In expression (1) F consists of the weight of the frozen soil G and the strength of its deformation resistance U: $F = G + U$.

The injection slide is formed by a shift up relative to the rest of the frozen roof of the closed talik, a round block of frozen soil. Inside the block there is an inequality (1), and on the block boundary $Q = F$. Substituting in this equation the parameters that determine the values of Q and F, we can derive a formula for calculating the diameter of the frozen block D:

D, m = $4\tau/(q/\xi - 0{,}01\rho)$ at $q > 0{,}01\xi\rho$ (2).

q – specific overpressure in talik, kPa; τ – specific shear force at the contact of the block with the frozen roof talik, kPa; ξ – the thickness of the roof talik at the shear, m; ρ – the density of the frozen soil composing the block, kg/m^3. The value D is the diameter of the vertex surface of the hillock.

The growth of the hillock is carried out through a series of successive cycles. During each cycle there is a shift and the rise of the frozen block in the form of a disk, accompanied by the introduction into its sole under pressure of thawed soil (water), followed by its freezing and formation of the frozen core of the hillock. Each subsequent cycle occurs with an extension of the area of heaving (and, accordingly, the diameter of the hillock D) in comparison with the previous cycle. So the slope of the hill is formed, the steepness of which α can be calculated by the formula:

$\alpha \approx \mathrm{arctg}[(q/\tau - \mathrm{tg}\varphi)(100q/\xi\rho - 1)]$ $0{,}01\xi\rho \leqslant q \geqslant \tau\mathrm{tg}\varphi$ (3).

φ is the slope of the soles of the frozen roof of talik to the side of the hill.

Gas geochemistry of the ground ice samples from the exposure in Central Yamal

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Tabular ground ice widely distributed in Yamal Peninsula is of special interest due to its geochemical properties evidencing its origin. Activity of cryogenic processes since 2012 resulted in well-exposed geological sections enclosing ground ice of various types. One of such exposures in the area of Vaskiny Dachi research station, Central Yamal peninsula, is of special interest because of complicated character of the section with tabular ground ice body in the bottom, ice wedges above and peat plateau ontop. Tabular ground ice in the study section is represented by various ice facies including vitreous ice (without inclusions), bubbly ice (with easily observed gas bubbles) and stratified ice (thin vitreous ice layers interbedding with layers of icy deposits).

We analyzed a range of geochemical features, including permanent and hydrocarbon gases composition, ion composition of water, dissolved organic and inorganic carbon (DOC, DIC), in 16 monoliths of ground ice collected from the exposure during the 2017 field campaign. The samples were stored frozen until laboratory analysis and showed a vast variability in content of free gas and lithogenic fraction. We present here the results of gas geochemistry analyses.

According to our measurements, permanent gases in the free gas/bubbled gas fraction extracted from the samples are represented predominantly by nitrogen (varying from 86,5 to 98,8 %) and oxygen (5,6% - 17,9%). Methane concentrations do not correlate with the values of a gas bubbles volume, which suggests that methane is stored as dissolved in water.

Methane showed a wide range of concentrations from 6 to 1928 μM in 16 analyzed samples of both tabular ground ice and ice-wedge ice. Maximum methane concentration appeared in four samples from the lowermost part of the exposure represented by tabular ground ice (from 215 to 1928 μM). Stable isotope composition of methane in these samples demonstrates acetoclastic methanogenesis as predominant pathway (Whiticar, 1999).

Based on molecular composition of hydrocarbon gases C1-C5 we split our samples into groups, probably reflecting different stages of successive methane depletion (fractionation) while samples with anomalous methane indicate the source gas composition. The four samples enriched with methane make up two pairs 1708 (Stratified, high lithogenic fraction), 1733 (Bubbly), and 1706 (Bubbly with few lithogenic inclusions), 1730 (Bubbly), with more than 1000 and more than 200 μM methane concentration, respectively, each pair consisting of the samples from different parts of the section. One can see that neither methane concentration nor its isotopic signal (d13C values between −67 ‰ and -88‰) depend on the ice facies.

As result of this work, we may speculate about the common source of the high methane in the analyzed samples, which is predominantly in dissolved form. Methane enrichment of the ground ice may be due to either discharge of methane rich ground water, or is in-situ methanogenesis by archaea community operating at subzero temperature. We suppose that the potential for in-situ methanogenesis is supported by low free gas content in the frozen ground (always holding significant amount of oxygen as follows from our data), high content of the solid fraction responsible for anaerobic micro-niche formation as well as making up the water binding surface. However, we observe high methane concentration in different ice facies including those that contain huge amount of bubbled gas and low amount of lithogenic fraction. So based on our data we assume that contribution from in situ generated methane is minor.

The cryogenic origin of the Yamal phenomenon

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The subject of the report is the results of a study of a unique natural crater-shaped object in the central part of the Yamal Peninsula, carried out in 2015 by the research team of Lomonosov Moscow State University, Geological Faculty supported by Innopraktika and PAO NOVATEK.

Complex studies included field and laboratory investigations: detailed description the territory; drilling 20 m wells for the cryogenic structure study and sampling of soils and ice for determination of physic and mechanical properties; thermometric measurements; topographic works, a complex of geochemical and geophysical studies. Radiological measurements were conducted. Sampling of surface water, soil, frozen and thawed rock, free and adsorbed gases were carried out. Methane and carbon dioxide contents were determined in the wellbores using field gas analyzers and trapping of gases enclosed in frozen soil and ice were performed. Trace elements of soils and ice were determined by ICP-MS. Mathematical modeling of heat exchange processes in the rocks and assessment of the pressure required for a pingo destruction were performed.

On the basis of the materials obtained, the authors developed their own concept of a cryogenic origin of the Yamal Crater, explaining its formation by the process of cryovolcanic event on the Earth. Cryovolcanism is understood as the explosion-like effusive destruction of pingo with the eruption of a substance under the action of high cryogenic pressures as a result of freezing of closed water and gas saturated systems (a closed talik).

It was established that on the site of the crater the injection pingo took place. It was formed as a result of the freezing of the talik after the descent of the ancient lake, which was accompanied by the release of water and dissolved gases from the freezing front into the thawed zone and a significant increase in internal pressure. This pressure at some point led to the destruction of the layer of frozen soils, overlapping the residual part of the talik above. Evaluation of the pressure for the destruction of pingo with a 7–9 m thickness with physical properties of frozen soils leads to 1.0 MPa value. The process of destruction of the pingo was accompanied not only by the scattering of the frozen fragments of