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Natural Gas and Gas Hydrate Association in Permafrost of Yamal Peninsula (West Siberia)

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Numerous intensive gas blowouts and liberations from permafrost are documented at shallow depths in the number of permafrost regions (such as North Siberia, Arctic coast of Canada and Alaska and others). The north-west part of Yamal peninsula where large intrapermafrost natural gas accumulations were discovered, is one of such areas. The main natural gas accumulations (methane of microbial genesis with gas flow rates at well heads up to 10000 m^3/day) are associated to the depths of about 60-80 meters. Special research which included analysis of monitoring wells in cryolithozone, as well as detailed research of permafrost cores recovered during drilling, were made. Based on these researches it can be assumed that at least a part of gas in similar intrapermafrost accumulations exists in the form of relict gas hydrates. They were formed in the past and exist now due to the self-preservation effect.
Many data indicate gas hydrate presence. Among them are: high gas saturation of low-permeable permafrost (in horizontal and vertical directions), large gas yields (hundreds and thousands m^3/day) at high (up to 99 %) degree of sediment pore filling with ice and unfrozen water. A number of relations, connecting permafrost gas content with its phase composition, structure and properties, points to the gas hydrate presence within intervals of gas accumulation. Also, it was established that gas liberations are associated to the soil zones with lower salinity. And, the increase of common rocks' salinity is noted beneath gas-containing horizons. Possible mechanism of free gas and gas hydrate accumulations formation within permafrost is suggested on the base of the study.

1 Introduction

Permafrosts' unique and not enough explored characteristic is its ability to hold inside plenty small gas accumulations. This was confirmed by numerous fixed gas blowouts from permafrost intervals and beneath-permafrost sediments during drilling of oil and gas exploration and production wells situated in permafrost areas (Yakushev et al., 1992; Istomin et al., 1992; Dallimore et al., 1998; Skorobogatov et al., 1998). Taking into consideration the fact that permafrost regions occupy large territories within continental and shelf areas of northern latitude achieving hundreds of meters' thickness, study of natural gas accumulations in permafrost could be not only of scientific, but also of practical value.

The special interest excites the fact that intrapermafrost gas accumulations are documented for shallow depths down to 200-300 m (West of North Siberia (Russia), Alyaska's North Slope (USA), Mackenzie Delta (Canada)). A lot of questions concerning conditions of their formation and existence, in particular, about possibility of intrapermafrost occluded gas existence in the form of clathrate compounds with water – gas hydrates could be raised in this relation.

2 Region of study

A new detailed study of gas accumulations within permafrost has been conducted at the Bovanenkovo gas condensate field (Fig. 1) in the northwestern part of Yamal peninsula (West Siberia).

Fig. 1 Map showing locations of permafrost gas release studies.

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Most of the data were received during drilling of the monitoring wells in the southern part of the field by Scientific-Technical Company (STC) "Krios".

The Bovanenkovo gas condensate field is situated in the Northern Geocryologic Zone which is characterized by harsh natural conditions (Baulin et al., 1996). Permafrost is continuous, shallow taliks beneath large rivers and lakes. The thickness of the hard permafrost layer varies between 160 m in river valleys and 250 m at elevated terrain. The mean annual temperature determined from 10 m depth (depth of zero annual temperature variation) varies between -2 to -7 °C depending on the landscape form.

The permafrost layer in the study region is enriched by organic matter. In upper part of the section (20-30 m) organic matter is represented by layers of peat and plant remains (detritus). The lower part of the section contains organic matter in the form of coal tracks and inclusions. In general, the organic matter content increases with depth and reaches maximum values at the lower boundary of the permafrost layer.

The permafrost layer is characterized by high values of water and ice content decreasing with depth (85 % to 25 %). The unfrozen water content increases with depth (1 % to 20 %). The organic-rich sediments containing saline fluids have lower freezing points and lower thermal conductivities, when compared with ice-containing sands. The salinity of the permafrost section is irregular although some trend to salinity increase with depth was observed.

The sedimentary geologic section in the gas field area is represented by Mesozoic-Cenozoic terrigenous rocks (sandstones, clays, alevrites). The upper horizon consists of about 300 m thick Quaternary deposits of marine origin (silt, loam, clay). According to the drill data of STC "Krios", the deepest monitoring wells (550 m) had penetrated unconsolidated sediments of loam-clay composition presumably (Fig. 2).

Geological index	Depth of layer bottom	Lithology	Short description
a Q_{IV}	5.4		Sandy silt with peat,ICV*50 % down to depth 2.2 m, lower-<3 %
	10		Gray silt, CT** is net-like, ICV is 10-20 %
m Q_{III}^{1}	29		Sandy silt with peat layers, CT is massive
	130		Gray silt with fine-grained sand thin layers of 2-10 mm thickness. Down to depth 62 m with peat and plant remains inclusions. In depth interval 81-83 m inclusions of small stones, CT is massive. **Gas liberation in intervals: 54-58, 71-76 and 91-94 m**
m Q_{I-II}^{1-2}	165		Gray silt, CT is massive. **Frozen rocks bottom at depth 165 m**
	205		Gray clay, with black coal spots and thin layers, peat inclusions at depth 180-183 m. Clay is unfrozen
	243		Silt of gray color with sand and gravel
m ₽$_{1-2}$	283		Interbedding of gray silt and fine-grained sand
	314		Gray clay with sand layer at the bottom of the interval (311-314 m)
	507		Dark-gray consolidated clay with stoned macrofauna inclusions and thin layers of sandstone
m K_2	550		Dark-gray aleurolite with clay layers of 10-20 cm thickness and stoned fauna inclusions. Gas production reservoir from depth 600 m

**ICV - visible ice content **CT - cryogenic texture*

Fig. 2 Geological section of 610-P-3 monitoring well.

3 Gas releases from permafrost

Analysis of data of about 40 wells on the research area specifies to the gas blowouts wide propagation both in plan and in section. They could be found in depth interval from 20-30 to 130 m (Fig. 3). Only rare gas releases were registered close to the permafrost bottom. Statistic analysis of the data received demonstrates that about 90 % of gas releases from permafrost intervals are timed to the marine loamy deposits of Yamal series of mid-Quaternary age (m Q_{I-II}^{1-2}). Maximum measured gas flow rates (up to 14000 m^3/day) are also associated with them. Other gas releases from permafrost rocks in the research area are connected with silt-sand-loamy marine deposits of late-Quaternary age (m Q_{III}^{1}). On present showing, gas flow rates from this play are rather small, and maximum stabilized gas flow rate does not exceed 100 m^3/day. In its turn, more than 80 % of gas manifestations in Yamal series deposits are documented for the depth of about 60-80 m.

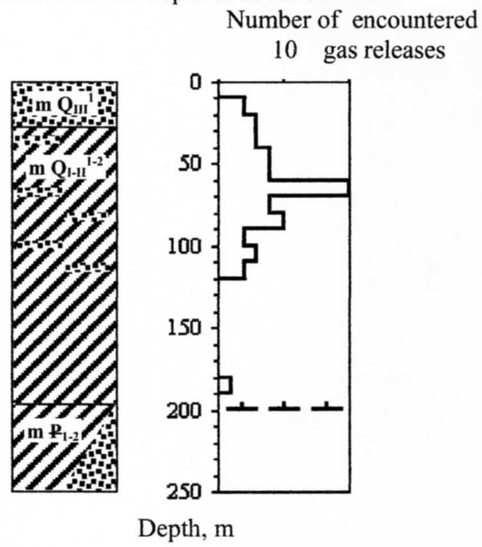
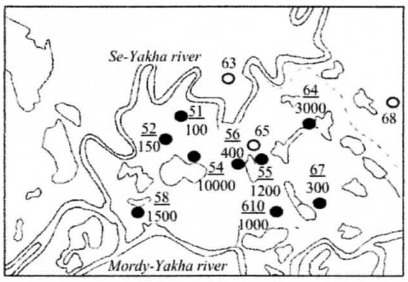


Fig. 3 Distribution of gas releases and their intensities with permafrost depth at Bovanenkovo gas field.

This gas-enriched horizon is spread on the area of 120 km^2 (Fig. 4). This interval is correlated well with the horizon of maximum reported gas flow rates (up to 10000 m^3/day) (Chuvilin et al., 2000).



Open circles - well cluster number; filled circles - wells producing from depth interval 60-80 m and max. gas flow rate (m^3/day)

Fig. 4 Map showing monitoring wells location.

Gas flow rates decreased with time at all wellheads. Duration of gas flow ranged from several days up to several months (observations were limited by the duration of drill/scientific personnel presence at the well). Studies of gas blowout intensities changing with time have been conducted on several wells. The most representative was conducted on well 64-P-2 (well cluster #64), where observations had been conducted during 6 months. A gas blowout with a flow rate of 3000 m^3/day and gas pressure at the wellhead of about 0.7 MPa occurred at depth 72-80 m (frozen silt with rare layers of fine sand with thickness 1-3 cm). Two days later the flow rate decreased to 2000 m^3/day and gas pressure reduced to 0.5 MPa. After 10 days the flow rate was 1200 m^3/day (pressure - 0.4 MPa). Though the intensity of gas release was obviously decreasing, 6 months later gas flow rate was still about 500 m^3/day, wellhead pressure - about 0.15 MPa. Calculations have shown that the total volume of gas liberated from this interval is no less than 120 000 m^3.

Chemical analysis of gas cored from permafrost releases is characterized by larger (on the average 99 %) content of methane (Tabl. 1). Nitrogen, carbon dioxide and some other gases are present in small values. According to the isotopic-spectrometric analysis, gas (Tabl. 2) is of microbial origin (δ ^{13}C = -75 - -77 %o) and was generated during microbiological processing of organic matter contained in the rocks (Skorobogatov et al., 1998).

4 Intrapermafrost gas and possible gas hydrates form of existence's evidence

Geological analysis of gas releases from permafrost interval of north-west part of Yamal peninsula allows to establish some regularities connecting gas

Table 1 Chemical composition of gas.

Well number	Depth of sampling	Chemical composition of gas, %	
51-P-1	59-64	CH_4	98.17
		CO	0.88
		N_2	0.75
		H_2	0.15
		CO_2	0.05
51-P-3	62-69	CH_4	99.65
		N_2	0.35
52-P-1	69-70	CH_4	98.25
		N_2	1.63
		CO_2	0.12
	119-123	CH_4	98.02
		N_2	1.9
		CO_2	0.08
52-P-2	46-52	CH_4	99.98
		N_2	0.02
	114-120	CH_4	99.49
		N_2	0.51
52-P-3	89-96	CH_4	99.79
		N_2	0.21

Table 2 Gas isotopic composition.

Well number	Depth of sampling	Gas flow rate (m^3/day)	$\delta^{13}C$ (CH_4), %o
51-П-1	28-33	400	-73.9
51-П-1	59-64	50-100	-74.6
51-П-2	15-19	50	-70.4
51-П-2	38-44	50	-72.2
51-П-3	62-69	3000	-72.3
52-П-1	63-70	100-150	-71.0
52-П-1	119-123	100-150	-71.8
52-П-2	46-52		-70.4
52-П-2	114-120	800	-70.4
55-П-3	103-113		-73.6
56-П-2	70-80		-76.8
58-П-1	100-107	150-200	-72.7
VNIIGAZ data ↑			
58-П-2	27		-59.56
58-П-2	105		-90.41
Institute of Polar Research named after Alfred Vegener (Germany) data ↑			

releases with peculiarities of composition, structure and properties of permafrost in the research area.

Practically all gas emissions are lithologically associated with silt and clay horizons containing thin sand layers with organic matter elevated content. At depths more than 130 m in more clayish deposits gas emissions from permafrost intervals are practically not documented.

Gas liberations association to the soil interval with reduced salinity can be traced for permafrost, and general salinity slightly increases below studied gas-containing horizons (Fig. 5). Study of perma frost-associated underground water showed that intrapermafrost mineralized waters are basically situated below gas-containing intervals.

In most cases reduction of general salinity in gas-releasing intervals is in synchronism with local minimums of weak-decomposed organic remains content (Fig. 5). Upon that, organic matter content falls on 3 and more times. Reduced organic content in such horizons can be defined by more intensive process of microbial gas formation *in situ*.

The results of laboratory measurement of permafrost gas content during core defrosting in gas-extractor allowed to establish connection between structural distinctions of pore space of permafrost soils in research area with their gas content. Volume of liberated gas 2-3 orders exceeded the free space in soil pores which gas could fill in free state (Tabl. 3). This can be explained only by hydrate form of gas.

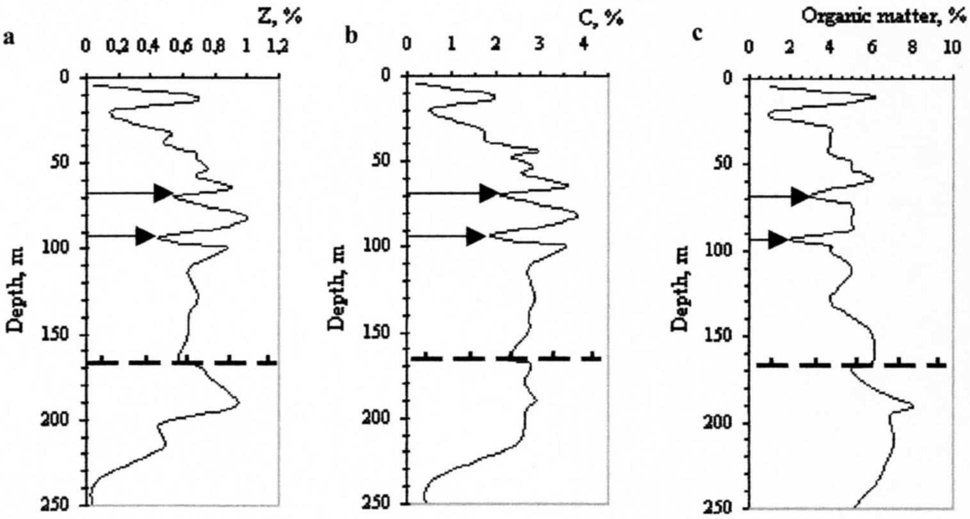


Fig. 5 Gas releases relation to: a - general salinity (Z); b - pore solution concentration (C); c - organic matter content (according to monitoring well 610-P-2 drill cores). Gas releasing intervals at depths: 63-67 m (gas flow rates 500 m^3/day) and 91-95 m (gas flow rates 1000 m^3/day).

Table 3. Results of laboratory measurement of specific gas content during core defrosting.

Well number	Depth of sampling	Sediments	Share of pore space filling with ice and unfrozen water, %	Free pore space, cm^3/g	Gas content, cm^3/g
58-P-2	25	Silt	99	0.0005	0.50
	26	Sand	99	0.0027	0.56
	105	Silt	99	0.0009	0.36
58-P-1	27	Sand	99	0.0015	0.31
	100	Silt	99	0.0016	0.50

5 Possible generation and forms of existence of permafrost gas at the Bovanenkovo gas field

Revealed high gas-saturation of permafrost both in area and in section, large gas flow rates, high (up to 99 %) degree of pore space filling with ice and unfrozen water, gas releases association with certain lithological layers with reduced values of general salinity and organic matters content - all these factors can indirectly indicate existence of at least part of occluded gas in pore space of permafrost rocks in a form of clathrate compound (gas hydrate).

Besides, the possibility of formation and accumulation of gas hydrate in the permafrost sediments is confirmed by the results of special experimental study (Chuvilin et al., 2001). During all the experiments on synthetic hydrate formation in drill cores recovered from permafrost section of the Bovanenkovo gas field, hydrate formation in pores of sediments was observed visually during petrographic research of frozen hydrate- saturated samples. Hydrate was stabile at subzero temperature conditions due to the self-preservation phenomenon. Upon that, hydrate formation in pore space of the studied sediments followed by formation of different types of hydrate cement and textures (inclusions) similar to these in frozen (ice-enriched) sediments.

Experimentally received values of P/T conditions of methane hydrate formation and decomposition in the researched drill cores differ from those in free space and are shifted to the area of higher pressure and low temperatures. Average shift of hydrate dissociation parameters constitutes about 1.6 °C and 1 MPa according to the temperature and baric axis respectively. This was recognized as input parameters for the calculation hydrate formation/decomposition P/T conditions in permafrost section. The study has shown that more than 95 % of gas-releasing layers, including regionally observed horizon at depth 60-80 m, are located higher than up-to-date roof of methane hydrate stability zone. This circumstance leads to the question about possible mechanisms and conditions of accumulation in frozen rocks of gas with transition of at least part of it into hydrate shape on relatively small depths.

Received data allows the assumption of a widespread occurrence of disseminated hydrates in permafrost rocks. Probably, the process of gas generation, accumulation and partial hydrate formation in this region occurred in stages (Fig. 6). At the first stage (before freezing), microbial processing of organic matter resulted in micro-accumulations in relatively permeable layers. Then epigenetic (one-side) freezing of the section resulted to cryogenic concentration of free and formerly water-dissolved gas in sandy layers (Chuvilin et al., 2000). During this process in some lithologically isolated permeable layers, gas was compressed by freezing and a part of it fomed hydrate (Yakushev et al., 2000).

Hydrates could be formed in these intervals during arctic sea transgression or regional ice cover formation, when the overburden pressure was elevated. After pressure reduction, hydrates passed through the self-preservation stage and remained metastable for a long time (Ershov et al., 1991). It is proper to note, that harsh climatic conditions are documented in this area for whole Pleistocene and Holocene periods. These conditions caused continuous growth of permafrost thickness without thawing even at the Holocene climatic optimum (about 5000 years ago). These data support the possibility of long-time safety of self-preserved hydrates in permafrost.

However, the hydrate formation in this area might have a more complex character, so further study of permafrost rock genesis, composition, properties and paleogeologic simulation is necessary for a detailed understanding of the gas component evolution in this area.

6 Conclusion

Research results showed natural gas wide spreading (95-99 % methane content) in permafrost at shallow depth from 20 to 130 meters. Flow rates of intrapermafrost gas releases can reach thousand m^3/day, and duration of these releases can reach many months.

Geochemical analysis of intrapermafrost gas proved its microbial genesis, although there is relative proximity to productive Cretaceous reservoir of thermogenic gas situated at depth 550 m.

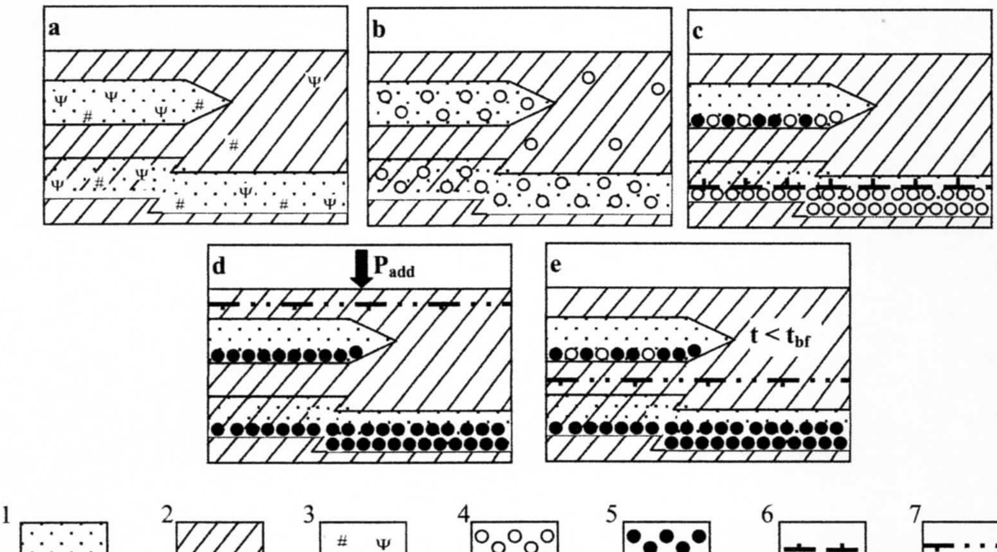


Fig. 6. Scheme of possible gas and gas hydrate formation mechanism in permafrost interval of the Bovanenkovo field.

a - formation of sandy-loam sediments containing organic matter, **b** - gas generation during microbial processing of the organic matter, **c** - formation of gas and gas hydrate accumulation during permafrost formation, **d** - transformation of remains free gas to hydrate within permafrost under additional pressure, (P_{add}), **e** - self-preservation of gas hydrates within permafrost after additional pressure drop; **1** - sandy sediments, **2** - loam sediments, **3** - organic inclusions, **4** - gas-containing sediments, **5** - gas-hydrate containing sediments, **6** – freezing front, **7** - Hydrate Stability Zone (HSZ) top.

The studied regularities connecting gas content of permafrost sediments with their composition, structure and properties, allow to assume the possible existence of at least a part of intrapermafrost gas in the form of relict gas hydrates.

In accordance with the model suggested, gas hydrate formation at relatively shallow depths could occur at the frost stage of the section when P/T conditions in the rock pore space were sufficient for the hydrate formation process. Additional hydrate formation could occur under icecaps (glaciers), marine transgressions and other geological factors favoring to the higher pressure in geologic section.

Up-to-date relict (metastable) gas hydrate existence in the permafrost is conditioned by the effect of gas hydrate self-preservation at subzero temperatures. Upon that, according to the shallow depth and metastable state, intrapermafrost gas hydrate accumulations have tendency to dissociate due to the global climate warming, as well as to different technogenic effects such as drilling and mining.

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References

Baulin, V.V., Aksenov, V.I., & Dubikov, G.I. (1996). Engineering-geological monitoring of Yamal oil and gas fields. In two volumes. V.II. Geocryological conditions of Bovanenkovsky gas-field assimilation. Institute of Northern Development Siberian Division Russian Academy of Sciences, Tyumen, 240 pp. (in Russian).

Chuvilin, E.M., Yakushev, V.S. & Perlova, E.V. (1998). Gas and possible gas hydrates in the permafrost of Bovanenkovo gas field, Yamal Peninsula, West Siberia. *Polarforshung* **68** (erschienen 2000), 215-219.

Chuvilin, E.M., Perlova, E.V., & Dubinyak, D.V. (2001). Experimental modeling of existence conditions of gas hydrates in marine sediments of Yamal peninsula. *Proceedings of the 2th Russian Conference of Geocryology*, Moscow, Russian, v.1, pp. 169-173 (in Russian).

Dallimore, S.R., & Collett, T.S. (1998). Gas hydrates associated with deep permafrost in the Mackenzie Delta, N.W.T., Canada: regional overview. *Proceedings of the 7th International Permafrost Conference,* Yellowknife, Canada, pp. 201-206.

Ershov, E.D, Lebedenko, Yu.P, Chuvilin, E.M., Istomin, V.A., & Yakushev, V.S. (1991). Peculiarities of gas hydrates existence within permafrost. *Doklady Akademii Nauk SSSR* **321**, 788-791 (in Russian).

Istomin, V.A., & Yakushev, V.S. (1992). Gas hydrates at natural conditions. Moscow, Nedra Publish., 236 pp. (in Russian).

Skorobogatov, V.A., Yakushev, V.S., & Chuvilin, E.M. (1998). Sources of natural gas within permafrost North-West Siberia. *Proceedings of the 7th International Permafrost Conference,* Yellowknife, Canada, pp. 1001-1007.

Yakushev, V.S., & Collett, T.S. (1992). Gas Hydrates in Arctic Regions: Risk to Drilling and Production. *Proceedings of the Second International Offshore and Polar Engineering Conference,* San Francisco, USA, **1**, pp. 669-673.

Yakushev, V.S., & Chuvilin, E.M. (2000). Natural gas and gas hydrate accumulations within permafrost in Russia. *Cold Regions and Technology,* **31**, 189-197.