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# CRYOGENIC RELIEF-FORMATION PROCESSES: A REVIEW OF 2010–2015 PUBLICATIONS

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The paper presents a review of 110 publications, almost 40 in Russian and more than 70 in international journals, devoted to the study of cryogenic relief-forming processes and published mainly during the last 5 years. This review focuses primarily on research trends and methods, as well as results obtained by Russian and international research teams. A substantial part of recent publications is based on the integrated interdisciplinary studies in the permafrost regions, involving groups of researchers with different expertise, and representatives of various scientific schools. Ambiguous interpretation of the scope of concepts and definitions, determining specific cryogenic process, is noticed in the analyzed publications. Accordingly, in their considerations of the cryogenic processes, the authors of the paper rely on the multilingual Glossary on permafrost adopted by the International Permafrost Association. The results obtained in the course of studies of thermokarst, thermoerosion, thermoabrasion, thermodenudation, frost heaving, and cryogenic slope processes are considered in the paper.

*Cryogenic processes, thermokarst, frost heaving, thermal erosion, thermal abrasion, thermal denudation, cryogenic slope processes*

## INTRODUCTION

This paper analyzes scientific publications (limited mostly by the period of 2010–2015) dedicated to the studies of cryogenic processes and their response to climate fluctuations and related alterations in ecosystem structure. The review was done as a contribution to the section: "Permafrost-related processes, coastal erosion, thermokarst and recent changes in thermokarst lake development" within the framework of SWIPA-2015 international science report "Snow, Water, Ice and Permafrost in the Arctic", an addition to SWIPA-2011 Overview Report, which also included earlier Russian publications missing from the previous reports.

More than 200 publications, including the 'classical studies' of cryogenic processes, of which 110 entered in the list of references, have been examined. The purpose of this paper is to summarize the information related to actual cryogenic processes resulting from climate fluctuations, and to incorporate speculative inferences concerning the "permafrost degradation" into strictly scientific discourse.

Degradation (a decrease in thickness and (or) area) of permafrost (i.e. perennially frozen ground/deposits) and associated with changes in relief due to activation of a wide range of processes, including thermokarst (thawing of ice-rich permafrost or massive ground ice, followed by the subsidence of ground surface and subsequently filled with water to form a water body), thermoerosion (thermal and mechanical effects of flowing water) and slope processes (downslope transport of rocks driven by creep, solifluction and cryogenic landslide activity resulting in active-layer detachments and retrogressive thaw slumps). At the same time, local permafrost aggradation associated with a complex of cryogenic processes (such as frost cracking and frost heave, including formation of perennial frost-heave mounds) are manifested against the backdrop of a marked climate warming trend. For example, when thermokarst lakes drain, taliks are found to be in the zone of influence of negative mean annual temperatures, and are subjected to freezing and thereby benefit the formation of segregation and intrusive-segregation massive ground ice.

## THERMOKARST

Thermokarst landforms develop as a result of the thawing of ice-rich permafrost or the melting of massive ice [*van Everdingen, 2005*]. Thermokarst effects are manifested in various forms [*Jorgenson et al., 2008; Kokelj and Jorgenson, 2013*]. Accumulation of water in the depressions formed by massive ice melting cause lake inception and its further evolution. Given that thermokarst lake formation is determined by massive ice volume and by the sub-bottom talik dimensions, its depth varies from 1–3 to 10–20 m, and more [*Shur et al., 2012*].

Thaw settlement greater than 20 m is observed in thaw-lake basins formed in the Ice Complex deposits with the presence of large volumes of ice-wedges [*Soloviev, 1962; Romanovskii et al., 2004; Grosse et al., 2007, 2013; Konishchev, 2011; Shur et al., 2012; Kokelj and Jorgenson, 2013; Morgenstern et al., 2013; Schirrmeister et al., 2013; Kanevskiy et al., 2014; Ulrich et al., 2014*]. Considerably thick massive ice bodies (for example, in the north of Western Siberia) also result in thaw subsidence and formation of the lakes 30–50 m deep [*Badu et al., 1986; Kritsuk, 2010*]. Besides thermokarst, coastal erosion and cryogenic landsliding contribute to thermokarst lakes evolution [*Biskaborn et al., 2013*].

A number of researchers consider thermokarst lake dynamics as an indicator of climate change in the Arctic [*Kravtsova and Tarasenko, 2011*]. Remote sensing data have been widely used for monitoring lake dynamics in Alaska [*Jorgenson et al., 2008, 2012; Arp et al., 2011; Jones et al., 2011, 2012; Parsekian et al., 2011; Roach et al., 2011; Hinkel et al., 2012; Necsoiu et al., 2013; Liu et al., 2014; Raynolds et al., 2014*], Canada [*Bouchard et al., 2011; Carroll et al., 2011; Sannel and Kuhry, 2011*], China [*Ling et al., 2012; Pan X. et al., 2014*], Russia [*Kravtsova and Tarasenko, 2011; Sannel and Kuhry, 2011; Bryksina and Kirpotin, 2012; Iijima et al., 2012; Sannikov, 2012; Biskaborn et al., 2013; Sjöberg et al., 2013; Trofaier et al., 2013; Liu et al., 2014; Manasypov et al., 2014*], and in Sweden [*Sannel and Kuhry, 2011*]. Mathematical landscape morphology modeling methods for lake-thermokarst and erosion-thermokarst plains have been given a new impetus to in the context of changing climate [*Victorov et al., 2015*].

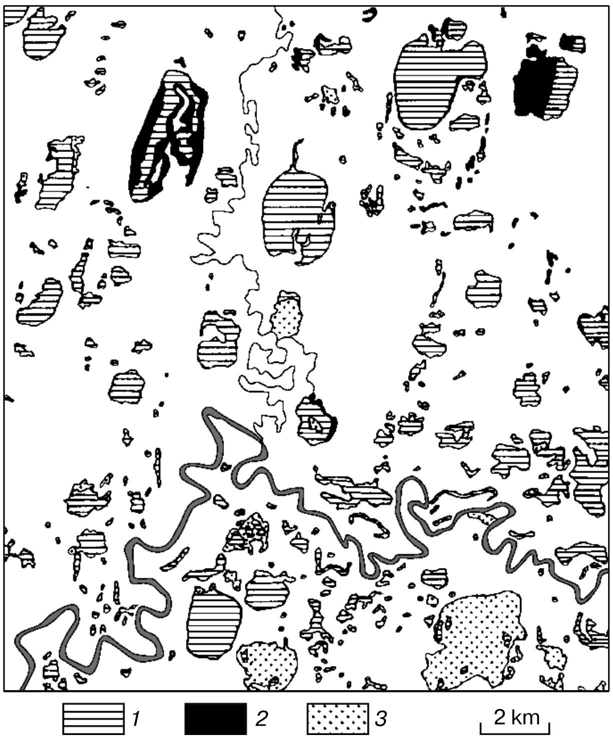



**Fig. 1. Schematic map of changes in thermokarst lakes distribution at the site in the Yana-Indigirka lowland representation in 1972–2000 [*Kravtsova and Bystrova, 2009*].**

*1* – water extent in 1972 and 2000; *2* – dry land in 1972; flooded by water in 2000; *3* – water extent in 1972, which became dry land in 2000.

Both increase and decrease in lake areas as a response to climate fluctuations occur at a regional scale (Fig. 1, 2) [*Kravtsova and Bystrova, 2009*], and are associated with area-specific landscape and climatic factors. Basically, thermokarst lakes tend to increase in number and size within the continuous permafrost zone, and to decrease in areas underlain by discontinuous and island permafrost [*Smith et al., 2005; Jones et al., 2011*]. The lake dynamics is different for large and smaller lakes. In the tundra, dimensions of small lakes are most prone to changing due to their shallow depths [*Carroll et al., 2011*]. There is a trend for formation of new smaller lakes parallel to reducing and subsequently disappearing medium and large lakes, characteristic of the entire Western Siberia [*Bryksina and Kirpotin, 2012; Bryksina and Polishchuk, 2015*], as well as northeastern Alaska, the Seward Peninsula [*Jones et al., 2011*], and peat plateaus in the sporadic permafrost zone in northernmost Sweden [*Sannel and Kuhry, 2011*]. Conversely, thermokarst lakes are expanding in alases (thermokarst lake basins) of Central Yakutia in the Lena River valley [*Iijima et al., 2012*].

The variations in sizes of thermokarst lakes are bi-directional in the Alaska taiga ecosystem [*Roach et al., 2011; Jorgenson et al., 2012; Chen et al., 2013*]. In Canada, thermokarst lakes are considerably shrinking in the northern parts, and expanding in the southern parts of the region [*Carroll et al., 2011*]. Thermokarst lakes exhibit no significant variations in size within peatland areas underlain by continuous and discontinuous permafrost on the Hudson Bay coast (Canada) and in northeastern European part of Russia [*Sannel and Kuhry, 2011*].

Thus, researchers have emphasized essential regional variations in thermokarst-lake dynamics. These variations though can also result from differences in research methods and the use of different source data.

**Fig. 2. Thermokarst lakes of the Yamal Peninsula (photo by M.O. Leibman).**

Along with interannual dynamics, thermokarst lakes experience significant seasonal fluctuations in their spatial extent. For instance, in Central Yakutia, the total area of lakes at low geomorphologic levels reduced by 30 % over one summer period [*Kravtsova and Tarasenko, 2011*], whereas in the Yukon River lowland their reduction constituted 42 % [*Chen et al., 2013*]. The established decrease in lake water table extent in the context of active thermokarst development appears of paramount importance [*Parsekian et al., 2011; Jorgenson et al., 2012*]. The formation of near-shore floating vegetation mat indicates a rapid degradation of the permafrost table and lake expansion [*Parsekian et al., 2011; Chen et al., 2013*]. The thermokarst lake area expansion is favored by shoreline retreat due to thermoabrasion and subsequently deepening thaw settlement. The measured shoreline retreat rates in Alaska range from 0–2 m/yr for shallow lakes to 1–8 m/yr for deeper lakes [*Arp et al., 2011*].

A decrease in lake area creates multiple feedbacks into the climatic system through modification of surface albedo, evapotranspiration and carbon cycling [*Carroll et al., 2011*]. Peat accumulation in drained thermokarst lake basins initiates the formation and provides for preservation of lenses of permafrost [*Shur and Jorgenson, 2007; Jones et al., 2012; Kanevskiy et al., 2014*]. In many cases, the freezing of lake taliks runs in parallel with palsa formation in the areas of rapid peat accumulation, where the surface of vegetation rises above water level [*Kuhry, 2008; Seppälä, 2011; Shur et al., 2011*]. Given the favorable climatic conditions, the long-term freezing progressing from the margins of the lake basins inwards is accompanied by frost cracking and frost heave [*Konichshev, 2011; Jones et al., 2012*].

Among the thermokarst evolution controls, the precipitation – evaporation ratio appears more critical than warming air temperature [*Konichshev, 2011*].

In Central Yakutia, the formation of new and expansion of existing lakes in alases therefore occurs only in years with high annual precipitation, which enhances both moistening and thickening of the active layer (AL) [*Bosikov, 2007; Iijima et al., 2012*].

Modern temperature conditions in the Yakutian coastal plains with widely distributed Ice Complex benefits the inception of multiple forms of thermokarst. However, at higher elevations (Yedoma) the potential for their further development is limited due to the high drainage rates assisted by the relief dissection, and accumulation of organic layer with good heat-insulating properties in the primary thermokarst forms [*Morgenstern et al., 2011; Shur et al., 2012*]. Given that the underlying rocks previously experienced thawing, and freeze back did not result in the formation of ice-rich sediments after initial lake drainage, the development of thermokarst lakes in the existing alases is also limited [*Morgenstern et al., 2011*].

Thus, thermokarst response to recent climate warming shows no uniform trend for the permafrost zone. The identified variations in areas of thermokarst lakes are related to regional and local landscape and climatic factors.

## THERMAL EROSION

Thermal erosion is defined as "wearing away of surface deposits by the combined thermal and mechanical action of moving water" [*van Everdingen, 2005*].

Erosion network in permafrost zone, specifically, in northernmost regions typically develops along polygonal patterns, which provide natural paths along the polygonal troughs with ice bottoms over ice wedges (Fig. 3, 4). Gullying that commences in ice wedge-affected areas eventually develops an exten-

**Fig. 3. Thermoerosion expanding over the network of polygonal ice wedges, northern Yamal; helicopter view (photo by M.O. Leibman).**

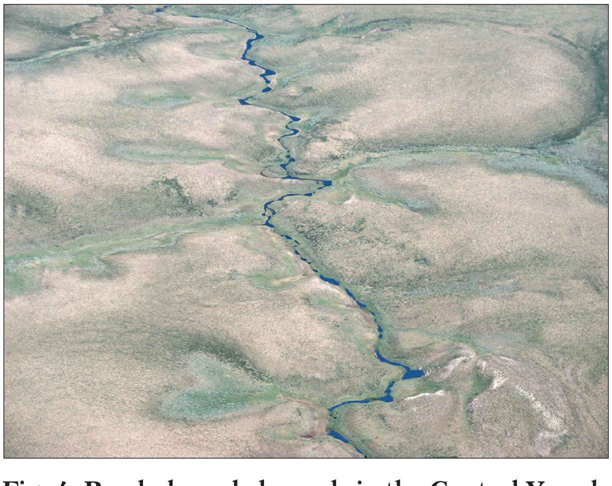


**Fig. 4. Bead-shaped channels in the Central Yamal; helicopter view (photo by M.O. Leibman).**

sive erosion network [*Fortier et al., 2007; Haltigin et al., 2012*]. The depth of such gullies normally ranges from 1 to 5 m in depth, reaching hundreds of meters in length [*Godin and Fortier, 2012*], whereas in northern Yakutia, the authors observed gullies with depths exceeding 30 m where thicker (in excess of 40 m) ice wedges occurred.

Thermo-erosion rates in the context of different types of sediments were monitored for many years on Bylot Island [*Godin and Fortier, 2012*]. The results of this spatio-temporal monitoring in the period between 1958 and 2012 using field observations, differential GPS mapping and aerial and satellite imagery from different years show that part of the gullies almost stabilized and others were evolving during the 2007–2011 period at rates ranging between (14 ± 3) to (25 ± 4) m/yr.

The growth rate of thermoerosion landforms can be prompted by other natural phenomena, such as cryogenic landslides, surface subsidence driven by instability of the permafrost temperature regime, and active expansion of water-carved pits in the upper portions of the gullies. Alternatively, the development of vegetation cover, desiccation of AL deposits and as a result, their cooling thereby can eventually stabilize erosion gullies [*Godin and Fortier, 2012*].

River thermal erosion is most intense during high spring floods, when river waters inundate the ice-rich coasts, resulting in thermal and mechanical erosion of rocks. During summer rainfall floods, river thermal erosion is also likely to reactivate. The high interannual variation in the islands' coastal retreat rate in the Lena delta is associated with different duration and timing of the floods. At one of the sites, in just a few days, the coastline retreated by 22 m driven by the action of the 2010 spring flooding [*Costard et al., 2014*]. The two factors that control the erosion rates are: water temperature and ice content in the deposits composing the banks [*Dupeyrat et al., 2011*]. Thermodenudation on the coastal bluffs contributes to thermal erosion of ice-rich permafrost coasts [*Shur et al., 2002*].

The interactions within the complex of hydrological and cryogenic processes are observed in the erosion-affected small river catchments, which may result in bead-shaped channels developing thereby (Fig. 4). Bead-shaped channels in the upper portions of erosional network with a V-shaped cross-section are caused predominantly by cryogenic landsliding, with the subsequent formation of temporary dammed flow-through lakes. In the middle course of small rivers with U-shaped cross-section, thermokarst activity along ice wedges manifests itself in the formation of bead-shaped channels [*Gubarkov and Leibman, 2010; Gubarkov et al., 2014*].

Thermo-erosion gullies affect the local runoff, and through the extent of the AL deposits moistening govern distribution and composition of plant communities. The gullying mode is responsible for the variability of sedimentation processes in the lower courses of river systems [*Godin and Fortier, 2012*]. It is believed that thermal erosion activates with climate warming [*Kokelj and Jorgenson, 2013*], however, local relief features of a particular catchment and feedbacks between hydrological processes and variations in plant associations introduce essential area-specific corrections to the observed patterns.

## COASTAL RETREAT

Coastal retreat is driven by two main processes: thermal abrasion and termodenudation of coastal bluffs composed of permafrost (Figs. 5, 6). The coastal zone with permafrost-affected coasts is considered a unique natural system providing a complex of driving forces and feedbacks [*Vasiliev et al., 2001, 2011;*

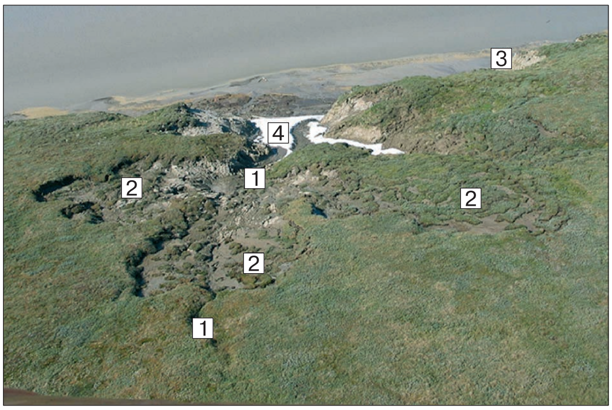



**Fig. 5. A complex of coast destruction processes (photo by M.O. Leibman).**

*1* – thermoerosion; *2* – landsliding; *3* – thermo-abrasion; *4* – nivation.

**Fig. 6. Block fall of a coastal bluff over the wave-cut niche (photo by M.O. Leibman).**

*Grigoriev et al., 2006; Are, 2012*]. Climate warming exerts its influence on the coastal retreat through shrinking sea ice cover and rising air and seawater temperature.

Averaged for the entire Arctic, coastal retreat rates account for approximately 0.5 m/yr, but in different parts of the coast they differ considerably and vary greatly over time [*Lantuit et al., 2013*]. Results of the long-term monitoring of western Yamal coastal dynamics near Marre-Sale since the late 1970s indicate that the mean coastline retreat rate constituted about 1.7 m/yr, with maximum peaks at 3.3 m/yr [*Vasiliev et al., 2011*].

The 2008–2012 research revealed the retreat rate of coasts on Alaska and other regions [*Lantuit et al., 2013*]. The Elson Bay segment of the Beaufort Sea coast, northern Alaska, was found to be retreating on average at a rate 1–4 m/yr in the period between 2003 and 2011 [*Tweedie et al., 2012*]. Given that the coast is protected by islands, the retreat rates appear lower than in any other parts of the Beaufort Sea. The open-sea coasts with ice-rich permafrost retreat rates averaged 5.7–7.5 m/yr (1955–1979), 7.5 m/yr (1979–2002), 8.5 m/yr (2002–2007), and 13.8 m/yr (2007–2009) [*Jones et al., 2009*].

The same high rates of ice-rich coasts retreat feature the eastern sector of the Russian Arctic. In the East Siberian Sea, the mean rate of the coastal retreat composed of the Ice Complex deposits is 2.4–4.3 m/yr, peaking at 11–15 m/yr [*Grigoriev et al., 2006*]. The ice-rich coasts of Chukchi Sea retreated at a mean annual rate of 0.5–4.0 m/yr between 1930 and 1950, with peaks up to 6 m/yr [*Grigoriev et al., 2006*].

The action of waves coupled with sea water temperature are primarily responsible for thermal abrasion, whereas an increase in air temperature affects the coastal retreat through thermodenudation, which largely determines the rate of ice and permafrost thawing in the coastal bluffs [*Kizyakov et al., 2003; Are, 2012; Günther et al., 2013*]. In recent years, the western sector of the Russian Arctic witnessed an increase in the rates of thermodenudation on coastal bluffs, resulting in greater number of thermocirques associated with the thawing of tabular ground ice (Fig. 7). Observations conducted on the Kara Sea coast indicate that the high rate of coastal retreat in the period of 2007–2010 was caused by the activation of thermodenudation processes. Thermocirques growth rates reached 13 m/yr on Yugorsky peninsula [*Khomutov and Leibman, 2008*], and 8 m/yr on the Cape Sopochnaya Karga in Yenisei Bay [*Gusev, 2011*].

The joint analysis of field observations and remote sensing data allowed to determine the growth rates of thermocirques at Kolguev island (Barents Sea). In 2009–2012, they were estimated at 14.5–15.1 m/yr, averaging about 2.6 m/yr [*Kizyakov et al., 2013*]. That same period was also marked by a growing trend in thermal abrasion rates which increased to 1.97 m/yr versus 0.84 m/yr in 2002–2009 [*Perednya et al., 2003; Kizyakov et al., 2013*]. That high coastal retreat rates are associated with the extended duration of dynamically active period in this part of the Barents Sea, in conjunction with the air temperature rise.

A lesser coastal retreat was observed on the Lyakhov islands of the Laptev Sea: driven by thermal abrasion at a rate of 0.5–5.4 m/yr, and up to 5.9 m/yr – by thermodenudation [*Pizhankova and Dobrynina, 2010; Pizhankova, 2011*]. The mean thermal abrasion rates show a growing trend for Muostakh island from 1.8 m/yr observed since 1951 up to 3.4 m/yr in 2010–2013. Thermodenudation rate has averaged 3.1 m/yr in the recent years [*Günther et al., 2015*].

The coastal retreat rate estimates for Bykovsky Peninsula disposed close to Muostakh island are lower and ranged from 0.59 to 1.05 m/yr in the period between 1951 and 2006, which is accounted for a large amount of sediment transport due to their proximity to the Lena Delta, as well as for local features of seabed topography, impeding wave action [*Lantuit et al., 2011*].

**Fig. 7. Thermodenudation of Ice Complex (*a*), and tabular ground ice (*b*) distribution (photo by A.I. Kizyakov).**

*a*: thermo-terrace forming as a result of enhanced thermodenudation rates affecting the Ice Complex deposits vs. costal abrasion, Kotelny island; *b*: coastal thermocirque, associated with exposure followed by thawing of tabular ground ice, Yugorsky peninsula.

Thermal erosion resulting from melting of snow accumulated on the surface of the coastal bluffs can contribute significantly to the coastal retreat as well. In some years, featured by highest seasonal snowfall and reduced intensity of wave action, thermoerosion and cryogenic landsliding triggered by the melting of snow, dominated among the coastal retreat controls [*Gubarkov et al., 2008*].

Coastal retreat thus appears to result from thermal abrasion assisted by processes on coastal bluffs, with thermodenudation, cryogenic slope processes and thermal erosion being the key drivers. The influences of hydro-meteorological factors on the coastal retreat rates are governed by summer air temperature, amounts of summer and winter precipitation, and wave action, in particular, frequency of storms, dictated by the duration of the ice-free period.

## FROST HEAVE

Seasonal frost heave is the upward movement of the ground surface associated with the formation of ice in the AL due to the freezing of pore water and moisture migration towards the freezing front, where ice lenses form [*van Everdingen, 2005*]. In addition to direct field measurements, the radar interferometry (InSAR) method is used to evaluate annual cycles of the ground surface movements caused by frost heave [*Fortier et al., 2012; Chimitdorzhiev et al., 2013; Liu et al., 2014*]. At the same time, one shouldn't ignore the fact that annual frost heave cycles can superimpose the linear trend of the surface subsidence driven by increased AL depth, as well as neotectonic and glacio-isostatic movements [*Fortier et al., 2012*].

**Fig. 8. Frost heave mound growing in the small channel in the vicinity of Kharasavey settlement (photo by M.O. Leibman).**

Perennial frost heave reveals itself in the form of intrusion or migration frost-heave mounds (the cover picture, Fig. 8), including those confined to peatlands. Lenses of permafrost form during winter freezing of peatlands due to a difference in thermal conductivity of peat in frozen and thawed state [*Chizhova et al., 2012; Vasil'chuk et al., 2013*]. Therefore, the development of peatlands in the southern limits of the permafrost zone is the main cause of permafrost existence here because lenses of permafrost are associated with peat mounds [*Daanen, 2012*].

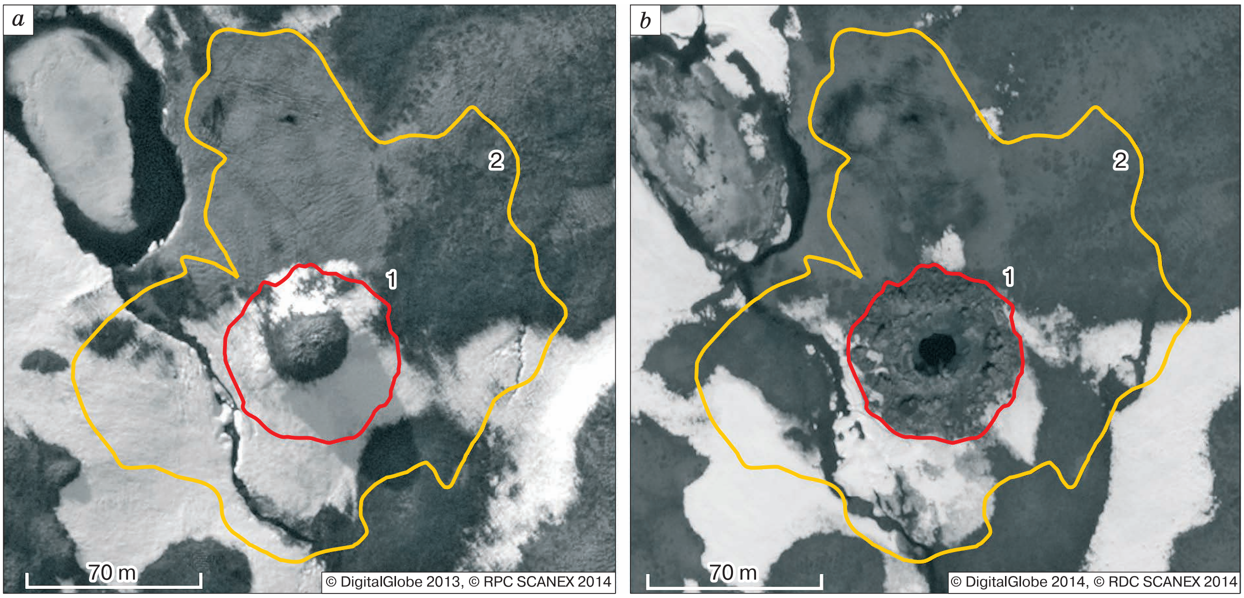



**Fig. 9. Gas emission crater on Yamal on very-high resolution satellite images [*Kizyakov et al., 2015*].**

*a*: mound pre-existed at the site of the crater formation (WorldView-1 image as of 09.06.2013); *b*: crater in existence (WorldView-1 image as of 15.06.2014). 1 – outer boundary of the crater parapet; 2 – limits of the zone of scattered debris ejected from the crater.

Long-term observation data obtained at the sites in the northern taiga of Western Siberia allowed to ascertain that despite the climate warming since the 1970s, perennial frost heave is proceeding actively within peat plateaus and middle parts of frost-heave mounds in winters with little snow [*Ponomareva et al., 2012*]. The state of frost mounds in this region is therefore defined as unstable equilibrium. Permafrost aggradation beneath the annually growing hummocks and small ridges is associated with areas of modern frost heave [*Berdnikov, 2012; Osadchaya and Tumel, 2012; Ponomareva et al., 2012*].

Frost heave provides a basic mechanism for the formation of perennial intrusion type frost-heave mounds (hydrolaccoliths, bulgunnyakhs, or pingos), defined as perennial frost-heave mounds with ice core formed by freezing of injected groundwater [*van Everdingen, 2005*]. Most of pingos (82 %) are found in the tundra climatic zone [*Grosse and Jones, 2011*], and are confined to lake bottoms ,either drained or overgrowing with vegetation [*Andreev, 1936; Soloviev, 1952; Shpolyanskaya, 2013*]. The coastal areas of western Canadian Arctic are one of the well-studied regions where concentration of pingos is appreciable. Several pingos completely collapsed there during the last 60 years, while other pingos degraded partly due to the effects of coastal thermal abrasion, thawing of ice core, cryogenic landslides, slope erosion processes, and wind action [*Mackay and Burn, 2011*]. The isotope techniques have been actively employed in studing the process of and conditions favorable for pingo formation [*Yoshikawa et al., 2012*].

A new cryogenic phenomenon, the gas emission crater identified in the Central Yamal, has become the object of special studies [*Leibman et al., 2014b; Kizyakov et al., 2015*]. Though the origin of the crater is unclear, it is hypothesized that the abnormally warm summer of 2012, facilitating the permafrost temperature rise and gas hydrates decomposition and prompting thereby the formation of a pingo-like dome driven by the expansion of gas under enormously high pressure, which ended up in its explosion (Fig. 9) [*Leibman and Kizyakov, 2016*].

## CRYOGENIC SLOPE PROCESSES

Cryogenic slope processes are referred to as downslope movement of soil and rock under gravitational influence. Cryogenic slope processes include both slow displacement of rocks, such as creep (decerption) and solifluction, and faster detachments, for example, various forms of cryogenic landslides [*Kaplina, 1965; van Everdingen, 2005; French, 2007; Leibman and Kizyakov, 2007*]. Results of the studies with a focus on rapid cryogenic slope processes, responding to short-term climate fluctuations are considered below. Cryogenic landslides in permafrost have been studied fairly extensively and they are divided into two main types: retrogressive thaw slumps (or earth/mud flows), and active-layer detachments (or translational landslides) (Fig. 10).

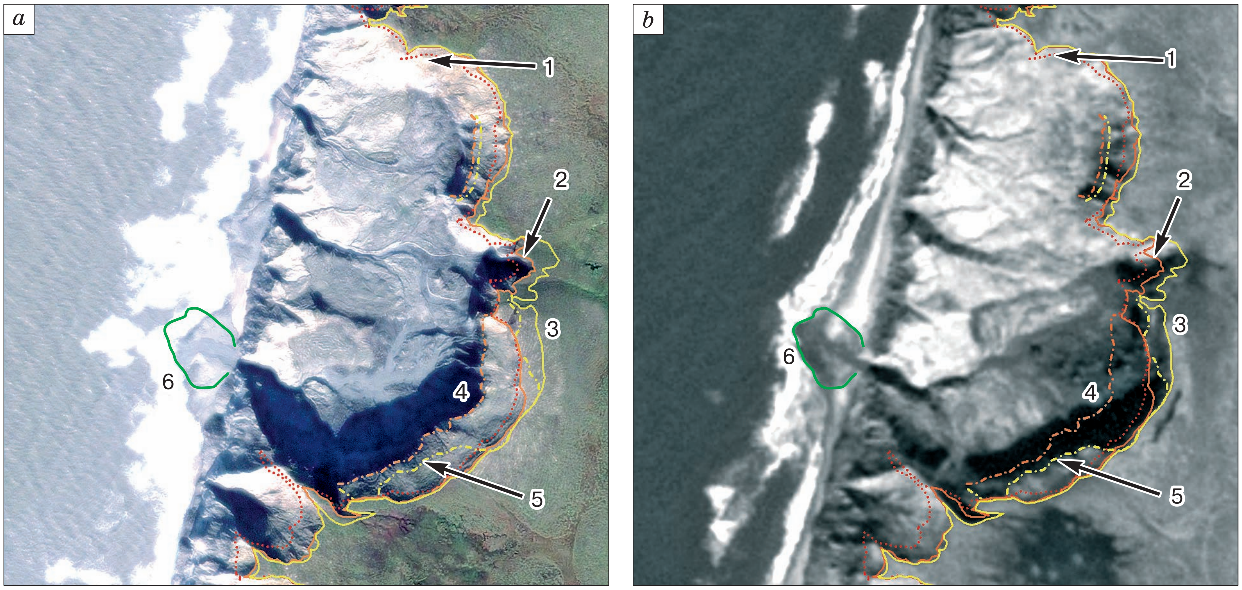
Retrogressive thaw slums are activated by the thawing of massive ground ice occurring in permafrost, while active layer detachments are caused by the thawing of ice lenses at the AL base [*Leibman et al., 2014a*]. These types of cryogenic landslides occur mainly in the continuous permafrost zone where massive ground ice formed during the initial sediment freezing and never thawed thereafter. Main areas of cryogenic landslides distribution and study in the Arctic are: Alaska [*Swanson, 2012*], North Canada [*Short et al., 2011; Lantuit et al., 2012; Sloan and Pollard, 2012; Brooker et al., 2014*], and Central Yamal [*Leibman and Kizyakov, 2007; Khomutov and Leibman, 2011; Yermokhina and Myalo, 2013; Leibman et al., 2014a*]. Quite a number of publications addressed the impacts of cryogenic landslide activity on alteration of the tundra ecosystems, and on economic infrastructure [*Khomutov, 2012; Yermokhina and Myalo, 2012; Gubarkov et al., 2014; Ukraintseva et al., 2014*].

The activation of cryogenic landslides is mainly controlled by two drivers: an increase in the amount of atmospheric precipitation, and in mean summer air temperature. In case the warming trend persists, the activation of active layer detachments promoted by the growing thaw depth is likely to set in in more northerly regions, where conditions for ice segregation at the AL base remain. The arena for retrogressive thaw slump activities will also move northwards, given the AL base will be approaching the deeper-seated massive ice table currently lying far down from the seasonal thaw [*Leibman et al., 2014a*].

The timing of landslide events is determined using radiocarbon dating of the buried organic matter [*Leibman et al., 2000; Lantuit et al., 2012; Leibman et al., 2014a*]. It is established that previous activation of cryogenic landslides dates back 350–300 years ago on Herschel Island and the bordering Mackenzie Bay coast (Canada) [*Lantuit et al., 2012*]. Activation of the similar phenomena on the Yugorsky Peninsula, determined by the sedimentation cycles in the erosion fans, took place about 770–140 year ago, averaging 455 years [*Leibman and Kizyakov, 2007*]. Given the uncertainty of the dating, it can be assumed that the cycles few hundred years long are global in nature.

The results of radiocarbon dating in the Central Yamal determined the rhythmic pattern of active-layer detachments with cycles lasting from 350 to 500 years [*Leibman et al., 2014a*].

Cryogenic slope processes have a significant impact on the dynamics of the tundra plant communities in vast areas [*Abbott et al., 2012; Flinn et al., 2012; Ukraintseva et al., 2012*]. Redistribution of chemical elements in the soil cover and surface runoff following the landslide events determines the nature of the



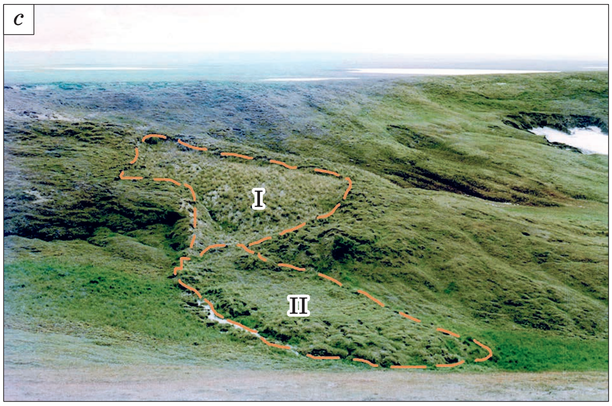




**Fig. 10. Cryogenic landslides.**

*a*, *b*: satellite imagery-based monitoring of thermocirque produced by retrogressive thaw slumps development [*Kizyakov et al., 2013*] dated: *a* – 2009; *b* – 2012. Position of thermocirque edges: 1 – in 2002; 2 – in 2009; 3 – in 2012; lower scarp: 4 – in 2009; 5 – in 2012; 6 – limits of debris fan in 2012. *c*: active-layer detachment, Yugorsky peninsula (photo by authors). I – shear surface; II – landslide body.

plant community succession and generates a mosaic pattern of the tundra vegetation cover developing within slopes affected by landslides [*Rebristaya et al., 1995; Sloan and Pollard, 2012; Yermokhina and Myalo, 2012*]. Azonic high willows developed on the saline from the surface marine sediments in the typical tundra subzone in Yamal indicate ancient cryogenic landslides, thus providing a basis for mapping landslide processes using aerial and satellite images [*Ukraintseva et al., 2014*].

Both cryogenic slope processes and ecosystems to which they belong are highly vulnerable to climate fluctuations. The study of their distribution patterns and evolution features in the permafrost landscapes is necessary, in order to assess the potential environmental impacts from activation of these processes.

## GEOGRAPHICAL EXTENT OF STUDIES OF CRYOGENIC PROCESSES

Geographical distribution of the locations where cryogenic processes were investigated is associated, firstly, with the environmental/natural uniqueness of the area featured by the active manifestation of a related process; secondly, with the presence of facilities for field research (polar stations, settlements and etc.), where long-term studies are conducted; thirdly, with several supported major projects related to study of permafrost regime in a particular area facilitating active multidisciplinary research; fourthly, with intensive economic development of particular areas in the permafrost zone, when the studies and monitoring of cryogenic processes are needed to ensure safe operation of facilities.

Studies dedicated to thermokarst (dynamics and regime of thermokarst lakes) are focused mainly on the areas of distribution of: 1) Yedoma and alases in the Northeast of Russia; in Alaska, Arctic coastal plain; on the Northwest Coast of Alaska, in the Yukon river valley, 2) extensive peatlands in the areas underlain by discontinuous and island permafrost, including northern regions of Canada, the Hudson Bay Coast, northeast of the European part of Russia, and northern West Siberia. A number of studies comprising large areas of West Siberia, Central Yakutian lowland, the Northern Yakutian plains, Alaska regions analyze regional variations in quantity and size of thermokarst lakes using remote sensing data. Thermokarst dynamics is actively studied in the areas of alpine permafrost in China.

Field study of thermal erosion was disposed on Bylot island, Canadian Arctic Archipelago, providing long-term monitoring; on the Yamal Peninsula and in the Lena river basin (in its middle and lower reaches). The studies of the Arctic coastal dynamics continued from 2010 to 2015 at the research stations set up on the Barents, Kara, Chukchi, Laptev and Beaufort Sea coasts. The long-term comprehensive research of permafrost continued at the Marre-Sale station, Western Yamal; the Vaskiny Dachy station, Central Yamal; the Nadym station, Tazovsky peninsula; the Bolvansky station, Pechora river mouth; at the stations on Samoilovsky island, Muostakh island, and the Bykovsky peninsula on the Laptev Sea coast, and in the vicinity of Point Barrow, Alaska.

Cryogenic landslides were under study on the Yamal Peninsula (north of West Siberia), on the northwestern coast of Canada, and on Alaska. The study of peatlands and segregation frost heave mounds was conducted in the Bolshezemelskaya tundra, in the northeast of the European part and in Western Siberia (Russia), in Alberta (Canada).

The aforesaid indicates the uneven spatial state of knowledge of cryogenic processes within the permafrost zone. The problem of expanding geographic coverage of research can be achieved using remote sensing methods. It should be emphasized, though, that research employing remote sensing data are to be based on the analysis of regional field data, coupled with ground truth obtained in key areas, to ensure reliable interpretation of these data.

## CONCLUSION

Based on the analyses of research results from past years and the reviewed publications over the five-year period (2010–2015) the following conclusions have been drawn:

1. Despite the existing general trend for activation of destructive cryogenic processes under certain conditions studied mainly near the southern limit of the permafrost zone, there is a possibility for permafrost aggradation, confined to peatlands, as well as to lakes, either overgrowing by vegetation or drained.

2. Satellite imagery of optical and radar range have been widely used in recent studies of cryogenic processes. The use of these data allowed obtaining new quantitative information on frost heave and thermokarst settlement, thermal erosion, thermal abrasion and thermodenudation rates. Thermokarst lake dynamics in permafrost areas is studied using remote sensing data as well.

3. A new research line related to discovered in recent years gas emission craters, is prompted by aiming to particularize conditions for and mechanism of their origination.

4. The most promising areas for further research to be considered are the continuation of the long-term series of observations complemented by new experiments at the research stations, and the expansion of the monitoring network for uniform coverage of the areas with different environmental conditions.

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