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NEW DATA ON INTENSIVE EARTH DEGASSING IN THE ARCTIC IN THE NORTH OF WESTERN SIBERIA: THERMOKARST LAKES WITH GAS BLOWOUT CRATERS AND MUD VOLCANOES

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In the last decade, in the north of Western Siberia, the authors have carried out a large amount of comprehensive research, which has made it possible to obtain fundamentally new information about the gas-dynamic mechanisms of dangerous processes in the Arctic permafrost. According to remote sensing data, at the bottom of thermokarst lakes, rivers and coastal zones of the Kara Sea, more than 4.5 thousand zones of powerful gas blowouts with the formation of craters (pockmarks) have been found. There are reasons to believe that powerful gas blowouts mainly come from shallow deposits with ultrahigh (superlithostatic) pressures. For the first time, large mud volcanic uplifts with pronounced craters have been found at the bottom of the Arctic thermokarst lakes. Based on the monitoring of the ice situation and the water environment on the basis of retrospective satellite images on thermokarst lakes Otkrytiye, Labvarto and Yambuto, the presence of periodic emissions of formation fluids, including gas, is shown. Based on the combination of a number of features, the discovered objects can be classified as active mud volcanoes with a high level of probability. The results of the studies allow us to state that mud volcanism is widespread in the Circum-Arctic megaregion.

Keywords: Arctic, *Western Siberia, Yamal, Earth degassing, thermokarst lakes, taliks, gas blowouts and explosions, mud volcanoes, gas hydrates, remote sensing (RS).*

1. Introduction

In the last decade, scientific researches in the Arctic have taken a considerable interest in the phenomenon of Earth degassing, which is mainly due to the observed stable global increase in the concentration of greenhouse gases (mainly carbon dioxide and methane) in the atmosphere and the highest warming rate in the Circum-Arctic megaregion [1-4]. It is obvious that warming in the Arctic expands the scale of permafrost (PF) degradation, which intensifies greenhouse gas emissions into the atmosphere, and this, in turn, contributes to further climate warming. However, the real scale of this phenomenon is not obvious and debatable. Many hundreds of papers have been devoted to the study of the spread of anomalous zones and the main causes of intense gas emissions into the atmosphere in the Arctic and the World Ocean, including [1-11].

In 1965-1969 on the Scottish shelf (New Scotland, Canada), for the first time, zones of gas blowouts from the seabed were recorded in the form of subsurface craters with a diameter of 15 to 45 m and a depth of 5-10 m, called pockmarks [12]. The discovery of pockmarks as a new dangerous natural phenomenon associated with the degassing of the Earth attracted the attention of many researchers, which resulted in a number of articles about their presence in various parts of the World Ocean [13-16]. Additionally, in the early 1970s, thermokarst lakes were discovered on the Taz Peninsula in the area of the Urengoy and Samburg oil and

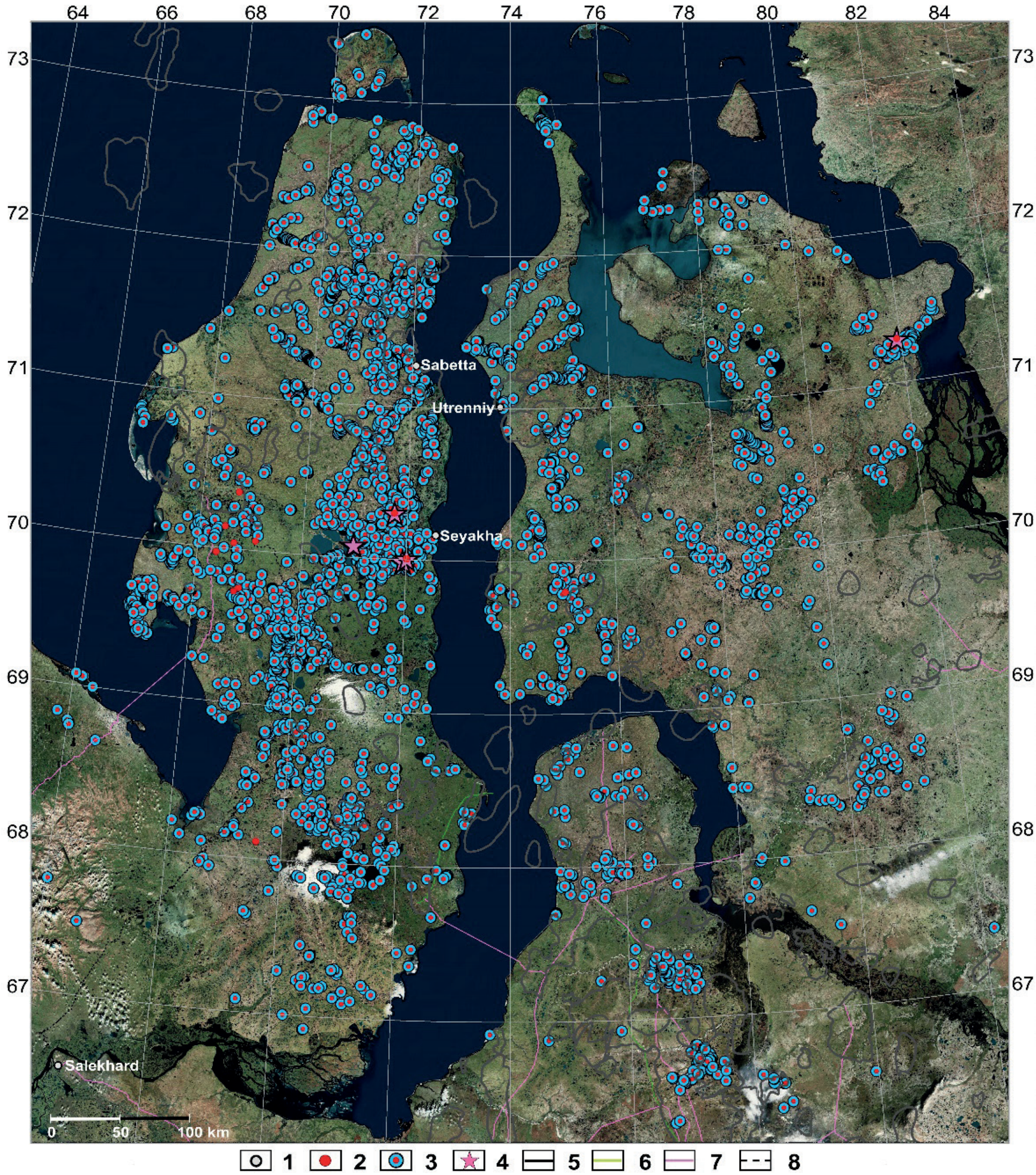

Fig. 1. Distribution of powerful gas blowout zones in the North of Western Siberia. Legend: 1 — settlements, 2 — isolated craters of gas blowouts, 3 — craters of gas blowouts on the water bottom, 4 — mud volcanic manifestations, 5 — contours of oil and gas fields, 6 — oil pipelines, 7 — gas pipelines, 8 — railway. The base map is a mosaic of satellite images by ESRI

gas condensate fields (OGCF), at the bottom of which numerous gas blowouts were observed in the form of craters of various diameters [17], similar to the above-mentioned pockmarks. Half a century of research has not reduced interest in this phenomenon, and its study is still actively continuing [1; 2; 10; 11; 18-25].

In the last decade, the Oil and Gas Research Institute of the Russian Academy of Sciences (OGRI RAS) has significantly expanded the studies using ultrahigh resolution remote sensing (RS) data from space in the optical frequency range, as well as during expeditions [21-25]. As a result, over 4.5 thousand zones of powerful gas blowouts from the bottom of shallow parts of the coastal zones of the Kara Sea, rivers and thermokarst lakes with gas blowout craters (TLGBC) have been discovered in the north of Western Siberia (Yamal, Gydan and Taz peninsulas) [21-23]. In addition, about 20 giant craters in the PF have been found on land in the north of Western Siberia, formed due to powerful gas blowouts with explosions (see Fig. 1) [11; 26; 27].

One of the widespread dangerous forms of Earth degassing is mud volcanic eruption. According to Russian State Standard (GOST) R 57123-2016 [28], mud volcanoes (MVs) are "... geological formations that constantly or periodically erupt mud and gases... There may be mud volcanoes in places of pre-existing faults."

The atlas, unique in its completeness of generalization, compiled by Azerbaijani scientists [29], contains data on 2505 MVs and mud volcanic manifestations, including 1401 (55.9%) at the bottom of the World Ocean. Mud volcanism is undoubtedly one of the most dangerous natural phenomena, in which powerful gas blowouts often self-ignite and explode. The height of the burning MV flares can reach several hundred meters, more than 500 m [29; 30], and in 1940 on the mud volcano island of Khare-Zira (before 1991 — Bulla, 39.996° N, 49.644° E) — even 1200 m [30, p. 18]. In our opinion, confirmed by a number of available facts, spontaneous ignition and gas explosions during gas eruptions occur due to the electrification of space and electrostatic discharges [11; 25], and such high flares indicate gigantic volumes of gas emitted (many millions of cubic meters).

The triggers for MVs are earthquakes, but MVs themselves generate seismic events. The presence of MVs is one of the prospecting indicators for oil and gas, while they provide significant information about the lithology of the sedimentary strata covered by the mud volcanic process [11; 25; 29; 30].

The study of the MV distribution in the Arctic is at an early stage: most generalizing publications mention only one or three volcanoes [29-31]. Traditionally, the main mud volcanic basins are linked to the zones of Alpine tectogenesis, which reduces the interest of researchers in the search for MVs in the Arctic. However, in the Circum-Arctic megaregion, there are sedimentary basins with large complexes of terrigenous Meso-Cenozoic sediments in which they could well have been formed. It should be noted that as a result of detailed studies of a number of pingo-like features (PLF) by the geological surveys of the USA and Canada (USGS and GSC) in the Beaufort Sea, more than 10 of them have been proved to be MVs [32; 33]. The analysis of the published materials allows us to assert the existence of an incomparably larger number of MVs at the bottom of the Beaufort Sea in the area of discovery of many hundreds of insufficiently studied PLFs.

Moreover, MVs have already been discovered and there are signs of their existence in other parts of the Circum-Arctic megaregion both offshore and onshore [25; 32-38], including the north of Western Siberia [25; 35; 36]. In particular, on the Tazovsky Peninsula in the area of the Pestsovoye Field, A.A. Nezhdanov [35] found "traces of a separate mud stream on the slope of a large hill." In the north of the Gydan Peninsula near the Deryabinsky crater C4 (250 m to the south) in a local area of 35×110 m with two conical elevations V.A. Epifanov [36] discovered an abundance of pieces of rocks, possibly moved from deep deposits by a mud volcanic eruption.

The aim of this work is to identify new dangerous Earth degassing objects of mud volcanic genesis in the Russian Arctic. The northern part of the West Siberian oil and gas basin has been chosen as a priority region, including the Yamal Peninsula, where hydrocarbon production has been carried out for about a decade at the Novoportovskoye, Bovanenkovskoye and Yuzhno-Tambeyskoye fields.

2. Materials and Methods

Since 2014, OGRI RAS has conducted a large amount of expeditionary research on the Yamal Peninsula of a new dangerous phenomenon — explosive degassing of the Earth with the formation of giant craters on land and the bottom of thermokarst lakes, rivers and coastal zones of the Kara Sea [11; 21-27; 38]. Complex geological and geophysical studies included echo sounding, ground penetrating radar (GPR), seismic prospecting, photography from unmanned aerial vehicles (UAVs), shallow wells drilling and geochemical analysis of gas samples taken.

Particularly important results were achieved using UAVs [21; 26; 27], which made it possible to obtain fundamentally new data in three- and four-dimensional form (3D-4D). At the same time, digital photogrammetric processing was performed using specialized software Pix4Dmapper (Pix4D SA, Switzerland) and Agisoft Metashape Professional (Geoscan, Russia) [39].

Geospatial data on the detected zones of intensive Earth degassing are accumulated in the geographic information system "Arctic and World Ocean" (GIS "AWO") along with other data forming the "Big Data" using the ArcGIS software (ESRI, USA) (for example, see Fig. 1) [11; 21—27].

In complex research in the Arctic, particularly important information was obtained from multi-spectral and radar RS data from space. The research used data of various spatial resolutions, including ultra-high resolution (up to 1 m) — KeyHole (KH) from Corona program (USA), WorldView (WV), QuickBird (QB), Resurs-P (until September 2021) and Canopus-V, as well as high, medium and low resolution (10-80 m) — Sentinel (S), Landsat (LS), etc. A retrospective analysis of the studied objects condition with a possible search depth of about 60 years (KH satellites) provided unique monitoring information [11; 21-27; 41-43]. 3D-4D construction of digital terrain models by ArcticDEM (USA) were also very informative [26; 27; 42-44].

3. Results

On the Yamal Peninsula, in more than three thousand thermokarst lakes, direct signs of intensive degassing from the subsurface were found in the form of craters and gas bubbles frozen into ice (see Fig. 1). For some

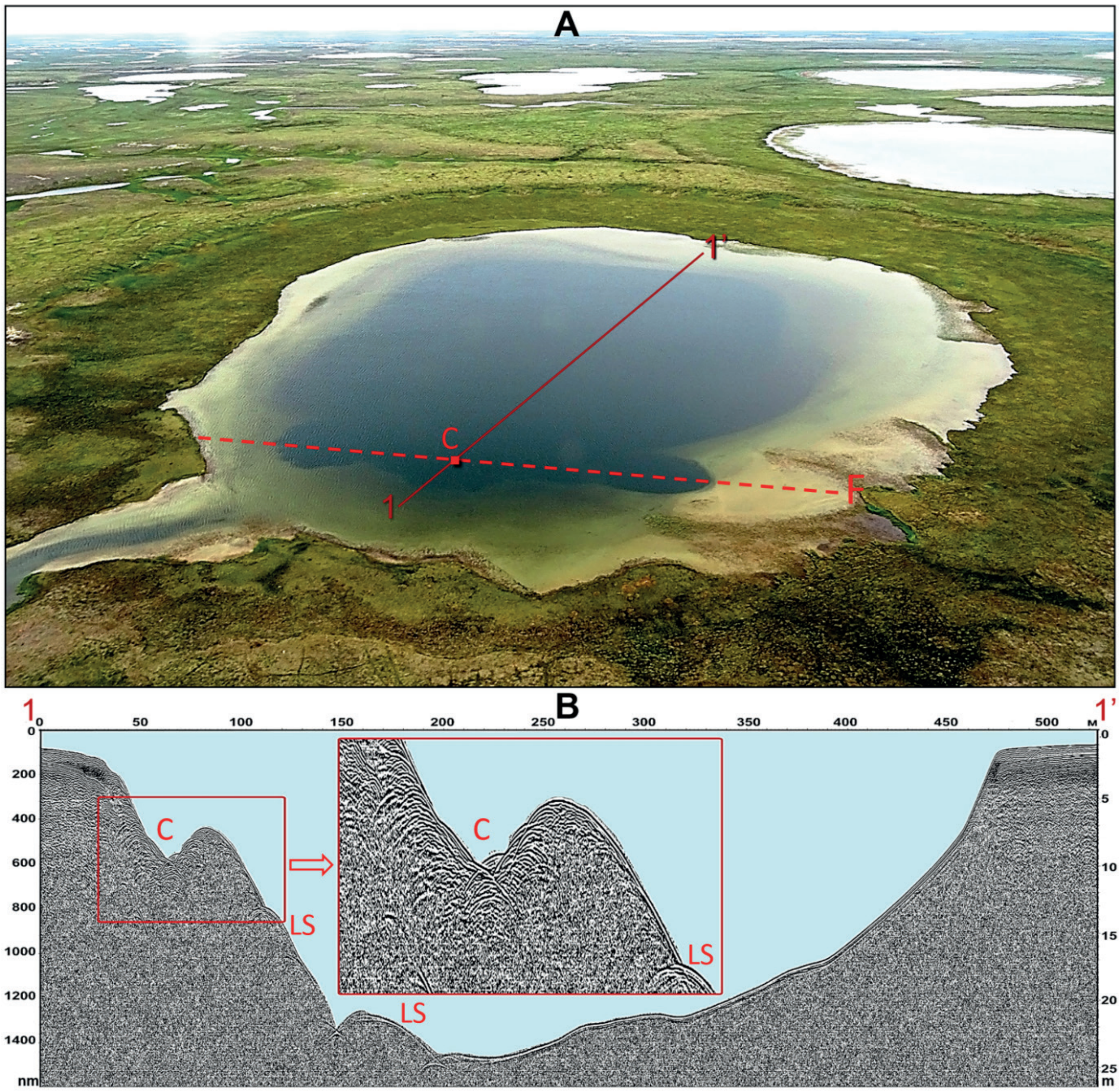

Fig. 2. Aerial photograph of thermokarst Lake Otkrytiye from a helicopter (A) and ground penetrating radar (GPR) profile (B) with an enlarged fragment in the crater area. Legend: 1-1' — position of B profile, F — predicted position of the fault strike, C — gas blowout crater, LS — landslides

of the degassing objects at the bottom of thermokarst lakes, the authors justified the mud volcanic eruption mechanism according to GOST R 57123-2016 [28]. In particular, in the central part of the Yamal Peninsula, on the basis of expeditionary research and RS data, thermokarst lakes Otkrytiye, Labvarto and Yambuto were discovered, at the bottoms of which large craters were observed with clear water, including in the tops of conical uplifts, identified by us as mud volcanic structures.

3.1. Thermokarst Lake Otkrytiye

The thermokarst Lake Otkrytiye, measuring 440×750 m, is located in the central part of the Yamal Peninsula (70.006° N, 72.01° E, see Figs. 1 and 2A). We named it Lake Otkrytiye («Discovery» in English) after receiving fundamentally new important information about gas dynamic phenomena in the Arctic [21; 22; 45]. In the spring of 2019, a phenomenally powerful blowout (pneumatic explosion) of gas occurred from the lake bottom, breaking the ice sheet about 1.5 m thick and scattering huge blocks of ice over 50 m from the epicenter of the explosion.

Retrospective analysis of Sentinel-2 (S-2) and Landsat-8 (LS-8) satellite images during ice melting (May-June) proved that gas emissions occurred in the same place in winter time annually in 2016-2019, however, in 2020-2023 evidence of significant gas emissions in ice were not detected.

Based on ultra-high-resolution RS data and results of expedition (see Fig. 2A) four adjacent large craters

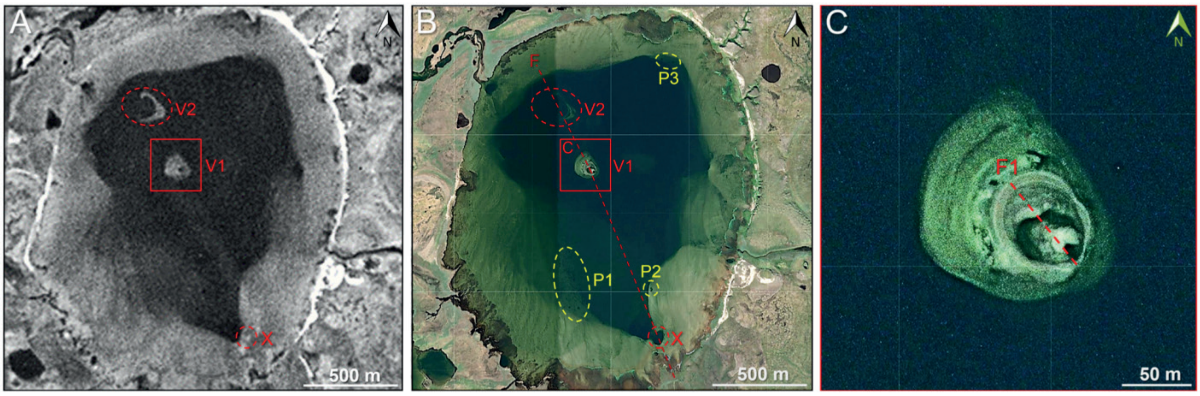

Fig. 3. Satellite images of thermokarst Lake Labvarto KH-9 (A) and WV-4 (B) with its enlarged fragment (C) from ESRI database. Legend: P1, P2 and P3 — pockmarks, V1 and V2 — mud volcanoes, X — probable place of gas blowout, F and F1 — predicted faults

(with a diameter from 30 to 45 m) located linearly along the predicted deep submeridional fault (azimuth 345°), as well as several small-diameter craters (up to 4-6 m) were found at the bottom of the TLGBC Otkrytiye (see Fig. 2B). According to echo sounding data gathered in 2019, the depths of four large craters were 4 to 5 m. As a result of microseismic 4D monitoring, the azimuth of the extent of an isolated deep fault traced to the main Cenomanian gas horizon was 325° [45].

Using echo sounding and GPR in expeditionary studies made it possible to detect landslide bodies (LS) on the crater walls and the lake bottom formed by presumably loamy rock erupted from vents. In view of the above, four underwater objects with large craters on Lake Otkrytiye, according to [28], can be attributed to MVs with high probability. The results of comprehensive studies on TLGBC Otkrytiye are given in more detail in [21; 22; 45].

3.2. Thermokarst Lake Labvarto

The thermokarst Lake Labvarto (69.985° N, 71.9354° E), which name from the Nenets language according to M. N. Okotetto means "Lake of collapsed shores", measures 1550×2140 m, is located 3.7 km southwest of the craters of Lake Otkrytiye and 32 km east of Lake Yambuto. Figures 3A and 3B show summer satellite images of Lake Labvarto with ultra-high spatial resolution from the KH-9 satellite on August 22, 1976 (resolution 60 cm) and WV-4 on August 26, 2018 (resolution 30-50 cm), mainly indicating minor changes over a half-century period. These images show two large uplifts V1 and V2 in the central and northwestern parts of the lake, 580 and 310 m away from the shore identified by authors as mud volcanic structures. Also, in the satellite image (Fig. 3B), three zones of small craters' existence (P1, P2 and P3), not visible in Fig. 3A, were found on the shallow bottom. In addition, in Fig. 3A, object X (an uplift) is observed, which we deciphered as the sun shadow "game" [22; 42], and in Fig. 3B, in its place there is a crater-like elliptical object with a size of 45×80 m. Very likely, that the X uplift was a PLF of gas-dynamic genesis, and the crater-like object was formed due to the blowout and explosion of gas like other craters on Yamal [11; 26; 27].

It is important to note that the F line connecting the centers of V1 and V2 (see Fig. 3B) has a north-westerly orientation in azimuth about 333°, and its continuation to the southeast falls exactly into the center of the P2 crater zone. In addition, the line between the centers of the V1 uplift and the crater-like depression X has an azimuth of 337°, and the average azimuth between these two is 335°. Most likely, the F line reflects the position of the deep discontinuity - the F fault.

The western side of the V2 uplift is presumably dilapidated (washed out), so below we will consider in detail only the V1 uplift. The grounds for the assignment of the object V1 to MV are its characteristic conical slightly asymmetric shape and the crater/caldera presence with eruptive channels (vents), clearly visible on the enlarged fragment (Fig. 3C). The top of the V1 uplift has dimensions of 70×80 m, and the lower part visible through the water is 130×150 m, while the actual size of the uplift base is significantly larger, since the bottom is not visible. Heterogeneities resembling accumulative and landslide forms are well distinguished on the top of the V1 uplift. Also, in the upper part, possible additional lateral channels (seeps or gryphons) are observed, which are often formed on the side walls of mud volcanoes [29; 31].

The upper part of the V1 object outlines an elliptical caldera with major axis (F1) orientation in a northwest direction at azimuth 323°, which is presumably also associated with fault tectonics. The ratio of the ellipse axes is 1:1.33 (ellipse compression ratio R_{ce} = 0.75).

Considering that the thickness of lake ice in these latitudes can reach 1.5—2.0 m, we believe that the depth of the top of the MV is close to these values. Due to new eruptions of mud breccia the top of the MV can periodically rise above the water level, but its formation is limited by erosion and annual cutting by melting ice moving in the wind. Note that the topographic map of the 1980s at a scale of 1:50,000 shows an

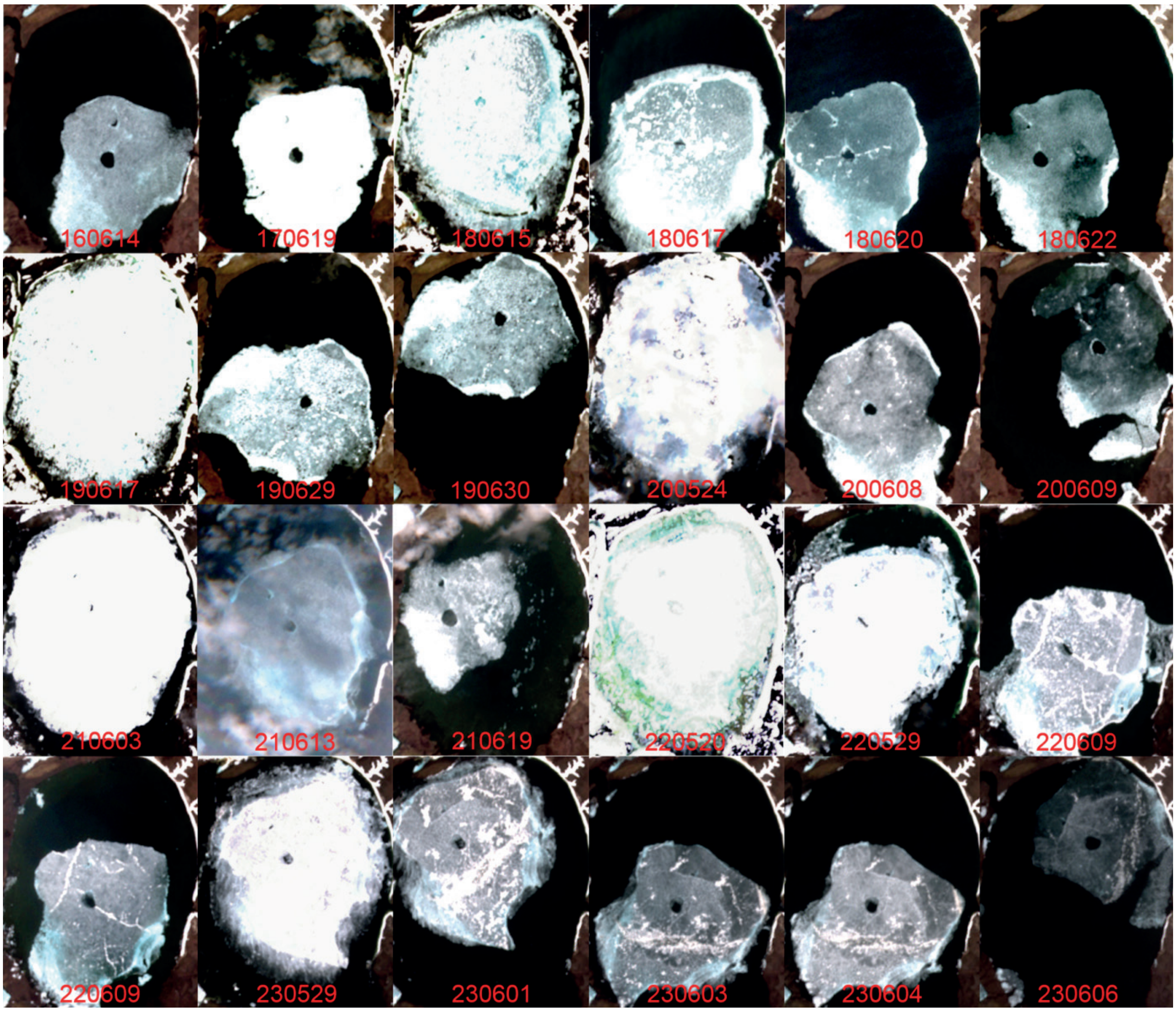

Fig. 4. Ice condition monitoring on thermokarst Lake Labvarto based on Sentinel-2 satellite images from May-June 2016-2023 (numbers — year, month, day)

island measuring 75×85 m at the top of V1. Due to the fact that the Soviet-time mapping was carried out on the basis of interpretation of aerial photographs, it is possible that the presence of the island is shown incorrectly, which is quite acceptable even based on satellite images of KH-9 and WV-4 in Fig. 3.

As a result of comprehensive monitoring analysis of a series of available high-resolution (10 m) Sentinel-2 L1 (S-2) satellite images of the European Space Agency (ESA) for nine years (2015-2023), direct signs of fluid emission from the peaks of volcano-like objects V1 and V2 were revealed at TLGBC Labvarto, some of which illustrated below. Unfortunately, due to the very frequent clouds over the Yamal Peninsula, most of the S-2 satellite images (up to 80-90%) turned out to be substandard.

During the spring ice melting (May-June) of 2016-2023, isolated thawed patches in the ice were observed on S-2 satellite images (Fig. 4). They usually occur in areas of decreasing ice thickness due to inclusions of gas bubbles and/or periodic occurrence of holes in the ice during powerful gas emissions [11; 46]. Such effects are often observed on satellite images over many natural zones of intense gas emission from the bottoms of lakes detected by authors, including TLGBC Otkrytiye [11; 41; 45], as well as on man-made pools (flooded craters) in areas of catastrophic gas blowouts at Gubkinskoye, Kumzhinskoye, Kharasaveyskoye and Bovanenkovskoye fields [11; 46]. According to cloudless Sentinel-2 L1C satellite images, thawed patches on Lake Labvarto were recorded in 2021 from May 30 to June 19, in 2022 from May 19 to June 9, and in 2023 from May 29 to June 6 (see Fig. 4). Thawing above the V1 top in all cases was significantly larger than above V2, apparently indicating larger fluid flows from the V1 object.

In the summer-autumn ice-free period (June-October-November) 2015-2023 relatively short (from 80 to 500 m) plumes of whitish-colored fluids were often observed annually on S-2 satellite images of the lake (Fig.

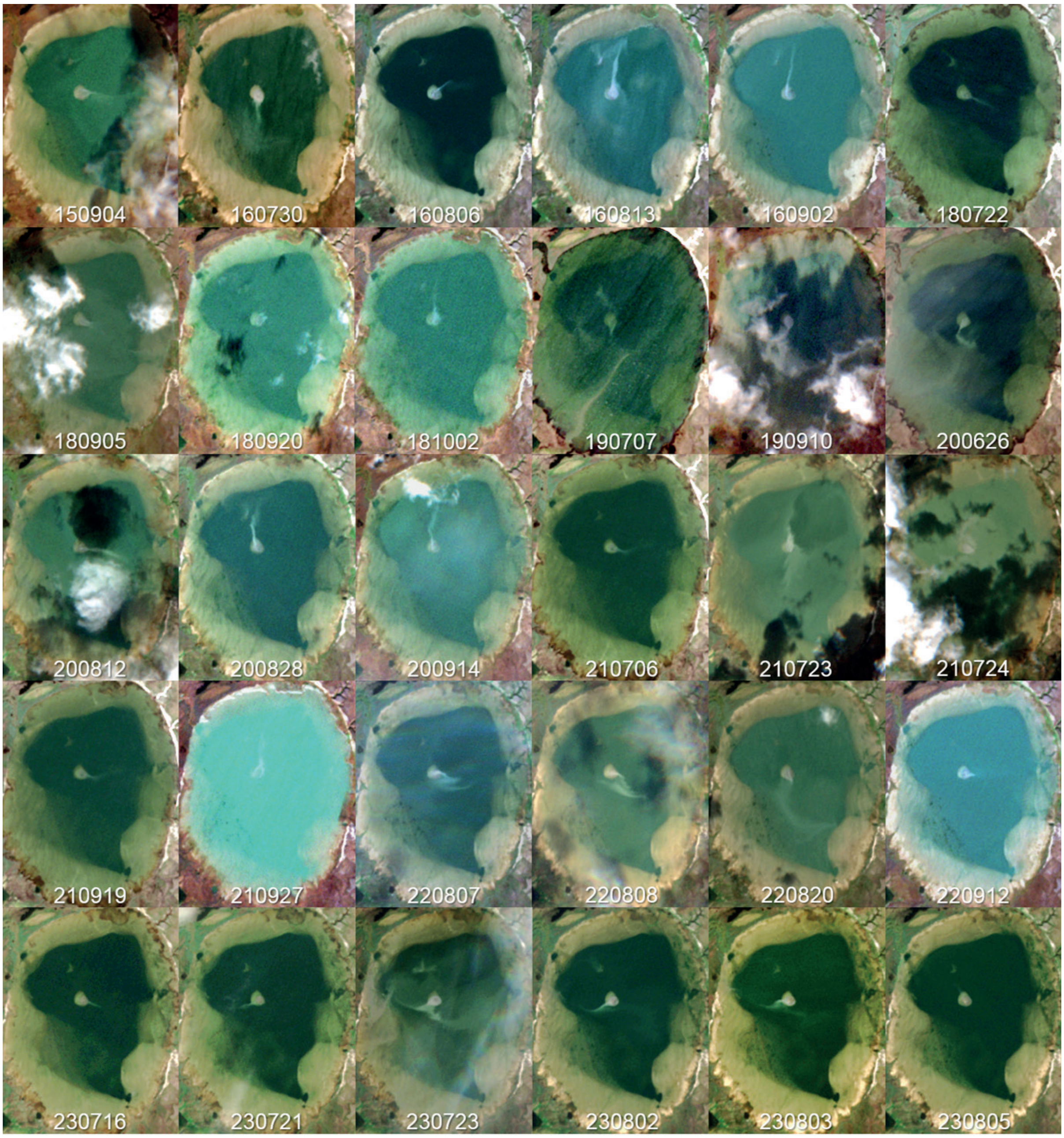

Fig. 5. Fluid manifestations monitoring on thermokarst Lake Labvarto based on Sentinel-2 satellite images from 2015–2023 (numbers — year, month, day)

5) emerging from the tops of V1 and V2 and spreading in the direction of the near-surface water layer moved by the wind. In the optical range satellite images, the whitish color of water occurred due to an increase in albedo in the presence of light mud (turbid) flows, gas bubbles (gas jets), the outlet of reservoir waters with dissolved gas released in the form of bubbles due to a decrease in pressure (decompression) [25]. In 2021, whitish fluid flows were recorded on July 6, 23 and 24, September 19 and 27, and in 2022 — on August 7, 8, 20 and September 12. According to Fig. 5, the longest (most intense?) fluid flows were in 2016 (June 13 and September 2), in 2020 (August 12 and 18, September 14) and in 2022 (August 7 and 8). Perhaps this was due to the strength of the wind and water waves. In the first half of the summer of 2023, fluid flows were recorded on the images from July 16 to August 7 (July 16, 18, 21, 23, 24, 26 and August 2, 3, 5, 7), while they were apparently continuous, but of varying intensity (see Fig. 5). The most intense fluid flows were on July 23 (from V1 and V2), and the most weak ones were on July 28, 31 and August 5, 7.

Additional information about Labvarto Lake was obtained from satellite images from Landsat (LS), available from June 18, 1985 to the present. The LS-5, LS-7 and LS-8 satellite images had low and medium spatial resolutions (60, 30 and 15 m, respectively), and therefore their information content was significantly lower than that of the S-2. Despite the very limited number of conditional images, they allowed us to draw a number of the following conclusions. According to LS7 data, turbid plumes were observed on August 13, 2001, July 24, 2008, July 27 2009, and according to LS-8 — September 28, 2014. Holes in the ice at the sites of the studied objects in June were observed annually (when images are available): June 18, 1985, July 8, 1987, June 27, 1998 (LS-5); June 10, 2000, June 27, 2004, June 29 2007 (LS-7); June 22, 2014 and June 2, 2015 (LS-8).

Interestingly, the LS7 image from July 16, 2000 showed a strong turbidity of the water in the lake, possibly associated with intense mud emissions. Note that on July 22, 1972 (KH-4 satellite) the water in the entire lake was also turbid, one peak (V1) was visible, which may be due to its elevation above the water level. All the above results of the analysis of RS data in combination with satellite images on Fig. 3, 4 and 5 allowed us to conclude with high probability that the mud volcanic objects V1 and V2 were formed much earlier than the 1970s.

3.2. Thermokarst Lake Yambuto

The thermokarst Lake Yambuto (translated by M. N. Okotetto from the Nenets language as “Long Lake”) is located in the central part of the Yamal Peninsula a little east (0.4—3.3 km) from the three large Neyto Lakes (Neyto — “Burbot Lake”). It is the third in Yamal in terms of water surface area (169 km^2), but the longest (22 km) and water-intensive (about 2.35 km^3) [47]. Lake Yambuto is considered the deepest due to the presence of local depressions in the northern part with depths up to 59 and 63.7 m (possible craters of gas blowouts), while its average depth is about 14 m [47]. In relation with a sparse (regional) network of echo sounding profiles made by Moscow State University (MSU) staff in 2007 [47], there is no doubt about the existence of missing local objects at the bottom of the lake, both depressions and uplifts.

Three large cone-shaped uplifts have been discovered for the first time on the basis of ultra-high resolution satellite images in the northeastern part of Lake Yambuto (70.0762° N, 70.9856° E) (Fig. 6). Visible lower parts of these objects have an elliptical shape, and their lateral dimensions are 90×315 m (V1), 90×270 m (V2) and 50×210 m (V3). At the same time, the ratios of the ellipse axes are 1:3.5; 1:3.0 and 1:4.2 (R_{ce} — 0.29, 0.33 and 0.24). The centers of these objects are 490 (V1), 620 (V2) and 650 m (V3) away from the shore. Due to the invisibility of the bottom near these uplifts, it can be assumed that their real dimensions near the bases are somewhat larger. In particular, the V1 uplift seems to have a length of 380-400 m and a width of more than 120 m. Given the sparse echo sounding network [47], the predicted heights of the analyzed elevations reach and possibly even exceed 10 m.

An important feature of the V1, V2 and V3 objects location is that their long axes lie along a slightly curved line F, very likely representing the line of intersection of the bottom by a deep fault of north-western orientation at azimuths from 328° (near V1) to 342° (near V2 and V3), on average 335°. This exactly coincides with the average azimuth of the predicted fault on Lake Labvarto. It should be noted that the continuation of line F to the eastern shore lies exactly on the ravine system, which further strengthens the justification for the F fault existence.

On the well-visible tops of the V1 and V2 uplifts, many specific elements of their structure are observed (see Fig. 6 B). Among them, we highlight crater depressions (calderas) of an elliptical shape in the central parts with internal dimensions of 45×120 m (V1) and 30×65 m (V2), for which the axis ratios are 1:2.7 and 1:2.2 (R_{ce} — 0.37 and 0.45). On the edges and walls of the V1 and V2 uplifts there are characteristic features of layered (sinter) deposits, as well as landslide and lumpy deposits.

The top of the V3 object is deeper than V1 and V2, due to which the structural features of its surface are not visible, and it has been selected only as a predictive object based on general patterns of location with two clearly visible neighboring uplifts.

The available Sentinel-2 L1C and Landsat satellite images analysis from 2016-2022 showed periodic eruptions of extended turbid streams from the V1 and V2 calderas (mainly from V1) on Lake Yambuto, spreading mainly southward in the direction of prevailing water and/or wind currents. Turbidity flows on Lake Yambuto were recorded most confidently: in 2016 — on August 12, October 1, 5 and 24; in 2017 — on July 9 and 10; in 2019 — on September 10 and 11; in 2020 — on July 19; in 2022 — on September 12. It can be noted that in summer and autumn, the activity of eruptions on Lake Yambuto is significantly lower than on Lake Labvarto.

Near the southeastern part of the V1 base, a shallower part of the bottom is observed, formed due to periodic deposition of loamy material carried out from the vent of the V1 uplift mainly in the south direction.

According to RS data, large (over 20 m) thawed areas were not detected during the ice melting, which apparently indicated a lower gas activity of the V1 and V2 objects in winter compared to the V1 object on Lake Labvarto.

4. Discussion

Thermokarst lakes are characterized by the presence of non-through or through taliks, while it is assumed that through taliks are developed under large lakes that do not freeze to the bottom, measuring about 1.5 km and more [48, p. 15]. The genesis of taliks and the nature of their distribution depend on various exogenous and endogenous factors, among which

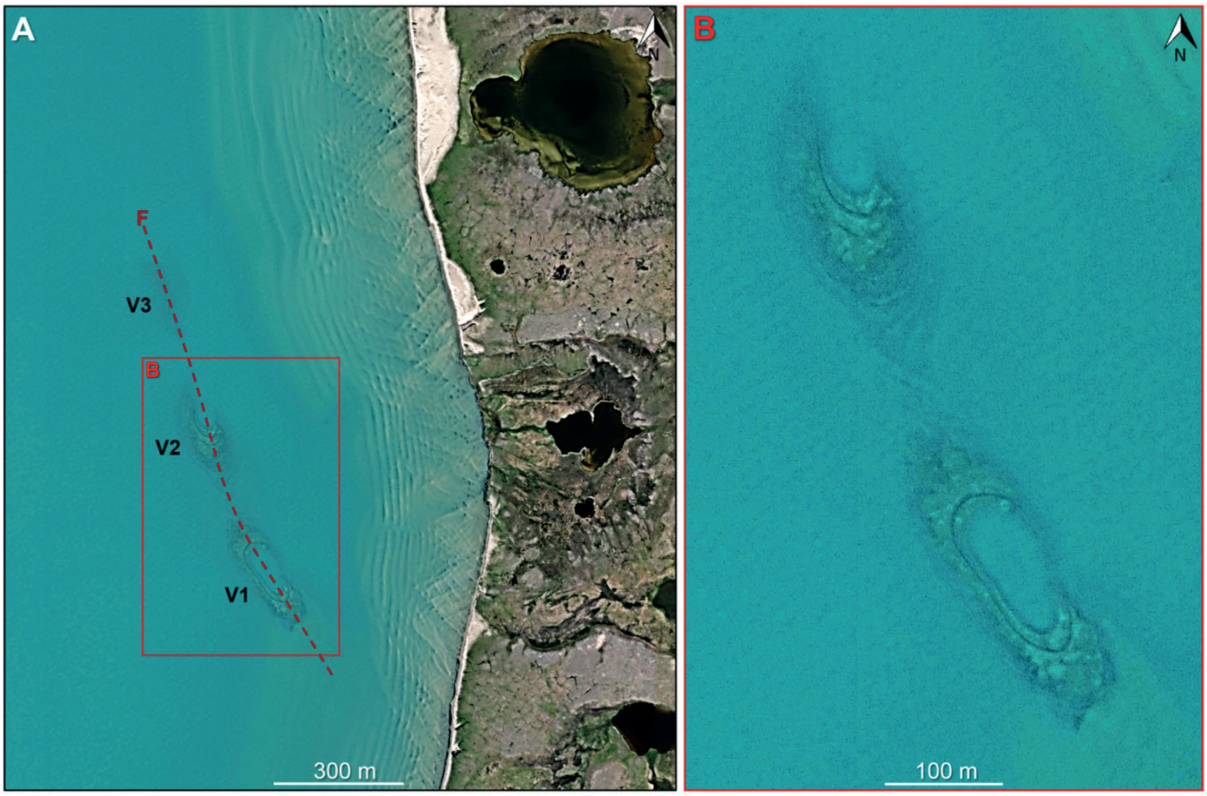

Fig. 6. WorldView-2 satellite image from July 20, 2022 of a part of thermokarst Lake Yambuto (A) with its enlarged fragment (B) from ESRI database. Legend: V1, V2 and V3 — mud volcanoes, F — predicted position of the fault

geological influence, including tectonic and hydrological, stand out: "All kinds of taliks... are essentially polygenic, since their formation and the conditions of existence are always affected by heat flows from the earth interior. In through taliks, this effect is more direct... The thermal regime of through taliks is also always determined by the flow of heat from the earth subsoil, i.e. it depends on geostructural conditions" [49, pp. 24, 28].

Due to the existence of taliks, thermokarst lakes are better channels for vertical migration of reservoir fluids, including hydrocarbons, than the surrounding PF. In addition, the degradation of PF with the formation of thermokarst lakes can include gas hydrate saturated zones, which leads to a violation of the cryogenic gas hydrates thermobaric conditions and their dissociation [48; 50]. As a result of PF degradation the rocks in talik zones undergo significant changes in the physical characteristics, including elastic-strength properties, the propagation and velocity of elastic waves and permeability. The dissociation of gas hydrates leads to the liquefaction of sandy-clay deposits, which contributes to active gas emissions through bottom sediments with the formation of underwater craters and possible processes of mud volcanism.

The origin of pockmark craters is mainly explained by the gas-dynamic mechanism, which is also characteristic for mud volcanoes, while they often exist in close proximity [18]. This in some cases makes it difficult to distinguish their genesis [15]. Pockmarks are mainly associated with gas blowouts from shallow deposits and do not have deep roots, as most of the known MVs [18]. However, it is possible that after detailed research, many pockmarks will be recognized as mud volcanoes. A similar situation arose during a detailed study of pingo-like features (PLF) at the bottom the Beaufort Sea, which, after special studies, were recognized as MVs [32; 33].

On the Yamal Peninsula, there are all the main factors accompanying the formation of MVs in Azerbaijan: "plastic clay strata, reservoir waters, accumulations of hydrocarbon gases, tectonic faults and ... abnormally high reservoir pressure (AHRP)" [29, p. 26].

Lake Yambuto has a 2.3—2.5 times higher content of liquid hydrocarbons and about 1.7—3.8 times higher electrical conductivity than the neighboring Neyto Lakes [47]. These phenomena can be explained by an increased influx of underground fluids, including salt water (cryopegs), the existence of which in the PF has been proven by drilling at depths "from several meters to 215 m" [48, p. 19]. At the same time, the penetration of cryopegs is usually accompanied by gas shows.

Attention is drawn to the strong elongation (ellipticity) of the bases and caldera-shaped craters of the mud volcanic structures of Lake Yambuto: the ratio of the axes of the ellipses varies from 1:2.2 to 1:4.2 (R_{ce} — from 0.45 to 0.24). It should be noted that the elongated (elliptical) shape of the base of the caldera and/or the vent of the known MVs of the world is not uncommon, but indicates that it is confined to disjunctive (discontinuous) dislocations (faults and/or cracks) [29; 30]. In particular, in Azerbaijan, MVs elongated along the faults are known: Toragay, Galmaz, Bala Bahar and others, as well as the volcanic islands of Khare-Zira, Garasu and Zabil [29]. Elongated shapes have some MVs at the bottom of the Black Sea (Vodyanitsky, Ekolog, Manganari) and the Beaufort Sea (Kopanoar) [29]. According to seismic data, the cross sections of the eruptive channel are also "ellipses of irregular shape" [30, p. 51].

It is on record that MVs often occur in groups and form chains stretched along faults [1; 29-31; 38; 51]. On Lake Otkrytiye, located 40 km southeast of the volcano-like structures of Lake Yambuto and 3.5 km southwest of the volcano-like structures of Lake Labvarto according to RS data, a fault at azimuth 345° has been predicted along the line connecting four large underwater craters. Based on the seismic survey data, determining the azimuth of the fault at 325°, the average azimuth is 335° (see section 3.1 and [45]). This azimuth is surprisingly accurate with the average azimuths of the predicted faults on lakes Labvarto and Yambuto (see sections 3.2 and 3.3). As a result, we note that the orientation of the predicted faults on lakes Otkrytiye, Labvarto and Yambuto is well aligned with the orientation of the Yamal Rift isolated from the West Siberian rift system (according to various data, the azimuth is 318-330°) and the seismic data on fault tectonics [25; 38; 52; 53].

At the end of spring 2020, the perennial heaving mound (PHM) C17 exploded at the Bovanenkovskoye OGCF under gas dynamic influence with a powerful gas blowout [27; 42; 43], as a result of which a giant cavity in the ground ice massif was exposed. Its base had an elliptical shape with the major axis oriented in the northwest direction at an azimuth of 350°, which is close to the azimuths of deep faults identified according to seismic data in the Jurassic-Cretaceous complex (mainly 353 ± 6°) [43] and the orientation of the volcanogenic objects described above. The ratio of the axis lengths of the ellipse 1:4.4 (R_{ce} = 0.228) is comparable to the characteristics of the three objects on Lake Yambuto (R_{ce} from 0.45 to 0.23). The main explanation for such pronounced elliptical shapes of the base of the C17 cavity and mud volcanic objects of Lake Yambuto is the occurrence of disjunctive dislocations.

By their genesis, the uplifts identified on thermokarst Lakes Labvarto and Yambuto cannot in any way be attributed to cryogenic PHMs (bulgunnyakhs-pingos) having an ice core. They exist in a year-round non-freezing aquatic environment at the bottom of large thermokarst lakes with most likely through taliks. According to [47] and our measurements, the water temperature in large thermokarst lakes of central Yamal in the summer is 5-9°C. In addition, cryogenic PHMs usually have a rounded or slightly elliptical shape, which radically distinguishes them from the three objects on Lake Yambuto with a very small R_{ce} value and a large eccentricity. The studied objects have all the attributes of MV, and we do not see any other model capable to explain their genesis as convincingly.

It is very possible that other mud volcanic structures exist at the bottom of Lake Yambuto and the neighboring three Neyto lakes (Neyto 1st, Neyto-Orto and Neyto-Malo). According to S2 satellite image, on September 19, 2021, there was a very strong turbidity in the central part of Yambuto (there was no turbidity on September 15 and 27). On the same day, in the central part of Lake Neyto 1st, was observed to be large in size but weak in intensity turbidity around a conical uplift of about 25 m high with a base diameter of about 1 km [47], which was also located according to RS data (70.1655° N, 70.7687° E). Without going into details, we note that gas manifestations of all large lakes in the central part of Yamal require further research.

5. Conclusion

In the last decade, the authors have carried out a large amount of expeditionary research on the Yamal Peninsula, which has allowed, in the process of extensive integration with RS data from space, to obtain fundamentally new information about the gas-dynamic mechanisms of dangerous processes in the cryolithozone, including catastrophic gas blowouts and explosions with the formation of numerous giant craters on land and bottoms of thermokarst lakes [11; 21-27; 38, 41-43; 45; 46]. RS data in remote regions of the Arctic, including the northern part of Western Siberia, provide a unique opportunity for retrospective analysis of the situation in the areas of the studied objects with a depth of research of about 60 years.

According to RS data, in the north of Western Siberia, at the bottom of thermokarst lakes, rivers and coastal zones of the Kara Sea, more than 4.5 thousand zones of powerful gas blowouts with the formation of craters have been identified. The Yamal Peninsula is characterized by the highest concentration of objects with near-surface gas dynamic activity, where over 3 thousand zones of intensive degassing have been found. Compared with permafrost rocks, taliks at the bottoms of thermokarst lakes, rivers and shallow waters of the Arctic Ocean that do not freeze to the bottom create significantly better ways of subvertical migration of gas and facilitate its emission into the hydrosphere and atmosphere. There is reason to believe that powerful gas blowouts mainly originate from shallow deposits with ultrahigh (superlithostatic) pressures [11; 25; 38; 51]. In these deposits, gas can accumulate due to migration from deep and/or shallow sources, including dissociation of cryogenic gas hydrates, as well as through the inflow of microbial gas (in situ).

For the first time, large mud-volcanic structures with clearly visible craters have been discovered at the bottom of Arctic thermokarst lakes. When monitoring the situation using retrospective satellite images on lakes Otkrytiye, Labvarto and Yambuto, the presence of periodic emissions of reservoir fluids, including gas, is shown. According to the combination of a number of signs, the detected objects with a high level of probability can be attributed to active MVs. Earlier, such obvious mud-volcanic structures at the bottom of thermokarst lakes were unknown throughout the Circum-Arctic megaregion. It should also be noted that currently, in addition to lakes Otkrytiye, Labvarto and Yambuto, several more lakes with similar objects are being investigated.

The results of studies of mud volcanic structures at the bottom of thermokarst lakes of the Yamal Peninsula, taking into account a number of previously discovered MVs on the land of Alaska, Greenland and Iceland, as well as at the bottom of the Beaufort, Norwegian, Barents and Kara seas [25; 32-34; 37] and manifestations of mud volcanism in the North of Western Siberia [11; 22; 25; 35; 36; 45] allow us to assert the wide distribution of MVs in the Circum-Arctic megaregion.

The study of various manifestations of Earth degassing, especially considering the cryogenic specifics of the Arctic, is an important area of geological science, the relevance of which has increased significantly due to global climate change.

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