EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth`s Cryosphere, 2020, vol. XXIV, No. 6, pp. 17–26 http://earthcryosphere.ru/

GEOLOGICAL CRYOGENIC PROCESSES AND FORMATIONS

DOI: 10.21782/EC2541-9994-2020-6(17-26)

FROST MOUNDS WITHIN THE GAS-BEARING STRUCTURES, NORTHERN PART OF WEST SIBERIA

Yu.B. Badu, K.A. Nikitin

Lomonosov Moscow State University, Faculty of Geography, Department of Cryolithology and Glaciology, 1, Leninskie Gory, Moscow, 119991, Russia; yubadu@mail.ru, nikitin.kirill@yandex.ru

Distribution of frost mounds is considered based on the concept of subaqueous freezing of gas-saturated marine sediments. For the first time, the areas with maximum density of frost mounds have been identified. Frost mounds in the areas of gas-bearing structures are confined to marine terraces of different ages. It is assumed that frost mounds in such areas can naturally collapse due to blowout of gas-saturated ice core and the underlying deposits.

Frost mound, gas-blowout crater, gas-bearing structure, marine terraces, marine deposits

INTRODUCTION

Recently, a group of cryogenic processes and landforms related to the emergence and development of frost mounds, which have long been known about [*Andreev, 1936; etc.*], generated increased interest of scientists [*Vasil'chuk et al., 2008, 2014; Ponomareva et al., 2012; Bogoyavlenskiy, 2014a,b, 2015, 2018; Kasymskaya, 2014; Bogoyavlensky, Garagash, 2015; Kizyakov et al., 2015, 2017; Olenchenko et al., 2015; Bogoyavlenskiy et al., 2016, 2017, 2018a,b; Khilimonyuk et al., 2016; Leibman, Kizyakov, 2016; Khimenkov et al., 2017a,b, 2018; Orekhov et al., 2017; Perlova et al., 2017; Streletskaya et al., 2017; Vlasov et al., 2017; Epifanov, 2018; Leibman et al., 2018; Titovskiy et al., 2018; Yakushev, 2018; Vorobyev et al., 2019*]. External gas occurrences during the formation of gas craters as a result of natural blowout, cryovolcanism in Eastern Siberia [*Alekseev, 2012, 2013*], mud volcanoes [*Nezhdanov et al., 2011; Khimenkov et al., 2017b; Bogoyavlenskiy et al., 2019a,b*], many of which are located near the gas production facilities and oil and gas pipelines, pose a serious hazard to the operation and condition of the Far North infrastructure facilities [*Bogoyavlenskiy, 2014a,b*].

This problem is being studied by geophysicists, geologists and geographers who use various field and desktop study methods – cryolithological, comparative geographical, cartographic, etc. – aimed at studying a complex mechanism and predicting the development of the hazardous cryogenic process.

The specific permafrost data on the Yamal Crater phenomenon have been obtained by scientists from the Department of Geocryology, Faculty of Geology, Lomonosov Moscow State University (MSU). As a result of the complex studies, the most plausible mechanism of the development of the frost mound and its transformation into a gas-blowout crater (GBC) has been revealed [*Khilimonyuk et al., 2016; Buldovicz et al., 2018; Vorobyev et al., 2019*].

According to the results of a complex geocryological survey of the West Siberian plate, carried out by the Tyumen expedition of the Faculty of Geology, MSU, in 1966–1978 [*Trofimov et al., 1980*], it has been revealed that, on the one hand, many frost mounds have undergone complex history of development and experienced changes in the natural freezing conditions during the Holocene. On the other hand, the areal distribution of frost mounds differs within marine terraces, watersheds, floodplains, laidas, in the rivers' lower and upper reaches [*Badu et al., 1986*].

Later, in the work [*Gevorkyan, Koreysha, 1993*], the explosive mechanism of the frost mound growth has been described in detail, and a computational method has been used to study the development of stresses in the core of the mound and in the deposits overlying the core.

Today, the fact that the frost mounds were located at the sites where GBCs have been recently discovered suggests that the crater formation is a natural stage in the development of the frost mounds which have a gas-saturated ice core. However, there is no consensus on the mechanism of the crater formation. This paper focuses on the specific natural conditions for the formation of frost mounds and GBCs in the northern part of West Siberia. Questions arise: what types of frost mounds can be the predecessors of the GBCs, and are they the only type responsible for the crater formation, in what king of terrain do they develop and occur?

What types of frost mounds should be analyzed: frost mounds (pingo, bulgunniakh), mud volcanoes, cryovolcanoes, cemetery (thermokarst) mounds or the Patomski cone (in Eastern Siberia)? Within the territory under consideration (to the north of the Arctic Circle), all frost mounds (except for the last two, the East Siberian ones) are of interest as rounded landforms projecting above ground surface, of the same genetic type. They are formed by progressive doming during freezing of saturated sediments under the open- or closed-system conditions, which provide either unlimited and pressurized water flow to the freezing front, or limited water supply.

Research tasks included the study of the frost mounds distribution within the gas-bearing structures and at various geomorphic levels. The existing concepts and hypotheses often do not take into account the specific natural terrain conditions of the frost mound development and can be explained only by means of geographic cryolithological analysis of the frost mound distribution, their association with the gas-saturated deposits in the upper portion of the permafrost interval of the gas-bearing structures, including terrain and geomorphic features of the area.

The results of the frost mound study, including mechanisms of their formation will allow in the future to identify potentially hazardous areas in the northern part of West Siberia and other permafrost regions with high probability of the GBC catastrophic development.

METHODS

Key sites have been selected within the zone of continuous permafrost to conduct the detailed study of the frost mound distribution and development. The geographic position of the objects has been determined and recorded on 67 sheets of topographic maps of the USSR General Staff at a scale of 1:200,000 published in the 1960–1990s. Frost mounds (bulgunniakh, ice hill, ice mound) are shown as symbols on these maps. 1425 frost mounds have been identified within the territory of the Yamal, Gydan and Tazovsky peninsulas to the north from 66°30′ N latitude (Fig. 1). GBCs were mapped using data published by [*Bogoyavlenskiy et al., 2019a*].

To determine the conditions under which various frost mounds and GBCs develop, and their relationship with the areas of gas-bearing structures (GS), the contours of 240 areas of gas-bearing structures of the III, IV and V groups have been plotted on the map [*Badu, 2017a, 2018*]. The near-surface portion of the GS section of the III group is represented by the Late Pleistocene marine silty clay and clay with sand interlayers; that of the IV group is composed of Late Pleistocene lagoon-marine silty clay, silt and sand; and that of the V group is presented by the Middle Pleistocene silty clay and clay with interlayers of sand and silt. Within their limits and at a distance of 5–10 km beyond the GS contour, the number of mounds has been calculated, and the density of the mound distribution on the GS area for each peninsula has been determined.

Figure 1 shows the GS areas and the key sites. The compiled map is based in the map of ice content [*Trofimov, Badu, 1982*], the map of permafrost thickness and structure at the West Siberian Plate [*Trofimov, Baulin, 1984*], the map of oil and gas resources of the Yamalo-Nenets Autonomous Okrug at a scale of 1:1,000,000, and topographic maps at a scale of 1:200,000.

Recently formed GBCs quickly turn into lakes with retreating banks [*Kornienko et al., 2014; Kizyakov et al., 2015, 2017; Khomutov et al., 2017*], and the dynamics of the lake's shape depends largely on the geomorphic position of a GBCs, i.e. its location in the basins, thermokarst depressions, or on the slope [*Kizyakov et al., 2015*]. Distinctive features of the water-infilled GBCs are reliably identifiable on high-resolution aerial photographs [*Khomutov et al., 2017; Titovskiy et al., 2018*]. Thermokarst lakes in the areas of subsurface degassing with numerous underwater craters are also indicative of the influx of fluids into the permafrost zone [*Kornienko et al., 2014; Bryksina, Polishchuk, 2015; Bogoyavlenskiy et al., 2019b*]. In addition, in different landscape environments in such places, new frost mounds appear [*Bogoyavlenskiy, Garagash, 2015*], which can be identified by comparing topographic maps at a scale of 1:200,000 (for the year of their publication) with the latest high-resolution satellite imagery.

All the viewpoints, hypotheses and assumptions are analyzed when studying specific data on the relationship of the GBCs with frost mounds and their distribution within gas-bearing structures, under various geomorphic and permafrost terrain conditions.

In accordance with the provisions of the cryosystem analysis [*Badu, 2016*], the concept of the frost mound cryosystem includes frost mounds with an ice or icy core within the geomorphic level with a certain type of structural unit of the landscape. The boundary of the frost mound cryosystem is delineated by the areas of landscape morphological units.

The complex evaluation and forecast of the explosiveness of the frost mound formation and development includes the following three cryosystem types with associated subtypes:

The First type: Late Holocene and Recent frost mounds in the river valleys:

– Recent frost mounds located near the shallow oxbow and thermokarst lakes on the floodplain and within large lake depressions, with drain into the river network;

– Recent and Late Holocene frost mounds located at the bottom of drained thermokarst lakes (khasyreys) within river valleys.

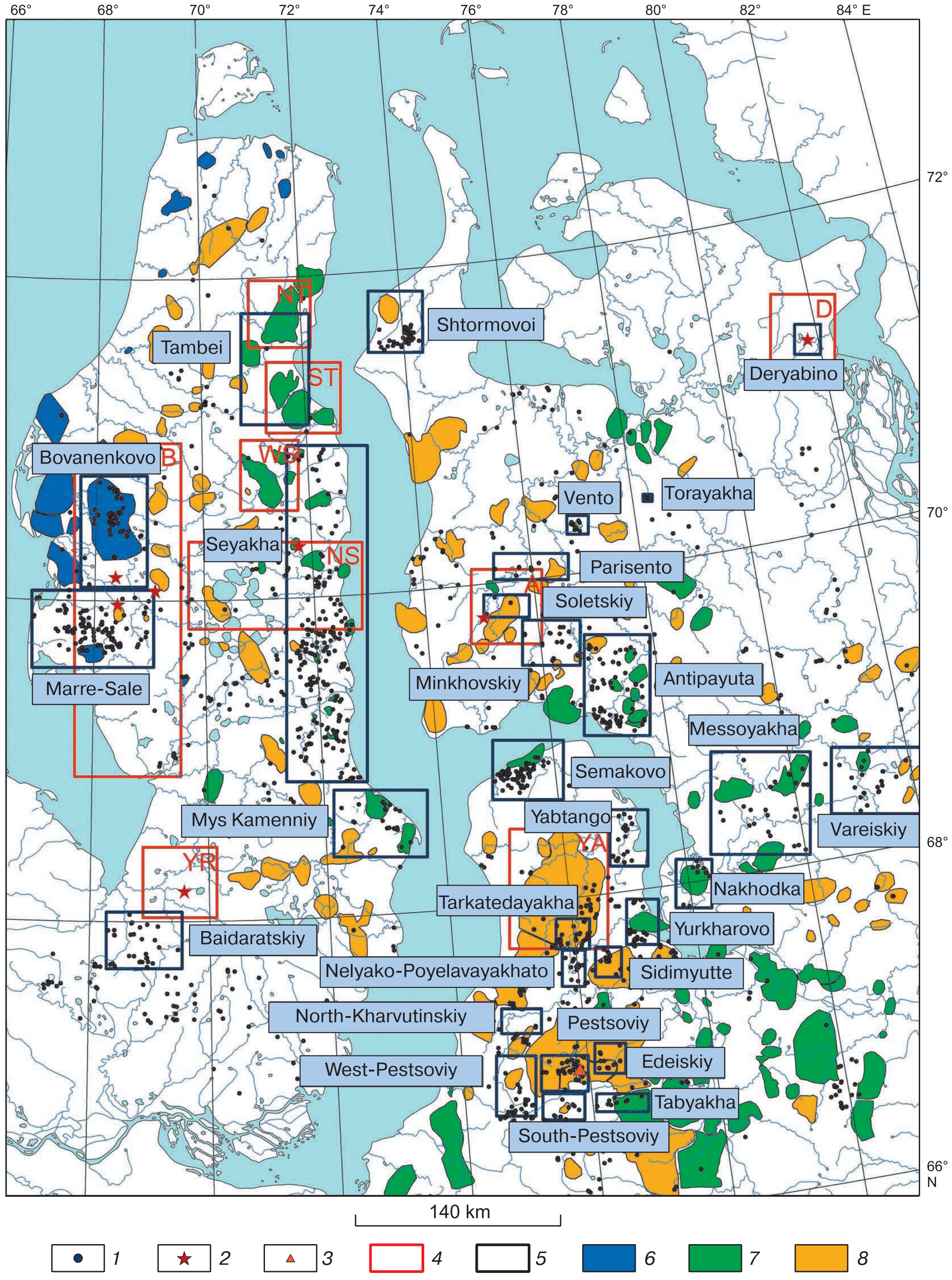

Fig. 1. Key sites of research.

1 – frost mounds; *2* – gas-blowout craters [*Bogoyavlenskiy et al., 2019a,b*]; *3* – mud volcanoes [*Nezhdanov et al., 2011*]; *4* – areas of detailed research by the Oil and Gas Research Institute RAS: B – Bovanenkovo, ST – South Tambei, NT – North Tambei, NS – North Seyakha, WS – West Seyakha, YR – Yerkuta, D – Deryabinskoye, YA – Yamburg, A – Antipayuta [*Bogoyavlenskiy, 2014a,b*]; *5* – key sites. Groups of gas-bearing structures [*Badu, 2017b,c, 2018*]: *6* – III group; *7* – IV group; *8* – V group.

The Second type: Late Holocene and Recent frost mounds within marine terraces:

– Recent and Late Holocene frost mounds in terraced depressions and khasyreys within Middle and Late Pleistocene marine plains and terraces;

– Late Holocene frost mounds in Late Pleistocene khasyreys on the surface of lagoon-marine terraces.

The Third type: Recent frost mounds on the slopes:

– Recent frost mounds near the upper reaches of the gullies on the gentle slopes of the Late Pleistocene marine plains with tectonically oriented thermal erosion gully network;

– Frost mounds on the slopes of intermittent streams and gullies of the relict and recent thermal erosion network.

To characterize and correlate the relationship between the distribution of frost mounds with permafrost landscapes in the area of the GS and geomorphic levels, the coefficient of the areal distribution of frost mounds (the number of frost mounds per 100 km^2) is introduced (CAD). It allows: *Firstly*, to determine the relationships between the frost mound development and the gas deposit of the gas-bearing structure, taking into account the likelihood of the gas presence in the lake (river, etc.) talik, within which the frost mound formed, and either have exploded resulting in GBC, or have become potentially explosive. *Secondly*, to determine whether the objects are associated with a typical geological section of the floodplain of tectonically oriented river valleys, which began to form at the end of the Late Pleistocene over tectonic faults in the earth's crust cutting through the cover of Quaternary deposits. *Thirdly*, to confirm the association of the frost mound with a certain type of landscape.

The descriptions of the natural conditions in which GBCs have been formed are not always informative and comprehensive; therefore, it remains necessary to study the geological and geomorphic features of the GBC development throughout the area of their distribution in continuous permafrost zone. In the south, in the areas where the frozen strata experienced thawing during the Holocene Climatic Optimum, the age and duration of the frost mound growth may be limited by the duration of the period of noticeable climate warming, which sharply changed the thermal state of the deposits in the uppermost portion of the geological section.

The relationship between the location of frost mounds and gas-bearing structures of different orders

There is no doubt about the geographic and cryolithological understanding of relationship between frost mounds and GBCs with large neotectonic structures, since the GSs as structures of the 3rd order, located above mega-arches, mega-troughs, swells and depressions, are a source of the gases migrating from under the cap of the gas reservoir [*Badu, 2018*]. The gas contained in frozen sediments and groundwater saturates the talik waters, which migrate or inject upward during the freezing, forming the frost mound core. The development of mounds often ends with the natural destruction of the soil roof or the disturbance of its continuity owing to the drop of mechanical stresses due to the ice core growth. In that case, during thawing, the exposed part of the ice evaporates the absorbed gas, saturating the circumambient air to a concentration of 9–16 % [*Vyakhirev, Shushunova, 1975*] and explodes, covering the underlying sediments and the ice stock of the root injection system.

Formulating the point of view on the importance of methane in the formation of a GBS, the authors take into account that methane from the mantle and coal-bearing deposits of the Permian–Triassic migrates along tectonic faults and concentrates in anticlinal folds of Cenomanian deposits under the thick Upper Cretaceous cover of the productive gas reservoir. Having filled the traps completely, the gas rushes into the overlying layers. This process has been going on for many millions of years. Due to the disturbance of the cap deposits, the gas is constantly being released into the overburden, saturating marine sediments accumulated during Pleistocene and today [*Badu, 2018*]. Thus, the formation of both a frost mound with gas-saturated ice or ice-rich soil of the core and a GBC as a result of the FM development is associated with the gas saturation of the Pleistocene marine sediments, in which the talik is being formed. This assumption is confirmed by the results of permafrost studies. They have demonstrated that during the freezing and the formation of a frost mound the large amount of gas is concentrated in the icy core of the mound [*Kurchatova, Rogov, 2018*].

The authors do not share ideas about the frost mound-to-GBC transformation: 1) if they do not account for the gas saturation of the Pleistocene marine sediments containing such formations; 2) if gas is considered to be a marsh methane of the Holocene age, the presence of air or gas cavities in the body of the ice stock, and the gas squeezing out the ice stock; 3) if it is considered as an elementary process of volcanism – a 'hot' process, completely incomparable with the cryogenic process in temperature, energy and dynamics, in the nature of heat exchange between the Earth's spheres, in terms of development and consequences, but only remotely – in the form of occurrence of ice intrusion in the section. Of course, unlike the positions of P.A. Shumskiy, B.P. Weinberg and I.Ya. Baranov, professor O.K. Lange and the Polish geologist A.B. Dobrowolski attributed the product of crystallization of groundwater (ice) to the class of igneous rocks, but only in a comparative sense [*Badu, 2010*].

The author's ideas about the development of a GBC in the place of a frost mound are based on the fact that the frost mound is formed in the place of a talik according to the classical scheme of the sediment freezing in an open or closed system. But it is taken into account that:

– only within the GS area permafrost is saturated with gas or contain its accumulations in the anticlinal traps representing a lithological pair of clay-and-sand layers; the aquifers are saturated with the gas of the host deposits; the gas accumulated in the deposits in the course of their sedimentation and diagenetic transformation before freezing;

– frost mound growth is provided by the formation of a core of icy soil or pure ice saturated with gas; when the strength of the permafrost overlying the core is broken by the heaving forces, the it rips (bursts); the core ice is exposed, the gas evaporates out of it, at its concentration of 9–16 % in the air, the mound explodes; the entire gas ignites instantly: both out of the core and the ice injection stock, out of the aquifer and the underlying (possibly) massive ice bed;

– the pyrogenic nature of the frost mound explosion is not necessary, and the internal cryogenic pressure is the primary cause of the explosion; but cases of fire have already been recorded on the Seyakha Crater [*Bogoyavlenskiy et al., 2019a*].

Out of those concepts and the definition of the frost mound as the initial stage of the GBC development, the *author's cryolithological position* is formed – a mound confined only to the area of the GS, located within both the zones of uplifts and troughs, and monoclines, can be potentially explosive, because it is being formed in the freezing deposits of the talik, which has arisen in the thermokarst area on highly ice-rich soils overlying the marine and alluvial deposits saturated with gas.

According to this position, within the GS area (i.e. above the gas reservoir), the frost mound can turn into a GEC or turn out to be potentially explosive if two prerequisites are combined: neotectonic and permafrost ones. Let us pay attention to the first of them, which explains the reasons for the gas saturation of the deposits overlying the gas reservoir within the limits of GS.

Neotectonic prerequisite. The west of Yamal Peninsula is located above the edge of the Yamal monocline, and the south of it is situated over the slope of the Pripaikhoi monocline to the Baidaratsky mega-trough. The east of Gydan Peninsula is located over the edge of the monocline, and the Tazovsky Peninsular – over a complex combination of depressions, troughs, and groups of dome-shaped uplifts.

The maximum values of the coefficient of the areal distribution of frost mounds (more than 16 per 100 km^2) are confined to the coastal areas of marine and lagoon-marine terraces of the western and eastern parts of Yamal Peninsula, the north and south of Gydan Peninsular, the north and central parts of Tazovsky Peninsula (Fig. 2). The territories with a CAD of less than 16 per 100 km^2 occupy the largest area in the central parts of the watershed plains on the Tazovsky and Yamal peninsulas.

When combining the author's map 'Areal distribution of frost mounds in the northern part of West Siberia' (Fig. 2) and the map 'Structural diagram and zoning of the sedimentary cover of the West Siberian plate along the base of the Jurassic-Cenozoic plate complex' [*Nesterov et al., 1984*], it turns out that the areas of the largest CAD values of the mounds are located as follows:

Yamal Peninsula:

– in the western part – over the edge of the Yamal monocline, and the GBCs are over the Yumbdyakha trough (*the Marre-Sale and Bovanenkovo maxima of the CAD*);

– in the southwestern part – over the edge of the Pripaikhoi monocline in the place of the Baidaratsky mega-trough (*the Yerkuta maximum of the CAD*);

– on the eastern coast – over a part of the Seyakha mega-trough, crossed by the Central Yamal mega-trough (*the Seyakha maximum of the CAD*).

Gydan Peninsula:

– in the northwestern part – over the northern edge of the Khanara-Salya mega-trough (*the Shtormovoi maximum of the CAD*);

– in the center – over the northwestern slope of the Geofizicheskiy mega-swell and the eastern edge of the Central Yamal mega-swell (*the Geofizicheskiy maximum of the CAD*);

– on the coast of the Taz Bay – over the Antipayuta depression, and to the northwest over the Sydyyakha trough (*the Antipayuta maximum of the CAD*).

Tazovsky Peninsula:

– in the northern part – over a group of dome-shaped uplifts (*the Semakovo maximum of the CAD*);

– to the south – over the area of complex mutual arrangement of depressions, troughs and groups of uplifts located to south of the slope of the Yamburg dome-shaped uplift (*the Tabyakha and Pestsoviy maxima of the CAD*).

Permafrost prerequisite. The second prerequisite of the accepted cryolithological position is that potentially explosive frost mounds develop in a specific permafrost environment – when taliks freeze in gas-saturated deposits. If peat, silty clay and water-saturated sand occur in the section of frozen deposits from top to bottom, then when they freeze in an open system (with water inflow from the pressure aquifer), a frost mound with an ice-soil core of segregated ice appears. In a closed system without water inflow a mound with a core of injection ice forms in a closed talik. The sandy deposits and water of the aquifer are rich with gas, as well as the gas-saturated frozen and cooled sediments surrounding the talik. The sections

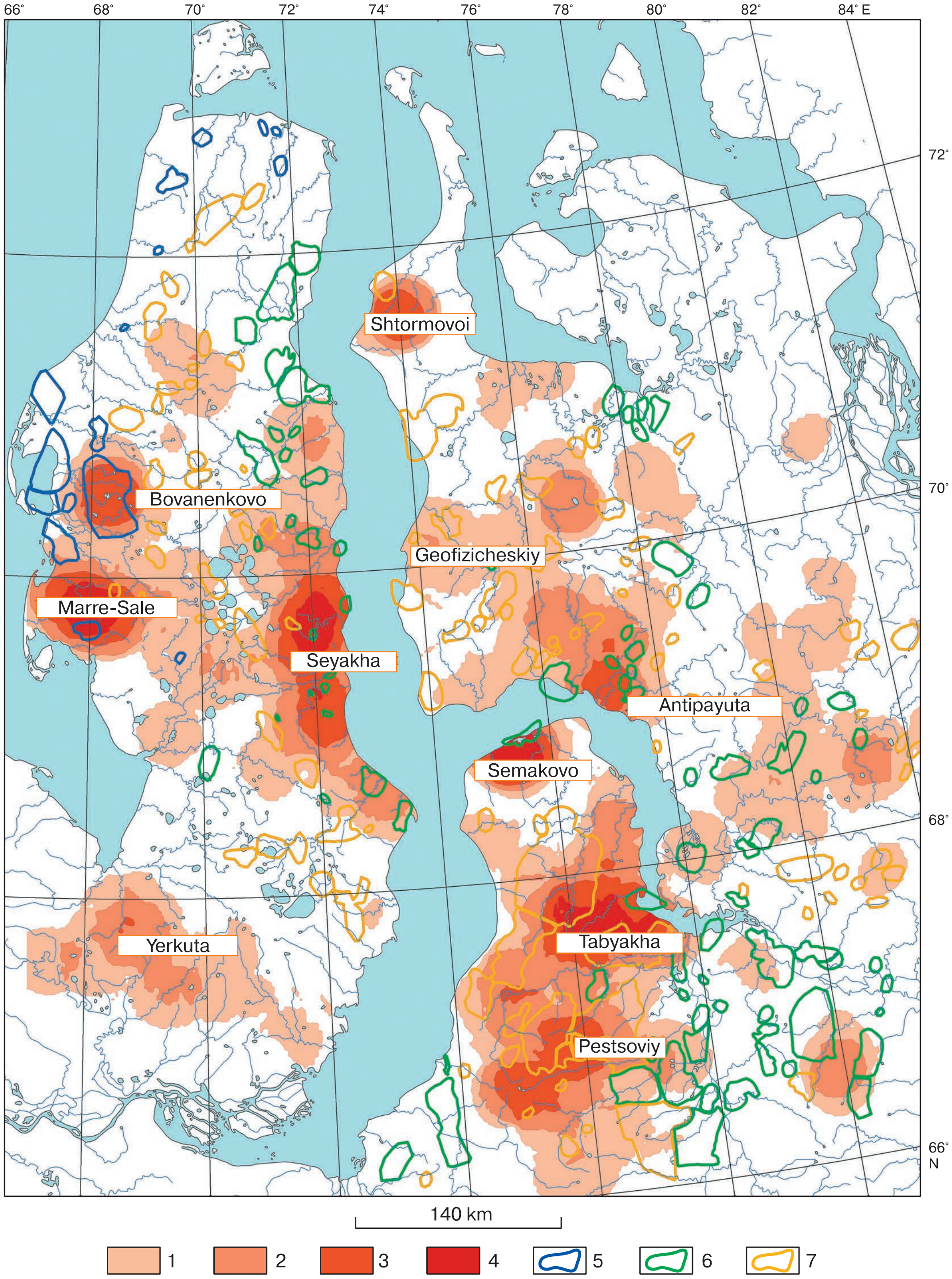

Fig. 2. Areal distribution of frost mounds and its maxima in the study area.

The number of frost mounds per 100 km^2: *1* – 2–8; *2* – 9–15; *3* – 16–22; *4* – more than 22. Groups of gas-bearing structures [*Badu, 2017b,c, 2018*]: *5* – III group; *6* – IV group; *7* – V group. The names indicated on the map are the names of the maxima of the areal distribution of the mounds.

of such a structure can be underlain by massive ice bed.

So, under those two prerequisites, it is possible to assume a certain relationship between frost mounds location and GBSs and the territories where the most important source of gas is a gas reservoir of a gas-bearing structure.

Frost mounds (exploded, newly formed, destroyed) are located within the area of gas-bearing structures (Fig. 1), which is determined by the vertical projection of the plane of the gas-water contact on the day surface [*Badu, 2017a*]. Out of the 680 mounds located within the GS area, the largest number (350) is located on the Tazovsky Peninsula (51.4 %), and on the Gydan and Yamal peninsulas, they are significantly less: 30.3 and 18.3 %, respectively. In the same order, the total area of the GSs, for which the calculations have been performed, decreases.

52 % out of the 1425 mounds used for calculations are located outside the total area of the structures (Table 1). Here it should be taken into account that, firstly, the geological boundary of the GSs on the State Geological Map does not coincide with the drawn boundaries of the licensed land allocation for operation. Secondly, only BPs marked on a topographic map of 1:200,000 scale produced in 1967–1989 are included in the calculation. And, nevertheless, preliminary calculations of the confinement of frost mounds to the area of GSs already demonstrate a poor correlation (on average, $r = 0.46–0.48$).

The coefficient of the areal distribution of frost mounds in the areas of each group of GSs (Table 2) characterizes the big picture averaged over the studied territory. The largest and the smallest values of CAD indicate that the near-surface section of the marine terraces sediments of the Late Pleistocene is a more favorable environment for the formation of GBCs in the place of potentially explosive frost mounds. That environment is associated with a certain type of geological structure, with the conditions of sedimentation, freezing and gas saturation of the deposits in the upper portion of the section.

The confinement of frost mounds to the geological and geomorphic levels of the peninsulas is already confirmed by the preliminary obtained data (Table 3). Judging by the data in Table 3, on Yamal, the largest number of mounds is concentrated within the GS area of the III group: 48.1 % out of 206 and 25–26 % of them is concentrated within the limits of the IV and V groups. That distribution confirms the probability demonstrated in Table 2. Frost mounds formation conditions are similar within the Middle and Late Pleistocene lagoon-marine terraces and marine plains. But these conditions are most favorable within the Late Pleistocene marine terrace precisely within Yamal Peninsula.

On the Gydan Peninsula, the largest number of frost mounds is concentrated in its upland parts: 63.7 % of 124 are located within the GS area of the V group, and 36.3 % of the mounds are disposed within the IV group. Here the situation is different: within the limits of the Middle Pleistocene marine plain conditions for the development of mounds are more favorable.

On the Tazovsky Peninsula, the largest number of frost mounds is concentrated in its central part: 71.4 % of 350 mounds are located within the GS area of the V group, and 28.6 % of the mounds are disposed within the IV group. The situation is completely similar to the previous one: here, within the Late Pleistocene lagoon-marine terraces, the conditions for the emergence of mounds are less favorable than within the Middle Pleistocene marine plain.

Table 1. **The number of frost mounds within and outside the gas-bearing structures (GS)**

Peninsula	GS area, km²	Number of frost mounds*		
		Total	within the GS area	outside the GS area
Yamal	17 400	576 (40.4)	206 (30.3)	370 (49.7)
Gydan	11 000	344 (24.2)	124 (18.3)	220 (29.5)
Tazovsky	20 500	505 (35.4)	350 (51.4)	155 (20.8)
Total	48 900	1425	680	745

*The share (%) is indicated in brackets.

Table 2. **Coefficient of areal distribution of frost mounds by groups of gas-bearing structures (GS)**

Group of GS	Number of frost mounds within the GS group area	Total area of a group, km²	Coefficient of areal distribution of the mounds, number of frost mounds*	The share of the group area (of the total area of the GS), %
III	99	5791	1.71	11.8
IV	199	18 797	1.058	38.4
V	382	24 312	1.57	49.7

*The number of frost mounds per 100 km².

Table 3. **Number of frost mounds by the groups of gas-bearing structures (GS) within the peninsulas**

Peninsula	Number of frost mounds within the GS area	Number of frost mounds by the GS group area*		
		Group V	Group IV	Group III
Yamal	206	53 (25.7)	54 (26.2)	99 (48.1)
Gydan	124	79 (63.7)	45 (36.3)	0
Tazovsky	350	250 (71.4)	100 (28.6)	0
Total	680	382	199	99

* The share (%) within the peninsula is given in brackets.

Note. Group V – glacial-marine and marine plain $gmII_{2-4}$; group IV – coastal marine plain $pmIII_1$; group III – third marine terrace $mIII_{2-3}$.

The obtained data preliminarily demonstrate quite reliable specificity of the regional areal distribution of the frost mounds, – their confinement to landscape morphological units at which taliks under drained lakes froze in the areas composed of icy deposits of the marine and lagoon-marine Late Pleistocene terraces, i.e. to areas with a certain geological structure and heterogeneous relief structure, to sections of gas-saturated deposits. That confinement is ambiguous in each of the surveyed peninsulas and requires a specific study in specially designated key sites.

CONCLUSIONS

There is still no consensus on the origin of craters in various natural settings. A preliminary study of the features of the frost mound distribution on topographic maps at a scale of 1:200,000 allows us to determine a number of natural conditions in which those mounds arisen and developed over the past 30–50 years.

Preliminary results demonstrate that in the study area:

– the highest density of the mound distribution on the Yamal, Gydan and Tazovsky peninsulas is naturally concentrated over the neotectonically heterogeneous part of the sedimentary cover section, in which the gas reservoirs of gas-bearing structures are concentrated at depths of no more than 700–900 m from the surface;

– less than half (48 %) of 1425 frost mounds, marked on maps of different years of release, are located within the GS area. The largest number of the mounds is confined to the GS with an area of less than 50 km^2 and increased fracturing of sediments;

– the maxima of the areal distribution of mounds are confined to the coastal areas of the marine and lagoon-marine terraces of the western and eastern parts of the Yamal, the northern and southern parts of the Gydan, the northern and central part of the Tazovsky peninsulas.

Neotectonic and permafrost prerequisites for the formation and development of frost mounds within the Middle and Late Pleistocene marine plain are more favorable than within the Late Pleistocene lagoon-marine terraces.

Within the area of each of the peninsulas, that ratio is unequal. It's important that within the Late Pleistocene coastal-marine and the Middle Pleistocene marine plains, a set of natural conditions (ice content of deposits, sandy-clayey interbedding in the geological section, gas saturation of sediments, position of aquifers, salinity of sediments, etc.) is most favorable for the development of frost mounds with the formation of gas-blowout craters. The question remains: why is that so?

The work has been carried out in accordance with the fundamental theme 'Changes in the Earth's cryosphere under the influence of natural factors and technogenesis' (State Assignment I.5 AAAA-A16-116032810095-6) with the support of the Russian Foundation for Basic Research within the framework of project 18-05-60080.

References

Alekseev, V.R., 2012. Cryovolcanism and the riddle of the Patom cone. Geodinamika i tectonofizika (Geodynamics and Tectonophysics), No. 3 (3), 289–307.

Alekseev, V.R., 2013. Patom Crater: burial ground and bulgunnyakh? Nauka i tehnika Yakutii (Science and Technics of Yakutia), No. 2 (25), 68–78.

Andreev, V.I., 1936. Hydrolaccoliths (bulgunnyakhs) in the West Siberian tundra. Izvestiya Gosudarstbennogo Geograficheskogo Obshchestva (Proceedings of State Geographic Society), 68 (2), 186–210.

Badu, Yu.B., 2010. Cryolithology. Knizhniy Dom Universitet, Moscow, 528 pp. (in Russian).

Badu, Yu.B., 2016. Cryosystem analysis of gas-bearing structures of the Yamal Peninsula. Akademicheskiy zhurnal Zapadnoi Sibiri (Academic Journal of West Siberia), 12, No. 2 (63), 8–12.

Badu, Yu.B., 2017a. Gas-bearing structures and cryogenic strata of the Yamal peninsula cryolithological provinces. Inzhenernaya Geologiya (Engineering Geology), No. 1, 39–50.

Badu, Yu.B., 2017b. Gas shows and the nature of cryolithogenesis in marine sediments of the Yamal Peninsula. Earth's Cryosphere XXI (5), 36–45.

Badu, Yu.B., 2017c. Foundations of the conception of subaqual cryolithogenesis of marine deposits of gas-bearing structures of the Yamal Peninsula. Earth's Cryosphere XXI (6), 65–72.

Badu, Yu.B., 2018. Cryogenic strata of gas-bearing structures of the Yamal Peninsula. On the influence of gas accumulations on the cryogenic strata forming and development. Nauchniy Mir, Moscow, 232 pp. (in Russian).

Badu, Yu.B., Vasil'chuk, Yu.K., Kashperyuk, P.I., et al., 1986. Geological processes and phenomena caused by long-term temperature changes in the layer of permafrost and freezing rocks. In: Exogeodynamics of the West Siberian plate (spacetime patterns). Publishing House of Moscow State University, Moscow, pp. 92–166 (in Russian).

Bogoyavlenskiy, V.I., 2014a. Risk of catastrophic gas blowouts from the Arctic cryolithic zone. Yamal and Taymyr craters. Part 1. Bureniye i Neft' (Drilling and Oil), No. 9, 13–18.

Bogoyavlenskiy, V.I., 2014b. Threat of catastrophic gas blowouts from the Arctic permafrost zone. Cones at Yamal and Taymyr. Part 2. Bureniye i Neft' (Drilling and Oil), No. 10, 4–8.

Bogoyavlenskiy, V.I., 2015. Oil and gas emissions on land and offshore areas of the Arctic and World Oceans. Bureniye i Neft' (Drilling and Oil), No. 6, 4–9, DOI: 10.25283/2223-4594-2018-1-48-55.

Bogoyavlenskiy, V.I., 2018. Gas-hydrodynamics in the Arctic craters of gas blowout. Arktika: ekologiya i ekonomika (Arctic: Ecology and Economics), No. 1 (29), 48–55, DOI: 10.25283/2223-4594-2018-1-48-55.

Bogoyavlenskiy, V.I., Bogoyavlenskiy, I.V., Kargina, T.N., et al., 2019a. Earth degassing in the Artic: remote and field studies of the thermokarst lakes gas eruption. Arktika: ekologiya i ekonomika (Arctic: Ecology and Economy), No. 2 (34), 31–47, DOI: 10.25283/2223-4594-2019-2-31-47.

Bogoyavlenskiy, V.I., Bogoyavlenskiy, I.V., Nikonov, R.A., 2017. Results of aerial, space and field investigations of large gas blowouts near Bovanenkovo field on Yamal Peninsula. Arktika: ekologiya i ekonomika (Arctic: Ecology and Economy), No. 3 (27), 4–17, DOI: 10.25283/2223-4594-2017-3-4-17.

Bogoyavlenskiy, V.I., Bogoyavlenskiy, I.V., Nikonov, R.A., et al., 2018a. Technologies for remote detection and monitoring of Earth degassing in the Arctic: Yamal Peninsula, Neito Lake. Arctica: ecologia i economika (Arctic: Ecology and Economy), No. 2 (30), 83–93.

Bogoyavlenskiy, V.I., Garagash, I.A., 2015. Justification of generation of gas emission craters in the Arctic by mathematical modeling. Arktika: ekologiya i ekonomika (Arctic: Ecology and Economy), No. 3 (19), 12–17.

Bogoyavlenskiy, V.I., Sizov, O.S., Bogoyavlenskiy, I.V., et al., 2016. Remote identification of areas of surface gas and gas emissions in the Arctic: Yamal Peninsula. Arktika: ekologiya i ekonomika (Arctic: Ecology and Economy), No. 3 (23), 4–13.

Bogoyavlenskiy, V.I., Sizov, O.S., Bogoyavlenskiy, I.V., et al., 2018b. Technologies for remote monitoring of surface degassing in the permafrost area (Yamal Peninsula). In: Actualniye problemy nefti i gasa (Actual Problems of Oil and Gas), 4 (23), 75.

Bogoyavlenskiy, V.I., Sizov, O.S., Mazharov, A.V., et al., 2019b. Earth decontamination in the Arctic: remote and field studies of the Seyakha accident gas emission on the Yamal Peninsula. Arctica: ekologiya i ekonomika (Arctic: Ecology and Economy), No. 1 (33), 88–105, DOI: 10.25283/2223-4594-2019-1-88-105.

Bryksina, N.A., Polischuk, Yu.M., 2015. Analysis of changes in the number of thermokarst lakes in permafrost of West Siberia on the basis of satellite images. Earth's Cryosphere XIX (2), 100–105.

Buldovicz, S.N., Khilimonyk, V.Z., Bychkov, A.Y., et al., 2018. Cryovolcanism on the Earth: Origin of a Spectacular in the Yamal Peninsula (Russia). Scientific Reports. United Kingdom, Nature Publishing Group, 8, p. 13534, DOI: 10.1038/s41598-018-31858-9.

Epifanov, V.A., 2018. Explosive craters-wells and the relevance of studying the role of subsoil degassing of in climatic events and landscape transformations of the Quaternary period. In: Bulletin of the Commission for the Study of the Quaternary, No. 76, 5–40 (in Russian).

Gevorkyan, S.G., Koreysha, M.M., 1993. Explosions of frost mounds. In: Proceeding of Glaciological Research, No. 77, 120–130 (in Russian).

Kasymskaya, M.V., 2014. Seasonal and perennial frost mounds in the north-east of the Yamal Peninsula. Research publications, No. 15 (19), 13–18.

Khilimonyuk, V.Z., Ospennikov, E.N., Buldovich, S.N., et al., 2016. Geocryological conditions of the Yamal crater location. In: Proceedings of the Fifth Conference of Geocryologists (Moscow, June 14–17, 2016). Universitstslaya Kniga, Moscow, pp. 245–255 (in Russian).

Khimenkov, A.N., Sergeev, D.O., Stanilovskaja, Yu.V., et al., 2017a. Gas emissions in the cryolithozone as a new type of geocryological hazards. Georisk (Georisk), No. 3, 58–65.

Khimenkov, A.N., Stanilovskaya, Yu.V., Sergeev, D.O., et al., 2017b. Development blasting process in cryolithozone in connection with the formation of the Yamal Crater. Arktika i Antarktika (Arctic and Antarctic), No. 4, 13–37.

Khimenkov, A.N., Vlasov, A.N., Volkov-Bogorodskiy, D.B., et al., 2018. Fluid-dynamic geosystems in Cryolithozone. Part 2. Cryolithodynamic and cryogasodynamic geosystems. Arktika i Antarctika (Arctic and Antarctic), No. 2, 48–70.

Khomutov, A.V., Leibman, M.O., Dvornikov, Yu.A., 2017. Gas-emission craters in the process of their formation. Kholod'Ok (Kholodok), 1 (15), 5–13.

Kizyakov, A.I., Sonyushkin, A.V., Leibman, M.O., et al., 2015. Geomorphologic conditions of the gas-emission crater and its dynamics in Central Yamal. Earth's Cryosphere XIX (2), 13–22.

Kizyakov, A.I., Sonyushkin, A.V., Khomutov, A.V., et al., 2017. Assessment of the relief-forming effect of the Antipayuta gas-emission crater formation using satellite stereo pairs. Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa (Modern problems of remote sensing of the Earth from space), 14 (4), 67–75.

Kornienko, S.G., Kritsuk, L.N., Yakubson, K.I., et al., 2014. Study of the lakes dynamics and processes of permafrost new growth in the Yamal Peninsula, on the basis of aerospace observations data. Aktualniye problemy nefti i gaza (Actual Problems of Oil and Gas), No. 1 (9), 14–32.

Kurchatova, A.N., Rogov, V.V., 2018. Formation of geochemical anomalies in hydrocarbon migration in the permafrost zone of West Siberia. Led i Sneg (Ice and Snow), 58 (2), 199–212.

Leibman, M.O., Dvornikov, Yu.A., Streletskaya, I.D., et al., 2018. Connection between the gas emission craters formation and methane emission in the north of West Siberia. Aktualniye problemy nefti i gaza (Actual Problems of Oil and Gas), 4 (23), 1–4.

Leibman, M.O., Kizyakov, A.I., 2016. New natural phenomenon in the permafrost zone. Priroda (Nature), No. 2, 15–24.

Nesterov, I.I., Podsosova, L.L., Rudkevich, M.Ya., et al., 1984. Structural diagram and zoning of the West Siberian plate at the base of the Jurassic–Cenozoic plate complex. Scale 1:500,000. Funds of the Geological Institute of the Russian Academy of Sciences, Moscow, 9 sheets (in Russian).

Nezhdanov, A.A., Novopashin, V.F., Ogibenin, V.V., et al., 2011. Mud volcanism in the north of West Siberia. In: Proceedings of TyumemNIIgiprogaz. Flat, Tyumen, pp. 74–79 (in Russian).

Olenchenko, V.V., Sinitsky, A.I., Antonov, E.Y., et al., 2015. Results of geophysical serveys of the area 'Yamal crater', a new geological structure. Earth's Cryosphere XIX (4), 84–95.

Orekhov, P.T., Popov, K.A., Slagoda, E.A., et al., 2017. Frost mounds of Bely island in coastal marine settings of the Kara Sea. Earth's Cryosphere XXI (1), 41–51.

Perlova, E.V., Miklyaeva, E.S., Tkacheva, E.V., et al., 2017. Yamal Crater as an example of a rapidly developing cryogenic process in the context of climate warming in the Arctic. Vesti gasovoy nauki (News of Gas Science), No. 3 (31), 292–297.

Ponomareva, O.E., Gravis, A.G., Berdnikov, N.M., 2012. Current dynamics of frost mounds and flat-hummocky peatlands in the northern taiga of West Siberia (on the example of the Nadym station). Kriosfera Zemli (Earth's Cryosphere), XVI (4), 21–30.

Streletskaya, I.D., Leibman, M.O., Kizyakov, A.I., et al., 2017. Underground ice and its role in the formation of the gas-emission crater on the Yamal Peninsula. Vestnik Moskovskogo Universiteta. Seriya 5: Geografiya (Bulletin of Moscow University. Series 5: Geography), 1 (2), 91–99.

Titovskiy, A.L., Sinitskiy, A.I., Pushkarev, V.A., et al., 2018. Comprehensive studies of the Yamal craters, new facts. Aktualniye problemy nefti i gaza (Actual Problems of Oil and Gas), 4 (23), 61–71.

Trofimov, V.N., Badu, Yu.B. (Eds.), 1982. Map of Genetic Types and Ice Content of the Upper 10-meter Part of the Permafrost Section of the West Siberian Plate. Glavtyumengeologiya, MGU, PNIIIS, Moscow, 9 sheets (in Russian).

Trofimov, V.N., Badu, Yu.B., Dubikov, G.I., 1980. Cryogenic structure and ice content of permafrost sediments of the West Siberian plate. Publishing House of Moscow State University, Moscow, 246 pp. (in Russian).

Trofimov, V.N., Baulin, V.V., 1984. Map of Thickness and Structure of Permafrost Strata of the West Siberian plate. Glavtyumengeologiya, MGU, PNIIIS, Moscow, 9 sheets (in Russian).

Vasil'chuk, Yu.K., Budantseva, N.A., Vasil'chuk, A.C., Yoshikawa, K., Podborny, Ye.Ye., Chizhova, Ju.N., 2014. Isotope composition of pingo ice core in the Yevo-Yakha river valley, north-west Siberia. Earth's Cryosphere XVIII (4), 41–51.

Vasil'chuk, Yu.K., Vasil'chuk, A.C., Budantseva, N.A., et al., 2008. Convex frost mounds of permafrost peat massifs. Moscow University Press, Moscow, 571 pp. (in Russian).

Vlasov, A.N., Khimenkov, A.N., Volkov-Bogorodskiy, D.B., et al., 2017. Natural explosive processes in the permafrost zone. Nauka i tekhnologii razrabotki (Science and Technology Development), 96 (3), 41–56.

Vorobyev, S., Bychkov, A., Khilimonyuk, V., et al., 2019. Formation of the Yamal crater in Northern West Siberia: Evidence from Geochemisty. Geosciences 9 (12), p. 515, DOI: 10.3390/geosciences9120515.

Vyakhirev, D.A., Shushunova, A.F., 1975. Gas Chromatography Guide. Vysshaya Shkola, Moscow, 220 pp. (in Russian).

Yakushev, V.S., 2018. Mechanisms of natural gas concentration in the cryolitozone. Actualniye problemy nefti i gaza (Actual Problems of Oil and Gas), 4 (23), 71–75.

Received August 21, 2019
Revised version received January 23, 2020
Accepted July 25, 2020