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GAS SHOWS AND THE NATURE OF CRYOLITHOGENESIS IN MARINE SEDIMENTS OF THE YAMAL PENINSULA

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The basic conditions in which gas shows in frozen rocks of cryogenic strata are related to their composition, genesis and structure are defined. The stages of development of submarine cryolithogenesis in marine deposits in the Pleistocene, peculiarities of its development under a sequential change in facial conditions of sedimentation and freezing of bottom sediments of the shelf are shown.

Gas saturation, frozen rocks of cryogenic strata, types of cryolithogenesis, facies environments of sedimentation and freezing, freezing mechanisms of offshore rocks

INTRODUCTION

Gas saturation is the main regional feature of the frozen rocks of cryogenic strata of the north of Western Siberia, both on land and in the offshore rocks, through which migration of natural gas into the hydrosphere and further into the atmosphere proceeds. The information and the physical and chemical causes of forming different phases of natural gas in the cryolithosphere and the main regularities of genesis, migration, accumulation and phase transformations of natural gas are summarized in [*Chuvilin et al., 1999; Yakushev et al., 2003; Yakushev, 2009*].

Yet, some researchers [*Drushchits and Sadchikova, 2015*] believe that analysis of the distribution of methane emission locations in the Quaternary sediments will allow the possible source of gas and the causes of emission or leak to be revealed. In their opinion, formation of permafrost having specific characteristics resulted in formation of specific landscape forms, precipitations having negative temperatures and containing ice, in the burial and conservation of huge masses of organic matter; now permafrost rocks often serve as impediment for the natural gas to penetrate to the surface of offshore rocks and further into the atmosphere. The Quaternary sediments, completing the cross section of the sedimentary cover, are a matrix of caprocks, traps and through “windows” for gases of different nature migrating in the sedimentary cover, including methane, and its significant emissions may be related to migration of free natural gas through continuous permafrost taliks and tectonic fault zones into the frozen rocks of cryogenic strata.

Gas shows in offshore sediments, surface deposits of underflow and underlake taliks, in lake waters, in active layer rocks and in permafrost

The presence of gas in the pores of Quaternary rocks essentially influenced the character of manifestation of cryolithogenesis in freezing and already frozen deposits from different facies environments, while distribution of the areas of gas shows points to gas emissions onto the surface of the offshore bottom sediments, to the accumulating sediments, to the waters of seas, lakes, estuaries, and to the day surface into the atmosphere.

Methane in offshore deposits. The places of methane discharge in the bottom sediments on the surface of the offshore bottom sediments, related to new formation of permafrost, are indicated in the studies by *S.I. Rokos* [*2008*], *S.I. Rokos and G.A. Tarasov* [*2007*], *V.N. Bondarev et al.* [*2002*], *D.A. Kostin and S.I. Rokos* [*2004*] et al., which indicate that gas saturation of the bottom sediments in the Pechora and Kara Seas results in freezing of their waters. S.I. Rokos emphasized that the bottom sediments of the upper part of the cross section (in isobaths from 0 to –70 m) are saturated with free gas practically everywhere. According to D.A. Kostin and S.I. Rokos, in the area of elevations of the piercement type, biogenic gas filled the small cavities under the nearest caprock of disperse soils as pinched bubbles. Diagenetic compression of such sediments pressed out gas accumulations, together with the pore water, into such cavities.

Methane emission from the surface of the vegetative and soil cover, from lakes, active layer soils, underflow and underlake taliks. Measurements conducted within the Bovanenkovo gas condensate field (GCF) have shown that the flow of methane from the natural landscape surface varies from 0 to 100 mL/(m^2·h) [*Rivkin, 1996, 1998, 2003*]. In thermokarst depressions on the surface of terraces and in the flow hollows, it constitutes on average 8–50 mL/(m^2·h). The absolute maximum of methane emission has been recorded in the flow part of the rivers, in deep parts of their tributaries near the river mouths and in underflow taliks, which is connected with formed isolated anaerobic conditions under the flows of small rivers and creeks, which may exist for several years. When taliks were opened in such areas, rather intense gas shows were discovered (up to 1200 mL/(m^2·h)), and at the depth of 0.2 m below an underflow talik, an intense flow of methane from a well was discovered, exceeding 9000 mL/h.

Minimum values of methane flows (0.3 mL/(m^2·h)) were recorded for the Bovanenkovo gas condensate field on flat areas and slopes of sea terraces composed of sandy silts and sandy loams, with scarce vegetation cover or without it. Here methane formed near the ground surface is fully consumed by methanotrophic bacteria.

The author saw degassing of the Yamal lakes during the field works of 1977, and later similar facts were described in the publications by *I.L. Kuzin* [*1990, 1992, 1999*] and *L.N. Kritsuk* [*2010*].

According to the opinion of *B.M. Valyayev* [*1997, 1999, 2007*], the emission rate of methane proved to be the highest for methane coming from under rivers and lakes, which seems to be inexplicable from the viewpoint of the biogenic nature of this flow but becomes clear, considering that practically all the rivers and most of the large lakes mark tectonic disturbances, i.e. the channels of in-depth degassing of the Earth.

O.S. Sizov [*2015*] identified three types of ground gas flows: 1) gradual gas flows, which occur during long periods of time, coming from the bottom sediments of lakes and from the flow parts of rivers with permanent runoff; 2) active gas shows, which originate on eroded slopes with a disturbed top layer, for example, in formation of small lakes having intensely ablated shores, as well as in the flow parts of rivers and on the bottoms of the lakes; 3) sudden gas shows, which occur mainly during the critical growth of frost mounds and look like small conic craters of a regular shape, with round walls and a circular rampart of the ejected ground.

Methane on permafrost rocks. F.M. Rivkin showed [*1998, 2003*] that gas migration could be fully ruled out in the rocks with a high degree of ice filling and high water content. However, the highest concentration of methane is characteristic of the peripheral areas of the lake beds, khasyreys, and underflow taliks (up to 22.5 mL/kg). Such high concentrations of methane have a secondary character and are caused by thawing of these areas in the Holocene and by further epigenetic freezing or conservation of taliks, which contributed to formation of anaerobic conditions.

Here the concepts of *V.S. Yakushev* [*2009*] should be mentioned that in the freezing section, gas is actively emitted from the forming pore ice and migrates into the permeable alternations of permafrost rocks, accumulating there. As a result, generation, migration, and accumulation of the biochemical gas inside permafrost are largely suppressed by further freezing of the sediments, while the gas-saturated alternations get sealed with hardly permeable dispersed and icy rocks. Yet, permafrost is generally permeable for accumulations of deep-earth gas, migrating from below through the rock inhomogenuities and neotectonic faults. Most importantly, the accumulations of deep-earth gas discovered in the permafrost were formed before freezing of the section, and their formation is not different from that in the thawed section.

The available materials have been summarized and analyzed in terms of their use for evaluating the concentration of natural gas hydrates in the over-Cenomanian deposits in the north of Western Siberia [*Agalakov, 1997; Agalakov and Kurchikov, 2004*]. We identify three intervals of the permafrost gas hydrate zones.

The first interval is related to the gas-bearing Cenomanian and Turonian deposits, which in the north of Western Siberia are in thermobaric conditions which are favorable for gas hydrate formation.

The second interval includes under-permafrost deposits of the Cenomanian and Paleogenic age, in which the existence of gas hydrate screens is possible, as well as the presence of non-traditional collectors – silty gaize-like clays and fissured siliceous argillites.

In the third interval, the strata with negative temperatures consist of rocks which differ most for their composition, the pores of which contain fluids in the gaseous, liquid and solid states. Here traps with cryohydrate screening are possible.

In the second interval, the presence of hydrocarbons is proven by the numerous gas shows in drilling exploration wells in the survey areas located in the vast permafrost territory of Western Siberia – from the Semakovskoye field in the north to the Samotlor field in the south, from the Tazovskoye field in the east to the Yarudey field in the west. As the wells were drilled, uncontrollable gas blowouts occurred with absolutely free debit of 10,000–20,000 m^3/day, which lasted for a long time.

S.E. Agalakov stressed that accumulation of hydrocarbons in the third interval (in the permafrost interval) is recorded in drilling wells by numerous gas shows, registered at the depths from 40 to 170 m as short-time outbursts. On the Kharasavey field, intense gas shows necessitated drilling of a new pit shaft, while on the Bovanenkovo field well drilling resulted in the 10-m rise of the drill fluid. Cases are known of prolonged, lasting about three months, gassing with the debit of 500–1000 m^3/day, with gas springs emerging in the thawed frozen soils around the well head.

In the opinion of S.E. Agalakov, the interval of permafrost rocks is very poorly studied, and the relief-forming Quaternary deposits all over the north of Western Siberia are even less known for their gas shows. Gas accumulations in them are considered only as a factor generating an emergency situation in well drilling and operation. However, surveyors drilling small exploration wells (up to 10–20 m) continuously come across the problem of gas shows.

It is currently known [*Nezhdanov et al., 2011*] that gas shows of different degrees of intensity in the upper part of the sedimentation cover (Paleogene–Quaternary deposits) have been identified on practically all the gas fields of Yamal, and the gas-bearing capacity of the Quaternary deposits has been studied rather thoroughly for the Bovanenkovo field.

The main intervals of gas saturation of permafrost rocks. The stratum of over-Cenomanian deposits in the depth interval of 10–450 m contains gas accumulations and gas hydrates in the zone of favorable thermodynamic conditions for gas hydrate formation and especially in the permafrost part of the section. *V.S. Yakushev* [*1989*] proved the presence of the latter, having shown that the relic permafrost metastable gas hydrates are the most significant result of permafrost genesis in the Neo-Pleistocene of Yamal. He was the first to emphasize that the outbursts of deep-earth gas are related to open taliks above the faults in the sedimentation cover.

Judging by the materials of drilling parametric and production wells in the permafrost formation of the Kharasavey and Bovanenkovo gas-bearing structures [*Baulin, 1985; Kleimenov et al., 1998; Budantseva, 2006; Kondakov et al., 2006a; Badu, 2011a,b; Cherepanov et al., 2011; Podborny, 2012; Badu and Podborny, 2013*], it has been found that the gas show intervals (Table 1) are located in the deposits of the Upper, Middle, and Lower Neo-Pleistocene at the depths of 15–220 m from the ground surface [*Podborny, 2012, 2013*].

Over 80 % of gas show intervals were found in the deposits of the Salekhard Formation (mg II_{2-4}) of Middle Pleistocene, most commonly in loams with inclusions of lenses or sand layers. Gas shows most often occur in the areas of reduced permafrost depth: under the flows of the lower sections of the Mordyyakha and Seyakha Rivers and in the areas of large khasyreys and lakes.

Weak gas inflows (50–100 m^3/day) were obtained from the Kazantsevskaya Formation deposits (m, pm III_1) in the depth interval of 28–33 m (the solid frozen part of the permafrost tier), from the Kazym Formation deposits in the depth interval of 100–150 m (the plastic frozen part of the permafrost tier) and from the Poluy Formation in the depth interval of 166–210 m of the tier of chilled rocks of the cryogenic strata. Debits reaching 800 m^3/day were recorded for the solid frozen part of the section with absolute depths of −35...−85 m [*Podborny, 2013*].

Ample gas influxes were obtained from formations (with the debit of 1000 m^3/day and more) in the range of absolute depths −60...−115 m (the plastic frozen part of the section). Below in the plastic-frozen and chilled parts of the section, formations with maximum debits reaching 14 000 m^3/day were found [*Podborny, 2013*].

In the Paleogenic deposits forming the tier of chilled rocks of the permafrost, no gas-saturated formations have so far been found. It is quite likely that gas either wore away in the Neogene or had not entered the hydrate formation zone before the Neogene.

Table 1. **Occurrence, medium intervals of bedding and thickness of the strata of gas-bearing rocks in the genetic complexes of cryogenic strata deposits of the Bovanenkovo gas-bearing structure [*Podborny, 2013*]**

Geologic-genetic complex	Occurrence among all the gas-bearing strata, %	Intervals of bedding, m	Stratum thickness, m
m, pm III_1	6.5	25.9–29.3	3.4
mg II_{2-4}	80.6	81.6–89.8	8.2
m I_2–II_1	8.1	124.7–130.4	5.7
mg I_1	4.8	181.8–189.3	7.5

DATA ANALYSIS

It follows from the above data that in the ice-containing rocks found in the territory of the Bovanenkovo gas condensate field in the interval from 0 to 20–30 m, constituting the solid frozen part of the permafrost, 7 % of the gas-bearing strata with weak gas inflows when opened are concentrated. More than 80 % of the gas-bearing strata with large debits of gas inflows when opened are concentrated in the frozen rocks of the Salekhard Formation of the Late Neo-Pleistocene. In the plastic frozen part of the section (the Kazym and Poluy Formations), 13 % of the gas shows with weak gas influxes but very strong debits have been drilled in. Some collector interbeds in the cooled rocks are saturated with gas hydrates and water to the depths of 260–280 m. Gas shows are most often discovered closer to the steep wings of the gas deposit cupola, but they occur very rarely above extended and flat wings, while the zones of deep-earth gas shows are related to grabens in the caprock of the productive formation but not with plicativs and stepwise discharges [*Podborny, 2013*].

However, as similar distribution is observed also above a group of gas-bearing structures in the part of the offshore rocks adjacent to the Yamal Peninsula, we should consider the provision that the offshore bottom sediments may get frozen during adiabatic expansion of the gas migrating upwards in areas localized above Neotectonic disturbances of the Mezozoic caprock of the gas cupolae [*Melnikov and Spesivtsev, 1995; Melnikov et al., 1998*]. Earlier, it was considered that this occurs above the wings of the rock bends of the crystalline foundation [*Ostry, 1962; Baulin, 1985*].

Considering the specific features of the manifestation of cryolithogenesis in the sediments of marine origin, the data obtained indicate that gas is always localized in the permafrost rock: it enters up the fractures and cavities present in the rocks overlapping a gas deposit or under the influence of the mechanism of segregating ice formation ousting gas from the pores of frozen or freezing rocks. This confirms that freezing fixates the position of the gas accumulations formed already by the end of the Middle Pleistocene, while the complete Neo-Pleistocene cycle of the cryogenic strata development is characterized by regional features [*Badu, 2011b, 2014, 2015a,b*].

Another important feature of the process of sedimentation of different facies of marine deposits should be taken into account. Earlier *V.I. Vernadsky* [*1933*] and later *P.N. Kropotkin* [*1986*] stated that the gas respiration of the Earth takes place all the time; this was confirmed by the works conducted by geologists dealing with oil and gas. The presence of thermogradients accounts for intense heat and mass transfer and degassing. The entire spectrum of the volatile mantle matter gets evaporated at the atomic and molecular levels, including gases – H, O, He, and other. As a result of chemical reactions, compounds are formed, migrating upwards under the influence of baro-and thermogradients: gases condense to form oil, gas condensate, methane, and water, filling permeable elements of the Earth's crust – collectors. Water fills all the water-bearing horizons, inside which methane gets accumulated in the anticlinal foldings and migrates upwards, consecutively saturating both metamorphized rocks and sedimentary diagenetically transformed rocks and loose pressed rocks. The process of gas saturation of the rocks proceeds epichronically with sedimentation in the already formed fractured mineral porous structure of the rocks of the sedimentary cover, including permafrost rocks.

The mechanisms of the crossflow of migrating gases in the void volume of the rocks were proven by *V.I. Avilov and S.D. Avilova* [*2009, 2011*]. Crossflows of gases along fractures and shear ruptures in the fault systems were indicated in the work of *A.A. Nezhdanov et al.* [*2011*]. The conclusions of *V.I. Bogoyavlensky* [*2014; Bogoyavlensky et al., 2016*] and *O.S. Sizov* [*2015*] summarize the significance of this process in the cryolithogenesis.

In the area of accumulation, bottom sediments of the not yet formed structure and texture get saturated, i.e., saturation proceeds simultaneously with sediment accumulation, and the accumulated sediment may get frozen in the submarine environment in three different ways:

– by additional heat takeoff from the bottom ground by masses of surficial seawater cooled to low negative temperatures in winter [*Shpolyanskaya, 2005, 2010*];

– by absorption of heat from embedding rocks due to the throttling effect of gas expansion [*Melnikov and Spesivtsev, 1995; Melnikov et al., 1998; Rokos, 2008*];

– by way of cryosyneresis processes in the rocks cooled below 0 °C [*Popov, 1985, 1991; Maslov, 1988, 1992, 2008*].

In the area of ancient accumulation (marine and glacial-marine plains, marine terraces), gas-saturated are rocks which have passed the stages of diagenesis and cryodiagenesis in a subaerial environment, in which also accumulations of biogenic gas are conserved.

However, it is evident that there exists a certain chronological sequence of stepwise formation of the cryogenic stratum under the gas deposit, as during the consecutive phases of the Neo-Pleistocene, related to periodicity of transgressive-regressive cycles of the Polar basin, sediment accumulation was accompanied by gas saturation and submarine freezing, and upon completion and emergence on the surface – by freezing in the subaerial environment.

The chronological sequence of the evolution of cryolithogenesis

Pre-Quaternary phase – marine Paleogenic sediments were saturated with migrated deep earth gas, which was weathered away into the atmosphere in the continental Neogene.

Early Quaternary phase – gas saturation of the marine facies of the sediments of the Poluy and Kazym Formations was localized only in large river valleys above neotectonic faults in different periods of transgression, but later, as the sea level rose, it started also above those gas deposits which proved to be under that area.

Middle Quaternary phase – gas saturation of the sediments of the Salekhard Formation, characterized by the largest thickness and, accordingly, longer duration of sedimentation and intensity of gas saturation.

Late Quaternary phase – the process of gas saturation of the littoral-marine sediments of the Kazantsevskaya Formation and marine terraces I–III is localized and differentiated by the lithological-facies environments of sedimentation and freezing – of the marine, lagoon-marine or estuary-delta types. It is to be noted that freezing fixates gas in the frozen rock until the stage of the littoral-marine syncryolithogenesis sets in [*Badu, 2010, 2015a,b*], when the unthawed part of the active layer of permafrost within a laida becomes transformed into the permafrost state. In these moments, gas is weathered away from the rocks practically fully by the freezing-thawing processes in the active layer. It is quite likely that biogenic gas may be conserved contemporaneously with gas accumulation. Yet, *V.S. Yakushev* [*2009*] has shown that the majority of the samples of intrapermafrost gas sampled from different formations in Yamal are of biogenic origin, and it is the emission of this gas that is recorded by modern measuring devices, which is confirmed by the values of the isotopic composition compared to the deep-earth methane.

Holocene – the modern phase – the process of gas saturation of the bottom sediments is manifested on the bottom surface by pockmarks, ploughmarks and seeps, while the process of freezing of gas-saturated vapors completes already in the subaerial environment and is accompanied by eruptions of hydrolaccoliths in khasyreys, embedded into the marine sediments, without fire eruptions – in khasyreys in nonmarine rocks. The known and not yet erupted hydrolaccoliths on the Tazovskoye Peninsula emit gases and liquid clay [*Nezhdanov et al., 2011*], as they are located under milder geocryological conditions than in Kharasavey and in Bovanenkovo. With lower average annual temperatures of the rocks, gas-saturated icy clayey rocks of the hydrolaccolith cast would certainly erupt, like in Bovanenkovo, in Antipayutinskaya tundra, and in other territories located closer to the north.

DISCUSSION

Our materials on the cryogenic rocks divided into stratigraphic members with characteristics of the lithological and granulometric composition, the cryotexture and the paleographic material [*Badu, 2006, 2011a,b, 2012*], illustrate our viewpoint on formation of permafrost in the region under study. However, there are different viewpoints regarding its genesis. For example, *S.E. Agalakov* [*1997*] believes permafrost to be a horizon of local gas accumulation in the Pleistocene. In the works by *S.E. Agalakov* [*1997*], *A.R. Kurchikov* [*1992, 2001*], *A.R. Kurchikov and S.E. Agalakov* [*2004*], numerous data are provided on discharge of hydrocarbons in certain areas of fault junctions of the oceanic bottom, confined to the piercement metrostructures of penetration and even to low-profile local deformities of loose sediments.

In the opinion of *R.M. Bembel et al.* [*1997*] and *B.M. Valyayev* [*1997, 1999, 2007, 2010*], "erupted" gases of the nitrogen or methane type freeze rocks and create permafrost above the gas fields of the north of Western Siberia. *L.A. Zhigarev* [*1997*], *N.F. Grigoryev* [*1987*], *Ya.V. Neizvestov et al.* [*2009*] referred submarine permafrost to the regions of degradation of frozen rocks in the periods of Late Neo-Pleistocene transgressions. The viewpoints of *V.S. Yakushev* [*2009*], *A.N. Dmitriyevsky and B.M. Valyayev* [*2002, 2010*] and others are known, confirming the existence of vertical crossflows of hydrocarbons in the supra-Cenomanian section up to the Earth's surface.

However, until recently no one has written that the submarine permafrost is formed in the section of the gas-bearing structures simultaneously with sediment accumulation[1]. In that:

1. Bottom sediments are saturated with gas, and, as soon as collector is under the clayey layer, the coming gas, adiabatically expanding, freezing the above clayey soil with ice production[2]. This is how strictly localized permafrost areas emerge.
2. These areas merge with the areas freezing during cooling of offshore rocks, on which additional heat takeoff occurs by masses of waters with negative temperatures cooled in winter on the sea surface.
3. These areas merge or border the areas where the masses of offshore rocks cooled below 0 °C were subject to erosion and plicative folding.
4. The newly formed submarine permafrost could emerge also in the area of occurrence of relic Early- and Middle-Pleistocene permafrost evolved in the periods of deep regressions of the Polar basin.

On the nature of cryolithogenesis of offshore sediments. The author believes that lithogenesis and diagenesis "transform" into cryolithogenesis in the cryolithosphere, into its complex system of a triple process [*Badu, 2010*]. In the area of accumulation, syncryolithogenesis develops in different lithic-facial modifications [*Badu, 2010, 2015a,b*]. In the area of stabilization, epicryolithogenesis takes place, and the process of cryogenic conservation of gas-saturated rocks lasts contemporaneously with it. In this process, rocks with gas in the pore water and in the pore cavities get cooled below 0 °C, and the pore pressure increases due to the fact that in the freezing water gas is emitted into the water from the forming ice due to the change in its solubility in ice and in water, with gas ousted from the pores into the gas-bearing strata and horizons.

The ambivalent nature of submarine cryolithogenesis is noted, depending on the position of the freezing soil in the section.

1. Surficial sediments. If the bottom ground gets frozen in the areas of active gas shows and close (10–15 m) to the bottom surface, layers are formed with maximum ice content, or icy ground, constituting formations of the piercement type (similar to hydrolaccoliths). The probability is taken into account of the fact that in diffuse seepage methane oxidizes, and, according to the reaction $CH_4 + O_2 = CO_2 + 2H_2O$, practically distilled water dilutes seawater, raising its freezing point. This is what happens in the areas of discharge in the modern sediments of the offshore Kara Sea, which are the areas of mixing of fresh and sea water – "zones of marginal filters": the Tambey

[1] According to the oral statement of Doctor V.S. Yakushev that intra-permafrost gas is syngenetic with the embedding permafrost rocks [*Arivyan et al., 1988*], it is to be noted that gas accumulated in the process of sediment accumulation and was then conserved during epigenetic freezing.

[2] The author agrees with the statement of Doctor V.S. Yakushev that the response of gas to the dramatic baric change of the environment in the effective drainage zone of a well is not similar to that in the offshore rocks, Yet, it is evident that with certain values of the thermogradient and barogradient in the offshore rocks the gas coming from below is warm enough to cool and freeze the above-lying ground.

Table 2. **Types of cryolithogenesis in the main concepts of submarine freezing in different facies environments**

Concept authors (for types of submarine cryolithogenesis)	Types of cryolithogenesis (the names are given by the concept authors)
1 – A.I. Popov, A.D. Maslov	Submarine cryodiagenesis
	Sedimentary cryodiagenesis (active cryosyneresis)
2 – N.A. Shpolyanskaya	Submarine syncryolithogenesis
3a – V.P. Melnikov, V.I. Spesivtsev	Submarine piercement-generating cryodiagenesis
3b – S.I. Rokos, V.N. Bondarev, D.A. Kostin, A.G. Dlugach	
4 – Yu.B. Badu	4a – endogenous-diffusive (3a)
	4b – plicative (1)
	4c – submarine (2)
	4d – submarine piercement-generating cryodiagenesis
	4e – littoral-marine

area of the Gulf of Ob, the Kharasavey area of the western coastline of the Yamal Peninsula and the Yuribey area of the Baidaratskaya Gulf, where activity of methane emission from the surface of the offshore sediments is also recorded. This process is clearly visible in laidas, shallow waters of bays, estuaries and semi-looped lagoons, where storm discharges of organic matter build up and finely dispersed sediments of alongshore lakes separated from the sea by offshore bars get accumulated. In such areas, methane is formed as actively as in the facies of the shallow offshore slopes. It is evident that this process occurred during accumulation of more ancient sediments of similar facies in the Late Neo-Pleistocene and Holocene. As shown in [*Lein et al., 2013*], the temperature of seawater was constantly low and did not obstruct sulfate reduction and methane genesis.

2. Offshore sediments. If the offshore ground gets frozen deep from the surface, at small gradients of the negative temperature (not more than 0.3–0.5 °C/m), freezing is accompanied by discharge of the segregation ice.

The freezing process occurs in a similar way in plicative deformities of the strata resulting in extraction of desalted water from the clayey horizons into sandy horizons, where it freezes, to form massive or shlieren cryogenic structure.

Thus, in the manifestations of the marine cryolithological process, their sequence and the stepwise character, corresponding to the facies environments of sedimentation and freezing, can be identified.

The possibility of submarine cryolithogenesis was discussed and developed by A.I. Popov, and E.M. Katasonov, was investigated by A.D. Maslov, M.A. Velikotsky, I.D. Danilov, Yu.B. Badu, N.A. Spolyanskaya, A.N. Khimenkov and others (Table 2).

The essence of the author's model consists in the fact that the main concepts regarding the possible ways of submarine freezing of the offshore sediments of the Kara Sea represent a sequence, depending on the facies environments of sedimentation (Fig. 1)[3] [*Badu, 2010*].

1. Submarine cryodiagenesis. A.I. Popov, when developing the concept of the submarine type of cryodiagenesis (1 in Table 2; 4b in Fig. 1), contoured the area of its evolvement by the boundaries of submarine creeps, stating [*Popov, 1985, 1991*] that the sedimentation process in a negative temperatures environment is often accompanied by submarine creeps, with plicative dislocations arising in the offshore sediments, accompanied by ice production in over-moist sandy-clayey and silty sediments, which have running and thixotropic properties.

However, the cryogenic transformation of cooled offshore sediments is much more common. Their consolidation takes place also beyond the boundaries of the creeping processes but also with direct participation of cryosineresis, when cooled offshore sediments, solidifying and selectively extracting the pore solution, assume a more stable cooled state [*Maslov, 1988, 1992, 2008*]. In addition, A.D. Maslov noted that after transition of marine sediments which underwent different stages of submarine cryodiagenesis, into the subaerial mode of development, chilled soils get frozen, and the previously frozen strata increase their ice content due to reduction of the natural temperature in the strata. A.I. Popov and A.D. Maslov stated that in creeps and deformation of cooled saline sandy-clayey members of the sediments, the pore solution is extracted from the interlayer of the clayey soil into sandy soil and, having lower concentration, freezes there. That means, in diagenesis of cooled marine sediments, the remaining rocks become saline and the extracted solution loses salt, with gas extracted from the freezing strata of the sandy soil.

2. Submarine syncryolithogenesis (2 in Table 2; 4c in Fig. 1). Freezing of the offshore sediments is possible in convective (vertical) transport of negative-temperature water masses, when colder layers of seawater become more solid due to contacts with the

[3] These concepts were developed on the basis of field works, confirmed by the modern investigation methods, and theoretically substantiated and proven.

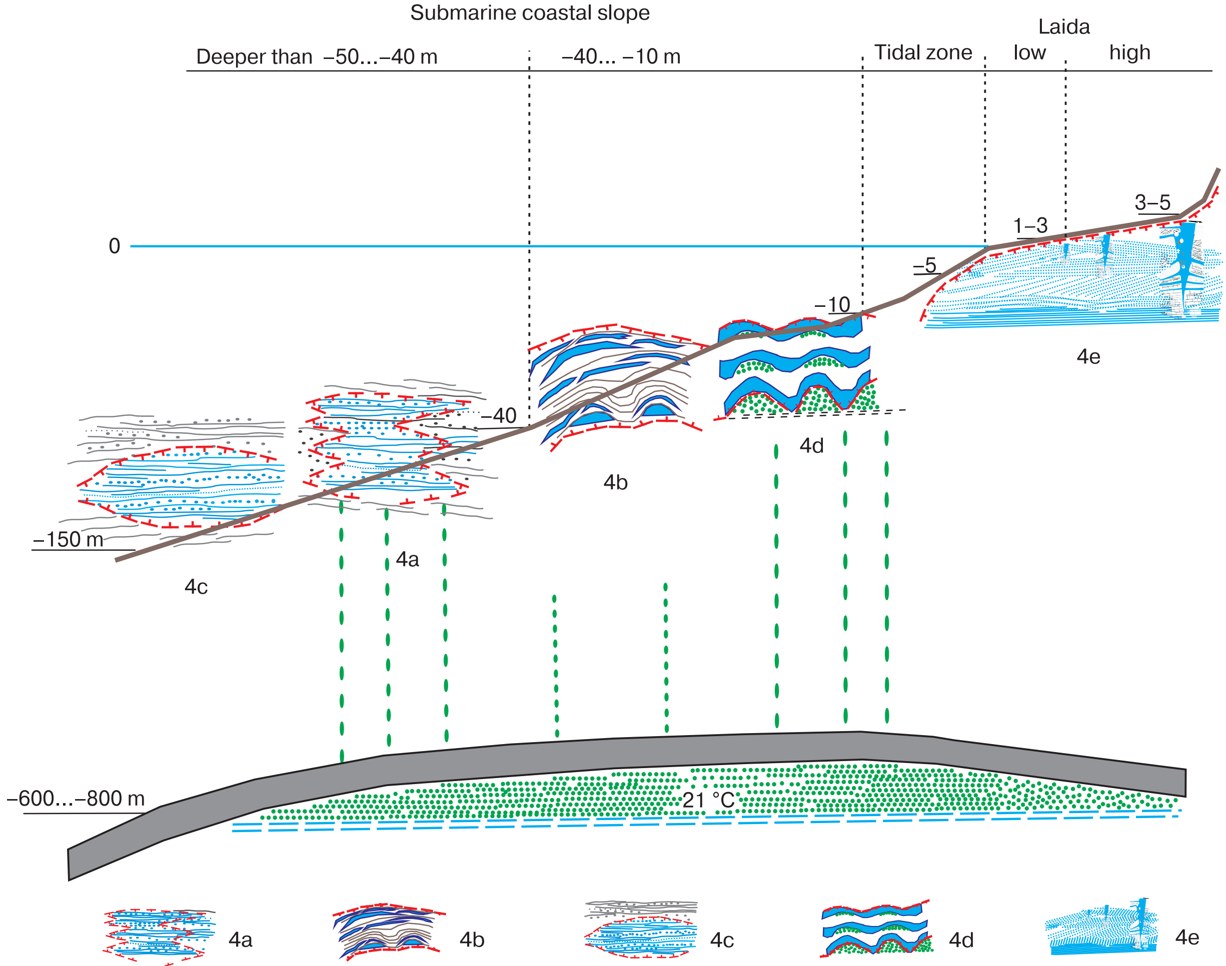

Fig. 1. The typological schematic of consecutive and stepwise development of submarine cryolithogenesis in the offshore deposits.

Types of submarine cryolithogenesis: 4a – endogenous-diffusive; 4b – submarine cryodiagenesis; 4c – submarine syncryolithogenesis; 4d – submarine piercement-generating cryodiagenesis; 4e – littoral-marine syncryolithogenesis.

sea ice bottom and precipitate onto the bottom. Then segregated ice production in the benthic layer of the sediments occurs on condition the temperature of the seawater is lower than the temperature of the beginning of freezing of the sediments' pore solution.

Such a mechanism of freezing of deep-sea sediments is considered in the works by *N.A. Shpolyanskaya* [*2005, 2010*]. As the sediments accumulate, the horizon in which conditions emerge for their freezing moves forward. And the sediments saturated with water freeze contemporaneously with their accumulation.

3. Endogenic diffusive and submarine piercement cryodiagenesis. According to *V.P. Melnikov and V.I. Spesivtsev* [*1995; Melnikov et al., 1998*] (3a in Table 2; 4a in Fig. 1), areas of increased ice content in the offshore sediments are connected with the degassing areas of the gas deposits (by faults, shifts, and mass overthrusts), accompanied by cooling of the rocks at adiabatic gas expansion. *S.I. Rokos* [*2008*], *V.N. Bondarev et al.* [*2002*] (3b in Table 2; 4d in Fig. 1) showed the geological and geocryological conditions of this process. It was noted in their works that normally gas shows are related to sand interlayers and lenses in the stratum of Late Pleistocene loams and clays of the benthic part of the cross section of the offshore deposits. The same stratified members are subject to syncryolithogenesis according to the schematic proposed by A.D. Maslov and A.I. Popov.

4. Littoral-marine syncryolithogenesis. The classification of syncryolithogenesis [*Badu, 2010, 2015a,b*] combined all the previously distinguished types of cryolithogenesis (1–3b in Table 2) and demonstrated that its development consists in consecutive change of the facies environments and the conditions of marine sedimentation under conditions of negative temperatures as the sea depths decrease from the submarine coastal slope to the tidal zone, the

beach, the low, and then to the high laida (4c–4a–4b–4d–4e in Fig. 1 and in Table 2), where the submarine process finishes, and all its events become recorded in the cryogenic structure of the rock strata.

At the sea depth greater than 40–50 m, the deepest offshore sediments get accumulated, cooled by the masses of winter surface waters to the temperature below 0 °C and frozen. At the sea depth less than 40–50 m, rocks thus cooled in the areas of plicative rockslide deformities freeze similarly to the areas where gas emission from bottom sediments takes place. In the tidal zone, freezing is to a larger extent ensured by exogenous cooling of the bottom water and by congelation of the lice cover with the bottom sediments. The submarine stage of development of the cryolithological process completes as the accumulated deposit member reaches the level of the low laida and then of the high laida. From this time on, the cryogenic strata begin to develop in a subaerial mode, continuing the stage of littoral-marine syncryolithogenesis (4e in Fig. 1; 4e in Table 2).

The stages of development of the types of cryolithogenesis are directly related to the chronological phases of development of the sea basin in the Middle and Late Neo-Pleistocene and in the Holocene. Granted the initial moments of the sea basin regressions coincided with the maxima of the climatic cooling of the Middle and Late Neo-Pleistocene epochs, those were the chronological phases of the manifestations of cryolithogenesis. Its main feature is the following: as the deposits get accumulated, they become saturated with gas. Under the influence of excessive pressure in a gas deposit, dissipated fluid flows penetrate the rock strata, triggering the process of primary migration [*Avilov and Avilova, 2009, 2011*]. Subject to excessive pressure, fluids dissipate across the rocks to form bubbles, drops, and cavities, which either form new dissipated flows or thrust to the deconsolidations in the form of fractures, including secondary migration processes. The cavities collapse, get filled and collapse again, i.e., they work as a cyclically operating pump.

There is more gas in the soil pores, cavities, fractures, and shear ruptures where the pore volume is less occupied by interstitial pore ice, which was confirmed in analyzing the drilling data for the Kharasavey gas-bearing structure [*Badu, 2006; Kondakov et al., 2006a,b*]. Gas is present in the water of underflow and underlake taliks, in cryopegs, and in the ice of hydrolaccoliths; yet, in the cores of the migrating frost mounds it cannot be where there is no gas in the underlying deposits and in the talik waters.

Gas shows in the deep-sea deposits (both of biogenic and migrated gas of different genesis, as they are always mixed in the rock strata) indicate the possibility of formation of locations of frozen strata here. In the subaerial environment, the continuity and the thickness of the frozen strata dramatically increase, and the areas of gas shows become conserved in the frozen strata. Gas migration suspends, and only the emission flow coming from the active layer is detected from the undisturbed surface.

CONCLUSIONS

The data referring to the occurrence, the gross intervals and the thickness of the strata in the gas- and water-bearing interbeds and lenses in the genetic complexes of the sea facies of the cryogenic strata rocks of the Yamal Peninsula confirm the following.

1. Natural gas is the cryolithological component of the cryogenic strata in a gas-bearing structure, as epichronous freezing records in the cryogenic strata that gas saturation of the rocks which had formed by the beginning of cryogenic lithification of the cross section, independently of the gas genesis.

2. Gas migration lasts for millions of years, whereas freezing of the rocks in the cross section of the gas-bearing structure recorded in its cryogenic composition started at the end of the Middle Neo-Pleistocene. For this reason, in the marine deposits accumulated within the given period of time, gas shows have been recorded only in the lower part of the Kazantsevskaya Formation of the Late Neo-Pleistocene, while the upper (syncryogenic) stratum of the sands with a high content of ice of the sea terraces III–I of the Late Neo-Pleistocene–Holocene forms a strong barrier – a caprock preventing migration of the deep-sea gas.

3. In more ancient deposits of the marine facies of the rocks of the Yamal Peninsula, migration of gases and of gas-bearing stratal waters in sandy rocks was suspended by the Late Neo-Pleistocene freezing, but it continued only in the largest underflow and underlake taliks which emerged in the Holocene after intense thermokarst along ice wedges and massive ice layers пластовым залежам льда.

4. Gas accumulations in marine loams of the cryogenic strata were formed not only from the local organic material by way of microbial processing. The facies appurtenance of such parts of the cross section does not refer to the submarine coastal slope. This is not glacial-marine but shallow lagoon-marine and littoral-marine facies, enriched with outwashed and redeposited organic matter of the tundra vegetation and peat bogs with low shrubs.

5. In the sections of the gas-bearing structures, where gas came from a gas deposit to the above-laying stratum of sediments through lithological inhomogeneities and neotectonic foldings, the temperature of the rocks changed dramatically towards cooling, ensuring the possibility of local submarine ice formation in the offshore sediments of the marine facies of the Neo-Pleistocene and Holocene sediments in the same way as it was found for the modern offshore sediments in the areas adjacent to the coastline of the Yamal Peninsula.

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