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Explosive Processes in Permafrost as a Result of the Development of Local Gas-Saturated Fluid-Dynamic Geosystems

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Abstract: The relevance of studying explosive processes in permafrost lies in the prospect of gas production from small gas-saturated zones in the subsurface; the influx of significant amounts of greenhouse gases from frozen soils creates a threat to infrastructure. The purpose of this article is to reveal the general patterns of frozen soils' transformation in local zones of natural explosions. The greatest volume of information about the processes preceding the formation of gas-emission craters can be obtained by studying the deformations of the cryogenic structure of soil. The typification of the elements of the cryogenic structures of frozen soils that form the walls of various gas-emission craters was carried out. Structural and morphological analyses were used as a methodological basis for studying gas-emission craters. This method involves a set of operations that establishes links between the cryogenic structure of the crater walls and the morphologies of their surfaces. In this study, it is concluded that gas-emission craters are the result of the self-development of local gas-dynamic geosystems that are in a non-equilibrium thermodynamic state with respect to the enclosing permafrost.

Keywords: permafrost; gas hydrates; transit zone; plastic deformations; physical explosion; fluids

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1. Introduction

Gas-emission craters (GEC) are a recent phenomenon involving poorly understood cryolithic structures atop permafrost landforms. First discovered in the Yamal Peninsula in 2014, the crater rims show explosive origins and are related to the deposition and/or accumulation of highly combustible methane (CH_4). Since their discovery, nearly twenty GEC have been detected and monitored, sharing similar cylindrical dimensions of roughly 5–20 m in diameter and reaching depths of 50 m. These GEC collapse and fill with water relatively quickly (<1–2 years), thereby mimicking Thermokarst lakes.

Despite the great interest in this phenomenon on the part of the media and the scientific community, particularly when the GEC are related to Arctic warming, the geological uncertainty of GEC and their complex dynamical parameters is still poorly understood. This is mostly due to the incompleteness of the in situ data, the remote location of the study areas (e.g., Yamal, Siberia), and the absence of a theory for the natural explosive processes in the cryolithozone.

The issues of gas-emission crater formation are highly relevant at the present time. This is primarily due to the problem of greenhouse gases entering the atmosphere. Until quite recently, it was believed that the cryolithozone was a kind of gas-tight cap that kept hydrocarbon in the lithosphere, but hotspots of methane (CH4) are observed to move through permafrost where deeper conduits can migrate to the surface [1,2]. The economic development of the Arctic—continental and off-shelf—with the associated technogenic impacts on the permafrost zone (permafrost drilling and/or the thermal impact on permafrost) greatly increase the risks of the negative effects on infrastructure associated with GEC. Therefore, understanding the processes occurring in frozen soils, similar to those that occur during the preparation of gas-emission craters, will allow for the development of measures to eliminate these hazards. The presence of gas-saturated zones occurring in frozen soils at shallow depths makes their economic development promising. Furthermore, data on the behavior of gas-saturated frozen soils under pressure are of great interest, as they potentially impede economic development or present hazards. The materials considered herein will allow us to increase our understanding in order to develop a solution to this problem.

We began our investigations concerning GEC by analyzing the cryogenic structure of soils in the walls of the craters. We proceeded on the initial assumption that the explosions that forms the GEC are preceded by the emergence and subsequent development of a local fluid dynamic. The cryogenic geosystem with its structure, morphology, boundaries, and life cycle are shaped by the alterations in these pore-fluid-phase changes. Hence, the modeling of GEC characterizes the numerous plastic and bursting deformations associated with phase changes in pressure and temperature, which are bounded by the complexity of cryogenic development and gas accumulation. We first proposed this approach in 2017, when studying the structure of the walls of the first Yamal crater [3]. According to several specialists dealing with the problem of GEC origins, such as V.I. Bogoyavlensky [4–6], M.O. Leibman and A.I. Kizyakov [7], M.I. Epov et al. [8], S.N. Buldovich and V.Z. Khilimonyuk [9], A.N. Khimenkov and Yu. V. Stanilovskaya [10], E.M. Chuvilin [11], and others, importantly, these formations were formed due to the release of underground gases.

From these theories, it is possible to identify multiple uncontested explanations of the origins of GEC. First, a gas-saturated zone develops a buildup of increased gas pressure in the near-surface permafrost (e.g., at <50 m). Second, the buildup reaches a phase transition and leads to an abrupt explosion, which is preceded by a long preparatory stage. We proceeded from the idea that during this preparatory stage, a local feedback loop of the gas dynamic is formed atop the gas-saturated zone under the influence of increased pressure. The stages of development of the latter are determined by the change in complexes of intra-soil processes. Furthermore, the corresponding cryogenic formations reflect the features of the dynamic metamorphism of the primary structure of frozen soils and underground ice. Even though all the craters are located in the permafrost, the geocryological aspects of their structures are practically ignored. This article is devoted to the study of the transformation of primary cryogenic structures and the formation of cryogenic neoplasms occurring at the preparatory stage of explosive processes.

2. Study Area

To date, around 20 gas-emission craters (GEC) have been found in the north of the Western Siberian permafrost [5]. Figure 1 shows the locations of some of the most famous GEC. They have been repeatedly characterized in works devoted to their study; therefore, only their main indicators are given. The names and designations of the craters differ from author to author. The description of GEC given in the presented work was compiled using materials from various researchers [6,12–15].

GEC-1, so called the Yamal crater, was discovered in 2014 situated 30 km south of the Bovanenkovo oil and gas condensate field in the central region of the Yamal Peninsula [16]. So far, the most data on GEC have generally been obtained from the study of GEC-1. Its depth and width are estimated at 50 m and 30 m [17]. The scattered soil surrounding the crater suggests an explosion that accompanied its formation. No traces of human activity were found near the crater. This crater is a regular elliptical cylinder, slightly widened at the surface [18]. In the cylindrical region, a vertically oriented interbedding of ice and mineral inclusions of silty composition was found. In the lower part of the northeastern wall of the crater, there is a grotto that extends 5–8 m deep into the wall. This crater is in a region of an anomalously high heat flow, perhaps leading to an increased intensity of subvertical gas migration [16,17].

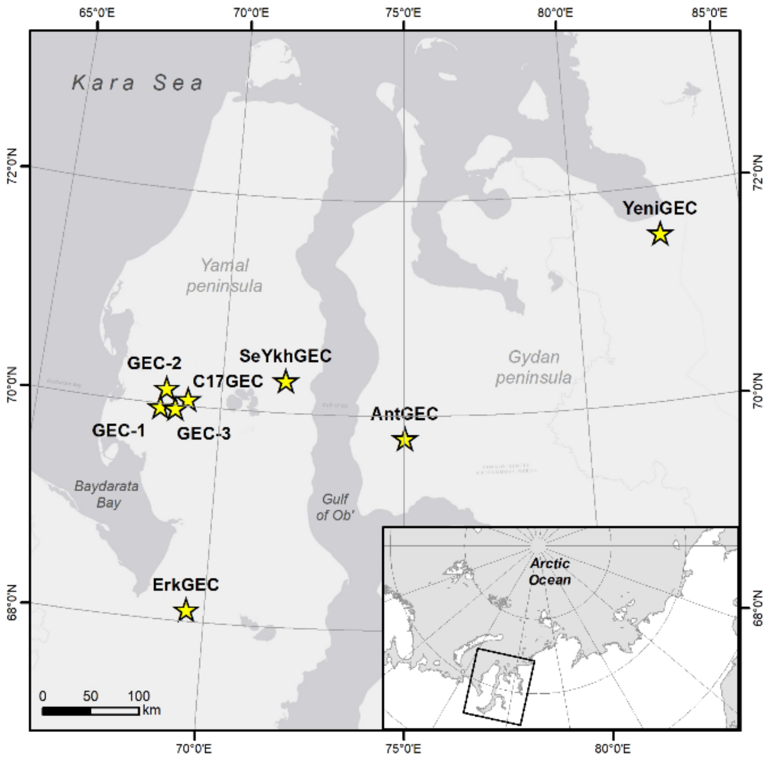

Figure 1. Location of gas-emission craters (marked by stars) in the north of the Western Siberia.

GEC-2 is located 20 km north of GEC-1 and 10 km south of the Bovanenkovo field. V.I. Bogoyavlensky showed that in the place of the lake in 2009–2010 there was a large heaving mound with a diameter of ~60 m. In 2013, in its place, there was already a reservoir with a size of 100 × 60 m and a depth of up to 6 m, around which there were more than 35 small and rounded lakes with diameters of up to 8 m and with shafts of ejected soil [4].

GEC-3 was discovered 1.6 km from the Obskaya–Karskaya railway in 2013. Judging by the ridge of the ejected soil and several shallow depressions on the exposed surface from fallen pieces of ejected ice, it can be assumed that gas was released in the summer of 2012 [14].

C-17 GEC, the latest detected crater, was discovered in the Bovanenkovo gas field in 2020. Its structure is similar to the Yamal crater. Here, there is an expanding cavity, where the entrance atop has an elliptical shape of 15 × 18 m, and the bottom also has an elliptical shape of roughly 14 × 60 m. The diameter of the upper part of the crater is 25 m. The depth reaches several tens of meters [6].

SeYkhGEC was formed 34 km northwest of the Seyakha village in the Mordyakha river in 2017. Gas inflow continued after the explosion, manifesting itself in the form of boiling river water on the surface. According to current research, the emitted gas is methane [19]. The explosion was accompanied by the ignition of the escaped gas.

ErkGEC was discovered in the floodplain of the Erkutayakha river in 2017. The diameter of this gas emission crater at the time of the first survey was 8 m, and its depth was roughly 20 m [20].

Osokin's crater was pictured from a helicopter on the Yamal peninsula in 2013. Its exact location has not been established. Around the crater, there are at least two series of concentric cracks that formed during subsidence of the soil after the explosion.

AntGEC is in the southern part of the Gydan Peninsula within the Soletsko–Khanaveyskoye gas condensate field. This crater is a circular depression that is 30 m in diameter and was discovered in 2013. Its formation was preceded by the existence of a mound ~2 m high with a base diameter of about 20 m [7].

YeniGEC is located on the southwestern coast of the Yenisei Gulf near the Deryabinsk gas condensate field in the eastern part of the Gydan Peninsula. It was discovered in 2013.

3. Methods

Studies of GEC share common structural features. It is widely agreed that their formation is a result of the dynamic pressure phase of intra-permafrost gas and via a single substrate represented by ice-saturated soil. The strength and deformation properties of this ice-saturated matrix are determined by the cryolithic depositional history forming the ice or permafrost. These factors, common to all craters, make it possible to apply a specific research method, which we define as a structural–morphological analysis of gas-emission craters. This analysis is a set of operations that establish links between the cryogenic structure of crater walls with the morphology of their surface. Cryogenic structures and morphological elements of the surface have clear boundaries and structures. Therefore, they can be identified and studied by appropriate methods.

To carry out this analysis, it is necessary to conduct a complex of studies, including:

(1) The study of the surface morphology of gas-emission craters;
(2) The allocation of structural elements of the surface of gas-emission craters;
(3) The selection of cryogenic elements corresponding to various elements of the surface of the craters;
(4) Analysis of the cryogenic structure and signs of dynamometamorphic transformations of individual cryogenic elements;
(5) Analysis of the relationship between the structure of individual cryogenic elements with the morphology of the crater surface;
(6) Identification of the stages of development of the gas-dynamic geosystem from a zone with increased pressure to the stage of an explosion, which forms a gas-emission crater.

With the help of structural and morphological analysis, it becomes possible to: (1) evaluate the structure of each element and the paragenetic connections between them; (2) to clarify the paragenetic relationships between the structural elements and morphological elements of the crater's surface and, as a consequence, identify the sequence of stages in the formation of the geosystem; (3) show that the structural elements of any level correspond to the general direction of the geosystem's development; and (4) identify and simulate the history of the development of gas-dynamic geosystems that are realized in natural explosive processes in frozen soils.

Currently, one of the problems that hinders the identification of the mechanisms of formation of gas craters is the genetic approach. The authors of various hypotheses directly link the formation of craters with the genesis of gas. At the same time, it is not considered that the accumulation of gas in local zones and subsequent development of gas-dynamic geosystems are different processes. The accumulation of gas with increased pressure forms a zone of thermodynamic instability in the frozen soil. Next, a gas-dynamic geosystem is formed, developing according to its own laws. Analyzing materials corresponding to the different stages of development of these geosystems makes it possible to reveal the history of their development. The main objective of the methodology used in this article is to study the processes that precipitate explosive processes. This makes it possible to objectively consider only geological and morphological data, and to consistently, and from a unified standpoint, consider the materials researched by different authors.

It ought be considered that the study of gas-emission craters is possible only after the event (explosion) has already occurred. The study of the morphological parameters of craters (e.g., their shape, length, width, depth, angles of inclination of their surfaces, etc.) fixes the state of the crater after the explosion, i.e., the final result. This makes it difficult or potentially even currently impossible to reveal the initial histories of crater development.

Hence, the characteristic data of the frozen strata under the influence of gaseous fluids are partly destroyed, creating difficulties for hypothesizing initial conditions. This does not allow one to assess the dynamometamorphism of frozen soils under the initial influence of subsoil gas under pressure. The study of the chemical composition of the gas makes it possible to reveal its genesis but does not enable the identification of the processes that took place in the frozen massif before the explosion. Thus, it is difficult to examine the numerous currently existing hypotheses of the formation of gas-saturated zones in frozen soils leading to GEC. There are only assumptions on prior conditions without sufficient factual material to substantiate one geosystem state over another. By studying the post-cryogenic structures of the craters, it is now possible to reveal the staging of the dynamomeramorphism of primary cryogenic structures and restore the sequence of events that took place in the frozen soil during the period preceding the explosion. This is a common practice used in geology, volcanology, glaciology, and other earth sciences where, in order to understand the processes that form geological bodies, researchers study the structure and morphology of their constituent post-elements. In our case, this is the study of the cryogenic structure of the walls of gas-emission craters. To date, this is the only reliable way to objectively study the preparation of natural explosive processes in the permafrost zone. Knowing the tensile strength properties of frozen soils, the magnitude of deformations on the crater surface, and the morphology and the number of gas inclusions then facilitates investigations for determining the pressures that occurred, shear and plastic deformations, and the initial stages before the eruption. This proposed method for studying GEC investigates the stages before eruption by the analysis of post-structural elements. Our results detail how to recover and reveal the stages of preparation leading to natural explosions in frozen soils and the formation of GEC.

4. Results

4.1. Morphology of Cryogenic Formations in Gas Emission Craters

GEC formation includes several stages. Initially, a local gas-saturated area is formed in frozen strata. The most favorable conditions for this are areas of hydrate-containing frozen soils, cryopegs, and intrapermafrost taliks formed when subaqueous sediments freeze from above. The sources of gas can be decomposing gas hydrates (released upon the thawing of soils or the relief of pressure), deeper thermogenic gases (i.e., geological), and free gas localized due to cryogenic concentration during the freezing of taliks or during the epigenetic freezing of subaqueous sediments. In this latter case, gas pressure can reach significant values (e.g., 2.6 MPa) during the dissociation of methane gas hydrates in a closed cavity [21]. The frozen soils surrounding the high-pressure area begin to deform and gas begins to filter upward into the area of lower pressures. Further, the process gradually involves the overlying frozen soils and, thus, the final stage of GEC formation is realized. The surface layer is ejected during the explosion and partially crumbles into the formed post-thermokarst depression. Thus, the process of inducing the explosion occurs from the bottom up. The morphology of the cryogenic formations accompanying the formation of GEC will be considered in the same sequence. The analysis of the patterns of the structure of craters was based on the materials obtained during the study of the Yamal crater, with the addition of data on other objects. The work used a wealth of information published in scientific articles, conference materials, and that was available on the Internet.

4.2. Paragenesis of Cryogenic Formations at Different Stages of the Preparation of Gas Emissions

Cryogenic formations occurred at different stages of the initial conditions leading to explosive processes in all the studied GECs. For individual craters, typical examples are considered and objects with a similar structure are indicated. As a result of external influences (e.g., an increase in temperature or pressure), changing thermodynamic conditions evolve. Consequentially, the sub-section of the permafrost is removed from a stationary state and transforms into a gas-dynamic geosystem. This leads to a multistage structural transformation of the primary cryogenic structure of the permafrost. A series of plastic and bursting deformations is formed, along which intense heat and mass transfer take place, thereby redistributing the substance in liquid, solid, and gaseous states. In frozen soils, ice is the most deformable component. Therefore, the greatest amount of information about the processes preceding the formation of GEC can be obtained by studying the morphology of the cryogenic formations observed in the walls of formed craters, as well as in non-melted fragments of the frozen soils ejected onto the surface. Studies of crater structures show that they have some common morphological features. The lower, widened part is called the zone of caverns and grottoes; the middle part is narrower and sometimes represents a cylinder with vertical walls; and the upper, widened part is often in the form of an overturned truncated cone. In some craters, there is a zone of layered ice adjacent to the walls.

4.3. Zone of Caverns and Grottoes

The lower part of the Yamal crater (GEC-1, Figure 1) contains a series of grottoes and caverns (Figure 2) [16]. At the time of their discovery in July 2014, they were clusters of rounded depressions in the lower part of the crater wall ranging in size from 20–30 cm to 2–3 m, separated by ice–soil partitions (Figure 2). Already by the end of summer 2014, owing to the thawing of partitions, the shallow depressions merged and formed extensive single cavities (grottoes). Gas-saturated zones with an increased gas content are formed in frozen soil masses as a result of various mechanisms. They are not cavities, but zones of gas-saturated soils. Only after the explosion and ejection of frozen soils will cavities form in the lower part of craters (from a series of small caverns to significant grottoes). The model for the formation of a cavity in frozen soil due to the melting of underground ice was proposed by V.I. Bogoyavlensky [3].

Figure 2. Zone of caverns and grottoes in the lower part of the Yamal crater. Designations: the red line marks the zone of dislocated, layered, gas-saturated ice. July 2014. Reproduced with permission from V.V. Olenchenko.

A characteristic feature of the zone of caverns and grottoes is a strong dislocation of deposits. In the lower part of this zone of the AntGEC, numerous deformations of sheet ice are traced throughout the visible layer with observed plastic deformations of the primary bedding. The intrusion of individual blocks of ice into the overlying massif is noted. The block itself has acquired a wedge shape and the ice within it is strongly deformed with an acquired scaly structure. In front of the block, the ice mass layer r was deformed into a fold, with the overlying layers bent. In some places, the ice mass was broken into separate blocks, broken by cracks, and crumpled into folds, which sometimes acquired a spiral shape. The deformations in the lower part of the zone of caverns and grottoes of the AntGEC indicate powerful local pressures directed both from the bottom-up and laterally. The ice mass has been torn apart, and plastic deformations, ice flow, the twisting of individual ice blocks, and their penetration into the main ice mass can be observed.

The array of primary mesh cryogenic structures is split into separate blocks. Numerous plastic deformations, dome-shaped folds, cracks, and ruptures are observed in the layered gas-saturated ice–ground layer. The deformations of the overlying sediments also testify to the high pressures that occurred in the zones with caverns and grottoes. The above-mentioned deformations of the primary cryogenic structures are depicted in Figures 3 and 4. Here, the primary bedding forms a dome-shaped, enveloping grotto structure in which numerous plastic and discontinuous deformations can be observed (Figures 3 and 4). The most probable cause of the local deformation of the bedding over the grottoes is the impact of high pressure. In some cases, the primary cryogenic structure was destroyed under this influence. The decomposition of gas hydrates can be one of the reasons for a significant increase in pressure in frozen soil. For example, in the Yamal crater, the zone of caverns and grottoes is probably confined to the gas hydrate layer [22,23].

Figure 3. Large grottoes formed due to the amalgamation of a series of small depressions. November 2014. Photo credit: V.A. Pushkarev.

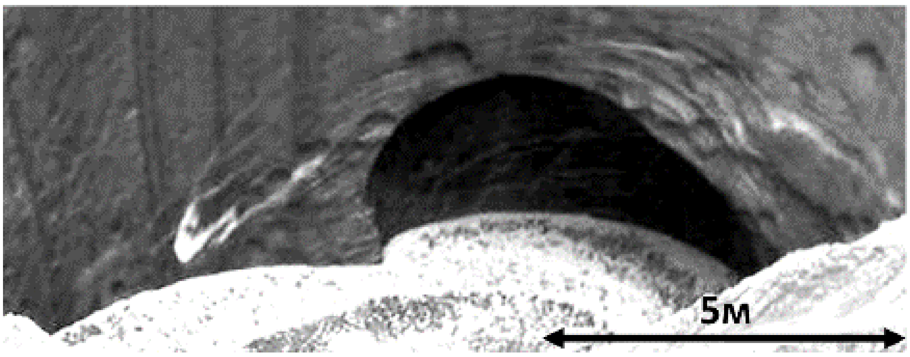

Figure 4. Deformation of primary bedding over the zone of caverns and grottoes. Plastic deformation of the ice layers shows that the pressure was applied in the frozen, and not in thawed, soils. Photo credit: V.V. Olenchenko.

4.4. Plastic and Bursting Deformations of Gas-Saturated Frozen Soils Constituting the Walls of the Craters above the Zone of Caverns and Grottoes

The structure of the walls of the Yamal crater above the zone of caverns and grottoes indicates that the frozen strata underwent inhomogeneous and multidirectional local deformations. Along the entire inner vertical surface of the walls of the Yamal crater, there are numerous subvertical and sub-horizontal wavy, branching cracks filled with gas-saturated ice, as well as numerous meandering ice–ground layers of variable thickness crumpled into folds, with traces of ice flow and breaks pinching out (Figures 2–5). Thus, the entire soil layer overlying this zone and forming the vertical walls of the Yamal crater turned out to be permeated with various kinds of local deformations (the bending of the primary bedding, numerous multidirectional schlieren of gas-saturated ice, etc.). At the same time, the frozen massif did not collapse into separate blocks and retained its integrity. This could have happened if the gas pressure in the caverns and grottoes led to local deformations of the overlying strata. Through them, the gas, possibly together with water formed during the decomposition of gas hydrates in the form of separate jets under high pressure, penetrated the frozen soils.

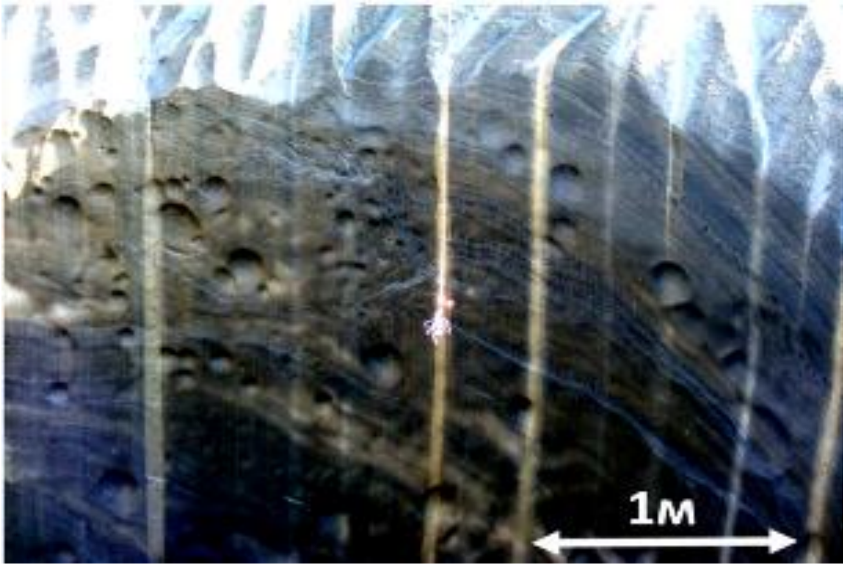

Figure 5. Plastic and discontinuous deformations of the walls of the Yamal crater. Photo credit: V.V. Olenchenko.

In the borehole drilled in the immediate vicinity of the Yamal crater, a layer of gas-saturated ice with traces of numerous cracks of plastic deformation was discovered [24]. In some places, ice-crushing zones are observed, where individual isometric blocks with traces of plastic deformation are surrounded by rounded channels of cleaner ice [9].

Plastic and rupture deformations often occur together. Figure 6 shows the penetration of gas-saturated ice in contact with the overhead roof and the gas-saturated zone. The intrusive fragment (white ice in Figure 6) shows a core with a stiff and deformed isometric formation, which is forced through the enclosing layered ice–ground massif. The force of indentation can be judged by the cracks that form a wedge-shaped pattern. These can also be traced along the lower and upper boundaries of the stiffness core. A sharp unconformity of the layers formed during the movement of the stiff core and the enclosing layers, which are broken and deformed, is observed. Along the movement zone, reel bands of strongly deformed ice can be traced. This process corresponds to the final stage of the formation of the local gas-dynamic geosystem immediately before explosion, when inhomogeneous intra-soil pressures in local zones are high enough to cause the introduction of individual ice fragments into the frozen massifs, but still insufficiently high to rupture the overlying roof.

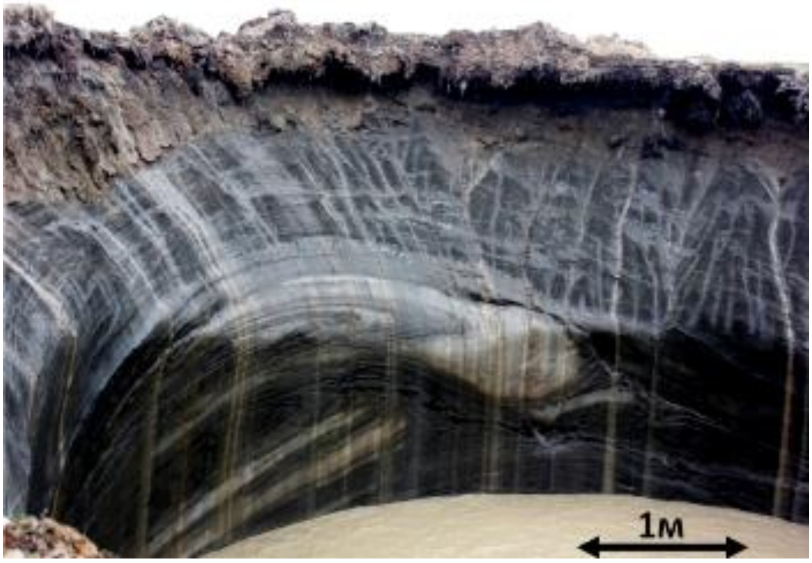

Figure 6. Deformed gas-saturated ice pushed into the layered ice–ground massif. July 2015. Photo credit: A.V. Lupachev.

Together, these data indicate the stage of the formation of a primary cavity filled with a high-pressure gas, which is realized in the form of cracks, channels, and weakened zones. They penetrate the frozen strata overlapping the zone of caverns and grottoes and allow for the movement of gas fluids along them (Figures 2–5). These processes were observed in laboratory conditions when gas was pushed through frozen clay and ice samples [3].

The numerous and diverse deformation structures are paragenetically related to similar structures observed in the zone of caverns and grottoes. This is the result of significant uneven pressures that arose in the frozen massif, leading to the destruction of its continuity and significant internal deformations. The differences probably lie in the fact that in the zone of caverns and grottoes, the pressure was more localized and more powerful, leading to stresses that formed the internal cavities. With the local destruction of the rooves of these cavities, gas and water (in the case of the decomposition of gas hydrates) penetrated through the cracks into the overlying layers and deformed them.

4.5. Ring Structures Confined to the Walls of the Craters

One of the most unusual formations in GEC are ring structures. They form the crater walls and are layered, vertically oriented formations consisting of alternating pure ice and ice–ground deposits, or a series of concentric cracks. In a horizontal cut, they form ring structures with a thickness of several tens of centimeters to one to two meters. The ring structure in the Yamal crater (GEC-1) (Figure 7) [25,26] consists of alternating ice–ground layers that are 0.5–2.5 cm thick [18].

The samples taken and analyzed by E.I. Galeeva et al. [27] show that layering is due to the viscoplastic flow of ice. Shear deformations lead to the deformation of the ice reservoir, forming a vertical stock with numerous folds, and secondary bedding (cleavage) oriented at an angle of up to 60° with respect to the horizontal primary bedding. The study of the structure of the layered ice of the Yamal crater showed a clear division of ice into layers about 1.5 cm thick, where ice crystals are elongated and oriented with their longer sides matching the orientation of the layering of the ring structures. Here, inclusions of small gas bubbles with a diameter of roughly 0.01 cm are observed, located randomly or parallel to the layering of the ring structures [27].

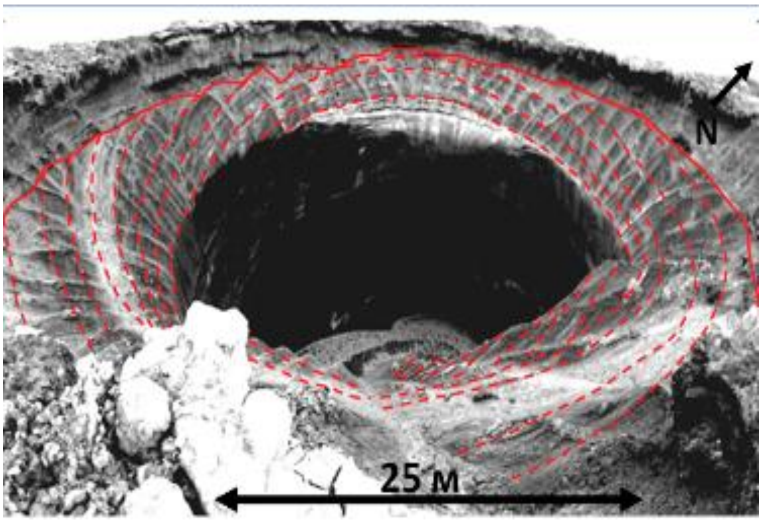

Figure 7. Ring structure (red dotted lines) enclosing the Yamal crater. Designations: the shading indicates the direction of the subvertical layers in the zone adjacent to the crater walls; the solid line marks the lower boundary of the active layer. Photo credit: V.V. Olenchenko.

Layers of sub-vertically oriented ground-ice structures formed the walls of the Yamal crater, which remained after the explosion. In 2014, this entire surface layer was iced over, but by mid-summer 2015, was almost completely thawed. A similar ring structure is present in the AntGEC crater, found in the southwest of the Gydan Peninsula. Judging by the morphology of the gas inclusions (e.g., elongated, isometric, large, flattened, and with sinuous boundaries), the walls experienced significant pressure from the center with a simultaneous upward displacement. As a result, an annular zone with vertically oriented bedding was formed.

In the marginal part of the Erkuta crater, there is also a local annular zone of deformed ice, which is a series of concentric cracks. Most likely, this series was formed under a fast and strong mechanical impact during an explosion. This is evidenced by the layers of ice, which are curved upward, and the crushed fired soils. There is evidence that a fire was observed during the explosion.

In the C17 crater, a subvertical layering of ice forms an annular structure in contact with the host clay strata. The vertical orientation of the ice layers is clearly visible and similar to the ring structure of the Yamal crater. The thickness of the ring structure of the C17 crater is small and amounts to the first tens of centimeters.

In laboratory experiments, similar ring structures were obtained by forcing a die through a layer of clay. Under shear conditions, a system of ruptures or shear cracks is formed in the contact zone [28]. The predominant forms developed consist of cracks oriented at an angle of 15 to 20° to the general strike-slip [28]. In the case of GEC, a system of long, densely spaced subvertical cleavages and cracks appears, forming an annular structure.

V.I. Solomatin's experiments, in which a locally oriented pressure was exerted on the ice mass, showed that in the case of lateral expansion in the direction of the normal to acting force, formations similar to the described ring structures developed. The emerging squeezing flow forms structures of a macrofluidic banded composition with a layered arrangement of mineral and gas inclusions [29].

This makes it possible to consider ring structures in GEC as a result of high-pressure action with displacement at the boundary of the local gas-saturated ice–ground body and the host frozen soil massif. The different morphologies and thicknesses of the ring structures depend on the duration of the impact associated with the preparation of the explosive process (from one to two to tens and hundreds of years), the granulometric composition of the mineral component (sands, loams), the ice content, the depth of the gas-saturated zone, the magnitude of the pressures that arise, and other factors.

4.6. Domed Roof of a Gas-Saturated Area

During the initial examination of the Yamal crater in July 2014 [16], the remains of the domed vault were inclined surfaces overhanging the vertical shaft of the crater. The vault was formed by a layered ice–soil massif, passing below into an annular structure that wrapped around the surface of the vertical shaft. It can be assumed that the vault in the form of a dome was formed at the upper boundary of the stock of gas-saturated ice, pushing through the permafrost strata. The surface of the vault is even and dotted with numerous isometric, rounded cavities up to 10 cm in size. This morphology of the surface may indicate that a lens of compressed gas has formed between it and the underlying gas-saturated soils.

4.7. Plastic Deformation of the Roof of Frozen Soils with the Formation of Mounds on the Surface

To date, several hypotheses have been proposed for the development of local geodynamic systems leading to the formation of gas-emission craters. Each hypothesis is characterized by a different set of processes and intermediate structures. However, one structure in the composition of geodynamic systems is required for all hypotheses. This is an overlying layer of frozen soil that, under the influence of pressure from below, undergoes plastic deformation, which is expressed in the formation of a tubercle of heaving. After an explosion, this part of the crater is destroyed the fastest, so insufficiently informative fragments often remain. Below are some examples of the structures of surviving heaving mounds.

The layered loams, which make up the upper part of the frozen soils of the Yamal crater (GEC-1), were strongly affected by the gas-saturated ice stock. This impact led to plastic deformations of the frozen roof and the formation of a mound ~5 m high and about 50 m in diameter. Note that the proposed mechanism is found incomparably less frequently than those that form typical perennial heaving mounds.

For the YeniGEC, similar processes are observed. The explosion that led to the formation of this GEC was preceded by a stage of intensive movement of the ice body, which deformed the overlying deposits and formed a heaving mound. Here, in a layer of clayey sediments adjacent to the bulging ice core, there is a zone of cracks subparallel to the interface. For all the dissimilarity of the structure of these two heaving mounds, the mechanism of development of the contact zone between the moving ice core and the enclosing soil layer is similar to the mechanism of the formation of the ring structures discussed above.

The mounds considered above are composed of loamy soils. The pressure from below led to the development of plastic deformations preceding the explosion. The growth of the mounds has been continuing for decades. S.P. Arefiev estimates their age near the Yamal crater at 62–75 years, and the vertical growth rate at about 8 cm/year [30]. In the case where the upper part of the section is composed of frozen sandy soils, the growth of mounds occurs much faster. For example, the mound at the ErkGEC grew for about 2 years, approximately the same age as the mound near the SeYkhGEC.

In both cases, the upper part of the section is composed of frozen sand. This is probably because brittle deformations grow faster in such sediments, destroying the roof of the gas-saturated zone. In some cases, clearly defined mounds may not form, for example, in the case of the Osokin Crater where the frozen strata are represented by a stratum deposit, covered by a thin soil layer (about 1–2 m). The explosion happened quickly with a short preparatory period. The walls of the crater are angular, with no annular structures framing the walls. In this case, an expansion in the lower part of the crater (zone of caverns and grottoes) is formed. An interesting feature of this crater is the formation of two well-defined annular cracks around it, which are much larger than the crater itself. It is likely that, at a shallow depth at the base of the reservoir, a gas cavity was formed. The resulting pressure was sufficient to raise the frozen roof. The growth of brittle deformations led to the release of ice to the surface. The scatter of debris does not exceed 20 m. After ejection, subsidence occurred, resulting in ring crack formations.

5. Discussion

From the examination of GEC, the structure of frozen soils composing the crater walls showed that these strata were subjected to significant pressure from below [31]. These impacts manifested themselves in local intra-soil deformations of primary bedding, numerous plastic and ruptured deformations, and the appearance of ice-crushing zones. Signs of ice flow and the indentation of blocks were observed in the surrounding frozen mass. There is a great deal of evidence for the inclusion of a gas component in these pressure processes. For example, there is always a series of caverns and grottoes at the base of the craters, suggesting a zone of influx of gas fluids in ribbons that penetrate along cracks to the crater walls. They are associated with isometric gas accumulations. Numerous gas bubbles create sub-vertically oriented stripes or various accumulations of honeycomb ice that form layers with the enclosing soils at the border of the crater. Hence, the overwhelming majority of researchers suggest that GEC are the result of the impact of a high-pressure, intra-ground gas. Analysis of the crater structure showed a combination of constantly occurring formations with quite definite structural features and common causes. These form stable parageneses, i.e., they are located together, but are not necessarily genetically related.

During GEC formation, a certain sequence of successive stages is observed, with each distinguished by an individual set of paragenetic processes and their inherent formations. Regardless of the gas's genesis (various options will be discussed below), a primary gas-saturated zone appears at a certain depth. The gas under pressure begins to deform the enclosing soils. In this case, a continuous filtration flow is formed, in which the gas fluid from the area with higher pressure is filtered into the area with lower pressure (as a rule, towards the surface). The unsteady "single filtration space" is heterogeneous, as the pressure gradients appear in various parts and provide filtration mass transfer in frozen soil. Penetrating into cracks, the gas fluid exerts force on the walls, which leads to their expansion [32].

There is a widespread presence of various kinds of deformations, indicating heterogeneous and multidirectional local processes that form the structures of extrusion, flow, penetration, etc. P.A. Shumsky associates such structures with the flow of extrusion in ice accompanied by intense folding with the appearance of a macrofluidal banded formation [33]. The concave, rounded depressions form vertically oriented chains or large isometric accumulations (cellular ice). Their wide distribution is associated with the specificity of the deformation of gas inclusions in frozen soils at the applied pressure. In this case, the flattening of air bubbles is observed, acquiring the shape of disks oriented perpendicularly to the direction of pressure (Figures 4 and 5) [33]. The migration and coalescence of individual gas bubbles occur in moving ice [29]. A gas-saturated ice–ground body was penetrated under the heaving mound judging by the structure of the crater walls and the central massif. The formation of the body was accompanied by multidirectional cracks, abundant plastic deformations, and numerous forms of gas inclusions causing additional instability (chains; isometric, rounded inclusions; worm-like, honeycomb structures; and so on). At the contact of this gas-saturated ice–ground body, a layered ring structure is formed, consisting of alternating ice and ice–earth layers. All of these formations appear in a variety of forms, but are all parageneses formed under the influence of a common cause: the impact of underground gas under significant pressure. After the plastic deformation of the frozen roof reaches a certain limit, its rupture occurs, leading to a sharp release of pressure (decompression) and the release of ice–soil material saturated with pressurized gas.

During the formation of the Yamal crater, a series of successive stages occurs (Figure 8), each distinguished by an individual set of inherent paragenetic processes and formations. The features of geosystem development at each stage prepare and largely determine its evolution at the next one.

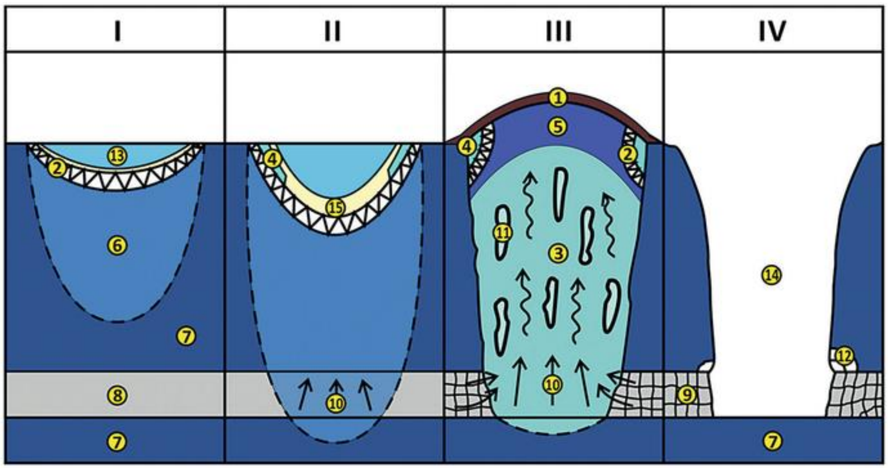

Figure 8. Stages of development of the Yamal crater (stages I, II, III, and IV). Legend: 1, cover horizon; 2, layer of ice between thawed and frozen soils; 3, frozen gas-saturated ice-bounded soil with traces of plastic deformations; 4, infiltration-segregating ice; 5, gastight roofing of permafrost; 6, zone of temperature increase in permafrost under the lake; 7, permafrost outside the heating effect of the lake; 8, layer of hydrate-containing permafrost; 9, zone of decompaction in the layer of hydrate-containing permafrost around the crater; 10, direction of the movement of fluids; 11, gas fluids; 12, caves and caverns in the lower part of the crater; 13, lake; 14, crater formed after the release of gas-saturated deposits; 15, talik.

Stage I. The appearance of a lake above the perennially frozen soils containing a layered deposit of underground ice. A talik with a thickness of about 6–8 m is formed under the lake [24]. Below are icy soils and a reservoir of underground ice. The temperature of permafrost lying under the surface reservoir and talik is in the range of -1–-3 °C, which is higher than the surrounding strata. In the thawed zone, gas permeability increases, strength characteristics decrease, porosity increases, and numerous continuity defects appear. The pore pressure here corresponds to the hydrostatic pressure.

Stage II. The thawing zone in permafrost reaches a layer of gas hydrates at a depth of more than 60 m (at a pore pressure of about 0.7 MPa). When the gas hydrates are heated, the process of their dissociation begins, accompanied by the release of gas (methane), which is under a pressure of about 2–3 MPa. Under these conditions, the released gas cannot eject the overlying permafrost, but can filter through it. Gas fluids in the form of separate gas jets begin to penetrate into the least stable area, which is the zone of high-temperature permafrost (stratal ice). The squeezing of gas from the dissociation zone leads to a decrease in pressure, followed by recovery due to the ongoing decomposition of the gas hydrates.

Stage III. As a result of the impact of gas under pressure in the zone of high-temperature permafrost (stratified ice), two paragenetically related processes are realized: gas filtration and the viscoplastic flow of ice and ice–soil. The general direction of gas and ice movement is oriented upwards. Uneven stresses cause local changes in the direction of gas filtration, as well as plastic and discontinuous deformations in the ice. This determines the presence of predominant vertical layering and local multidirectional dislocations. As a result of gas filtration and ice flow in the frozen soils, a stock is formed, consisting of layered, highly deformed gas-saturated ice. The pressure in the gas inclusions penetrating the stock corresponds to the pressure developed in the gas hydrate dissociation zone. The height of the formed stock is about 50 m, and the diameter is about 15 m. Subsequently, a heaving mound is formed above the gas-saturated ice stock.

Stage IV. After the tensile strength of the frozen roof is overcome, it breaks and abruptly releases pressure. The expansion of gas in a gas-saturated, dislocated rod leads to the layer-by-layer ejection of ice–ground material (the mechanism of which is described above).

In general, the pre-explosion preparation mechanism can be summarized in the following stages. First, (1) the gas under pressure begins to filter into the least durable frozen soils of the high-temperature zone and simultaneously deforms them; (2) this penetration significantly weakens the strength of the enclosing massif and causes plastic and rupture deformations. The emerging cracks and dislocations accelerate gas filtration. A filtration flow is formed, in which the gas fluid from the area with higher pressure is filtered to the area with lower pressure (as a rule, towards the surface). The "single filtration space" established in the frozen soil mass is heterogeneous; pressure gradients appear in its various parts, causing local variability of deformations and gas distribution in the frozen strata. The totality of these processes, defined by the authors as a filtration-deformation mechanism [34], allows the gas fluids to penetrate deep into the icy frozen massif and redistribute the pressures characteristic of the zone of caverns and grottoes to higher levels. This facilitates the occurrence of potential explosive processes. Around the formed gas-saturated ice–soil stock, which is displaced upward in some cases, a cocoon consisting of layered ice can form. This is formed at a slow pace of the displacement of the gas-saturated ice–ground stock. For example, as noted above, the mound on the site of the Yamal crater has been growing for about 70 years (about 1 cm/year). The mechanism of motion of a gas-saturated rod can be briefly presented in the following form. Saturated with gas, the frozen soils will begin to swell. As a result, a complex volumetric stress–strain state will arise. In this case, swelling stresses in the radial direction will be compensated by reactions of the surrounding soils. Therefore, they are implemented mainly in the vertical direction. Then, according to Rebinder's law, the gas-saturated soils will also change their strength properties in the direction of their decrease, without practically affecting the surrounding soils. The swelling of the permafrost volume will lead to its shift in the vertical direction. In this situation, those parts of it that have reduced their strength properties and are located closer to its axis of symmetry will ascend faster, causing a bump to appear on the surface. Along with swelling stresses, it is necessary to consider vertical forces, whose source is the pressure of the gas in the free space in the lower part of the gas-saturated zone. These forces act in one direction and move the gas-saturated permafrost upward. The total value of these forces must exceed the shear strength of frozen soils (ice) in order to raise them [35].

In the case of a rapid increase in pressure, the layered ring structure with traces of dynamometamorphism does not have time to form. In this case, a network of annular cracks develops. An example is ErkGEC, where a mound with a height of about 3 m was formed in 2–3 years, or other craters where ring structures have not formed at all (Osokin's crater).

The considered mechanism of gas movement over a gas-saturated cavity leads to the formation of a highly deformed ice–ground body penetrated by numerous gas fluids of various morphologies. Outwardly, this formation resembles a stockwork, i.e. "an irregular ore body formed by a mass of soil penetrated by a dense network of differently oriented veins and small veins" [36]. The main feature of this stockwork structure is the localization of veinlets in areas where there is a maximum concentration of compressive stresses. Then, as a result of the appearance of cleavage cracks under conditions of compression and shear, the voidness of the enclosing massif sharply increases, facilitating the penetration of magmatic melts [37]. In our case, the network of veins and small veinlets was formed by gas-saturated ice schlieren (Figure 7). In the case of GEC, instead of magma, gas under high pressure is filtered into the permafrost through the zones of local deformations.

The gas-saturated ice–ground massif exerted pressure on the enclosing sediments, and the area of abnormally high gas pressure from the bottom squeezed it upwards. At the same time, an annularly layered structure formed on the border of a stationary massif, and a gas-saturated ice–ground body pushed through it. The formation in the upper part of the section of a low-temperature and gas-impermeable layer of frozen soils can lead to the development of a gas cavity in the form of a concave dome, the remains of which are found in the section of the Yamal crater.

Gas-Emission Craters as a Cryogenic Phenomenon

The GECs in the north of western Siberia are located in permafrost; therefore, it is extremely important to identify the role of cryogenic factors in their formation. A prerequisite for the formation of such craters is the appearance of a local gas-saturated zone with an increased gas pressure in frozen soils. As mentioned above, there may be several reasons for the occurrence of these zones. If gas is supplied through channels associated with tectonic faults, this will show abiotic signatures and indicate thermogenic gas. Gas conduits do not typically break through the frozen ground in continuous permafrost, although changing hydrological conditions—typical of discontinuous permafrost—can give rise to taliks that enable gas migration. In this case, larger outcrops of deep gas would be recorded, but this is not observed due to the limits of geophysical tools. Seismic data show multiple gas flows at depths greater than 500 m, but geophysical methods need to be developed to obtain signals in the upper part of the geological section, where the permafrost is located (depth up to 500 m). Consequently, if there are gas supply conduits, then they contact near the zones of the unloading and accumulation of gas. In this case, the cryogenic factor is the most important and will localize near areas where the transit zone passes into the accumulation zone. So far, patterns relating talik-faults to zones of GEC areas have not been identified, but perhaps can be determined by future geophysical surveys investigating the influences of thermogenic gas movement in subsurface accumulation zones. It is important that even at this stage, the cryogenic factor plays an essential role, acting like a cryospheric cap atop deeper thermogenic gas accumulation, including intrapermafrost gas hydrates. In the case of freezing taliks compressing gas hydrostatically, the formation of a gas-saturated zone and high pressure is then entirely determined by cryogenic factors, which can also lead to the formation of gas pockets. Epigenetic freezing leads, firstly, to the cryogenic concentration of groundwater, gases, and dissolved salts; secondly, it forms a screen that prevents the escape of water and gases to the surface. In the zone of the formation of ice massifs, the freezing front lags significantly behind less water-saturated areas. This causes additional cryogenic head, which concentrates water at the place of the reservoir's formation. G.I. Dubikov established a connection between stratal ice and the underlying sands [38]. As a result of the imposition of natural factors, (a) uneven epigenetic freezing, (b) the movement of gas-saturated groundwater, (c) the formation of sheet ice, and lastly (d) cryopegs allow for the formation of a complex cryogenic geosystem. The thickness of permafrost, including paragenetic cryogenic formations, develops the conditions for frozen sediments, strata deposits of underground ice, and gas-saturated zones under pressure. Both the emergence of intra-permafrost gas hydrates and gas-saturated zones due to the decomposition of gas hydrates are determined by cryogenic processes that accompany the formation of stable gas cavities and affect the strength and deformation properties of frozen soils. Hence, gas-saturated zones and/or intra-permafrost gas hydrates are most commonly investigated and typically most useful to discerning the mechanisms of GEC.

The formation of underground primary cavities is a necessary but insufficient condition for the formation of GEC. Through emerging deformations, gas from the accumulation zone can be filtered to the surface. This is quite common in lakes where gas filtration occurs (so-called "blue" lakes). If the gas-saturated zone is surrounded by sufficiently strong icy enclosing soils, the gas under pressure can remain without any movement for a long time. In both cases, a gas-saturated zone with increased pressure is formed, but the explosion and formation of a crater does not occur.

The precipitation of the explosive process is observed when, under the influence of pressure arising in the gas cavity, deformations begin to develop in the enclosing (mainly in overlapping) frozen soils. The lower the temperature, the more pressure is required for deformations to occur. Laboratory studies have shown that deformations in frozen ice samples and the gas filtration occurring within them depend on the ratio of gas pressure to soil temperature. In ice and frozen clay samples, filtration took place at a temperature of about −1 °C and a pressure of 0.2–0.4 MPa [39]. Under natural conditions, much higher pressures can arise. After the temperatures in the layer of gas hydrates occurring at depth exceed the values that ensure their stable state, the process of dissociation begins with the release of methane with an initial pressure of 2.2–2.6 MPa [21].

The formation of this geosystem is achieved by a series of cryogenic processes replacing each other. Internal stresses arising from the saturation of gas in the area of frozen soils located above the zone of caverns and grottoes will be removed due to the displacement towards least resistance, in this case, upwards. An additional factor contributing to the movement of the gas-saturated ice–soil stock relative to the enclosing mass of frozen soils is the pressure from the bottom of the gas cavity formed in the zone of caverns and grottoes. The total value of the resulting pressures must exceed the shear strength of the frozen soils [3,35,40]. Gas fluids begin to filter upward into the area of lower reservoir pressures. They form various kinds of gas inclusions in the form of chains, isometric accumulations, gas tapes, honeycomb structures, etc. A local gas-dynamic cryogenic geosystem is formed above the gas cavities, shifting upward relative to the stationary enclosing strata, and forming a perennial heaving mound above it.

If we analyze most of the publications related to the formation of GEC, it can be noted that the most attention is given to morphometry, the dynamics of the bumps preceding the explosion, the morphology of the field of scattered debris, and hypotheses on the origin of a given gas. The gas composition is sometimes examined in order to identify its genesis. An analysis of the carbon isotopic composition of methane (δ 13C) from the Yamal crater showed its "bacterial origin" (from −58‰ to −75‰), while in one sample δ 13C is close to −45‰ "thermogenic methane" [15]. This sample may indicate a possible limited gas inflow into the Yamal crater from the Upper Cretaceous deposits below the base of the permafrost. In the arch of the Bovanenkovo uplift, the top of the Cenomanian layer lies at a depth of about 500 m. It is only 300–330 m below the permafrost base. According to the results of the analysis carried out by F.M. Rivkin (JSC Yamal LNG), methane from the Seyakha crater (formed on 28 June 2017) unambiguously testify to a biogenic origin (δ 13C = −80.6‰) [41]. At the same time, the preparation of an explosive gas outburst, structural changes in the permafrost massif, and the processes involved in these changes have not been analyzed, with rare exceptions [10,31]. Thus, the geocryological factor is not considered when studying the developmental history of a local area of permafrost strata, in which an underground gas explosion is likely forming.

This is most likely due to the fact that, within the framework of generally accepted concepts, many of the processes revealed in the study of GEC are still poorly studied or are not yet included in the conceptual apparatus of geocryology. The traditional concepts should be extended by theoretical positions used in geology, tectonics, volcanology, and other earth sciences [5]. According to V.V. Olenchenko et al., who studied the electrical resistivity of frozen soils in the area of the Yamal crater at the depth range of 60–80 m, a horizon with resistivity (400–880 Ohm·m) has been noted. Below lies a layer of soils with a resistivity of 7.5–11.0 Ohm·m [23]. The layer with high resistivity values is explained by high ice content or a large number of inclusions of relict gas hydrates (methane clathrates). As a rule, gas hydrates occur in reservoirs representing horizons with interlayers of sand or sandy loam with a low salt content [42]. The position of the layer with high resistivity correlates with the depth of the maximum occurrence of gas shown in the section of the Bovanenkovo gas condensate field. The underlying layer with high resistivity is interpreted by frozen Lower-Middle Pleistocene marine saline deposits of the Yamal Group [43]. On the geoelectric section at a depth of 135–190 m, the top of the conductive layer, with a resistivity of 3.4–5.1 Ohm·m, is interpreted as a water–ice phase boundary in soils, i.e., the bottom of the permafrost layer [23]. In the course of the survey of the Yamal crater by georadar GROT 12 and GROT 12N, according to the characteristic signs of attenuation of the reflected signal at 750–1030 ns, at depths of 50–70 m, it was possible to localize the boundaries of the layer of the supposed gas hydrate deposit. At a depth of 135 m, a boundary is clearly seen associated with signal attenuation at around 2000 ns, corresponding to the lower boundary of permafrost [22]. Independent data allow us to reasonably assume the presence of a layer of gas hydrates at a depth of 60–70 m and a lower boundary of frozen soils at depths of about 135–190 m.

In this case, it is necessary to develop new approaches that consider the dynamic processes occurring in the frozen massif. For example, it is necessary to move from the structural-genetic method of studying frozen soils based on identifying the formation processes of certain cryogenic structures to the structural-dynamic method, which studies the transformation of already formed cryogenic structures. It is necessary to develop several new methods for studying the frozen strata associated with the possibility of gas filtration in frozen soils, the conditions for the formation of cavities and the movement of ice–ground masses in the permafrost, etc. The most promising direction in assessing the conditions for the restructuring of the primary structure and the formation of new cryogenic forms is the widespread use of methods regarding the mechanics of permafrost, mathematical modeling, and geophysical research.

6. Conclusions

The analysis of the deformation and gas-saturated formations in the structure of GEC allowed us to conclude that they are a complex of structural parageneses formed under similar dynamic conditions. The explosive process is the result of the self-development of a local cryogenic gas-dynamic geosystem that has arisen in the thickness of frozen soils and is in a nonequilibrium thermodynamic state. The diversity of the structures of these geosystems is determined by paragenetic relationships between the processes of gas filtration and the deformation of gas-saturated ice–soil material (from viscoplastic motion to brittle fracture). The similarity of structural parageneses between different craters, which differ in terms of their geological structure, occurrence, and rate of development, indicates the general patterns of the functioning of these geosystems.

The considered GECs are special cases of the complete life cycle of the development of local gas-dynamic geosystems in various natural conditions from the initial stage (the formation of gas cavities in the permafrost) to the final stage (the explosion and release of ice–ground material). The formation of this geosystem is due to the change in complexes of cryogenic processes and the corresponding parageneses of cryogenic formations. During the induction of an explosion, the primary structure of the frozen strata is deformed and rebuilt in accordance with the arising pressures and volumes of incoming gas.

It is necessary to distinguish between the factors influencing the occurrence of local gas-saturated zones and those leading to the development of associated gas-dynamic geosystems. The former lead to the creation of conditions suitable for the disturbance of the thermodynamic equilibrium in permafrost, and the latter ensure the formation and development of a local gas-dynamic geosystem that precipitates an explosion. Gas in a frozen massif can accumulate for various reasons: the filtration along a fault from depth, the decomposition of gas hydrates, the cryogenic concentration of free gas or its accumulation in a lithologically conditioned “gas pocket” (a sand lens in a clay layer), etc. In this case, an explosion will not occur if the gas is sealed.

The variety of cryogenic forms observed in GEC is primarily due to the processes of dynamometamorphism transforming the primary cryogenic structure under the influence of high, inhomogeneous pressures. The set of processes that form GEC should be classified as cryogenic, since they correspond to strength and deformation properties, the phase transitions of water, structural and textural features, and mass transfer processes characteristic of frozen soils.

The problems arising in the analysis of GEC structures can be solved only by expanding the classical concepts in geocryology and including the provisions developed in the frameworks of geology, glaciology, tectonics, and volcanology.

The main hypotheses for the occurrence of gas cavities in which the gas is under high pressure (the inflow of deep gas, all-round freezing of taliks, and the decomposition of gas hydrates under the influence of permafrost thawing) and explosive process initiation mechanisms likely correspond to a variety of geological, tectonic, and landscape-related conditions. To make any of these conditions generalizations would be a clear oversimplification. These hypotheses will be implemented in the form of various scenarios for the development of local gas-dynamic geosystems corresponding to specific territories.

The current state of knowledge of GEC requires a transition from hypothetical ideas about the cause of the occurrence of local zones of increased gas pressure in frozen soils to identifying scenarios for the development of local gas-dynamic geosystems in specific geocryological conditions. This requires the further improvement of geocryological, geochemical, and geophysical research methods and their wider application in the study of these formations.

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