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PERMAFROST RESPONSE TO CLIMATE WARMING

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The response of permafrost to global Late Pleistocene–Holocene warming has been investigated in the ice complex of Yakutia. Thermokarst erosion of the complex was found out to depend on the properties of landscape and its components that change as a consequence of warming. In addition to the degradation tendency, aggradational stabilization in ice complex remnants may occur in certain conditions as formation of a protective layer.

Any external effect on permafrost, including climate, is never direct, unlike on a glacier surface, but is rather mediated by the overlying vegetation, soil, active layer, i.e., by various landscape components. The resulting positive and negative feedbacks control the permafrost responses which differ in intensity and may show unexpected trends.

Changes in surface conditions attendant with warming or cooling may change the evolution trend of permafrost and cause its aggradation or degradation. They may act either together with or against the climate trend and, correspondingly, amplify or damp the climate effect [*Koreisha et al., 1997*].

An illustrative example in this respect may come from dynamics of the ice complex over the latest Pleistocene–Holocene interval. An ice complex (IC) is a complex of syngenetically frozen sediments, tens of meters thick, which are thermally unstable. Such complexes were deposited in harsh Late Pleistocene climates between 50–40 and 12–11 kyr BP.

At that time, the mean annual temperature of permafrost was as low as −25...−28 °C or locally −30 °C in northern Yakutia and no warmer than −10 °C in central Yakutia, while the air temperature was naturally still lower [*Konischev, 1997*]. The map in Fig. 1 shows the extent of the Yakutian ice complex except shelf where it was destroyed by the Holocene transgression of the Arctic seas.

The dramatic climate change at the Last Glacial–Holocene boundary caused permafrost warming and gave rise to thermokarst erosion of the ice complex, which has been the main evolution process in its terrain-forming deposits through the past 13–12 kyr.

The basic landforms in the present North and Central Yakutian coastal lowland include, besides river valleys, the so-called *yedomas* (IC remnants) and *alas* depressions (result of subsidence of thawed permafrost) that reach surface areas of tens of square kilometers. Alases occupy up to 75 % of the northern Yakutian coastal plains [*Lomachenkov et al., 1965; Bosikov, 1978*] and up to 50 % in central Yakutia [*Ivanov, 1981*].

Although being approximate, these estimates indicate that the ground surface composed of IC deposits is more strongly affected by thermokarst processes in northern Yakutia than in its central part. The reason is that alases in both northern and central areas of Yakutia result from water ingression (showing up as the number and sizes of lakes) rather than from climate warming per se or from other temperature agents.

The glacial deposition completed in the end of the last cryochron (Last Glacial), and the top surfaces of its remnants (yedomas) generally have experienced no denudation since then. This inference follows from many radiocarbon dates showing latest Pleistocene ages of the youngest IC deposits [*Ivanov, 1981; Kaplina, 1981*]. Therefore, through the Holocene the IC deposits have been subject to different alteration trends [*Shur, 1988*].

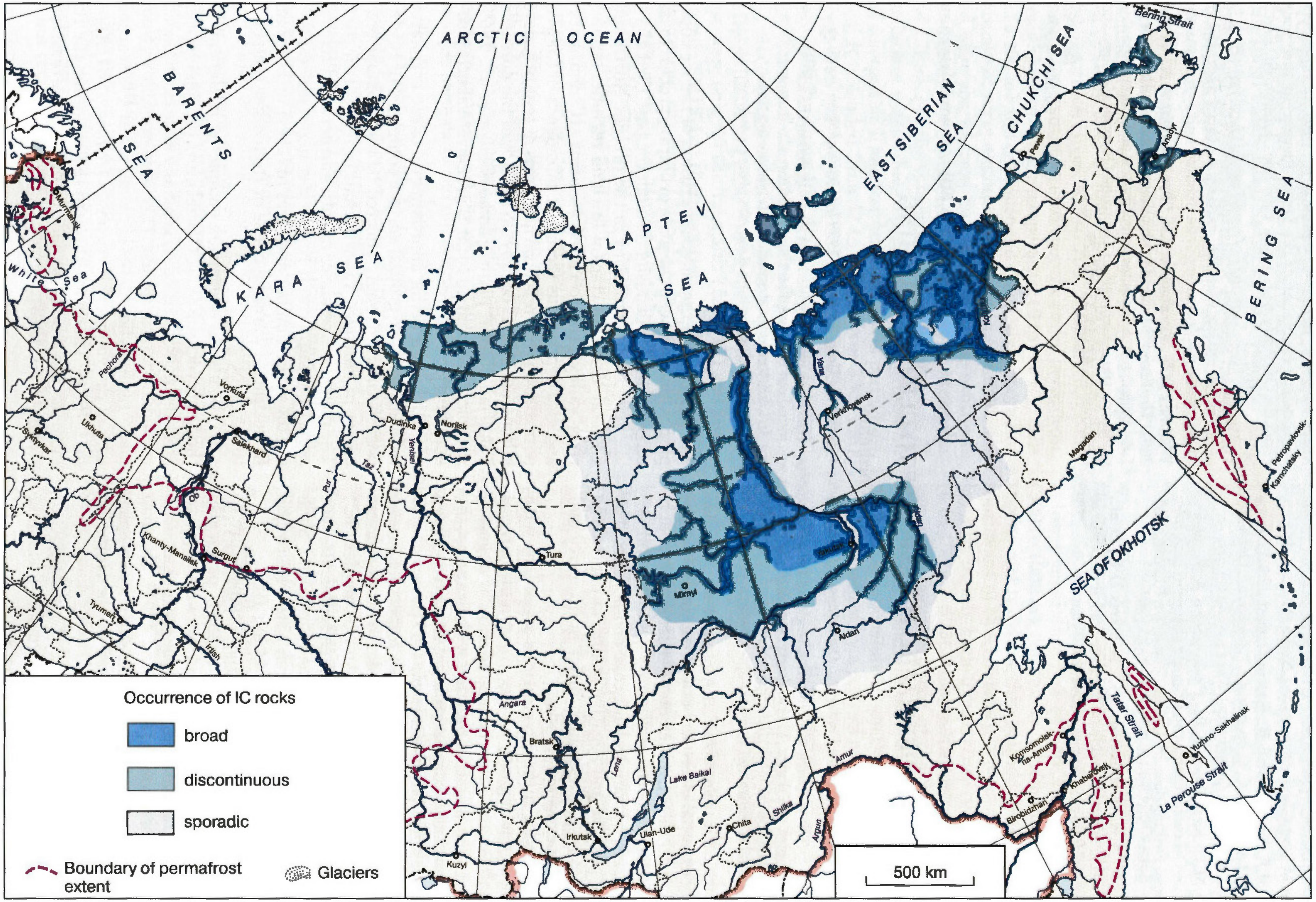

Fig. 1. Map of ice complex.

Compiled by V.N. Konishchev and N.A. Koroleva after [*Romanovsky, 1993; Konishchev, 1997; Kunitsky, 2007; Streletskaya et al., 2007*].

Some factors acted in latest Pleistocene–Holocene time that preserved the IC remnant top surfaces and made them more stable.

Since the 1940s, it has been understood that there exists a protective layer underneath the active layer [*Efimov and Grave, 1940*], namely, a 1.5–2.0 m thick frozen layer was found under thick forest between alases in Central Yakutia. However, deforestation increased the thaw depth by 30–40 % (originally 1.3–1.4 m) and the protective layer started thawing.

The protective layer is widespread on IC remnant surfaces in northern coastal plains as well but has been referred to in different ways: either a "cover" [*Kaplina, 1981*] or a "transition" layer [*Shur, 1984*].

This layer is remarkable by a very high ice content (up to 60–70 %) and by massive-agglmerate or reticulate cryostructures. It is most often silty and has a thickness of 1.5–1.7 m.

The origin of the protective layer is controversial. It was interpreted as a remnant from the Holocene climate optimum [*Kaplina, 1981; Konchenko, 1999*], but there are views [*Gravis, 1969; Torgovkin, 1988; Shur, 1988*] that the thaw depth in the Holocene decreased rather than increasing because of greater soil moisture contents and profuse growth of hydrophilic vegetation (moss and subshrubs).

The effect of landscape changes was to decrease the thaw depth in unthawed areas through the Holocene history of the ice complex, after its deposition had been completed. As a result, the permafrost surface became shallower and there formed an ice-rich transition layer [*Shur, 1988*].

Another essential agent is moisture migration from the active layer into the upper permafrost, which has been well studied both in field and in laboratory [*Parmuzina, 1978; Ershov, 1979; Konstantinov, 1991*].

The ice-rich transition cover is widespread on IC surfaces and is an important screen that protects permafrost from various effects of climate warming, including temperature variations. That is why *protective* (the original term from [*Efimov and Grave, 1940*]) appears to be a better name than *cover* or *intermediate* for the layer of high ice content in the upper permafrost.

The destructive effect of the Holocene warming and the thermokarst erosion of IC deposits is only one component of the permafrost response to climate change. Another component is stabilization as a consequence of physiographic changes such as increasing soil moisture, growth of hydrophilic moss, or accumulation of soil organic matter.

It is owing to the protective layer, that a great part of the ice complex has survived through more than 10 kyr and remains an important environment control of permafrost-related landscapes and ecology over a vast territory of East Siberia.

In northern Yakutian coastal, the protective layer formed when the temperature rise from −22...−28 to −8...−10 °C allowed moisture migration from the active layer into the underlying frozen ground. In Arctic areas, it is as thin as 0.4–0.5 m and cannot prevent the ground below it from thawing associated with active layer dynamics. As a result, the upper ice complex becomes prone to destruction, such as, for instance, the Yedoma section of the Oiyagos Yar which misses Sartan strata (an effect called *frontal thermal planation* in [*Tomirdiaro and Chernenkii, 1987*]). On the contrary, the ice complex degrades very little from the surface in areas further to the south, as far as southern Yakutia, where the protective layer thickens up to 1.5–2.0 m.

In addition to the reported physiographic features of alas formation, the protective layer is subject to spatial inversion.

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BURIED SNOW IN THE LENA-AMGA PLAIN

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Some new forms of buried stratified ice have been discovered in the Late Pleistocene section of the Lena-Amga Plain (Central Yakutia, Russia) in the course of core drilling at several watershed sites elevated to 220–250 m asl. The buried ice, which belongs to the traditionally distinguished ice complex, makes three separate layers of firn (snow recrystallized to difference degrees), at the depths 12.0 to 17.0, 23.3 to 24.5, and 33.6 to 39.0 m below the ground surface lying under wedge ice found in the uppermost section between 2.5 and 5.0 m. The firn layers are separated by syngenetically frozen sandy silt and silt.

INTRODUCTION

Buried ice is widespread in plainland Central Yakutia, especially in the Lena–Amga–Aldan interfluve (Lena-Amga Plain) where it belongs to the ice complex [*Soloviev, 1959; Katasonov, 1975, 1979; Ivanov, 1984*]. The ice complex of the area consists of up to 70–80 m thick fine-grained sediments that bear frozen water in the form of ice wedges and structure-forming ice. The total permafrost thickness reaches hundreds of meters, the upper layer of at least 100 m being syngenetically frozen ground.

More evidence of the composition, age, and geomorphic setting of the ice complex has been obtained recently through core drilling in the Lena-Amga Plain, at altitudes 220–250 m asl (Fig. 1), run by the Institute of Permafrost (Yakutsk) [*Spektor and Spektor, 2002*].

Boreholes drilled at several sites of the plain near watersheds stripped previously unknown forms of buried stratified ice which turned out to be snow recrystallized to difference degrees (firn). The discovery of firn ice in drill sections, a very important outcome of the drilling project, provides clues to the Late Pleistocene climate in the area and has additional implications for the origin of the ice complex.

FIELD DATA

The most complete section with different forms of buried ice was found in the borehole drilled in 2004 at 62°08′ N, 131°18′ E, 82 km east of Yakutsk city. The experiment of 2004 consisted in core drilling with successive bit diameters of 147, 127, 108, 89, and 76 mm, and core recovery using an air-flushing system. Thus obtained undisturbed core material selected for further studies was then transported, in the frozen state, to an underground laboratory of the Institute of Permafrost (Yakutsk).

The core section included three ice layers of different thicknesses: wedge ice in the uppermost part at 2.5–5.0 m below the ground surface and two firn layers at 12.0–17.0 m and 33.6–39.0 m separated by syngenetically frozen sandy silt and silt [*Spektor et al., 2008*].

Another hole drilled in 2011 three meters off the former one provided more details of the section as it tapped layered ice at two depth intervals of 13.5–14.2 m and 23.31–24.50 m below the ground surface. Additionally, the upper and lower snow cover was sampled above the hole (5–10 and 30–40 cm below the snow surface, respectively, the total snow thickness at the time of 19.03.2011 being 43 cm).