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The main features of permafrost in the Laptev Sea region, Russia – a review

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ABSTRACT: In this paper the concepts of permafrost conditions in the Laptev Sea region are presented with special attention to the following results: It was shown, that ice-bearing and ice-bonded permafrost exists presently within the coastal lowlands and under the shallow shelf. Open taliks can develop from modern and palaeo river taliks in active fault zones and from lake taliks over fault zones or lithospheric blocks with a higher geothermal heat flux. Ice-bearing and ice-bonded permafrost, as well as the zone of gas hydrate stability, form an impermeable regional shield for groundwater and gases occurring under permafrost. Emission of these gases and discharge of groundwater are possible only in rare open taliks, predominantly controlled by fault tectonics. Ice-bearing and ice-bonded permafrost, as well as the zone of gas hydrate stability in the northern region of the lowlands and in the inner shelf zone, have preserved during at least four Pleistocene climatic and glacio-eustatic cycles. Presently, they are subject to degradation from the bottom under the impact of the geothermal heat flux.

1 INTRODUCTION

This paper summarises the results of the studies of both offshore and terrestrial permafrost in the Laptev Sea region performed within the framework of the Russian–German programmes "Laptev Sea System" and "System Laptev Sea 2000." These results were analysed together with numerous data obtained by Soviet researchers before the 1990s. The mathematical simulation of permafrost evolution and cryogenic phenomena was of great importance for generalising all existing data and understanding the current state of permafrost within the sea shelf and coastal lowlands. The main palaeo-geographic interpretation, geological model and mathematical calculations have been reported previously (Romanovskii and Hubberten, 2001). The aim of this paper is to outline the new concepts of permafrost conditions in the Laptev Sea region that have emerged from these studies.

2 ENVIRONMENTAL CONDITIONS OF THE REGION

The region under study includes the vast flat shelf of the Laptev and, partly, East Siberian sea, as well as Arctic islands and coastal lowlands bordered by mountains from the south. The width of the shelf is up to 1000 km (Fig. 1). All this territory has never been subject to larger glaciation. Therefore, the sea level fluctuations in the Late Cenozoic were mainly of glacio-eustatic nature. The geology of the region, including the shelf, is extremely complex. It consists of tectonic structures of different ages, including several rift zones (Tectonic Map of Kara and Laptev Sea, 1998; Drachev *et al.*, 1999). The continental rifts extending across the shelf cause significant variations in geothermal heat flux values q_{gt} between 40 and 70 mW/m^2 within undisturbed blocks and more than 100 mW/m^2 in rift zones (Balobaev, 1991; Duchkov *et al.*, 1994). Neotectonic movements had a predominantly descending character and were accompanied by the compensatory accumulation of sediments. An important hydrological feature is the predominance of negative (subzero) mean annual near-bottom seawater temperature t_{sb} that varies between -0.5 and -1.8°C, except for shallows where the summer temperature of water and bottom sediments exceeds 0°C (Dmitrienko *et al.*, 2001).

3 CONCEPTS OF REGIONAL PERMAFROST CONDITIONS PREDATING THIS STUDY

Detailed data on permafrost conditions were available for coastal lowlands and islands (Geocryology of the USSR, 1989). These areas have continuous permafrost with a thickness of up to 500–600 m. The permafrost temperature zonality is traced on the lowlands northward from the mountains and on the islands. For the mean annual ground temperature, t_{ma}, the temperature gradient reaches 1.5°C per 1° latitude. For example, t_{ma} is -6 to -7°C in the south of coastal lowlands and decreases to -14°C or -15°C in the north of Arctic islands. Taliks exist under numerous thermokarst

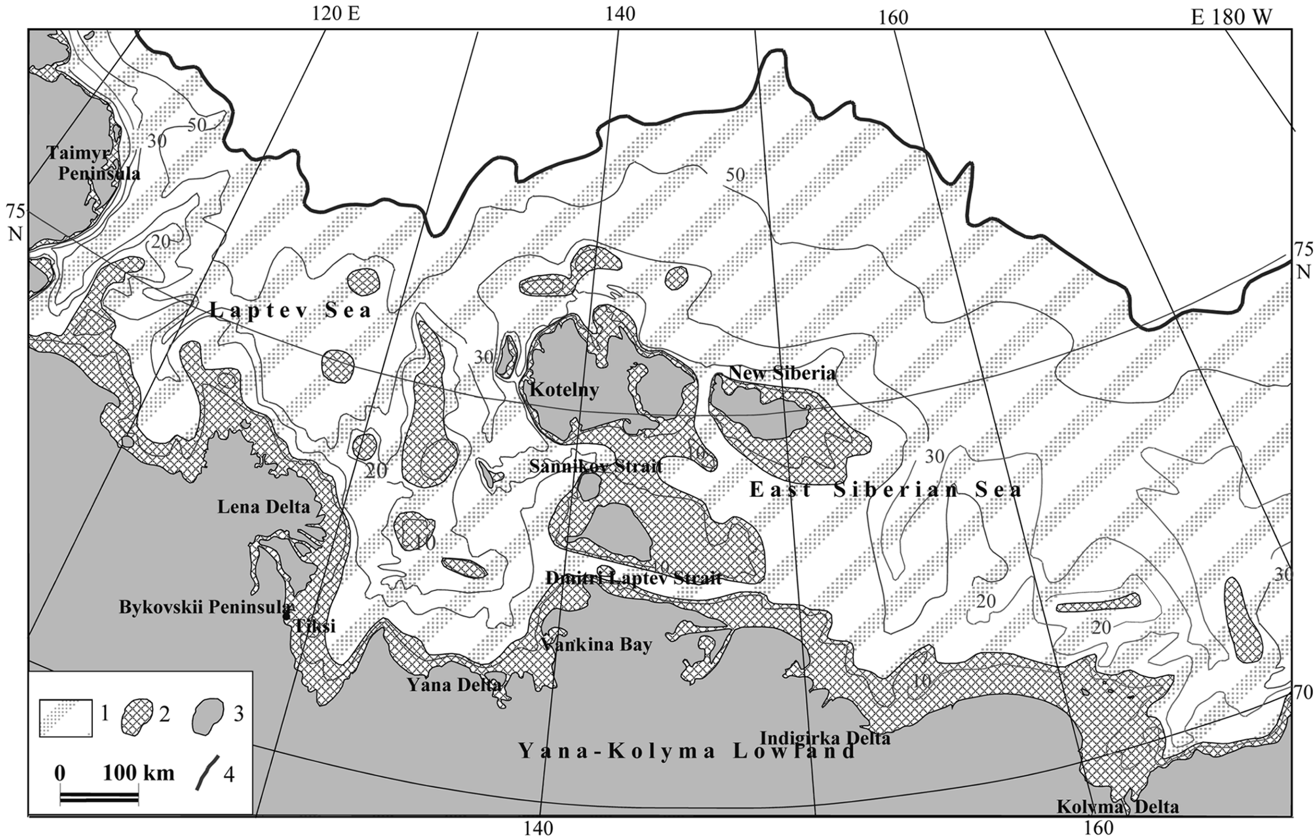

Figure 1. Map of the permafrost state. 1 – Ice-bearing offshore relic permafrost; 2 – Ice-bearing and ice-bonded offshore relic permafrost; 3 – Terrestrial ice-bonded permafrost; 4 – Edge of the shelf.

lakes. Open lake taliks were presumed to appear under large lakes having a diameter of more than 1 km.

Very scarce information existed on the subsea permafrost and lake taliks until the mid-1990s. I.D. Danilov and L.A. Zigarev (1977) stated that discontinuous permafrost exists under the sea only within a narrow strip in the littoral zone (Zigarev, 1997). V.A. Solov'ev (1981) believed that a continuous subsea permafrost with a thickness of 200–300 m occurs near the coast being replaced by discontinuous permafrost further into the sea, up to the isobath of 50–60 m. The idea of a thick (up to 1000 m) continuous permafrost under the whole shelf zone of the Laptev Sea was first advanced by A.I. Fartyshev (1993). This hypothesis was based on the concept of glacio-eustatic emergence of the shelf and its deep freezing during the last glacial maximum. Large values of permafrost thickness were derived from computer simulations based on a simplified palaeo-geographical scenario. The presence of deep relic permafrost in the Laptev Sea shelf was indirectly confirmed by data on its presence in the Beaufort Sea shelf near the Mackenzie River mouth (Judge, 1984). A review of concepts concerning permafrost on the shelf of Eurasian Arctic seas to the east of the Taimyr Peninsula, including the Laptev Sea shelf, was published earlier (Gavrilov *et al.*, 2001).

4 NEW CONCEPTS OF REGIONAL GEOCRYOLOGICAL CONDITIONS ARISING FROM THIS STUDY

4.1 *Distribution of permafrost and taliks*

During the first stage of our investigation, it was found that ice-bonded permafrost extends seaward to the shelf edge (Romanovskii *et al.*, 1998). At the same time, a rather uneven upper permafrost table was observed in numerous seismic-acoustic profiles obtained with the PARASOUND device during the TRANSDRIFT l–VIII marine expeditions (Niessen *et al.*, in prep.). Ice-bonded permafrost is covered by non-frozen cryotic deposits with predominantly subzero temperatures. This ice-bonded permafrost includes both Holocene marine sediments and underlying Pleistocene marine and continental sediments. Seismic-acoustic studies confirmed the results of drilling performed during geological mapping in this region in the 1970s and 1980s. Later, the results of geophysical studies were confirmed by special drilling performed by the TRANSDRIFT VIII expedition (Kassens *et al.*, 2000).

As noted above, the results of seismic-acoustic studies and drilling data indicated the presence of both relic ice-bearing permafrost and cryotic deposits, the thickness of which varied between 1–2 m and 100–150 m. The thickness of cryotic deposits on the shallows in places of former islands destroyed by thermal abrasion is only a few meters, although they have been under the sea for some hundreds to thousand years.

4.2 *Lake thermokarst in the Ice Complex*

Based on the study of the "thermokarst lagoon" on the Bykovskii Peninsula and the analysis of maps and satellite and aerial photos of coasts, it was supposed that subsea taliks composed of cryotic deposits represent closed lake taliks submerged under the sea in the course of their postglacial transgression (Romanovskii *et al.*, 2000a). This idea was based on the following facts: A complex of syncryogenic deposits called the Ice Complex (IC) (in American terminology, the "Yedoma formation") was formed on the emerged surface of the Arctic shelf and on the coastal lowlands in the Russian Arctic to the east of the Taimyr Peninsula during the Late Pleistocene sea regression. The ice content in the Ice Complex is 90–95 vol.% and its thickness is 60–80 m. For the Bykovskii Peninsula, the average rate of its accumulation in the second half of the Late Pleistocene was calculated as 0.5 to 1.5 cm per year (Schirrmeister *et al.*, 2002). Using the notions of the lifetime of dried shelf areas (Romanovskii *et al.*, 2000), V.E. Tumskoy *et al.* (2001b) estimated the maximum possible thickness of the IC in the areas of neotectonic setting. According to his estimates, the thickness of permafrost could reach 7–8, 10, 25–30, 50 and 70 m for the 100, 80, 60, 40 and 20-m isobaths, respectively.

T.N. Kaplina and A.V. Lozhkin (1979) found that numerous thermokarst lakes and alases (thermokarst depressions) already existed on lowlands in the Early Holocene, 9.6 kyr BP. We tried to estimate the time necessary for the thawing of ICs of different thicknesses in conditions of the emerged dried shelf zone at different latitudes, i.e., under different temperature conditions. Knowing the duration of thawing, we were able to reconstruct the time of the beginning of the thermokarst lake formation. For this purpose, a mathematical simulation based on the Stefan equation was performed for the formation of thaw lakes and lake taliks (Tipenko *et al.*, 2001). The most favourable conditions for the thermokarst development were taken: the absence of lake drainage; rise in temperature of bottom sediment from 0 to +4°C upon deepening of thaw lakes as a result of the IC thawing; and enlargement of lakes at a rate similar to that observed currently in the Chukotka region equal 2 m/y (Tomirdiaro, 1974).

Thermokarst development within the IC proceeds in two stages. At the first stage, the IC thaws through and the thawed out organic and mineral components (called in Russian terminology "taberal deposits") are accumulated on the lake bottom. At the second stage, after the complete thawing of the IC, a lake talik is formed in the underlying deposits.

The simulation of thawing for ICs of different thickness and at different latitudes showed the following:

1. The duration of the IC thawing varies from 800 to 1200 years depending on its thickness. Complete thawing of the IC with a thickness of 40–60 m in conditions of the dried shelf in the Late Pleistocene required 2000 to 3000 years;
2. Taking into account that alases already existed during the Early Holocene (9.6–8.6 kyr BP), the extensive formation of thaw lakes must have begun during one of the relatively short warming phases in the Late Pleistocene (about 12.8 kyr BP);
3. The curve of the last glacial-eustatic transgression (Fairbanks, 1989), which was proved to be representative for the Laptev Sea (Bauch *et al.*, 2002), showed that about 9000 years ago the sea level corresponded to the modern 50-m isobath. Thus, it was found that the extensive formation of thermokarst lakes and alases on the shelf preceded their submergence under the sea;
4. The transgressing sea in the eastern regions of Eurasian Arctic submerged the shelf surface with abundant thaw lakes. These lakes became bays (called "thermokarst lagoons"). The coastline sinuosity increased significantly, as well as the total effect of thermal abrasion. As a result, during the Holocene, i.e. within about 9000 years, the coastline moved southward by 300–400 km into the Laptev Sea region and by 800 km into the western regions of the East Siberian Sea;
5. A high rate of transgression and intensive coastal abrasion resulted in a decreased arrival of suspended mineral and organic matter onto the outer shelf and continental slope in the Holocene (Bauch *et al.*, 1999). This paradox was related to the fact that the thaw lakes and thermokarst lagoons served as traps for deposits eroded by thermal abrasion (Romanovskii *et al.*, 2000a);
6. Only closed lake taliks could form under thermokarst lakes on the shelf before their submergence. Their depth increased in southward direction (from the outer shelf to the near-coast shelf);
7. During the formation of thaw lakes and lake taliks, permafrost thaws out not only from the top (under the lakes) but also from the bottom, due to the geothermal heat flux. Therefore, open taliks could develop only from lake taliks, which were formed over fault zones with higher values of geothermal heat flux, $q_{gt} > 60$–80 mWt/m^2 (Tumskoy *et al.*, 2001 a, b);
8. The progressive development of taliks under continental thaw lakes was and is suppressed by their drainage and formation of thermokarst depressions

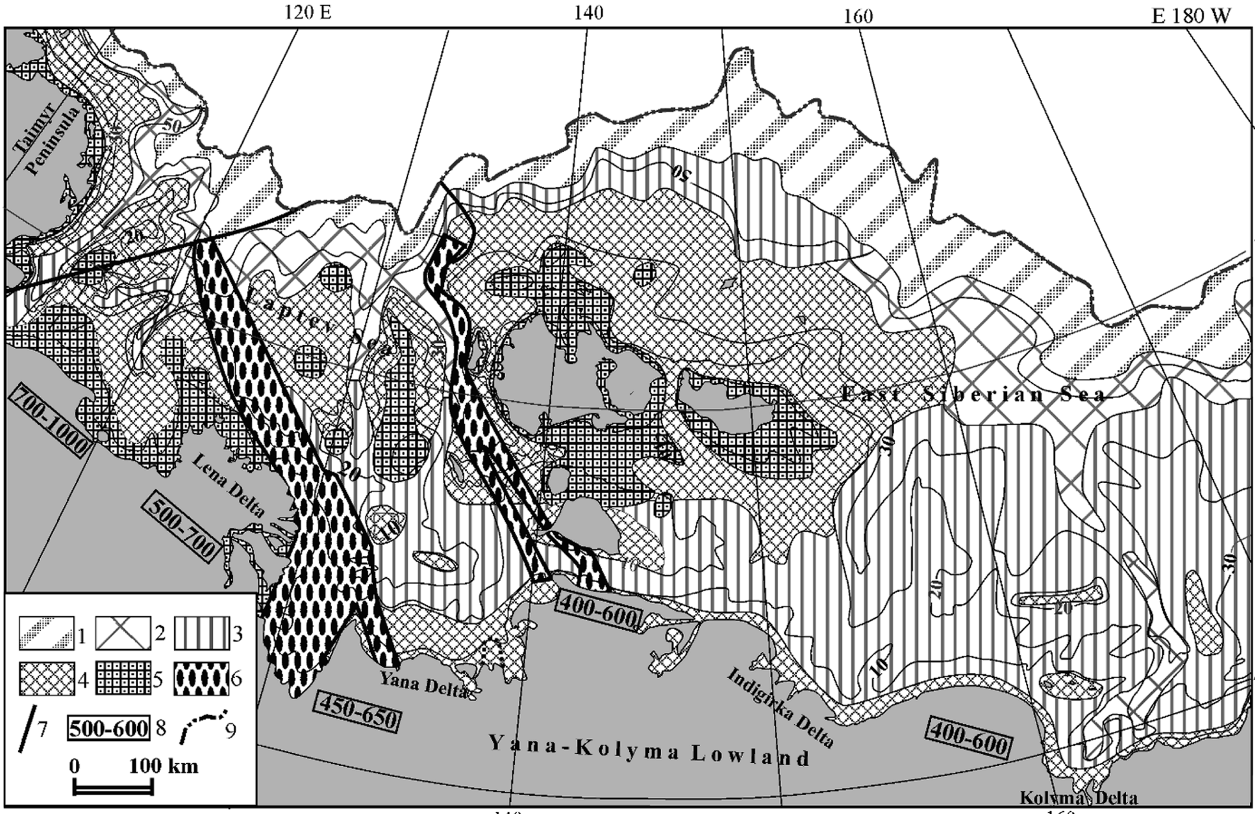

Figure 2. Map of Relic Offshore Permafrost Thickness (in accordance with results of permafrost thickness simulation, q_{gt} value equal to 45 mW/m2). Ice-bonded and ice bearing permafrost thickness (in m): 1 – till 100; 2 – 100–200; 3 – 200–300; 4 – 300–400; 5 – 400–600; 6 – rifts with permafrost thickness from 20 to 200–600; 7 – main faults with permafrost thickness of 10–200 and probably open taliks; 8 – terrestrial permafrost thickness; 9 – edge of shelf.

(alases) in their place. In these conditions, taliks are subjected to freezing, and syncryogenic deposits with ice wedges form on the bottom of alases;

9. When thaw lakes are submerged under the transgressing sea and transformed into "thermokarst lagoons", lake taliks become subsea taliks. Some of these taliks with fine grained clayey freshwater sediments in surface horizons freeze under sea with the water temperature of −1 to −1.5°C and form subsea pingos (Romanovskii *et al.*, 1998). These formations were detected by seismo-acoustic profiling.

4.3 *Permafrost thickness*

The thickness of permafrost is 400 to 650 m on the coastal lowlands composed of fine grained (silty, loamy) ice-saturated deposits. It increases to 700−1000 m at the foothills composed of hard rocks. V.V. Devyatkin found that the permafrost in a borehole near the settlement of Tiksi was 670 m thick (personal communication). A geophysical study performed on the coast and from the sea ice in the Tiksi Bay showed that no appreciable decrease in the permafrost thickness is observed when going from the coast to the shelf (Nim, 1989).

Mathematical simulation was performed in order to estimate the possible permafrost thickness. The more detailed description of the model and calculation results are considered in the paper published in this volume (Romanovskii *et al.,* 2003). Simulation was first performed for a single climatic and glacio-eustatic cycle (from about 120 kyr BP to the present days) and single value of q_{gt} (50 mW/m^2 for undisturbed blocks and 100 mW/m^2 for fault zones (Hubberten and Romanovskii, 2001; Kholodov *et al.*, 2001). More recently, a similar simulation was performed for four cycles (from about 420 kyr BP to the present day) (Romanovskii and Hubberten, 2001). It was found that the thickness of relic permafrost on the shelf decreases with increasing water depth for all simulation variants. For a similar water depth, it increases northward. The reason for this is that the freezing of halomorphic saline deposits (with a freezing point of −2.0°C) on the dried shelf proceeds under the permafrost temperature zonality typical of terrestrial systems. It was taken equal to the current value. Therefore, it was presumed that the highest thickness of relic permafrost (500–600 m) should exist under shallows north of Kotel'nyi and the New Siberian islands. This was confirmed by results of seismic study (Hinz *et al.*, 1998).

4.4 *Current state of permafrost*

The study of the permafrost evolution showed that the highest permafrost thickness within the shelf and coastal lowlands of the Laptev Sea region was reached after the last glaciation maximum, i.e., later than 18 kyr BP. A gas hydrate stability zone (GHSZ) exists under the shelf and lowlands (Romanovskii *et al.*, 2003). At present, a universal decrease in the permafrost thickness takes place because of its thawing from the bottom under the impact of geothermal heat flux. Permafrost thawing from the bottom is estimated at 200–300 m. It depends on the lake lifetime, the composition of rocks, their ice content and the value of q_{gt}.

In Figure 2 the map of recent permafrost thickness is presented which was compiled on the base of simulation results.

In order to estimate the current permafrost status, a simulation was performed with due account for the freezing/thawing temperature range of halomorphic and fine-grained clayey deposits (Romanovskii and Hubberten, 2001). It was found that relic permafrost within the major part of the shelf exists as ice-bearing permafrost. The deposit temperatures below −2.0°C and ice-bonded permafrost persist near the coasts and are presently subject to thermal abrasion and in the place of islands recently destroyed by thermal abrasion (Fig. 1). The degradation of ice-bearing permafrost proceeds from the bottom at a rate proportional to the value of q_{gt}. This results in a strong differentiation of permafrost thickness in the rift zones on the shelf separating lithospheric blocks with different values of geothermal heat fluxes.

5 CONCLUSIONS

1. Ice-bearing and ice-bonded permafrost exists presently within coastal lowlands and under the shallow (down to the isobath of 50–60 m) shelf. Open taliks can develop from modern and palaeoriver taliks, in active fault zones and from lake taliks over the fault zones or lithospheric blocks with a geothermal heat flux $q_{gt} > 60–80\ mW/m^2$.
2. Ice-bearing and ice-bonded permafrost, as well as the zone of gas hydrate stability (Tipenko *et al.*, 1999), form an impermeable regional shield for groundwater and gases occurring under the permafrost. Emission of these gases and discharge of groundwater are possible only in rare open taliks predominantly controlled by the fault tectonics. The gas emission from thaw lakes (Zimov *et al.*, 1998) is mainly due to the decomposition of organic remains from thawed Cenozoic deposits rather than to gases concentrated under the permafrost as was suggested previously.
3. Ice-bearing and ice-bonded permafrost, as well as the zone of gas hydrate stability in the northern regions of lowlands and in the inner shelf zone with q_{gt} values of up to 60 mW/m^2, are preserved during at least four Pleistocene climatic and glacio-eustatic cycles. Presently, they are subject to degradation from the bottom under the impact of geothermal heat flux. The long-term (100 kyr) cycle of permafrost degradation is still far from the end because of global warming and a significant delay of the permafrost thickness extremes from the mean annual temperature extremes (Romanovskii *et al.*, 2003).

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