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Onshore and Offshore Permafrost of the Laptev Sea Region during the Last Pleistocene-Holocene Glacial-Eustatic Cycle

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THEME 12: Gashydrates and Permafrost, Onshore and Offshore

Summary: Terrestrial permafrost of the Laptev Sea Region (LSR) is continuous; its thickness varies between 500–800 m. Mean annual ground temperature $-t_{ma}$ decreases northward from -5 °C in the south of coastal lowlands to -15 °C in the north of Kotelny Island. An important component of the upper part of permafrost is the "ice complex" with a thickness of 40–50 m. It is the basis for the formation of thermokarst lakes and alas. Offshore, ice-bonded permafrost (IBRP) is relic, continuous to the 65 m isobath, and discontinuous to the 100-120 m isobath. Its thickness decreases northwards with increasing water depth and is higher in tectonic depressions than on uplifts. The IBRP thickness has a maximum north of Kotelny Island (450-530) and decreases with increasing depth to 80-50 m between 100 and 120 m isobaths

INTRODUCTION

Onshore and offshore permafrost are the most important components of the environment in the Laptev Sea Region (LSR). The area belongs to the active margin of Eurasia. Its compound geological composition, in combination with new active tectonic movement, differing geothermal heat fluxes and various quaternary deposits, both syncryogenic and epicryogenic, are typical for this region. Very cold climate is also characteristic for the LSR, although it was never glaciated, and therefore not subject to glacial-isostatic movements. Hence the LSR is a key area for the investigation of offshore and onshore permafrost formation typical to non-glaciated (ice-sheet) Arctic regions belonging to an active continental margin.

Onshore permafrost

Onshore permafrost in the LSR region is continuous, thick and old. It reaches to a depth of 500-800 m on lowlands and on the margins of the LSR (Geocryology of USSR 1989, Geocryological Map of USSR 1996). The mean annual ground temperature $-t_{ma}$ ranges from -8 to -9 °C in the Yana River Delta region to -15 °C on the northern Kotelny Islands. The modern regional latitudinal temperature gradient is approximately 1.5 °C per one degree of latitude. The upper part of the onshore permafrost on the lowlands is composed of both syncryogenic and epicryogenic ice-rich deposits. The lower portion of the permafrost in the lowlands and the entire profile in the mountainous regions are composed of epicryogenic frozen deposits.

Ice-bonded permafrost (IBP) presents a barrier impermeable to gases and water and there is evidence for gas hydrates in and below the IBP. The characteristic syncryogenic deposit in this region is the ice complex.

Ice complex

An ice complex is a polygenetic geological body including fluvial, slope, boggy, aeolian and other facies and two main types of ground ice: ice wedges and segregated ice. Ice-wedge ice forms from snow melt-water while segregated ice forms from suprapermafrost ground water in the active layer. Ice complexes typically contain high levels of organic matter, including peat, mammalian skeleton remains and diatoms. These features of ice complexes all reflect environmental conditions at the time of its formation and are good sources of paleogeographical information.

Ice complex are formed under severe environmental conditions, a continental climate with very cold and windless winters, thin snow covers and $-t_{ma}$ lower than -12 to -15 °C. The landscape was a tundra-steppe with high biological productivity (SHER 1992). The generally accepted theory is that the period of ice complex formation embraced all of the Late Pleistocene over an area including not only lowlands but also the exposed portion of the Laptev Sea Shelf (LSS). At the same time, the environmental, facial and permafrost conditions conducive to the formation of such ice complexes and the reasons why the phenomenon is not present in all apparently similar Arctic regions, as for example the North Slope of Alaska are not clear and demand additional investigation using new methods. Syncryogenic ice-rich deposits are very sensitive to climatic fluctuation and to such events as marine transgressions and regressions. These deposits are the foundation for the formation of many periglacial phenomena such as thermokarst lakes, talik, and river and coastal thermoerosion. The LSR has a complicated geological composition (DRACHEV et al. 1995). Investigations in the Lena Delta have shown that vertical tectonic displacements occurred during the formation of the ice complex. The thickness of ice complexes belonging to downward displaced tectonic structures is around 50-60 m. We hypothesize the existence of ice com-

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plex sections over 100 m thick in lowered tectonic blocks of the LSR.

Large and deep lowland thermokarst lakes occur in regions of recent tectonic sinking and near rivers as a result of better surface water drainage (Romanovskii 1961). Thus, ice complex thickness, its modern distribution, and the location of thermokarst lakes are under the control of recent tectonic activities (Fig. 1).

Prediction of permafrost thickness depends on lake thermokarst history: time of thermokarst filling and drainage, duration of lake existence, its size and other factors.

Offshore permafrost

Offshore ice-bonded permafrost of the LSS has been recognized since the last decade of the 18th century. It is shown on the many permafrost maps as being discontinuous and occurring on islands from the modern shoreline out to the 60 m isobath (Baranov 1960, Soloviev et al. 1987, Geocryological Map of USSR 1996), or out to the 30 m isobath (Danilov & Zigarev 1977, Zigarev 1997). Only Fartyshev (1993) assumed the existence of continuous permafrost 700 to 1100 m in thickness. These affirmations have been made on a basis of mathematical calculations using simplified formulae.

New investigations within the framework of the joint Russian-German program "Laptev Sea System" have strongly argued for the existence of predominantly continuous relic offshore IBP (Romanovskii et al. 1998). According to our paleoreconstruction, offshore IBP developed during the last Pleistocene-Holocene glacio-eustatic regression and degraded after flooding of the shelf by cold seawater. The time and duration of the two processes have been determined approximately relative to the bathymetry of the shelf using last glacial-eustatic curves (Chappel et al. 1996). The paleogeographical scenario from 120 Kyr until modern time and a geological model of the shelf (adopted from Drachev et al. 1995) have been compiled (Romanovskii et al. 1998) and used for mathematical simulation of permafrost evolution.

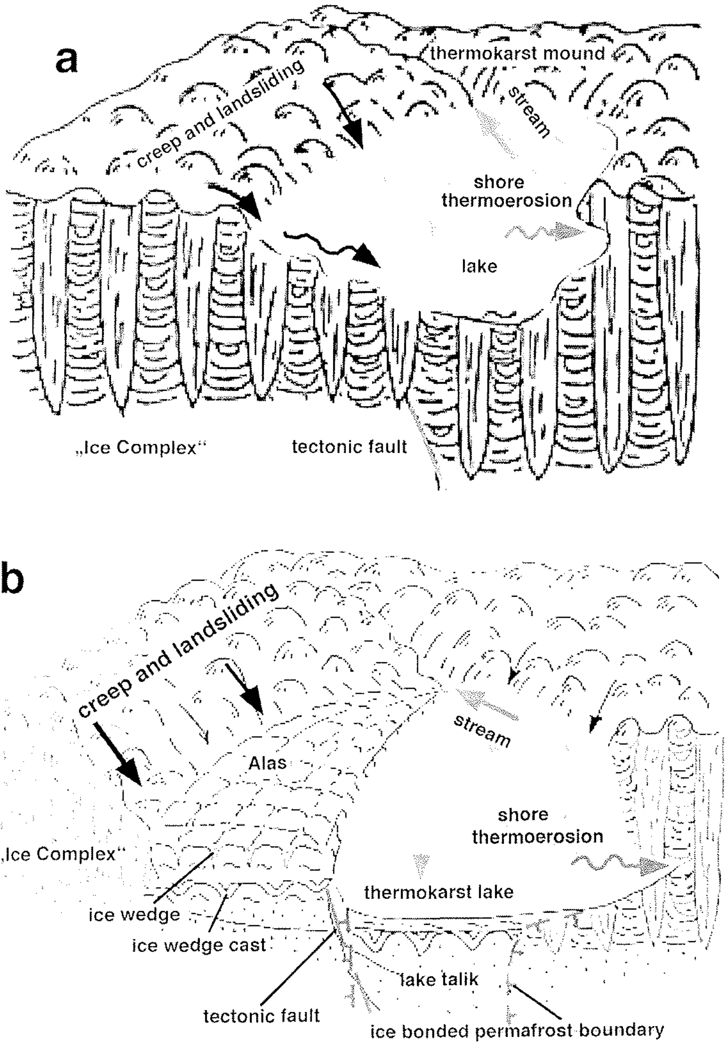

Fig: 1: The stages of formation of (a) thermokarst lake and (b) thermokarst depression typical for coastal lowlands of the Laptev Sea Region (LSR). The "Ice Complex" displays varying thicknesses due to modern tectonic movements. The migration of thermokarst lakes is controlled by the lower boundary position of the ice complex.

Paleogeographical events during Pleistocene-Holocene glacio-eustatic cycle and the geological model of the LSS

The paleogeographical scenario and a geological model adopted for mathematical simulation of permafrost evolution take into consideration the following natural events and environmental conditions:

1) duration of permafrost development during the last glacio-eustatic cycle versus time and recent shelf bathymetry;
2) fluctuation of $-t_{ma}$ during periods of shelf exposure;
3) onshore permafrost temperature zonation on exposed shelf;
4) environmental events such as the accumulation of syncryogenic deposits with fresh ground ice, sea shore thermoerosion etc.;
5) freezing and thawing of sediments and deposits saturated by sea water with freezing and thawing temperatures $t_{t,f}$−2 to −1.5 °C;
6) variations in mean annual sea water and sea floor temperature $-t_{t,f}$ depending on age and sea shore position at the time of exposure and flooding;
7) compound tectonic construction of LSS;
8) thermal and physical properties of deposits and sediments both frozen and unfrozen (ROMANOVSKII et al. 1997);
9) various geothermal fluxes –q according to the new geological construction of the LSS – for undisturbed tectonic blocks, heat fluxes of 40-50 mW/m^2 are typical, and for fault zones separating the blocks, fluxes reach 100 mW/m^2;
10) different rate of sea level rise during the last transgression;
11) rate of sea level rise was high (15 mm/year) from 13 Kyr B.P. until 7 Kyr B.P., and low from then until modern time (1-2 mm/y).

Flooding of ice rich deposits was characteristic for the first stage of very rapid shoreline advance, while the second stage was characterized by thermoerosion (ARE 1988). The latter process led to the demolishing of the ice-rich portion of the permafrost section and to the exposure of sediments with low ice content, saline pore water and $-t_{f,t}$ below 0 °C.

One of the central assumptions of the above scenario is the absence of IBP on the LSS during the Kasancevskaya transgression (from 139 to 112 kyr B.P.). This assumption should be tested, as it seems unlikely that the ice-bonded permafrost was completely degraded between the shoreline and the 30 to 40 m isobaths.

The authors will extend the reach of the scenario backward to 160 kyr B.P. using Chappell's curve, ice cores obtained from Greenland and Antarctica and paleo-reconstructions from Siberian permafrost. The main purpose of this work is to improve via calculation our understanding of the thickness of onshore and offshore permafrost before the Kasancevskaya transgression.

To improve the latter assumption we require information on the deposits containing the ice complexes. These deposits have been observed near the Lena Delta and Oyagossky Yar outcrops.

Calculated offshore permafrost thickness on the LSS

Based on the above scenario of permafrost development and thickness, its evolution has been calculated using the computer program HEAT. The results for offshore permafrost modeling are presented in the form of a schematic map and of profiles for the eastern LSS. According to the performed simulations, the maximum offshore permafrost thickness reaches 750-800 m (including ice-bonded permafrost and cryotic deposits) at the end of the Sartansky cryochron (approximately 18000 years B.P.) near the recent shoreline when the shelf was totally exposed. From 18 to 10 Kyr B.P. the offshore permafrost thickness remained constant. The position of the lower boundary of IBP remained virtually constant even during the short warming events at the end of the Late Pleistocene (13 to 10 Kyr B.P.). Flooding of the shelf by seawater induced the thawing of IBP.

Currently, the thickness of relict ice-bonded permafrost varies from 50-80 m near the shelf edge to 310-330 m in the lowland coastal zone (isobaths 10 and 20 m) and near the Novosibirsk Islands. The largest offshore IBP thickness was estimated for stable blocks within the limits of positive tectonic structures. So, at the 20 m isobath they vary in structures with geothermal heat fluxes of 50 mW/m^2 from 310-330 m at 72 °N to 470-530 m at 77 °N, i.e. northern Kotelnyi Island.

On the whole, negative tectonic structures are characterized by lower permafrost thickness compared to those of positive tectonic structures due to a different construction of geological sections.

In general, the IBP thickness on the modern shelf decreases with increasing water depth. At 77 °N latitude along the profile in the western direction from Kotelnyi Island, within the limits of stable blocks, the IBP thickness varies from 530-470 m (at depths of 20 m) to 450-290 m at greater depths (45 and 65 m). Minimal thickness (80 m) is typical at shelf sites with water depths of 100 m, where the duration of IBP formation was the shortest, while the submarine degradation was the longest. At depth ranges around 20 m, active tectonic faults with q of 100 mW/m^2 are characterized by an IBP thickness of 80-100 m at 72 °N to 210 m at 77 °N.

IBP is connected everywhere with layers of cryotic deposits 80-100 m thick. At sites with totally degraded IBP, cryotic deposits lie immediately under the sea floor. Depending on the duration of permafrost degradation period and the magnitude of heat flow, thaw from bottom occurs to different depths. Within stable blocks the depth of thaw for the last 7 millenary (20 m isobath) is 80-100 m when q is taken to be 40 mW/m^2, and 120-170 m, if q is taken to be 50 mW/m^2. At depths of 45-65 m ice-bonded permafrost has thawed from the bottom up to a thickness of 160-230 m at a q of 40 mW/m^2 and to 220 to 280 m at a q value of 50 mW/m^2. At the shelf sites with water depths of 100 m, the duration of degradation amounts to 13 Kyr and ice-bonded permafrost in active tectonic faults thawed completely and has been replaced by cryotic deposits. In the shelf areas, the upper part of the deposit is composed by "ice complex" sediments with a-$t_{f,t}$ of 0 °C and no thermal thawing from above takes place due to negative t_{sf}.

Direction and perspectives for further investigations

Further work should seek to combine terrestrial and marine studies. The investigation of syncryogenic deposits, including ice complexes, should bring new information on the paleogeographical (especially paleopermafrost) conditions during the Late Pleistocene- Holocene. These data should be complemented by borehole sampling and analyses on the glacier of the Severnaya Semlya Islands. A full set of paleoenvironmental information can be obtained from a combination and comparison of ground ice, glacial ice cores, lacustrine, and marine sediment data. This information provides the basis for evaluating the assumptions for simulating shelf and onshore permafrost evolution and its modern state. A very important component of cold regions with thick and low temperature permafrost are green house gases in gas hydrate form. To predict the existence, evolution and recent position of the gas hydrate stability zone (GHSZ) inside and below the permafrost section a new mathematical model has been developed. The model predicts:

- the evolution of GHSZ due to marine transgressions;
- the behaviour of GHSZ during the last transgression under the influence of rising temperature and pressure due to sea level elevation and
- the behavior of GHSZ below thermokarst lakes and lake taliks.

There are field observations of greenhouse gas flow through thermokarst lake taliks in the Kolyma lowland (Zimov et al. 1997). Initial calculations suggested the possibility of GHSZ disappearance below open lake taliks and green house gas discharge into thermokarst lakes of the LSR. Field testing of discharge and determination of the age of the gas and its composition should be one of the tasks of any future investigation.

Another important paleogeographical problem is the reconstruction of thermokarst lake formation: the age, size and environmental conditions of the creation and evolution of such lakes.

The LSR belongs to the active margins of northeastern Eurasia, with intensive new tectonic movement. New tectonic sinking, along with a compensating accumulation of syncryogenic deposits, leads to the thickening of permafrost on intermountain depressions, lowlands (Basisty & Buiskich, 1995) and the shelf. It is therefore necessary to make a quantitative evaluation of modern vertical tectonic movements and their impacts on permafrost and GHSZ thickness for the LSS and the lowlands of the LSR. The solution of these problems is possible through a combination of fieldwork and simulation.

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