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Conceptual Models of Gas Accumulation in the Shallow Permafrost of Northern West Siberia and Conditions for Explosive Gas Emissions

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Abstract: Gas accumulation and pressurized unfrozen rocks under lakes (sublake taliks) subject to freezing in shallow permafrost may lead to explosive gas emissions and the formation of craters. Gas inputs into taliks may have several sources: microbially-mediated recycling of organic matter, dissociation of intrapermafrost gas hydrates, and migration of subpermafrost and deep gases through permeable zones in a deformed crust. The cryogenic concentration of gas increases the pore pressure in the freezing gas-saturated talik. The gradual pressure buildup within the confined talik causes creep (ductile) deformation of the overlying permafrost and produces a mound on the surface. As the pore pressure in the freezing talik surpasses the permafrost strength, the gas-water-soil mixture of the talik erupts explosively and a crater forms where the mound was. The critical pressure in the confined gas-saturated talik (2–2.5 MPa for methane) corresponds to the onset of gas hydrate formation. The conditions of gas accumulation and excess pressure in freezing closed taliks in shallow permafrost, which may be responsible for explosive gas emissions and the formation of craters, are described by several models.

Keywords: permafrost; thermokarst lake; sublake talik; gas accumulation; gas migration; gas hydrates; gas emission; methane

1. Introduction

The Arctic permafrost stores large amounts of hydrocarbon gases, especially methane [1–3], which can be released into the air. Active gas emissions have been observed in various permafrost settings during drilling [4–8], air gas chemistry surveys [9,10], and field monitoring of active layer and water bodies [11–19]. Gas emission from permafrost can be explosive (so-called cryovolcanism) and produce deep craters [18–25], which provides additional spectacular evidence for the existence of gas reservoirs in shallow permafrost.

Investigations into permafrost gas occurrences are of global and regional significance. Globally, the gas contents and emission patterns in permafrost have implications for future climate trends, such as global warming and the increase of hydrocarbon gases into the atmosphere [26]. The existing global models provide various scenarios involving increasing mean annual temperatures of air and surface soil that lead to permafrost degradation, active layer thickening, and additional methane emissions. At the regional level, spontaneous gas effluxes from permafrost, which are often observed during petroleum exploration and in developed oil and gas fields, pose risks to exploration drilling, construction, and facility operations. Thus, gas accumulations in shallow permafrost arouse both scientific and practical interests. In this respect, the recently discovered deep craters as markers of gas emissions attract much attention, such as the huge crater that is 40 m in diameter produced by a sudden explosive emission of gas in continuous permafrost of the Yamal Peninsula (northern West Siberia) in the beginning of 2014 near the Bovanenkovo oil-gas-condensate field [18,22,27].

Gas can migrate through permeable zones in permafrost, then accumulate and remain sealed in some confined zones in different forms: free or adsorbed on some surfaces, become dissolved in water, or become gaseous or solid in the clathrate form of gas hydrates [6,28–30]. The gas components of permafrost are currently classified in terms of their origin: (i) biogenic gas, which is generated by the microbially-mediated recycling of buried organic matter and accumulates due to cryogenic concentration in cold periods; (ii) deep gas, which is released during the maturation of sediments and migrates into permafrost through tectonic and depositional discontinuities; and (iii) coalbed methane that rises along discontinuities from coal-bearing sediments and becomes localized beneath impermeable permafrost [29,31].

Before large-scale petroleum exploration and development in cold regions, permafrost was often considered a gas-impermeable cap of sediments with fully or partly ice-filled porosity. Small accumulations (pockets) of methane found in the active layer were uniquely attributed to shallow biochemical reactions in buried organic matter. However, the carbon isotope composition of methane sampled during drilling of deep boreholes (to 500 m) in the permafrost of northern West Siberia or Canada indicates that biogenic methane can originate at depths far below the active layer and below the depth of zero annual amplitudes [31]. Years of integrated geocryological studies in coal basins of the Eastern Arctic and Northeastern Russia [32] have shown that permafrost can impede the migration of gases but favor the formation of reservoirs that store free or dissolved gas (methane), rather than being a perfect impermeable screen. Prerequisites for the emission of methane into air in the Arctic region were inferred [9,15,33–35] to arise most often in water-logged topographic lows, such as drained lakes, poorly flowing river channels, thermokarst depressions transformed into lakes, etc.

2. Gas Emission from Thermokarst Lakes

Natural gas emission often occurs from the bottom sediments of thermokarst lakes that are produced by the thawing of ground ice [36] and thermal erosion. Such thermokarst lakes cover large areas and create a particular landscape in Arctic lowlands in Siberia (Figure 1).

(a)

Figure 1. *Cont.*

(b)

Figure 1. Typical Arctic thermokarst landscape: (**a**) photograph by Vitaly Gorshkov and (**b**) Google Map image (from open sources).

Variations in the abundance and size of thaw lakes in continuous and discontinuous permafrost have been largely documented for the past two decades [37]. Lakes in the tundra ecosystems of West Siberia currently occupy about 17,000 km^2, or 5% of the territory [35]. The thermal erosion and frost heaving processes in northern West Siberia had been balanced for a long time but erosion became predominant as a result of recent global change [38]. The thermokarst patterns vary laterally, with thaw lakes expanding into areas of continuous permafrost (e.g., in the Yamal and Gydan Peninsulas, northern West Siberia [37]) and declining in discontinuous and sporadic permafrost. The net lake growth in the continuous permafrost of Siberia is traceable in satellite imagery archives from the 1970s through to 2004, showing a 12% increase in the total area and a 4% increase in the number of lakes [39].

Data from Central Yakutia [16] indicate that high CH_4 emissions mainly occur from thermokarst lakes. The active emissions of methane can be maintained by its generation in unfrozen sediments beneath lakes (sublake taliks), as well as by the migration of deep gas [1,14]. Gas can also be released from methane-bearing sediments that are exposed by landslides and other dynamic processes during the evolution of thermokarst depressions [40]. Gas emissions in northern West Siberia, including from thaw lakes [34], can be (i) slow, which come from the bottom sediments of lakes and permanent river channels; (ii) rapid, which come from eroded unstable slopes around small lakes or lake and river bottoms, or (iii) explosive, which are caused by critical overpressure that produces cylindrical craters in the place of mounds, with steep walls surrounded by a "parapet" of erupted material.

Methane emission from the surface of thermokarst lakes has been estimated in different ways, and the results from different territories and periods may be inconsistent. Measurements at specific small sites are extrapolated to similar typical objects, and then the results are summarized and averaged over the time intervals of interest. The field and experimental data are the basis for predictions and models that allow for estimating the total amount of CH_4 emitted from the northern lakes within a certain period or for a certain area. For instance, the average methane flux from thermokarst depressions within the Bovanenkovo gas-oil-condensate field ranges from 8 to 50 mL/(m^2·h) [11], and the West Siberian tundra lakes contribute 20 kt of CH_4 in total annually to the atmospheric methane budget [35]. The estimated methane emission from the northern lakes [41] accounts for up to 6% of the global emission. Note that water bodies in permafrost remain covered with ice for a vast majority of the year, while gases generated by bacteria become accumulated in ice, in unfrozen water beneath the ice, and in organic-bearing bottom sediments. The gases accumulated during the winter season only release for a month in spring and may be responsible for the seasonal methane increase in the troposphere [9].

The biogenic methane production alone hardly accounts for the rate and amount of methane emission from rivers and lakes. Additional gas inputs are possible due to subsurface degassing and gas migration along zones affected by deformation that are marked by rivers and lakes [42]. According to investigations of the Yamal Peninsula [17], deep gas migration was interrupted by Late Pleistocene cooling but continued in the largest taliks beneath rivers and lakes that formed in the Holocene after the thawing of ice wedges and ground ice.

The gas phase in sublake taliks predominantly consists of CH_4, lesser amounts of CO_2, and a few percent of other gases. Most of the gas is of biogenic origin; some components may result from sediment maturation, release from coal, or may have a mixed origin [29].

Active methane emissions from thaw lakes may have different manifestations. The blue color of lakes in summer is evidence of high methane contents in the water and lake sediments due to deep gases that percolate or break through the sublake taliks and change the water chemistry [13,33]. The color differences of lakes in northern West Siberia appear in aerial images: gas-rich lakes look greenish-blue and are transparent to a depth of 3–4 m. These clear lakes with a visible bottom differ from the typical dark brown northern lakes in which the bottom is obscured beyond a water depth of 0.5–1.0 m.

Other indicators that allow for the detection of gas in the Arctic thermokarst lakes with advanced remote sensing technologies include craters on lake bottoms, gas seeps in water, gas bubbles in seasonal ice, active thermal erosion, and frost heaving near the water table [15].

Gas can escape through the lake bottom, either by slow seepage or by abrupt blowing. Gas seepage produces a train of dissolved gas on the lake surface, while a sudden emission leaves a sinkhole or a crater surrounded by erupted rocks on the bottom (Figure 2). Such craters in West Siberia can reach sizes of 5–10 m or more [33].

Figure 2. Satellite image with the WorldView-2 (24 June 2011) of the thermokarst lake with gas emission craters north of Sabetta settlement in the Yamal Peninsula (Bing database) [15].

3. Gas Sources in Thermokarst Lakes

The inventory of published data shows several possible sources of gas in sublake taliks:

(1) microbial recycling of organic matter in lake sediments;
(2) the decay of organic matter in thawing permafrost;
(3) migration of intrapermafrost methane from permafrost around the taliks;
(4) migration of deep-seated methane along permeable zones in a deformed crust;
(5) dissociation of metastable (relict) and stable gas hydrates upon a talik expansion.

Sublake taliks can be open and under lakes that are wider than the double permafrost thickness, or closed and under smaller lakes [36]. The two types of taliks differ in their structure and history, as well as in their patterns of gas generation and accumulation (Figure 3).

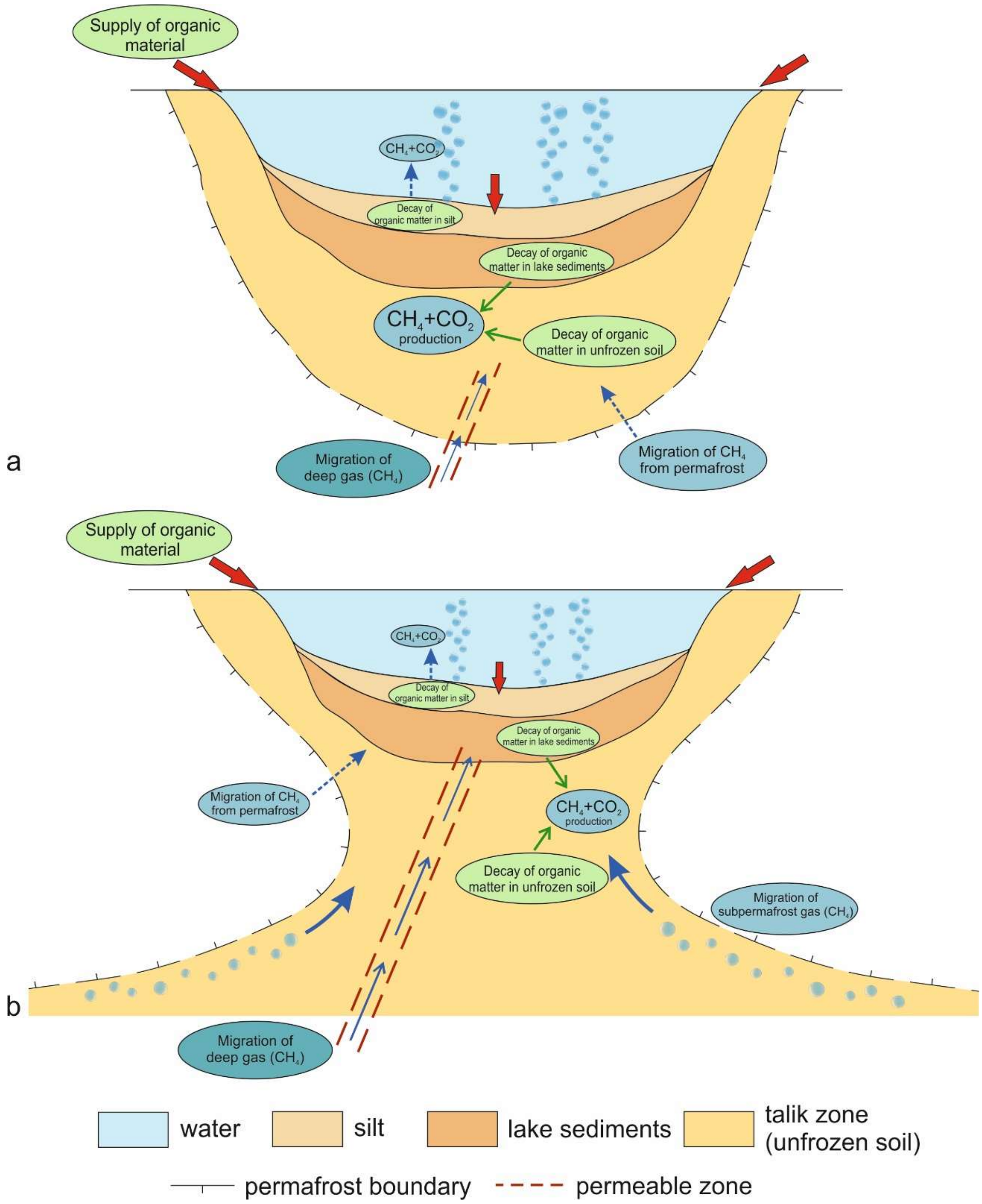

Figure 3. Generation and accumulation of gas in a thaw lake and in a closed (**a**) and an open (**b**) sublake talik.

Gas generation and accumulation in closed taliks may result from:

- the recycling of organic matter supplied from the lake surface;
- the decay of organic matter in unconsolidated bottom sediments, in older lacustrine sediments, and in thawing permafrost at the talik base;

- the migration of gas from permafrost into the talik, and the ascent of deep methane through permeable porous and fractured zones in monolith frozen and thawing rocks (Figure 3a).

The gas generation mechanisms in open taliks are generally the same as in the closed ones but have some specificity. In the same way, the gas inputs into a thaw lake with an open talik underneath are due to the decay of organic matter from the lake's surface, lake sediments, and thawing permafrost, as well as the migration of intrapermafrost gas through permeable zones. However, the CH_4 input includes an additional subpermafrost component, namely gas that can migrate freely through the open talik from originally unfrozen sediments below the permafrost base (Figure 3b).

The models include all possible gas inputs into sublake taliks, but in nature, some components may be more or less influential in each specific talik depending on its formation conditions and history.

4. Role of Gas Hydrates in Gas Accumulation in Sublake Taliks

Gas inputs into sublake taliks can include a component produced by the dissociation of gas hydrates. Gas hydrates are snow or ice-like solid clathrate compounds that form out of water and gas molecules without chemical bonding under high pressures [43]. A unit volume of gas hydrate stores up to 170 unit volumes of free gas under normal conditions. Gas hydrates can exist naturally in marine sediments and permafrost within the hydrate stability zone [44], which is a domain with a lithosphere and hydrosphere where hydrates of certain gases can form and remain stable under specific pressure, temperature, and chemical conditions [43]. For methane hydrate, such conditions exist inside and beneath 250–300 m thick permafrost [6,45].

Metastable gas hydrates can exist in permafrost above the current hydrate stability zone, at depths of 150–200 m, in paleozones where they were stable in the past and have survived till present due to self-preservation at negative temperatures [3,6,46–50]. According to implicit evidence, such relict intrapermafrost gas hydrates may occur in northern West Siberia (e.g., in the Bovanenkovo and Yamburg oil-gas-condensate fields) [2,3,49] and may dissociate upon the expansion of thaw lakes and sublake taliks (Figure 4).

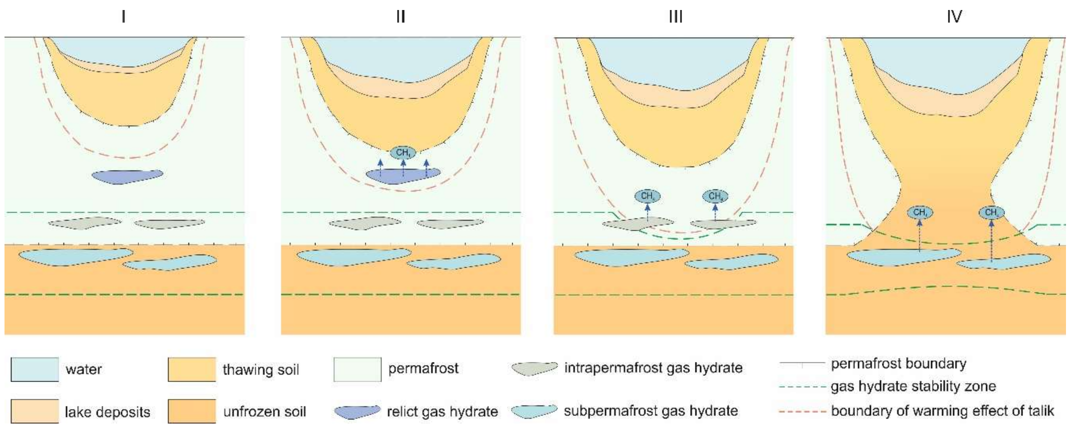

Figure 4. Stability of gas hydrates in and below permafrost under the thermal effect of thaw lakes: (**I**) no gas hydrate dissociation, (**II**) dissociation of relict gas hydrates, (**III**) dissociation of intrapermafrost gas hydrates, and (**IV**) dissociation of subpermafrost gas hydrates.

In the model (Figure 4), the original cross-section consists of permafrost above (pale blue) and unfrozen sediments below (light brown). The hydrate stability zone spans the lower part of the permafrost and the upper part of the underlying unfrozen rocks. The gas hydrates are one of three types depending on their position in the section: the deepest subpermafrost, intermediate intrapermafrost, and shallowest relict gas hydrates. The two former types occur within the gas hydrate stability zone. The four panels show different evolution stages of a deepening lake and a talik expanding under its thermal effect, with changing configurations of water, lake sediments, thawing soil, and permafrost (Figure 4); the permafrost around the talik remains frozen but is exposed to the warming effect.

At the onset of the process (panel I), the thermal effect from the lake does not reach the relict gas hydrates above the stability limit.

As the lake grows larger and deeper (panel II), the sublake talik correspondingly expands and taps the zone of metastable gas hydrates, which begin dissociating as the permafrost warms up. The released methane can penetrate the talik through permeable zones and can either accumulate within the talik or emanate through water into the air.

At the next stage of the talik history (panel III), the warming effect progresses downward and bends the top of the hydrate stability zone down, which thus approaches the permafrost base. Some of the intrapermafrost gas hydrates may fall within the thermal effect and start to dissociate, while the other part may remain stable. The dissociation of the intrapermafrost gas hydrates leads to CH_4 emission (as in panel I) toward the talik and its subsequent accumulation or release into the air.

Warming at the final stage (panel IV) spreads across the permafrost base and affects the intrapermafrost gas hydrates that survived the previous stage, as well as those beneath the permafrost. The intrapermafrost gas hydrates become metastable, and even minor pressure or temperature changes can trigger their dissociation.

Subpermafrost gas hydrates are exposed to warming from above, as well as from below by heat rising from a deeper crust. The deep heat flux shifts the lower boundary of gas hydrate stability upward and reduces the stability zone (see its upwarping base in panel IV). The thinning of the hydrate stability zone, both from above and from below, under the warming effects of the talik and the deep heat flux, respectively, induces dissociation of subpermafrost gas hydrates and increases the emission of gas that migrates along permeable zones within the affected volume of rocks.

5. Models of Gas Accumulation in Freezing Sublake Taliks

The main causes of stress buildup in shallow permafrost differ according to the gas' origin and can be modeled in different ways.

5.1. Freezing of Sublake Talik with High Contents of Biogenic Gas

A freezing closed talik can experience gas pressure buildup in several stages (Figure 5).

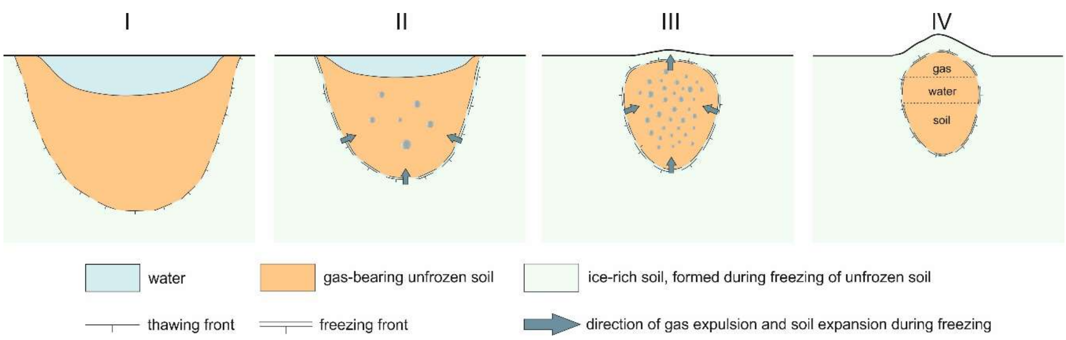

Figure 5. Gas accumulation and pressure buildup in a freezing talik saturated with biogenic gas: (**I**) a sublake talik with high gas contents; (**II**) the onset of talik freezing as the lake is drying; (**III**) cryogenic concentration and the onset of mound formation; and (**IV**) stratification of gas, water, and soil in the freezing talik and mound growth.

Stage I: A zone of gas-rich unfrozen bottom sediments (a talik) exposed to the warming effect of water forms beneath a lake. The closed talik is separated from the surrounding permafrost by the thawing front.

Stage II: The onset of talik freezing and pressure buildup as the lake is drying. The warming effect of water reduces as the lake becomes smaller and shallower, and the formerly unfrozen sediments freeze up. The advancing freezing front confines the remaining unfrozen rocks of the degrading talik and expulses dissolved gas into the talik (arrows).

Stage III: Confined freezing of the talik beneath the shoaling lake, buildup of cryogenic pressure, and the formation of a mound on the surface. While the lake existed, it provided periodic inputs of organic matter into the talik in summer seasons. The organic matter in the lake sediments was microbially recycled with the generation of biogenic methane, which accumulated in winter and was emitted into the air in spring. The lake drying causes freezing of the sublake unfrozen sediments from above, below, and the sides, with the ensuing cryogenic gas concentration and stress buildup in the talik. The gas-bearing sediments in the talik confined by the surrounding ice-rich sediments experience increasing gas pore pressure. As the pressure exceeds the overburden pressure, the permafrost cap above the talik becomes subject to creep (ductile) deformation and heaving. At this stage, gas, water, and soil in the residual talik can start to stratify.

Stage IV: Stratification of gas, water, and soil in the residual talik and mound growth. As a result of stratification, heavier and denser soil stays on the bottom, while the light volatile gas component rises to the top; liquid water is in the middle. The layers of predominant soil, water, and gas components are separated by dashed lines that are drawn tentatively because each layer contains some amounts of other components. Further mound growth is marked by the rising mound on the surface. Pressure buildup in the confined talik that is saturated with free water and gas may lead to an eruption of the water, fluids, and liquefied soil with the formation of a crater as the gas pressure exceeds the yield of the permafrost cap. The upper pressure limit in the latter case corresponds to the equilibrium pressure of hydrate formation for the predominant gas, which is ≈2.0–2.5 MPa for methane [51].

5.2. *Gas Accumulation in Freezing Taliks by the Dissociation of Intrapermafrost Gas Hydrates*

The scenario of pressure buildup in a freezing talik that is maintained by the dissociation of relict (metastable) gas hydrates may look as shown in Figure 6.

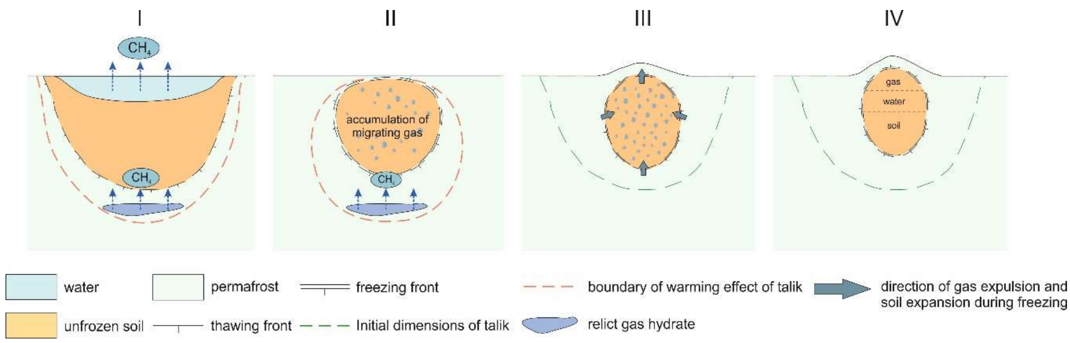

Figure 6. Gas accumulation and pressure buildup in a freezing talik that are maintained by the dissociation of metastable gas hydrates: (**I**) metastable gas hydrates in a sublake talik begin to dissociate under the warming effect of the lake; (**II**) confined freezing talik saturates with methane; (**III**) gas in a freezing talik undergoes cryogenic concentration and induces mound formation; and (**IV**) gas, water, and soil in the freezing talik stratify and the mound grows.

Stage I: The metastable gas hydrates (CH_4 hydrate) in a sublake talik that fall under the warming effect of the lake begin to dissociate and change their phase state from solid to gas. The released methane migrates through the pores and cracks in the permafrost into the overlying talik, passes through unfrozen soil, and then through water, and eventually emanates into the atmosphere.

Stage II: The talik becomes saturated with methane once the lake has dried out and its warming effect has reduced; the talik becomes confined and freezes from above, while the frozen cap impedes free gas release into the air. Gas liberated from dissociating gas hydrates, which are located in the degrading but still existing zone warmed up by the talik, migrates through ice-free pores, and cracks into the unfrozen zone, where it accumulates but cannot be released into the air.

Stage III: Confined freezing of the talik and related pressure buildup lead to mound formation. The boundary of the warming effect is not shown in the panel because its size is of no importance; all metastable gas hydrates are assumed to have dissociated and the released gas is assumed to have accumulated in the remaining unfrozen volume, which experiences increasing pressure from the surrounding freezing front. In general, stages III and IV (gas, water, and soil stratification and mound growth) in Figure 6 are the same as the respective stages in the model of Figure 5.

5.3. Gas Accumulation in a Freezing Talik Maintained by the Migration of Deep Gas

The pressure in a freezing talik may also increase due to gas migrating from the deep strata (Figure 7).

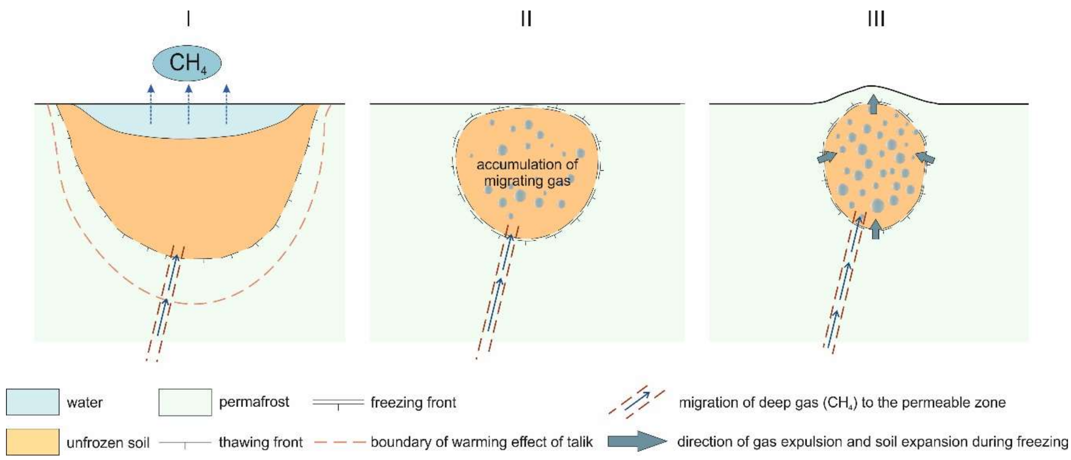

Figure 7. Accumulation of gas and pressure buildup in a freezing talik saturated with migrating deep gas: (**I**) a sublake talik before freezing, (**II**) saturation of the freezing talik with deep gas, and (**III**) gas-driven deformation of the permafrost cap and the onset of mound growth.

Stage I: Migration of deep gas through a sublake talik and its subsequent emission into the air. This stage is similar to stage I in the model of Figure 6 but with additional gas inputs from below. In this case, the size of the warming zone is not very important as methane migrates along permeable zones through the permafrost.

Stage II: Saturation of the sublake talik with deep-seated methane in a way that is similar to stage II of Figure 6 but with a different gas source. The boundary of the warming effect is not shown in the panel because its size does not influence the migration of deep gas through the permafrost.

Stage III: Gas-driven deformation and onset of mound growth. This stage is likewise similar to the respective stage in Figures 5 and 6, but unlike those models, gas inputs from below can continue during the freezing of the talik and its evolution does not affect the gas release patterns.

This model misses stage IV, with the stratification of gas, water, and soil in the confined freezing talik (stage IV in Figures 5 and 6), because the talik becomes an open system in this case. The constant influx of migrating gas interferes with the stratification of unfrozen sediments into the gas, water, and soil components. On the other hand, the input of gas that cannot be released into the atmosphere, and the related pressure buildup in the remaining unfrozen core confined by the freezing front, induce further mound growth. In fact, stage IV in this model is an analog and a continuation of stage III and is not worth separate consideration.

Two or even three of these scenarios can operate concurrently in a single talik. Thus, the simultaneous implementation of at least two scenarios was observed for a gas emission crater [52], which appeared in the winter of 2016–2017 in the continuous permafrost in the southern part of the Yamal Peninsula. The gas emission crater formed in the valley of the Erkuta River in an area with a large number of oxbow lakes. This territory has favorable conditions for intrapermafrost gas accumulation due to interbedding of the ice-rich alluvial sandy and silty clay Quaternary soils, which are saturated by organic matter and often include particles of plant dendrites. The result of the isotopic analysis of methane in underground ice sampling from the crater's sidewall indicated the biochemical origin of the gas (δ 13C was −72‰). Additional chemical analysis of the intrapermafrost gas showed a rather high content of methane homologs (ethane and propane) from fractions to a few cubic centimeters per kilogram of the frozen sample. This fact indicates the presence of not only biogenic methane but also deep-formed hydrocarbons in the ice samples. However, regardless of the gas source and the predominant mechanism, any freezing talik is exposed to increasing cryogenic gas pressure (up to 2.0–2.5 MPa for methane predominance), which may lead to a collapse of the frozen cap and explosive emission of the pressurized gas from the closed volume.

6. Conclusions

The comparison and analysis of available published materials and new data allow for several inferences.

1. Freezing sublake taliks allow for gas storage in shallow permafrost and the related pressure buildup leads to explosive gas emissions and the formation of craters.
2. The expanding warming effect from growing taliks can cause the thawing of organic-rich sediments and induce or accelerate the decay of organic matter, dissociation of gas hydrates, and migration of subpermafrost and deeper gases through permeable zones.
3. Active gas emission from thermokarst lakes may be due to gas generation in sublake taliks and the migration of deep gases.
4. Gas inputs into a freezing talik are maintained by:
    a. gas generation by the microbial recycling of organic matter;
    b. the dissociation of metastable relict gas hydrates beneath the talik;
    c. the migration of gas from a deep subsurface.
5. Cryogenic concentration of gas in a freezing talik creates a zone of overpressure, which causes creep (ductile) deformation of the frozen cap and surface heaving as the pressure inside the talik exceeds the overburden pressure.
6. The overpressure in the freezing talik may lead to the eruption of the gas–water–soil mixture and formation of a crater as it surpasses the critical limit of the frozen cap strength. In this case, the upper gas pressure limit corresponds to the equilibrium pressure of hydrate formation for the predominant gas (≈2–2.5 MPa for methane).
7. Gas accumulation and overpressure in freezing taliks are responsible for explosive gas emissions and the formation of craters can follow different scenarios, which can operate concurrently in a single talik.

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