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# The bottom of the cryolithic zone and conditions for the formation of gas hydrates at the T field in the north of West Siberia

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The initial data to estimate the gas hydrate stability interval at the T field in West Siberia has been summarized, i.e. the cross-section temperature, reservoir pressure, gas-to-air density, and formation water salinity. The position of the cryolithic zone bottom was modeled by combining the thermal gradient estimated during well testing and the permafrost bottom position based on resistivity logging data.

Due to the ambiguity in interpreting the position of the bottom of the permafrost and cryolithic zone, two options of the cryolithic zone bottom maps were built: the minimum and maximum. Thus, two options of the gas hydrate stability zone bottom maps were built: the minimum and maximum. It is shown that the upper gas-saturated reservoirs of the T field are located in the gas hydrate stability zone.

**Keywords***:* cryolithic zone, permafrost, gas hydrates, West Siberia

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## Introduction

Gas hydrates are a special form of natural gas and are a potential and strategically important raw material. In 2015–2020, at least 25 scientific thesis papers on topics related to gas hydrates were reviewed in Russia, and over 50 applications for Russian patents were submitted (Shits, 2021). Over the past few years, the number of publications on gas hydrates has increased even more. One of the important areas of research on gas hydrates is to study them in their natural occurrence.

The approach to gas hydrates as a resource potential of West Siberia in the late 70s and early 80s of the last century was developed by the efforts of V.G. Vasiliev, A.A. Trofimuk, Yu.F. Makogon (Vasiliev et al., 1970; Makogon, 1985; Trofimuk et al., 1983), Yakut scientists S.P. Nikitin, V.P. Tsarev, N.V. Cherskiy (Nikitin et al., 1982, Tsarev, 1976, Cherskiy et al., 1983, 1987). In the 1980s, resource assessments were carried out in Leningrad by E.S. Barkan, G.D. Ginzburg, A.N. Voronov, V.P. Yakutseni (Barkan et al., 1983, 1989; Ginzburg et al., 1990). In Tyumen, the features of gas hydrate processes in West Siberia were studied by S.E. Agalakov, V.A. Nenakhov, A.R. Kurchikov, V.P. Tsarev (Agalakov et al., 1990, 1996, 2003, 2019; Agalakov, 2010; Kurchikov et al., 1984; Nenakhov, 1982). In the 21st century, Moscow scientists are actively involved in resource assessments and methods for developing gas hydrates: K.S. Basniev, V.A. Istomin, S.A. Leonov, E.V. Perlova, A.L. Sukhonosenko, V.S. Yakushev (Basniev et al., 2010; Leonov, 2010; Yakushev et al., 2007, 2014; Perlova et al., 2017; Perlova, 2018; Sukhonosenko, 2013). Reviews on the problem of gas hydrates appear in the literature (Yakutseni, 2015; Gudzenko et al., 2016; Shits, 2021).

Although the main gas hydrate resources are confined to the sea shelf sediments, gas hydrates in the continental part also have significant potential. In West Siberia, the supra-Cenomanian sediments stand out in this regard. The knowledge of their structure and properties achieved to date makes it possible to analyze and model the properties that are key to assessing gas hydrate resources.

### Methodology for defining the position of the gas hydrate stability bottom

The main properties that determine the equilibrium thermobaric conditions for the existence of gas hydrates in the pore space (Makogon, 1985) are the section temperature, reservoir pressure, air-gas density, and formation water salinity.

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To estimate the gas hydrate stability bottom in the rock mass, an improved formula proposed in the work (Ponomarev, 1960) was used, obtained on the basis of processing experimental data on the conditions of hydrate formation in natural gases of various compositions.

The method and data necessary for building the regional map of the gas hydrate stability interval bottom for the conditions of West Siberia on the cross-section temperature, reservoir pressure properties, formation water salinity, and gas composition were collected and summarized in the work (Agalakov et al., 2023).

**Methodology for studying the temperature conditions of the cross-section**

The key factor in the existence of gas hydrates is the cooling of the cross-section caused by the presence of permafrost rocks. The following approaches were used to determine the depth of the cryolithic zone bottom (Volodko, 1989; Irbe, 1974; Ostryy, 1969; Agalakov, Nenakhov, 1990; Kurchikov, Agalakov, 2004).

1. The direct and most reliable method for determining the temperature regime of the cross-section is thermometry in settled wells – the GGM method (Geothermal Gradient Measurement).

2. The position of the cryolithic zone bottom and the temperature gradient in subpermafrost deposits are also determined based on the interpretations of temperature measurement data when testing individual intervals in wells.

3. Well logging materials were used. The position of the permafrost bottom is determined by well logging:

- Temperature log in unsettled wells by the bend of the cement top location;
- Resistivity Logging. The physical basis is the effect of increased rock resistivity when pore water is replaced with dielectric agent (ice);
- Caliper log – vugs are common in ice-containing rocks.

When building the maps of the cryolithic zone bottom, it is taken into account that high salinity of formation water and high clay content of the cross-section lead to the fact that the cryolithic zone bottom can be significantly below the permafrost bottom. Therefore, for each region and area, the possibility of a correct transition from the permafrost bottom to the cryolithic zone bottom was considered.

**Results of regional studies**

Regional maps of the bottom of the cryolithic zone in West Siberia were built using logging data from 735 wells. The data from published sources (Balobaev, Levchenko, 1988; Devyatkin, 1993), from the permafrost catalog (An et al., 2002), and from the Geothermal Atlas (Geothermal atlas of Siberia and the Far East, 2012) were also used. The map (Figure 1) was built solely taking into account the set of available data

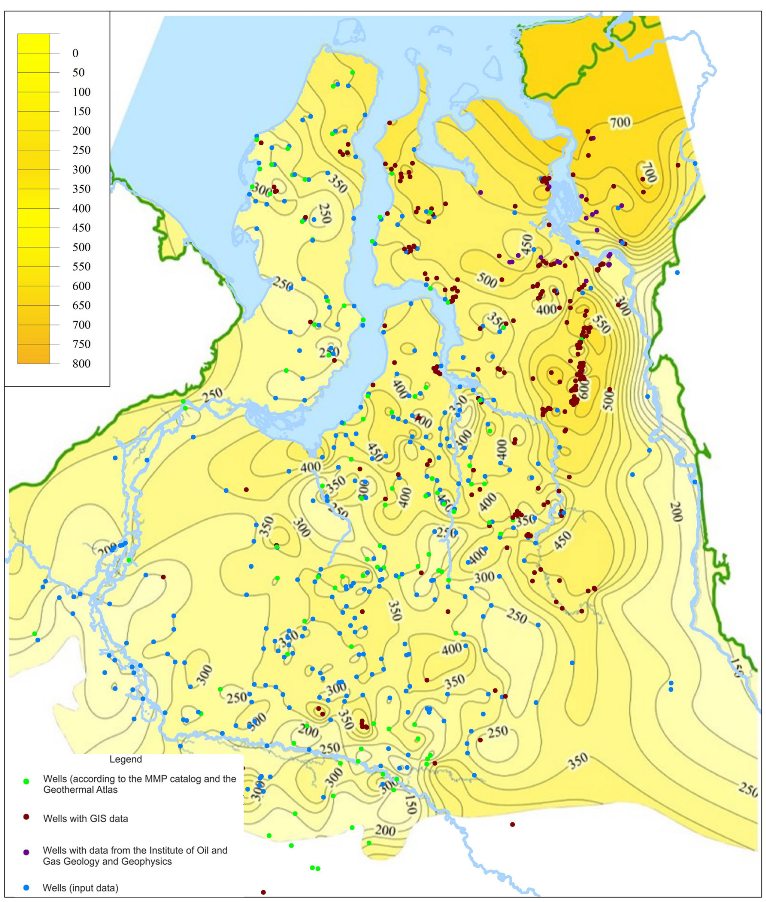



Figure 1. Depth map of the bottom of the cryolithic zone of West Siberia (Agalakov et al., 2023)

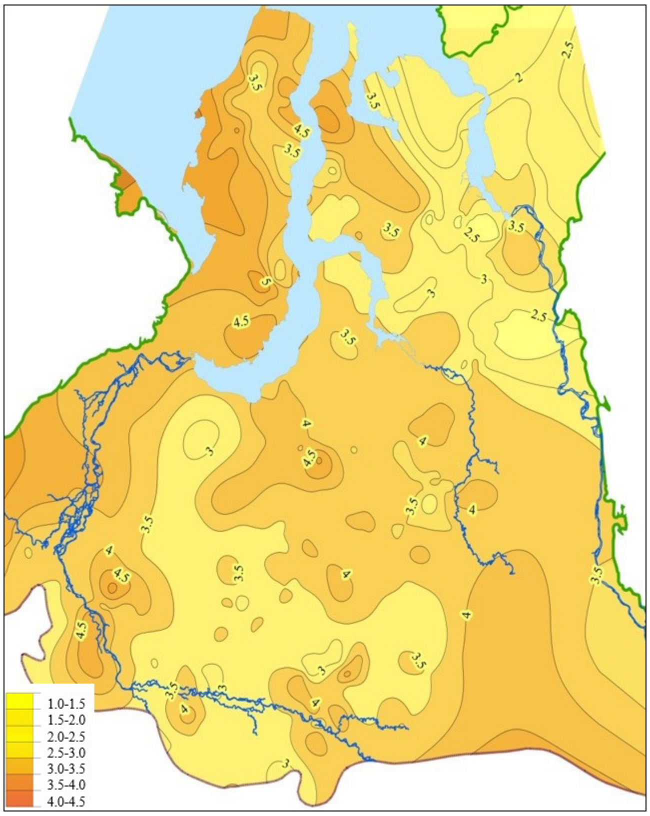



Figure 2. Temperature gradient map of the subpermafrost strata in West Siberia (Agalakov et al., 2023)

on wells within the study area. Ground-based logging, as well as other approaches related to model concepts of the formation and breaking up of permafrost rocks, were not used in map building (Agalakov et al., 2023).

Note that there is a vast meridionally elongated zone of increased permafrost thickness to the west of the Yenisei River. Here, in comparison with the western and central regions, the permafrost interval contains rocks with higher NTG and ice content and which are marked by a slow rise of the cryolithic zone bottom due to climate warming. In general, the resulting map is consistent with previously published maps (Baulin, 1985; Geocryology of the USSR. Western Siberia, 1989) and, in the authors' opinion, is a reliable updated basis for measuring the gas hydrate stability interval in West Siberia.

The final authors' temperature gradient map of the West Siberian Basin is shown in Figure 2 (Agalakov et al., 2023). Here, along the 3.5 deg/100 m isoline, areas of reduced geotemperature gradient are localized, i.e. the northeastern region of the eastern part of the Gydan Peninsula, the Yenisei-Khatanga Regional Trough and


Figure 3. Overview map with the location of the T field. X, Z are the nearest wells with temperature logs in settled wells

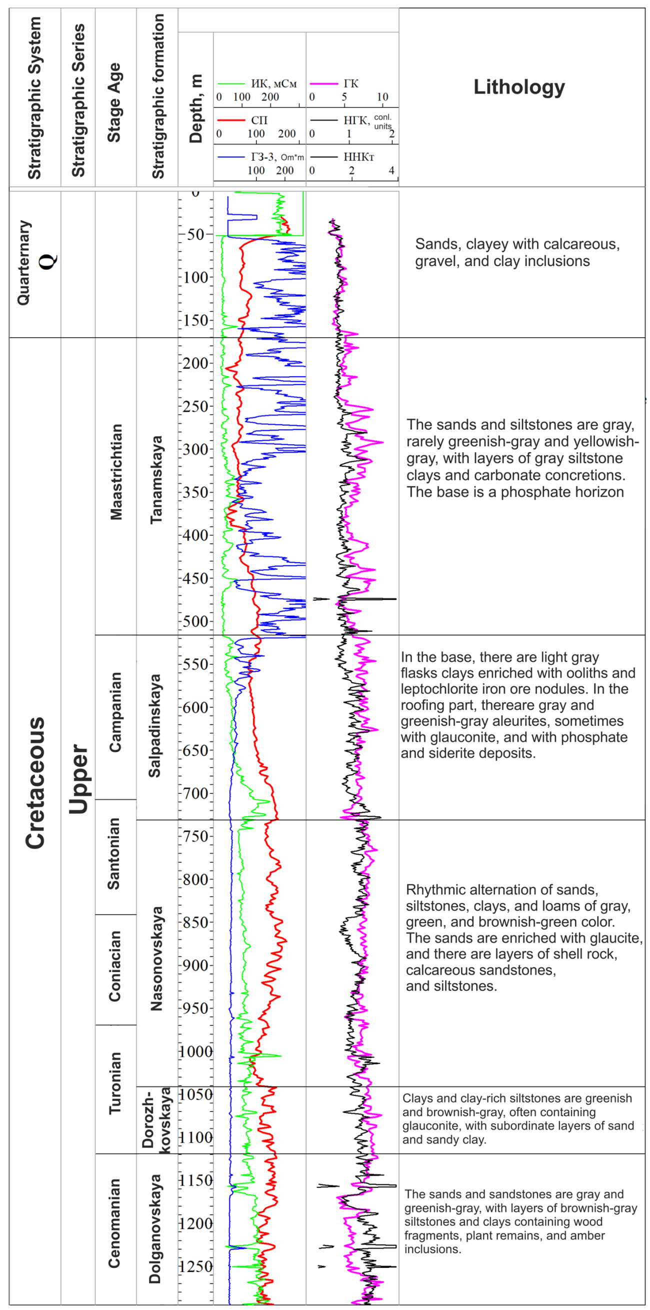



Figure 4. Upper part of the combined geological well section of the T deposit

the Bolshekhetskaya Depression, as well as the Ob-Nadym interfluve area. The area of increased geothermal gradients includes the west of the region and the Nadym-PUR-Taz interfluve.

### Results of T field research

In the north-east of West Siberia, along with the increased permafrost thickness, a number of fields with relatively shallow gas accumulations have been interpreted. One of them is the T field (Figure 3). The authors decided to study the field in more detail and determine the possibility of gas hydrate presence in the accumulations of the Dolgansky and Dorozhkovsky Series.

### Geological structure

In the frozen state at the T field are (downward) Quaternary deposits, as well as deposits of the Tanamskaya (Maastrichtian – Danian stages) and Salpadinskaya (Campanian stage) Series (Figure 4).

The cross-section is formed by of sandy-clayey deposits, and the clay content increases downward. Permafrost rocks have not been studied at the field. The lithology is based on the description of the official stratigraphic units. The physical properties of rocks have been studied at the neighboring Field X down to a depth of 380. Down to this depth, the total natural moisture content, depending on the grain size, varies from 0.17 to 0.33 and does not depend on the depth. Porosities vary from 0.18 to 0.54. The salt content does not exceed 0.13%.

The bottom of the permafrost occurs in the clayey deposits of the Salpadinskaya Series, which, compared to sandy deposits, makes it difficult to determine its position by well logging due to the gradual transition from ice-bearing rocks to ice-free rocks.

Productive gas-saturated deposits are represented by the Dr and Dl beds of the Dorozhkovskaya and Dolgan Series.

The Dolgan deposits are of coastal-continental genesis – uneven interbedding of fine-grained sandstones with interlayers of carbonaceous-micaceous material and mudstone-like clays, mudstones and siltstones with coal interlayers and lenses.

The Dl reservoirs are widespread. The reservoir properties are high. According to the core, the porosities vary from 3 to 41%, on average – 31%.

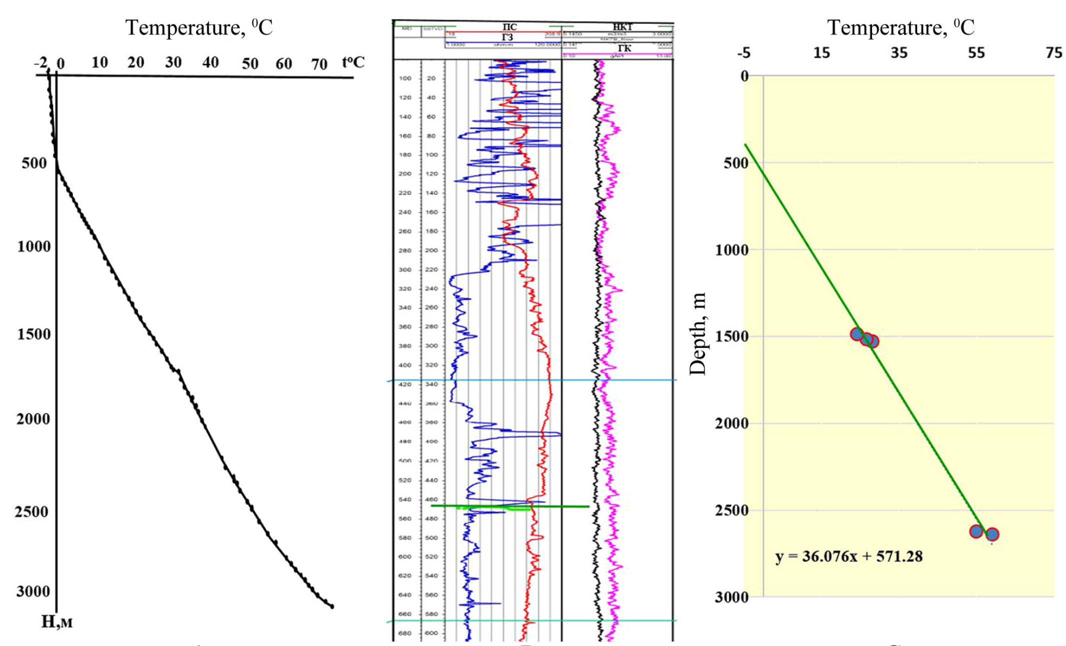
The units of the coastal-marine Dorozhkov Series (Dr) are composed of greenish-brown-gray clays and siltstones, often with glauconites and siderite concretions with rare interlayers of gray, fine-grained sands and sandstones. The reservoir properties are poorer than those of the Dl units. According to the core, the porosities vary from 1.6 to 38.5%, on average – 30%.

### Temperature conditions

No temperature logging was performed in the settled wells at the T field.

The closest temperature logging in the settled wells was performed at the X and Z fields, and at the Z field, the temperature was measured only down to a depth of 380 m.

The X field is located 300 km from the studied T field. According to the temperature logging at the X field, the bottom of the cryolithic zone is at 550 m (Figure 5). According to the gradient of the temperature logging




A B C

Figure 5. Defining the permafrost bottom position in well 3 based on temperature logging data, using well logging and thermal gradient: A – temperature distribution with depth, B – well logging data, C – defining the thermal gradient at the permafrost bottom

tests, the bottom of the cryolithic zone is at 570 m. According to electrical resistivity logging, the bottom of the permafrost at a depth of 550 m corresponds to the apparent transition from 25 Ohm to 15 Ohm.

According to laboratory studies at the neighboring Z field, the decrease in the freezing point of rocks due to insignificant salinity and high humidity of the cross-section is in the range from –0.17 to 0.23 $^0$C, which, with an average thermal gradient of 3 $^0$C per 100 m vertically, gives a difference in the position of the permafrost and cryolithic zone bottom of no more than 8 m, i.e. less than the error in the measurements by other methods. This fact was taken into account when predicting the position of the cryolithic zone bottom based on the permafrost bottom data.

Thus, three different methods yielded a comparable result, which provides grounds for using two indirect methods to reconstruct the temperature conditions of the T field vertical section.

At the T field, the position of the permafrost bottom was modeled by combining the thermal gradient estimated during well testing and the position of the permafrost bottom based on resistivity logging data.

As a result, the position of the zero isotherm was estimated using the thermal gradient of 9 wells (Figure 6), relatively evenly distributed in the dome part of the structure. The range of values was 626–687 m, with an average of 649 m. The RMS deviation (SD)

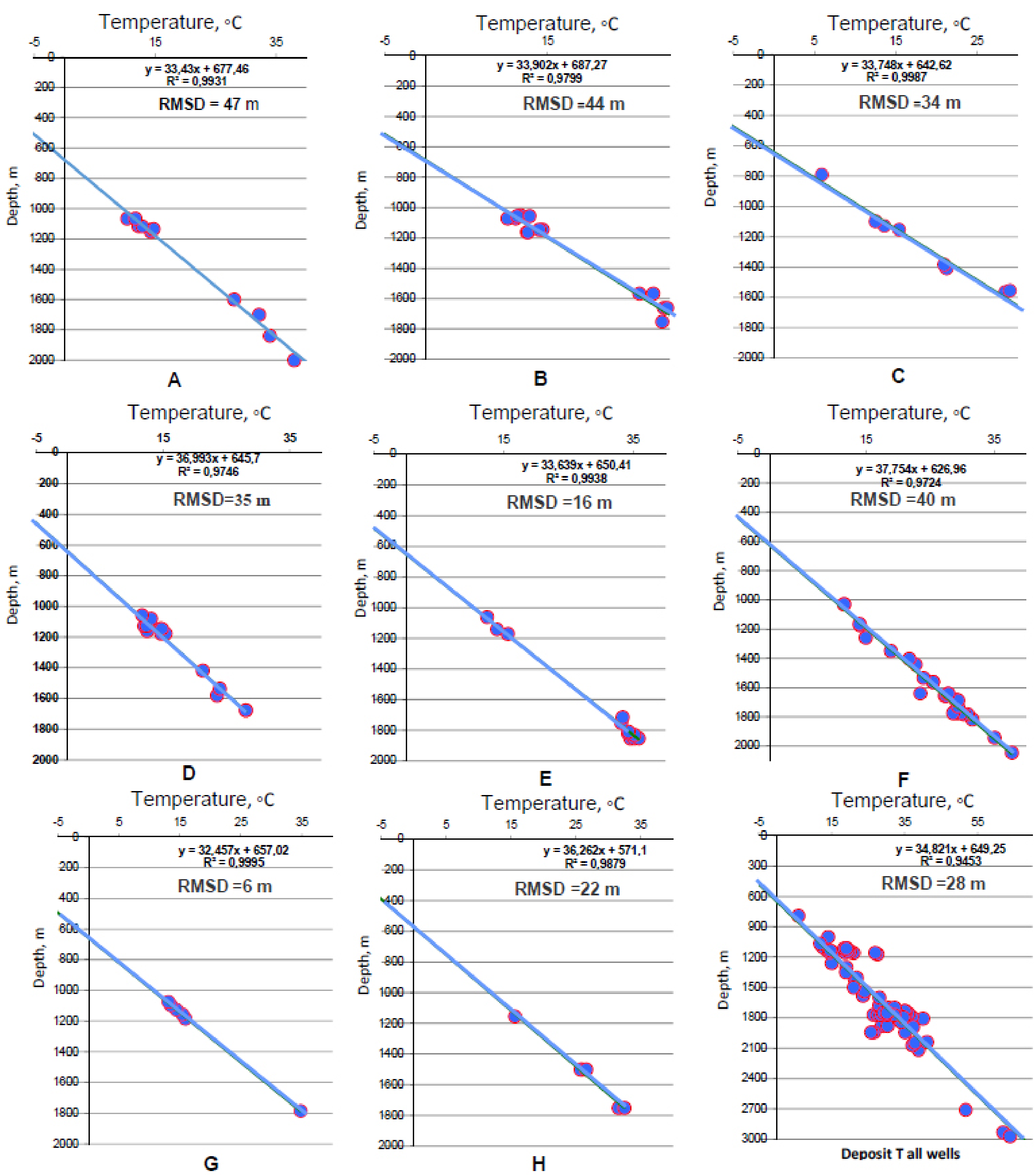



Figure 6. Determination of the position of the cryolithic zone bottom for the study area based on the thermal gradient of the test results from wells A–H

of determining the depth of the zero isotherm for various wells is in the range of 6–47 m. The average RMS deviation was 28 m.

One well with the minimum number of measurements (H) was not taken into account in the estimates, since the depth of the cryolithic zone bottom in it differs from the total sample by 70 m, which is 3.5 times greater than the deviation from the average in the other wells.

According to the well logging data at the field, the permafrost bottom, due to the uncertainty of the resistivity logging readings, was determined for two options – by decreasing the rock resistivities down from 25 and from 15 Ohm. In total, it was possible to use the well logging curves for 17 wells to determine the position of the permafrost bottom.

A comparison of the permafrost bottom position determined by the well logging data and the zero isotherm determined by the thermal gradient was possible for three wells T_A, T_B and T_H (Figure 7).

The uncertainty of determining the permafrost bottom using well logging data was ± 20 m. The difference in the position of the permafrost bottom from the cryolithic zone bottom due to salinity of formation water, as noted above, does not exceed 8 meters.

As a result, the uncertainties in determining the permafrost bottom using well logging and testing data (28 m) are comparable. At the same time, there is good agreement between these methods on well average – the average for the thermal gradient is 649 m, the average for well logging is 652 m.

Due to the ambiguity in determining the position of the permafrost and cryolithic zone bottom, it was decided to build two possible maps of the permafrost bottom – the minimum and maximum (Figure 8).

Work was also performed to determine other parameters necessary for estimating the position of the gas hydrate stability zone bottom – reservoir pressure, formation water salinity and natural gas composition.

### Reservoir pressure

According to test data, abnormally high pressure was not recorded in Dr and Dl formations. The anomaly coefficient in the estimates was taken to be 1.

### Formation water salinity and gas composition

Table 1 shows data on formation water salinity and gas composition.

The range of formation water salinity variation was 7600–8900 mg/l. The average salinity S = 8395 mg/l was used for the estimates.

Natural gas is of methane composition (about 99% of methane), the gas-to-air density varies in the range of

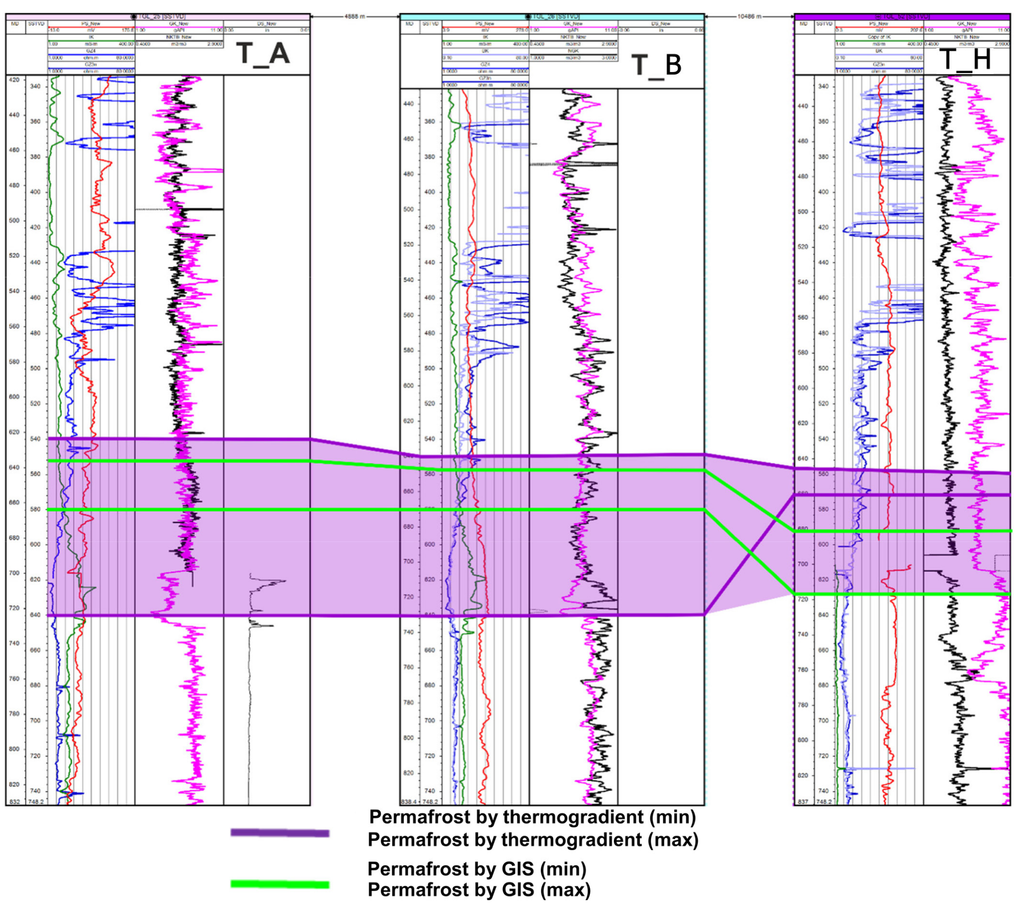
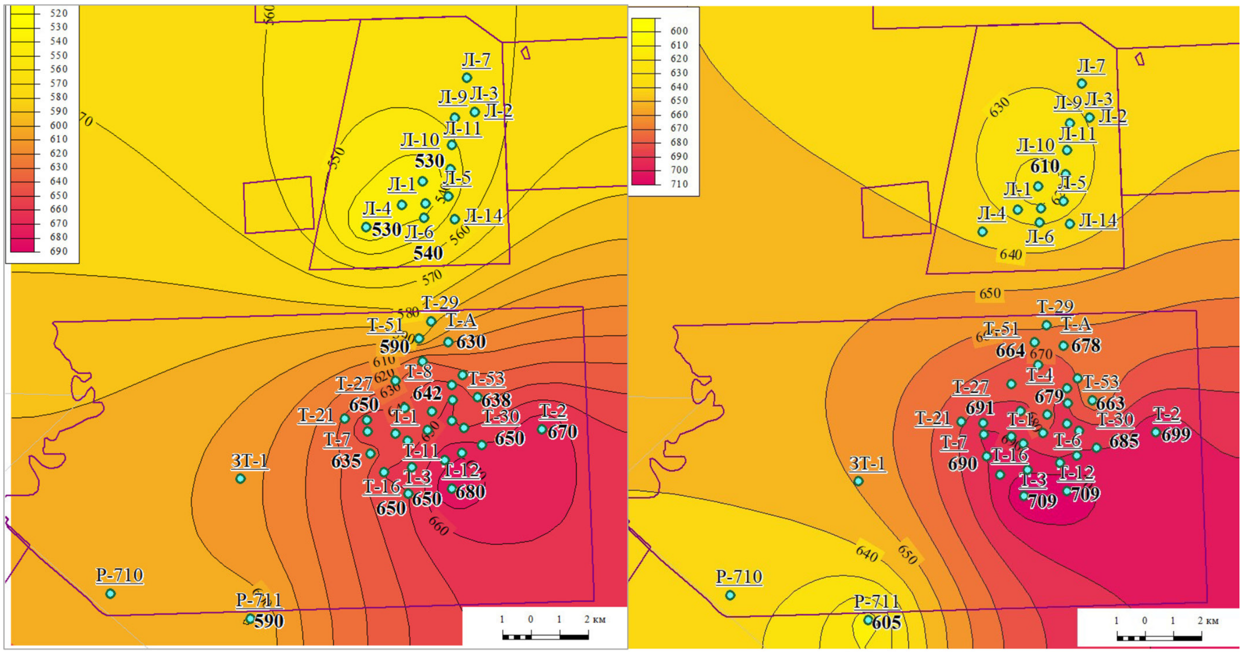



Figure 7. Wells with well logging and tests in the Dorozhkovsky and Dolgansky reservoirs. The range of uncertainty in the cryolithic zone bottom position is shown in lilac.



Minimum option Maximum option

Figure 8. Maps of the position of the cryolithic zone bottom of the study area in the minimum and maximum options

0.559–0.563 with an average of P = 0.561.

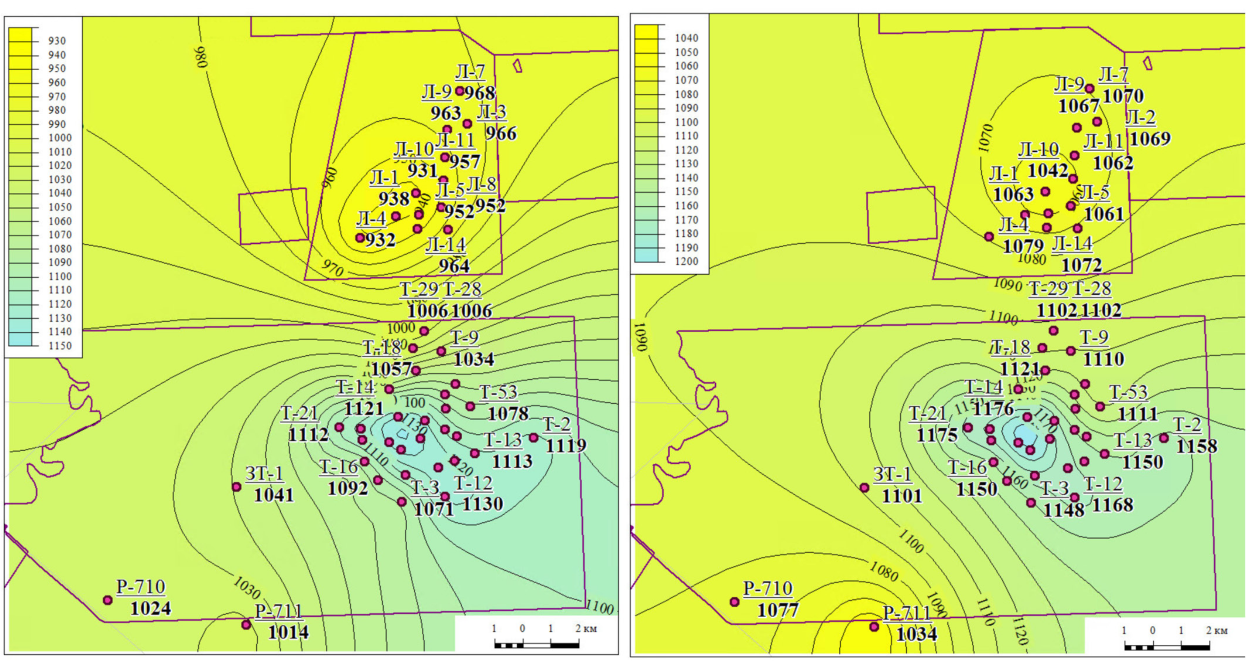
In accordance with the two maps of the cryolithic zone bottom, two options of the maps of the gas hydrate stability zone bottom were built – minimum and maximum (Figure 9).

In the maximum option, the gas hydrate stability zone bottom lies in the depth range of 1100–1180 m, in the minimum option – 1005–1140 m.

According to the maps, at a minimum, the gas hydrate stability zone cover the upper part of the accumulation in the Dr-1 formation, and at a maximum, it also covers the accumulations of the Dr-1, Dr-2 formations and the upper part of the accumulation of the Dr-3 formation (Figure 10).

## Summary

In the scientific literature on gas hydrates in West Siberia, the presence of gas hydrates in the Messoyakha field has been discussed. This study suggests another promising target for the presence of natural gas hydrates – the T field.



Minimum option Maximum option

Figure 9. Two options of the position of the gas hydrate stability bottom at the T field

| Formation Water Salinity | | Gas Composition | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reservoir | Total salinity | Reservoir, zone | Sampling Depth | Content, % mol. | | | | | | | | | | | | | Gas density |
| | | | | $CO_2$ | $N_2$ | He | Ar | $H_2$ | $CH_4$ | $C_2H_6$ | $C_3H_8$ | $iC_4H_{10}$ | $nC_4H_{10}$ | $iC_5H_{12}$ | $nC_5H_{12}$ | $C_{6+}$ | |
| Dr-I | 8850 | Dr-3 | 1082.0 | 0.025 | 1.019 | 0.011 | N/D | 0 | 98.728 | 0.147 | 0.011 | 0.004 | 0.005 | 0.004 | 0.002 | 0.044 | 0.562 |
| Dr-I | 8120 | Average for the accumulation | | 0.025 | 1.019 | - | - | - | 98.728 | 0.147 | 0.011 | 0.004 | 0.005 | 0.004 | 0.002 | 0.044 | **0.562** |
| Dr-I | 8900 | Dl-1 | 1130.6 | 0.043 | 1.018 | 0.01 | N/D | 0.001 | 98.667 | 0.161 | 0.002 | 0.004 | 0.001 | 0.002 | 0 | 0.091 | 0.563 |
| Dr-I | 8740 | | 1186.0 | 0.024 | 0.861 | 0.01 | N/D | 0 | 98.94 | 0.143 | 0.002 | 0 | 0 | 0.003 | 0 | 0.017 | 0.559 |
| Dr-II | 7659 | Average for the accumulation | | 0.034 | 0.94 | 0.01 | - | 0.001 | 98.804 | 0.152 | 0.002 | 0.002 | 0.001 | 0.003 | 0 | 0.054 | **0.561** |
| Dr-II | 8371 | Dl-2 | 1155.3 | 0.016 | 0.739 | 0.013 | N/D | 0 | 98.997 | 0.183 | 0.005 | 0.001 | 0.001 | 0.004 | 0.001 | 0.04 | 0.56 |
| Dr-II | 7961 | Average for the accumulation | | 0.016 | 0.739 | - | - | 0 | 98.997 | 0.183 | 0.005 | 0.001 | 0.001 | 0.004 | 0.001 | 0.04 | **0.56** |
| Dr-II | 8140 | Dl-3 | 1156 | 0.065 | 1.344 | 0.021 | N/D | 0 | 98.429 | 0.104 | 0.005 | 0.001 | 0.002 | 0.003 | 0 | 0.026 | 0.562 |
| Dr-II | 8590 | | 1216.0 | 0.026 | 0.945 | 0.014 | N/D | 0 | 98.845 | 0.139 | 0.01 | 0.002 | 0.005 | 0.002 | 0.002 | 0.01 | 0.56 |
| Dr-II | 8110 | | 1160.0 | 0.015 | 0.693 | 0.013 | N/D | 0 | 99.084 | 0.173 | 0.003 | 0.001 | 0.001 | 0.004 | 0.001 | 0.012 | 0.559 |
| Dr-II | 8900 | Average for the accumulation | | 0.035 | 0.994 | 0.016 | - | 0 | 98.786 | 0.139 | 0.006 | 0.001 | 0.003 | 0.003 | 0.001 | 0.016 | **0.56** |
| Average | 8395 | Taken in the estimates | | | | | | | | | | | | | | | **0.561** |

Table 1. Formation Water Salinity and Gas Composition

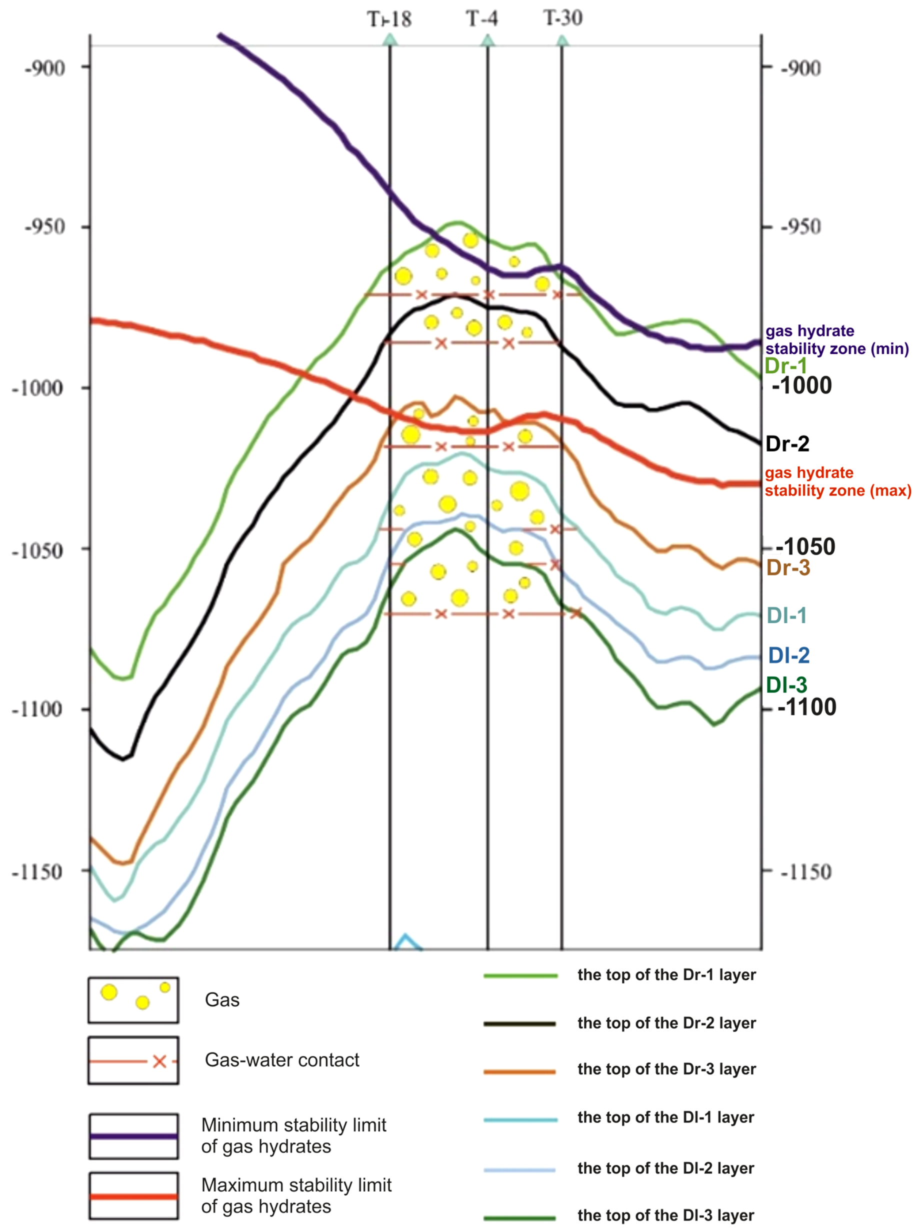



Figure 10. Position of the bottom of the gas hydrate stability zone on the geological cross-section of the T field

Summarized the data on the temperature conditions of the cross-section, the composition of natural gas, reservoir pressures, and formation water salinity of the T field.

Due to the existing uncertainties in the temperature conditions of the cross-section, the cryolithic zone bottom and, accordingly, the gas hydrate stability bottom for the T field were estimated in maximum and minimum options.

For the first time the authors showed that the upper gas-saturated layers of the T field are located in the gas hydrate stability zone.

Further studies should be related to:

• Temperature measurements in settled wells;

• Analysis of test results in gas and gas hydrate intervals;

• Special well logging studies in potentially hydrate-containing intervals;

• Gas hydrate laboratory studies on the core from productive reservoirs;

• Extracting sealed cores with undecomposed gas hydrates, studying them both at the well and in a specialized laboratory;

• Assessing gas reserves, adjusting gas development technology taking into account their hydrate saturation.

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# Подошва криолитозоны и предпосылки существования газогидратов на месторождении Т севера Западной Сибири

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Обобщены исходные данные для расчета интервала стабильности газовых гидратов на месторождении Т Западной Сибири – температура разреза, пластовое давление, плотность газа по воздуху, минерализация пластовых вод. Определение положения подошвы криолитозоны моделировалось комплексированием термоградиента, рассчитанного при испытаниях скважин и положения подошвы многолетнемерзлых пород (ММП) по данным каротажа удельного электрического сопротивления.

В связи с неоднозначностью определения положения подошвы ММП и криолитозоны построены два варианта карт подошвы криолитозоны – минимальный и максимальный. Соответственно, было построено два варианта карт подошвы зоны стабильности газогидратов – минимальный и максимальный. Показано, что верхние газонасыщенные пласты месторождения Т находятся в зоне стабильности газогидратов.

**Ключевые слова:** криолитозона, многолетнемерзлые породы, газовые гидраты, Западная Сибирь

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