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ORIGINAL PAPER - EXPLORATION GEOLOGY

Large undiscovered oil resources are predicted south of Russia

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Abstract

Stavropol Region is one of the oldest petroleum provinces on South of Russian Federation. Today, most of its fields are depleted and prospects for the discovery of new large hydrocarbon deposits considered exhausted. However, our studies allow us to talk about the possibility of the existence of previously undiscovered oil reservoirs, clamped in the source rocks associated with North-Stavropol tectonic element. In the middle of the last century, similar deposits have been identified within Prikumsk-Tyulenevskiy (Praskoveyskoe, Achikulakskoye, Ozek-Suat and a number of other fields) and Chernolesskiy (Zhuravskoye, Vorobyevskoye) tectonic elements. However, these findings were largely spontaneous due to lack of approved and unified approach to the petrophysical evaluation of dedicated reservoirs from well logs. At the same time the experience of shale reservoirs studies, as well as the results of its implementation to evaluation of deposits of Zhuravsky-Vorobyevsky petroleum accumulation zone, allows to revise existing well log materials for deep wells of explorational and depleted structures, and to identify promising intervals for further re-exploration and testing. In this work, Paleocene sediments of Blagodarnenskaya explorational structure of the Stavropol Region were studied. Despite the approval of the oil bearing of these deposits within the Prikumsk-Tyulenevskiy tectonic element and the positive signs of hydrocarbon saturation from initial well logs data, its evaluation and testing within Blagodarnenskaya structure associated with North-Stavropol tectonic element, were not conducted. However, the results of well logs analysis performed by us with the use of interpretation technique approved on reservoirs of Zhuravsky-Vorobyevsky petroleum accumulation zone, as well as the core tests indicate the presence of oil-saturated reservoirs in the Paleocene sediments of Blagodarnenskaya structure.

Keywords South of Russia · Stavropol region · Undiscovered oil resources · Wireline logs · Core analysis

Introduction

Deep-exploration drilling on the Blagodarnenskaya structure of the Stavropol Region was carried out from the late 1950s to the mid-1970s of the last century. The target of deep drilling was the Lower Cretaceous deposits, whose commercial gas productivity was confirmed within the North-Stavropol tectonic element on Mirnenskoye, Selskoye and a number of other fields.

After negative results of production tests of Lower Cretaceous deposits, the majority of deep-exploration wells (up to 3000 m deep) were plugged, and shallow gas reservoirs (400–600 m) of the Lower Miocene sediments, discovered earlier as a result of core drilling and associated with the Petrovsko-Blagodarnenskaya structure (Burshtar 1966), were put in production. Now, the shallow gas field discovered at Petrovsko-Blagodarnenskaya structure is being developed by "Gazprom Production Krasnodar" LLC (Fig. 1).

At the same time, testing of the Lower Paleogene sediments (the commercial oil production capacity of which was confirmed at the neighboring Vorobyevskoye, Zhuravskoye and Praskoveyskoye fields) in the deep-exploration wells of the Blagodarnenskaya structure was not carried out.

Up to date, the revision of the initial well logs data, to find and evaluate promising oil deposits in the Lower Paleogene sediments, was not performed neither by "Gazprom Production Krasnodar" LLC nor by the third-party organizations. The current development plan of the Petrovsko-Blagodarnenskoye gas field states that there are no oil reservoirs in the field section.

However, the analysis of the initial well logs data, as well as cores from the corresponding intervals of

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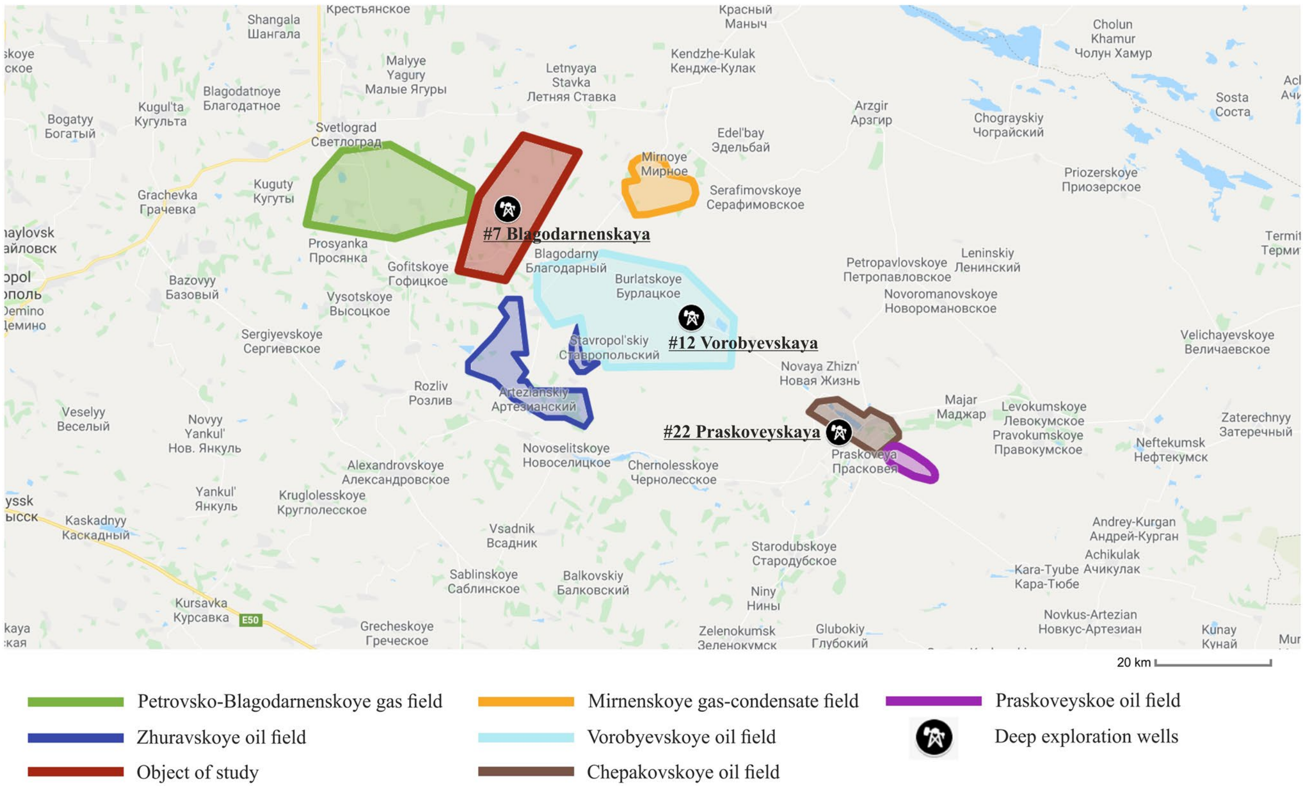


Fig. 1 Location of the Blagodarnenskaya structure

deep-exploration wells, allows to talk about the presence of oil reservoirs in the Lower Paleogene sediments of the Blagodarnenskaya structure.

Wireline logs analysis and core studies

To prove presence of oil reservoirs in Lower Paleogene sediments, we performed interpretation of the initial well logs from deep-exploration wells located both within the studied subsoil block and outside it on the territory of Petrovsko-Blagodarnenskoye gas field. In addition, cores retrieved from the appropriate intervals of deep-exploration wells were analyzed.

During interpretation, Well # 7 Blagodarnenskaya was selected as the reference, because it has the most complete set of wireline logs performed, such as: lateral logging, spontaneous potential, gamma and neutron gamma logs, mud resistivity, caliper, and temperature log.

Appropriate logs for the Well # 7 Blagodarnenskaya are shown in the Fig. 2. Curves' description and units of measurement are given in Table 1. Stratigraphic column presented in Table 2.

During interpretation, volume of clay was calculated from natural gamma ray logging data by linear equation; the effective porosity of the reservoir was calculated from the total porosity obtained by the neutron method, with correction to volume of clay; water saturation of the reservoir was obtained from Simandoux equation. True resistivity of the reservoir, necessary to calculate water saturation, was obtained by inversion of the array of lateral tools readings.

Results of wireline logs interpretation and array resistivity inversion are summarized in Tables 3 and 4.

To confirm the results of the interpretation, we conducted laboratory analysis of core sample (Fig. 3) from the Paleocene deposits of Well # 7. Analysis consisted from estimation of effective porosity by liquid saturation and the determination of resistivity at 100% water saturation. The results of the core sample analysis are given in Table 5.

From Table 3 it can be seen that in the Paleocene sediments, three supposedly oil-saturated intervals are recognizable. The intervals 8 and 15 are characterized by lower resistivity in flushed zone than in uninvaded. Sudden decrease in invaded zone resistivity for interval eight is apparently due to the annulus zone forming (Table 4). The interval 12 is characterized by higher resistivity in flushed zone than in uninvaded, which is due to its higher water saturation (Tables 3, 4). At the same time, the resistivity of the uninvaded zone for all three intervals exceeds the resistivity of the 100% water-saturated core sample by more than two

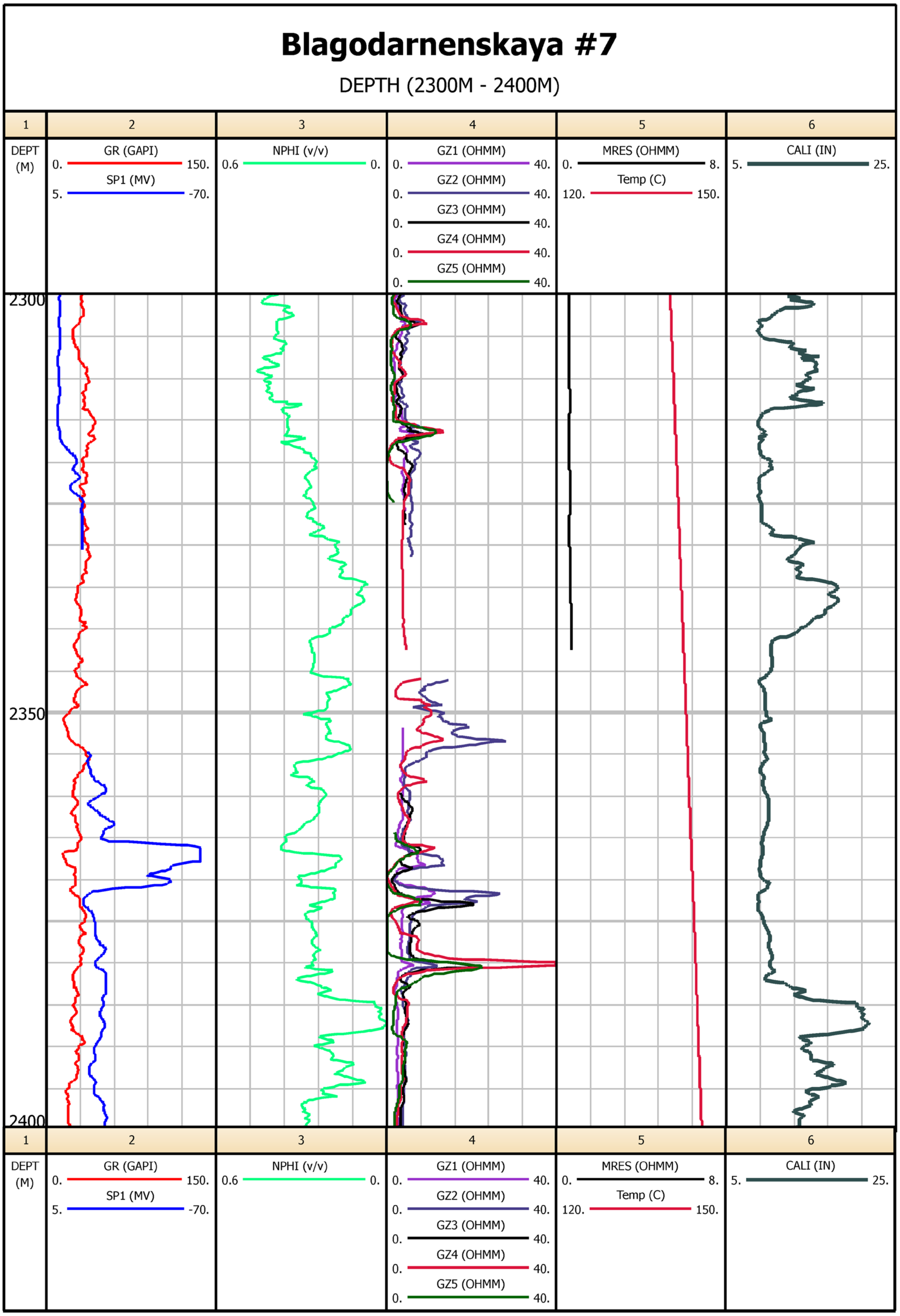


Fig. 2 Wireline logs for the Well # 7 Blagodarnenskaya

Table 1 Wireline curves' description

Curve name	Short description	Units of measurement
GZ1	"Bottom" lateral tool with spacing A0.4M0.1N	Ohm m
GZ2	"Bottom" lateral tool with spacing A1.0M0.1N	Ohm m
GZ3	"Bottom" lateral tool with spacing A2.0M0.5N	Ohm m
GZ4	"Bottom" lateral tool with spacing A4.0M0.5N	Ohm m
GZ5	"Bottom" lateral tool with spacing A8.0M1.0N	Ohm m
GR	Natural gamma ray log	GAPI
SP1	Spontaneous potential log corrected for shale baseline shifts	mV
NPHI	Neutron porosity from neutron gamma log	Fraction
MRES	Mud-resistivity log	Ohm m
Temp	Temperature log	Degrees of Celsius
CALI	Caliper log	Inch
DEPT	Depth of well	Meter

Table 2 Stratigraphical and lithological characteristics of the Blagodarnenskaya structure

Division, tier, formation	Lithological characteristics of rocks	Depth to top, (m)	Thickness, (m)
Quaternary system + Pliocene	Yellow–brown clays and loams	0	1–50
Neogene system			
Sarmat	Clays gray, dense, containing layers of sands, sandstones and marls	50	16–159
Conk	Clays gray, sandy with layers of gray, carbonate sands	209	45–116
Karagan	Clays brownish-gray, greenish-gray, sandy with layers of marls	325	37–105
Chokrak	Clay greenish-gray, sandy, mica, calcareous with layers of marls, limestones and sandstones	430	50–77
Paleogene system			
Maikop	Clays gray with brownish or greenish tinge, not calcareous. In the upper part sandy-siltstone layers are developed, which contain gas reservoirs	507	930–1290
Khadum	Clays brownish-brown with traces of gray mica siltstones and layers of dark gray, clayey siltstones	1797	50–77
Beloglinsky series	Marls light gray, greenish-gray, strongly calcareous clays	1874	12–18
The Kuma series	Dark brown marls, limestones, calcareous clays	1892	7
The Kerestinskaya series	Marls light gray with a greenish tinge	1899	5
Circassian series	Sandstones, siltstones, and shales	1904	260–340
Paleocene	Sandstones, siltstones, and shales	2244	200–210
Cretaceous system			
Upper Cretaceous	Limestones light gray-to-white with layers of clayey gray, greenish-gray marls	2454	210
Lower Cretaceous	Sandstones, siltstones, and shales	2664	250
Paleozoic era			
Paleozoic	Black slates with traces of phyllite	2914	–

times (Tables 4, 5), which proves hydrocarbon saturation of these intervals. The effective porosity value obtained from the core sample is generally consistent with the average values for the Paleocene sediments, taking into account the considerable thickness of the sampling interval capturing both zones of the reservoirs and shales (Tables 3, 5).

Since the question of the oil saturation of the Paleocene sediments within the Blagodarnenskaya structure is considered for the first time, it is important to confirm the type of saturating hydrocarbon. Unfortunately, the absence of acoustic and gamma-density tools at the time of logging does not allow to draw a conclusion about the type of saturating hydrocarbon by the characteristic separations between the readings of acoustic, neutron- and density-logging instruments. However, since the reservoirs of the Paleocene sediments of the Blagodarnenskaya structure represent siltstones of turbidite origin clamped in source rocks, conclusions on the type of saturating hydrocarbon can be made from

Table 3 Wireline logs interpretation for Paleocene deposits of Well # 7 Blagodarnenskaya

Interval	Top, (m)	Bottom, (m)	Gross thickness, (m)	Net pay, (m)	Effective porosity, fraction	Water saturation, fraction	Volume of clay, fraction	Comment
1	2200.00	2273.10	73.10	0.00	–	–	–	Non reservoir
2	2273.10	2275.80	2.70	2.70	0.151	0.989	0.250	Water saturated
3	2275.80	2281.80	6.00	0.00	–	–	–	Non reservoir
4	2281.80	2283.80	2.00	2.00	0.178	0.922	0.217	Water saturated
5	2283.80	2289.00	5.20	0.00	–	–	–	Non reservoir
6	2289.00	2290.90	1.90	1.90	0.217	0.864	0.226	Water saturated
7	2290.90	2312.50	21.60	0.00	–	–	–	Non reservoir
8	2312.50	2317.70	5.20	5.10	0.162	0.347	0.381	Oil saturated
9	2317.70	2324.50	6.80	0.00	–	–	–	Non reservoir
10	2324.50	2364.50	40.00	–	–	–	–	Break of logging
11	2364.50	2365.80	1.30	0.00	–	–	–	Non reservoir
12	2365.80	2366.80	1.00	0.80	0.271	0.468	0.199	Oil saturated
13	2366.80	2371.20	4.40	4.40	0.178	0.957	0.123	Water saturated
14	2371.20	2379.20	8.00	0.00	–	–	–	Non reservoir
15	2379.20	2381.10	1.90	1.80	0.141	0.213	0.235	Oil saturated
16	2381.10	2400.00	18.90	0.00	–	–	–	Non reservoir

Table 4 Results of inversion of array lateral logging for Paleocene deposits of Well # 7 Blagodarnenskaya

Interval	Top, (m)	Bottom, (m)	Flushed zone resistivity, (Ohm m)	Invaded zone resistivity, (Ohm m)	True reservoir resistivity, (Ohm m)
1	2200.00	2273.10	4.248	2.924	1.618
2	2273.10	2275.80	8.197	6.338	2.374
3	2275.80	2281.80	4.076	3.000	1.883
4	2281.80	2283.80	11.987	8.014	3.079
5	2283.80	2289.00	4.211	3.369	1.700
6	2289.00	2290.90	15.180	7.019	3.347
7	2290.90	2312.50	4.672	2.912	1.390
8	2312.50	2317.70	7.497	4.452	10.730
9	2317.70	2324.50	5.778	3.460	0.350
10	2324.50	2364.50	–	–	–
11	2364.50	2365.80	2.558	2.201	1.353
12	2365.80	2366.80	18.540	9.183	7.970
13	2366.80	2371.20	9.884	3.228	1.293
14	2371.20	2379.20	7.756	4.966	0.461
15	2379.20	2381.10	9.143	20.772	33.494
16	2381.10	2400.00	8.763	3.821	2.930

geochemical studies of core samples by the means of source rock pyrolysis.

For pyrolysis analysis, during which sample would be crushed, we used source rock sample from Well # 7 Selskaya, which has characteristics similar to Blagodarnenskaya structure section of rocks (Fig. 4). This plugged deep-exploration well also has the signs of oil shows at casing head (Fig. 5). The results of the pyrolysis are presented in Tables 6 and 7.

Comparing obtained pyrolysis parameters with typical values characterizing the quality of the source rock, type of organic matter and degree of its thermal maturity (McCarthy et al. 2011), it can be noted that the source rocks of the Paleocene sediments have an average generation potential and contain mixed-type II/III kerogen (sapropel–humus organic matter) characterized by an early maturity corresponding to the beginning of the "oil window". The component analysis of pyrolysis products (Table 7) also indicates that the main

a collection of rock samples from the interval 2364-2370 meters of Well # 7 Blagodarnenskaya

b core sample from the Paleocene deposits of Well # 7 Blagodarnenskaya, used tomeasure resistivity at 100 % water saturation

Fig. 3 Rock samples from the Paleocene deposits of Well # 7 Blagodarnenskaya. **a** Collection of rock samples from the interval 2364–2370 m of Well # 7 Blagodarnenskaya. **b** Core sample from the Paleocene deposits of Well # 7 Blagodarnenskaya, used to measure resistivity at 100% water saturation

product of the thermal transformation of the organic matter of the Paleocene sediments is hydrocarbons of the oil series. The geochemical characteristics of the Paleocene rocks are in many respects similar to the source rocks of the Khadum formation of the Zhuravsky-Vorobyevsky petroleum accumulation zone, which are also characterized by the presence of an organic matter of mixed type and early maturity (Kerimov et al. 2016). In general, the obtained results support the theory of the oil saturation of reservoirs clamped in source rocks of the Paleocene deposits of Blagodarnenskaya structure.

To assess the consistency of oil-saturated reservoirs within the Blagodarnenskaya structure, we also analyzed wireline logs for all exploration wells available at this moment. In addition to Well # 7 Blagodarnenskaya, five exploration wells were analyzed. The interpretation technique was slightly different from one for Well # 7, what was due to the reduced set of logs performed in these wells.

The majority of exploration wells were logged from the late 1950s to the late 1960s, at that time a standard set of logging tools included: lateral logging, spontaneous potential, caliper and temperature log. Nuclear logging methods, such as gamma and neutron gamma ray logging, at this time in Soviet Union were in the prototype stage and were included in the standard logging complex only in the late 1960s. Therefore, the analysis of these exploration wells consisted from estimation of oil saturations in promising reservoirs. Estimation of volume of clay and effective porosity was not performed due to the lack of gamma and neutron gamma logs. The widespread in Western Siberia practice to use solely SP curve in order to estimate the porosity and volume of clay when nuclear logging curves are missing, cannot be applied to the Lower Paleogene sediments of Stavropol Region due to absence of any significant separations from shale baseline in the reservoir zones on SP curves. This behavior is typical for the reservoirs of Lower Maikop sediments of neighboring Zhuravskoye and Vorobyevskoye oil fields, where oil rates up to 600 barrels/day were obtained from reservoirs that did not have significant separations on SP curves.

Table 5 The results of the core sample analysis from Well # 7 Blagodarnenskaya

Name of parameter	Numerical value
Well number	7 Blagodarnenskaya
Sample number	1
Sampling interval, (m)	2364–2370
Age of sediments	Paleogene/Paleocene
Salinity of NaCl solution, (ppm)	25,000
Temperature of sample during measurements, (^{o}C)	18
Resistance of the sample, (Ohm)	631.92
Resistivity of sample at the temperature of measurements, (Ohm m)	11.11
Bottom hole temperature at the top of sampling interval, (^{o}C)	143.79
Resistivity of sample at the bottom hole temperature, (Ohm m)	2.66
Volume of pore space, (cm^3)	3.964
Total volume of the saturated sample, (cm^3)	25
Effective porosity, fraction	0.159

Fig. 4 Rock sample used for pyrolysis analysis

Fig. 5 Oil shows at the casing head of Well # 7 Selskaya

Table 6 The results of the pyrolysis of core sample from Paleocene sediments

Name of parameter	Numerical value
Well number	7 Selskaya
Sample number	1
Sampling interval, (m)	2371–2377
Age of sediments	Paleogene/Paleocene
S_1, mg hydrocarbons/g rock	0.45
S_2, mg hydrocarbons/g rock	4.14
TOC, (%)	1.89
Hydrogen index, mg hydrocarbons/g organic carbon	219
Productivity index of source rocks	0.10

Table 7 Component composition of pyrolysis products for the core sample from Paleocene sediments

Component	Amount, (mol%)	Comment
CH_4	6	Methane
C_2–C_5	22	Wet gases
C_6–C_{14}	40	Light oil
C_{15+}	32	Heavy oil

The absence of separations on SP log is the result of hydrocarbon suppression effect, which further increases with increase of reservoir clay content. It is not related to the absence of permeability since the array of laterals demonstrates positive separations between resistivities of flushed, invaded, and virgin zones of reservoir (Fig. 2; Table 4). The separation between resistivities is a direct indicator of flushing of hydrocarbons by mud filtrate during invasion process and thus, the presence of permeability.

Typical limited set of logs for the Paleocene sediments of Well # 1 Blagodarnenskaya is shown in Fig. 6. The location of the exploration wells relative to the object of study is represented in Fig. 7.

Water saturation of the reservoir for wells with a limited logging suit was calculated by resistivity ratio method. Summary results of wireline logs analysis for the available exploration wells are presented in Table 8.

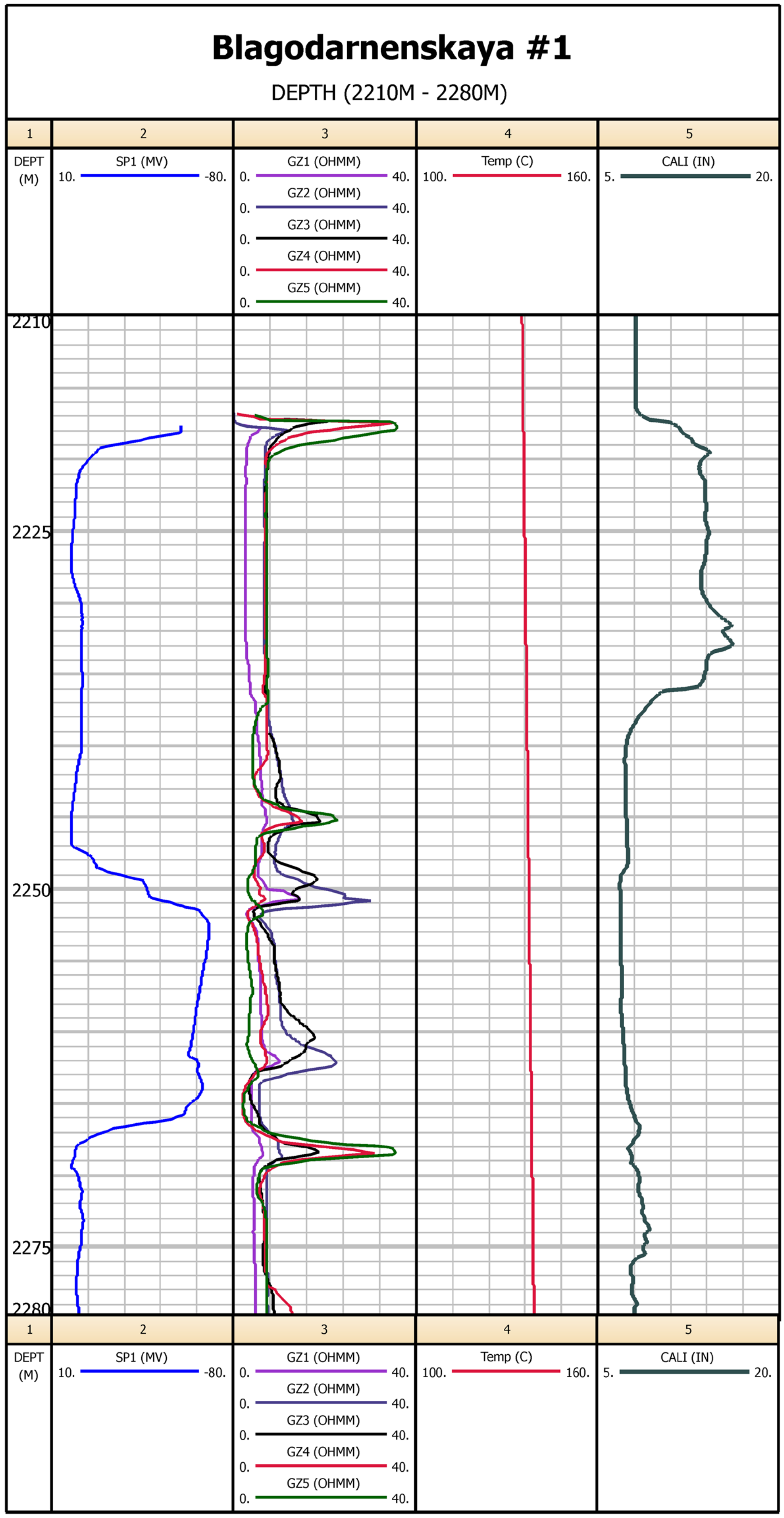
Analysis of wireline logs suggests that two probably oil-saturated intervals are traced in majority of exploration wells (Table 8). The upper interval is assigned the designation of the Paleocene Layer I, the lower one—the Paleocene Layer II.

It was discovered from logs, that in Well # 7 Sadovaya Layer I is replaced by clays. Layer II is present in Well # 7 Sadovaya at depth levels correlating with Well # 7 Blagodarnenskaya (Tables 3, 8). It appears, that Well # 7 Sadovaya crosses the reservoir of Layer I in pinch-out zone.

From analysis of the wireline logs for Well # 2 Zhuravsko-Blagodarnenskaya it was found that the Layers I and II are water-saturated (Table 8). That was confirmed by the results of a production test conducted in September 1973 in the interval 2276–2288 m, during which saline water was obtained with rate of 17.48 barrels/day. We suppose, that the Well # 2 Zhuravsko-Blagodarnenskaya penetrates Layers I and II in free water zone beyond the boundary of the oil–water contact.

Thus, basing on the results of analysis of wireline logs and core samples, at least two oil reservoirs are identified within the studied object.

Fig. 6 Wireline logs for the Well # 1 Blagodarnenskaya



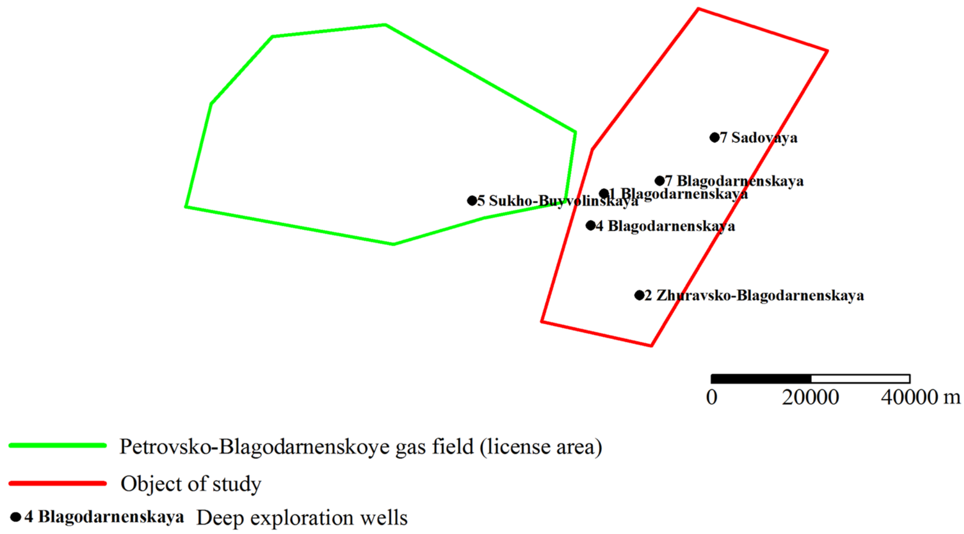


Fig. 7 Location of deep-exploration wells used in reservoir evaluation

Table 8 Results of wireline logs interpretation for deep-exploration wells of Blagodarnenskaya structure

Reservoir	Number and name of well	Measured depth, (m)		Gross thickness, (m)	Net pay, (m)	Effective porosity, fraction	Water saturation, fraction
		Top	Bottom				
Layer I	1 Blagodarnenskaya	2217.80	2220.00	2.20	2.15	–	0.146
	4 Blagodarnenskaya	2254.20	2256.50	2.30	2.20	–	0.158
	7 Blagodarnenskaya	2312.50	2317.70	5.20	5.10	0.162	0.347
	2 Zhuravsko-Blagodarnenskaya	2259.30	2263.80	4.50	4.50	–	1.000
	7 Sadovaya	–	–	0.00	0.00	–	–
	5 Sukho-Buyvolinskaya	2169.40	2171.90	2.50	2.40	–	0.168
Layer II	1 Blagodarnenskaya	2266.30	2268.50	2.20	2.10	–	0.320
	4 Blagodarnenskaya	2292.20	2295.00	2.80	2.70	–	0.209
	7 Blagodarnenskaya	2379.20	2381.10	1.90	1.80	0.141	0.213
	2 Zhuravsko- Blagodarnenskaya	2289.40	2295.80	6.40	6.40	–	1.000
	7 Sadovaya	2377.90	2380.70	2.80	2.70	–	0.197
	5 Sukho-Buyvolinskaya	2182.80	2184.30	1.50	1.40	–	0.191

Estimation of undiscovered resources

To understand scales of undiscovered oil resources, we have estimated them by volumetric method on static reservoir model.

Previously obtained wireline logs data (Table 8) were utilized for reservoir mapping and building of the structural grid. Results of structural mapping for Paleocene Layers I and II are summarized in Figs. 8 and 9. The general view of the reservoir model is shown in Fig. 10.

It can be seen from Fig. 9 that during structural mapping for Layer II, the oil–water contact was obtained partially lying in the oil zone. Such behavior may be caused by presence between Wells # 2 Zhuravsko-Blagodarnenskaya and # 7 Sadovaya either structure elevation or the pinch-out zone causing irregular placement of oil–water contact. However, the absence of wells in this area and, as a consequence, data points, does not allows us to perform the appropriate structural drawings with sufficient degree of reliability, therefore, the current structural drawings for the Layer II, at this stage of the study of the object, were left unchanged. Reduction of oil resources, caused by presence of probable pinch-out zone between Wells # 2 Zhuravsko-Blagodarnenskaya and # 7 Sadovaya, in our case will be compensated by large water-saturated zone in this area, which, similar to the pinch-out zone, reduces oil resources.

Reservoir temperatures for resource calculation were estimated from geothermal gradient value in area covering object of study.

Reservoir pressures were calculated from the pore pressure gradient that, in turn, was obtained from lateral

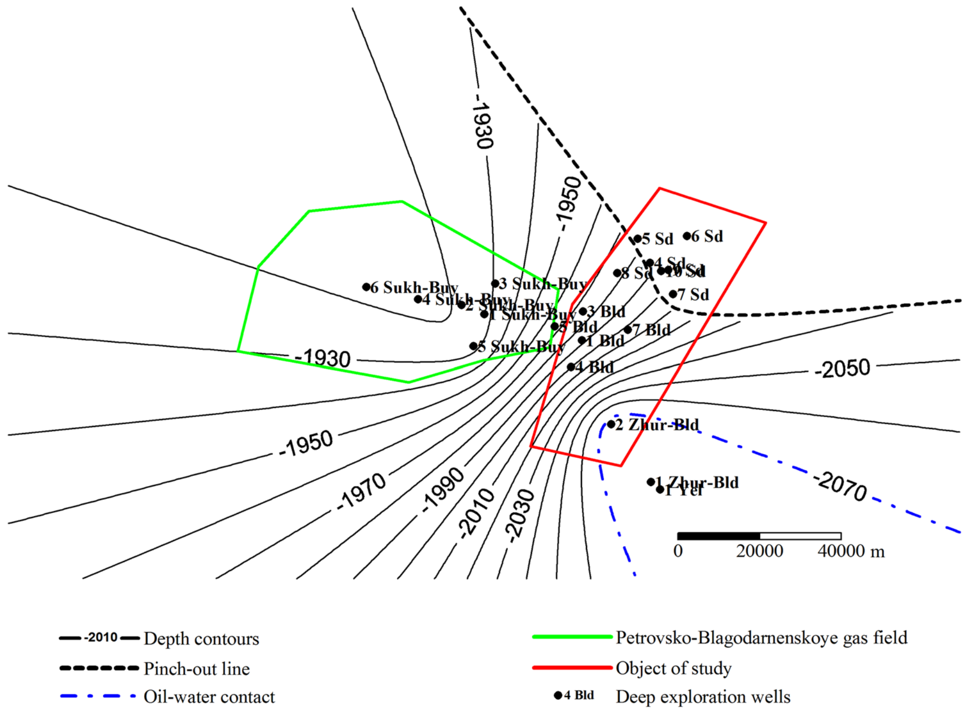


Fig. 8 Top of the Paleocene Layer I

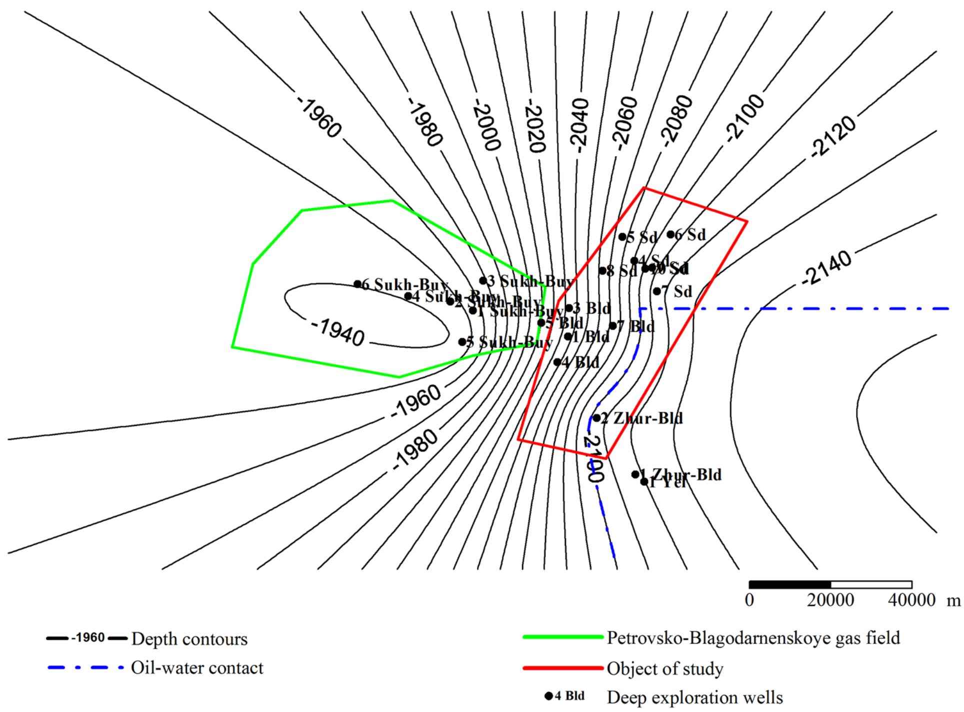


Fig. 9 Top of the Paleocene Layer II

electric logging by Eaton relationship. Wireline logs from Well # 7 Blagodarnenskaya were utilized for pore pressure estimations.

The reservoir fluid properties for the reservoirs of Blagodarnenskaya structure were calculated by correlations calibrated to PVT analysis of the reservoir fluid samples from Paleocene deposits of Well # 22 Praskoveyskaya that is located on neighboring Chepakovskoye oil field.

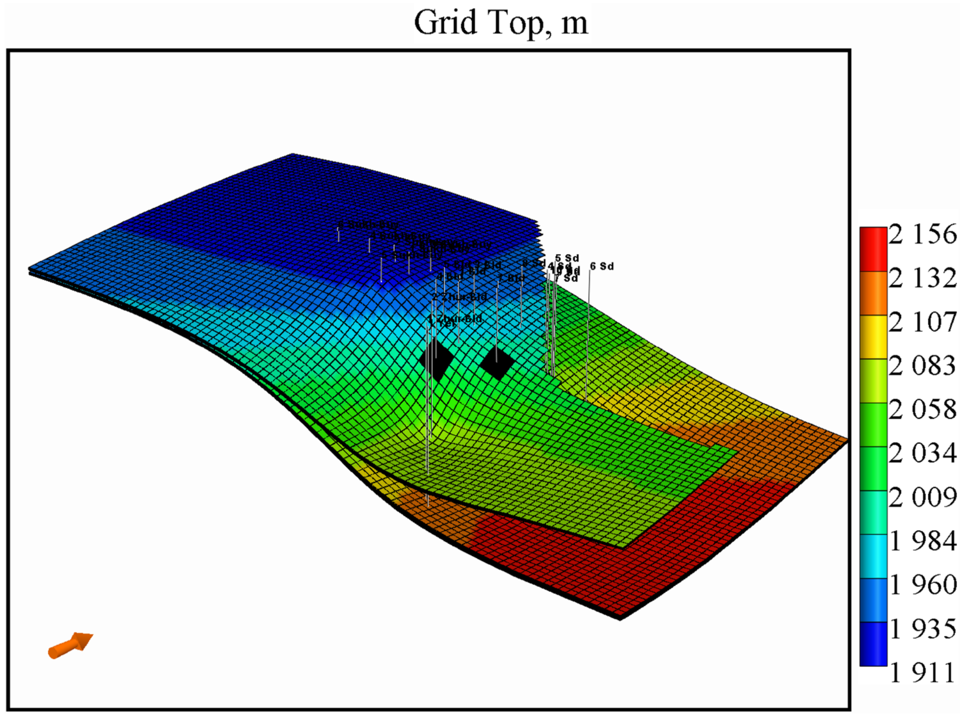


Fig. 10 General view of the reservoir model of Paleocene Layers I and II

Table 9 Expected values of reservoir pressures and temperatures for Paleocene Layers I and II

Reservoir	Name of parameter	Numerical value
Layer I	Depth of thermostatic layer, (m)	25
	Temperature of thermostatic layer, (°C)	13
	Geothermal gradient, (°C/m)	0.0559
	Depth at which reservoir pressures and temperatures were calculated, (m)	2242.64
	Expected reservoir temperature, (°C)	137.0
	Expected pore pressure gradient, (g/cm^3)	1.03
	Expected reservoir pressure, (kgf/cm^2)	231.07
Layer II	Depth of thermostatic layer, (m)	25
	Temperature of thermostatic layer, (°C)	13
	Geothermal gradient, (°C/m)	0.0559
	Depth at which reservoir pressures and temperatures were calculated, (m)	2297.97
	Expected reservoir temperature, (°C)	140.1
	Expected pore pressure gradient, (g/cm^3)	1.03
	Expected reservoir pressure, (kgf/cm^2)	236.77

Final values of the expected reservoir pressures and temperatures for Paleocene Layers I and II are summarized in Table 9. Actual and predicted properties of the reservoir fluids for Paleocene sediments are given in the Table 10.

Effective porosity values for reservoir modeling and resources estimation were taken from wireline logs interpretation for Well # 7 Blagodarnenskaya, since there are no other sources of data available (Table 8).

Values of connate water saturation were taken from the wells lying in oil zone and averaged for each layer of Paleocene.

Resulting resources estimation for studied subsoil block is represented in Table 11.

Attractiveness of reviewed resources in context of neighboring oil fields

Testing and trial production of identified resources represent commercial interest since the economical oil inflows were obtained from the similar reservoirs on number of neighboring fields.

Similar thin oil reservoirs were tested and even have been in development for some time on Zhuravskoye and Vorobyevskoye oil fields, lying in less than 5 km from object of study (Fig. 1). Reservoir rocks of Lower Eocene age are represented by highly radioactive siltstones and sandy mudstones associated with turbidite sediments. Typical well log response for the reservoirs of Zhuravskoye and Vorobyevskoye oil fields is shown in Fig. 11, results of petrophysical evaluation are given in Table 12.

The upper layer in the interval 6 (Table 12) according to local stratigraphical division was assigned as Batalpashinsky marker of the Lower Maikop formation (Table 2), the lower layer in the interval 10 was assigned to Khadum formation

Table 10 Actual and predicted properties of the reservoir fluids for Paleocene sediments

Object	Name of parameter	Numerical value
Well # 22 Praskoveyskaya (actual PVT analysis)	Reservoir temperature, (°C)	144
	Reservoir pressure, (kgf/cm^2)	309.97
	Oil formation volume factor	1.29
	Solution gas–oil ratio, (scf/STB)	488.98
	Bubble-point pressure, (kgf/cm^2)	117.79
	Oil viscosity at reservoir conditions, (cP)	0.507
	Oil compressibility, (kgf/cm^2)$^{-1}$	1.96×10^{-4}
	Oil density at reservoir conditions, (g/cm^3)	0.741
	Stock-tank[1] oil density, (g/cm^3)	0.8389
Layer I (expected values from calculations)	Reservoir temperature, (°C)	137
	Reservoir pressure, (kgf/cm^2)	231.07
	Oil formation volume factor	1.3
	Solution gas–oil ratio, (scf/STB)	488.98
	Bubble-point pressure, (kgf/cm^2)	99.55
	Oil viscosity at reservoir conditions, (cP)	0.47
	Oil compressibility, (kgf/cm^2)$^{-1}$	2.19×10^{-4}
	Oil density at reservoir conditions, (g/cm^3)	0.73094
	Stock-tank[1] oil density, (g/cm^3)	0.8389
Layer II (expected values from calculations)	Reservoir temperature, (°C)	140.1
	Reservoir pressure, (kgf/cm^2)	236.77
	Oil formation volume factor	1.3
	Solution gas–oil ratio, (scf/STB)	488.98
	Bubble-point pressure, (kgf/cm^2)	100.29
	Oil viscosity at reservoir conditions, (cP)	0.47
	Oil compressibility, (kgf/cm^2)$^{-1}$	2.18×10^{-4}
	Oil density at reservoir conditions, (g/cm^3)	0.73052
	Stock-tank[1] oil density, (g/cm^3)	0.8389

[1]Stock-tank conditions correspond to surface pressure of 1.03 kgf/cm^2 and surface temperature of 20 °C

Table 11 Oil resources predictions for Blagodarnenskaya structure

Name of parameter	Units of measurements	Numerical value
Original oil-in-place bound by studied subsoil block	$\times10^6$ m^3	124.9
	$\times10^6$ metric tons	104.8
	$\times10^6$ STB	785.5

of the Lower Eocene. Both layers are tracing on the whole area of Zhuravskoye and Vorobyevskoye oil fields. Results of production testing for each of the layers are presented in Tables 13 and 14.

Due to absence of experience and understanding of the nature of discovered reservoirs, development of the Zhuravskoye and Vorobyevskoye oil fields was complicated by mass of problems (Titorov et al. 2016), the main of which was premature watering. Later it was established that the source of water was multiple water-saturated layers covered by large perforation intervals in production wells. The large perforation intervals, in turn, were allocated according to conception which implies that reservoirs of Zhuravskoye and Vorobyevskoye oil fields are represented by thick sections of shales above and below Batalpashinsky marker. However, this conception was misleading from the beginning, since it stated that shales with 1 Ohm m resistivity contain mobile oil. Later (Titorov et al. 2016) it was disproved by core studies which have shown that the only oil-saturated reservoirs in Lower Eocene sediments are isolated, thin, highly resistive layers.

Nowadays, Vorobyevskoye oil field is abandoned and belongs to undistributed subsoil blocks. Zhuravskoye oil field, after changing four owners, currently in development; however, the state of that development can be described as rather dead than alive. The cumulative production, up to

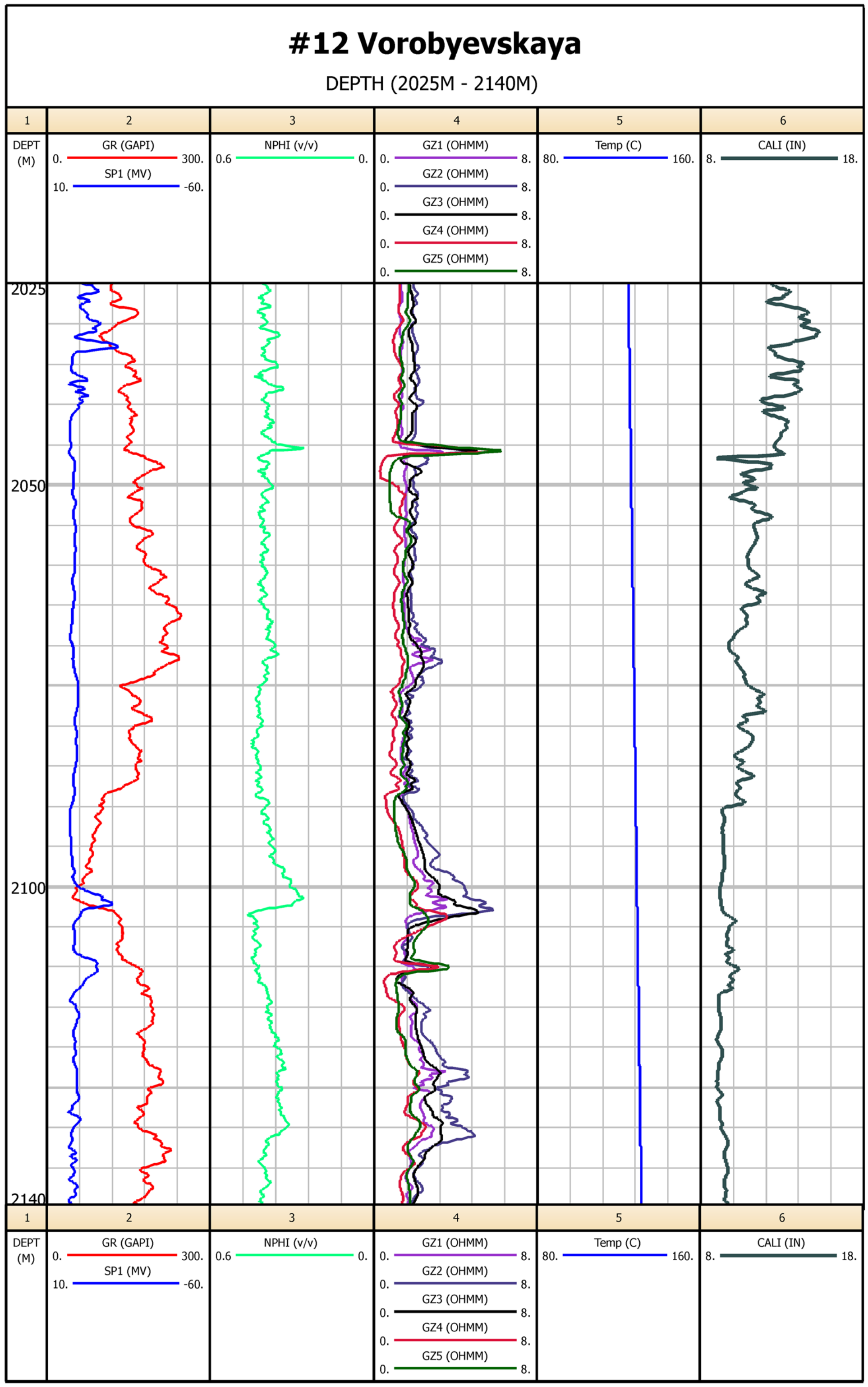


Fig. 11 Wireline logs for the Well # 12 Vorobyevskaya

date, from both fields combined has reached approximately 400,000 metric tons or 3 million STB of oil, with recovery factor less than 1% from initially predicted reserves.

The Paleocene sediments, directly, were tested on Praskoveyskoye oil field and associated with Chepakovskaya explorational structure during exploration activities in mid 1960s and early 1970s (Burshtar 1966). Reservoir rocks of

Table 12 Wireline logs interpretation for Lower Eocene deposits of Well # 12 Vorobyevskaya

Interval	Top, (m)	Bottom, (m)	Gross thickness, (m)	Net pay, (m)	Effective porosity, fraction	Water saturation, fraction	Volume of clay, fraction	Comment
1	1900.00	1952.80	52.80	0.00	–	–	–	Non reservoir
2	1952.80	2033.90	81.10	78.80	0.257	1.000	0.318	Water saturated
3	2033.90	2037.10	3.20	0.00	–	–	–	Non reservoir
4	2037.10	2039.00	1.90	1.40	0.172	1.000	0.452	Water saturated
5	2039.00	2043.20	4.20	0.00	–	–	–	Non reservoir
6	2043.20	2046.00	2.80	2.70	0.146	0.158	0.513	Oil saturated
7	2046.00	2087.10	41.10	0.00	–	–	–	Non reservoir
8	2087.10	2102.90	15.80	15.65	0.280	1.000	0.190	Water saturated
9	2102.90	2109.50	6.60	0.00	–	–	–	Non reservoir
10	2109.50	2110.30	0.80	0.70	0.186	0.328	0.566	Oil saturated
11	2110.30	2140.00	29.70	0.00	–	–	–	Non reservoir

Table 13 Production test results of Well # 12 Vorobyevskaya

Flow sequence	Choke size, (mm)	Date of testing in 1990	Casing pressure, (kgf/cm^2)	Tubing pressure, (kgf/cm^2)	Oil rate, (STB/day)	GOR, (scf/STB)	Bottom hole pressure, (kgf/cm^2)	Bottom hole temperature, (^oC)
							At depth of 2028 m	
1	Pre-test survey	04–12.10	130.01	131.41	–	–	284.90	127
2	8.0		23.96	16.51	413.50	339.16	135.77	133
3	6.0		32.53	25.55	351.11	309.12	159.11	136
4	5.0		48.03	41.04	302.63	313.28	191.05	138
5	3.0		80.05	76.03	212.88	331.86	233.34	138
6	2.0		95.96	93.18	176.97	284.75	242.98	140
7	3.0		80.97	77.49	217.47	313.67	234.67	137
8	Build-up		127.97	129.89	–	–	284.77	125

Age of sediments: Lower Maikop. Perforated interval: 2036–2056 m

Table 14 Production test results of Well # 12 Vorobyevskaya

Flow sequence	Choke size, (mm)	Date of testing in 1990	Casing pressure, (kgf/cm^2)	Tubing pressure, (kgf/cm^2)	Oil rate, (STB/day)	GOR, (scf/STB)	Bottom hole pressure, (kgf/cm^2)	Bottom hole temperature, (^oC)
							At depth of 2100 m	
1	Pre-test survey	27.08–05.09	139.48	131.39	–	–	292.07	128
2	7.0		28.98	5.31	77.98	95.18	110.21	128
3	5.0		35.13	7.96	69.87	95.40	129.32	128
4	3.0		48.37	18.76	56.10	105.62	163.01	128
5	2.2		51.59	23.26	51.32	104.33	172.95	128
6	5.0		30.84	8.16	68.74	99.17	131.33	128
7	Build-up		137.11	134.96	–	–	292.99	128

Age of sediments: Khadum formation. Perforated interval: 2095–2105 m

Table 15 Production test results of Well # 22 Praskoveyskaya

Flow sequence	Choke size, (mm)	Date of testing in 1965	Casing pressure, (kgf/cm^2)	Tubing pressure, (kgf/cm^2)	Oil rate, (STB/day)	GOR, (scf/STB)	Bottom hole pressure, (kgf/cm^2)	Bottom hole temperature, (°C)
1	2.0	30.08–05.09	59.41	74.39	102.51	660.75	268.64	143.5
2	3.0		48.15	72.33	155.97	583.54	247.98	143.5
3	3.7		38.54	35.34	201.25	608.03	229.38	144.0
4	4.0		35.44	31.41	188.67	598.82	232.48	144.0
5	build-up		–	–	–	–	309.97	144.0

Age of sediments: Paleocene. Perforated intervals: 2550–2561; 2568–2576 m

Paleocene age on both subsoil blocks are presented by siltstones of turbidite origin. Along with Paleocene reservoirs, Lower Eocene and Upper Cretaceous sediments also have been proved to be productive on Praskoveyskoye and Chepakovskoye oil fields.

Praskoveyskoye oil field is currently being developed by Rosneft, thus the cumulative production and the state of the development of Paleocene sediments are unknown due to closed nature of that data.

Chepakovskaya explorational structure was obtained by small independent operator in 2007, after that wells re-entry program was carried out and status of explorational structure was changed to oil field under development. It is known that Paleocene sediments were put in simultaneous production with Lower Eocene sediments. It is also known that the operator is experiencing similar, in nature, to Zhuravskoye and Vorobyevskoye oil fields, problems with premature watering. Unfortunately, other data are unavailable.

The production test data for Paleocene sediments from early days of exploration of the Chepakovskaya structure are given in Table 15.

Paleocene and analogous Lower Eocene reservoirs have been proved to be productive on neighboring to Blagodarnenskaya structure Zhuravskoye, Vorobyevskoye, Chepakovskoye and Praskoveyskoye oil fields; however, flaws in initial well logs interpretation and commitment to the misleading conception on type of reservoir did not allow to realize the full potential of those reservoirs during trial production and development. These flaws and resulting misconception also prevented discovery of similar reservoirs on adjacent subsoil blocks, especially when blow-outs were not achieved during drilling what was the case for the reservoirs of Zhuravskoye, Vorobyevskoye and Praskoveyskoye oil fields.

Re-exploration strategy for studied resources

The boundaries of subsoil block studied in this work cover 11 plugged deep-exploration wells, which can be utilized for testing predicted resources. The positive experience of previously mentioned wells' re-entry program on Chepakovskoye oil field, has shown that old production infrastructure in mature petroleum provinces (mostly abandoned wells) can be successfully utilized for re-exploration activities. In that case, exploration phase may be reduced to re-entry and testing of abandoned wells, what significantly reduces exploration costs and provides faster transition to trial production.

To clarify last statement we will compare exploration costs of more conventional cases with 3D seismic survey covering full area of subsoil block and drilling of one exploration well against re-entry and testing of one abandoned well.

With area, limited by Blagodarnenskaya structure, equalling 355 km^2 and average price of 3D seismic survey in Stavropol Region equalling 14,300 USD per square kilometer, total cost of seismic survey would be 5,076,500 USD. The average price of 1 m of drilling in Stavropol Region is about 715 USD, the cost of drilling of a new exploration well with depth of 2400 m, without taking into account the production equipment, will amount to 1,716,000 USD. Thus, the total cost of conventional exploration activities would amount to 6,792,500 USD.

From the other hand, re-entry and testing of one abandoned well would cost about 203,727 USD. This sum includes cost of the re-entering of one well, costs of the tubing and x-mas tree, as well as charges for wireline logging, perforation, testing and following plugging of the well (in case of absence of commercial inflow).

One can easily note that utilization of existing abandoned well for re-entry and testing provides almost 30 times less expenditure than conventional exploration activities. In case of absence of commercial inflow during testing, re-entry strategy allows to minimize irretrievable investment losses and rises benefits of operator in case of success.

Table 16 Expenses associated with wells re-entering program

Name of parameter	Numerical value
Cost of re-entering	
Charge for workover per rig hour, (USD)	266.67
Rig time for re-entering one well, (days)	8
Cost of re-entering per well, (USD)	51200.00
Number of wells to be re-entered, (pcs.)	2
Total cost of re-entering, (USD)	102400.00
Cost of tubing	
Weight per 1 m of 73 mm diameter tubing, (kg/m)	9.67307
Cost of 73 mm diameter tubing per metric ton, (USD/metric ton)	1666.67
Length of tubing needed for Well # 4 Bld, (m)	2250
Cost of tubing for Well # 4 Bld, (USD)	36274.01
Length of tubing needed for Well # 7 Bld, (m)	2300
Cost of tubing for Well # 7 Bld, (USD)	37080.10
Length of tubing needed for surface networks, (m)	10
Cost of tubing for surface networks, (USD)	161.22
Total cost of tubing, (USD)	73515.33
Cost of x-mas trees	
Cost of x-mas tree per well, (USD)	11666.67
Total cost of x-trees for all wells, (USD)	23333.33
Cost of oil tanks	
Cost per 1 horizontal oil tank of 200 m^3 volume, (USD)	18333.33
Total cost of oil tanks for all wells, (USD)	36666.67
Cost of measuring devices and gauges	
Cost of 1 wellhead pressure gauge, (USD)	833.33
Wellhead gauges needed for all wells, (pcs.)	6
Total cost of wellhead gauges, (USD)	5000.00
Cost of 1 level gauge for a tank, (USD)	2500.00
Total cost of level gauges for all tanks, (USD)	5000.00
Cost of 1 gas flow meter, (USD)	1000.00
Total cost of gas flow meters for all wells, (USD)	2000.00
Total cost of measuring devices and gauges, (USD)	12000.00
Charges for wireline logging and perforation	
Charges for wireline logging and perforation of 1 well, (USD)	41666.67
Total charges for wireline logging and perforation, (USD)	83333.33
Charges for well testing	
Charges for testing of 1 well, (USD)	10833.33
Total charges for well testing, (USD)	21666.67
Charges for PVT analysis	
Charge for 1 PVT analysis, (USD)	25000.00
Total charges for PVT analysis for all wells, (USD)	50000.00
Cost of exploration project	
State fee for the expertise of exploration project (volume of investments from 1.67 to 8.33 million USD), (USD)	5000.00
Exploration project price, (USD)	83333.33
Total cost of exploration project, USD	88333.33
Cost of reserves estimation according to state regulations	
State fee for the expertise of reserves estimation (unique oil field), (USD)	13333.33
Reserves estimation price, (USD)	83333.33
Total cost of reserves estimation according to state regulations, (USD)	96666.67
Cost of trial production project	
State fee for the expertise of trial production project (unique oil field), (USD)	6666.67

Table 16 (continued)

Name of parameter	Numerical value
Cost of trial production project, (USD)	83333.33
Total cost of the trial production project, (USD)	90000.00
Total expenses associated with wells re-entering program, (USD)	677915.33

Table 17 Final economic parameters of the re-exploration project

Name of the element	Year					Total
	2019	2020	2021	2022	2023	
Investments, (USD)	1 800 000					1 800 000
Oil production, (metric ton)	18 372	18 372	18 372	18 372	18 372	91 860
Production of petroleum products, (metric ton)						
Straight-run gasoline	4 445	4 445	4 445	4 445	4 445	22 224
Diesel fuel	5 830	5 830	5 830	5 830	5 830	29 149
Fuel oil	7 730	7 730	7 730	7 730	7 730	38 649
Revenue, (USD)	6 068 909	6 068 909	6 068 909	6 068 909	6 068 909	30 344 547
VAT, (USD)	1 213 782	1 213 782	1 213 782	1 213 782	1 213 782	6 068 909
Excises, (USD)						
Straight-run gasoline	866 739	866 739	901 409	901 409	901 409	4 437 705
Diesel fuel	741 206	766 683	797 348	797 348	797 348	3 899 932
Fuel oil	1 063 313	1 097 092	1 140 920	1 140 920	1 140 920	5 583 165
Total excises, (USD)	2 671 258	2 730 514	2 839 677	2 839 677	2 839 677	13 920 803
Tax on the extraction of minerals, (USD)	0	0	0	0	0	0
Depreciation, (USD)	245 580	245 580	245 580	245 580	245 580	1 227 899
Residual value of the main production assets, (USD)	982 319	736 739	491 159	245 580	0	
Average annual value of main production assets, (USD)	1 105 109	859 529	613 949	368 370	122 790	
Production costs, (USD)	614 312	614 312	614 312	614 312	614 312	3 071 561
Corporate property tax, (USD)	24 312	18 910	13 507	8 104	2 701	67 534
Transport tax, (USD)	989	989	989	989	989	4 943
Charges for use of subsoil, (USD)	3 194	3 194	3 194	3 194	3 194	15 969
Charges for lease of land plots, (USD)	98	98	98	98	98	492
Payments for air pollution, (USD)	3 882	3 882	3 882	3 882	3 882	19 410
Repayment of investments, (USD)	360 000	360 000	360 000	360 000	360 000	1 800 000
Income of company before the taxes, (USD)	931 502	877 649	773 889	779 292	784 695	4 147 027
Corporate income tax, (USD)	186 300	175 530	154 778	155 858	156 939	829 405
Net income of the production company, (USD)	745 202	702 119	619 111	623 434	627 756	3 317 621
Gross annual return on investments, (%)	25	25	25	25	25	
Payment of dividends in favor of the investor, (USD)	450 000	450 000	450 000	450 000	450 000	2 250 000
Withholding of personal income tax from dividends, (USD)	67 500	67 500	67 500	67 500	67 500	337 500
Net profit of the investor, (USD)	382 500	382 500	382 500	382 500	382 500	1 912 500
Net annual return on investments, (%)	21	21	21	21	21	
Residual income of the production company, (USD)	295 202	252 119	169 111	173 434	177 756	1 067 621

To better illustrate advantages of re-exploration activities in mature petroleum provinces we have simulated on dynamic model and calculated economical parameters of wells re-entry program with 5-year trial production period.

The general plan for re-exploration of studied subsoil block implies re-entering of the two wells – # 4 Blagodarnenskaya and # 7 Blagodarnenskaya with subsequent production testing. In case of receiving oil inflows in volumes that ensure the implementation of trial production with a given level of profitability, wells are put into production on an individual scheme with daily trucking of oil to the production base in the town Blagodarny. At the production base, it is planned to process all produced oil with the help of the compact refinery plant. Processed products, in the form of the straight-run gasoline, diesel fuel and fuel oil, are expected to be realized directly from the production base as retail and wholesale trading. Taking into account that the Stavropol Region is mainly an agricultural region, the abundance of agricultural machinery creates many small independent consumers, which, in turn, simplifies logistics for trial production period and increases asset turnover for operator.

Detailed breakdown of re-entry and testing costs is given in Table 16. Final economic parameters of re-exploration project are represented in Table 17.

As one can note from Table 17, the whole re-exploration project with wells re-entry program and trial production would cost three times less than previously mentioned conventional exploration activities. In case of success this project not only returns the whole volume of investments during 5 years, but also would generate equal-to-initial amount of investments net profit. Again, it should be pointed out that for re-exploration project the capital at risk would be costs associated with re-entry and testing of a single well, as was mentioned above, it is 30 times less than costs of conventional exploration activities (capital at risk for conventional exploration).

Conclusions

Wireline logs and core analyses indicate that previously undiscovered oil resources are present in the section of Blagodarnenskaya structure located in Stavropol Region. Estimations predict approximately one billion of undiscovered oil to be contained in those reservoirs.

Testing and trial production of identified resources represent commercial interest since the economical oil inflows were obtained from the similar reservoirs on number of neighboring fields. Old production infrastructure located on the Blagodarnenskaya structure can be utilized for wells re-entry and testing program, which would significantly reduce costs associated with re-exploration activities and provide smooth transition to trial production.

Re-exploration in mature provinces, according to discussed example, may provide up to 30 times less expenses compared to conventional exploration activities. In case of success, the initial investments may be doubled if the trial production phase would be considered as the part of re-exploration activities.

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