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Relief of degassing areas in the eastern part of the Pechora Sea

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ABSTRACT

Geological and geophysical studies of the bottom relief and the structure of the sedimentary cover of the Pechora Sea were carried out on the Akademik Nikolay Strakhov research vessel during the 38th and 41st expeditions (2018-2019). A detailed digital terrain model was created In the course of processing the data obtained by multipath sonar. The forms of relict permafrost relief were identified on this model by morphology (including specific polygonal structures). Seismoacoustic studies of the water area revealed marks of degassing in the structure of the sedimentary cover and the water column. Activation of the degassing process may be a result of the degradation of relict permafrost, which are fluid-resistant. In addition, gas emissions (the formation of gas flares) can be caused by the destabilization of gas hydrates in the process of thawing permafrost. Degassing can be hazardous for the construction and operation of oil and gas infrastructure objects (pipelines, drilling platforms, etc.), as well as for underwater vehicles and vessels. Gas emissions lead to decompaction of the loose bottom sediments, changes in their physical and mechanical properties (decline of bearing capacity, strength characteristics, etc.) Deformations of structures located on the bottom are possible as a result of these changes. The Pechora Sea is strategic importance region due to it's significant hydrocarbon reserves and transportation routes. It is important to study in detail the anomalies that arise as a result of degassing and the resulting landforms for the successful development of this region. It is necessary to forecast the further dynamics of these phenomena in the context of climate changes recorded in the Arctic region in recent decades.

KEY WORDS: Pechora Sea, shelf, permafrost, degassing, pingo-like structures

INTRODUCTION

Shallow water area (sea depth less than 100 m) of the Pechora Sea shelf is promising in terms of development. There are hydrocarbon deposits. Construction of oil and natural gas production and transportation facilities is in plan. However, in order to ensure the safety of oil and gas production infrastructure, as well as vessels involved in research and engineering surveys, it is necessary to study and map the zones of abnormally high lithostatic pressure. The key feature of this area is that during the Late Valdai glaciation it was not covered by the ice sheet (unlike most of the Barents Sea). That time the formation of permafrost took place here. Further flooding of the territory during the Holocene transgression initiated the process of permafrost degradation, which intensified decomposition of organic matter and accumulation of loose gases in the upper part of the sediments. Furthermore, frozen rocks are a good fluid reservoir, which contributes to the formation of gases accumulations under bottom. The combination of a large amount of gas with high lithostatic pressure and elastic highly frozen sediments in the upper part of the sedimentary cover results in development of specific pingo-like highs in the studied area of the shelf. These shapes can be considered as a marker of zones of abnormally high lithostatic pressure. In addition, the degrading permafrost on the shelf of the Pechora Sea loses its continuity, that leads to the development of gas emissions into the water column in areas with weakened or thawed permafrost. Mapping and study of these landforms have great importance both for fundamental scientific researches and for solving applied problems. Gas pockets in the sedimentary cover are a potential hazard during erection and exploitation of engineering constructions, primarily oil and gas infrastructure facilities (drilling platforms, pipelines, etc.).

The purpose of the study is to estimate the effect of gas accumulation in the Quaternary sediments on the relief development within the northeastern part of the Pechora Sea shelf.

GENERAL CHARACTERISTICS OF THE TERRITORY

The area with identified pingo-like highs is located in the northeastern part of the Pechora Sea (Fig. 1). The study area is characterized by a severe maritime Arctic climate with mean annual temperature below 0°C (Rokos, 2009). The polygon is located within the shallow shelf, the depth within the polygon varies from 48 up to 82 m. Morphologically the study area is located on the continuation of the Pechora lowland. The background bottom surface within the polygon is subhorizontal, complicated by numerous isometric uplifts with elevationof 14-16 m. In the northwestern part of the polygon, there is a local depression of the shelf topography with depth up to 8 m and a slope steepness of ca. 1.5°. The origin of this landform is not reliably known, but according to geomorphological features, the depression can be interpreted as a relict tundra bog, formed in the Sartan epoch in subaerial conditions. This is approved by the widespread distribution of relict polygonal landforms within the study area, as well as the presence of a peat horizon in the upper strata of marine clays of Kazantsevo age (Serebryanny et al., 1998; Rokos, 2009).

In the Late Valdai (Sartan), the ice sheet covered almost the whole continental Barents sea shelf, while the study area was not glaciated during that epoch and was located to the south of the glacier margin (Vorren et al., 2011). As a result of the last Sartan regression (about 18 ka BP), down to 100 m below present day sea level, the shelf of the Pechora Sea was dried up and the development of the study area took place already in subaerial conditions (Svendsen et al., 2004). The open surface that time was dissected by river valleys, so in many places there are lacustrine-alluvial sands of Sartan age, 2-5 m thick. Due to the location of this area in the periglacial zone, low air temperatures were observed, which contributed to the formation of permafrost. During the subsequent Holocene transgression (about 10 ka BP), the Pechora Sea shelf was flooded, and the permafrost began to degrade rapidly under the warming effect of sea water (Patton et al., 2017). This process was proceeding the most intensively during the initial phases of transgression, when the sea depth was quite small. Then, as a result of the sea level rise (up to the levels close to the modern ones), the melting process significantly slowed down, which is attributed to the low (ca. 0°C) bottom temperatures of the modern basin (Rokos et al., 2009). It is assumed that the relict frozen massif is currently experiencing slow melting from the base of the sedimentary cover upwards under the influence of methane fluids (Rokos, 2009).

The surface of the shelf within the study area reveals modern marine sediments represented by loams and sandy loams up to 5 m thick (Rokos, 2008). In the area of the paleovalleys, the roof of the Karginsky strata lies at a depth of 1 to 10 m. They are represented by alluvial-marine clays 10 to 50 m thick. The sediments have a rhythmic layered and semi-wavy or semi-flattened acoustic structure. The curves and folds are conformal to the undulating roof of the underlying deposits. No attenuation of the amplitudes of folds and bends is observed in the upward direction of the sedimentary cover. Below these deposits in shallow waterareas there are lenses of Zyryanka alluvial sands, which may have up to 20-30 m thick. Marine reconsolidated clays of the Kazantsevo interglacial are almost ubiquitous, with their roofs ranging from 5-10 m to 30-50 m from the shelf surface. The thickness of these deposits varies from 20-30 m to 100 m (Rokos, 2008). Since these formations are acoustically rigid or impermeable, no useful reflections are observed below their roof.

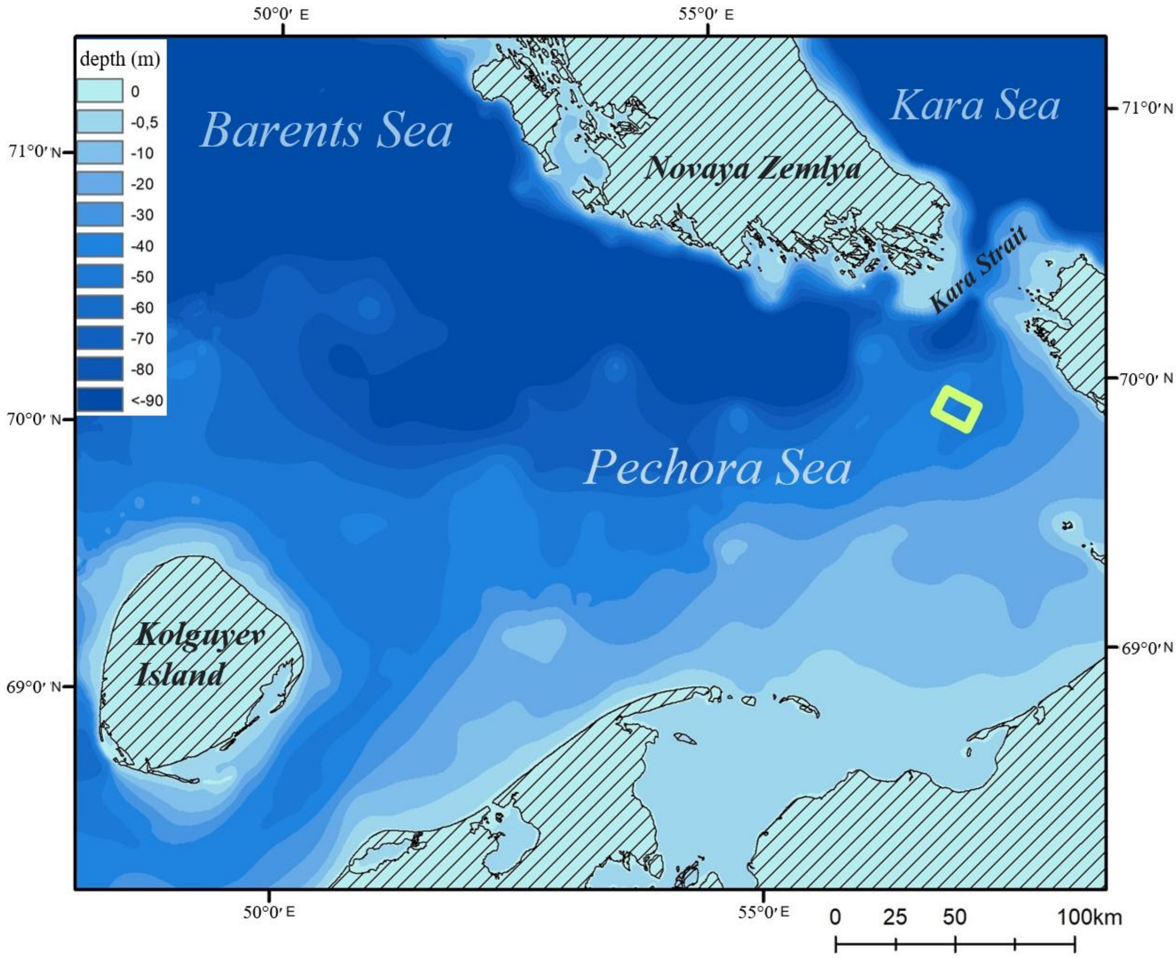

Fig.1 Location of the study area (yellow rectangle) on the bathymetric map created using IBCAO V4 data (https://www.gebco.net)

The roof of perennially frozen ice rocks is averagely fixed at a depth of 20-30 m from the bottom surface (Kazantsevo marine clays, Karginsky alluvial-marine clays) and their thickness is ca. 20-40 m (Rokos, 2008).

In the quaternary strata cover, there are loose gas pockmarks, which is mainly of biogenic origin. they are formed as a result of decomposition of organic matter by bacteria. They consist ofmainly (more than 95%) methane with an admixture of CO2 and other gases. Thermocatalytic gases are also found in surface sediments. They penetrate the upper parts of the sedimentary section as a result of vertical migration from bottom horizons of the sedimentary cover (Druschitz et al., 2011).

METHODS

The relief analysis was performed basing on multibeam bathymetry data obtained during 38 and 41 cruises of the R/V "Akademik Nikolai Strakhov" within the Pechora Sea shelf. The bottom topography imaging was performed using amultibeam shallow-water echo sounder RESON Seabat 8111 with the frequency of the emitted acoustic signal of 100 kHz. The data processing involved two steps. First, it is manual cleaning of the captured profiles in Editing. This operation allows us to mechanically remove low-quality signals, which are usually formed in the marginal parts of the strip. Second, processing in Surfer and ArcGis was performed to visualize the obtained data and analyze the constructed bathymetric maps.

Seismoacoustic studies of the upper part of the sedimentary cover were performed with a nonparametric EdgeTech 3300 profiler with a 2-12 kHz frequency-modulated signal. The resolution of the profiler is from 0.5 m to 1 m, and the depth of acoustic signal penetration (depending on sediment composition) is from 10 to 100 m. The results of profiling were processed using the RadexPro 3.96 software. The result of this work was a series of acoustic profiles, reflecting the peculiarities of the stratification of the sedimentary cover in the study area.

Basing on obtained DEM, seismoacoustic sections of the upper part of the sediment cover and published data of the geological structure of the study area, a comprehensive interpretation of the bottom topography of the area was performed.

RESULTS

According to materials of multibeam bathymetric survey more than 120 pingo-like uplifts were revealed within the polygon. Among them 20 largest uplifts are found in the lower part of the polygon (70-82 m depth) (Fig. 2).

They are represented by isometric positive landforms, sharply pronounced on the relatively flat shelf surface on the bathymetric map. Flat-top uplifts are also widely spread in addition to cone-shaped elevations. The slopes of uplifts tend to be between 13-15°. At the same time, some shapes are asymmetrical, which means that the gentle slopes are about 12-13°, while steep slopes are between 18-19°. The height of these forms is about 20-25 m with a base width of about 180-200 m in the central and northeastern parts of the polygon, where the area of local lowering of the shelf relief is located (Fig. 2, AB profile). In the eastern and southwestern parts, the uplifts tend to be smaller. Their height in this area is about 10-12 m, and the diameter is between100-120 m. Even smaller forms are observed in the shallow parts. Their height I s up to 5-7 m, while their diameter is up to 100 m. Twin triple forms separated by saddles are also found along with single uplifts (Fig. 2, profile CD). Short chains of small positive forms are also observed in some parts of the eastern part of the polygon.

The three horizons are clearly distinguished in the section (Fig. 3A). The first one is represented by acoustically transparent sediments from 1-2 to 5 m thick, located in topographic depressions. This horizon probably consists of modern sediments. The second horizon is observed only in the eastern part of the section; in the western part, it is wedged out. The horizon consists of rhythmically layered sediments up to 20 m thick. These sediments are layered clays of Karginsky age, which are mostly confined to paleorelief depressions. The third horizon is represented by acoustically opaque sediments, which probably consist of overcompacted marine clays of the Kazantsevo interglacial period. It is the sediments that form pingo-like highs. The thickness of the horizon has not been determined.

The seismoacoustic profile (Fig. 3 B) clearly shows gas torches, indicating active degassing within the study area. The height of the torches reaches 45-50 m. The process of degassing occurs irregularly. The gas torches are confined to the forms which were described earlier, with the most powerful gas outcrops observed in the area of spreading of relatively small uplifts.

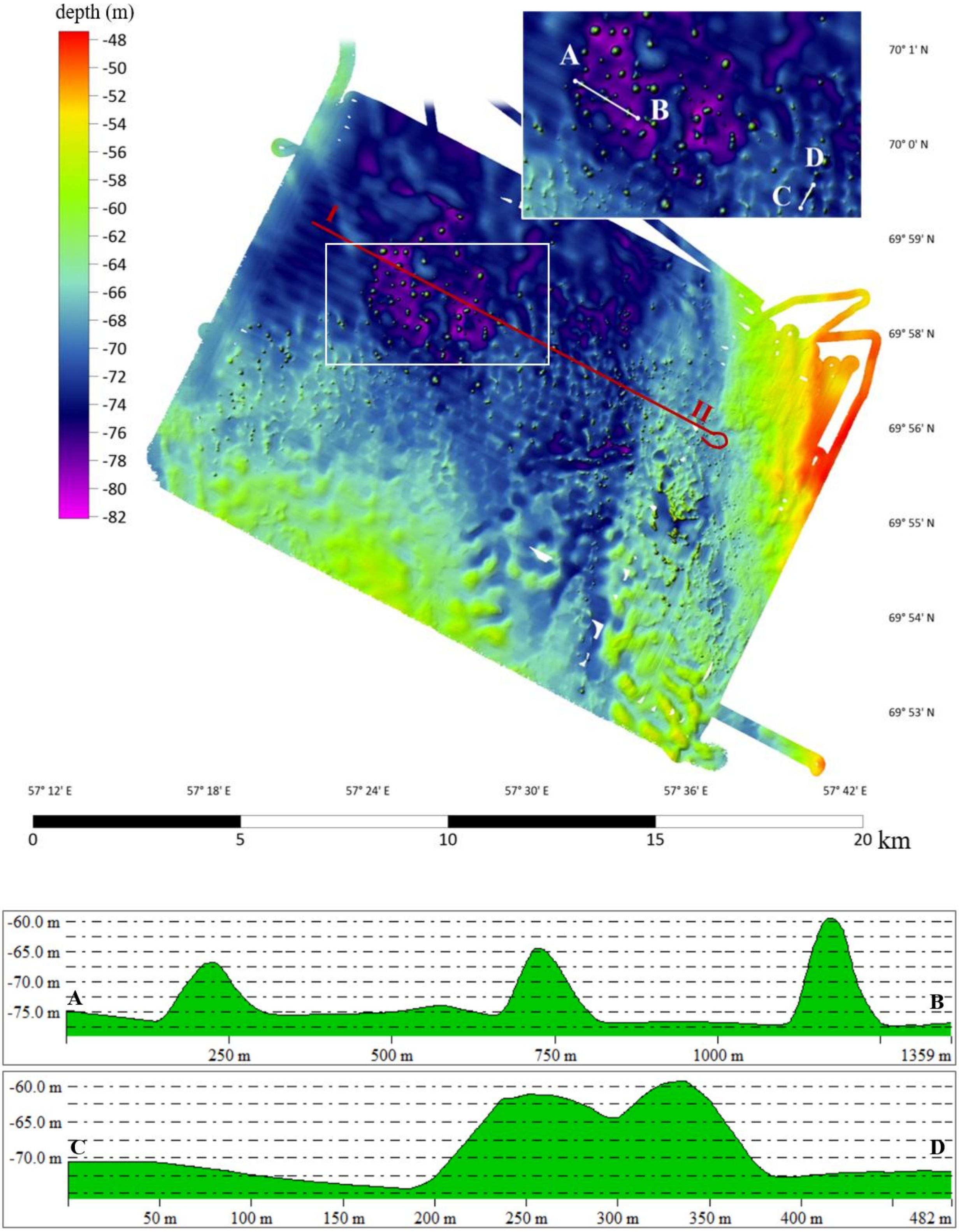

Fig. 2 Bathymetric map of the studying area with pingo-like highs, made by RESON Seabat 8111 shallow water echo sounder data (100 kHz) and profiles along AB and CD lines in the lower part of the studying area

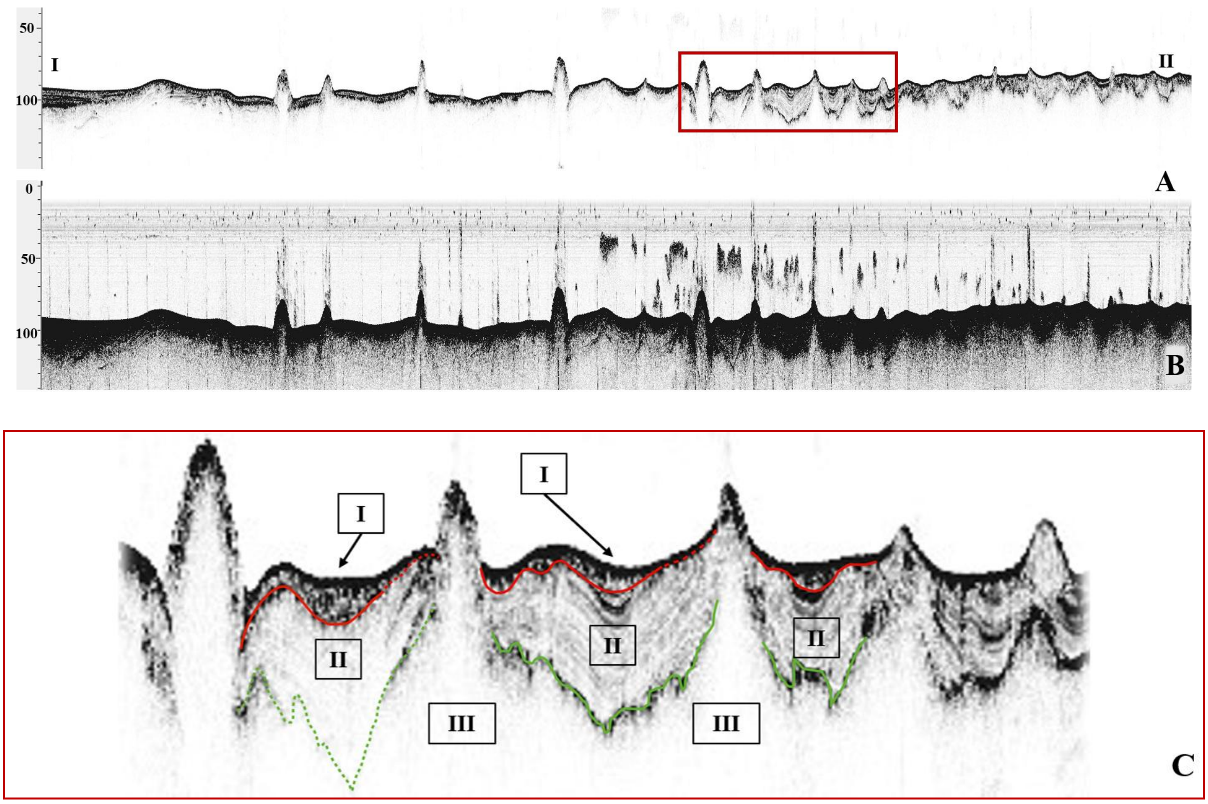

Fig.3 Profile ANS38-P3-19.001 The top of sedimentary cover structure according to profilograph data (2-12 kHz) (profile position is shown by the red line, see Fig.2). Vertical scale shows the number of milliseconds from the surface; A – The structure of the sedimentary cover in the area of development of pingo-like highs. B – Gas emissions into the water column (visualization of section A is made using software amplification). C – section with interpretation. Legend: I - modern marine sediments, II - Karginsky alluvial-marine clays, III - Kazantsevo marine reconsolidated clays and loams

DISCUSSION

The frozen soils, which are fluidproof, have a fairly good connexity and plasticity. Sands which are represented in the form of lenses, on the contrary, are reservoirs and, therefore, are more gas-saturated. Such accumulations with high reservoir pressure are displayed as "bright spot" anomalies on seismoacoustic profiles. The accumulation of gas under the base of the fluidproof structures (mainly represented by the Kazantsevo marine clays) and the increase of pore pressure in the upper part of the sedimentary cover gradually leads to its deformation and formation of peculiar uplifts, called pingo-like forms.

The largest pingo-like forms are observed in the local depressions of the shelf within the studying area. This pattern can be explained in terms of the physical and mechanical properties of frozen ground. Probably, during the formation of the permafrost, this depressed area was overwatered. This resulted in high ice content of the ground compared to the surrounding area. Ice-rich soils have greater plasticity and a greater ability to bend. In addition, frozen soils have higher temperatures in over-wetted areas, which is comes from the high value of phase transition heat of water. The plasticity of frozen soils also depends on their temperature: at higher temperatures, soils have better plasticity. This factor may serve as another reason for the formation of the largest pingo-like highs uplifts the local depression.

As a result of permafrost degradation, decomposition of organic matter intensified, which lead to the release of free gas and its moving up the section in thawed areas.

There are alternative hypotheses of the formation of the pingo-like uplifts. Firstly, these may be relict forms of cryogenic origin formed during the pre-Holocene regression (Shearer et al., 1971). This formation mechanism is confirmed by the fact that the central part of many forms contains an "ice core" (frozen ice-reach rocks), and their morphometry resembles frost bumps similar to the modern ones spread on the land. Secondly, pingo-like uplifts may be newly formed structures formed in subaquatic conditions during the freezing of low-mineralized sediments as a result of the active impact of cold (with the temperature below zero) sea near-bottom waters (Bondarev et al., 2002).

The seismoacoustic section distinguishes different types of pingo-like structures. The deposits of the third horizon mostly may break through the overlying sediments and form pingo-like uplifts on the shelf surface. In this case, sharp boundaries between horizons within the Quaternary sediments are formed. If there is no breakthrough the surface sediments, the uplifts are revealed not only at the surface, but also in the roof of the deposits of horizon III (Fig. 3A). It is worth noting that gas torches are confined to the areas where the underlying sediments come to the surface. Probably, the breakthrough of surface sediments by the Horizon III sediments is associated with high gas pressure, resulting in the rise of the roof of this horizon.

As result of degassing, morphosculptures including not only pockmarks (gas funnels), but also pingo-like forms with constantly functioning gas flares, are formed, which is typical for our case. The formation and growth of pingo-like uplifts is a modern geomorphological process, represented on the flat and gentle surfaces of the Pechora Sea shelf.

However, a more complete understanding of the mechanism of formation of pingo-like forms requires further more detailed studies. In order to study the dynamics of this process, it is necessary to carry out repeated surveys, which will allow us to estimate the evolution of the pingoforms. Moreover, drilling more wells with soil sampling within the study area may help to define the genesis of these forms.

CONCLUSIONS

1. About 120 large pingo-like forms, complicating the relatively flat subhorizontal piece of the Pechora Sea shelf are distinguished within the studying area. The largest of the pingo-like uplifts are confined to the local depressions within the study area, which can be explained by the bigger ice content and, consequently, the plasticity of the frozen ground in these areas.

2. The materials of acoustic profiling have shown that gas emissions into the water in the form of torches are confined to the pingo-like forms, and there are gas anomalies in the sedimentary pockets between them. The features of the structure of the upper part of the section and the water column revealed by the acoustic data confirm the direct participation of degassing processes in the process of forming of the uplifts.

3. Ice-reach permafrost, represented by overcompacted Kazantsevo marine clays (according to Rokos, 2008), act as "tires", under the base of which free gas gradually accumulates (Rokos, 2008). Pingo-like structures formed by strained, as a result of gas uplift, permafrost rocks and associated gas outbursts may be markers of anomalously high reservoir pressure zones.

4. Accumulations of gas in near-surface horizons are found at the studying polygon (in the area of distribution of pingo-like structures), which is an unfavorable factor for construction and operation of engineering facilities (drilling rigs, pipelines, etc.), as well as complicates geological exploration works. Degassing detected in a significant area of the studying polygon is a potentially dangerous geological process, as a result of which rapid changes of relief (growth

of pingo-like structures, ground deformations) and density changes of the water layer are possible.

REFERENCES

Bondarev V.N., Rokos S.I., Kostin D.A., Dlugach A.G., Polyakova N.A., 2002. Subpermafrost gas accumulations in the upper part of the sedimentary cover of the Pechora Sea. *Geology and Geophysics,* 43 (7), pp. 587-598. (In Russian)

Druschic V.A., Sadchikova T.A., Skolotneva T.S., 2011. Gas hydrates on land and shelf in the Arctic and changes in the natural environment in the quarter. *Quaternary Study Commission Bulletin,* 71, pp. 124-134 (In Russian)

Patton H., Hubbard A., Andreassen K., Auriac A., Whitehouse P., Stroeven A., Shackleton C., Winsborrow M., Heyman J., Hall A., 2017. Deglaciation of the Eurasian ice sheet complex. *Quaternary Science Reviews,* 169, pp. 148-172

Rokos S.I., 2008. Engineering and geological features of near-surface zones of anomalously high pressure on the shelf of the Pechora and the southern part of the Kara Seas. *Engineering Geology*, 4, pp. 22-28 (In Russian)

Rokos S.I., 2009. Gas-saturated deposits of the upper part of the section of the Barents-Kara shelf. Ph.D. Murmansk. (In Russian)

Rokos S.I., Dlugach A.G., Loktev A.S., Kostin D.A., Kulikov S.N., 2009. Permafrost of the Pechora and Kara Seas shelf: genesis, composition, distribution and occurrence conditions. *Engineering surveys*, 10, pp. 38-41. (In Russian)

Serebryanny L., Andreev A., Malyasova E., Tarasov P., Romanenko F., 1998. Lateglacial and early-Holocene environments of Novaya Zemlya and the Kara Sea Region of the Russian Arctic. *The Holocene*, 3, pp. 323-330

Shearer, J. M., Macnab R. F., Pelletier B. R., Smith T. B., 1971. Submarine pingos in the Beaufort Sea. *Science*, 174(4011), pp. 816-818

Svendsen J., Alexanderson H., Astakhov V., Demidov I., Dowdeswell J., Funder S., Gataullin V., Henriksen M., Hjort C., Houmark-Nielsen M., Hubberten H., Ingolfsson O., Jakobsson M., Kjær K., Larsen E., Lokrantz H., Lunkka J., Lysa A., Mangerud J., Matiouchkov A., Murray A., Moller P., Niessen F., Nikolskaya O., Polyak L., Matti Saarnisto M., Siegert C., Siegert M., Spielhagen R., Stein R., 2004. Late Quaternary ice sheet history of northern Eurasia. *Quaternary Science Reviews*, 23. pp. 1229-1271

Vorren T., Landvik J., Andreassen K., Laberg J., 2011. Glacial history of the Barents sea region. *Quarternary glaciations – Extent and chronology*. *Volume 15* pp. 361-373