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GEOMORPHOLOGICAL CONDITIONS OF THE GAS-EMISSION CRATER AND ITS DYNAMICS IN CENTRAL YAMAL

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This paper presents the characteristics of the relief in the area of crater formation in Central Yamal based on the analysis of remote sensing data, including stereo-pair very high-resolution data, as well as field observations. The time interval of the crater formation was defined as late fall 2013. Data on the morphology of the studied area before and after the crater formation were obtained. The existence of a bulge with the base diameter 45–58 m and the height of about 5–6 m in place of the crater was documented. Analysis of multi-temporal digital elevation models allowed calculating the volume of the crater void and the parapet formed around it. The volume of discharged material was determined to be nearly 6 times larger than the volume of material found in the parapet. The difference is due to a significant amount of ice, which, according to the results of field observations, was exposed in the walls of the cylindrical portion of the crater, and, apparently, comprised a major part of bulge material that got thawed after the ejection. The rate of the crater increase in diameter due to melting of its ice walls and the rate of its filling with water over the summer period were determined.

Gas-emission crater, ground ice, remote-sensing data, satellite stereo pair, digital elevation model

INTRODUCTION

The crater discovered in the central part of the Yamal Peninsula (Fig. 1) soon became an object which attracted close attention of the permafrost scientists studying the characteristics of permafrost and development of cryogenic processes, as well as of specialists ensuring safety of buildings and facilities in the permafrost zone.

The Governor of the Yamal-Nenets autonomous district commissioned to arrange a visit to the crater by a group of specialists including M.O. Leibman, to conduct examination of the object. The examination conducted in July 2014 brought about the first description of this unique natural feature; data were obtained on its morphometry and lithology. Based on

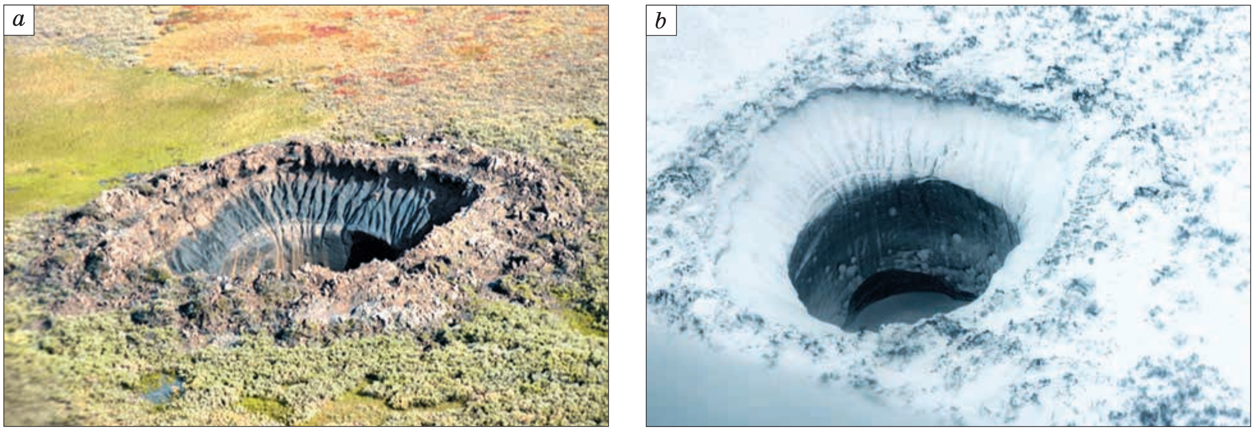

Fig. 1. The gas emission crater:
a – 25.08.2014 (photo by M.O. Leibman); *b* – 08.11.2014 (photo by A.I. Kizyakov).

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the examination results, a report was generated, submitted to the Government of the Yamal-Nenets autonomous district. To designate this unusual natural phenomenon, the scientists suggested a term “gas emission crater” [*Leibman and Plekhanov, 2014*].

In the crater area, there are fragments of the IVth coastal-marine plain 40–60 m high, composed of the upper quaternary deposits of the Kazantsevskaya suite (m, mlQ_{III}^{1}), formed under marine and coastal-marine conditions [*Ananyeva, 1997*]. The crater itself is situated on the border of a khasyrey (a drained lake) and a slope of a terrace-like surface, cut by erosion-thermokarst processes. 4 km west, there is *Bovanenkovo–Ukhta* trunk gas pipeline.

During the second brief examination of the crater conducted in August 2014, the main crater parameters were obtained, and the cross section of the crater walls was documented. In September 2014, the geological, geophysical, and geochemical studies (with soil and lake water sampling) were carried out by an expedition of A.A. Trofimuk Institute of Oil and Gas Geology and Geophysics, SB RAS, with GazpromVNIIGAZ participating in the project [*Epov et al., 2014*].

In November 2014, the Russian Center for Arctic Exploration and the Department for Science and Innovations of the Yamal-Nenets autonomous district initiated a new study, in order to further investigate the crater structure and to sample ice and the enclosing deposits from the crater walls. At that time, the authors analyzed the satellite images of the crater, in order to determine the date of the crater formation.

The following stage of the study was to select and to analyze the satellite images of the optical range to provide the geomorphological characteristics of the area prior to the crater formation, after it and for the case of its further evolvement.

The objective of this paper was to reveal the relief changes which occurred due to crater formation and to determine its morphometric characteristics. For this purpose, materials of field studies and remote sensing data were used.

DETERMINING THE TIME RANGE OF THE CRATER FORMATION

To determine the time of the crater formation, the satellite images of the *Landsat 8* and *SPOT 5* satellite systems were analyzed. The *Landsat 8* images used in solution of this problem have a number of uncontestable advantages: 1) sufficient spatial resolution of images (15 m in the panchromatic channel) to interpret the mesorelief shapes more than 15 m in size; 2) rather high (for non-commercial data) periodicity of recording a certain spot of the Earth surface; 3) free and convenient access to the image archives.

The *Landsat 8* satellite images were obtained from the USGS database using EarthExplorer (http://earthexplorer.usgs.gov). The *SPOT 5* image of 01.10.2013 was obtained from the *ScanEx* archives under the Moscow State University Geoportal project. An image with high spatial resolution (2.5 m on the Earth surface) (Fig. 2) shows the latest of all the recorded conditions of the Earth surface before crater formation. The complete list of the remote sensing materials used is shown in Table 1.

The *SPOT 5* image having the highest resolution was used as a basic image for the purpose of spatial aligning of the satellite images. The contour of the parapet on the crater periphery digitalized by very high-resolution images of 2014 was superposed onto the image. The parapet’s external diameter was about 70 m. The boundaries of the area in which the fragments of the ejected materials were found during the study of 16.07.2014 were indicated on the images, as well.

The field observations of July 2014 led to the supposition that the crater was formed not earlier than in the autumn of 2013. This followed from the character of vegetation in the ejection zone (fresh willow leaves sprouted through the sandy loam clods which covered the branches), the condition of the parapet materials (sharp “fragments” of the loam and clay were not washed out by the rain) and of the crater walls (the cleavage and cracks were not yet smoothened by the flows, the grass sod canopy was largely preserved around the crater and was hanging over the opening). This allowed us to narrow down the data range to bind the time of crater formation to the autumn and winter season of 2013–2014. The satellite images taken before 09.10.2013 show the presence of a bulge with the base diameter of 45–58 m in place of the current crater. This has been supported by the results of interpreting very high resolution imagery of

Table 1. **Satellite images used to determine the time range of the crater formation**

Date	Recording system	ID scenes	Spatial resolution of the panchromatic channel, m
22.07.2014	Landsat 8	LC81670112014203LGN00	15
03.04.2014	Landsat 8	LC81650112014093LGN00	15
16.03.2014	Landsat 8	LC81670112014075LGN00	15
21.02.2014	Landsat 8	LC81660112014052LGN00	15
01.11.2013	Landsat 8	LC81660112013305LGN00	15
09.10.2013	Landsat 8	LC81650112013282LGN00	15
01.10.2013	SPOT 5	142204_1310010650116_1A	2.5
03.07.2013	Landsat 8	LC81670112013184LGN00	15

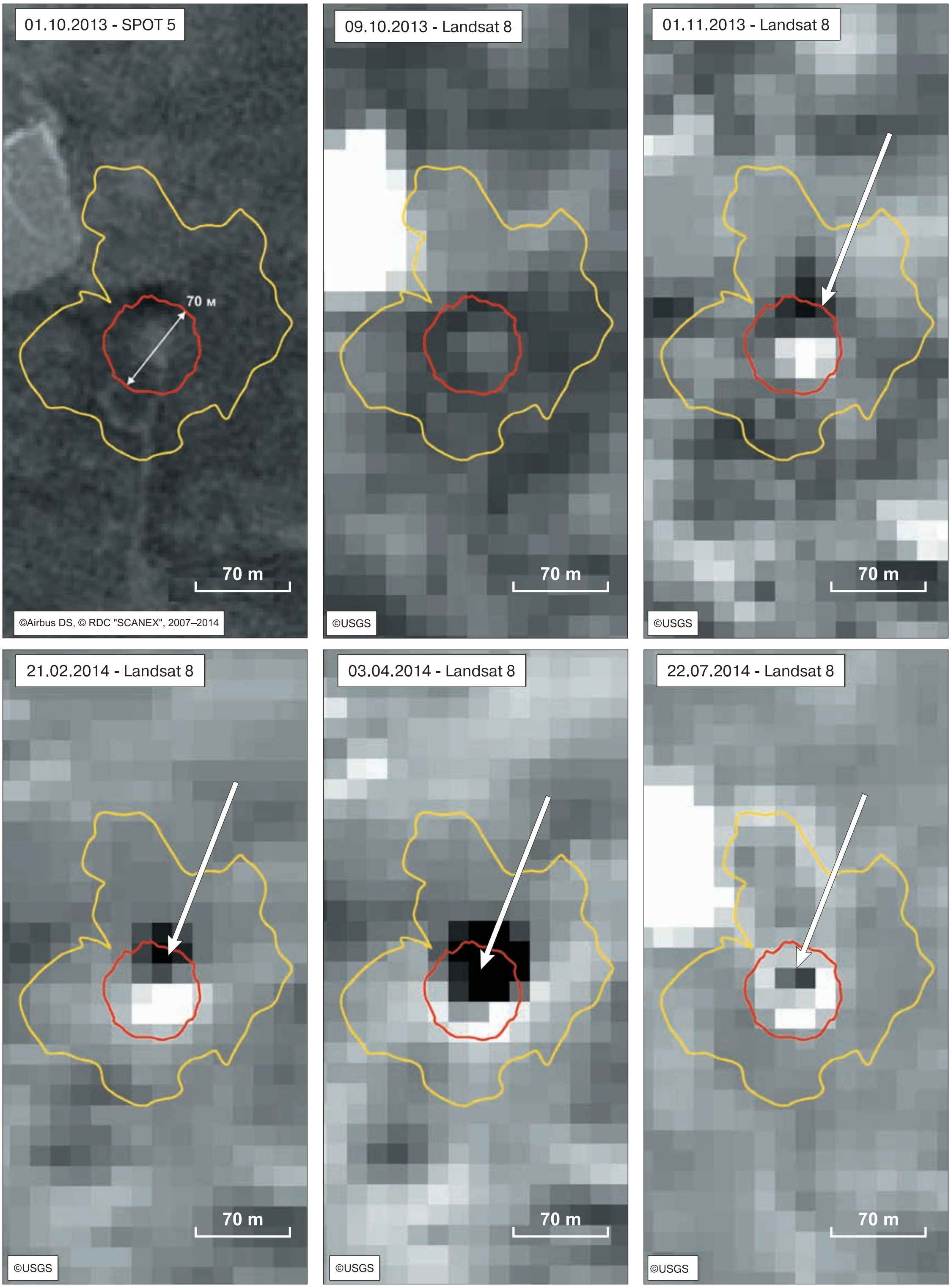

Fig. 2. Successive conditions of the study area according to remote sensing data.

A spot with low reflectance ability appears on the images (shown with an arrow), beginning with 01.11.2013. The red line contours the crater parapet; the yellow line is the zone of discovery of the material ejected from the crater.

09.06.2013. Beginning with 01.11.2013, the images of this area reliably demonstrate a spot with a low reflectance. The size of the spot increased till 03.04.2013. The spot seen in the image presumably covers the crater formed and the severely watered mineral material ejected onto the parapet. In summer the parapet surface partly dried up, and the exposed mineral ground (clays and loams) around the crater perimeter produced high reflection – it is displayed as a light-colored ring surrounding the central internal part of the crater in the images.

Thus, it has been established from the results of analyzing the satellite images that the crater was formed in the time range between 09.10.2013 and 01.11.2013.

DETERMINING THE MORPHOLOGY OF THE CRATER FORMATION AREA

In the absence of updatable large-scale topographic maps, plans, and instrumental field measurements, the only method of reconstructing the area relief for the purpose of identifying the changes which occurred is to use very high spatial-resolution satellite stereo pairs. To determine the morphological characteristics of the area relief before and after crater formation, digital elevation models (DEM) are to be developed. For this purpose, analysis of the global catalogues of the satellite images of high and very high spatial resolution was conducted. As a result of the search, two alternative stereo pairs of satellite images taken from the *WorldView-1* satellite closest to the time range of the crater formation were selected and purchased (Table 2).

The photogrammetric processing of the satellite images was conducted with a specialized software package *ScanEx IMAGE Processor*. It consisted of the following phases: 1) mutual orientation of the left and right images for each stereo pair; 2) transformation of the left and right images into a epipolar geometry; 3) automated measurement of the tie points; 4) automated stereo identification of the conjugate points using the simulated annealing method; 5) recalculation of the parallax map into the DEM and its post-processing (smoothing and interpolation of gaps and occlusions); 6) orthorectification of the left and right images with the rational function by the DEM obtained. After stereo pair processing, ortho images were obtained with the pixel projection in the area of 0.5 m and the DEM with the density of 1 m as of 09.06.2013 and 15.06.2014 in the Universal Transverse Mercator (UTM) and the heights in relation to the *WGS84* ellipsoid. Then, for the convenience of interpretation, ellipsoidal heights were reduced to the heights of the *EGM96* quasi-geoid. Then the absolute heights were reduced based on the *EGM96* model, which is different from the Baltic system of heights.

Based on the materials of high-resolution (2.5 m) and very high-resolution (0.5 m) satellite survey, the elements of the landform are reliably interpreted, corresponding to the condition of the key area before and after crater formation.

The general characteristic of the relief of the study area

To analyze the relief changes on the study area, satellite images taken in mid-July of 2013 and 2014 were used. In both seasons, the lower relief elements and the feet of the terrain slopes were covered with unmelted snow, and ice cover remained on the lakes.

In the northern part of the area under study, narrow elongated hills 42–48 m high are common (according to the *EGM96* model), dissected by erosion-thermokarst processes (Fig. 3). The surface is likely to be the surface of the IVth Kazantsevskaya plain. In some areas of the terrace-like terrain, polygonal micro-relief forms are common, caused by frost cracking.

In the upper parts of some of the valleys from different sides cutting the near the watershed surfaces, there are small lakes 80–230 m in diameter. The presence of lakes and of drain lake depressions accounts for the rounded shape of the erosion valley swellings breaking into the watershed slopes. Cryogenic landslides are widespread on the hill slopes and on lake shores.

The object under study is located south of the outlier of the IVth Kazantsevskaya plain on the surface with the height of 19–22 m. This surface is a small relatively levelled area in the upper part of the erosion landform, a submeridional valley 500–700 m wide, transforming in the south into a large valley with the bottom height of 10–12 m, through a system of lakes connected with the valley of the Myarongyakha River (the basin of the Mordy-Yakha River). A lower and more levelled khasyrey surface sized approximately 160 × 240 m may be identified within the uneven and ravine-cut expansion in the upper part of the valley. 75 m north-west from the crater within the khasyrey, there is a residual lake sized 95 × 115 m (Fig. 4).

Table 2. **Satellite images used to determine the morphology of the elevation under study**

Date	Recording system	Image ID	Spatial resolution on the surface, m	Stereo pair
15.06.2014	WorldView-1	102001002FA53E00	0.5	+
15.06.2014	WorldView-1	102001002FE69600	0.5	
09.06.2013	WorldView-1	102001002255D700	0.5	+
09.06.2013	WorldView-1	1020010023D37800	0.5	

Tundra meadow grass vegetation covers the khasyrey bottom. The hill slopes and partly the bottoms are covered with shrub vegetation.

The area microrelief before crater formation

The relief of the study area before the crater formation was reconstructed based on the digital elevation model, developed on the basis of a stereo pair of the *WorldView-1* images of 09.06.2013. In July 2013, there was a bulge in place of the crater – a positive elevation with the base diameter of 45–58 m (Fig. 5; 6, *a*, *b*). The hypsometric profiles crossing this elevation are shown in Fig. 7. The bulge top is hummocky, covered with grass; willow shrubs grow near its foot.

The microrelief of the area after crater formation

The morphometric characteristics of the new landform were determined during the field studies and by interpretation of the satellite image of 15.06.2014.

Well seen in the new landform is the wider upper part, which is a sloping funnel-like surface transforming, via a rather abrupt bend, into the vertical walls of the lower part of the crater (Fig. 8). According to the measurements performed in November 2014, the bend

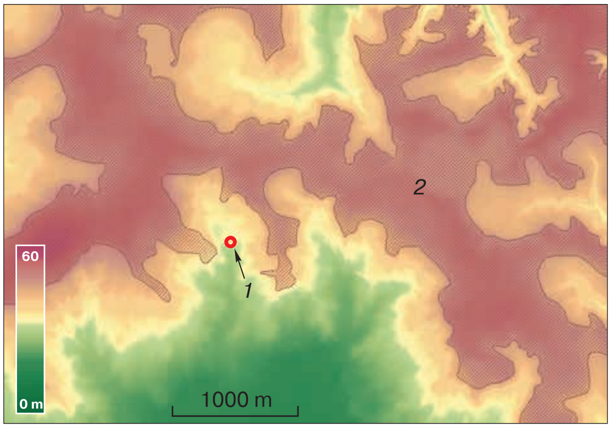

Fig. 3. Overview of the digital elevation model of the crater area.

The DEM was based on the stereo pair *WorldView-1* of 15.06.2014; *1* – the external boundary of the crater parapet; *2* – the surface of the outliers of the IVth Kazantsevskaya plain.

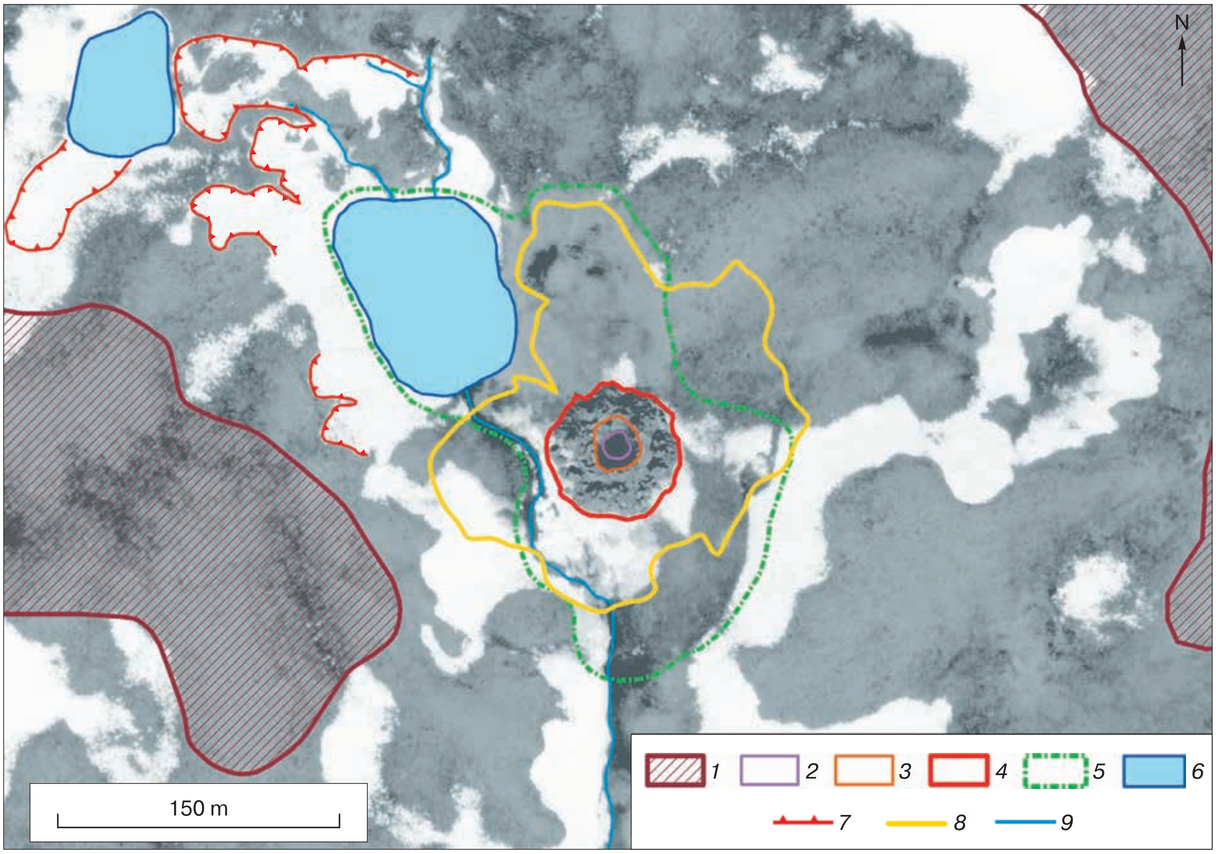

Fig. 4. The geomorphological plan of the study area.

1 – the watershed surface; *2* – the contour of the cylindrical part of the crater; *3* – the crater edge; *4* – the crater parapet contour; *5* – the khasyrey boundary; *6* – lakes; *7* – boundaries of cryogenic landslides; *8* – boundaries of the turf and rock blocks' scattering; *9* – water streams.

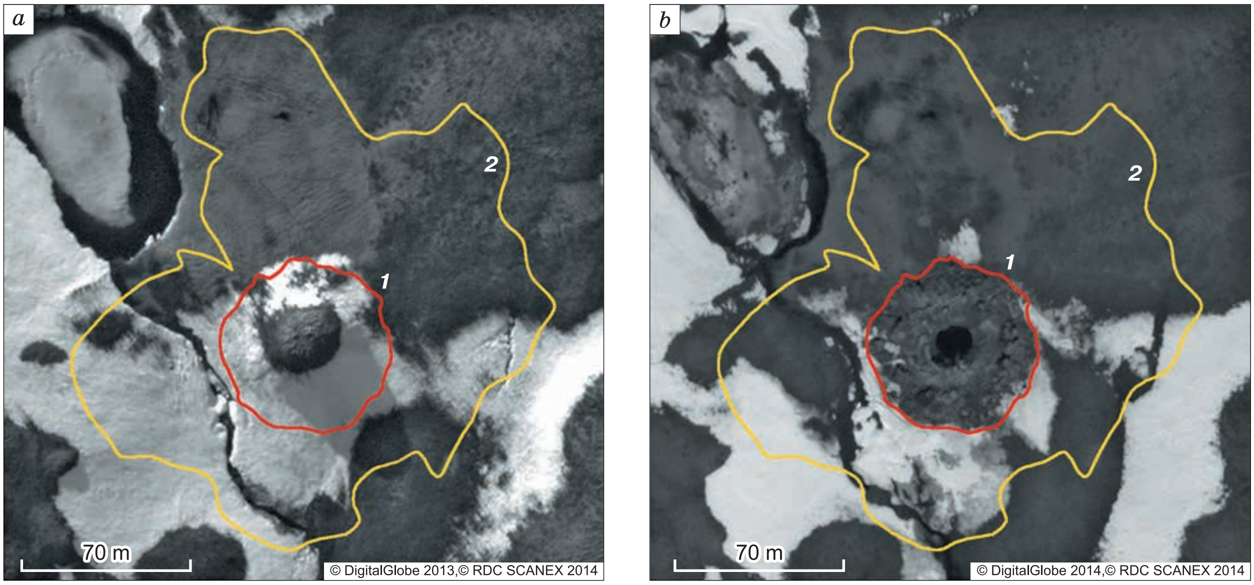

Fig. 5. The study area on very high resolution satellite images.

a – the area condition before crater formation (the *WorldView-1* image of 09.06.2013); *b* – the existing crater (the *WorldView-1* image of 15.06.2014); *1* – the external boundary of the crater parapet; *2* – the boundary of the material scattering zone.

in the vertical profile of the crater walls is at the depth of approximately 8 m from its edge. The upper sloping part of the crater is composed of deposits with high ice content, consisting of subvertically oriented interbedding of ground ice and loam (Fig. 9). Tabular ground ice is exposed below the bend, in the vertical and in some places overhanging cylindrical lower part, with rare vertically oriented laminations of silt coating the internal crater walls. In June–July 2014, in the lower part of the northeastern wall of the crater above water level, there was a grotto 5–8 m deep.

The crater is surrounded by a parapet: blocks of sandy loam, loam, and clay, composing the upper part of the section, and turf pieces with willow shrubs. The parapet height varies along the crater perimeter, forming hummocks and hills of different height – from 0.5 to 4.0 m (Fig. 5, 6). Certain fragments of the ground material and turf were found at the distance of up to 120 m. The size of the discovered blocks is reversely proportional to the distance from the crater. Near the crater, the block sizes are 1 m and more, while at the distance of 120 m, they are 10–20 cm in

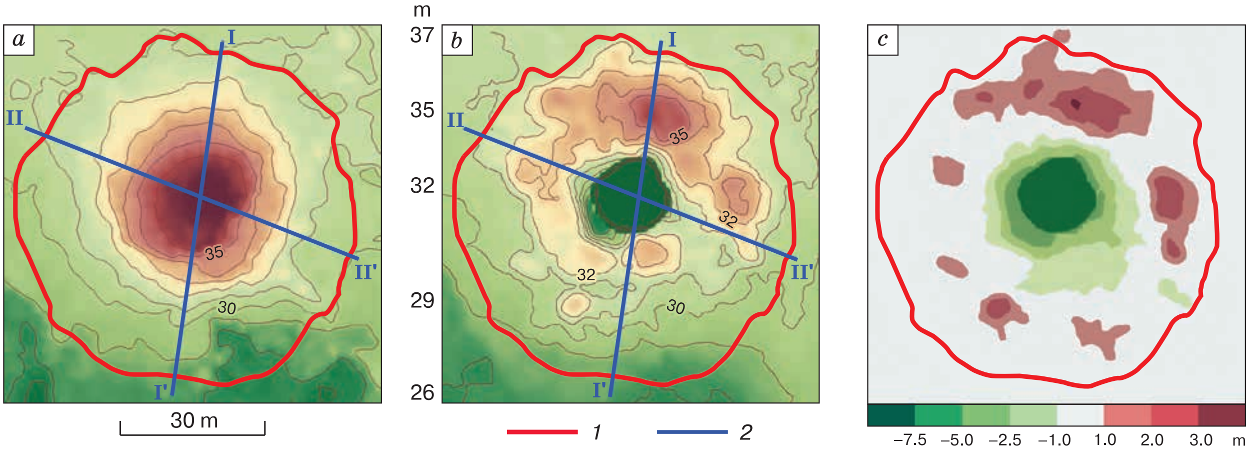

Fig. 6. Fragments of the digital elevation models of the study area, developed as a result of processing the stereo pairs of the satellite images.

a –DEM as of 09.06.2013; *b* – DEM as of 15.06.2014; *c* – changes in the hypsometric elevations after crater formation; *1* – the external boundary of the crater parapet; *2* – hypsometric profiles I–I′ and II–II′.

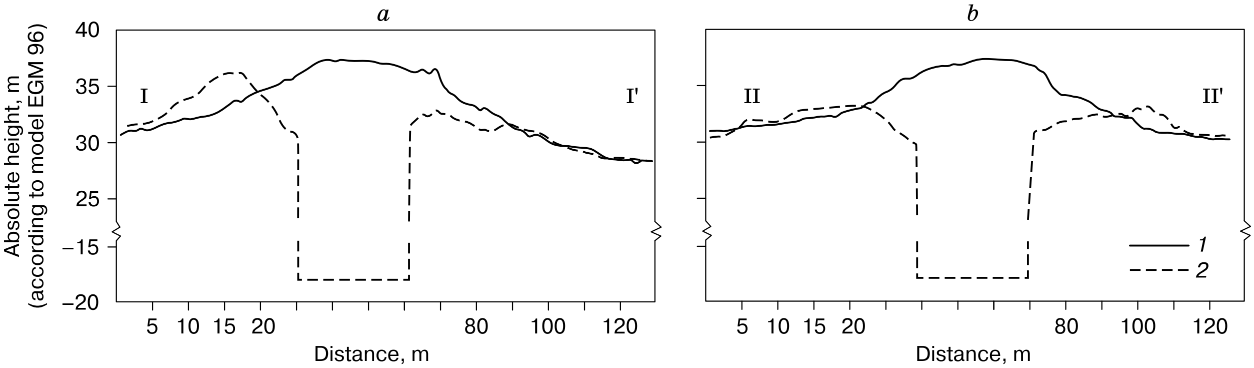

Fig. 7. Hypsometric profiles built on the basis of digital elevation models of 2013 and 2014.
a – line I–I′; *b* – line II–II′ (Fig. 6). *1* – profiles as of 09.06.2013; *2* – profiles as of 15.06.2014.

diameter. Large pieces of turf sized 50 × 100 cm were discovered at the distance of 60 m [*Leibman and Plekhanov, 2014*].

On the *WorldView-1* satellite images of 15.06.2014, the lower cylindrical part of the crater is displayed as a dark central area with low reflecting capacity due to the shadow on the internal walls (Fig. 5). According to the results of interpretation of the satellite images, the diameter of this cylindrical part of the crater was 15–16 m. The diameter of the upper part of the crater mouth measured by the edge with initial vegetation was 25–29 m. The parapet diameter (on the external boundary of the ejected material around the crater) was 70–72 m, both according to the *WorldView-1* image interpretation data as of 15.06.2014 and according to the field survey data as of 16.07.2014.

Due to the small size of the crater and the specific features of stereo photography performed with the angles essentially different from the nadir point, it was impossible to build a reliable relief of the internal part of the crater. In particular, it was impossible to determine the depth of the shadowed central part. In this regard, a necessity arose to adjust the DEM obtained. In July 2014, no instrumental measurements of the crater were conducted, and experts in field assessed the depth as exceeding 50 m. This assessment was used in the DEM adjustment performed on 15.06.2014; the height of minus 8 m was defined within the contour of the internal cylindrical part of the crater (reliably interpreted on satellite images). The walls of the cylindrical part of the crater were taken to be vertical.

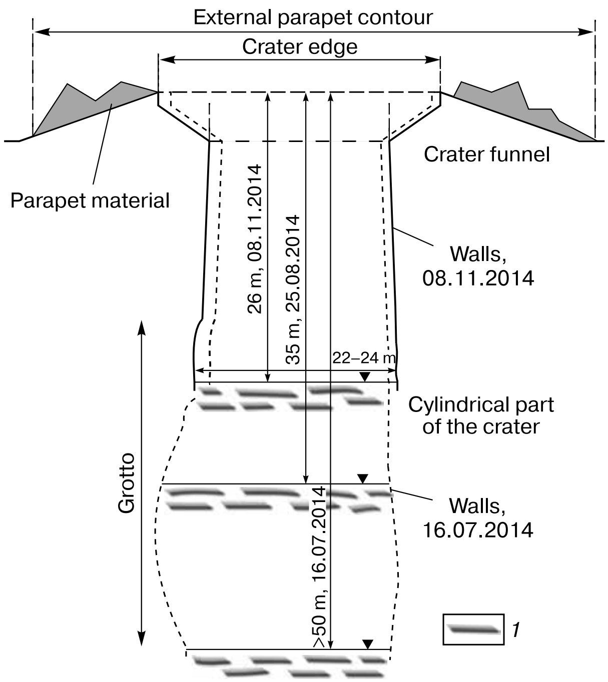

Fig. 8. Crater structure.
1 – lake water at the crater bottom.

Fig. 9. Vertical lamination in the section exposed in the sloping walls of the crater funnel.

Subtracting the DEM 2014 and 2013 (Fig. 5), the volume of the relocated material was calculated (the volumes of the partly destroyed bulge and of the materials ejected from the crater), which amounted to 11,200 m^3, and the volume of the material deposited around the periphery as a parapet – 1,940 m^3. The volume of the deposited material is nearly 6 times less than the volume of the void formed. The difference of 9,260 m^3 is the volume of ice ejected from the crater to the ground surface and melted in the spring-summer of 2014.

Shown in Fig. 6, *c* is the schematic view of redistribution of the height points as a result of the crater formation. The negative values correspond to the area of material ejection and of bulge destruction. The positive values correspond to the areas of material accumulation as a parapet around the crate perimeter. This diagram was obtained by subtracting the DEM 2014 and 2013. The accuracies of the DEM developed are within the range of 0.5–1.0 m. In this regard, the values of the height difference within the range from plus 1 to minus 1 m are within the error limits of the models and are shown on the diagram with white color as an area of minimum changes in the surface level. To illustrate the structure of the changes revealed, the color scale was developed with a varying height pace for positive and negative values, as negative values have a wider range.

It follows from Fig. 6, *c* that the material deposited as a parapet is non-uniformly distributed around the crater. The parapet deposits from the northern crater side are the largest; here the maximum parapet thickness of 3.2 m was recorded. In the southern and western parts of the parapet, the deposits are fragmentary; they are within the error limits of the model in the larger part of the area, i.e. they do not exceed 1 m in relation to the surface of 2013. It is likely that the revealed irregularity of the deposited parapet material is related to displacement of the emission axis in relation to the bulge top or its inclination.

The field studies conducted in the summer of 2014 revealed intense thawing of permafrost in the crater walls and collapsing of rock blocks from the edge. A lake got formed at the crater bottom. The rate of filling the crater with water was determined on the basis of field measurements of the water level, as well as by comparing the photos of the grotto in the lower part of the northeastern crater wall.

The deep grotto in the lower crater part recorded in the photos of July was filled with water by the end of August 2014, the water level in the lake rose by about 15 m from July 16 to August 25 (Fig. 10). In August, a much less deep grotto was recorded in the crater walls, which also turned out to be partly filled with water by November.

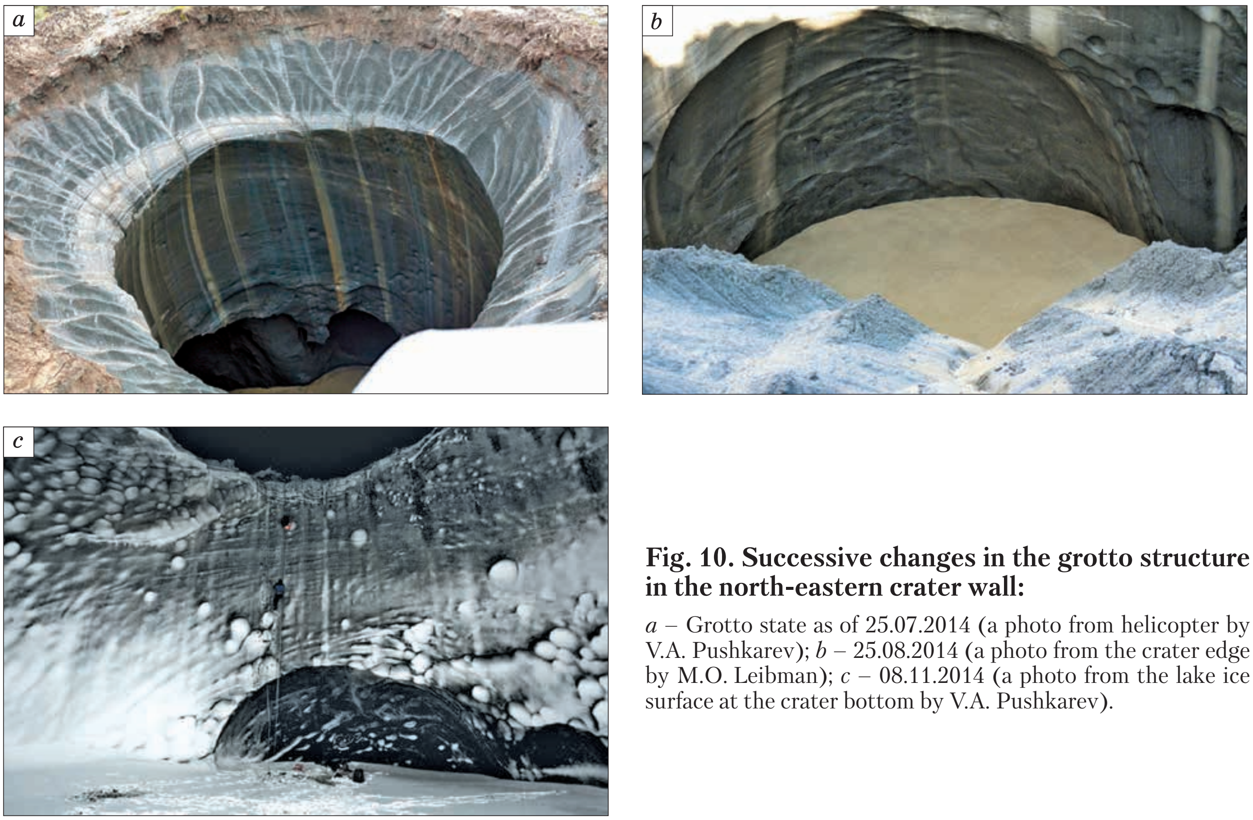

Fig. 10. Successive changes in the grotto structure in the north-eastern crater wall:

a – Grotto state as of 25.07.2014 (a photo from helicopter by V.A. Pushkarev); *b* – 25.08.2014 (a photo from the crater edge by M.O. Leibman); *c* – 08.11.2014 (a photo from the lake ice surface at the crater bottom by V.A. Pushkarev).

During the field works of 08.11.2014, we were able to measure the height difference between the crater edge and the bottom-lake ice surface, which was 25.5–26.0 m. The lake level rose by about 9 m from August 25 to November 8. This rise was also recorded by the change in the height from the lake surface to the grotto vault. The grotto expanded in size simultaneously with the rise in the water level: retreat of its rear wall and the rise of the vault due to ice melting in which the grotto was formed amounted approximately to 3–4 m during the warm season. Thus, in 2014 the lake level in the crater rose by about 24 m.

The experience of the winter works in Central Yamal shows that in the winter period of 2014/15 the crater may get fully filled with snow due to blizzards. In 2015, the spring melting of snow accumulated in the winter period will result in the rise in the lake level minimum by 10 m (about 25 m of snow having the average density of 0.4 g/m^3). Disruption and collapse of material blocks from the crater edge and thawing of permafrost in the crater mouth also make their contribution to the rise in the lake level.

The crater will get completely filled in approximately 1.5–2 years under conditions of snow accumulation in the winter period with the thawing rates of ice-bearing permafrost exposed in the crater walls preserved.

As a result of comparing the internal diameter of the crater measured on the satellite images and during the field studies, certain increase in the crater size from June to November 2014 was revealed.

The diameter of the cylindrical part of the crater was determined during the field study of 16.07.2014 by measuring the parapet width with a measuring tape and subtracting this value from the diameter of the external part of the parapet obtained by GPS survey. Due to the imperfections of the method, the diameter was evaluated as varying within the range of 25–30 m in the upper part of the expansion to 20–25 m in the cylindrical part.

The diameter was measured on 25.08.2014 with a measuring tape stretched between the edge sides. The measured value (25 m) includes some errors related to visual projection of the internal crater boundaries onto the measuring tape stretched in the upper part of the crater mouth. Due to significant inaccuracy, the measurement data were not used for calculating the crater size dynamics. A slightly higher value of the internal crater diameter (28 m) was obtained from the studies conducted in September 2014 [*Epov et al., 2014*]. Closer to the end of the warm season, the upper parts of the crater receded more intensely, and the part of the overhanging walls acquired a small positive slope.

The diameter of the cylindrical part of the crater with subvertical walls was measured to a high degree of accuracy with a lidar during a new study of 08.11.2014. The measurements were made at the level of the frozen lake surface (approximately 24–26 m below the crater edge). In this cross section, the crater shape is close to that of a regular circle. The diameters measured in the north-south and west-east directions were practically the same: 22.3–22.6 m. The grotto protruded into the crater wall by approximately 2 m, and the crater diameter was 24.2 m.

To evaluate the retreat rate, only precise direct measurements of the diameter of the crater, which constituted 15–16 m in the upper part of the cylinder, according to the satellite images of 15.06.2014, and 22–23 m, measured on 08.11.2014 at the depth of 24–26 m below the crater edge, were employed. According to these data, the diameter of the cylindrical crater part increased by 7 m from June to November 2014. It seems that the diameter increase is related to melting of the ice walls due to direct solar radiation, heat exchange with the air (air gets mixed by the wind, which was noted during the works inside the crater in November 2014), and dripping of the melted water down the frozen walls. The retreat rate of the ice walls from June to November, i.e., practically during the entire warm season of 2014, was 3.5 m.

The data on the thermal denudation rates of the walls composed of ice-bearing deposits on the Yamal Peninsula are shown in the monographs by *Dubikov* [*2002*] and *Kritsuk* [*2010*]. On the shore of Lake Neito, the retreat rate of the tabular ice exposures was 1.5–3.5 m/year, while on the right bank of the Se-Yakha River, within the limits of the Bevanenkovo uplift, the denudation rate of tabular ground ice on the terrace slope changed within the range 7 to 11 m/year [*Dubikov, 2002*]. In the area of the Marre-Sale polar station, the average retreat rate of the ice-bearing wall was about 3 m/year [*Kritsuk, 2010*]. On the shore of the Yugorsky Peninsula in 2001–2003, the average retreat rates of the thermocirques varied from 1.6 to 4.2 m/year, the maximum retreat rates varied from 3.3 to 5.8 m/year [*Kizyakov, 2005*]. The average retreat rates of the thermocirques on the western coast of Kolguev Island in 2002–2012 were 1.3–3.2 m/year [*Kizyakov et al., 2013*].

The retreat rates of the crater walls we calculated are close to the lower values of the thermal denudation rates, characteristic of this region. It seems to be attributed to the exposure shape, due to which the walls composed of ice turned out to be shadowed. In the lower part of the crater, cold air may get stagnated, which reduced the wall thawing rate.

The data on the morphology and dynamics of the crater formed in Central Yamal will be used in further studies to investigate the structure of the new feature and its connection with the cryolithologic structure. Ultimately, the joint analysis of these materials will allow us to substantiate the hypothesis of this object's formation, based on the actual data. In November 2014, the crater walls were sampled, in order to specify their cryolithologic structure.

The object studied is a unique feature for the permafrost zone. For the first time, the crater dynamics is being observed in the final phase of its development during field studies. In this regard, it seems necessary to organize full-scale study of the crater and the specific characteristics of the adjacent territory. The geophysical study should be supplemented by drilling to the depth of 50–100 m, sampling frozen rocks with preserved structure. The organized and well-planned system of the research will allow the origin and the formation conditions of the crater to be determined, as well as the main controls which contributed to its formation to be revealed. It is only on the basis of these results that we may be able to approach the possibility of predicting such features and of identifying the areas of their possible occurrence, including application of remote sensing data.

The gas emission crater in Yamal was discovered to a certain degree by chance from the helicopter board. Despite the existing gas production facilities, the vast expanses of the north of Western Siberia (and Yamal, in particular) are very scarcely populated, while the helicopter flight corridors are quite narrow. Regular observations are not conducted for these territories; therefore formation of such craters may remain unnoticed. Under these conditions, high-resolution and very high-resolution satellite survey is a rather effective tool for the search and early detection of the emerging craters. It is reasonable to apply such monitoring in the areas within which there is potential for forming such craters and where their emergence may be dangerous for the production and residential infrastructure (settlements, production facilities, gas- and oil pipelines).

Further studies will require differential GPS-survey of the basic structures of the crater formed and of the surrounding structures to specify the DEM developed and to assess the dynamics of the crater morphology.

CONCLUSIONS

Joint analysis of the field survey materials and of the satellite images, with digital models developed for the periods before and after the crater formation, allowed us to make the following conclusions.

1. The gas emission crater in Central Yamal got formed in the period between 09.10.2013 and 01.11.2013.

2. The crater under study spatially coincides with the bulge (a positive landform), which existed at the place before 09.10.2013. The bulge size was the following: the base diameter was 45–58 m, its relative height was 5–6 m.

4. The upper part of the crater funnel is located within the limits of the previously existing bulge. The boundary between the cylindrical part of the crater and the funnel coincides for the height with the level of the surface on which the bulge was located. Thus, the funnel was formed within the limits of the deposits which formed the bulge.

5. The crater size at the beginning of the warm season of 2014 was the following: the diameter of the cylindrical part was 15–16 m, the diameter of the crater mouth edge was 25–29 m, the parapet diameter was about 70 m, the depth from the edge to the lake surface exceeded 50 m. By the end of 2014, the diameter of the cylindrical part increased to 22–23 m, while its depth reduced to 26 m.

6. In 2014 the level of the lake water surface at the crater bottom rose approximately by 24 m.

7. The volume of the relocated material (ejected from the crater and partly destroyed bulge material) amounts to 11,200 m^3. This is nearly 6 times greater than the volume of the material deposited around the crate periphery (1,940 m^3). The greater amount of the ejected material (9,260 m^3) consisted of ice, which is exposed on the cylindrical walls of the crater, according to the field survey.

The field survey of the unique natural phenomenon, the gas emission crater in Central Yamal, was organized by the Russian Center for Arctic Exploration (director V.A. Pushkarev), the Department for International and Foreign Economic Relations of the Yamal-Nenets autonomous district (director, vice-governor of the Yamal-Nenets autonomous district A.V. Mazharov), and the Department for Science and Innovations of the Yamal-Nenets autonomous district (director A.L. Titovsky).

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