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Modeling of the Offshore Permafrost Thickness on the Laptev Sea Shelf

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Summary: Mathematical simulation of the offshore permafrost thickness evolution was performed using the one-dimensional solution of Stephan's problem with mixed boundary conditions (program „Heat"). The boundary conditions were accepted in accordance with the paleoscenario for the Laptev Sea shelf (LSS), which corresponds to the last Pleistocene-Holocene glacio-eustatic cycle (ROMANOVSKII et al. 1997a, b). The mean geological characteristic of this region are presented. In accordance with the results of calculations, the recent thickness of the model was adopted in conformity with the geostructural construction of the LSS (DRACHEV et al. 1995). The thickness of permafrost on the Laptev Sea shelf fluctuated from about 500 m near Kotelnyi Island to less than 100 m on the outer part of the shelf. Based on these results, a map of the recent ice-bonded permafrost thickness was compiled for the eastern part of the LSS.

INTRODUCTION

Ideas about the permafrost thickness on the Laptev Sea shelf (LSS) are based on general speculations (BARANOV 1956, 1964, Geocryological Map of the USSR, 1996, Geocryology of the USSR 1988) and on calculations using very simplified formulas (SOLOVIEV 1981, ZHIGAREV 1979, 1997). According to these calculations, the thickness of the ice-bonded permafrost decreased from 200-250 m near the recent seashore northward until the isobath of -60 m. The relic ice-bonded permafrost boundary passed recently near this sea depth. The only investigator, who predicted by his calculations the existence of continuous permafrost on the Laptev Sea shelf with a thickness up to 700-1000 m, was FARTYSHEV (1993). All other authors did not take into consideration the duration of the shelf permafrost formation and the existence of recent and former permafrost temperature zonation.

The aim of this paper is to present the results of the offshore permafrost simulation based on new ideas about evolution of the LSS during the last glacio-eustatic cycle (112 Kyr B.P. to present time) and to propose new geological and modern mathematical models.

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SETTING OF THE PERMAFROST EVOLUTION MODELING PROBLEM

The paleogeographic scenario used for the simulation purpose takes into consideration the time of the exposure and flooding of the shelf sites with different bathimetry, duration and conditions of permafrost aggradation and degradation, and the latitudinal temperature zonation (ROMANOVSKII et al. 1997a). The upper boundary conditions are presented schematically in the form of the LSS map, which is divided into "belts" in accordance with the conditions of permafrost formation and evolution during the last Pleistocene-Holocene glacioeustatic cycle (Fig. 1).

The duration of the exposure and flooding of the shelf, which takes into account its bathymetry, the time of IBP aggradation during the sea regression and its degradation in the course of transgression, were considered. For each of the defined isobath intervals, curves of the temperature variation on the surface of sea the floor (t_{sf}, °C) and the mean annual ground temperature (t_{ma}, °C) were plotted with consideration of the permafrost temperature zonation (ROMANOVSKII et al. 1997b). The above-cited curves of the temperature variation on the surface of deposits on the shelf were used as the upper boundary conditions. The latter correspond to the type I of boundary conditions.

A complex structural-geological composition of the LSS, its geological model, is taken into account with the assumed values of the geothermal flow density (mW/m²), and different composition and thermophysical properties of constituent deposits in different tectonic structures. Geological-structural regioning of the shelf was carried out for selecting the characteristic composition and properties of deposits and the lower boundary conditions which are required for solving Stephan's problem (GENERAL GEOCRYOLOGY 1978). It was based on the published data (DRACHEV et al. 1995) and presented in the form of a map of the main tectonic structures and geothermal heat fluxes value, mW\m2 (Fig. 2). The latter is presented in the map for both the undisturbed tectonic blocks (smaller value) and the fault zones (higher value). The map shows deep boreholes, where values of geothermal heat fluxes have been determined (BALOBAEV 1991, CATALOGUE 1985, VESELOV & LIPINA 1982).

Conditions of the type II, i.e. the geothermal flow, were set at the lower boundary of the area under modeling (the size of the model is 2-3 km). Computations were performed for the q values of 40 and 50 mW/m² as the background values within

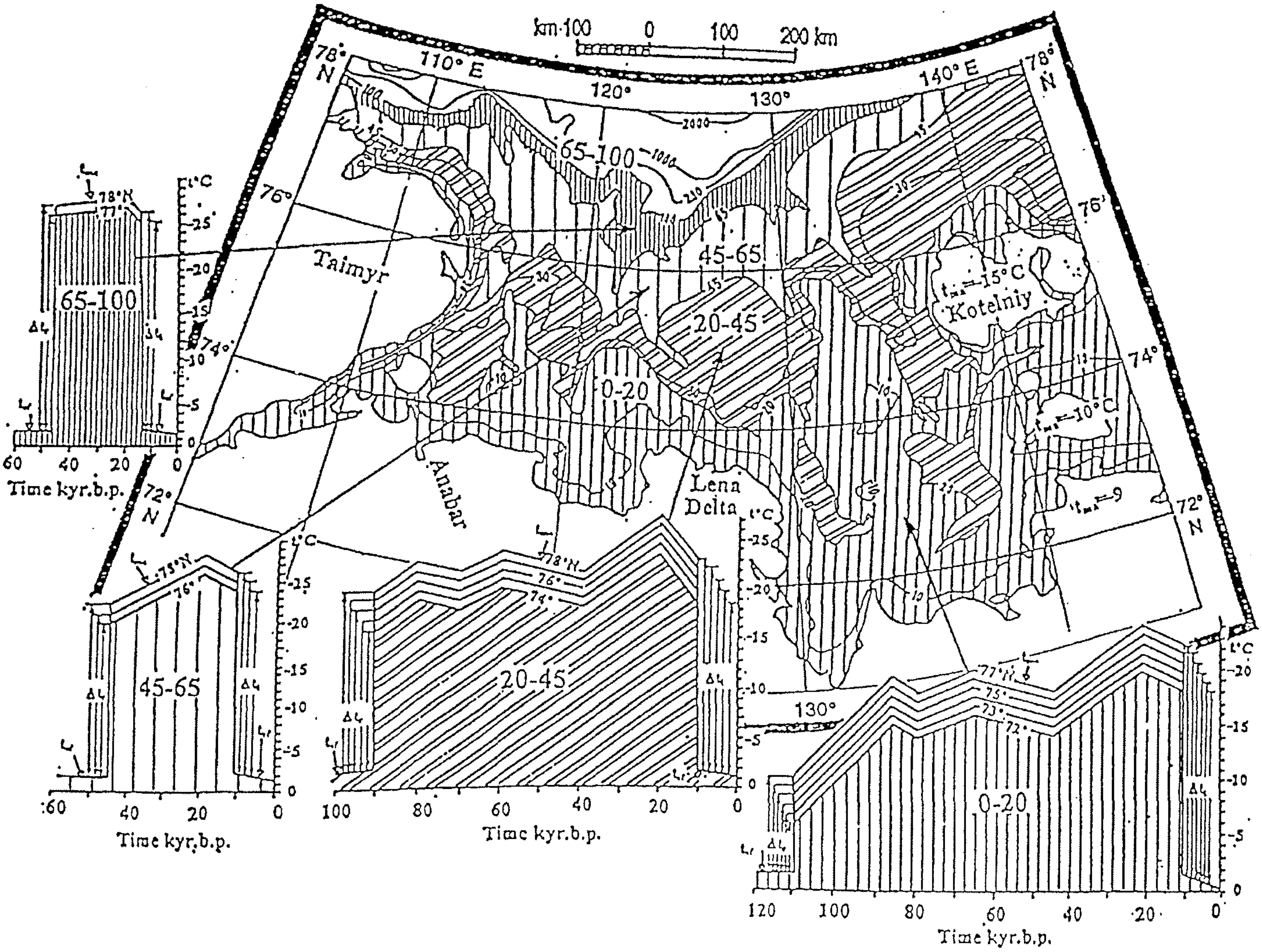

Fig. 1: Upper boundary conditions of offshore permafrost evolution on the Laptev Sea shelf (ROMANOVSKII et al. 1998).

the limits of tectonic blocks of the earth crust in this region and 100 mW/m² for the zones of active faults.

Geological cross-sections of structural blocks were selected for the modeling based on the seismostratigraphy scheme, de-

Interval of	Deposits	Humidity W %	Density g/cm³	Heat capacity C_v W•h/(m³•K) frozen	Heat capacity unfrozen	Thermal conductivity γ W/(m•K) frozen	Thermal conductivity unfrozen	Latent heat Q W•h/m³	$t_{f,t}$ °C
a) Tectonic depressions									
0-10	mud	71	1.4	860	678	1.42	2.3	10814720	-2
10-500	silt, aleurites	18-26	2-1.8	544-554	414-459	1.54-1	1.9-1	3427200-4455360	-2
500-1500	sand, clay	15	1.7	516	433	1.4	1.4	2427600	-2
1500-3000	sandstone	16-22	2-1.85	549-553	436-468	2.23-2	3-2	3646400-3874640	-2
b) Tectonic uplifts									
0-10	mud	57	1.6	859	548	1.98	2.7	8682240	-2
10-500	silt, aleurites	18-26	2-1.8	544-554	414-459	1.54-1	1.9-1	3427200-4455360	-2
500-750	sand, clay	12-22	2-1.55	443-454	376-422	1.05-1	1.2-1	2284800-3141600	-2
750-3000	sandstone	0.8-2	1.6-1	335-360	335-360	3.08-2	3.1-2	121856-190400	-2

Tab.1: Composition and properties of deposits taken for modeling of permafrost evolution.

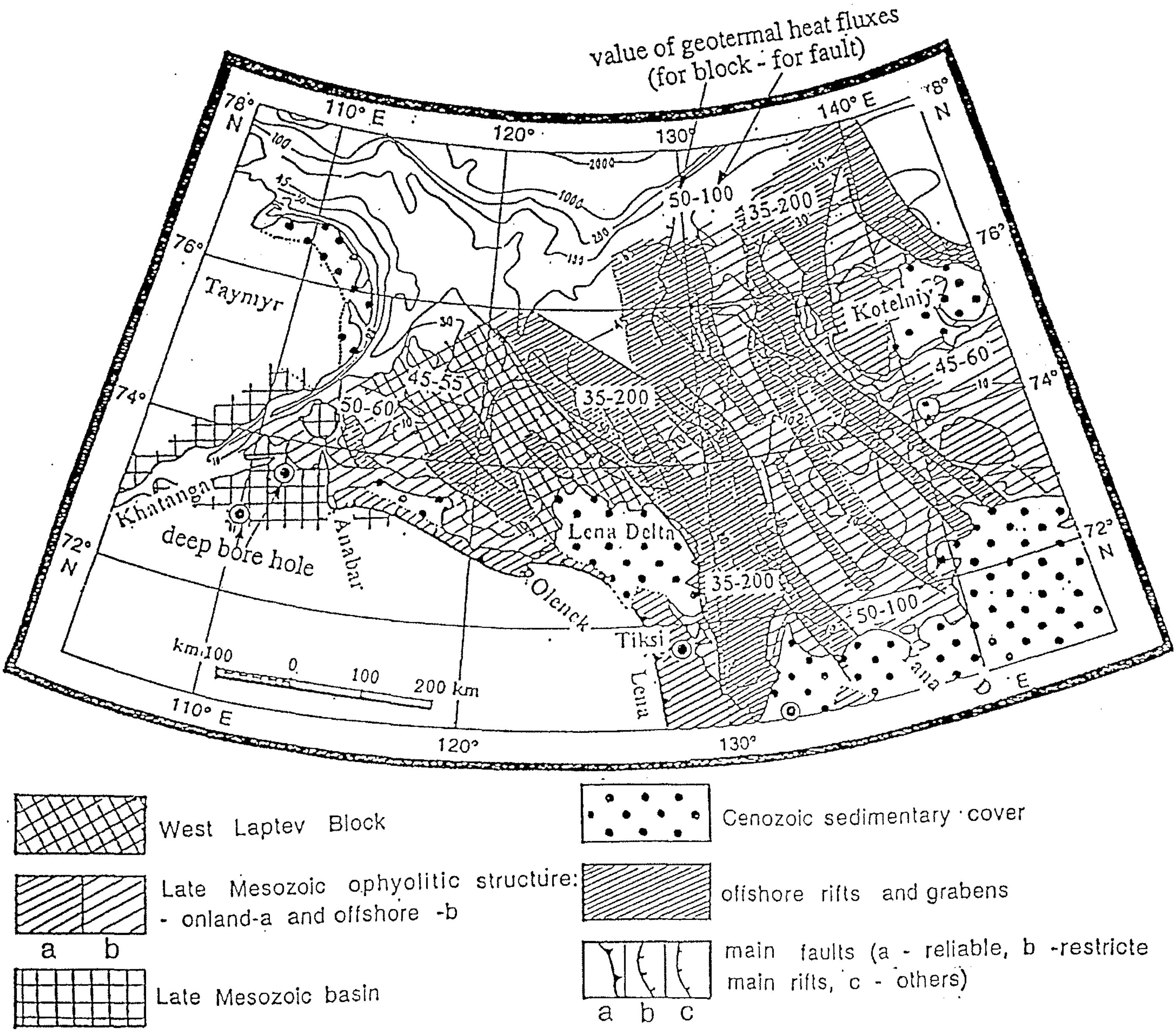

Fig. 2: Main tectonic elements of the Laptev Sea shelf (adopted from DRACHEV et al. 1995) and values of geothermal heat fluxes (mW/m²) (ROMANOVSKII et al. 1998.)

veloped by DRACHEV et al. (1995). The thermophysical properties of deposits were selected using the unpublished data characteristic of the saline deposits of West Siberia and some published data (ERSHOV et al. 1984) (Tab. 1).

The initial conditions were set proceeding from the assumption of the absence of permafrost on the Laptev Sea shelf at the moment of its exposure and the stationary distribution of temperature with depth.

$$\tau = 0:\ t_n(z,0) = t_{n-1}(0) + zq/\lambda_n,\quad 0 = z = z_c\ ,$$

where tn is the temperature of the deposits of the n-th layer, z is the depth, q is the geothermal flow and (n is the heat conductivity of the n-th layer.

VARIANTS OF COMPUTATION

It was necessary to solve the one-dimensional problem of the heat conductance of Stephan's type with the mixed boundary conditions (GENERAL GEOCRYOLOGY 1978). Computations were performed using the „Teplo“ (Heat) program developed by the team headed by Prof. Khrustalev. This program has allowed solution of the heat conductance problem by the method of finite differences.

Computations were done for the two types of geological cross-sections, which differ, by the depth of the top of the solid rock basement. In this way we tried to reflect the different conditions of the permafrost formation in tectonic uplifts and depressions. For each structure we assumed two variants of the properties of deposits (Tab. 1) with different moisture content, density of deposits and their thermophysical properties.

Sediments and deposits saturated with seawater at a freeze or thaw temperature (tf,t) of –2 °C were assumed to freeze. We considered two types of the conditions of the ice-bonded permafrost (IBP) degradation on the surface of the massif under computation. In the first variant, the upper part of the profile includes saline deposits with $t_{f,t}$ = -1.5 °C and their thawing proceeding from the surface. The second variant describes the situation in which the temperature of the phase transitions of deposits in the upper profile part is close to 0 °C. Other thermophysical properties of these deposits were assumed close to ice. In this case no thawing of syncryogenic deposits from above takes place in the sea.

Thus, our computations took into consideration that the syncryogenic deposits of the „ice complex" cover the exposed surface of the shelf. These deposits contain fresh ice and the fact of their degradation during the thermoerosion of shores and exposure of saline deposits in the offshore zone at the sea depths down to -20 m.

No borehole data are available to characterize the permafrost thickness on the LSS. Therefore, to check the validity of our scenario, the geological model and the assumed values of the deposit properties, we calculated the permafrost thickness for a well drilled near Tiksi (CATALOGUE 1985). Dr. Devyatkin kindly supplied the data on the temperature measurements and properties of deposits. The computational results demonstrated good correlation with the drilling data on the permafrost thickness.

RESULTS OF MODELING THE PERMAFROST THICKNESS ON THE LSS

We performed a series of calculations of the evolution of the thickness of submarine shelf permafrost, including IBP and cryotic deposits, as well as its actual state. Certain results for the shelf zone with the depth down to -20 m indicated the following. Recent distribution of the IBP thickness in the eastern part of the shelf (near the Novosibirsk Islands) is characterized, on the one hand, by the latitudinal zonation and, on the other hand, by the different thickness in the negative and positive structures (Table 2).

With the larger sea depth and, consequently, the decreasing duration of permafrost aggradation and the increasing time of its submarine degradation, the IBP thickness is reduced. Thus along the profile F-G (Figs. 3, 4) the calculated thickness of the IBP goes down in the following manner: approximately 450 m (isobath -20 m), -350 m (isobath -45 m), 200 m (isobath -65 m) and 50-80 m (isobath -100 m).

Everywhere, the layer of cryotic deposits is situated below the IBP in the profile of the shelf permafrost. The thickness of this layer varies from 70 to 100 m. Within the boundaries of the zones of tectonic perturbations with high values of the geothermal flux, the IBP may be totally replaced by cryotic deposits. This is most characteristic of the zone between the isobaths –65, -100 m and the offshore zone at the sea depths –10, -20 m, especially in places with the thawing from above.

The thawing from the sea floor is known to occur in the offshore zone of the Laptev Sea eastward of the Lena river delta, under the Dm. Laptev and Sannikov straits (FARTYSHEV 1993, ZHIGAREV 1997, and others). In these areas the upper part of the profile, initially composed of syncryogenic ice-rich deposits with fresh ices, is destroyed by thermokarst. As a result, the sea floor exposes relatively low-ice deposits which are presumably saline and have the ($t_{f,t}$) about -1.5 °C. The mean annual temperatures of the water and bottom deposits t_{sf} are negative tending to -1.5; 0 °C. According to our computations, these conditions are conducive to thawing to the depths of 50-100 m. As a result, in the shallow offshore zone the closed submarine taliks alternate with the sites where the IBP exists starting nearly from the sea floor. Such sites are localized on islands recently destroyed by sea and on the eroded shores built by the "ice complex".

In the historical aspect, the IBP thickness was the greatest at the end of the Sartanian cryochron (about 18 Kyr B.P). At that time, the IBP thickness was 150-200 m larger than today. Before the shelf flooding the IBP thickness varied rather insignificantly by some 20-40 m. Short thermochrons, which took place starting from 13 Kyr B.P. did not virtually affect the permafrost thickness; instead, they were conducive to local

Type of structure	Recent isobath	Latitudes 72N	73N	74N	75N	76N	77N
	-20	310	350	390	430	450	470
Uplifts	-45	-	-	350	370	410	450
	-65	-	-	-	250	290	280
	-100	-	-	-	-	-	80
	-20	330	370	410	450	490	530
Depressions	-45	-	-	370	410	450	479
	-65	-	-	-	290	310	330
	-100	-	-	-	-	-	80

Tab. 2: Recent thickness of ice bonded permafrost on the Laptev Sea shelf (results of modeling).

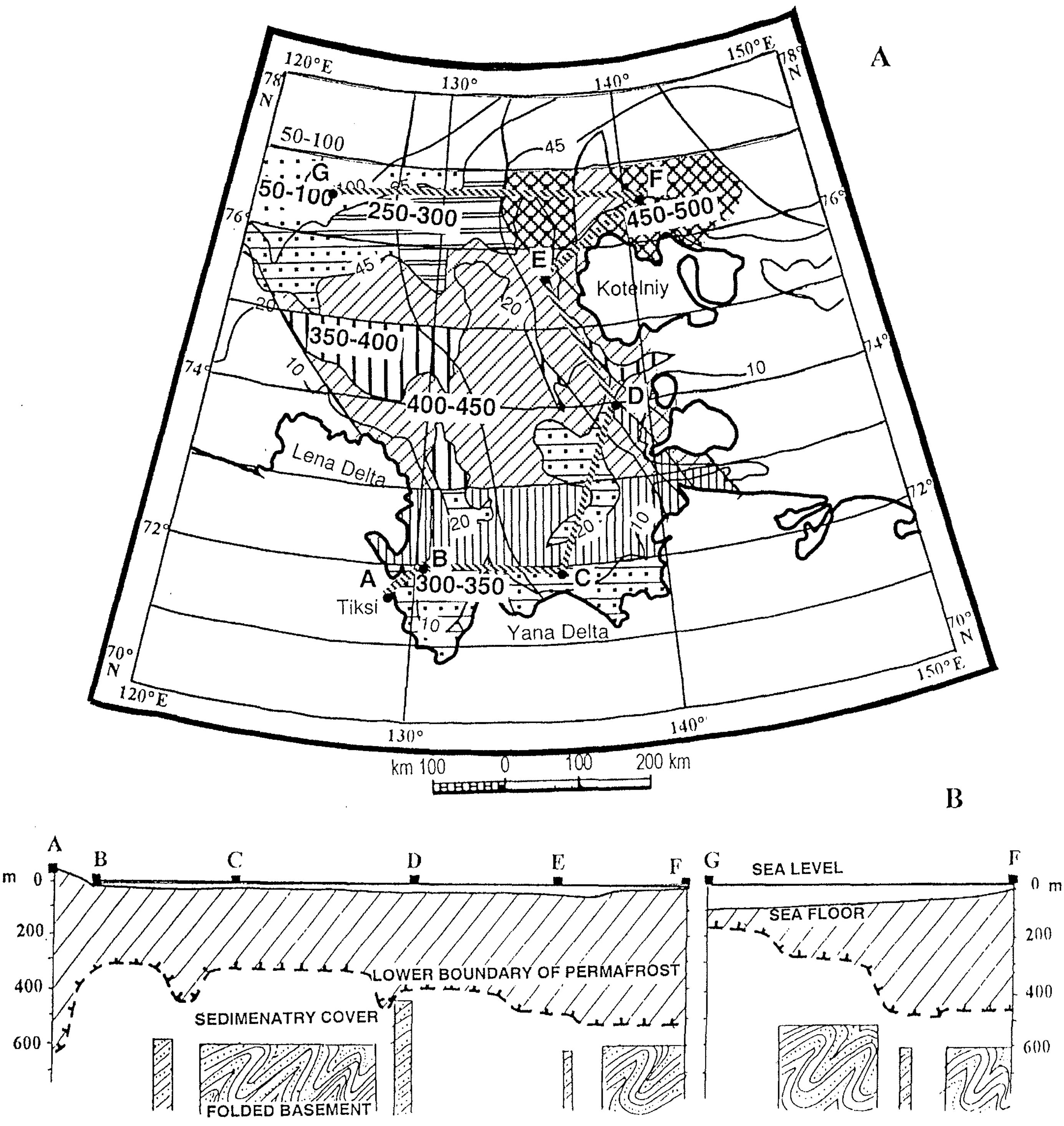

Fig. 3: Map (A) and profiles (B) of ice-bonded permafrost thickness on the eastern part of the Laptev Sea shelf. Results of mathematical simulation.

„outbursts" of thermokarst lakes on the „ice complex" deposits (KAPLINA 1981), though the harsh temperature conditions were preserved globally.

The beginning of the IBP degradation was induced by a sharp increase in the surface temperature resulting from the seawater submergence. The data from the field studies and computational results made it possible to compile a map predicting the distribution and the thickness of the ice-bonded permafrost for the best studied eastern part of the Laptev Sea shelf (Fig. 3) and the profile showing the IBP position and the 0 °C isotherm from both the recent time and 18 Kyr B.P (Fig. 4).

CONCLUSIONS

Major geocryological features of the LSS were predetermined by the history of its development, mostly during the last

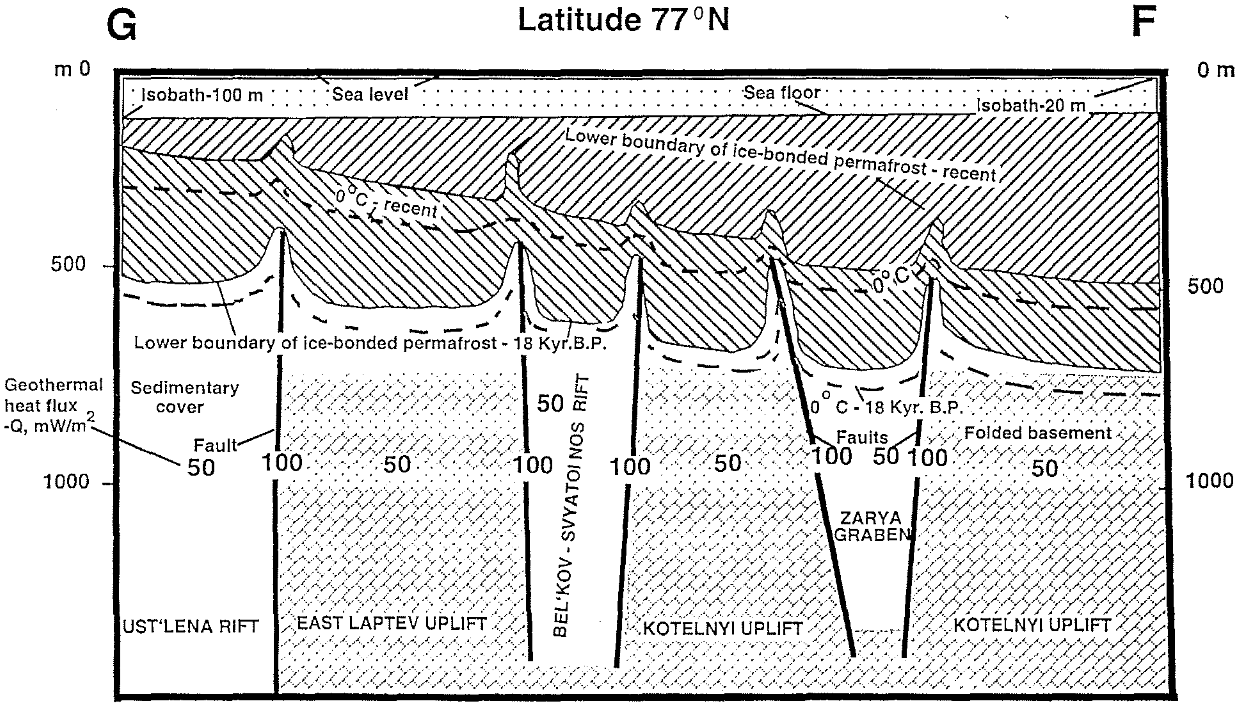

Fig. 4: Offshore permafrost thickness: Recent and 18 Kyr B.P. Profile along line G-F. Results of methematical simulation.

glacioeustatic cycle (140 Kyr B.P to present time).

1) The long-term character and the harshness of natural conditions during the subaerial stage in the inner and peripheral parts of the shelf determined a virtually continuous distribution of the relic IBP down to the isobaths of -60 to -70 m and, most likely, its discontinuous occurrence at large depths up to the outer shelf edge. It is predicted that the open linearly extended taliks exist in the zones of large, especially seismogenerative, faults with high values of thermal flows (from 100 mW/m^2 and more). Apparently, the closed and open taliks also exist in the channel part of the paleovalleys of large rivers.

2) Deep closed taliks exist in the offshore zone down to a depth of -15 to -20 m.. Massifs of frozen deposits, with their roof virtually coincident with the sea floor, are found here in places of recently eroded islands, which were composed by the „ice complex", and along the shores retreating under the impact of thermoerosion.

3) The largest thickness of the relict IBP layer (up to 500-550 m) is predicted for high latitudes (northward of the Kotelnyi island) in the band of isobaths 0-20 m. In this area, the degradation of IBP began (and is occurring nowadays) under the sea water with low negative temperatures (-1.5 to -2 °C). Still higher thickness of the IBP (more than 600-700 m) may be expected within the boundaries of the offshore zone of the consolidated blocks with geothermal flows of 30-40 mW/m^2 in the peripheral western part of the LSS.

4) The roof of the relict IBP layer is uneven everywhere. The lowest thickness of the non-consolidated cryotic (thawed) deposits above the IBP is supposed to be characteristic of the sites composed (from the surface) by the ice-rich syncryogenic deposits covered by the fine marine Holocene sediments, the lower part of which may be in the frozen state.

5) The maximal thickness of the shelf permafrost was formed at the end of the Sartan cryochron (about 18 Kyr B.P). A layer of deposits cooled below 0 °C is present everywhere beneath the IBP. At the present time, the thickness of the relict IBP layer has been reduced by 150-200 m due to thawing of these deposits from below under the influence of geothermal flows.

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