evidence of *n*-alkanes.

The second, more extensive group, comprises gases generated by source rocks, which organic matter was formed mostly in lacustrine–paludal facies of the Lower and Middle Jurassic. This is indicated by the high ratios of *iso*- to *n*-homologues of C_4 and C_5 the heavy $\delta^{13}C$ of the C_2–C_5 components. Compared to the gases at fields in the Latitudinal Ob area and southeastern Western Siberia, gases in the northern part of Western Siberia contain methane with isotopically heavier carbon, which may indicate a nonmarine type of the source organic matter and higher grades of its catagenesis. Gases of this isotope composition make up accumulations in the Lower and Middle Jurassic rocks and, together with gases of other genetic types, form the gas component of the whole Cretaceous stratigraphic section, from the Neocomian to Cenomanian.

The third type is generated by the organic matter of the Bazhenov horizon. Samples of the genetically purest gas of this type can be obtained directly from the "body" of rocks of the Bazhenovhorizon (at well tests of the horizon or from tubes with the core material). In contrast to the second ("non-marine") type, these gases have more negative $\delta^{13}C$ values, and the lines of these gases plot in Fig. 8a in the bottom part of the diagram. A similar composition was detected in gases from accumulations directly above the Bazhenov horizon (Achimov deposits) and beneath it (formation Yu_1). Accumulations with this isotope composition are atypical of the area and are commonly associated with oil accumulations (gas dissolved in the oil) that were generated by the marine organic matter of the Bazhenov horizon. Such accumulations can be easily distinguished from the rest (Tables 1 and 2) thanks to their low Pr/Ph (<2.2), lower $\delta^{13}C$ = –32 to –31‰ of the oils, and lower $\delta^{13}C$ = –40 to –33% of the C_3–C_5 gas components.

The fourth group of the gases was found exclusively in the Turonian–Cenomanian reservoirs (Beregovoe, Kharampurskoe, Severo-Kharampurskoe, and Yuzhno-Kharampurskoe fields). These gases are noted for the anomalously low $\delta^{13}C$ of the ethane (from –54 to –51‰) and propane (from –45 to –43‰). An association of such ethane and propane with methane depleted in the ^{13}C isotope provides grounds to think that the gases were generated very late during microbial methanogenesis and the earliest thermal destruction of the organic matter. Gases of this isotope composition are very rare and never form economic accumulations (Veklich et al., 2021). Their source may have been the thermally immature organic matter of the Cretaceous rocks enriched in the leuptinite and alginite components.

However, Chung's gas diagram does not make it possible to correlate between the dry gases of the giant Cenomanian accumulations and the organic matter that generated them. The reason for this is the very low content of methane homologues in it. However, the answer can be obtained using the Bernard–Milkov diagram (Fig. 8b) (Milkov and Etiope, 2018). As follows from this diagram, the dry gases and gases with the lowest $\delta^{13}C$ values of their methane (from –50 to –60‰) are early-generation primary microbial gases, which are formed as a result of acetate fermentation when the organic matter is transformed. The origin of these gases may be associated with thermally immature Cretaceous coals, as has been repeatedly hypothesized by several researchers of many hydrocarbon fields in Western Siberia (Stroganov, 1998; Stroganov and Skorobogatov, 2004; Nemchenko and Rovenskaya, 1968; Vasil'ev et al., 1970; Milkov, 2010). These assumptions have received one more confirmationfrom the newly acquired data.

The mechanism forming the carbon isotope composition of the gas components in rocks of the north of Western Siberia is generally well illustrated by the example of Well A, which was drilled from the pre-Jurassic rocks up to the Turonian (Fig. 9). The $\delta^{13}C$ of the methane extremely widely varies (from –51 to –32‰). The lower interval of the vertical section drilled through by this well (interval 1) is characterized by the highest $\delta^{13}C$ (from –32 to –33‰) and rather high gas saturation. This gas could have been generated by both the thermally mature organic matter of the Lower Jurassic and the pre-Jurassic rocks. Higher up the stratigraphic section (interval 2), as the reservoir properties become poorer, the gas content decreases, and the carbon isotope composition of the methane becomes lighter because of dilution of the isotopically heavy gas from the underlying rocks with syngenetic gas produced by less mature organic matter in the host rocks. The isotopically lightest gas is constrained to interval 3, which is characterized by the lowest gas parameters. This gas seems to be predominantly syngenetic methane generated by the disseminated organic matter of the host

Table 2. Carbon isotope composition ($\delta^{13}C$) of gas components at fields in the north of Western Siberia. For each component, the table lists the minimum and maximum values (if more than a single sample was analyzed) or a single value (if only one sample was analyzed)

No.	Field, area	Reservoir age	Horizon, formation	$\delta^{13}C$, ‰						
				CH_4	C_2H_6	C_3H_8	i-C_4H_{10}	n-C_4H_{10}	i-C_5H_{12}	n-C_5H_{12}
1	Arkticheskoe (literature data)	Lower Cretaceous		−38.5	−25.4	−24.6	−25.2	−24.4	–	–
2	Bajkalovskoe	Lower Cretaceous	Shura-tovskaya Formation	−42.0 to −36.6	−35.6 to −28.0	−35.1 to −30.2	−34.1 to −29.4	−35.0 to −30.0	−34 to −28.8	–
3	Bajkalovskoe	Middle Jurassic	Ml	−30.8	−26.5	–	–	–	–	–
4	Bovanenkovskoe (literature data)	Lower Cretaceous		−41.1	−24.6	−23.3	–	–	–	–
5	Bovanenkovskoe	Lower Cretaceous	BYa	−36.9 to −36.4	−30.1 to −28.8	−28.1 to −27.2	−28.0 to −27.6	−27.6 to −27.3	−27.1 to −26.7	−27.1 to −26.7
6	Bovanenkovskoe	Lower Cretaceous	TP	−37.4 to −36.3	−29.1 to −28.6	−27.4 to −27.2	−27.7 to −27.3	−27.3 to −27.0	−26.8 to −26.3	−26.9 to −26.4
7	Beregovoe	Upper Cretaceous	(RK_1	−58.2 to −53.6	−46.2 to −34.1	−6.7	–	–	–	–
8	Beregovoe	Lower Cretaceous	A_{7-8}	−45.9	−29.6	−27.0	−28.0	−28.6	−27.9	−30.0
9	Beregovoe	Lower Cretaceous	RK_{19}^2	−43.8 to −43.1	−26.9 to −26.0	−4.7 to 1.2	−20.2 to −18.5	−12.7 to −1.4	−19.8 to −17.8	−17.8 to −3.9
10	Beregovoe	Lower Cretaceous	RK_{20}	−49.5	−26.9	−19.0	−25.4	−21.3	−24.6	−23.3
11	Bol'she-Khikiglinskaja	Middle Jurassic	Ml	−42.3	−29.9	−26.3	−28.1	−24.6	−26.0	−19.2
12	Vankor	Lower Cretaceous	vYak	−45.3 to −44.1	−27.5 to −25.5	–	–	–	–	–
13	Vankor	Lower Cretaceous	Yak	−50.1 to −41.6	−27.9 to −25.5	–	–	–	–	–
14	Vankor	Lower Cretaceous	Nkh	−49.3 to −45.0	−38.2 to −35.4	−34.1 to −18.6	−36.2 to −33.4	−33.3 to −20.2	–	–
15	Vikulovskaja	Aptian–Albian	–	−51.2 to −51.0	−29.4 to −29.2	−17.5 to −16.7	–	–	–	–
16	Vikulovskaja	Upper Jurassic	–	−37.6	−29.4	−29.0	–	−29.1	–	−29.6
17	Vikulovskaja	Middle Jurassic	–	−40.7 to −39.6	−27.7 to −27.6	−27.2 to −19.7	–	−30.3 to −22.9	–	−27.3 to −25.1
18	Verkhnekubinskijj LA	Lower Cretaceous	Sd_{5-12}	−40.4 to −38.1	−29.1 to −20.4	−17.4 to 5.5	−26.8 to −12.9	−22.0 to −15.4	–	–
19	Verkhnekubinskijj LA	Lower Cretaceous	Nkh	−41.5 to −33.3	− 30.1 to −28.6	−28.7 to −27.0	−29.6 to −27.3	−29.8 to −26.7	–	–
20	Vostochno-Messojakhskoe	Upper, Lower Cretaceous	RK_{1-3}, BU_8	−43.9 to −41.1	−29.7 to −25.0	−27.9 to −17.2	−29.6 to −15.3	−29.0 to −22.7	−29.4 to −28.9	−29.0 to −25.5
21	Vostochno-Urengoy LA	Lower Cretaceous	Ach_{5-6}	−38.9 to −38.4	−29.1 to −27.4	−26.4 to −25.6	−26.7 to −25.6	−26.0 to −25.7	−25.6 to −23.4	−25.7 to −23.1
22	Vyngajakhinskoe	Lower Cretaceous	BP	−56.4 to −50.1	−41.6 to −39.7	−39.9 to −38.1	−37.4 to −35.2	−38.1 to −36.4	−34.2 to −32.1	−36.3 to −33.4
23	Gydanskoe	Lower Cretaceous	Ach	−30.7 to −30.0	−30.8 to −30.4	−30.1 to −29.5	−30.7 to −30.1	−29.2 to −28.5	−30.0 to −29.0	–
24	Zapadno-Lodochnaya	Middle Jurassic	Ml	−48.5 to −43.9	−41.5 to 31.6	−36.1 to −29.6	−31.0	−28.2	–	–
25	Zapadno-Irkinskoe	Lower Cretaceous	Nkh	−43.4	−38.0	−36.0	−35.5	−34.4	−32.3	−33.7
26	En-Ekhinskoe(literature data)	Middle Jurassic		−38.2	−26.4	−24.9	−27.8	−26.2	–	–

Table 2. (Contd.)

No.	Field, area	Reservoir age	Horizon, formation	δ13C, ‰						
				CH_4	C_2H_6	C_3H_8	i-C_4H_{10}	n-C_4H_{10}	i-C_5H_{12}	n-C_5H_{12}
27	En-Ekhinskoe(literature data)	Upper Triassic		−33.9	−24.4	−25.4	−28.6	−28.0	–	–
28	En-Ekhinskoe(literature data)	Lower Triassic		−19.4	−22.1	−30.8	−30.9	−30.5	–	–
29	Lodochnoe	Lower Cretaceous	Yak_1	−48.9	−27.4	−5.5 | −23.5	−16.4	−21.2	−24.2	-48.9
30	Lodochnoe	Lower Cretaceous	Yak_{3-4}, Yak_7	−49.3 to −46.7	−26.5 to −24.9	−7.3 to 1.0	−19.8 to −17.4	−19.0 to −12.1	−17.1	−17.6
31	Lodochnoe	Lower Cretaceous	(Nkh_{3-4}	−48.5	−38.4	−33.2	−34.9	−32.4	−31.8	−31.9
32	Lodochnoe	Lower Cretaceous	Mkh	−46	−24.3	−1.3 to 2.7	−16.9	–	–	–
33	Lodochnoe	Upper, Lower Cretaceous	Dl_{2-3}	−53.5	−26.7	−4.1	−18.7	–	–	–
34	Lodochnoe	Lower Cretaceous	Sd_{3-4}	−49.4 to −44.0	−27.2 to −22.7	−32.1 to −27.8	−25.9 to −24.3	−35.6 to −29.7	−27.1 to −25.6	−33.1 to −29.2
35	Novoportovskoe (literature data)	Lower Cretaceous		−43.2 to −35.2	−26.5 to −25.1	−25.9 to −24.4	−27.7 to −24.3	−26.5 to −24.3	–	–
36	Novoportovskoe (literature data)	Lower Jurassic		−40.0	−24.4	−25.4	−26.2	−24.8	–	–
37	Novo-Urengoy LA	Lower Cretaceous	Ach_{3-4}	−39.0 to −36.8	−28.9 to −27.0	−27.4 to −27.0	−27.6 to −25.4	−27.0 to −24.4	−26.1 to −23.6	−27.2 to −21.0
38	Novo-Chasel'skoe	Upper Cretaceous	RK_1	−52.1	−24.6	–	–	–	–	–
39	Pajyakhskoe	Lower Cretaceous	Nkh	−49.5 to −44.4	−39.7 to −36.8	−36.8 to −34.8	−37.5 to −34.3	−35.6 to −34.0	−33.6 to −31.5	−34.4 to −33.0
40	Pyreinoe	Upper Cretaceous	RK_1	−56.2 to −55.9	−37.2 to −34.1	–	–	–	–	–
41	Rogozinskaja (western dome)	Lower Jurassic		−41.1 to −40.1	−30.3 to −29.0	−28.8 to −28.4	−29.4 to −29.1	−29.6	−29.4 to −28.0	−29.3 to −28.0
42	Salmanovskoe	Lower Cretaceous	TP_1^4	−54.2 to −53.7	−27.3 to −27.0	−20.7 to −20.6	−25.6 to −25.5	−23.5 to −23.4	–	–
43	Salmanovskoe	Lower Cretaceous	$TP_{14,16,18,19,22}$	−46.2 to −40.9	−30.6 to −29.1	−28.5 to −25.5	−28.5 to −24.9	−28.3 to −26.2	−27.3 to −25.2	−27.2 to −25.2
44	Severo-Russkoe	Lower Cretaceous	$BT_{3,4,11,12}$	−38.2 to −34.8	−31.9 to −29.1	−31.6 to −18.9	−30.6 to −28.3	−32.1 to −21.7	−30.2 to −26.5	−32.2 to −20.3
45	Severo-Kharampurskoe	Upper Cretaceous	RK_1, Berezovskaya Formation	−57.1 to −54.7	−54.0 to −52.4	−44.2 to −43.5	−40.8 to −36.1	−41.7 to −37.8	−37.6	−34.1
46	Severo-Kharampurskoe	Cretaceous	RK_{18}^{1-2}	−49.7 to −48.7	−26.1 to −24.4	−14.3 to −13.0	−21.0 to −20.7	−31.1	−30.1	−30.8
47	Semakovskoe	Upper Cretaceous	RK_1	−44.3	−30.8	−8.0	–	–	–	–
48	Tasijjskoe (literature data)	Lower Cretaceous		−36.2 to −35.4	−26.8 to −26.0	−26.2 to −26.1	−26.3	−25.1	–	–
49	Urengojjskoe	Lower Cretaceous	Ach	−43.3 to −33.3	−34.8 to −28.8	−34.0 to −27.1	−35.3 to −25.3	−33.6 to −27.1	−32.3 to −26.0	−32.9 to −26.4
50	Khadyr'jakhinskoe	Lower Cretaceous	RK_{20}	−42.5	−24.8	3.2	−20.9	−9.8	−19.5	–
51	Kharampurskoe	Upper Cretaceous	RK_1)	−56.8 to −55.3	−50.8 to −34.0	−42.1 to −21.9	−33.3	−31.1	−30.1	−29.8
52	Shtormovoe	Middle Jurassic	Yu_{2-4}, Yu_{7-9}	−44.4 to −37.2	−31.9 to −27.6	−30.3 to −25.6	−30.8 to −26.7	−30.6 to −26.3	−28.5 to −26.0	−29.7 to −25.0
53	Juzhno-Kharampurskoe	Lower Cretaceous	RK_{20}^1, RK_{21}	−51.0 to −49.4	−33.2 to −23.1	−25.0 to −3.2	−18.4 to −14.5	–	−31.5	–
54	Juzhno-Kharampurskoe	Cretaceous	NB_1, BV_1	−59.0 to −55.8	−53.6 to −33.9	−42.8 to −29.8	−40.1 to −23.3	−36.9 to −35.2	−38.6	–

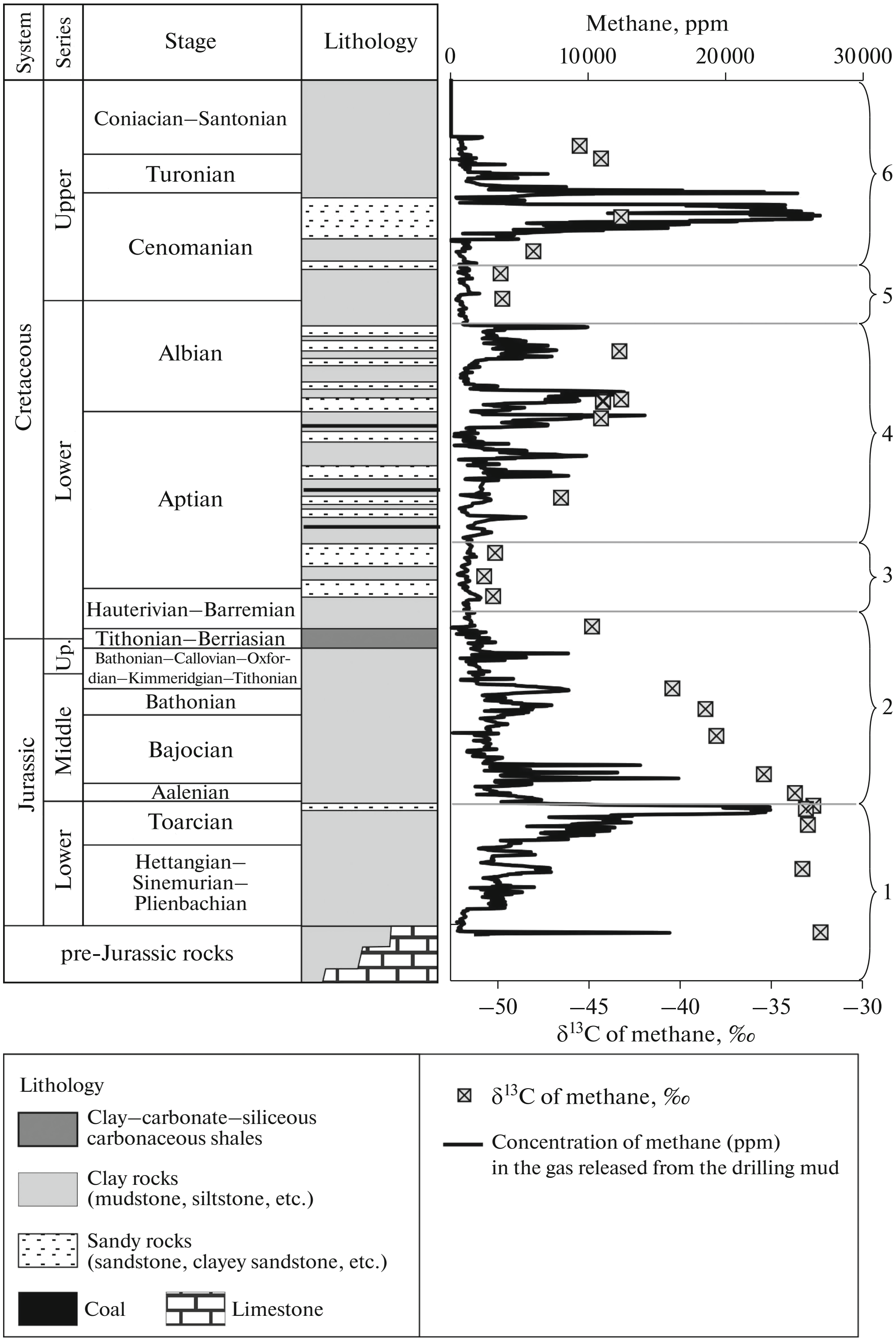

Fig. 9. Variations in methane content in the gas released from the drilling mud and variations in the carbon isotope composition of methane along Well A in northern Western Siberia.

rocks. In the next interval 4, the improvement of the reservoir characteristics is associated with an increase in the gas saturation and in the $\delta^{13}C$ of the methane. In this interval, a gas influx was obtained, and the core definitely contained heavy biodegraded oil. This heavier carbon isotope composition seems to resulted from the contribution of secondary microbial methane, which was generated by the vital activity of meth-

Table 3. The nature of fluids in various complexes in the North of Western Siberia

Complex	Accumulation type, phase state	Fluid nature	
		Liquid component	Gas component
1. Aptian–Albian–Cenomanian	Gas	B > pB	EGG > pB > B
	Oil and gas	B > pB	BDG > pB> B
	Gas and oil	B > pB	BDG > pB> B
2. Valanginian–lower Aptian	Oil and gas	B > pB	pB > BDG
	Gas and oil	B > pB	BDG > pB
3. Berriasian–Valanginian (Achimovskii horizon)	Oil in near-critical state	B > pB	pB > B > BDG
4. Yu_1–Yu_3	Oil in near-critical state	pB > B	pB > B
5. Yu_4–Yu_{15}	Condensate	pB	pB

EGG—early generation gases,
BDG—biodegraded gases,
B—fluids generated by the organic matter of the Bazhenov horizon,
pB—fluids generated by the organic matter of pre-Bazhenov rocks (Lower and Middle Jurassic).

anogenic bacteria. The process of methane generation always proceeds simultaneously with the biodegradation of oil in the hydrocarbon accumulation and leads to the formation of a dry gas cap, in which the $\delta^{13}C$ values of the methane lie in the range of –50 to –40‰. This process is discernible at fields in many areas with hydrocarbon accumulations in good reservoirs with reservoir temperatures below 70°C and with low TDS of the reservoir waters (Oblasov et al., 2018). The next interval 5 is, again, characterized by poor reservoir properties, low gas saturation, and lower $\delta^{13}C$ values of the methane, with a significant proportion of singenetic methane, as in interval 3. Interval 6 includes a good reservoir, from which gas influx was obtained. The conditions for the formation of the carbon isotope composition of the methane in this interval were similar to those in interval 4.

Nature of the Cenomanian Gases

Although the component composition of gases in the Cenomanian accumulations is similar, with >95% made up by methane, the carbon isotope composition of these gases broadly varies. Methane with the lowest $\delta^{13}C$ values is typical of the southern part of the Nadym–Pur oil- and gas-bearing province ($\delta^{13}C$ = –49 to –60‰), and the Jamburgskoe (–50.8‰), Arkticheskoe (–53.2‰), and Urengoy (up to –60‰) fields. The $\delta^{13}C$ values of methane notably increases in the gases of the Tazovskoe (–41.0‰), Messoyakhskoe (–38.3‰), Nejtinskoe (–38.3‰), and Pangodinskoe (–38.4‰) fields (Prasolov, 1990).

Significant differences in the $\delta^{13}C$ of methane (from –42 to –59‰) were found in Cenomanian rocks at the Urengoy field (Nesterov et al., 1981; Prasolov, 1990; Nemchenko-Rovenskaya et al., 2011). Various mechanisms were suggested to explain this differentiation: a chromatographic effect at migration (Gavrilov et al., 1972; Soboleva et al., 2019), a change in the reservoir pressure (Zor'kin et al., 1984), etc. We believe that the observed differences are explained primarily by genetic differences in the source organic matter. Obviously, the carbon isotope composition of the methane, $\delta^{13}C$ = –38 to –40‰, can occur only in gas generated by the thermally strongly modified organic matter of the pre-Bazhenov deposits, which have reached, in the buried parts of the basin, a catagenesis grade corresponding to the main gas window (wet and dry gas in wells Tyumenskaya SD-6, En-Jakhinskaya SD-7, and Gydanskoe-130). In the gas–oil and condensate–gas accumulations (Bajkalovskoe, Beregovoe, Bovanenkovskoe, Vankor, Vostochno-Messojakhskoe, Lodochnoe, Russkoe, Tagul'skoe, Salmanovskoe, Severo-Komsomol'skoe, Severo-Russkoe, Peljatinskoe, and others), methane in the gas cap is mainly secondary microbial gas ($\delta^{13}C$ of methane = –40 to –50‰), but the gas of these accumulations only insignificantly contributes to the overall balance of gas resources of the territory. Hydrocarbon accumulations with $\delta^{13}C$ of the methane lower than –50‰ were formed by the accumulation of gases of early generation (primary microbial gas, Fig. 8b) by transformations of the coaly organic matter of the Aptian–Albian–Cenomanian complex.

CONCLUSIONS

Data on the molecular and isotope composition of fluids and on the distribution of their accumulations in the sedimentary cover indicate that most of them are polychromous and polygenic. Currently available information suggests the following contributions of various sources to hydrocarbon accumulations in northern part of Western Siberia (Table 3). The composition formation of their liquid constituents occurred as a result of the hydrocarbons generation by the organic matter of the Jurassic sediments. The Lower and Middle Jurassic rocks, on the one side, and those of the Bazhenov horizon in the Upper Jurassic, on the other, produced hydrocarbons notably different in composition and properties. These differences are primarily of genetic nature, i.e., were inherited from the organic matter of the source rocks. These differences were predetermined by both the composition of the initial bioproducers and the conditions of their fossilization (Goncharov, 1987). In addition to the molecular and isotope parameters discussed above, the fluids of the Bazhenov horizon are enriched in sulfur, resins, and asphaltenes, but they contain lessparaffins, and these fluids have a higher density and viscosity but lower pour points. Conversely, the fluids generated by the organic matter of the pre-Bazhenov rocks are poor in sulfur, resins, and asphaltenes but are relatively rich in paraffins, and these fluids have lower densities and viscosities. According to its genesis and higher thermal maturity, such organic matter generates much more gas components, and hence, many hydrocarbon accumulations occur in a near-critical state.

The Lower and Middle Jurassic rocks with nonmarine (mixed) organic matter also significantly contributed to the gas components in hydrocarbon accumulations in northern part of Western Siberia. The Cretaceous rocks generated only dry gas. It seems to be these rocks that served as the main source of gas for the formation of gas accumulations with isotopically light carbon isotope composition of the methane.

The conclusions presented in the table are largely merely an expert opinion because they are based on a relatively small dataset. Conditions under which a hydrocarbon accumulation is produced are controlled by its geological setting in the territory. In view of this, these conclusions can be revised and specified with reference to each individual area with the use of the approach proposed above.

Data on the carbon isotope composition, considered together with data on the molecular parameters, enable to evaluate the fraction of the liquid components of the fluids of different genetic type when some hydrocarbon accumulation is produced to clarify the pathways and migration distances of the fluids to their accumulation sites. Because of this, all basin modeling operations must necessarily include comprehensive geochemical studies with correlations between fluids in already discovered accumulations with those in the likely source rocks. This would make it possible to verify the basin modeling results. The contributions of various sources can also be evaluated but only if the area in which the hydrocarbon accumulation was formed contained no microbial (biodegradation) gases.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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