Formation of giant Siberian gas emission craters (GECs)

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ABSTRACT

The recent discovery of eight giant gas escape craters (GECs) in the Russian Yamal and Gydan peninsulas has challenged researchers for the past decade. Despite numerous proposed models, ranging from meteor impacts to gas explosions, none provide a comprehensive explanation for why the GECs are found only in this specific region. This study proposes a new general model for the formation of GECs in which local permafrost thinning is linked to the local geology, i.e., discrete conductive faults bring natural gas and heat to the base permafrost, deforming and melting the base leading to the development of domal gas and heat traps. Atmospheric warming results in further local thinning and eventually mechanical collapse. The morphology of the GECs initially reflects the concentric deformation above domal base-permafrost structures but are after a short time disguised by water and sediment infill, and over time peatification, and cannot be distinguished from e.g., thermokarst lakes. Thus, the true number of GECs may largely exceed those already discovered.

INTRODUCTION

An increasing number of giant GECs with ejecta thrown hundreds of meters out have been discovered in Western Siberia since 2012 (Moskvitch, 2014; Chuvilin et al., 2020b) (Fig. 1). Explosive events have resulted in near vertical cylindrical structures that are initially up to more than 50 meters deep, and with diameters of tens of meters. So far, eight GECs have been discovered in the limited area of the Yamal and Gydan peninsulas (Bogoyavlensky et al., 2021; Chuvilin et al., 2021; Khimenkov and Stanilovskaya, 2022). The formation of GECs has been connected to global climate change, with increasing summer and fall temperatures resulting in permafrost warming and degradation, triggering the release of gases trapped within the permafrost (Leibman et al., 2014; Bogoyavlensky et al., 2022). The release of methane and carbon dioxide from thawing permafrost are positive feedback to climate change, and accelerated releases of the gases, from a storage of nearly 1700 billion metric tons in the Arctic permafrost, are of great concern (Miner et al., 2022).

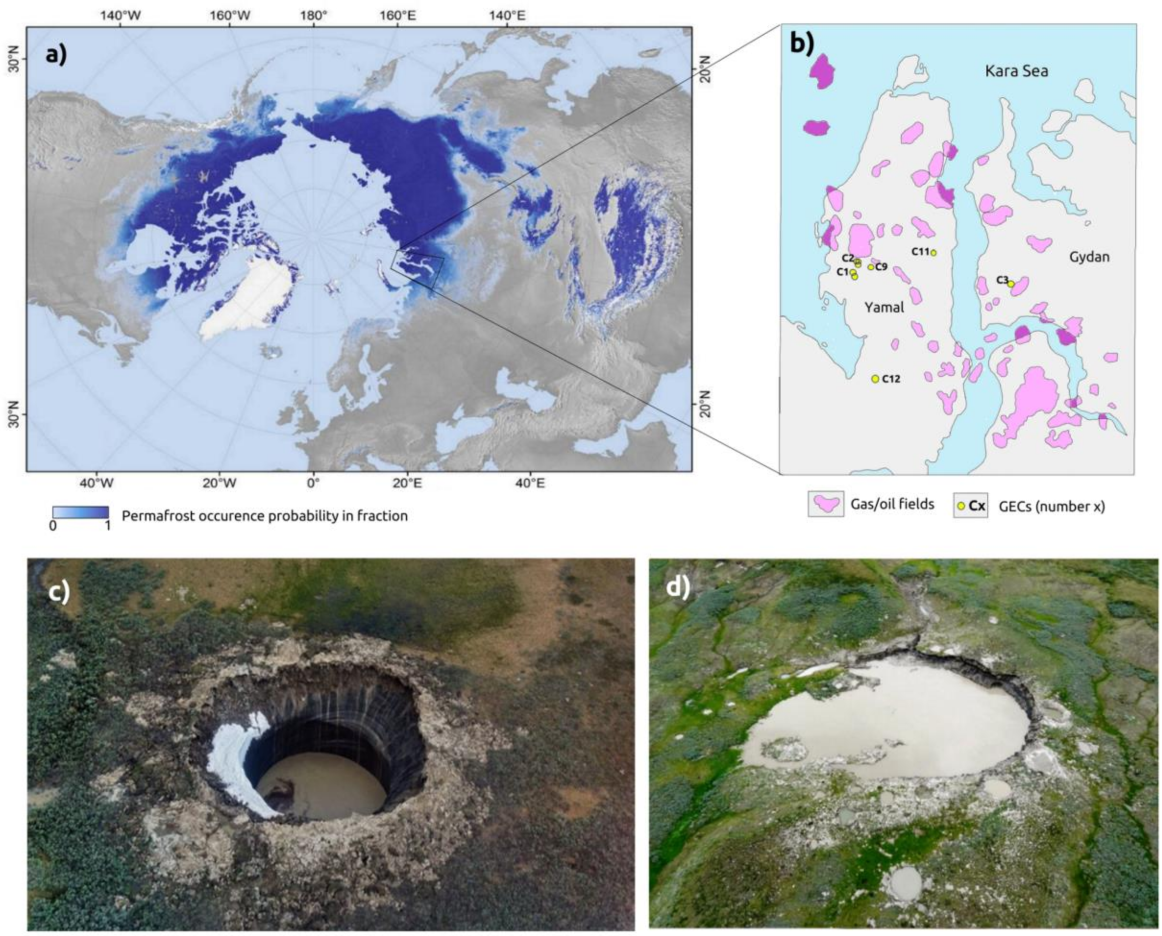

Figure 1. A) Probability map of arctic permafrost (modified from Obu et al.,2019); B) area of seven GECs (yellow circles) and gas/oil fields at the Yamal and Gydan peninsulas; C) and D) GECs C1 (Modified from Buldovicz et al., (2018)) and C2 (modified from Bogoyavlensky, 2015).

The GECs are constrained to the areas of the Western Siberian Yamal and Gydan peninsulas. This raises the question of why GECs only form in this area and not elsewhere in the northern-hemispheric belt of Arctic permafrost. The permafrost in the region is continuous but varies strongly in thickness due to variable local heat flows from faults open to fluids. The area is part of the West Siberia hydrocarbon province with rich natural gas resources, with evaluated reserves of 26.5 trillion cubic meters (TCM) of gas at the Yamal Peninsula and its adjacent offshore areas (Bambulyak et al., 2015). The GECs are found in proximity to active gas fields.

EXISTING GEC MODELS

There are a few suggested models for the formation of the GECs. None are general and can explain all structures formed. Local observations have explained some structures, with detailed examinations supporting a site-specific formation mechanism. The different models can be divided into two main groups based on pre-eruption structures and crater generation processes: (1) models that include a historic lake that later formed a cylindrical or lenticular gas-filled pre-eruption structure; and (2) models that form a gas-filled lenticular or cylindrical cave-structure within shallow ground ice or deforms the ground ice by intra-permafrost processes.

The historic-lake models

GECs may form within permafrost overlain by a pre-historic lake, forming a sub-lake talik (Buldovicz et al., 2018; Chuvilin et al., 2020a,b; Khimenkov and Stanilovskaya, 2022). During the lake stage, gas escapes through thawed sediments and out of the lake (Fig. 2a). At some point, the lake dries out or is drained (no details on the papers), and the ground below gradually re-freezes (Fig. 2b). At this point, the suggested models have different permafrost internal or external sources for pressure buildup, summarized in Chuvilin et al. (2020a,b). The pressure may be generated by an influx of deep natural gas through permeable zones in the permafrost below the closed talik, by dissociation of intra-permafrost hydrates, or by gas release from thawing ice. With time, permafrost isolates a cylindrical or lens-shaped object over-saturated with gas and at elevated pressure (Fig. 2c).

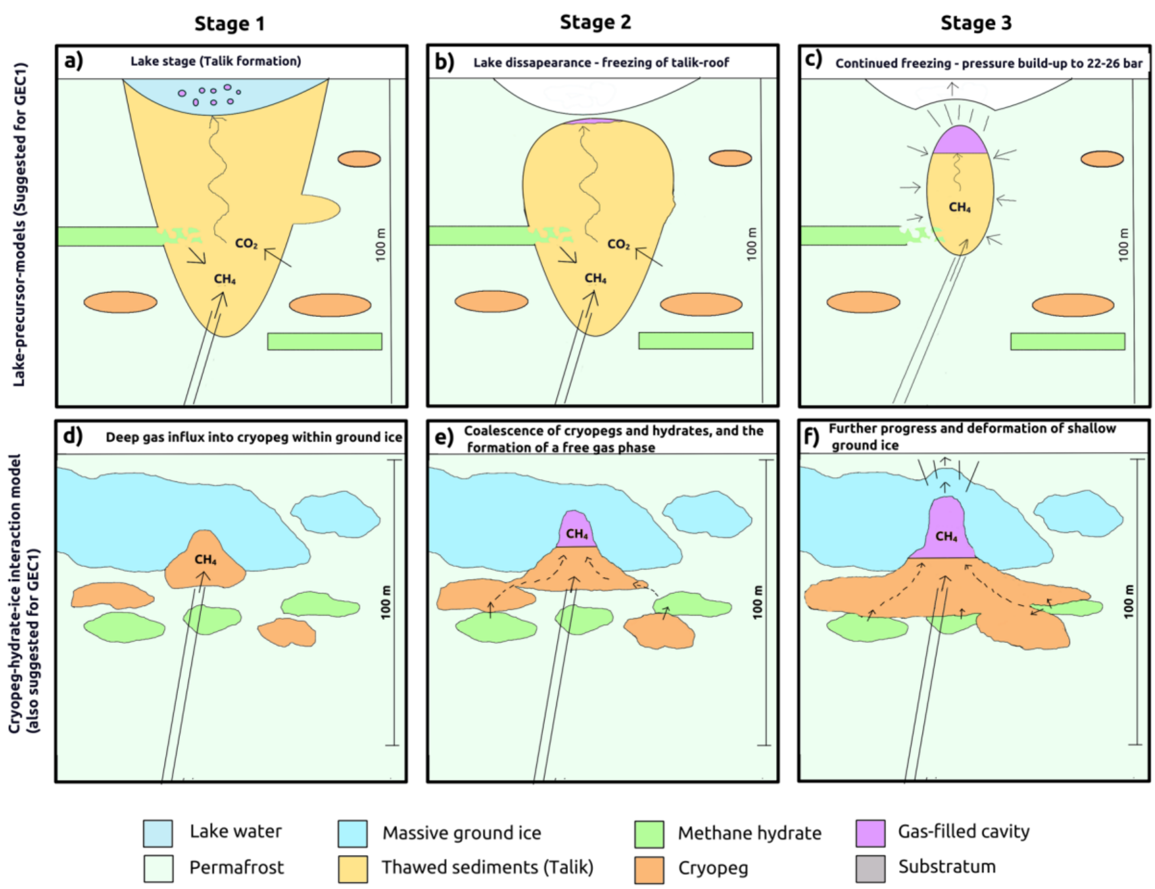

Figure 2. A summary of the suggested two groups of models for the GECs formation.

One model differs from the others by not forming a talik but a zone at increased temperatures below an ice layer under the lake floor (Khimenkov and Stanilovskaya, 2022). In this model, increased temperatures reach a methane hydrate layer that dissociates, releasing water and gas that migrate upward into permeable permafrost. At the latest stage of the model (stage 3 in our Fig. 2c), a lenticular body of ice and over-pressurized gas forms. The dynamics of the system, releasing water and apparently refreezing the water in the lenticular body together with the gas, is not clear from the paper. Buldovicz et al. (2018) suggested that the gas which accumulates in the talik during stage 2, is released from melting CO_2-rich ice. The solubility of CO_2 in water is much greater than that of methane, leading to a large fraction of dissolved gas that may be mobilized upon pressure release giving a "champagne" effect with more ice, sediments, and water being thrown out of the GEC.

Models based on melting and/or deformation of massive shallow ground ice

Three models are based on GECs formed from methane-filled cavities (karst features) formed in massive shallow ice (Dvornikov et al., 2019; Chuvilin et al., 2021; Bogoyavlensky et al., 2022). These models are supported by the occurrence of massive fragments of ground ice ejected from GECs and the observations of ground ice in the walls of several of the GECs (Bogoyavlensky et al., 2020; Chuvilin et al., 2020a, 2021).

Chuvilin et al. (2021) propose that cryopegs and methane hydrates occur at various depths within the permafrost and partly within a large ground ice body (Fig. 2d). One central cryopeg receives natural gas through a permeable zone sourced from below the permafrost. As climate change increases the permafrost temperature, cryopegs start expanding into ground ice, permafrost, and pockets of hydrate. Increased gas pressures, primarily from the dissociation of hydrates supported by the influx of gas through the permeable zone, leads to deformation above a coalesced larger cryopeg structure with a (cylindrical) dome shape (Fig. 2f). Bogoyavlensky et al. (2020), on the other hand, propose that the influx of deep natural gas drives the pressure buildup and melting of ground ice.

Teshebaeva et al. (2021) propose a model where local thinning of permafrost caused by increased heat fluxes from below might be a pre-requisite for ground deformation and the formation of GECs (Fig. 2g-h).

Key issues with the suggested models

GEC1 (C1) has been interpreted to have formed at the bottom of a historic lake (Chuvilin et al., 2020a), and this is the main reason for the various historic-lake models. The main drawback is that GECs form in a variety of geological settings (Khimenkov and Stanilovskaya, 2022). Thus, the formation of GECs points to conditions specific for the Yamal and Gydan peninsulas in general, and not specifically to sites earlier covered by lakes.

Several models include gas migration through permeable zones in the permafrost (Chuvilin et al., 2020a; Bogoyavlensky et al., 2022), but the nature of these zones is not well explained. They conveniently terminate at some point within the permafrost, e.g., below ground ice or within a cryopeg, instead of continuing through the entire permafrost as might be suggested by surface observations and resistivity tomography (Olenchenko et al., 2015; Misyurkeeva et al., 2022). One puzzling feature of the Bogoyavlensky et al. (2022) model is that natural gas is transported through the conductive zone and into the cavity, while liquid water that is released by melting of the ground ice is simultaneously transported out of the same conductive zone.

The lenticular/cylindrical shape of the objects at stage 3 (Fig. 2c, f) corresponds to the near-perfect sub-vertical cylindrical part of the observed GECs, and it has been envisaged that such an object is required to form the GECs. Concentric subsidence well beyond the craters has however been observed at GECs, pointing to subsurface structures that also go beyond the GECs themselves (Vlasov et al., 2018). This disputes the link between the shape of the subsurface talik or gas-filled traps (Fig. 2c, f), which is an integral part of all models where the structures formed within the permafrost.

The model suggested by Chuvilin et al. (2021) (Fig. 2d-f) has some additional issues. First, atmospheric warming induces the thawing of permafrost and large-scale expansion of saline cryopegs. This would lead to a dilution of the salt, moving the freezing point towards higher temperatures, eventually limiting the extent these cryopegs can expand before freezing at still negative temperatures. Second, the bell-shaped deformation structure formed in the gas-filled cavity of the ground ice lacks explanation by mechanical models. The pressure would be the same in the entire cryopeg, and a broader deformation structure above the cryopeg would be expected.

A NEW GENERAL MODEL FOR THE FORMATION OF GECs

The existing models are connected to specific intra-permafrost structures, which are widespread in other regions as well and not specific to the Yamal and Gydan peninsulas. Instead, it is likely that a common mechanism is responsible for all GECs formed in the limited area. That common mechanism may be the one proposed as a side note by Teshebaeva et al. (2021) in their paper on permafrost degradation in the area; being attributed to the abundant gas fields in the region providing local heat flow, thinning of permafrost, accumulation of shallow gas, and potential significant overpressures. Below is our conceptual model built on local thinning and extra-permafrost processes as prerequisite for the formation of the GECs.

Conceptual model

Stage 1: Formation of a gas-filled pre-eruption structure

The permafrost in the area likely formed after the retreat of glaciers more than 40,000 years ago (Forman et al., 1999), but the age of the permafrost is not known and may even be older. Local cryopegs and gas hydrates within the permafrost (Skorobogatov et al., 1998; Olenchenko et al., 2015) indicate the freezing of marine sediments and migration of methane-rich natural gas to the permafrost formed methane hydrates in low-saline waters at pressures higher than ~23 bar, being later engulfed by the progressing permafrost. Given the area's rich natural gas generation, we assume gas migrated buoyantly to local domal structures where the permafrost is at its thinnest.

During the early Holocene, temperatures rose ~2-4 °C above present at Yamal and Gydan (Forman et al., 2002), and this may have resulted in discontinuous permafrost during this time and open talik structures where fluids (water and gas) have been supplied at overpressure to the surface. Cooling during the Holocene culminated in the Little Ice Age peaking about 200 years ago in this area (Leigh et al., 2020). We assume that talik structures closed and that the shallowest parts of the permafrost table expanded to greater depths at this point, while Holocene cooling would not affect the deeper base permafrost (Fig. 3a)

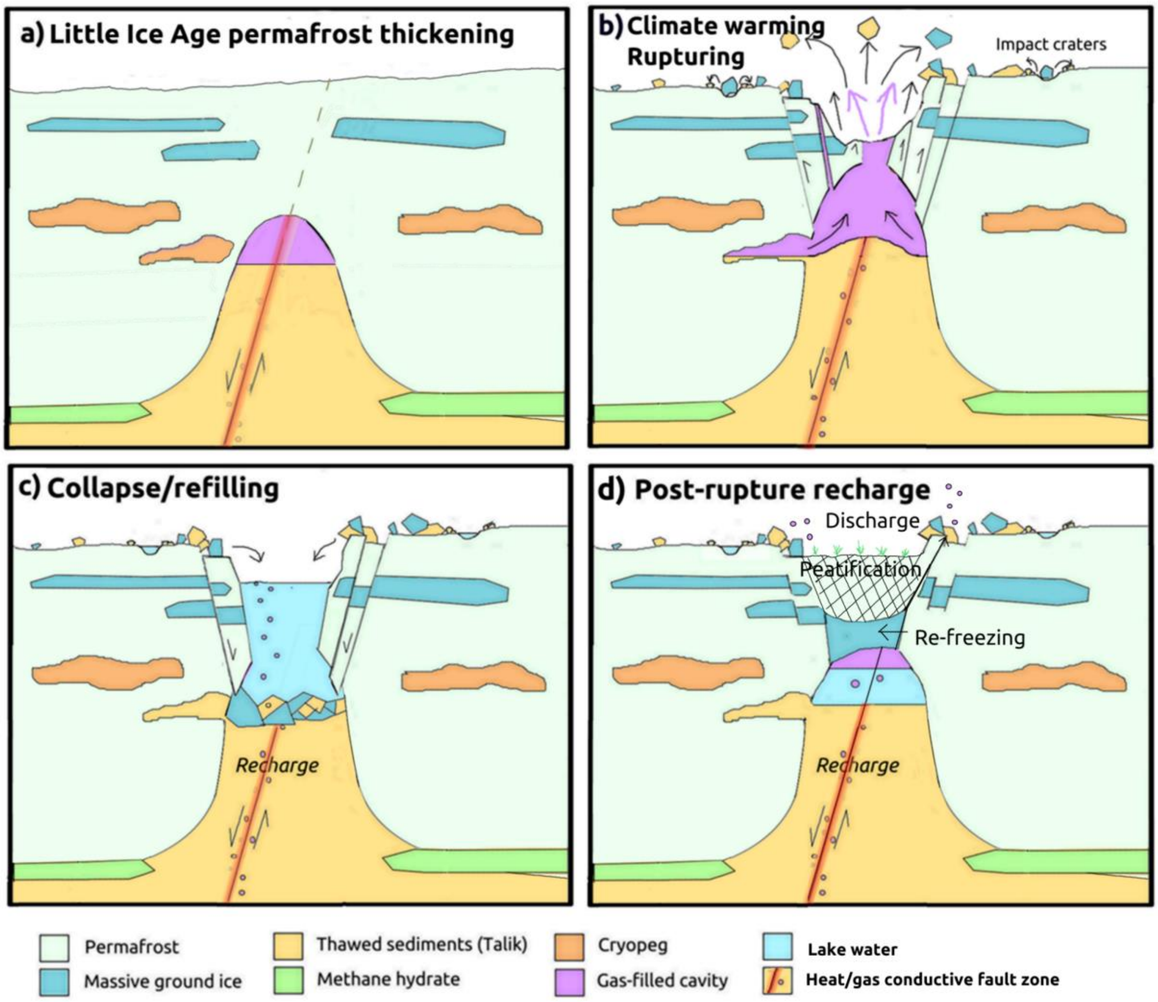

Figure 3. A new conceptual model for the formation of GECs. The model's main features are the geologically controlled local thinning of permafrost, accumulation of natural gas, and trapping of pressures in the resulting domal structures.

Stage 2: GEC formation

The average June-July temperatures in the area have risen by 2-2.5 °C since the Little Ice Age (Hantemirov et al., 2022), and the thinnest and shallowest parts affected by surface heating have experienced a gradual thawing from below. Because the thicker parts of the permafrost are both unaffected by the local geothermal heat and unaffected by surface warming, the variation in permafrost thickness in the region increases during climatic warm periods. The thickness of the permafrost at the Yamal and Gydan peninsulas varies today between a few tens of meters up to about 500 meters (Misyurkeeva et al., 2022).

With the thinning of the permafrost seal and a significant overpressure, we assume that the first phase of the failure must be the collapse of the thinnest mid-part of the remaining permafrost seal, explosively releasing fluids, ice, and sediments.

The overburden is deformed at the same time, leading to a weakening outside the main rupture volume. The rapid depressurization of the gas-saturated waters would give a "champagne effect," driving further mass out of the crater (Fig. 3b). During eruption, large blocks of ice can be thrown out. These may form impact structures around the main crater resembling smaller GECs, as seen around C2 (Fig. 1d).

The almost perfect cylindrical part seen in all observed GECs is hard to explain without a precursor object with such a shape, or that provides a weak mechanical zone leading to cylindrical deformation. It may be explained by a steep-walled domal structure, following earlier zones of weakness that may have formed over the same fault zones earlier in the Holocene. An alternative would be that failure propagates along pre-existing zones of weakness, such as those interpreted as vertical or subvertical faults separating permafrost from taliks (Misyurkeeva et al., 2022).

Stage 3: Collapse and refilling of GEC structure

Subsidence-related concentric faults have been observed to form at some distance from the crater, promoting a concentric permafrost structure with a diameter extending well outside the collapse structure itself (Vlasov et al., 2018). These may have formed along pre-existing weaknesses (faults or fractures) during the rupture as the hollow and de-pressurized crater could no longer carry the weight of the surrounding strata (Fig. 3c).

The final step in forming the structures is refilling the crater with water and sediments, and the closing of the lake by peatification. The sub-lake talik will then disappear and a frozen ice body following the old crater structure may form (Fig. 3d).

Stage 4: Post rupture recharge and discharge

The pressure released during the formation of GECs leads to the destabilization of hydrates that will recharge gas through hydrate dissociation, and the gas will migrate buoyantly to the permafrost base. At the same time, natural gas would be supplied from the deep-rooted fault system (Fig. 3d). The pressure will build up to new critical levels if the regrowth of impermeable permafrost seals the overburden. However, a new rupture may be prevented if gas can discharge through the overburden at an equal rate as the recharge, giving a lower steady-state pressure (Fig. 3d). This is suggested by field investigations observing natural gas escaping through the lake floor or conductive zones outside the crater lakes (Bogoyavlenskiy et al., 2017).

Attainable pressures

The former models of GEC formation are mostly at various conceptual levels, with little concrete information on the pressures that can be attained. Pressures of 20-25 bars mentioned by Chuvilin et al. (2020b) are, however, in good agreement with stability calculations in the liquid water (Lw) - ice (I) - methane gas (V) - methane hydrate (H) system (Dickens and Quinby-Hunt (1997)). If all four phases are at equilibrium, the maximum pressure will be given at the quadruple invariant point for the V – I – Lw – H system at about 24 bars for low-saline systems. It is first when the system temperature increases above the melting point of ice that the pressure can increase along the V – H – Lw univariant curve. This is only possible if the gases and pressures accumulate below the permafrost, as is suggested in this work. Simple Newtonian physics shows that pressures of 20-30 bars are sufficient to explain the m^3-sized ice and sediment ejecta observed around the GECs. This however depends on the size of the gas accumulation rather than the attained pressure, as pressure drops during accelerating the ejecta.

Concluding remarks

Various models have been suggested to explain the origin of GECs found in the Yamal and Gydan peninsulas. However, none of these models adequately explain why GECs are limited to this area. We propose that the formation of GECs is linked to the specific conditions in the area, including abundant natural gas generation and seepage and the overall limited thickness of the continuous permafrost. Our model suggests that GECs form above local heat and gas conduits, where the permafrost is the thinnest. Extra- and intra-permafrost processes contribute to pressure buildup, while climate change exacerbates permafrost degradation, leading to the deepening of thawed zones and an increased number of thermokarst lakes. According to our model, GEC formation results in the buildup of massive ground ice below the crater structure (Fig. 3d). This implies that similar structures may already exist today, associated with the local permafrost thinning, and GEC formation may have occurred earlier during warm periods such as the Holocene Climate Maximum approximately 8000 years ago (Forman et al., 2002). That may explain the large amount of ground ice seen as ejecta and associated with the GECs. Detailed examinations of the permafrost thickness and internal structures in the study area, as well as numerical simulations of the involved processes are required to test the current hypothesis.

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