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MAP OF PREDICTED OFFSHORE PERMAFROST DISTRIBUTION ON THE LAPTEV SEA SHELF

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Abstract

One of the most striking natural features of the Laptev Sea Shelf (LSS) is the ice-bonded offshore permafrost. It has aggraded due to the exposure of the shelf during the Late Pleistocene glacioeustatic regression. It includes epigenetic saline frozen deposits unevenly overlapped by syncryogenic ice-rich deposits - “Ice-Complexes”. At present, this permafrost is relic and degrading under the sea that flooded the shelf during the last transgression. Based on previous investigations, new field data, the compilation of paleo-environmental scenarios for the last glacioeustatic cycle and mathematical modeling of offshore permafrost evolution, a new model is presented of the distribution of ice-bonded permafrost and sub-sea taliks on the LSS. Ice-bonded offshore permafrost is relic and continuous, extending from the current shore line to the -60;-70 m isobaths and discontinuously to the -100 m isobath. Open taliks are linked with flooded valleys of main rivers and with active tectonic faults.

Introduction

Wide-spread distribution of perennially frozen ice-bonded deposits on the Laptev Sea Shelf (LSS) was found during the Joint Russian-German Research Program “The Laptev Sea System”. The ice-bonded relic offshore permafrost (IBROP) originated in the late Cenozoic due to a combination of cold climate and glacioeustatic fluctuations of the global sea level. It is currently preserved due to the effect of negative mean annual bottom temperatures in the Laptev Sea. The presence of IBROP prevents emission of greenhouse gases by the formation of a gas hydrate stability zone (GHSZ) near the lower boundary of permafrost.

The terrestrial part of the Laptev Sea region has a severe continental climate and continuous permafrost to depths of 600 to 1100 m. Taliks are present only below river channels and lakes with water depths greater than 2 m. The mean annual ground temperature (t_{ma}) decreases from -6 to -9°C near Tixy and the Yana-Indigirka lowland, to -15°C on the northern part of Kotel’nyi Island (Geocryology of USSR, 1989). This region was never glaciated and there are no glacial lakes near the Laptev Sea coast. Therefore, the primary source of information on the past environments in this region are syncryogenic deposits, containing syngenetic polygonal ice-wedges and segregation ice, underground gases, plant and animal fossils.

Review of Published Information

Information on the distribution, temperature regime, structure and thickness of the LSS offshore permafrost is extensive. However it has been developed mainly on the basis of general considerations, limited factual data, and results of calculations by very simplified mathematical models and paleogeographic scenarios. On most maps, offshore, ice-bonded permafrost has been shown as discontinuous near the shore-line and islands, and sporadic to the -60 m isobath (Baranov, 1960, 1974; Soloviev et al., 1987 ; Neisvestnov, 1984 ; Geocryological map of USSR, 1997, and others). L.A. Zhigarev and I.D. Danilov (1977; Zhigarev, 1981) consider that ice-bonded offshore permafrost exists only to the -30 m isobath. In contrast, A. Fartyshev (1993) predicted the distribution of continuous very thick relic permafrost to the -100 m isobath.

Evidence of distribution of offshore permafrost and sub-sea taliks on the LSS

There is considerable evidence that ice-bonded permafrost exists on the LSS. Many of the boreholes, which have been drilled across the straits between Novosibirsky Islands and in some shallow bays showed the existence of relic ice-bonded permafrost below suprapermafrost sub-sea taliks (Zhigarev, 1979; Telepnev, 1981; Fartyshev, 1993).

Investigations of sea-bottom sediments demonstrated the presence of ice-bonded deposits in shallow water under the sea floor across the inner part of the shelf (Dehn et al., 1995). Results of echo sounding also indicate frozen sediments close to the bottom surface. Where ice-bonded permafrost is in the near-surface, the depth of signal penetration is often less than one meter; this depth increases with increasing thickness of the ice-free sediment layer.

A PARASOUND System Paradigma subbottom profiler (Niessen and Whittington,1995) was used for seismoacoustic studies during the Russian-German marine expeditions ARCTIC IX (1993) and ARCTIC XI (1995). This device has a maximum penetration depth of up to 30 m in unconsolidated unfrozen sediments. The upper surface of ice-bonded permafrost, practically impenetrable for acoustic waves, can be traced on the majority of seismoacoustic profiles and differentiated from gas flow. The depth of IBROP position from the sea bed varies from 2-4 up to 8-10 m, under water depth ranging from about 45 to 85-140 m (Figure 1). The latter range of water depths corresponds to the edge of the shelf. Thus, according to our preliminary interpretation, the entire LSS and the upper part of the continental slope contain ice-bonded permafrost. Some of the sounding profiles reveal the presence of closed sub-sea taliks, channel-like depressions, filled with cryotic sediments, pingo-like hills and ice-gouges penetrating to the permafrost table (see Figure 1) .

Temperatures of the near-bottom water of the LSS generally range from –0.5°C to –1.8°C and the water has a high salinity. Especially low-temperature waters are formed at present beneath the Siberian Polynya. Continuous formation of new sea-ice and its northward drift in winter is accompanied by the production of cold and heavy brines (Dethloff, 1994; Churun and Timokhov, 1995) which migrate to the bottom, and prevent ice-bonded permafrost from thawing.

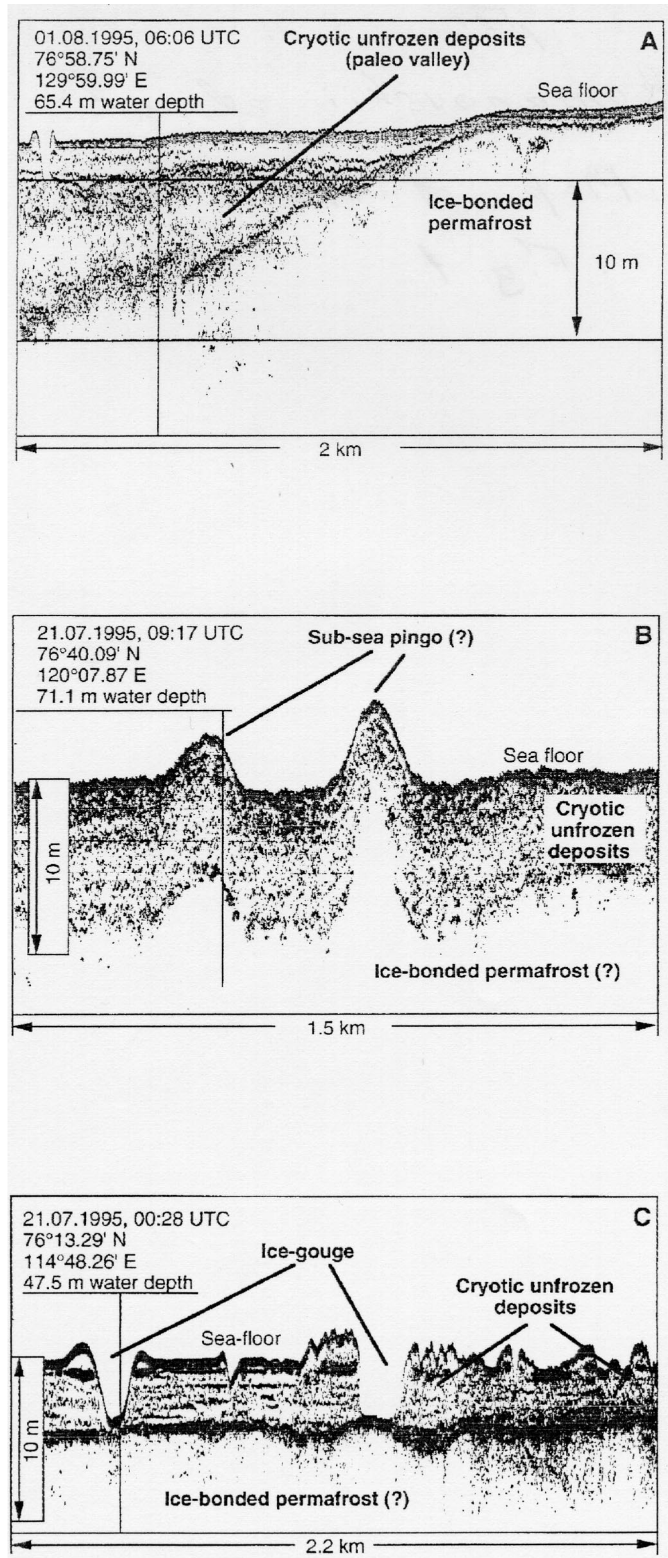

Figure 1. Evidence of ice-bonded offshore permafrost on acoustic profiles (PARASOUND).

Recontruction of paleo-environmental events on the LSS form 140 KA BP to the present

In order to better understand contemporary permafrost conditions of the LSS, the reconstruction of paleo-environmental events during the Late

Table 1. Formation of ice-bonded permafrost on the Laptev Sea Shelf (events versus time)

Zone Between modern isobaths	Permafrost evolution			Environmental events and Ice-bonded permafrost evolution
	Start, Ka BP	Finish Ka BP	Duration Ka BP	
0 to 20	from 115 to 110	from 75 to recent times	>100	Shelf exposure; permafrost aggradation.
20 to 60	110	87	23	Sea level fluctuation; aggradation and degradation of permafrost
20 to 45	87	9.5	77.5	Shelf exposure; permafrost aggradation
45 to 65	77	44	33	Sea level fluctuation; aggradation and degradation of permafrost
45 to 65	44	10.5	33.5	Shelf exposure; permafrost aggradation
65 to 100	44	24	20	Sea level fluctuation; aggradation and degradation of permafrost
65 to 100	24	13	11	Shelf exposure; permafrost aggradation
100 to 120	from 24 to 19	From 18 to 13	11-1	Shelf exposure; permafrost aggradation

Pleistocene-Holocene glacioeustatic regression-transgression cycle has been undertaken (Romanovskii et al.,1997).

The geological structure of the LSS is very complicated. The main structural elements of the LSS (including structural highs and tectonic depressions) are overlain by Cenozoic sediments of uneven thickness. Geological features indicate that the LSS subsided during the Late Cenozoic (Drachev et al., 1995). The latter resulted in a flat shelf morphology and created a relatively uniform geological section for the aggradation of shelf permafrost and its recent distribution, both in the tectonic depressions and highs.

The LSS was never glaciated, so glacoisostatic movements in this area are absent. This allows for the adaptation of a recent glacioeustatic sea level curve covering the last 140 ka (Chappel et al., 1996) and a more accurate curve of the last transgression (Fairbanks, 1989) to reconstruct sea and land interactions and classify zones on the LSS with different permafrost development histories (Table 1). The times of shelf exposure and of flooding by sea-water were determined and the duration of shelf permafrost aggradation was estimated. The zones of short-term aggradation and degradation of near-shore permafrost due to sea-level oscillation, were ignored.

During the Late Pleistocene Regression, the exposure of LSS was not uniform (see Table 1). Aggradation of permafrost on the shelf took place due to freezing of sediments and rocks saturated with sea water with a freezing temperature of approximately -2°C. The exposed shelf was covered by tundra- steppe vegetation (Sher, 1992) under the influence of very cold, continental climate. The period of shelf permafrost aggradation decreased from the interior of the exposed shelf towards its periphery (see Table 1). Upper boundary conditions for permafrost aggradation within the LSS lowered northward in accordance with permafrost temperature zonality.

The mean annual ground temperature (t_{ma}) during the Late Pleistocene (24-18 ka BP) was lower than at present by 8 to 12°C (Kaplina, 1981; Tomirdiaro, 1975; Baulin et al., 1981; Sher, 1992). Thus t_{ma} was as low as -15 to -20°C along the modern coast, and as low as -24 to -26°C within the shelf area limited by the -100 m isobath north of Kotelnyi Island.

The complicated geology of the LSS created diverse lower boundary conditions for permafrost formation and variations in its thickness. The latter was therefore dependent on a range of geologically mediated geothermal heat flux values: from 40-50 mW/m^2 in undisturbed blocks (Balobaev, 1991) to 80-200 mW/m^2 in active tectonic faults. Very cold conditions led to aggradation of deep shelf permafrost and GHSZ.

One important geological event during the regression was the accumulation of syncryogenic sub-aerial ice-rich deposits associated with syngenetic ice-wedges ("Ice-Complexes") of the surface of the exposed shelf. The freezing/ thawing temperature of these deposits occurs at 0°C. Their thickness varied from several meters to 50-60 m. We suggest the existence of the thickest section of syngenetic deposits in the lower structural depressions and blocks of LSS. Now parts of these sections are below sea-level. The location of taliks was limited to the river channels of the Khatanga, Lena and Yana Rivers and a few deep lakes. The Laptev Sea Polynya disappeared as a result of the shore-line shift northwards and the cold climate. Sea-ice conditions were very severe; the temperature of sea water was as low as -2°C. S. Tomirdiaro (1975) suggested deep freezing of the Arctic Ocean and the existence of a permanent pack ice cover.

The last transgression began approximately 18 ka BP. Environmental and sea-ice conditions to 13 ka BP remained severe and the rate of sea-level rise (from the -120 to -100 m isobath) was relatively slow (~4 mm/ year). From 13 to 7-8 ka BP, the rate of sea-level rise increased to 14 -15 mm/year. High rates of sea-level rise lasted from the -100 m isobath up to the -20 m isobath. These caused a rapid flooding of the gently sloping shelf by cold sea water (t_{sb} =-1 to -2°C). This resulted in the preservation of the ice-rich syngenetic deposits under the sea instead of their destruction by seashore thermoerosion (Are, 1988). Erosion at depth by sea water and sedimentation on the sea floor controlled the transition of frozen deposits in the cryotic state and thermal subsidence due to thawing on the sea bottom. At erosional sites, these processes occurred. At sites where fine-grained cryotic sediment accumulation took place, preserved ice-bonded permafrost and "Ice Complexes" were "buried".

A reduction of offshore permafrost thickness and thickness of GHSZ took place from below, particularly along active faults under the influence of geothermal heat fluxes.

Rapid sea level rise from 13 to 7.5 ka BP transformed river valleys near the coast into estuaries. The concentration of fresh-water flows and rising water temperatures probably resulted in permafrost thaw under the inlets and their submarine extensions. From 12-11.5 ka BP, active lake thermokarst processes began on the exposed parts of the shelf and on the adjacent territory of the North East lowlands (Kaplina, 1981) as a results of a relatively short-lived warming event. At this time there were only a few open taliks and sites of greenhouse gas discharge. The advancing sea flooded both frozen deposits and thawed sediments of thermokarst lakes saturated by fresh water. This process induced downfreezing lake taliks and the formation of a closed system of sub-sea pingos (Are, 1988).

The second stage of the last transgression started about 7 ka BP. The main characteristics of the natural events were reconstructed as follows:

The Laptev sea level rose more slowly and the sea coast retreated at a rate of 4-6 m/year (about 30-50 km in 7000 years) due primarily to thermal erosion. Thermal erosion destroyed the uppermost ice-rich part of the syncryogenic deposits (Baranov, 1956) and exposed older, often saline deposits with freezing/thawing temperatures below 0°C. This created favorable conditions for their thawing and the formation of sub-sea taliks. Thermoerosion and the disappearance of islands built of the "Ice Complexes" was typical (Are, 1988).

The formation of fresh water with positive temperatures within the areas of river influence in the coastal zone, played an important role in the origin of suprapermafrost sub-sea taliks between the modern coast and the -20;-15 m isobaths. Deep thaw and transformation of ice-bonded permafrost into non-ice-bonded cryotic deposits found in Dmitry Laptev and Sannikov straits is related to the sandy composition of those deposits as a result of washing out of the clayey fraction (Aksenov and Dunaev, 1987). The Laptev Sea Polynya originated and started to cool the near-sea bed layers of water and sediments of the outer part of the LSS. Supra-permafrost lake taliks were transformed into open taliks and became on-land locations for the discharge of greenhouse gases (Zimov et al., 1997).

Paleo-temperature reconstruction and mathematical modeling

On the basis of the paleo-geographical scenario and simplified glacioeustatic curves, paleo-curves of mean annual temperatures of the sea bed and ground have been created. These curves take into consideration the temperature conditions on the sea floor before regression and after transgression, temperature changes on the shelf surface due to exposure and flooding, and changes of t_{ma} on the drained shelf due to climatic fluctuations. The value of t_{ma} for specified times intervals has been chosen in accordance with existing reconstructions of former permafrost and environmental conditions for North East of Siberia. For each identified zone of the shelf, a series of curves were constructed to reflect the geocryological zonality of t_{ma} (Romanovskii et al., 1997).

The paleo-geographical scenarios and curves of paleotemperature were used for mathematical modeling of the shelf permafrost evolution during the last glaciaceustatic cycle based on a digital solution of the Stefan problem (Kudryavcev, 1978). The model indi-

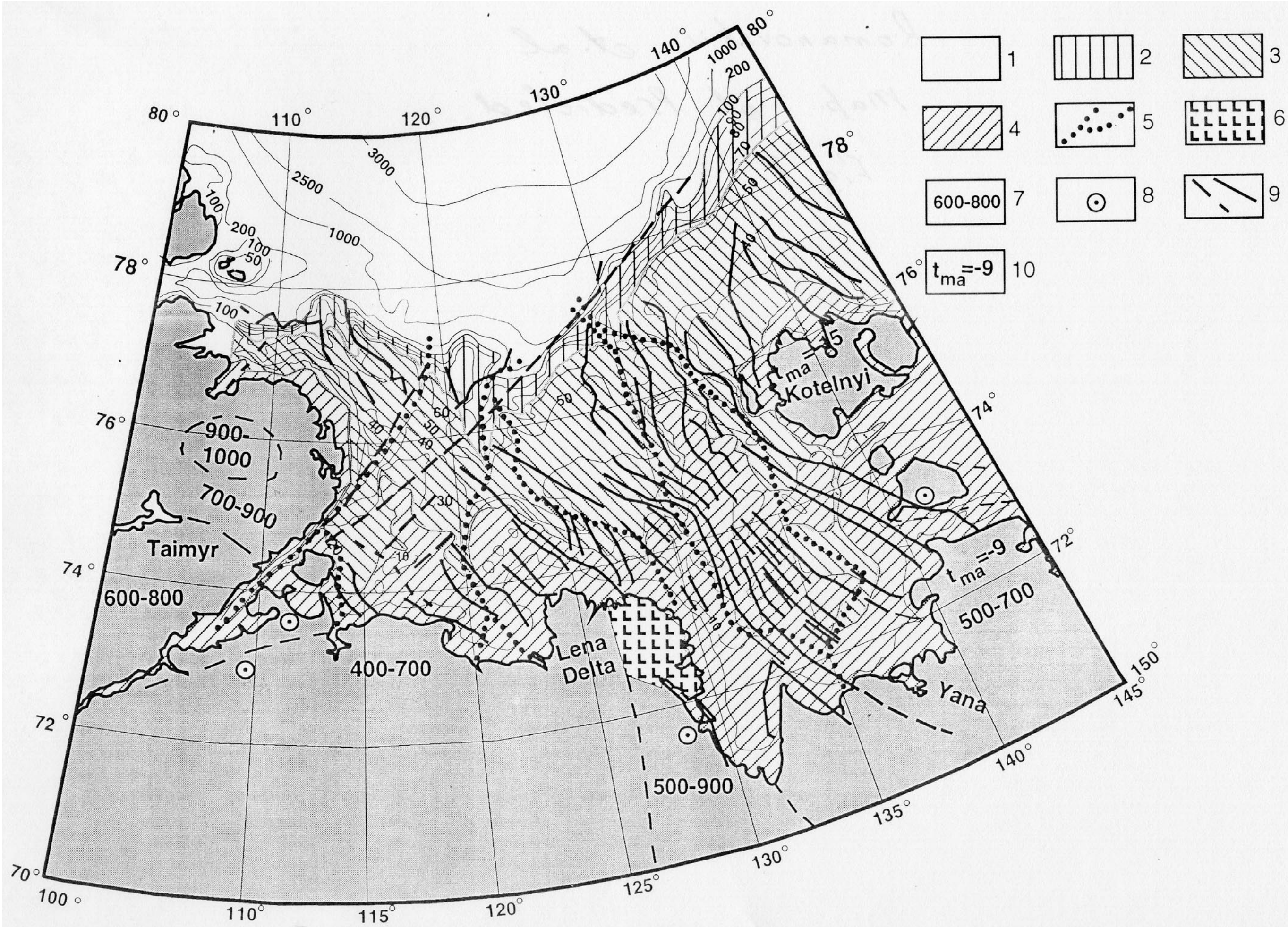

Figure 2. Map of predicted distribution of offshore permafrost and sub-sea talik on the Laptev Sea Shelf. Legend: 1-zone of cryotic deposits; 2 -zone of widespread discontinuous relic ice-bonded permafrost; 3- zone of continuous ice-bonded relic permafrost with discontinuous uneven cover of cryotic sediments; 4- zone of continuous ice-bonded relic permafrost with supra-permafrost sub-sea cryotic taliks and islands of ice-rich permafrost near sea floor; 5- open sub-sea taliks of flooded relic river valleys; 6- permafrost in river deltas; 7- on-shore continuous permafrost thickness, m.; 8- deep wells where geothermal heat flux was determined (Balobaev, 1991); 9- open sub-sea taliks of active tectonic faults; 10- mean annual ground temperature of on-shore permafrost, °C.

cates: (1) where geothermal fluxes range from 40 to 50 mW/ m^2 ice-bonded offshore permafrost was not completely degraded; (2) ice-bonded permafrost degraded often completely along some active tectonic faults where geothermal fluxes are 100 mW/m^2 and more; (3) in the LSS zone from the recent shore line to the -20 m isobath, thawing of frozen sediments takes place both downward from sea bed and upward from the base of permafrost; (4) downward thawing of ice-bonded permafrost between the -20 and -100 m isobaths is limited by the existence of the cover of syngenetic deposits containing fresh ice, and by sea water with negative mean annual temperatures.

Main features of Laptev Sea shelf offshore permafrost distribution

The main features of the predicted contemporary offshore permafrost distribution on the LSS are shown on the map (Figure 2) based on modern field data, paleoreconstruction, regionalisation and mathematical modeling. These features are as follows:

-Practically continuous extent of IBROP to the –60 m and -70 m isobaths and widespread discontinuous to the -100 m isobath.

- Existence of open linear taliks above large seismic-active faults with high geothermal heat fluxes (100-200 mW/m^2). A special case is the river delta and its ancient-valley channels, where open taliks are possible.

- From the modern sea shore to the –15 m and -20 m isobaths, both deep supra-permafrost sub-sea taliks and bodies of ice-rich permafrost exist. The latter are distributed in shallow depths at the locations of recently eroded islands and along retreating thermoerosional coasts.

- The maximum thickness of relic permafrost (200-600 m) is a characteristic of the lithospheric blocks with low heat flux (40-50 mW/m^2) and is predicted within the area from the north coast of Kotel’nyi Island to the -45 m isobath, where freezing temperatures were most prolonged and climate most severe. IBROP degradation extends to the present in these areas under sea water temperature from -1.5 to -2°C.

-The upper limit of the IBROP is variable and modern oceanographic conditions play a very important role in its evolution and conservation.

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