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Mesozoic-Cenozoic climate and the geothermal regime of the oil source Kiterbyutskaya suite of the Arctic region of Western Siberia

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Abstract. Using the example of paleotemperature modeling of the Kiterbyutskaya suite of the Mesozoic-Cenozoic section, opened by a deep well at the Bovanenkovskoye oil – gas condensate field (Yamal Peninsula), the influence of paleoclimate factors on the thermal history of the Lower Jurassic oil source deposits, the duration of the main phase of petroleum formation and the value of the paleothermometric maximum and oil generation density. The original computer methodology is described, which takes into account the parameters of the tectonic and sedimentation history, as well as the history of the thermophysical properties of the sedimentary formation, including permafrost and glaciers, and not requiring a priori information about the values and nature of the deep heat flow is given.

The features of the model parametrization are shown. The reliability of the results is confidently controlled by the geophysical criterion of the “discrepancy”, comparison with experimental data on the heat flow, and consistency with the drilling data. The presentation is based on the works of the Tomsk School of Geothermics, carried out as part of the development of a methodological base of geothermics as a geophysical oil prospecting method.

Keywords: Yamal Peninsula, paleoclimate, Kiterbyutskaya suite, modelling of geothermal regime, hydrocarbon resources, works of the Tomsk School of Geothermics

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Introduction

A quantitative assessment of the prospects for the oil and gas potential of the territories – the assessment of the density of hydrocarbon (HC) resources – is performed by the volumetric-genetic method (basin modeling). The number of generated hydrocarbons is calculated based on the reconstruction of the geothermal regime of oil source sediments (Tissot, 2003; Khutorskoy et al., 2011; Kontorovich et al., 2013; Galushkin, 2016).

The temperature regime of a sedimentary cover, the thermal history of directly source deposits, and, consequently, the degree of realization of their generation potential can be affected by directly (actually) or indirectly (in calculations, reconstructions) by the following paleoclimate factors:

1) the age-old temperature course in the Mesozoic Cenozoic on the surface of the Earth, causing an exogenous source of heat for hydrocarbon generation processes;

2) permafrost strata overlying source deposits and having anomalously high thermal conductivity;

3) ice sheets, peculiar lithologic-stratigraphic complexes, increasing the thickness of the overlying sediments.

Significant research material has been accumulated, giving an estimate of the influence of paleoclimate factors on the temperature regime of sedimentary-volcanic and magmatic complexes (Golovanova et al., 2014; Demezhko, Gornostaeva, 2014; etc.). A series of papers has been published (Lobova et al., 2013; Isaev et al., 2016; etc.), which show the influence of Mesozoic-Cenozoic climatic changes on the thermal history of directly source source deposits in the south-east of Western Siberia.

The Arctic region of Western Siberia has unique paleoclimatic features (Kurchikov, Stavitskii, 1987).

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A global event occurred in the Pleistocene – a sharp cooling of the climate. This could lead to cooling of the sedimentary strata, a significant non-stationarity of the temperature field in the entire sedimentary section, including oil source sediments (Kurchikov, 2001). The publication of the Arctic Expedition IODP 302 notes (Nelskamp et al., 2014) that the evolution of temperatures on the Earth's surface has a great influence on the maturity of the source rock: there may be more or less volumes of produced hydrocarbons depending on temporal variations in surface temperatures.

The Upper Jurassic deposits of the Bazhenov Formation ($J_3 + K_1bg$) of Western Siberia are the main source of hydrocarbon deposits in the traps of the Upper Jurassic and Cretaceous oil and gas complexes (OGC), as well as a priority shale formation (Kuzmin et al., 2014; Isaev et al., 2018). Due to the strategy of developing the hydrocarbon resource base of the Russian Federation, exploration and promotion of the oil and gas industry in the north of Western Siberia have been intensified (Igenbaeva, 2015). However, unlike the south-eastern and central regions of the West Siberian petroleum province (WSOGP) (Isaev et al., 2018b), the Bazhenov sediments in the Arctic region vary significantly (Neftegazonosnye basseiny i regiony Sibiri…, 1994) as for concentrations of dispersed organic matter (DOM), often decreasing to 1-2%, and by DOM type, moving to the humus-sapropel type (Database of the Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences, 2017).

The article (Isaev et al., 2018a), with a full illustration using the Rostovtsevskaya 64 well (Yamal Peninsula, Fig. 1), presents a detailed analysis of the impact on the

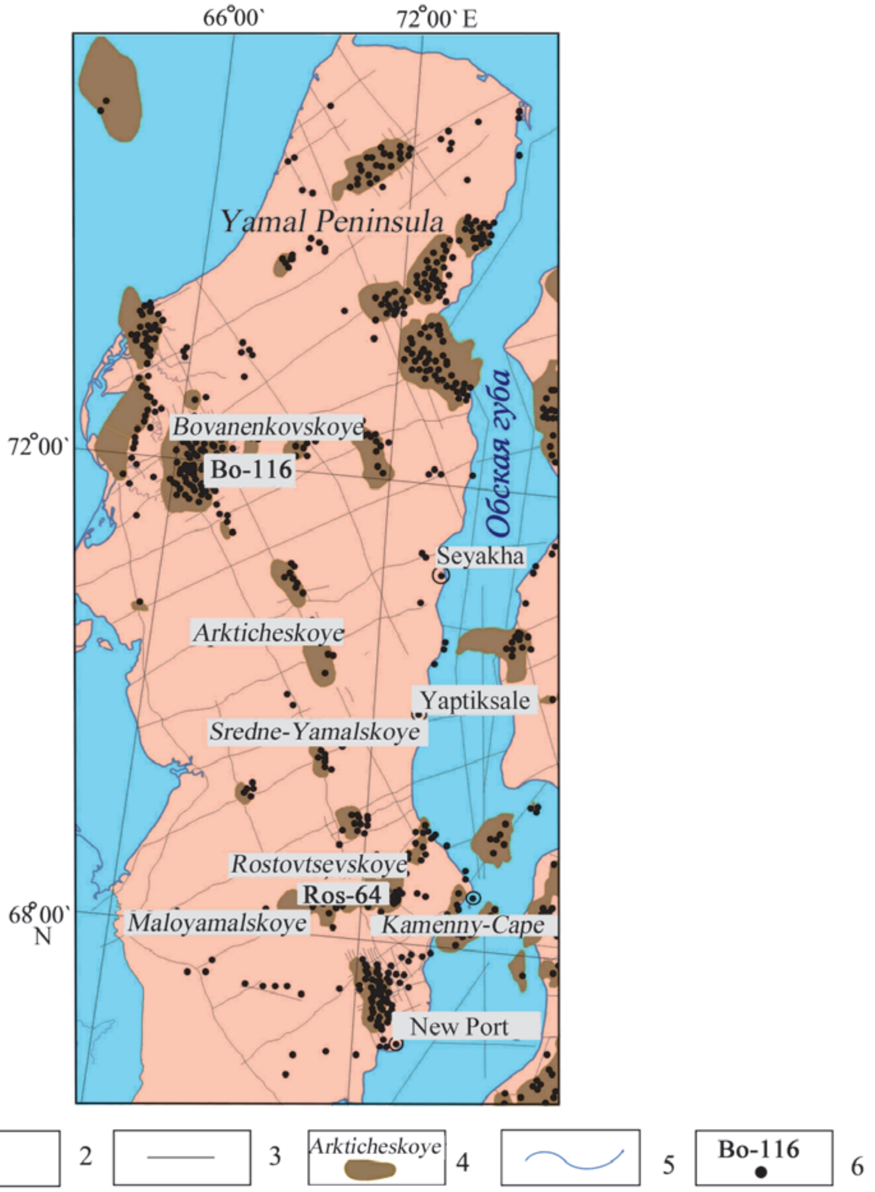

Fig. 1. Review scheme of the research area: 1 – a settlement and its name; 2 – exploration well; 3 – seismic profile of CDPM 2D; 4 – contour of the field and its name; 5 – hydrography and coastline; 6 – simulated well and its index: Ros-64 – Rostovtsevskaya 64, Bo-116 – Bovanenkovskaya 116

thermal history of the Bazhenov formation of a complex of paleoclimatic factors (the Mesozoic-Cenozoic secular temperature variation on the Earth surface, the secular variation of the Neopleistocene permafrost layer thickness and the secular variation of the thickness of the Late Quaternary ice caps. It has been established that in the paleo-temperature modeling scenario, which takes into account paleoclimate factors, the geological time of the maternal suite in the main oil generation zone is increased by 25 Ma (by 50%), and the absolute paleo-temperature maximum increases by 10°C. Here, the first results were obtained on the evaluation of the role of the Late Quaternary ice caps, which showed their insignificant effect on the thermal regime of the Bazhenov oil-source rock.

At the same time, the geothermal regime of the Kiterbyutskaya suite (J_1kt), which is the source for the formation of hydrocarbon deposits in the traps of the Lower Jurassic and, possibly, pre-Jurassic OGC, is of undoubted interest. The pre-Jurassic (Paleozoic) OGC is one of the priorities for the development of tight oil resources (Polukeev et al., 2013; Lobova et al., 2018). Kiterbyutskaya argillaceous facies, which has an oil source potential, has formed during the time of boreal transgressions in the early Jurassic – Toar. In contrast to the Bazhenov deposits, the dispersed organic matter of the Kiterbyutskaya formation of the Arctic regions (Neftegazonosnye basseiny i regiony Sibiri..., 1994) has more stable concentrations (Database of the Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences, 2017).

Therefore, the determination of the influence of paleoclimate factors on the reconstruction of the geothermal regime and on the assessment of the degree of realization of the generation potential of oil source Kiterbyutskaya deposits in the Arctic region of Western Siberia is an important task.

In the work (Iskorkina et al., 2018), the experience of assessing the influence of paleoclimate factors on the calculated geothermal regime of the Kiterbyutskaya formation is given.

The main objective of these studies is the further arguing of the significant influence of paleoclimate factors – the secular variation of temperatures on the Earth's surface and the Neopleistocene permafrost strata – on the calculated geothermal regime of the oil source Kiterbyutskaya suite. And defining the role of ice caps is of particular relevance when assessing the oil and gas potential of the Arctic territories of Western Siberia (Kontorovich et al., 2013). Below are the results of detailed paleotemperature studies of the Kiterbyutskaya deposits, which were penetrated by a deep well in the well-known Bovanenkovskoye field (Yamal Peninsula, Fig. 1). The presentation of the results is largely based on a review of the published works of the authors, performed as part of the development of the methodological base of geothermics as a geophysical oil prospecting method.

About the methodology of paleotemperature studies

The restoration of the thermal history of the oil source suite is based on solving the direct and inverse problems of geothermy (Starostenko et al., 2006; Isaev et al., 2018a). The deep heat flow q is determined by solving the inverse problem of geothermy, which is performed within the parametric description of the sedimentation history and the history of thermophysical properties of the sedimentary layer only, without invoking information about the nature of q and geodynamics below the base of the sedimentary section. For the conditions of Western Siberia, characterized, starting from the Jurassic time, by the quasistationarity of the deep heat flow (Duchkov et al., 1990; Kurchikov et al., 2001; Isaev et al., 2018), the solution of the inverse geothermy problem – determining q – in the adopted model has been performed uniquely. The mathematical model in a rigorous mathematical form includes geotemperatures from the definitions of vitrinite reflectance (VR), as "observed". No separate "calibrations" for VR temperatures are required.

The calculation of paleotemperature consists of two stages. At the first stage, the heat flow q through the surface of the base of the sedimentary cover, i.e., is calculated from the temperature distribution T "observed" at the well cut points, i.e., the inverse problem of geothermy is solved – the classical inverse problem of geophysics. At the second stage with a known value of q, direct geothermal problems are solved – temperatures U are calculated at given points of the sedimentary sequence Z (including in the oil source suite) for any given moments of geological time t.

To solve the inverse problem of geothermics, we use as "observed" both measurements of reservoir temperatures obtained during well tests and geotemperatures recalculated (Isaev, Fomin, 2006) from VR.

The first boundary condition of the model is determined by the temperature of the surface of sedimentation in the Mesozoic-Cenozoic, i.e. paleoclimate factor, and is given as a piecewise linear function of the "arctic" secular temperature pattern on the Earth's surface. The "Arctic" secular temperature pattern built by A.A. Iskorkina is based on a synthesis of published experimental definitions and paleoclimatic reconstructions for the north of the West Siberian Lowland (Iskorkina, 2016).

The formation, existence and degradation of the permafrost in the Neopleistocene and Holocene are taken into account as a kind of dynamic lithologic-stratigraphic complexes with anomalously high thermal conductivity and thermal diffusivity a. The formation, existence and degradation of ice mass in the Neopleistocene takes into account their anomalously low density σ. The secular course of the thickness of permafrost and ice sheets was built by A.A. Iskorkina based on a summary of published experimental definitions and paleocryological reconstructions (Iskorkina, 2016; Isaev et al., 2017).

Direct geothermal problems are solved for key points of geological time, corresponding to the start/end times of formation of each suite, overlapping the parent suite, as well as the “breaks” of the secular temperature variations on the Earth’s surface and the “turning points” of formation and degradation of the Neopleistocene permafrost and ice cover.

A quantitative assessment of the influence of paleoclimate on the calculated geothermal regime of oil source sediments is carried out based on an analysis of the variability of the results of four options for paleotemperature reconstructions:

Option 1 – without taking into account paleoclimate factors;

Option 2 – taking into account the secular variation of temperatures on the Earth’s surface, excluding permafrost and glaciers;

Option 3 – taking into account the secular temperature variation, accounting for the dynamics of permafrost;

Option 4 – taking into account the secular variation of temperatures, taking into account the dynamics of permafrost and glaciers.

The main criterion for the adequacy and preference of the results of paleotemperature modeling is the optimal consistency (“discrepancy”) of the maximum calculated geotemperatures with the “observed” temperatures of the “maximum paleothermometer” – temperatures determined by VR. The optimality of the “discrepancy” of calculated geotemperatures with “observed” reservoir temperatures is equally important. The optimal “discrepancy” is the mean square difference between the calculated and “observed” values, which is equal to the error of observations. This error is of the order of ± 2ºC (Isaev et al., 2018a).

As the second main criterion of the adequacy and preference of the results, the degree of consistency of the foci of intense hydrocarbon generation identified by the geotemperature criterion in the maternal suite (Fomin, 2011) with the oil and gas prospecting of the subsoil is established.

An important criterion for the reliability of the results of paleotemperature modeling is the consistency of the calculated values of the heat flow density q with the data of experimental determination of the heat flow density in the study area.

Parameterization of sedimentation history and thermophysical properties

The dedicated breakdown of the well No. 116 of the Bovanenkovskoye oil – gas condensate field (Fig. 1) from the bottom of the sedimentary cover to the Upper Cretaceous, including the Berezovskaya suite, is taken from the database of the Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences (2017). The subdivision of the Lower-Middle Paleogene assemblies, from the Gankinsky to the Irbitsky is borrowed from the materials of A.P. Karpinsky Russian Geological Research Institute (the State Geological Maps of VSEGEI. The map of the Pre-Quaternary formations R (40) -41, R-43, 44 (45) is taken from (http://vsegei.ru/ru/info/georesource/)). The overlying strata are dissected on the basis of work (Stratigrafiya neftegazonosnykh basseinov Sibiri, 2002; Volkova, 2011). Within the Bovanenkovsky area, accumulation of sedimentary strata went to the middle of the Miocene (18.5 million years ago, the formation of the Abrosimov Formation). In the Early Bicheul time, for 4 million years, the Abrosimov, Turtass, Novomikhailovsk, Atlym, Tavda, Nyurol, Irbit, Serov and Tibasalinsky formations (238 m) were washed out. From the end of the Bicheul time to the end of Novoportov, the boreal sea coagulation in the Middle Miocene-Early Pliocene was due to accumulation of 143 m thick sediments, which in the subsequent stage of positive tectonic movements over 1.3 million years were denudated. With the onset of the Late Miocene, Pliocene-Quaternary lacustrine-alluvial sediments accumulated.

Thus, when parameterizing the sedimentation-thermophysical model (Table 1), stratigraphic breakdowns were used, taking into account the dynamics of tectonic events during the formation of a sedimentary section (Isaev et al., 2018a).

The density parameter of the rocks σ (g/cm^3) of each suite was adopted taking into account the actual lithological filling of each straton. The calculated thermal conductivity of sedimentary rocks λ (W/m·K) is used.

For the calculations, petrophysical dependences of the thermal conductivity of λ sediments on their density σ were used. The choice of the coefficients of thermal diffusivity a (m^2/s) and specific heat generation f (W/m^3) was determined by the lithological composition of the suites, based on published tabular data. The strata of permafrost and ice cover have anomalously high values of thermal conductivity and thermal diffusivity a (Ivanov, Gavril’ev, 1965; Galushkin, 2007).

Formalized accounting of the permafrost stratum is carried out, starting from 0.52 million years ago, by “instantaneous” (by the standards of geological time, 0.3+3.0 thousand years) the replacement of “normal” sedimentary sediments with 600 m layer with specific

Suite, sequence (stratigraphy)	Thickness, m	Age, mln years ago	Accumulation times, mln years	Density, g/cm	Thermal conductivity, W/m K	Temperature conductivity, m^2/s	Heat generation, W/m^3
Neopleistocene Q- N_2	-	0.015-0.00	0.015	-	-	-	-
	-500	0.02-0.015	0.005	0.92	2.25	1.2e-006	1.22e-007
	-	0.04-0.02	0.02	-	-	-	-
	-1000	0.05-0.04	0.01	0.92	2.25	1.2e-006	1.22e-007
	-	0.120-0.050	0.070	-	-	-	-
	+1000	0.130-0.120	0.010	0.92	2.25	1.2e-006	1.22e-007
	-	0.177-0.130	0.047	-	-	-	-
	+500	0.182-0.177	0.005	0.92	2.25	1.2e-006	1.22e-007
	300	0.18215-0.1820	0.00015	2.10	2.09	1.05e-006	1.22e-006
	300	0.1823-0.18215	0.00015	2.10	1,3	7e-007	1.22e-006
	-600	0.1826-0.1823	0.0003	-	-	-	-
	-	0.5167-0.1826	0.3341	-	-	-	-
	600	0.5197-0.5167	0.003	2.10	2.09	1.05e-006	1.22e-006
	-600	0.520-0.5197	0.0003	-	-	-	-
Quarter + Pliocene Q- N_2	212	4.1-0.520	3.58	2.04	1,29	6.5e-007	1,1e-006
N_{1-2}	-143	4.1-5.4	1.3				
Novoportov N_{1-2}	80	5.4-8.4	3	2.08	1.33	7e-007	1.2e-006
Tavolzhan N_1	25	8.4-12.5	4.1	2.08	1.33	7e-007	1.2e-006
Bischeul N_1 *bsch*	38	12.5-14.5	2	2.08	1.33	7e-007	1.2e-006
N_1	-238	14.5-18.5	4				
Abrosimov N_1	10	18.5-23.0	4.5	2.08	1.33	7e-007	1.2e-006
Turtass ₽$_3$ *tur*	20	23.0-28.0	5	2.08	1.33	7e-007	1.2e-006
Novomikhaylov ₽$_3$ *nvm*	15	28.0-30.0	2	2.08	1.33	7e-007	1.2e-006
Atlym ₽$_3$ *atl*	37	30.0-34.0	4	2.08	1.33	7e-007	1.2e-006
Tavda ₽$_2$ *tv*	50	34.0-42.6	8.6	2.08	1.33	7e-007	1.2e-006
Nyurol ₽$_2$ *nl*	37	42.6-50.4	7.8	2.08	1.33	7e-007	1.2e-006
Irbit ₽$_2$*ir*	5	50.4-55.0	4.6	2.09	1.35	7e-007	1.2e-006
Serov ₽$_1$*sr*	20	55.0-58.0	3	2.09	1.35	7e-007	1.2e-006
Tibasalinsky ₽$_1$*tb*	44	58.0-63.7	5.7	2.09	1.35	7e-007	1.2e-006
Gankinsky K_2+ ₽$_1$*gn*	35	63.7-73.0	9.3	2.11	1.37	7e-007	1.25e-006
Berezovskaya K_2b	279	73.0-89.0	16	2.15	1,41	7.5e-007	1.25e-006
Kuznetsov K_2kz	37	89.0-92.0	3	2.18	1,43	8e-007	1.25e-006
Marresalinsky K_2-K_1mr	523	92.0-102.0	10	2.26	1.49	8e-007	1.25e-006
Yarongsky K_1jar	168	102-108.5	6.5	2.39	1.6	8e-007	1.25e-006
Tanopchinsky K_1tn	746	108.5-133.2	24.7	2.44	1.62	8e-007	1.25e-006
Akhsky K_1ah	522	133.2-142.7	9.5	2.44	1.64	8e-007	1.25e-006
Bazhenov J_3+K_1bg	15	142.7-149.3	6.6	2.42	1.62	8e-007	1.3e-006
Nurminsky J_2 *nr*	83	149.3-161.7	12.4	2.42	1.62	8e-007	1.3e-006
Malyshevsky J_2ml	84	161.7-171.0	9.3	2.45	1.63	8e-007	1.3e-006
Leontievsky J_2ln	90	171.0-173.0	2	2.47	1.65	8e-007	1.3e-006
Vymsky J_2 *vm*	143	173.0-175.0	2	2.45	1.63	8e-007	1.3e-006
Laydinsky J_2 *ld*	83	175.0-177.0	2	2.47	1.65	8e-007	1.3e-006
Nadoyakhsky J_2+J_1 *nd*	73	177.0-182.5	5.5	2.45	1.63	8e-007	1.3e-006
Kiterbyutskaya J_1kt	68	182.5-184.0	1.5	2.47	1.65	8e-007	1.3e-006
Sharapovsky J_1shr	85	184.0-186.0	2	2.45	1.63	8e-007	1.3e-006
Levinsky J_1 *lv*	111	186.0-186.70	0.7	2.47	1.65	8e-007	1.3e-006
Zimny J_1 *zm*	13	186.7-200.2	13.5	2.45	1.63	8e-007	1.3e-006
Section thickness, m	3370						

Table 1. A parametric description of the sedimentation history and thermophysical properties of the sedimentary sequence exposed by the Bovanenkovskaya well No. 116 (Iskorkina et al., 2018). The brown fill shows the accumulation times of the source-material Bazhenov and Kiterbytskaya suites and their parametric description. Gray fillings show erosion of Paleogene-Neogene deposits. The blue fill shows the times of formation, existence and degradation of the permafrost strata, the light blue shows the times of formation, existence and degradation of the glaciers

thermal characteristics. Then, this layer of frozen rocks was present in the sedimentary cover for 334 000 years. Further, "instantly" (0.3 + 0.15 + 0.15 thousand years), the frozen ground degrades in a volume of 300 m. And, further, frozen rocks exist in a volume of 300 m to the present during the last 182 000 years.

The recording of the ice cover is carried out starting from 0.182 million years ago. For 5 thousand years, a 500-meter glacier with its thermal characteristics was formed and existed in such a volume for 47 thousand years. Then, over 10 thousand years, the glacier's capacity has grown to 1500 m, and in such a volume it existed 70 thousand years. Further, over 10 thousand years, the glacier is reduced to 500 m and existed for 20 thousand years. By the time of 15 thousand years ago (the end of Sartan time) the glacier was completely degraded.

Reconstruction of the geothermal regime of the Kiterbyutskaya suite

Solution of the inverse problem of geothermy. *Comparison of the calculated and "observed" geotemperatures* are given in Table. 2. Since the "observed" (measured) temperatures (including those determined by VR) have an error of the order of ±2ºC, then *options 1 and 2* of the solutions (not accounting, not full accounting of paleoclimate factors) cannot be considered as acceptable. In these cases, the "residuals" exceed the optimum by 2 times and much more, and in option 1, the difference with the temperature according to VR reaches 18ºC. In the case of paleoclimate (*options 3 and 4*), both the "discrepancies" for reservoir temperatures and the convergence with the "maximum paleothermometer" are optimal and about equivalent. It seens the most optimal (acceptable) is *option 3*.

Analysis of the calculated values of the heat flux density from the base of the sedimentary section shows that when the factors of paleoclimate are taken into account, the heat flow increases. *The reliability of the results of paleotemperature modeling* of the Bovanenkovskaya borehole 116 is supported by the good consistency of the obtained *calculated* values of the heat flow density 60-62 mW/m^2 with the calculated values (Isaev et al., 2018a) of the heat flow density in the Rostovtsevskaya well 64 is 49-50 mW/m^2 (Fig. 1). This is confirmed by experimental determinations of the heat flow density for the Yamal Peninsula. The range of experimental definitions for the Yamal Peninsula is 47-58 mW/m^2, with the established pattern of the heat flow density increasing in the north-west direction (Khutorskoy et al., 2013).

Solutions to direct problems of geothermy*. An analysis of the thermal history of the Kiterbyutskaya suite* (Table 3) in the well section Bovanenkovskaya 116 indicates that, in *option 1* (without taking into account all paleoclimate factors), the oil source series "survived" the shortest and "coolest" main oil generation phase (MOGP).

In *variants 2, 3 and 4* (taking into account the factors of paleoclimate), the Kiterbyutskaya suite has "rich" thermal histories of MOGP. The main phases of oil formation in these variants have different values of the absolute maxima of paleotemperatures.

In *option 3*, the presence of a permafrost stratum with high thermal conductivity and thermal diffusivity leads to the maximum calculated values of the heat flow density, which, in turn, leads to a longer duration of the MOGP and increases the calculated geotemperature of the mother sediments to the maximum values.

Note that the addition of the ice sheet (*option 4*) had little effect on the calculated value of the heat flux density from the base, and, as a consequence, on the intensity and duration of the MOGP.

As noted above, the Kiterbyutskaya suite is the source of the formation of hydrocarbon deposits in the traps of the Lower Jurassic and, possibly, the pre-Jurassic hydrocarbons bearing sequence. In this regard, it is important to assess the consistency of the foci of intensive generation of Kiterbyutskaya oil, identified by the geothermal criterion in the well section, with the test results of the Lower Jurassic formations. In the Bovanenkovskaya area, the Kiterbyutskaya formation,

Depth, m	Measured temperatures, ºC	Measuring method	Option 1		Option 2		Option 3		Option 4	
			Value	Difference	Value	Difference	Value	Difference	Value	Difference
2610	94	formation	100	+6	97	+3	96	+2	97	+3
2657	97	formation	102	+5	99	+2	97	0	99	+2
2795	103	formation	107	+4	104	+1	103	0	104	+1
3050	113	formation	116	+3	113	0	112	-1	113	0
2615	120	by VR	102	-18	113	-7	119	-1	115	-5
Standard deviation ("residuals"), ºC			±9		±4		±1		±3	
Calculated heat flow from the base, mW/m^2			57		59		62		60	

Table 2. Comparison of measured and calculated subsoil temperatures in well No. 116 of Bovanenkovskoye oilfield – gas condensate field, using (Iskorkina et al., 2018). Brown fill shows the options that are optimal by the criterion of «discrepancy»

Time, mln years ago	«Arctic» secular temperature pattern, °C	Thickness of frozen rocks, m	Thickness of ice flow, m	Depth of Kiterbyutskaya suite, m	Geotemperatures of Kiterbyutskaya suite, °C				
					Option 1	Option 2	Option 3	Option 4	
								Geotemperatures	Depth of Kiterbyutskaya suite, m (accounting for the ice cover)
0	-4	300	-	3127	118	116	115	115	3111
0,015	-10	300	-	3126	118	115	115	114	3110
0,02	-8	300	500	3126	118	115	115	113	3610
0,030	-5	300	500	3125	118	116	114	113	3609
0,04	-6	300	500	3125	118	115	114	112	4109
0,050	-7	300	1500	3125	118	116	114	111	4608
0,070	-4	300	1500	3123	118	115	113	109	4609
0,110	-5	300	1500	3121	118	115	112	107	4609
0,120	-6	300	1500	3121	118	114	111	107	4609
0,130	-7	300	500	3120	118	114	111	106	3609
0,150	-6	300	500	3119	118	114	111	106	3608
0,177	-7	300	500	3118	118	114	122	106	3607
0,1820	-7	300	-	3118	118	114	119	106	3108
0,1826	-7	600	-	3118	118	114	112	106	3087
0,200	-8	600	-	3117	118	114	111	106	3107
0,240	-9	600	-	3115	118	113	111	106	3107
0,5167	-10	600	-	3100	114	112	119	114	3089
0,5197	-11	-	-	3100	117	112	126	114	2907
0,520	-11	-	-	3100	117	112	118	114	3127
1,8	-13	-	-	3034	114	109	115	110	3051
3,2	+5	-	-	2962	111	120	126	121	2968
4,1	+4	-	-	2915	110	119	125	120	2915
4,9	+4	-	-	3003	113	121	127	123	3003
5,4	+4	-	-	3058	115	124	130	125	3058
8,4	+5	-	-	2978	112	118	127	122	2978
10	+6	-	-	2968	111	122	127	123	2968
12,5	+6	-	-	2953	110	121	127	122	2953
14,5	+6	-	-	2915	110	121	126	122	2915
18,5	+7	-	-	3153	120	132	138	133	3153
23	+8	-	-	3143	119	132	138	133	3143
28	+8	-	-	3123	118	131	137	132	3123
30	+9	-	-	3108	117	131	137	132	3108
34	+9	-	-	3071	116	130	136	131	3071
35	+9	-	-	3065	116	130	135	130	3065
42,6	+12	-	-	3021	114	131	136	131	3021
50	+15	-	-	2986	112	132	137	132	2986
50,4	+15	-	-	2984	112	132	137	132	2984
55	+15	-	-	2979	112	132	137	133	2979
58	+16	-	-	2959	111	132	136	132	2959
63,7	+16	-	-	2915	109	130	135	130	2915
70	+16	-	-	2891	108	128	134	129	2891
73	+15	-	-	2880	107	127	133	128	2880
85	+13	-	-	2671	98	116	121	116	2671
89	+13	-	-	2601	95	113	118	114	2601
92	+13	-	-	2564	94	111	116	112	2564
100	+15	-	-	2146	77	95	99	96	2146
102	+15	-	-	2041	73	91	95	92	2041
108,5	+15	-	-	1873	67	85	88	85	1873
120	+16	-	-	1526	54	72	75	73	1526
134	+15	-	-	1083	34	55	57	55	1083
135	+15	-	-	1028	32	52	55	53	1028
142,5	+15	-	-	616	22	38	39	38	616
Calculated heat flow from the base, mW/m^2					57	59	62	60	

Tab. 3. Estimated geotemperatures of the Kiterbytskaya suite in the section of the well Bovanenkovskaya 116, using (Iskorkina et al., 2018). Option 1 – without taking into account paleoclimate factors. Option 2 – taking into account the "arctic" secular temperature pattern. Option 3 – taking into account the "arctic" secular temperature pattern and the Neopleistocene permafrost. Option 4 – taking into account the "arctic" secular temperature pattern, the Neopleistocene permafrost and ice cover. Brown fill shows the temperature of the main oil generation phase (MOGP), dark brown fill shows the temperature maximum of MOGP. The gray fill indicates the times of erosion of the Paleogene-Neogene deposits

according to the simulation results, has been located in the main zone of oil formation since the Marresala time (100 million years ago). And for about 15 million years, before the main erosion in the Neogene, the sequence closely approached the lower gas formation zone, warming up to 138ºC (Table 3). And, indeed, the well Bovanenkovskaya 116 revealed the oil-and-gas-saturated Lower Jurassic formations Yu6, Yu10 and Yu12.

Conclusions and discussion

1. On the representative section of the Bovanenkovskoye field of the Yamal Peninsula, it has been established that taking into account the "arctic" secular variation of temperatures on the Earth's surface and the Neopleistocene permafrost allows us to correctly reconstruct the thermal history of the oil source rocks of the Kiterbyutskya suite.
2. Accounting for paleoclimate leads to an increase in the estimated duration of the hydrocarbon fomation by 10 million years and an increase in the calculated paleotemperature maximum by 18°C, and, therefore, provides a more correct estimated density of Kiterbytskaya oil.
3. The reliability of the results of paleotemperature modeling is confidently controlled by the geophysical criterion of the "discrepancy", comparison with experimental data on heat flow in the study area, consistency with drilling and well testing data.
4. The results of assessing the role of Late Quaternary ice sheets (on the lands of the Yamal Peninsula) make it possible to argue the insignificant influence of the ice sheet on the thermal regime of oil source rocks of the Kiterbyutskaya suite.
5. The results obtained for the Kiterbutskaya suite of the Arctic region of Western Siberia are in complete agreement with the nature of the previously obtained estimates of the significant influence of the Mesozoic-Cenozoic climate on the geothermal regime of the Bazhenov Formation of the Yamal Peninsula.

It is important to note the following. A quick calculation of the density of the generation of the Kiterbyutskaya oil shows (Iskorkina et al., 2018) that not taking into account the paleoclimatic factors, leading to a decrease in the intensity and duration of the main oil generation phase, leads to an underestimation of the prognostic hydrocarbon resources by 30%. A similar calculation of the generation density of Bazhenov oil (Isaev et al., 2018a) showed an underestimation of the prognostic hydrocarbon resources by 40-50%. The express calculation cumulatively takes into account the times of the oil source formation in the main oil generation window.

It should be suggested why, in paleotemperature modeling of both Bazhenov and Kiterbyutskaya maternal sediments, accounting for the ice cover had little effect on the magnitude of the calculated heat flow density from the base q, and on the intensity and duration of the main oil generation phase. This result may be explained by the fact that the temperature wave of "disturbance" of the thermal model in the upper part of the section – reaches fully to depths of about 3000 m not earlier than in 0.2-0,3 million years (Khristoforov, Abrosimova, 2012). Such a "delay" was established by us earlier (Isaev, Fomin, 2006; Osipova et al., 2015). Obviously, this "lag" is more concerned with the influence of ice caps, whose age was assumed to be no more than 0.18 Ma.

This article provides an overview of the publications of the Tomsk Research School of Geothermals, which consistently, based on borehole observations and computer modeling, develops the idea of the evolution of the geothermal conditions of oil source deposits in Western Siberia. This methodology formulates new exploration tasks that can be solved by measuring, mapping and modeling the spatial-temporal parameters of geothermal fields.

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References

Demezhko D., Gornostaeva A.A. (2014). Reconstructions of long-term ground surface heat flux changes from deep-borehole temperature data. *Russian Geology and Geophysics*, 55(12), pp. 1471-1475. https://doi.org/10.1016/j.rgg.2014.11.011

Duchkov A.D., Galushkin Yu.I., Smirnov L.V., Sokolova L.S. (1990). Evolyutsiya temperaturnogo polya osadochnogo chekhla Zapadno-Sibirskoi plity [The evolution of the sedimentary cover temperature field of the West Siberian Plate]. *Geologiya i geofizika = Russian Geology and Geophysics*, 10, pp. 51-60. (In Russ.)

Fomin A.N. (2011). Katagenez organicheskogo veshchestva i neftegazonosnost' mezozoiskikh i paleozoiskikh otlozhenii Zapadno-Sibirskogo megabasseina [Catagenesis of organic matter and petroleum potential of the Mesozoic and Paleozoic sediments of the West Siberian megabasin]. Novosibirsk: INGG SO RAN, 331 p. (In Russ.)

Galushkin Yu.I. (2007). Modelirovanie osadochnykh basseinov i otsenka ikh neftegazonosnosti [Modeling of sedimentary basins and evaluation of their oil and gas content]. Moscow: Nauchnyi Mir, 456 p. (In Russ.)

Galushkin Yu.I. (2016). Non-standard Problems in Basin Modelling – Switzerland: Springer, 274 p.

Golovanova I.V., Sal'manova R.Y., Tagirova C.D. (2014). Method for deep temperature estimation with regard to the paleoclimate influence on heat flow. *Russian Geology and Geophysics*, 55(9), pp. 1130-1137. https://doi.org/10.1016/j.rgg.2014.08.008

Igenbaeva N.O. (2015). Resource potential and environmental risks of oil and gas development of the Northern districts of KHMAO-Yugra. *Vestnik Yugorskogo gosudarstvennogo universiteta* [Yugra State University Bulletin], S2(37), pp. 176-178. (In Russ.)

Isaev V.I., Fomin A.N. (2006). Centers of generation of bazhenov- and togur-type oils in the southern Nyurol'ka megadepression. *Geologiya i geofizika = Russian Geology and Geophysics*, 47(6), pp. 734-745. (In Russ.)

Isaev V.I., Iskorkina A.A., Kosygin V.Yu., Lobova G.A., Osipova E.N., Fomin A.N. (2017). Integrated assessment of paleoclimate factors of reconstructing thermal history of petromaternal Bazhenov suite in arctic regions of Western Siberia). *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov* [Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering], 328(1), pp. 13-28. (In Russ.)

Isaev V.I., Iskorkina A.A., Lobova G.A., Fomin A.N. (2016). Paleoclimate''s factors of reconstruction of thermal history of petroleum bazhenov and togur suites southeastern West Siberia. *Geofizicheskii zhurnal*, 38(4), pp. 3-25. (In Russ.)

Isaev V.I., Lobova G.A., Stotskiy V.V., Fomin A.N. (2018). Geothermy and zoning of shale oil prospects of the Koltogor-Urengoy paleorift (southeastern part of West Siberia). *Geofizicheskii zhurnal*, 40(3), pp. 54-80. https://doi.org/10.24028/gzh.0203-3100.v40i3.2018.137173 (In Russ.)

Isaev V.I., Iskorkina A.A., Lobova G.A., Starostenko V.I., Tikhotskii S.A., Fomin A.N. (2018a). Mesozoic–Cenozoic Climate and Neotectonic Events as Factors in Reconstructing the Thermal History of the Source-Rock Bazhenov Formation, Arctic Region, West Siberia, by the Example of the Yamal Peninsula. *Izvestiya. Physics of the Solid Earth*, 2, pp. 310-329. https://doi.org/10.1134/S1069351318020064 (In Russ.)

Isaev V.I., Lobova G.A., Mazurov A.K., Starostenko V.I., Fomin A.N. (2018b). Zoning of mega-depressions by shale oil genegation density of Togur and Bazhenov source suites in the southeast of Western Siberia. *Geologiya nefti i gaza = Oil and Gas Geology*, 1, pp. 15-39. (In Russ.)

Iskorkina A.A. (2016). Paleoclimate factors of reconstructing thermal history of the petromaternal bazhenov suite of the Arctic region in Western Siberia. *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov* [Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering], 32(8), pp. 59-73. (In Russ.)

Iskorkina A.A., Prokhorova P.N., Stoskiy V.V., Fomin A.N. (2018). Reconstructions of geothermal mode of the petromaternal Kiterbutsk suite of the Arctic region in Western Siberia taking into account the influence of paleoclimate. *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov* [Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering], 329(2), pp. 49-64. (In Russ.)

Ivanov N.S., Gavril'ev R.I. (1965). Teplofizicheskie svoistva merzlykh gornykh porod [Thermophysical properties of frozen rocks]. M.:Nauka, 74 p.

Khristoforov A.V., Abrosimova I.S., Burganov B.T. (2012). Interference of the temperature waves. Laboratory experiment. *Georesursy = Georesources*, 1(43), pp. 28-30. (In Russ.)

Khutorskoi M.D., Podgornyi L.V., Suprunenko O.I., Kim B.I., Chernykh A.A. (2011). Termotomograficheskaya model' i prognoz neftegazonosnosti osadochnogo chekhla shel'fa morya Laptevykh [Thermotomographic model and oil and gas potential prediction of the sedimentary cover of the Laptev Sea shelf]. *Doklady akademii nauk* = Proc. of the Academy of Sciences], 440(5), pp. 663-668. (In Russ.)

Khutorskoy M.D., Akhmedzyanov V.R., Ermakov A.V. et al. (2013). Geotermiya arkticheskikh morey [Geothermy of Arctic seas]. Moscow: GEOS, 232 p. (In Russ.)

Kontorovich A.E., Burshtein L.M., Safronov P.I., Gus'kov S.A., Ershov S.V., Kazanenkov V.A., Kim N.S., Kontorovich V.A., Kostyreva E.A., Melenevskiy V.N., Livshits V.R., Malyshev N.A., Polyakov A.A., Skvortsov M.B. (2013). Historical-geological modeling of hydrocarbon generation in the Mesozoic-Cenozoic sedimentary basin of the Kara Sea (basin modeling). *Russian Geology and Geophysics,* 54(8), pp. 917-957. https://doi.org/10.1016/j.rgg.2013.07.011 (In Russ.)

Kurchikov A.R. (2001). Geotermicheskii rezhim uglevodorodnykh skoplenii Zapadnoi Sibiri [Geothermal regime of hydrocarbon accumulations in Western Siberia]. *Geologiya i geofizika = Russian Geology and Geophysics*, 42(11-12), pp. 1846-1853. (In Russ.)

Kurchikov A.R., Stavitskii B.P. (1987). Geotermiya neftegazonosnykh oblastei Zapadnoi Sibiri [Geothermy of oil and gas regions of Western Siberia]. Moscow: Nedra, 134 p. (In Russ.)

Kuzmin Iu.A., Kuzmenkov S.G., Polukeev S.M., Novikov M.V., Korkunov V.V. (2014). Hard-to-recover oil reserves of Bazhenov deposits in KhMAO-Yugra. *Nedropol'zovanie XXI vek*, 3, pp. 56-63. (In Russ.)

Lobova G.A., Luneva T.E., Kirillina M.S. (2018). Zoning of oil-gas potential of preJurassic reservoirs in Nyurol'ka megadepression (using paleotemperature modeling and drilling). *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov* [Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering], 329(3), pp. 123-133. (In Russ.)

Lobova G.A., Osipova E.N., Krinitsyna K.A., Ostankova Yu.G. (2013). The effect of paleoclimate on geometry mode and oil generation potential of Bazhenov formation (at Tomsk region latitudes). *Izvestiya Tomskogo politekhnicheskogo universiteta* [Bulletin of the Tomsk Polytechnic University], 322(1), pp. 45-50. (In Russ.)

Neftegazonosnye basseiny i regiony Sibiri [Oil and gas bearing basins and regions of Siberia] (1994). Is. 2: Zapadno-Sibirskii bassein [West Siberian basin]. Ed. A.E. Kontorovich, V.S. Surkov, A.A. Trofimuk et al. Novosibirsk: SO RAN, 201p. (In Russ.)

Nelskamp S., Donders T., van Wess J.-D., Abbink O. (2014). Influence of Surface Temperatures on Source Rock Maturity: An Example from the Russian Artic. *ROGTEC*, 18, pp. 26-35.

Osipova E.N., Lobova G.A., Isaev V.I., Starostenko V.I. (2015). Petroleum potential of the lower cretaceous reservoirs of Nyurol'ka megadepression. *Izvestiya Tomskogo politekhnicheskogo universiteta* [Bulletin of the Tomsk Polytechnic University], 326(1), pp. 14-33. (In Russ.)

Polukeev S.M., Shpilman A.V., Kuzmin Iu.A., Korkunov V.V., Novikov M.V., Kuzmenkov S.G. (2013). Stabilization of oil production in Ugra by means of hard to recover reserves – myth or reality? *Nedropol'zovanie XXI vek*, 5, pp. 12-19. (In Russ.)

Starostenko V.I., Kutas R.I., Shuman V.N., Legostaeva O.V. (2006). Obobshchenie statsionarnoi zadachi geotermii Releya-Tikhonova dlya gorizontal'nogo sloya [Generalization of the stationary problem of the Rayleigh-Tikhonov geothermy for a horizontal layer]. *Izvestiya. Physics of the Solid Earth*, 12, pp. 84-91. (In Russ.)

Stratigrafiya neftegazonosnykh basseinov Sibiri [Stratigraphy of Siberian oil and gas basins] (2002). Book 9: Kainozoi Zapadnoi Sibiri [Cenozoic of Western Siberia]. Ed. V.S. Volkova. Novosibirsk: SO RAN, 246 p. (In Russ.)

Tissot B.P. (2003). Preliminary Data on the Mechanisms and Kinetics of the Formation of Petroleum in Sediments. Computer Simulation of a Reaction Flowsheet. *Oil & Gas Science and Technology – Rev. IFP*, 58(2), pp. 183-202.

Volkova V.S. (2011). Paleogene and Neogene stratigraphy and paleotemperature trend of West Siberia (from palynologic data). *Russian Geology and Geophysics*, 52(7), pp. 709-716. https://doi.org/10.1016/j.rgg.2011.06.003

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