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The role of paleogeographic events in the evolution and current state of the East Siberian Shelf permafrost

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ABSTRACT

Mathematical modeling is used to study the role of natural events in the evolution and current state of the permafrost zone and the gas hydrates stability zone in the northern part of the East Siberian shelf. One of the main events of the last 200 thousand years was the cover glaciation of the end of the Middle Pleistocene, which left sheet ice in the sediments of the Anzhu Islands (New Siberia and Faddeevsky), 20-30 m thick and 2-3 km long. A paleogeographic scenario of the shelf development in the last 200 thousand years and a geological structure model, which characterizes the composition and thermophysical properties of rocks, have been constructed. A model of thermophysical processes in the shelf sediments was used for a geological section with a thickness of 1500 m to calculate the temperature of the rocks. The simulation results showed the following. The permafrost thickness in the glacial region is 30-160 m less, and the base of the gas hydrate stability zone is located 140-600 m closer to the seabed surface than in non-glacial conditions.

Keywords: East Siberian Arctic shelf; submarine permafrost; glacioisostatic movements; paleotemperature scenario; mathematical modeling.

1. INTRODUCTION

The submarine permafrost of the Arctic shelf is subaerial, submerged during the sea-level rise after the Last Glacial Maximum [1-4]. Earlier, the subaerial genesis of submarine permafrost was noted in publications [5, 6]. Information on the submarine permafrost zone of the East Siberian Arctic shelf is of great importance for the compilation of forecast scenarios of climate warming. Degrading submarine permafrost is a source of planetary greenhouse gases. The destruction of subaqueous permafrost can cause a violation of the conditions for the existence of methane hydrates occurring within and below the permafrost layer [7, 8], and the corresponding additional emission of methane into the Arctic atmosphere. Therefore, assessing the state of submarine permafrost and the gas hydrate stability zone (GHSZ) is of great practical importance.

The shelf permafrost zone has been studied by drilling methods only in the coastal zone [1, 9, 10]. The maximum distance of the boreholes from the coast is 25 km. Currently, there is not a single borehole that has passed the permafrost to its total capacity. The application of seismic methods did not leave the stage of method development. The lack of the possibility of obtaining complete information on the distribution and thickness of the permafrost using drilling and geophysical methods predetermined the widespread use of mathematical modeling [3, 4, 11-15].

It is necessary to construct paleogeographic scenarios to develop climatic conditions in the region to analyze the evolution of submarine permafrost of the Arctic shelf using mathematical modeling, [14, 16, 17, 18]. This study examines the role of natural events in the evolution and current state of the permafrost zone and the gas hydrates stability zone in the northern part of the East Siberian shelf.

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2. MATERIALS AND METHODS

One of the main events was the cover glaciation of the Late Pleistocene. It left sheet ice in the sediments of the eastern islands of Anzhu (New Siberia and Faddeevsky). Their thickness is 20-30 m, and their length is 2-3 km. Ablation moraine and glacial dislocations are also associated with glaciation. The center of glaciation was presumably the De Long archipelago [19-21]. The formation of the Late Pleistocene marine terrace up to 40 m high on the islands of New Siberia and Faddeevsky is also associated with the glacier.

Glaciation took place in marine conditions. At the base of the section of the islands of New Siberia and Faddeevsky, there are sea sandy-silty deposits dislocated by a glacier with a thickness of more than 50 m with shells of modern molluscs, including subarctic species, indicating a warmer sea compared to the modern one. Glaciation was accompanied by alternating glacioisostatic movements. The transition of the glacial bed to subaerial conditions is dated by 14C (no later than 54 thousand years before) by another major paleogeographic event - the beginning of the formation of syncryogenic deposits of the ice complex Late Pleistocene with numerous remains of mammoth fauna [19-21]. The deposits are saturated with wedge ice up to 4-6 m wide at the top. Their total volumetric ice content is 70-95%. The beginning of the postglacial transgression dates back to the end of the Late Pleistocene. The flooding of the glacial area, according to [16], was carried out from 8 to 3 thousand years ago.

These natural events served as the basis for compiling a paleogeographic scenario. This study is a development of the results presented in [18]. The paleogeographic scenario of the history of the last 200 thousand years is detailed by taking into account deglaciation events. Also, it captures the effect of glaciation on the climate and permafrost of the surrounding area. This influence was recorded in the section of the northern and southern shores of the Dm. Laptev Strait, located 300-350 km from the islands of New Siberia and Faddeevsky [22]. The coasts of the strait are further associated with "near" non-glacial conditions. It is assumed that this effect does not appear within the East Siberian shelf at greater distances from glaciation. Such conditions are referred to hereinafter as "far" non-glacial conditions. For glacial, "near," and "far" non-glacial conditions, paleogeographic scenarios were compiled (Fig. 1), and mathematical modeling was carried out at a heat flux from the depths of 60 mW/m^2.

The scenario includes the initial temperature of the rocks, the curve of the change in abs. heights of the glacial bed surface, curves of sea-level change in glacial and non-glacial conditions [18], and a series of curves of the dynamics of the ground surface temperature during the last 200 thousand years. This series consists of curves of the dynamics of the ground surface temperature in the areas of isobaths of 5, 20, 40 m in the glacial area and outside it (Fig. 1). The calculation is carried out for the corresponding zones: glacial (S3 scenario), "near" (S2 scenario), and "far" (S1 scenario) non-glacial zones. The data [19-21, 23, 24] were used to construct a geological model, including information on the composition, structure, properties of deposits. Calculations are carried out at a heat flux from the depths of 60 mW/m^2 [25].

A model of thermophysical processes in the sediments of the shelf and the gas hydrates stability zone for a geological section of 1500 m was used [26] to calculate the temperature of the deposits. The framework of the scenario was formed by a model of glacioisostatic movements of the earth's crust [18]. The main parameters of glacioisostasis within the boundaries of New Siberia Island were reconstructed following geophysical [27] and geological data. These are the depth of subsidence of the glacial bed, its current hypsometric position, the glacier's thickness, and the time of transition of marine sedimentation to continental one. The paleogeographic scenario has been verified using mathematical modeling [18] and data from the borehole on New Siberia Island, where geothermal observations were carried out to a depth of 200 m.

3. RESULTS

The results of modeling the permafrost thickness show that they reflect the influence of both sea depth and glaciation (Fig. 2). The effect of sea depth is the effect of the duration of drainage and periods of shelf flooding for certain isobaths. The thickest permafrost (450 m in non-glacial conditions) is confined to the sections of the 5 m isobaths, the smallest (260 m in glacial conditions), to the 40 m isobath. The role of the sea depth is most significant. For non-glacial conditions, the permafrost thickness on the 5 m isobath is 130 m greater than on the 20 m isobath and by 160 m - than on the 40 m isobath.

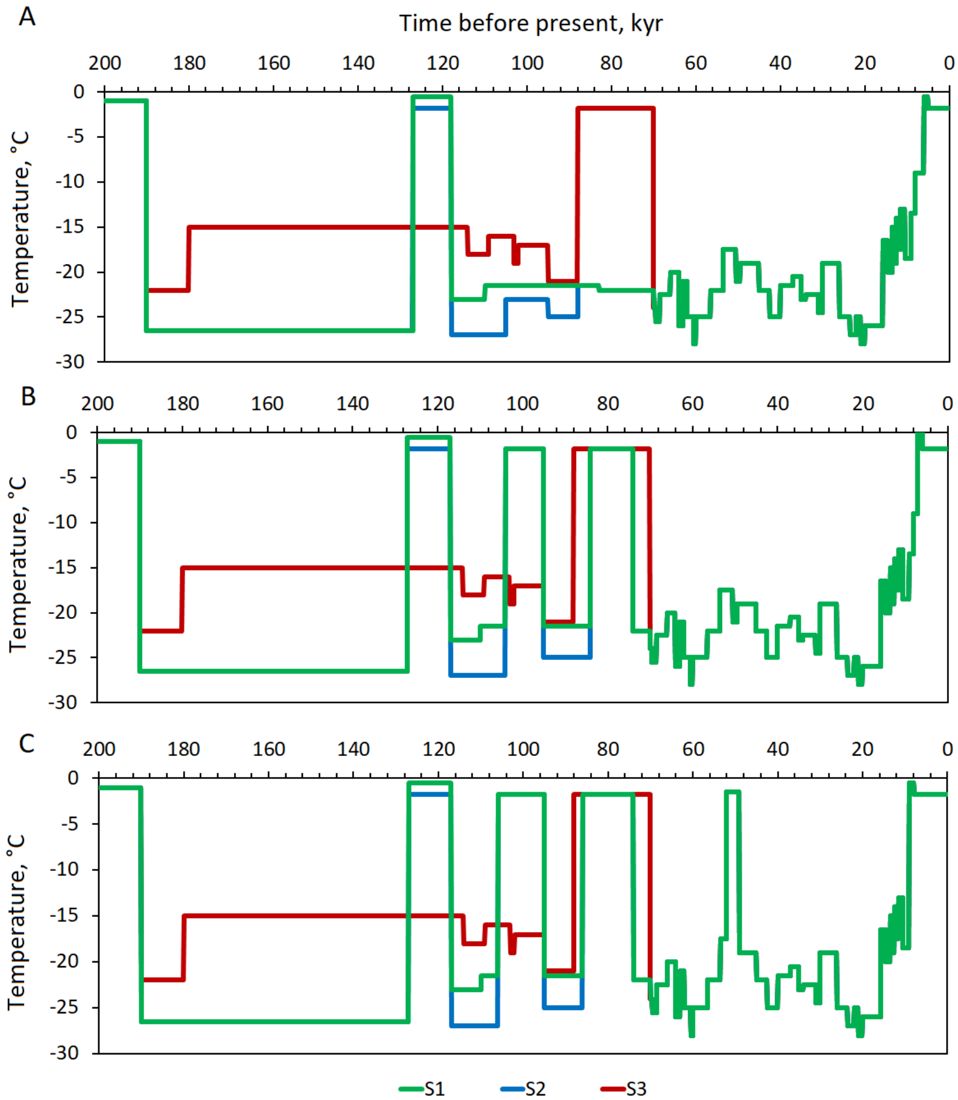

Figure 1. Model of the evolution of the ground surface temperature in the areas of isobaths: A - 5 m; B – 20 m; C - 40 m. The paleogeographic scenarios correspond to the zones: S1 scenario for "far" non-glacial zones, S2 scenario for "near" non-glacial zones, and S3 scenario for glacial zones.

The dependence on the presence/absence of a glacier is also most pronounced only at a sea depth of 5 m. Here it is about 160 m less in glacial conditions than in non-glacial conditions. On isobaths of 20 and 40 m, this difference is about 40 m. The difference in thickness due to the distance from the glaciation area varies from 6 to 15 m at sea depths of 5 and 20 m.

The results of modeling the gas hydrate stability zone (GHSZ) also reflect their dependence on the sea depth and the presence/absence of a glacier (Fig. 3). The depths of the top of the GHSZ (Fig. 3A) in the sections of isobaths of 5 and 20 m for glacial (S3), "near" (S2), and "far" (S1) non-glacial conditions are the same - 160 m from the sea bottom. On the 40 m isobaths, they are closer to the bottom surface: 135 and 140 m for non-glacial and glacial conditions, respectively.

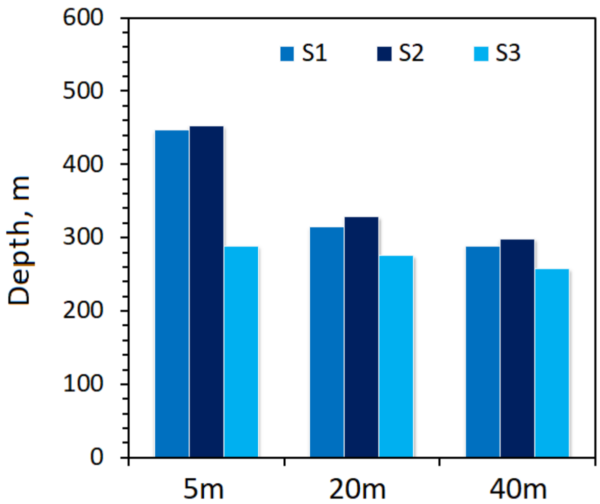

Figure 2. Shelf permafrost on 5, 20, and 40 m isobaths. Modeling results for the recent period for the scenarios S1, S2, S3.

The depths of the lower boundary of the GHSZ (Fig. 3B) are more closely related to the depths of the sea and the presence or absence of a glacier. At a sea depth of 5 m, it is the deepest in non-glacial conditions. At S1, it is located at 1100 m from the bottom surface, in S2 - at 1075 m. At sea depths of 20 and 40 m, this boundary is much closer to the bottom surface. At S1, it lies deeper: at 730 and 670 m at sea depths of 20 and 40 m, respectively. At S2, the depths are 780 m on the 20 m isobath and 708 m on the 40 m isobath. Under glacial conditions S3, it occurs significantly higher on all isobaths: at 628, 587, and 570 m from the bottom at sea depths of 5, 20, and 40 m, respectively. The indicated distribution of the lower boundary of the GHSZ is due to the thickness of the permafrost. It is significantly higher in the coastal zone at 5 m isobaths. The thickness of the GHSZ is greater in non-glacial conditions. Here it is 500-900 m, depending on the depth of the sea. In glacial conditions, the thickness of the GHSZ is 430 - 470 m.

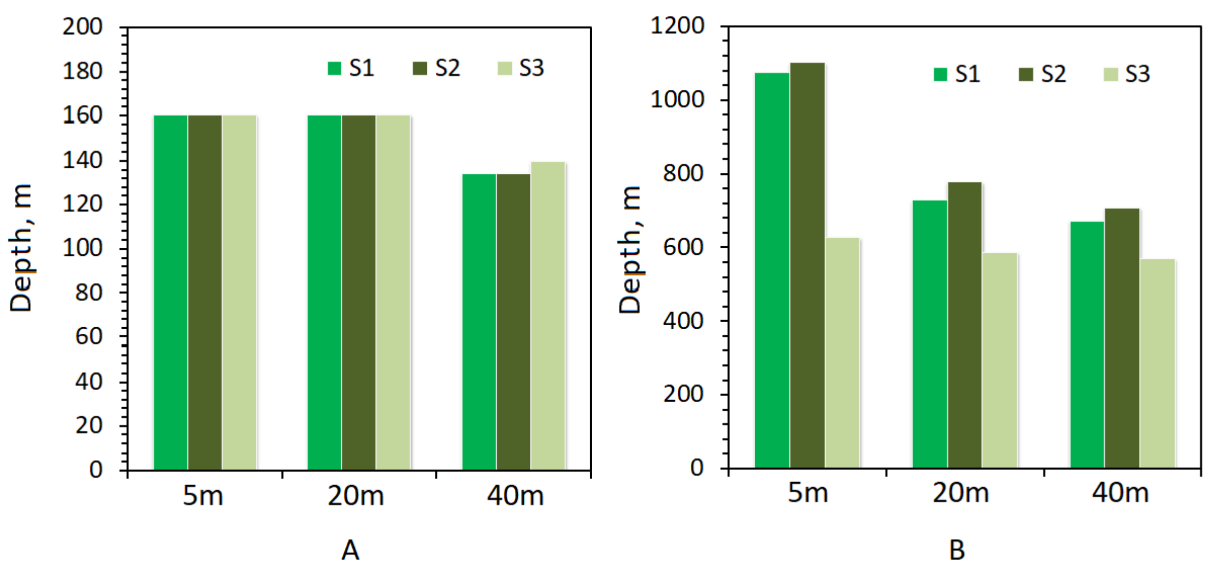

Figure 3. The upper (A) and lower (B) boundaries of the methane hydrate stability zone on 5, 20, and 40 m isobaths. Modeling results for scenarios S1, S2, S3.

Comparison with the model [18] shows that the permafrost thickness, according to the results of these studies in glacial conditions, increased by 15 m. This scenario was set for a more extended existence of a degrading glacier (130-88 thousand years ago, MIS 5e-5b). According to the scenario [18], it degraded in MIS 5e (127 thousand years ago). An increase in the permafrost thickness also took place in “near” non-glacial conditions at the 5m isobath. It was observed in connection with the cooling effect of the degrading glacier. However, modeling with a new detailed scenario confirmed from a fundamental point of view the main conclusion obtained in [18]. These results demonstrate a powerful influence of glaciation at the end of the Middle Pleistocene on the current thickness of the submarine permafrost and the GHSZ. Only the nature of the evolution of the permafrost and the GHSZ has changed.

4. CONCLUSION

Mathematical modeling is used to study the role of natural events in the evolution and current state of the permafrost zone and the gas hydrates stability zone in the northern part of the East Siberian shelf. Despite the limited field data, modeling helped us understand the paleogeographic scenarios' role in estimating the thickness of the submarine permafrost.

1. The glaciation of the Middle Pleistocene had a local character and is remote from the present day. Nevertheless, it had a very significant impact on the distribution of permafrost and GHSZ thickness.
2. The most significant glaciation affected the reduction in the permafrost thickness in the coastal zone. On the sections of the 5 m isobaths, the reduction was 160 m. On the 40 m isobath, it decreases to 30 m.
3. The impact on the GHSZ is even more pronounced. The lower boundary of the GHSZ at the 5 m isobath in glacial conditions is 580 m higher than in non-glacial conditions. In the area of the 40 m isobaths, this difference decreases to 160 m. This decrease is due to the dependence of the lower boundary of the GHSZ on the sea depth in non-glacial conditions and its absence in the glacial area.
4. The difference in the parameters of permafrost and GHSZ between the “near” and “far” non-glacial conditions is insignificant. The thickness of the permafrost in the first of them is 7-15 m higher, the position of the lower boundary of the GHSZ is deeper by 20-40 m, and the thickness of the GHSZ is the same amount.

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