We would like to thank the reviewers and the Editor for their careful review of our manuscript. Our point-by-point responses to all the comments and annotations are presented below. The comments from the reviewers are shown in black, and our responses in red. Where indicated, additions to the manuscript are shown in blue and deleted text is indicated by red strikethrough, and line numbers are based on our revised (non-track) manuscript. Besides, we added some information about changes in the paper that are not mentioned in the response to the Reviewers They are located below the responses to the comments above the marked-up manuscript version.

1. We cropped the Figures 2, 3, 6 and 9 (previous № 8): in the previous version of the article, the map covered part of the Laptev Sea, in this version there is just the Kara Sea.
2. Fig.2: The site №12 was missed; we added it to the current version.
3. The numbers of the figures were changed caused by the additional figure.
4. We made several changes in the Reference list.

==

Referee #1

Comments from the reviewer #1 and our responses:

General response

Comment

1. My main criticism of the paper is that the model used has not been adequately explained. It would not be possible for someone using the same or a different model to reproduce the work without a great deal of extra information. In my specific comments, I try to identify and ask questions at points in the text where vague language is used, or where important details are omitted. To allow comparison of their work, I encourage the authors to be as explicit and detailed as possible about how they achieved their results. Examples of open questions regarding how the model works:

Line70: what is meant by “double-layer” explicit solution? Is the Qfrost software publically available (e.g. on GitHub) – if so, why not reference it? If the model is well-documented, this might be a sufficient means of answering many of the questions regarding the method.

Response

→ Most likely, the comment appeared due to incorrect translation, since the explicit two-layer scheme, the method of balances and the enthalpy formulation of Stefan’s problem are all standard terms used for numerical calculations of the ground heat transfer. Therefore, «the explicit two-layer scheme» has to be used instead of « double-layer explicit solution».
Unfortunately, the Qfrost software for geocryological modeling (Certificate of the State Registration No. 2016614404 of 22) is no more available on-line despite the fact that, according to the idea of its main developer Denis Pesotsky it had to be publicly available for free (previously, the program was posted at http://www.qfrost.net). But due to his early death the web page no longer works and the software and its usage and distribution is limited to his colleagues and collaborators at Moscow University. Nevertheless, we hope to make it available soon. But the code is in open access on GitHub https://github.com/kriolog/qfrost . We are not sure it is worth inserting into the article, since there is a large part of the information in Russian.

The next sentences were added (Lines 78-79):

→ ~~It provides a double-layer explicit solution obtained with the heat balance method, for an enthalpy problem formulation.~~ The explicit two-layer scheme is applied using the balance method and the enthalpy formulation of the problem. The code used is publicly available under https://github.com/kriolog/qfrost (last access: 15 February 2020) (kriolog, 2020).

→ Reference (Lines 493-494):

→ kriolog: Software for a numerical geotechnical modeling of thermophysical processes in freezing and frozen soils, available at: https://github.com/kriolog/qfrost, last access: 15 February 2020

Comment

Line 80: "extrapolated" – what method was used to extrapolate results from monolithic stratigraphies to more complex stratigraphies? Introducing changes in porosity, grain size, thermal properties, etc. would presumably change the temperature field solutions?

Response

→ We added the results extrapolation algorithm (Lines 90-103):

→ We consider two cases to extrapolate our results:In the first case, we consider the uniform alternation of homogeneous layers with a relatively low thickness (relative to the total thickness of the permafrost). The linear interpolation is simply performed in accordance with the percentage of the thickness of frozen ground obtained during modeling for two "pure" soils at a given moment.The second case relates to the two-layer structure of the section, when a sufficiently thick (as compared with the permafrost thickness) homogeneous layer is underlained by a second homogeneous layer of unlimited thickness. Then the following considerations are valid. If the thickness of the upper layer is zero, then the thickness of the permafrost is equal to the result of simulation for "pure" rocks/sediments of the second layer. If the thickness of the upper layer is equal to (or more) the thickness of the permafrost obtained for the first layer, then the problem becomes single-layer and the thickness of the permafrost is equal to that of the first layer. Therefore, when the thickness of the upper layer changes from zero to the thickness of the permafrost of the first layer, the thickness of the two-layer section changes from the thickness of the permafrost of the second layer to the permafrost thickness the first layer. Therefore, as a first approximation, this change is linear (which is not entirely true) and a simple linear interpolation formula can be obtained.

Comment

On **line 82**, all rocks (please replace) were assumed to be saline – why? how saline was the sediment assumed to be? Did salinities vary with depth? Was salt diffusion permitted? How did salt content affect the freezing characteristic curve or liquid water of frozen material? - How are discontinuities avoided at the borders between domains/subdomains/areas/subareas?

Response

→ Very high degree of averaging over the properties was used for the modeling caused by the lack of data on the water area. The rare drilling data showed the salinization of sediments through the entire drilling depth. So there was not possible to take into account the salt diffusion, and the salinity did not vary with the depth.

→ We added the next text (Lines 103-107) :

→ All reference rocks and sediments were considered saline with Ds = 0.8-1.1% according to the concentration of pore saline solution corresponding to that of Kara sea bottom waters concentration (32-34 ‰). Therefore the freezing temperature of the pore solution is close to -1.8 °C. Thermophysical properties, the content of unfrozen water and the heat of the phase transitions of water in the pores, the freezing point of the deposits were set taking into account the indicated salinization.

→ As for the question about the borders between domains/subdomains/areas/subareas we inserted the following text in the section that describes the methodology (Lines 73-75):

→ The zoning is determined by the allocation of territorial units that are characterized by uniformity of formation conditions and, accordingly, by similar (on the given scale of the studies) parameters of permafrost: its distribution, thickness, depths of the top (Kudryavtsev, 1979).

Comment

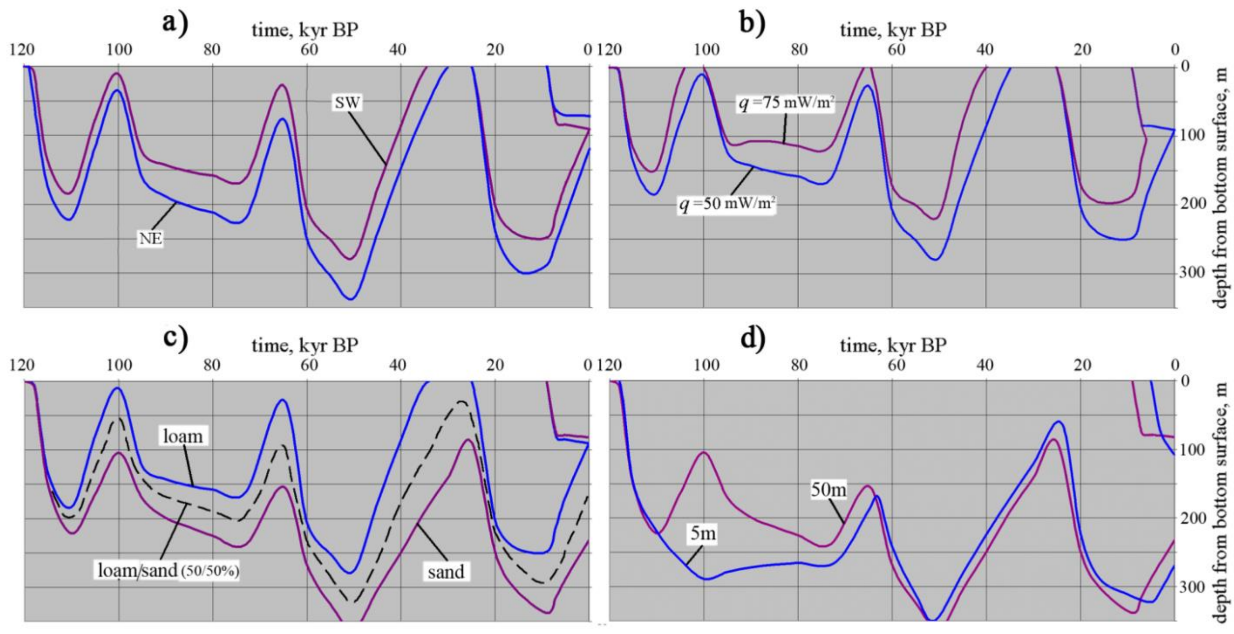
As a result, claims are made in the paper, but there is not enough information given to the reader to be able to judge whether the claim is justified or on what basis it has been made. For example: - section 4.2 lists 8 controls on the "pattern of permafrost distribution", but 2 of the 8 (lithology and properties or rocks, and Holocene climate optimum) are not described in any detail, making it impossible for the reader to follow the argument or design studies that reproduce the work. A 3rd control (thermal effect of river waters) is not even modeled, so it is not clear how the authors can conclude that this acts as a control. It seems to be an assumption in the model design, but not enough information is provided for the reader to be able to judge. -

Response

→ Thank you, you are absolutely right, the influence of control factors within the periglacial is not visualized. Therefore, we added four figures showing the dynamics of the Kara shelf permafrost (top and base) for the past 125 Kyr. The figure is presented in the supplements showing the influence of zonation, heat flux, lithology and properties and the influence of sea depths. The link to the reference is at the Line 306 in the section « 4.2. Distribution of permafrost, its thickness and depth to the permafrost table»

:

→ This pattern has several controls (Supplementary Figure 1):



→ Supplementary Figure 1. The influence of various environmental factors on the dynamics of shelf permafrost over the past 125 kyr according to the results of mathematical modeling

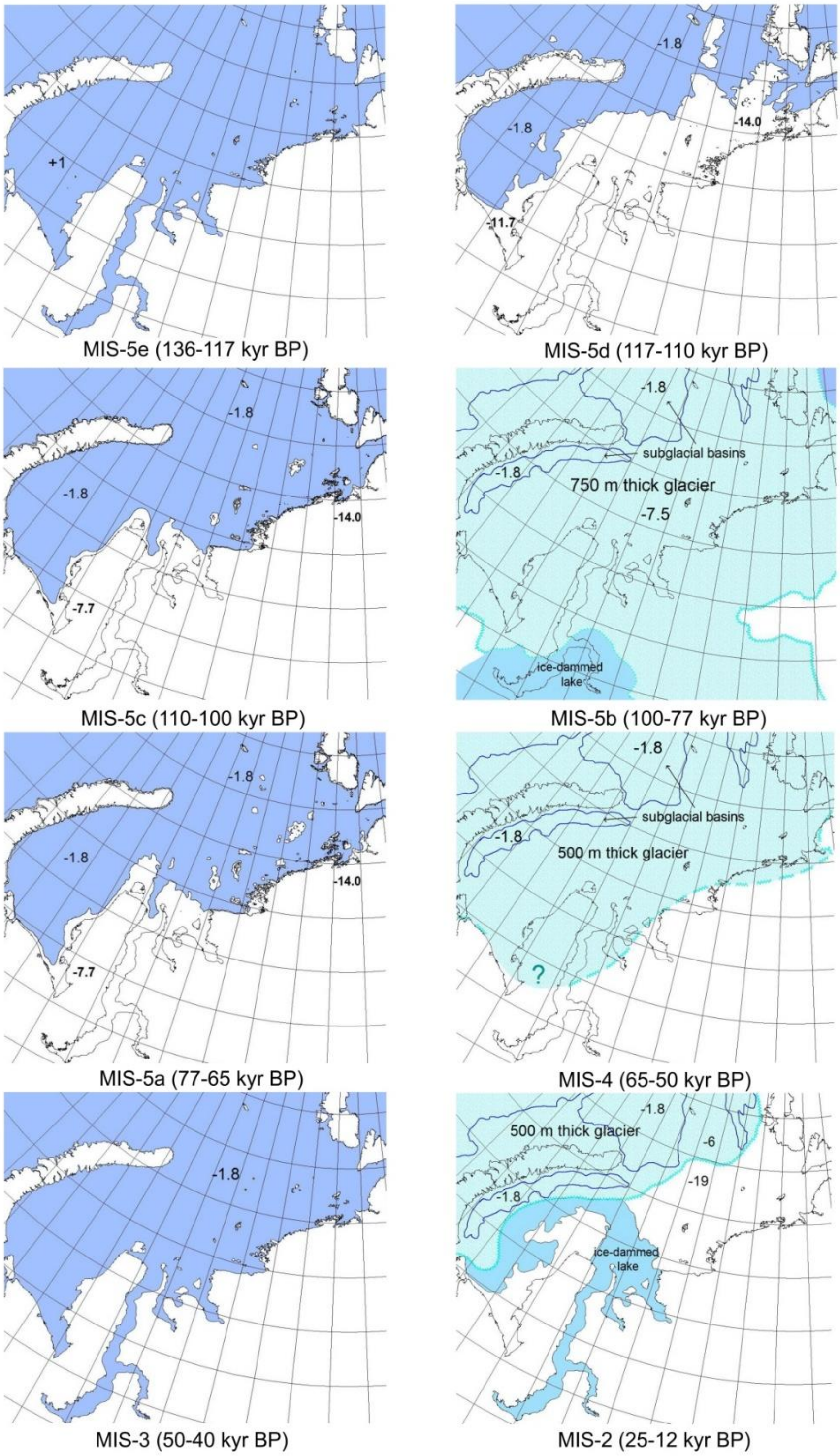
a) the influence of latitudinal climatic zonation and division into sectors : southwestern (SW) and northeastern (NE) shelf parts (the loam, 50 m isobaths, q=50 mW/m2)

b) the influence of heat flux: 50 mW/m2 and 75 mW/m2 (the loam, 50 m isobaths, SW)

c) the influence of lithology and properties of deposits : sand and loam (50 m isobath, q=50 mW/m2, SW)

d) the influence of sea depths (bottom isobaths): 5 and 50 m (the sand, q=50 mW/m2, SW)

→ We did not model the influence of the dammed basin, but it is shown at Fig.7 and described in the paper above the Figure 7. The influence of rivers is described according to actual data. An increase in water temperature in the Holocene optimum took place only in the southwestern part, the heated water came from the Barents Sea and is also described in the paper. Besides, we added the series of cartographic schemes illustrating , the change in surface conditions for the 125 kyr history of the Kara sea shelf (Lines 281-283)



→ Fig. 8. The series of cartographic schemes illustrating , the change in surface conditions in the Kara Sea shelf for the following moments : MIS 5e (130-120 kyr, MIS 5d (117-110 kyr) MIS 5c (110-105 kyr); MIS 5b (100-75 kyr); 5a (75-65 kyr); MIS -4 (kyr); MIS -3 (50-25kyr); MIS -2 (25-15 kyr).

Comment

Tables 2-7 lists the model output for "depths to permafrost top" – but what is meant by "permafrost top" has not been defined anywhere. Does this correspond to an isotherm, the presence of any ice, or of some minimum amount of ice? Or does the model output the depth of the phase change boundary?

Response

→ This is a very right comment. The permafrost table corresponds to the -1.8° C isotherm, according to the saline concentration in the seawater that was set for the pores of the deposits. Now it is shown in the abstract describing the salinity as mentioned above: (Lines 103-107) :

→ All reference rocks and sediments were considered saline with Ds = 0.8-1.1% according to the concentration of pore saline solution corresponding to that of Kara sea bottom waters concentration (32-34 ‰). Therefore the freezing temperature of the pore solution is close to -1.8 °C. Thermophysical properties, the content of unfrozen water and the heat of the phase transitions of water in the pores, the freezing point of the deposits were set taking into account the indicated salinization.

→ as well as in the 4.1 section (Lines 289-291):

→ 4.1. Distribution of frozen, cooled, and ~~unfrozen~~ thawed deposits~~rocks~~

Here we consider the permafrost table (frozen permafrost) corresponds to the -1.8° C isotherm, Therefore further in the text we mean frozen permafrost when talking about «permafrost» and the cryotic unfrozen deposits are «cooled» deposits (marine cryopeg).

Comment

3. The language used in the paper is sometimes imprecise or even incorrect; the paper should be proof-read by an native-speaker with some background in the topic. As examples: a. "cold": is probably being used to refer to cryotic conditions, or to conditions below the freezing point. As it stands, it is a vague descriptor. b. "rock": is used to refer to earth material, including either rock or sediment, consolidated or unconsolidated material. In English, "rock" is used to refer only to bedrock material, and would exclude sedimentary deposits of terrestrial, marine or other origin. As it stands, all instances of the use of "rock" need to be replaced with something more precise. c. More examples are given below in the specific comments.

Response

→ Accepted, thank you for a very important comment

«cold» is changed to «cooled» that means the cryotic unfrozen deposits known as marine cryopeg according to the Multi-Language Glossary of Permafrost (Everdingen, Robert van, ed. 1998 revised January 2002. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology). We still have chosen «cooled», because in Russian literature the cryopeg always means an isolated cryopeg, and this can create a lot of confusion for non-native speakers. Therefore we decided to add that description «the cryotic unfrozen deposits are «cooled» deposits (marine cryopeg)».See Lines 290-291:

→ the cryotic unfrozen deposits are «cooled» deposits (marine cryopeg).

→ As for the rocks, we replaced the «rock» for the «deposits» (instead of rock and sediments) or «ground» (ground temperature instead of rock temperature) wherever it was necessary

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Comment

4. The abstract is extremely short and does not provide enough information for a reader to decide whether he/she wants to read the paper. It needs to introduce the larger context for the study, the central question/focus/hypothesis, more detail on the method. It should report key results, findings and conclusions, and may suggest implications or outlook based on the study.

Response

→ Accepted, the abstract is extended according to the comment (Lines 13-26):

→ Abstract. ~~The evolution of permafrost in the Kara shelf is reconstructed for the past 125 Kyr. The work includes zoning of the shelf according to geological history, compiling sea-level and ground temperature scenarios within the distinguished zones, and forward modeling to evaluate the thickness of permafrost and the extent of frozen, cold and unfrozen rocks. The modeling results are correlated to the available field data and are presented as geocryological maps. The formation of frozen, cold, and unfrozen rocks of the region is inferred to depend on the spread of ice sheets, sea level, and duration of shelf freezing and thawing periods.~~ The evolution of permafrost in the Kara shelf is reconstructed for the past 125 kyr. The work includes zoning of the shelf according to geological history, compiling sea level and ground temperature scenarios within the distinguished zones, and modeling to evaluate the thickness of permafrost and the distribution of frozen, cooled and -thawed deposits. Special attention is given to the scenarios of the evolution of ground temperature in key stages of history that determined the current state of the Kara shelf permafrost zone: characterization of the extensiveness and duration of the existence of the sea during the marine isotope stage MIS -3, the spread of glaciation and dammed basins in MIS-2. The present shelf is divided into areas of continuous, discontinuous to sporadic, and sporadic permafrost. Cooled deposits occur at west and northwest water zone and correspond to areas of MIS-2 glaciation. Permafrost occurs in the periglacial domain that is a zone of modern sea depth from 0 to 100 m, adjacent to the continent. The distribution of permafrost is mostly sporadic in the southwest of this zone, while it is mostly continuous in the northeast. The thickness of permafrost does not exceed 100 m in the southeast , and ranges from 100 to 300 m in the northeast. Thawed deposits are confined to the estuaries of large rivers and the deepwater part of the St. Anna trench. The modeling results are correlated to the available field data and are presented as geocryological maps. The formation of frozen, cooled and -thawed deposits of the region is inferred to depend on the spread of ice sheets, sea level, and duration of shelf freezing and thawing periods.

Comment

5. The reference list is incomplete. Vasiliev & Rekant (2018) are missing, for example. The reference list needs to be cross-checked with the submitted paper. Some reference citations still include initials (see Fig. 4 caption, for example).

Response

→ Accepted, thank you
The reference list and the article has been carefully checked and corrected in accordance with the changed links.

Comment

6. This paper stays true to the general phenonmenon of Russian authors citing mostly Russian work, and Canadian/Alaskan researchers citing mostly North American. For citations dealing with regionally specific processes, this is understandable. But neglecting to look at how the North American community has approached modelling the exact same processes under different conditions is harmful in two ways: it exposes the work to the criticism of being too narrow in its

approach, and it makes it less likely that the work will be found and cited by North Americans. I encourage the authors to show their familiarity with the field by referring to the work of researchers from outside of their region, who have presented novel ideas in the field of subsea permafrost modelling. Some examples: - Whitehouse, P. L., Allen, M. B., Milne, G. A. Glacial isostatic adjustment as a control on coastal processes: an example from the Siberian Arctic, Geology, 35,747–750,doi:10.1130/G23437A.1,2007. –anything from the group of Romanovsky and Nicholsky (e.g. Nicolsky, D., Shakhova, N. Modeling sub-sea permafrost in the East Siberian Arctic Shelf: the Dmitry Laptev Strait. Environmental Research Letters 5(1), 15006, 2010.). - anything from Taylor, A. (e.g. Taylor, A. E., S. R. Dallimore, P. R. Hill, D. R. Issler, S. Blasco, Wright, F. Numerical model of the geothermal regime on the Beaufort Shelf, Arctic Canada since the Last Interglacial, J. Geophys. Res. Earth Surf. , 118, doi:10.1002/2013JF002859, 2013.).

→ This phenomenon on mathematical modeling is quite understandable. Soviet (Russian) permafrost scientists started the modeling back in the 1960s. (Sharbatyan A.A. To the history of the development of permafrost (on the example of the West Siberian Plain) // Transactions of the Institute of permafrost. Academy of Sciences of the USSR, v. XIX, 1962). Modeling was carried out on extremely slow analog devices. For the shelf, the first modeling was carried out in 1969 (Molochushkin E.N. Thermal conditions of rocks in the southeastern part of the Laptev Sea. Abstract of thesis , 1970). The methodology and simulation results were widely debated in the former USSR in the late 1970s – early 80s. Therefore, the literature on modeling in Russian is at least an order of magnitude more extensive than in English, which, in fact, determines its greater citation.

However, it should be noted that Russian-language literature is widely represented in the international database. In addition to the references cited in this article, the state of mapping of the submarine cryolithozone by Russian researchers at the turn of the 20th and19th centuries is characterized in the next paper: Gavrilov A.V. (2001) Geocryological Mapping of Arctic Shelves. In: Paepe R., Melnikov V.P., Van Overloop E., Gorokhov V.D. (eds) Permafrost Response on Economic Development, Environmental Security and Natural Resources. NATO Science Series (Series 2. Environment Security), vol 76. Springer, Dordrecht.

In current work the authors used the developments from N.E. Shakhova and D. Nikolsky for construction the scenarios. Moreover, D. Nicolsky et al., 2012 used data of modern warming to set the Holocene temperature of bottom water, while we did set more realistic data - the reconstructed temperatures in each of the Holocene warmings and coolings. Besides, in the present paper, the authors tried to take into account the increase in the temperature of bottom water in the coastal zone warmed up in summer, which occurred during the transgression of the sea on each section of the shelf

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Specific comments:

Comment

Line 13: the use of Kyr as a unit does not follow SI.

Response

→ «Kyr» corrected to «kyr» everywhere through the text

Comment
Line 24: "In the latest ... earliest ..." needs correction.
Response

→ Line 32 : ~~In the latest 1970s-earliest 1980s~~ By late 1970s - early 1980s,

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Comment
Line 45: "raised high" – please quantify
Response

→ Line 53: Corrected, «…which are raised high (+45, +55,+60 m , Bolsiyanov et al., 2006)»

Comment
Line 49: add "and" and remove "and so on"
Response

→ Done
→ Line 57 «…glacio-isostatic movements and fluctuations in sea level. ~~, and so on.~~»

Comment
Line 58: replace "provide their progress" with "extend their work"?
Response

→ Thank you, we changed this according to your suggestion.
→ Lines 64-65 « We follow these methods in our research~~work~~ and are trying to ~~provide their progress~~ extend their work»

Comment
Line 59: what is meant with "geocryological results"? Please specify
+
Line 61: "obtained estimates" – of what? Please specify
Response

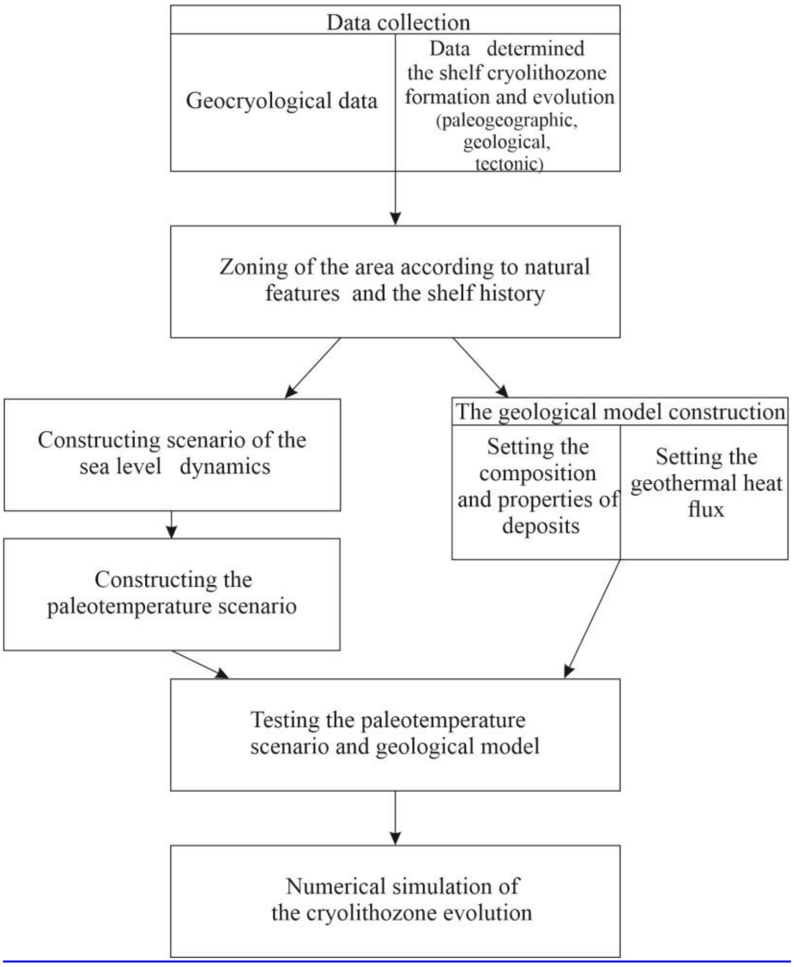
→ The sentences were corrected (Lines 65-68):
→ The work includes compiling a database of paleogeographic, geological, tectonic, and geocryological ~~results used further for dividing the region according to geological history and for creating possible scenarios of sealevel and ground temperature variations~~ conditions used further to divide the region according to geological history and for creating possible scenarios of sea level and ground temperature variations that serve as boundary conditions in heat transfer modeling. The general scheme of the methodology is presented in Figure 1. ~~The obtained estimates serve as boundary conditions in heat transfer modeling.~~

Comment
Fig. 1. This figure provides an overview of the method, but uses many general or non-specific terms that reduce the amount of information communicated: - in the top box, what is meant by "environmental data"? - in the second box, what is meant by "conditions"? - in the left third box, delete "dynamics" (adds nothing to "history") - in the third right box and in the fourth left box, replace"rocks"-in the fourth right box: "density of the heat flow from the depths" is usually referred to "geothermal heat flux" - in the fifth box: "Testing ... of the model" is almost entirely free of content. How was which model tested? More specific word choice could make this box informative - the lowest box is actually two steps: "coordination" and "mapping" - what is meant by "coordination"? This question is never really answered in the paper, but is critical for understanding what was done. Does the model output get changed in some way by comparison

with field data? Where and where not? How? These are important points for anyone wanting to reproduce or apply the method in the same or in other geographical regions.

Response

→ The figure was adjusted in accordance with the comments using more specific terms (Line 69)



→ The testing consists in the production of mathematical modeling for an area provided with actual geocryological data. During modeling, adjustments are made to the paleotemperature scenario or/and geological model until the model data matches the actual. The adjusted scenario or/and model are used for the final simulation. This information is located within the Lines 107-108 : «The paleotemperature scenarios and the geological-tectonic model were tested by comparing the present permafrost state estimated by forward modeling with the available field data from well documented areas, to achieve the best fit.» and Lines 114-115: « The modeling results were correlated with field data and both datasets were used for the final geocryological zoning of the Kara shelf region.»

Comment

Line 72: “Permafrost dynamics were...”

Response

→ Sorry, but we don’t get why it has to be plural here

Comment

Line 73: “including...” suggests that other scenarios/conditions were NOT included? How many and why not?

Response

- → Thank you for the notice. The sentence was corrected to sound more clear (Lines 82-83):
- → The permafrost dynamics was simulated for numerous paleoclimate scenarios that cover the full range of presumable conditions in the Arctic shelves., ~~including forty scenarios for the Kara shelf~~. The total number of paleo-scenarios for the Kara sea used in the course of mathematical modeling was 30.

Comment

Line 77: how were regions of different geothermal heat flux mapped or determined?

Response

- → In accordance with the data of geothermal studies (Khutorskoy et al., 2013), the Kara shelf is characterized by a heat flux density of 50 to 75 mW /m^2. There is very few no point-referenced data. Therefore, the technique involves modeling for two extreme density values. Based on the simulation results and actual data, it was possible to draw conclusions about the heat flux values characteristic of various tectonic structures. This is written in the text(Lines 85-86):

  «The heat flux was assumed to be 50 mW/m2 , which corresponds to the average for most of the shelf territory or 75 mW/m2, as in zones of relatively high heat flux in gas-bearing bottom sediments (Khutorskoy et al., 2013)».

Comment

Line 79 and in all following text: modelling was probably not restricted to the "rock".

Response

corrected. Lines 87-89:

- → The modeling was performed for several uniform reference ~~rock~~rock and sediment -types in order to reduce the number of possible solutions in the conditions of high lithological diversity in the area.
- → We edited this terminology everywhere in the text. Please find responses above.

Comment

Line 87: "subsea permafrost had presumably fully degraded..." – this statement requires a reference, especially in light of modelling, for example by Romanovsky, N. N., showing permafrost elsewhere persisting through interglacials; this point is important, since other researchers have shown that a systematic bias in model results is obtained depending on the initial conditions. Such results show that setting permafrost to zero at the interglacial will introduce a warm bias, that at least would need to be tested.

Response

- → Romanovsky's conclusions are about the Laptev Sea shelf, where there are almost no marine terraces of MIS-5e. The very different conditions occured for the Kara region, where the entire north of the West Siberian Plain had been covered by the sea from 140 to 120 Ka.

  Link to MIS-5e: The State Geological Map of the Russian Federation Scale 1:1000000 (third generation). Ser. West Siberia, Sheet R-42, Yamal Peninsula, 2015 (in Russian).; Map of Quaternary deposits in the Russian Federation, scale 1:2 500 000, Explanatory note. Minprirody, Rosnedra, VSEGEI, VNII Okeangeologiya, 2010 (in Russian).

- → We revised the sentence as follows(Lines 111-114):
- → At that time, subsea permafrost had presumably fully degraded over the whole studied part of the Kara Sea,as the entire north of the West Siberian Plain had been covered by

the sea from 140 to 120 Ka (Zastorozhnov et al., 2010; Shishkin et al., 2015) and the temperatures of unfrozen bottom sediments approached the steady state.

Comment

Fig. 2: it looks like only 14 sites out of more than 100 are located on the shelf, i.e. pertain to subsea permafrost. Is this correct? Please add a description of the red line (which is currently not described until Fig. 8).

Response

→ Yes, it is correct. There are few publications containing data on submarine permafrost in Fig. 2. They are actually few. But the figure is called: Late Pleistocene geology of the Kara region: data coverage. They are the paleogeographic data necessary for scenario and mathematical modeling.The red line description, which is research region boundary was added on Fig 2,3,6

→ Fig. 2. Late Pleistocene geology of the Kara region: data coverage (the red line is the research region boundary). The numbers on the map correspond to the following publications:

→ Fig. 3. ~~Division~~ Zoning of the Kara shelf according to its geological history for 125 kyr. Abbreviations are explained in the text and in Table 1. The red line is the research region boundary

→ Fig. 6. Location of onshore and offshore sections (points) with marine sediments (^{14}C - figures, thousand years ago) of MIS-3 in the Kara Sea shelf, after Gusev et al. (2011; 2012a, b; 2013a, b; 2016 a, b); Baranskaya et al. (2016); Vasil`chuk et al. (1984); Molodkov et al. (1987); Bolshiyanov et al. (2009). The red line is the research region boundary

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Comment

Line 106: “the existence of a number of idea about its development...” is not a peculiarity of any region, it is true of every region!

Response

→ The sentence is revised accordingly (Lines 131-132):

~~The peculiarity of the paleogeography of the Kara region is the existence of a number of ideas about its development in the Late Pleistocene.~~ There is number of ideas about the paleogeography of the Kara region and its development in the Late Pleistocene.

Comment

Line 115: dammed lakes are invoked to explain the unfrozen zone. Why is the sensible and convective heat transport at the river bed and in the estuarine regions not sufficient to explain the absence of frozen material? Surely the rivers maintain and have maintained positive benthic temperatures for long periods?

Response

→ We invoke the dammed lakes to explain the unfrozen zone based on the next assumptions and speculations: The riverbeds are lines. Here there is a large area of the flatten bottom and river valleys are traced incomparably worse than on the periglacial shelf of the Laptev and East Siberian seas. There bathymetry shows that the rivers functioned the entire period of MIS-2. But it is absent on the West Siberian shelf. Instead of river deltas to the west and east of the coast of Western Siberia, the estuaries of the Ob, Taz, and other rivers deeply protrude into the land. And even the small river Gyda has an estuary, the width of which is almost the same as the length of the Gydy river, and the length of the estuary is like 3-4 Gyda rivers. This has to be an ice-barrier basin. This is an assumption. But it is well confirmed by talik on the water continuation of the rivers of

Western Siberia, and estuaries deeply protruding into the land. The question is how could the Ob and the Yenisei, flowing through the whole Western and Middle Siberia, carrying a mass of sediment (since they drain the Altai and Sayan mountain systems), form not a delta, such as Lena, but estuaries? In our opinion, the assumption is very realistic.

Comment

Line 119: "Insignificance of the severity" is convoluted language that should be simplified.

Response

- → Accepted, changed (Lines 144-145) :
- → ~~The insignificance of the severity~~ The poor expression of the ancient valley network is especially clearly seen when comparing it with that in the eastern sector of the Arctic, where there were no glaciations

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Comment

Line 154: explain the abbreviation "MMP"

Response

- → corrected. (Lines185-186):
- → The modeling we carried out for the G-1 area showed that, to date, the ~~MMPs~~ permafrost formed in the MIS-2 have not survived.

Comment

Line 156: "sea level" rather than "sealevel"

Response

- → corrected (Line 187):
- → «…the effect of climate-driven eustatic sea level change. The sea level…»

Comment

Line 201: on what basis was it decided how long each portion of the shelf spent in the coastal zone (400-2000 years)? Why were waters in this zone saline? – is this not the zone most affected by the freshwater layer above the halocline, by snow melt and river runoff? Dmitrenko et al (2011) show the freshwater nature of the coastal zone in the Laptev Sea. And why was this zone warmer? Bedfast ice can result in cooling of the seabed from 0 – 2 m water depth. A little more justification and specification of these boundary conditions, which determine the most immediate and rapid response of permafrost to inundation by seawater, are necessary.

Response

- → Thank you, we added a detailed explanation to the text (Lines 237-251)
- → During transgressions in the Holocene, each shelf part stayed for 400-2000 years in the coastal zone where bottom sediments were flooded with saline and warm near-bottom water. It is known that at sea depths from 2 to 7 m in the 1970s (Zhigarev, 1981), up to 10 m in the 2000s. (Dmitrenko) the mean annual temperature of bottom waters in the Laptev Sea stays positive and bottom sediments thaw from above. For the Kara Sea, there are no such data on isobath intervals, but it is known that temperatures are generally lower. Therefore, we assumed that the interval of isobaths with such water temperatures was limited to 5-6 m. Episodes with such water temperatures occurred on the shelf during the postglacial transgression even in its initial periods, since the July temperature is reconstructed for pre-Holocene warming (allered) exceeding 2 ° C the temperature of the 1980s. (Velichko et al., 2000). Therefore, we constructed scenarios for these episodes. To determine their duration, dated data on the absolute altitudes of the sea level during the transgression of the Laptev Sea were used (Bauch et al., 2001). The transgression rate was not the same. The shortest episodes (400 and 375 years) of positive temperatures are determined for periods 15-11 and 10-9 ka respectively. The longest

intervals were 11–10, 9–5, and 5–0 Ka with 1000, 750 and >5000 years according to simple calculations. Special mathematical modeling for desalinated coastal zones was not performed due to the relatively small area of their distribution and the specific nature of salinity distribution over the water column. Desalination of waters was taken into account directly when constructing a geocryological map.

Comment

Fig. 8: The map shows permafrost thickness, which can clearly result as output from 1D numerical modelling. What conditions were applied to determine zonation of permafrost based on continuity (continuous,discontinuous,sporadic)? I.e. how do conclusions about distribution result from 1D modelling? Caption: why are only “fragments” of the map shown? Why not present the reader with the whole map?

Response

→ A paleogeographic scenario was constructed, consisting of a series of paleotemperature curves (or scenarios), in which the main factors that formed the modern permafrost were taken into account. Among these factors were: zoning, sectorality, fluctuations in sea level and its depth, which determined the period of freezing during shelf drainage and the thawing period when it was in the flooded state, the period of glaciation and thickness of the ice sheet, geothermal gradient, ground composition and properties, area, within which the water temperature rose at the Holocene optimum etc. In accordance with the indicated curves, modeling was carried out, the results of which reflected the influence on the permafrost of all of the above factors. The whole map is being prepared for publication in the atlas

Referee #2

Comments from the reviewer #2 and our responses:

Comment

1. Plot the air temperature (ground surface temperature) for different regions for the last 125k years. As I understand there is a temperature zonation factor involved. What is it? How does the air temperature differ between various regions, subzones?

Response

→ The article presents graphs of mean annual ground temperatures over the past 125 kyr depending on paleogeographic events (shelf drying, flooding, glaciation, etc.) according to latitudinal zoning and meridional sectorality (Fig. 4,5,7). When specifying latitudinal zonality during periods of shelf drying, the authors followed differences in ground temperatures reflected on the Russian Geocryological Map (Yershov ed., 1991). The mean annual ground temperature is 4-6 °C lower in the NE of the region (north of Taimyr) adjacent to the Kara coast, than as for the SW (south-west of Yamal). When zoning the shelf (Table 1, Fig. 3), the southwest (68-71 ° N) and north-eastern (72-77 ° N) areas were distinguished. During the periods of drainage in the periglacial part of the shelf in MIS-2, the following values for the ground temperature were taken: -19 ° C for the north-eastern area, and -15 °C for the south-western one .

Reference:

Yershov E.D. (Ed.): Geocryological Map of the USSR, scale 1:2 500 000. Moscow State University, Moscow, 1991 (in Russian).

The next additional information is added to the text (Lines 156-160):

→ When specifying latitudinal zonality during periods of shelf drying, the authors followed differences in ground temperatures reflected on the Russian Geocryological Map (Yershov ed., 1991). The mean annual ground temperature is 4-6 °C lower in the NE of the region (north of Taimyr) adjacent to the Kara coast, than as for the SW (south-west of Yamal). During the periods of drainage in the periglacial part of the shelf in MIS-2, the following values for the ground temperature were taken: -19 ° C for the north-eastern area, and -15 °C for the south-western one.

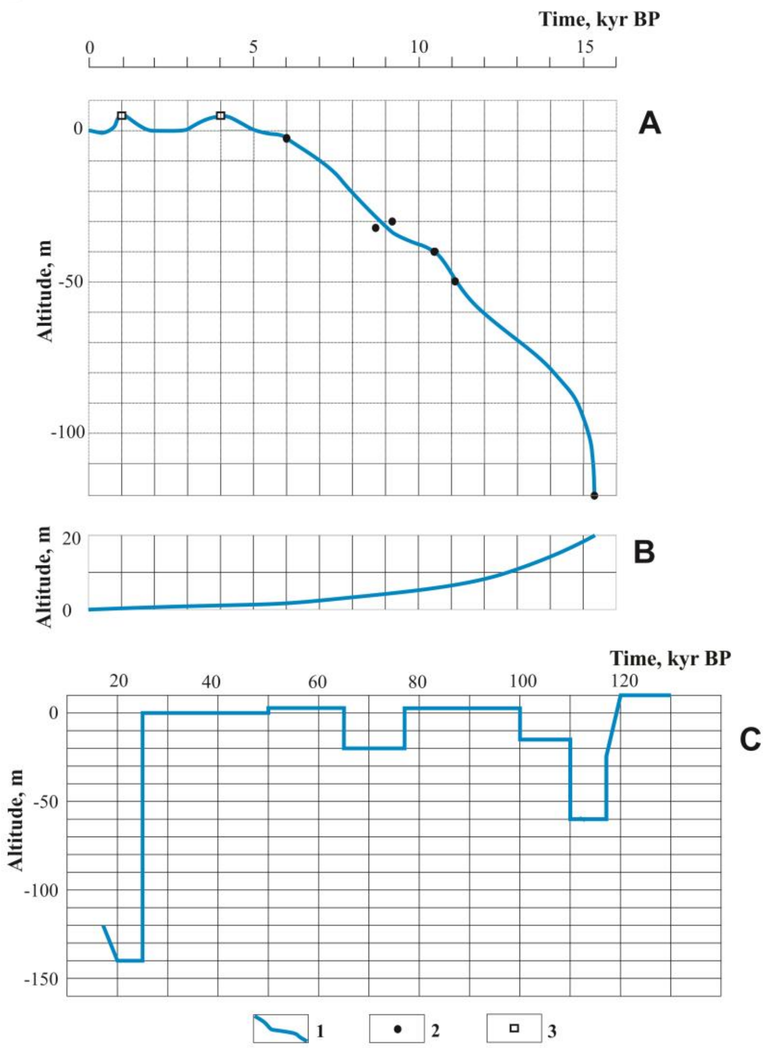
Comment

2. It is stated that “about 50-75ky bp the sea level was the same as present”. Unfortunately, the paper lacks the sea level dynamics, I think it was used in the scenario building, but not explicitly shown. Please supplement Figure 4 with a plot of the relative sea level curve with respect to the present-day conditions for the last 125k years.

Response

→ The paper claims that the sea level was the same as current 50-25 kyr BP (not 50-75, see Lines 257-258): «The available data, though far incomplete, show that the sea level between 50 and 25 kyr BP(almost all MIS-3 through) was the same as at present (Fig. 6)…» This is shown at Fig. 6 based on the marine sediments dating (50-25 Kyr BP) on the islands, shelf and the sea coast. We modified Figure 4 adding the plot showing fluctuations of the sea level during the modeling period of 125-15 kyr (Fig.4c). The revised sentences, figure and caption (Lines 192-197):

→ Special focus by authors was in the recreating on the Late Pleistocene-Holocene transgression (Fig. 4a,b). The Figure 4shows the scenario on fluctuations of the sea level during the modeling period of 125-15 kyr.



→ Fig. 4. Late Pleistocene-Holocene transgression and shelf flooding (was drawn up by Gavrilov A.V.).

A: periglacial domain 1 = sealevel curve, from 15 Kyr BP to Present; 2 = dated bottom sediment cores from Ob' Gulf, Yenisei Gulf, and adjacent offshore (Stein, R. et al., 2009) and Vilkitsky Strait (Levitan, M.A.et al., 2007) sites; 3 = onshore data (Romanenko, F.A., 2012);

B: glacial domain.

Fig. 4. Scenarios of sea level fluctuations:

for the 15-0 kyr .: A -periglacial domain, B- glacial domain; for the 125-0 kyr: C - periglacial domain.

1 - sea level curve; 2 - dated bottom sediment cores from Ob' Gulf, Yenisei Gulf, and adjacent offshore (Stein, et al., 2009) and Vilkitsky Strait (Levitan.et al., 2007) sites; 3 - onshore data (Romanenko, 2012);

Comment

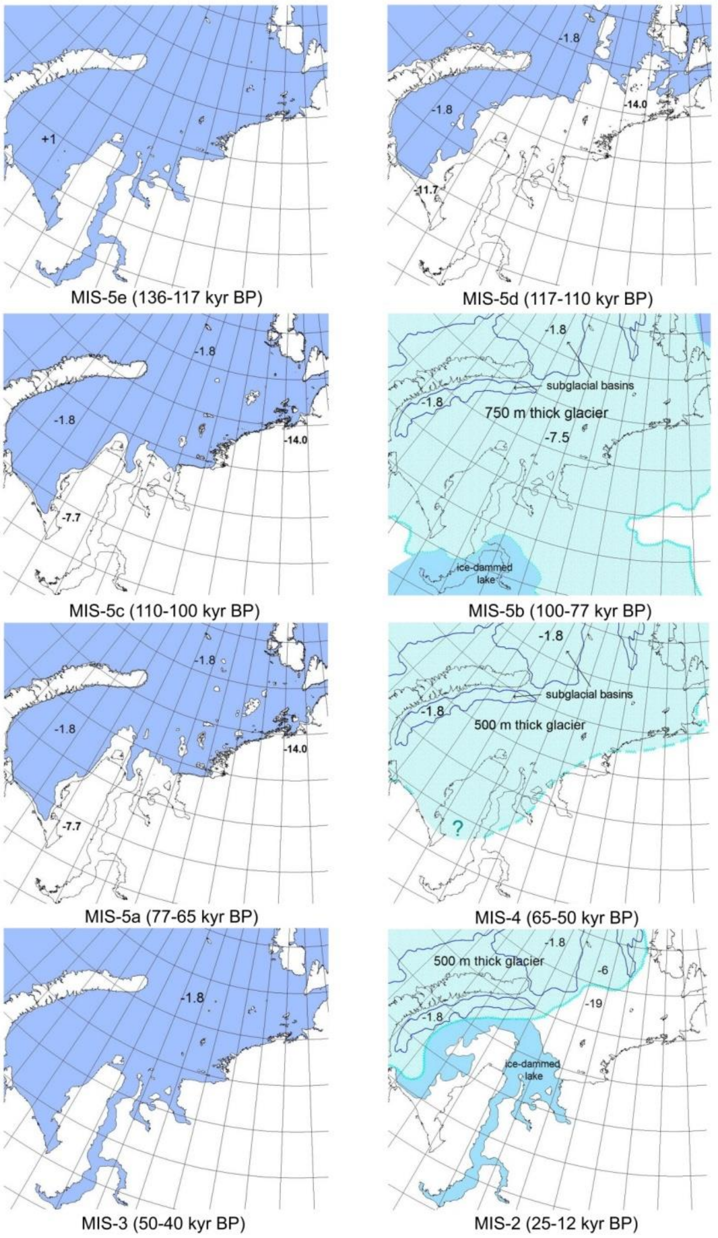
3. Make a series of maps to show which areas were flooded, glaciated or exposed to air 10, 20, 40, 55, 70, 80 ky bp. It will help a reader. It is okay to take different times, e.g. middle of the MIS periods. The goal is to help future researchers to understand when a certain part of the shelf was exposed to the air. Right now, it is not clear. Also, change the y-labels in Figure 4 to "Sea level with respect to the present-day datum, m". Make values in Figure 4a negative. '

Response

→ The authors totally agree with the reviewer: the relevant illustrative material will help the reader to understand the content of the article. Therefore, the change in surface conditions is illustrated by a series of cartographic schemes for the following moments: MIS 5e (130-120 kyr, MIS 5d (117-110 kyr) MIS 5c (110-105 kyr); MIS 5b (100-75 kyr); 5a (75-65 kyr); MIS -4 (kyr); MIS -3 (50-25kyr); MIS -2 (25-15 kyr). See Lines 281-283:

→ As for the Figure 4 (a,b,c) we have changed y-labels for «altitude» to have them the same for all three plots to make it easier to the reader and made values values in Figure 4a negative . Please refer to our above response.

→ The series of cartographic schemes illustrating , the change in surface conditions for the 125 kyr history of the Kara sea shelf is presented in the Fig 8



→

→ Fig. 8. The series of cartographic schemes illustrating , the change in surface conditions in the Kara Sea shelf for the following moments : MIS 5e (130-120 kyr, MIS 5d (117-110 kyr) MIS 5c (110-105 kyr); MIS 5b (100-75 kyr); 5a (75-65 kyr); MIS -4 (kyr); MIS -3 (50-25kyr); MIS -2 (25-15 kyr).

Comment

4. How are the effects of salts taken into the account? Does the salt lower the freezing point depression? Do you take into the account unfrozen liquid pore water while freezing the saline water? How are the salt effects parameterized in the model? Explain and clarify in the paper.

Response

→ The freezing temperature equal to the freezing temperature of sea water (- 1,8°C) was set for all types of soils for the modeling. This assumption was made due to the fact that all the marine sediments composing the Yamal Peninsula have the close values of the salinity to a depth of 300 m and more (Chuvilin et al., 2007).Very high degree of averaging over the properties was used for the modeling caused by the lack of data on the water area. The rare drilling data showed the salinization of sediments through the entire drilling depth. So there was not possible to take into account the salt diffusion, and the salinity did not vary with the depth. Because the modeling has evaluative nature a scheme with complete freezing (thawing) of moisture in the ground at the moving front of phase transitions was used. The content of unfrozen water in the sediments was taken into account by reducing the volumetric heat of phase transitions in the model by the value corresponding to the average content of unfrozen water in different types of rocks at negative temperatures typical of the process under study.

Reference:

Chuvilin E.M., Perlova E.V., Baranov Yu.B., Kondakov V.V., Osokin A.B., Yakushev V.S. The structure and properties of cryolithozone sediments of the southern part of the Bovanenkovo gas condensate field. M.:"Geos", 2007, p.20

To clarify this issue, we added next several sentences (Lines 102-107):

→ All ~~rocks~~ deposits were assumed to be saline from top to bottom of the modeling domain. All reference rocks and sediments were considered saline with Ds = 0.8-1.1% according to the concentration of pore saline solution corresponding to that of Kara sea bottom waters concentration (32-34 ‰). Therefore the freezing temperature of the pore solution is close to -1.8 °C. Thermophysical properties, the content of unfrozen water and the heat of the phase transitions of water in the pores, the freezing point of the deposits were set taking into account the indicated salinization.

Comment

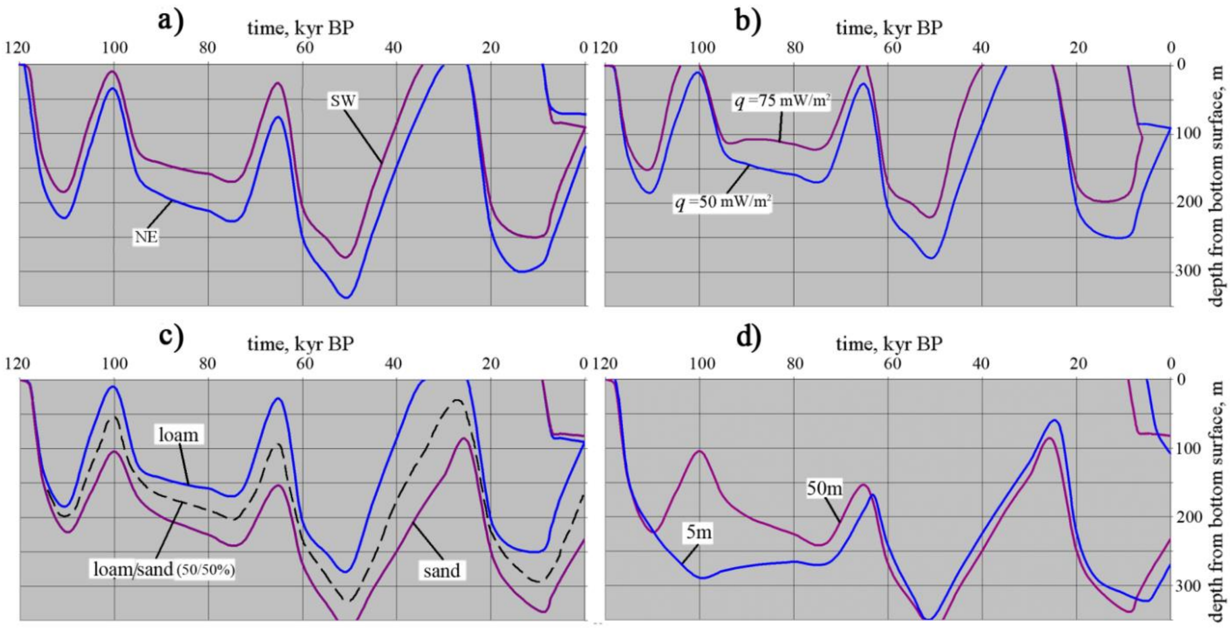
5. The paper goes into the discussion of various ground layers (sand, clay,etc) and heat flux values. I suggest moving this analysis into a separate section, e.g."Sensitivity analysis". Do you do sensitivity analysis with respect to salt concentration?

Response

→ Actually we have a related comment from the first reviewer about lack of information on the influence of control factors of permafrost dynamics (section 4.2). Therefore, it seems to be more convenient to expand that section with four figures showing the dynamics of the Kara shelf permafrost (top and base) for the past 125 Kyr. The results obtained during modeling for the following aspects for the southwestern and northeastern areas are presented now. The figure is presented in the supplements showing the influence of zonation, heat flux, lithology and properties and the influence of sea depths. The link to the reference is located at the Line 306 in the section « 4.2. Distribution of permafrost, its thickness and depth to the permafrost table»

:

→ This pattern has several controls (Supplementary Figure 1):



→ Supplementary Figure 1. The influence of various environmental factors on the dynamics of shelf permafrost over the past 125 kyr according to the results of mathematical modeling
a) the influence of latitudinal climatic zonation and division into sectors : southwestern (SW) and northeastern (NE) shelf parts (the loam, 50 m isobaths, q=50 mW/m2)
b) the influence of heat flux: 50 mW/m2 and 75 mW/m2 (the loam, 50 m isobaths, SW)
c) the influence of lithology and properties of deposits : sand and loam (50 m isobath, q=50 mW/m2, SW)
d) the influence of sea depths (bottom isobaths): 5 and 50 m (the sand, q=50 mW/m2, SW)

→ As for the salinization, the modeling was provided for the uniform salt concentrations as we described in the response to the previous comment.

Comment

6. The manuscript is understandable, but terminology is used unconventionally

Response

→ Thank you, we moderated the language focusing on precision and word choice according to the Multi-Language Glossary of Permafrost (Everdingen, Robert van, ed. 1998 revised January 2002. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology).
Some of the modifications are listed below:
«cold» is changed to «cooled» that means the cryotic unfrozen deposits known as marine cryopeg We still have chosen «cooled», because in Russian literature the cryopeg always means an isolated cryopeg, and this can create a lot of confusion for non-native speakers. Therefore we decided to add that description «the cryotic unfrozen deposits are «cooled» deposits (marine cryopeg)».See Lines 290-291:

→ the cryotic unfrozen deposits are «cooled» deposits (marine cryopeg).

→ As for the rocks, we replaced the «rock» for the «deposits» (instead of rock and sediments) or «ground» (ground temperature instead of rock temperature) wherever it was necessary. Besides we have modified «unfrozen» deposits to «thawed» and made some more changes

Author comments about major changes in the article not mentioned in the response to the Reviewers

1. We cropped the Figures 2,3,6 and 9 (previous № 8): in the previous version of the article, the map covered part of the Laptev Sea, in this version there is just the Kara Sea.
2. Fig.2 :The site №12 was missed, we added it to the current version
3. The numbers of the figures was changed caused by the additional figure
4. We made several changes in the Reference list

The Current State and 125 ~~Kyr~~ kyr History of Permafrost in the Kara Sea Shelf: Modeling Constraints

Anatoliy Gavrilov [1,3], Vladimir Pavlov [4], Alexandr Fridenberg [4], Mikhail Boldyrev [5], Vanda Khilimonyuk [1,3], Elena Pizhankova [1,3], Sergey Buldovich [1,3], Natalia Kosevich [1,3], Ali Alyautdinov [2,3], Mariia Ogienko [1,3], Alexander Roslyakov [1,3], Maria Cherbunina [1,3], Evgeniy Ospennikov [1,3].

[1] Lomonosov Moscow State University, Geological faculty, Moscow, Russia

[2] Lomonosov Moscow State University, Geographic faculty, Moscow, Russia

[3] Foundation «National Intellectual Resource», Moscow, Russia

[4] Rosneft Oil Company, Moscow, Russia

[5] LLC «Arctic Research Center», Moscow, Russia

Abstract. ~~The evolution of permafrost in the Kara shelf is reconstructed for the past 125 Kyr. The work includes zoning of the shelf according to geological history, compiling sea-level and ground temperature scenarios within the distinguished zones, and forward modeling to evaluate the thickness of permafrost and the extent of frozen, cold and unfrozen rocks. The modeling results are correlated to the available field data and are presented as geocryological maps. The formation of frozen, cold, and unfrozen rocks of the region is inferred to depend on the spread of ice sheets, sea level, and duration of shelf freezing and thawing periods.~~ The evolution of permafrost in the Kara shelf is reconstructed for the past 125 kyr. The work includes zoning of the shelf according to geological history, compiling sea level and ground temperature scenarios within the distinguished zones, and modeling to evaluate the thickness of permafrost and the distribution of frozen, cooled and thawed deposits. Special attention is given to the scenarios of the evolution of ground temperature in key stages of history that determined the current state of the Kara shelf permafrost zone: characterization of the extensiveness and duration of the existence of the sea during the marine isotope stage MIS -3, the spread of glaciation and dammed basins in MIS-2. The present shelf is divided into areas of continuous, discontinuous to sporadic, and sporadic permafrost. Cooled deposits occur at west and northwest water zone and correspond to areas of MIS-2 glaciation. Permafrost occurs in the periglacial domain that is a zone of modern sea depth from 0 to 100 m, adjacent to the continent. The distribution of permafrost is mostly sporadic in the southwest of this zone, while it is mostly continuous in the northeast. The thickness of permafrost does not exceed 100 m in the southeast , and ranges from 100 to 300 m in the northeast. Thawed deposits are confined to the estuaries of large rivers and the deepwater part of the St. Anna trench. The modeling results are correlated to the available field data and are presented as geocryological maps. The formation of frozen, cooled and thawed deposits of the region is inferred to depend on the spread of ice sheets, sea level, and duration of shelf freezing and thawing periods.

1. Introduction

Permafrost studies and mapping in the Kara Sea shelf (Fig. 1) have a long history. The first evidence of its distribution in the Kara and other Eurasian Arctic shelves appeared in early permafrost maps of the USSR (Parkhomenko, 1937; Baranov, 1960). The ~~extent~~ distribution and approximate thickness of the Kara shelf permafrost were first calculated numerically in the early 1970s (Chekhovsky, ~~1973~~1972). ~~In the latest 1970s-earliest 1980s~~ By late 1970s - early 1980s, Soloviev and Neizvestnov mapped the whole Russian shelf, and ~~the~~ their work became part of the later 1:2 500 000 Geocryological Map of the USSR (Yershov, 1991). The dynamics of subsea permafrost in the Kara shelf during regression and transgression events was reconstructed by modeling (Danilov and Buldovich, 2001). Drilling was first used to study the features of permafrost and its recent formation in the near-shore zone of the Yamal Peninsula (Grigoriev, 1987).

Since 1986, drilling and seismoacoustic surveys have been run by the Arctic Marine Engineering Geological Survey (AMEGS) to constrain the extent of the Kara shelf permafrost and the depths to its top and base; the results were reported in a number of publications (Melnikov and Spesivtsev, 1995; Dlugach and Antonenko, 1996; Bondarev et al., 2001; Rokos et al., 2009; Kulikov and Rokos, 2017; Vasilyev et al., 2018). However, the available data are restricted to the southwestern part of the shelf while the more severe northeastern part remains poorly documented and undrilled.

Another recent map of permafrost distribution and thickness in the southwestern Kara shelf (Portnov et al., 2013) is based on seismoacoustic data and modeling with reference to the glacial eustatic curve but without regard to regional features related to the existence of MIS-3 marine terraces. ~~Judging by~~Followed by drilling and seismoacoustic results from the western Yamal Peninsula shelf (Melnikov and Spesivtsev, 1995; Dlugach and Antonenko, 1996; Baulin 2001; Baulin et al., 2005; etc.), geocryological modeling has become quite realistic lately, but its quality is still insufficient for economic activity, even within the best documented southwestern Kara shelf. As for the northeastern and central shelf parts, the knowledge is very preliminary.

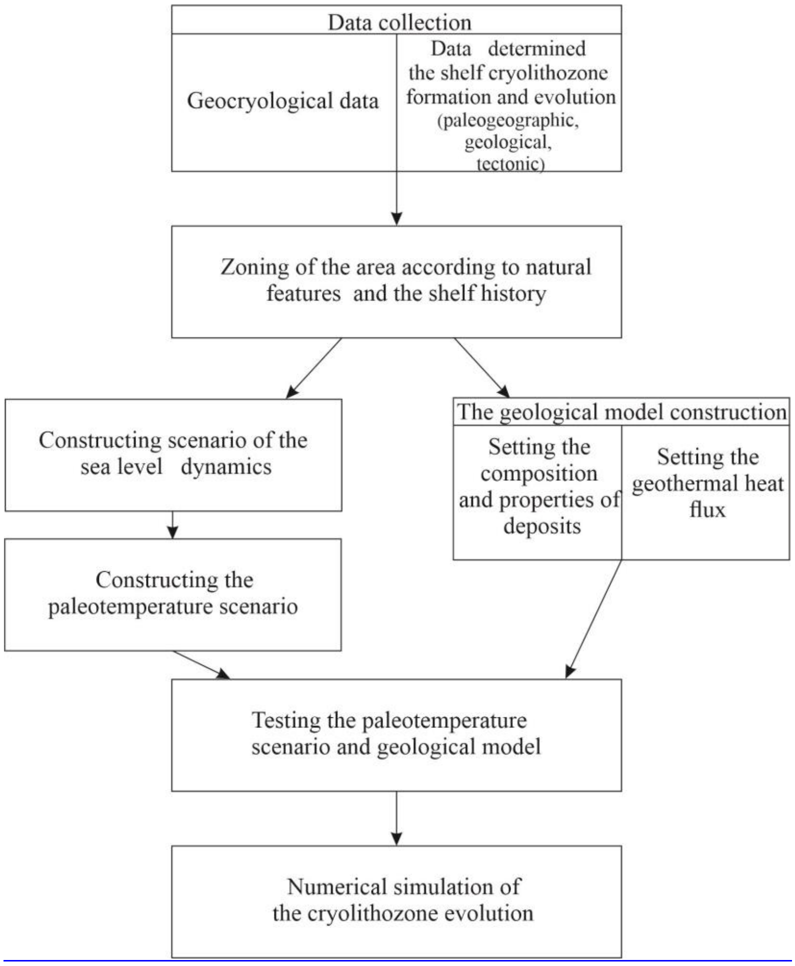
The available permafrost maps refer to the isobaths the datum sea depth of the maximum regression during the peak of cold stage 2 of the marine oxygen isotope stratigraphy (MIS-2). This reference is yet uncertain because the sea depths and level apparently varied in a range of at least tens of meters during the Late Pleistocene-Holocene glaciation history and related isostatic movements, as one may infer from the elevations of MIS-4 and MIS-3 marine terraces in Novaya Zemlya Islands which are raised high (+45, +55,+60 m, Bolsiyanov et al., 2006). and the adjacent continent (Yamal, Gydan) terraces on which were formed at low sea level (-100 and -70 m respectively, Siddall et al., 2003; 2006)

Given the logistic challenge and high costs of field studies, the knowledge of the Kara shelf permafrost can be extended by numerical modeling. Its application makes it possible to establish the connection of permafrost with components of the natural environment, including glaciations, glacio-isostatic movements and fluctuations in sea level. , and so on.

2. Research methodology and its implementation

Permafrost in the Arctic shelf is mostly of relict origin: it formed during regressions and cold climate events and then degraded during Late Pleistocene-Holocene transgressions.

The methods for subsea permafrost research have been developed since the 1970s and use the retrospective approach of reconstructing the permafrost evolution (Gavrilov, 2008; Romanovsky and Tumskoi, 2011). The history of methods applied to study the structure and extentt distribution of permafrost of the eastern Russian Arctic was reviewed previously (Gavrilov et al., 2001; Gavrilov, 2008; Nicolsky et al., 2012). We follow these methods in our researchwork and are trying to provide their progress extend their work . The work includes compiling a database of paleogeographic, geological, tectonic, and geocryological results used further for dividing the region according to geological history and for creating possible scenarios of sealevel and ground temperature variations conditions used further to divide the region according to geological history and for creating possible scenarios of sea level and ground temperature variations that serve as boundary conditions in heat transfer modeling. The general scheme of the methodology is presented in Figure 1. The obtained estimates serve as boundary conditions in heat transfer modeling.


Data collection
Geocryological data
Data determined the shelf cryolithozone formation and evolution (paleogeographic, geological, tectonic)
Zoning of the area according to natural features and the shelf history
Constructing scenario of the sea level dynamics
The geological model construction
Setting the composition and properties of deposits
Setting the geothermal heat flux
Constructing the paleotemperature scenario
Testing the paleotemperature scenario and geological model
Numerical simulation of the cryolithozone evolution

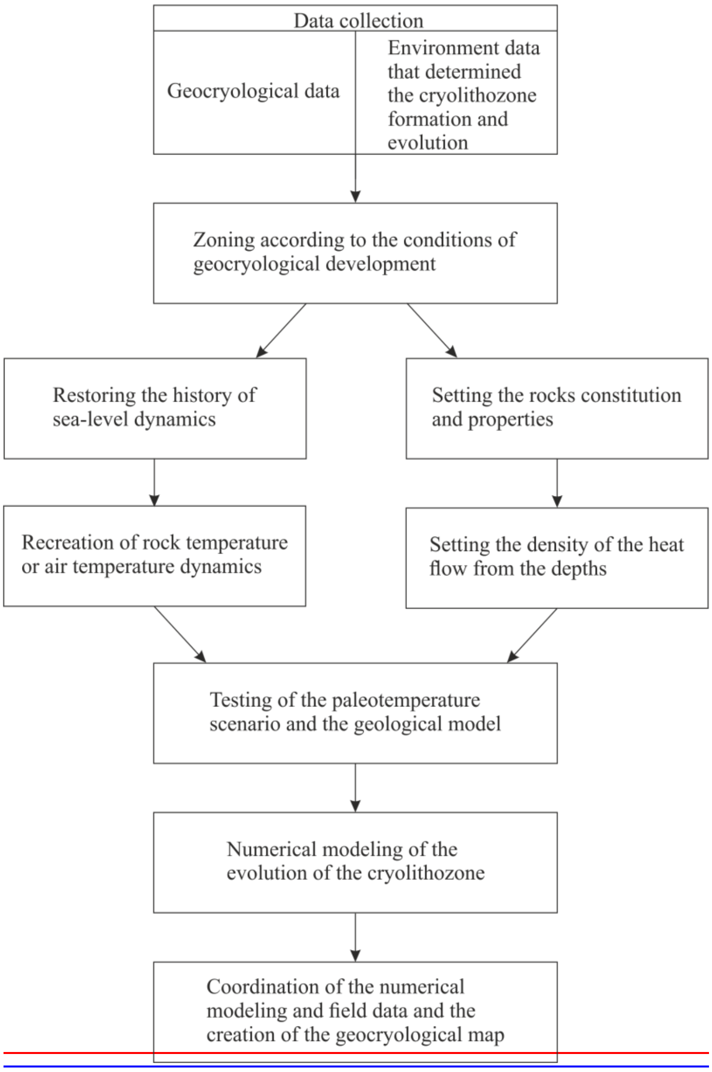


Fig. 1. The general scheme of the methodology.

The zoning is determined by the allocation of territorial units that are characterized by uniformity of formation conditions and, accordingly, by similar (on the given scale of the studies) parameters of permafrost: its distribution, thickness, depths of the top (Kudryavtsev, 1979).The history of subsea permafrost has been modeled using software designed at the Department of Geocryology of the Geological Faculty in the Moscow State University (Khrustalev et al., 1994; Pesotsky, 2016). The software can solve Stefan’s problems for non-steady state thermal conductivity assuming moving fronts of pore moisture phase transitions within the modeling domain and variable boundary conditions. ~~It provides a double-layer explicit solution obtained with the heat balance method, for an enthalpy problem formulation.~~ The explicit two-layer scheme is applied using the balance method and the enthalpy formulation of the problem. The code used is publicly available under https://github.com/kriolog/qfrost (last access: 15 February 2020) (kriolog, 2020).

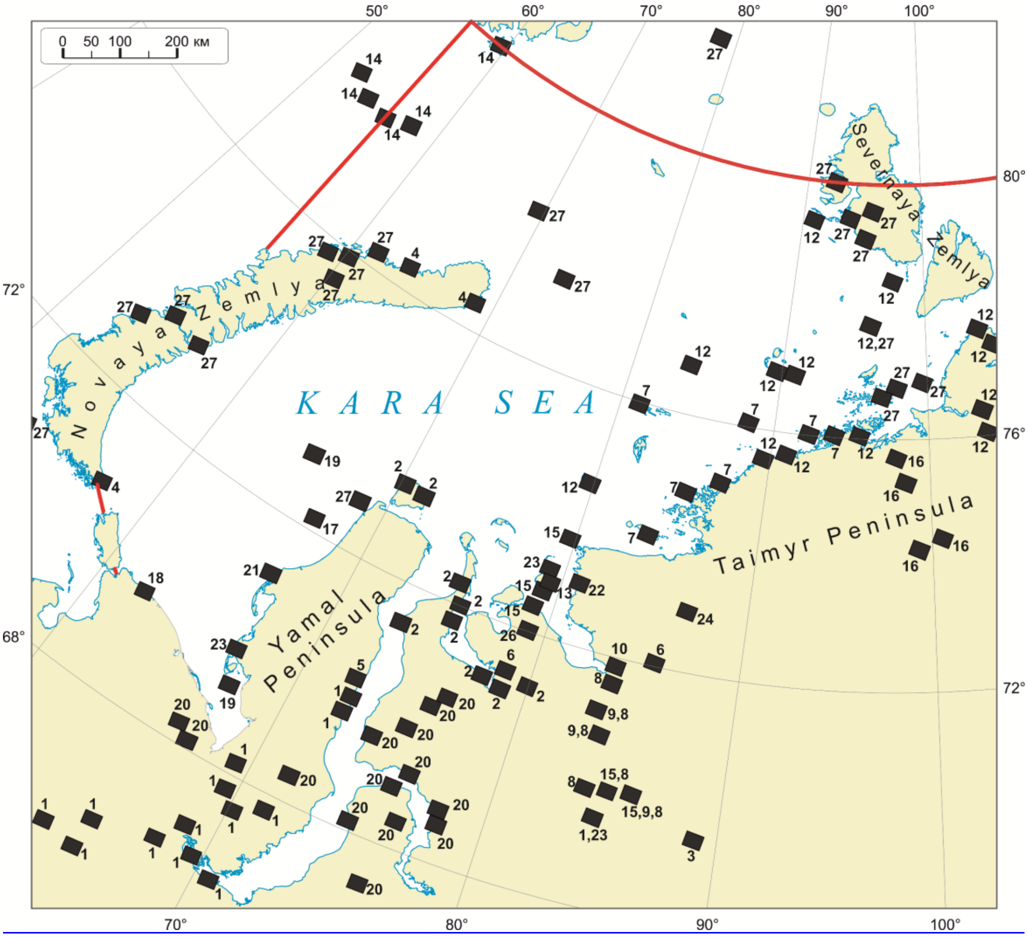
The permafrost dynamics was simulated for numerous paleoclimate scenarios that cover the full range of presumable conditions in the Arctic shelves.~~, including forty scenarios for the Kara shelf~~. The total number of paleo-scenarios for the Kara sea used in the course of mathematical modeling was 30 ~~)~~.The 1D modeling domain had a vertical size of 5 km to avoid the effect of its base on the permafrost dynamics. The temperatures at the surface according to the available paleoclimate reconstructions and a heat flux at the base of the modeling domain were used as the first- and second order boundary conditions, respectively. The heat flux was assumed to be 50 mW/m2 , which corresponds to the average for most of the shelf territory or 75 mW/m2, as in zones of relatively high heat flux in gas-bearing bottom sediments (Khutorskoy et al., 2013).

The modeling was performed for several uniform reference ~~rock~~rock and sediment ~~-~~types in order to reduce the number of possible solutions in the conditions of high lithological diversity in the area. Then the modeling results were extrapolated to complex sections that comprise alternating reference lithologies or different combinations of relatively thick layers. We consider two cases to extrapolate our results:In the first case, we consider the uniform alternation of homogeneous layers with a relatively low thickness (relative to the total thickness of the permafrost). The linear interpolation is simply performed in accordance with the percentage of the thickness of frozen ground obtained during modeling for two “pure” soils at a given moment.The second case relates to the two-layer structure of the section, when a sufficiently thick (as compared with the permafrost thickness) homogeneous layer is underlained by a second homogeneous layer of unlimited thickness. Then the following considerations are valid. If the thickness of the upper layer is zero, then the thickness of the permafrost is equal to the result of simulation for "pure" rocks/sediments of the second layer. If the thickness of the upper layer is equal to (or more) the thickness of the permafrost obtained for the first layer, then the problem becomes single-layer and the thickness of the permafrost is equal to that of the first layer. Therefore, when the thickness of the upper layer changes from zero to the thickness of the permafrost of the first layer, the thickness of the two-layer section changes from the thickness of the permafrost of the second layer to the permafrost thickness the first layer. Therefore, as a first approximation, this change is linear (which is not entirely true) and a simple linear interpolation formula can be obtained.All ~~rocks~~ deposits were assumed to be saline from top to bottom of the modeling domain. All reference rocks and sediments were considered saline with Ds = 0.8-1.1% according to ~~-~~the concentration of pore saline solution corresponding to that of Kara sea bottom waters concentration (32-34 ‰). Therefore the freezing temperature of the pore solution is close to -1.8 °C. Thermophysical properties, the content of unfrozen water and the heat of the phase transitions of water in the pores, the freezing point of the deposits were set taking into account the indicated salinization.

The paleotemperature scenarios and the geological-tectonic model were tested by comparing the present permafrost state estimated by forward modeling with the available field data from well documented areas, to achieve the best fit.

The evolution of the shelf permafrost was reconstructed by heat transfer modeling for the Late Pleistocene-Holocene, since 125 kyr ~~BP~~, the end of a long-term interglacial transgression. At that time, subsea permafrost had presumably fully degraded over the whole studied part of the Kara Sea,as the entire north of the West Siberian Plain had been covered by the sea from 140 to 120 Ka (Zastorozhnov et al., 2010; Shishkin et al., 2015) and the temperatures of unfrozen bottom sediments approached the steady state.

The modeling results were correlated with field data and both datasets were used for the final geocryological ~~division~~ zoning of the Kara shelf region. The Kara shelf has been quite well studied in terms of paleogeography. Figure 2 compiles the various studies available for the paleogeography of this region.



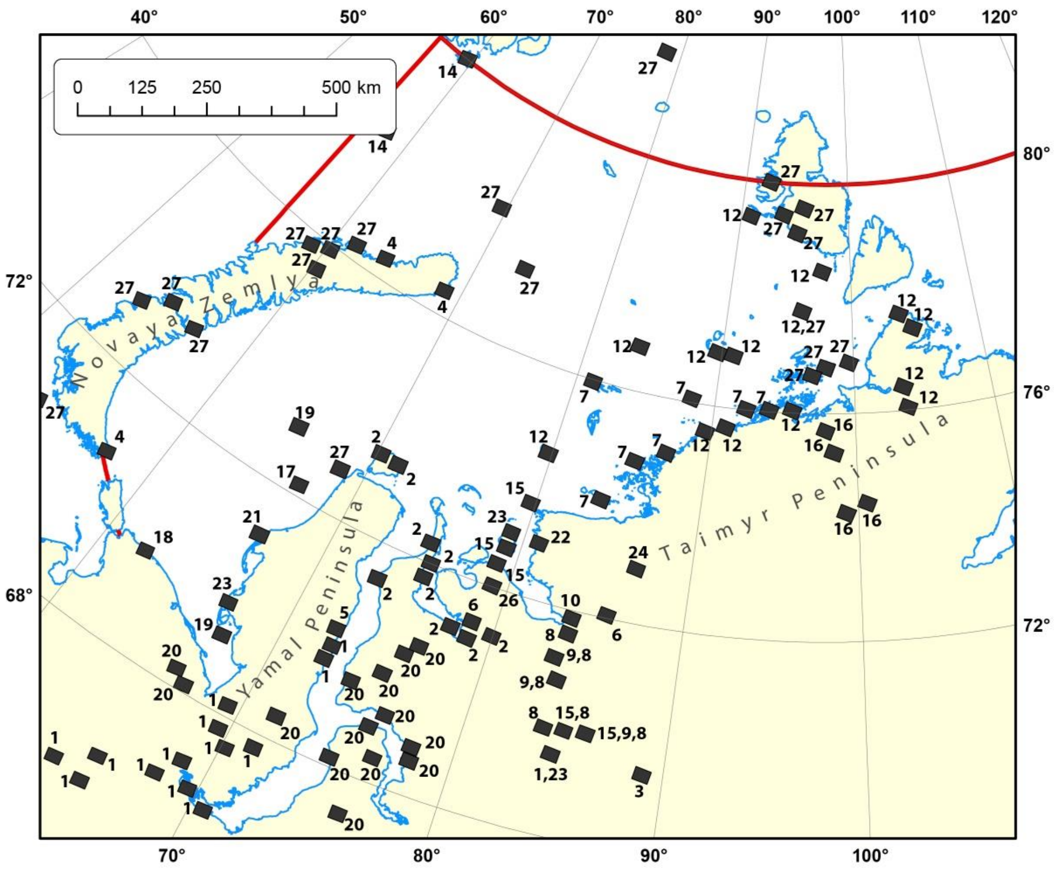


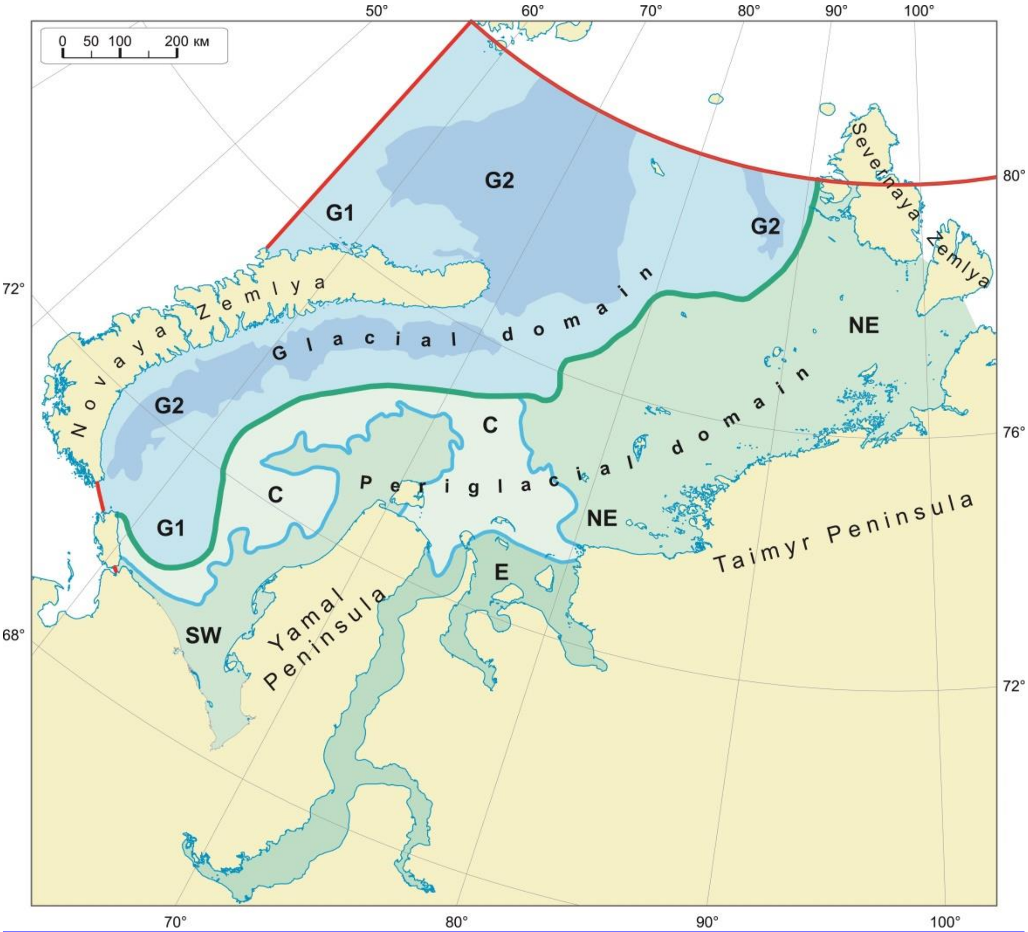
Fig. 2. Late Pleistocene geology of the Kara region: data coverage (the red line is the research region boundary). The numbers on the map correspond to the following publications:

Black squares are sites studied in different years by different research teams. Numbers 1 to 28 refer to publications: 1 = Astakhov and Nazarov (2010); 2 = Baranskaya ~~and Romanenko~~ et al. (2018); 3 = Bolshiyanov et al. (2007); 4 = Bolshiyanov et al. (2009); 5 = Vasil`chuk (1992); 6 = Geinz and Garutt (1964); 7 = Gusev et al. (2016a); 8 = Gusev et al. (2016b); 9 = Gusev et al. (2015a); 10 = Gusev et al. (2015b); 11 = Gusev et al. (2013~~a~~); 12 = Gusev et al. (2012a); 13 = Gusev and Molod`kov (2012); 14 = Gusev et al. (2012b); 15 = Gusev et al. (2011); 16 = Derevyagin et al. (1999); 17 = Kulikov and Rokos (2017); 18 = Leibman and Kizyakov (2007); 19 = Melnikov and Spesivtsev (1995); 20 = Nazarov (2011); 21 = Grigoriev (1987); 22 = Streletskaya et al. (2012); 23 = Streletskaya et al. (2015); 24 = Sulerzhitsky et al. (1995); 25 = Forman et al. (2002); 26 = Gilbert et al. (2007); 27 = Hughes et al. (2016); 28 = Svendsen et al. (2004).

3. Paleogeographic scenarios

~~The peculiarity of the paleogeography of the Kara region is the existence of a number of ideas about its development in the Late Pleistocene.~~ There is number of ideas about the paleogeography of the Kara region and its development in the Late Pleistocene. Evaluation of the validity of these ideas and the selection of the most reasonable of them was one of the objectives of the present studies. The most popular are two controversial hypotheses implying the presence (Svendsen et al., 2004; Hughes et al., 2016) and absence (Gusev et al., 2012a) of ice sheets in the area. The absence of ice sheets is, however, inconsistent with the existence of (I) Late Pleistocene marine terraces in the Yamal and Gydan Peninsulas and (II) large unfrozen zones in the offshore extensions of major West Siberian rivers (Ob', Yenisei, Taz, and Gyda). The terraces most likely result from a 100 m sea level fall during the Zyryanian cold event (MIS-4). Their origin was possible only by subsidence and uplift due to ice loading (glaciation and low stand) and isostatic rebound (deglaciation and high stand), respectively. The unfrozen zone on the extension of the Ob', Yenisei, Taz, and Gyda river valleys ~~s~~ is detectable by drilling and seismic surveys run by AMEGS (Kulikov and Rokos, 2017). In our opinion, it was formed in the place of a freshwater dammed lake (Fig. 3) that existed during the MIS-2 cold event when ice obstructed the continuing river flow. Currently, the largest part of the lake contoured according to the modern bathymetry looks like a shallow-water flat, which area occupies many hundreds of thousands of square kilometers. Within it, only the paleo-valley of the Ob is expressed, it is absent from the Yenisei. ~~The insignificance of the severity~~ The poor expression of the ancient valley network is especially clearly seen when comparing it with that in the eastern sector of the Arctic, where there were no glaciations. ~~Paleodoliny~~ Paleovalleys of Khatangi-Anabar, Olenek, Lena, Indigirka, and Kolyma rivers are clearly traced in bathymetry up to the outer shelf. The existence of a dammed lake produced by an ice dam during the MIS-2 cold event is recorded in the estuaries of the West Siberian rivers, which are much longer and farther advanced than those of any other river of the Eurasian Arctic basin. The duration of its existence is explained by the length of the Ob, Taz and Pur estuaries and their flatness. Both of these indicators are close to the record, if not the record for Eurasia: ~~800 km - the length of the Ob estuary and 1-2 cm / 1 km - the average longitudinal slope of its bottom~~ the length of the Ob estuary is 800 km and the average longitudinal slope of its bottom is 1-2 cm/1 km .

Thus, the paleogeographic scenarios used by authors for reference in the modeling of this study assume the existence of ice sheets (Svendsen et al., 2004; Hughes et al., 2016). For the modeling purposes, the shelf is divided by authors into domains, subdomains, areas and subareas according to its 125 k~~K~~yr history of glaciations and the respective effects on bottom sediments (Fig. 3; Table 1). The largest taxa — the domains— were distinguished by the presence / absence of glaciation and its type during MIS-2, subdomains — by the presence and impact of ice and water cover on bottom deposits in MIS-2. When specifying latitudinal zonality during periods of shelf drying, the authors followed differences in ground temperatures reflected on the Russian Geocryological Map (Yershov ed., 1991). The mean annual ground temperature is 4-6 °C lower in the NE of the region (north of Taimyr) adjacent to the Kara coast, than as for the SW (south-west of Yamal). During the periods of drainage in the periglacial part of the shelf in MIS-2, the following values for the ground temperature were taken: -19 ° C for the north-eastern area, and -15 °C for the south-western one.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G1
G2
G1
Novaya Zemlya
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Glacial domain
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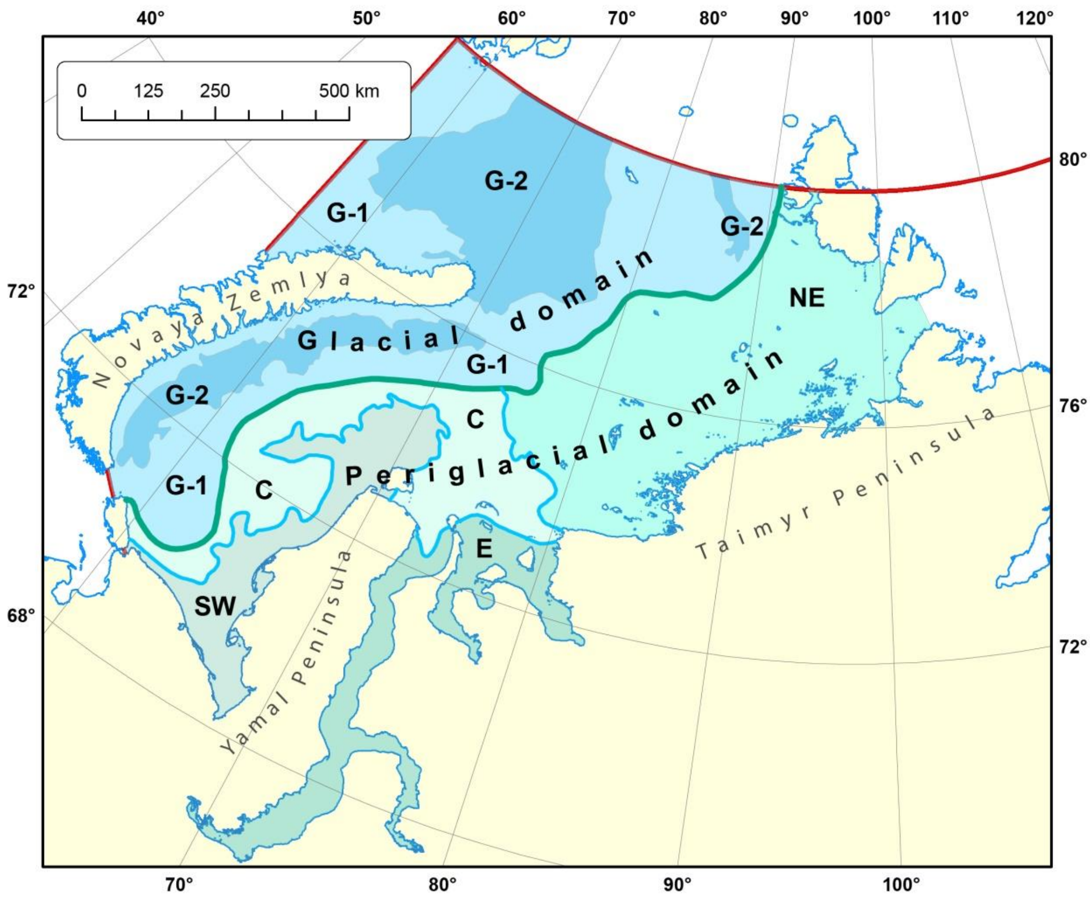
Yamal Peninsula
Taimyr Peninsula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G-2
G-1
G-1
Novaya Zemlya
Glacial domain
Periglacial domain
NE
C
C
E
SW
Yamal Peninsula
Taimyr Peninsula

Fig. 3. Division Zoning of the Kara shelf according to its geological history for 125 kyr. Abbreviations are explained in the text and in Table 1. The red line is the research region boundary

The glacial domain includes zones where the MIS-2 ice sheet reached the sea bottom (G-1) and those of shelf ice at greater sea depths (G-2); the periglacial domain consists of subaerial and subaqual (under the ice-dammed lake) subdomains, which are further divided into areas of the present sea bottom (central shelf, C) and estuaries (E) within the subaqual subdomain and southwestern (SW, 68-71 ° N) and northeastern (NE, 72-77 ° N) shelf parts within the subaerial subdomain (Fig. 3; Table 1). The SW and NE areas had different landscapes during MIS-2 and, correspondingly, differed in ground temperature and freezingfrost depth. The areas C and E were flooded by cold (<0°C) sea water and warmer (>0°C) river water, respectively, in the Holocene

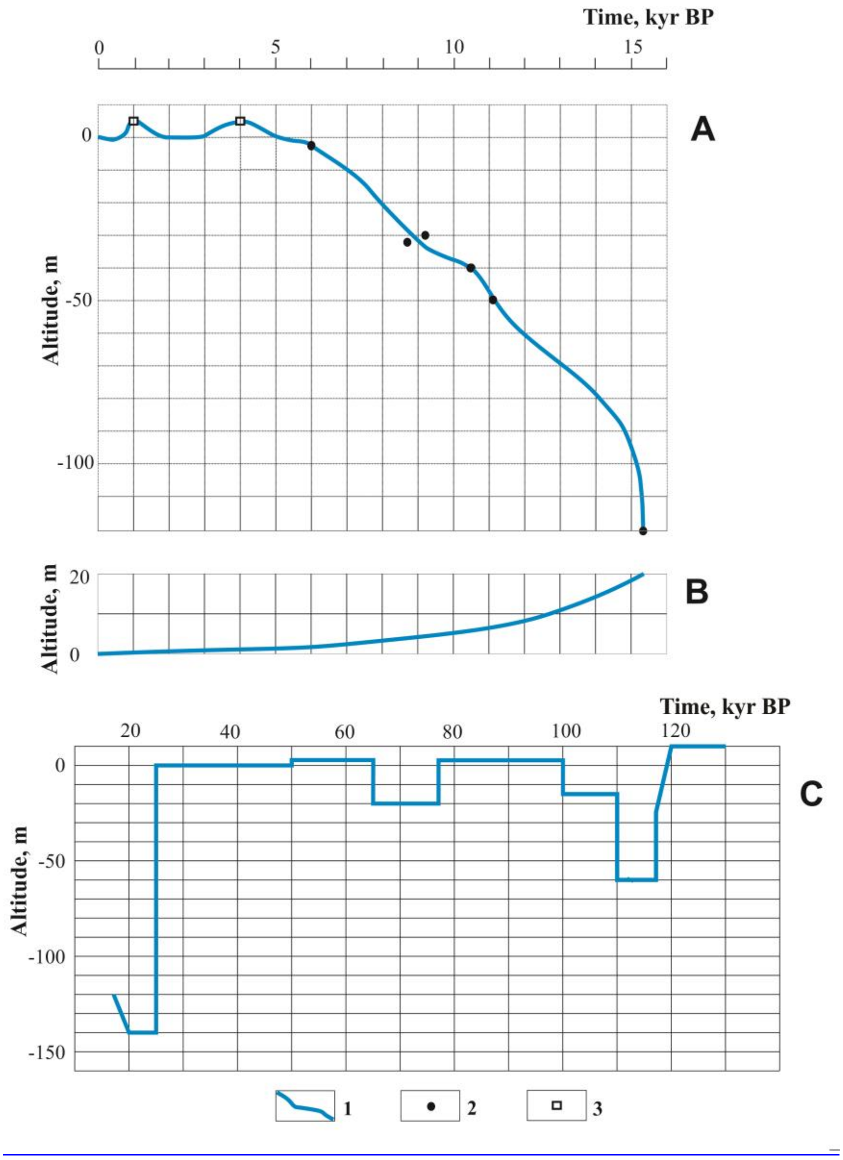
Table 1. Zoning of the Kara shelf (Late Pleistocene-Holocene history, past 125 kyr, events MIS-2 – MIS-1)

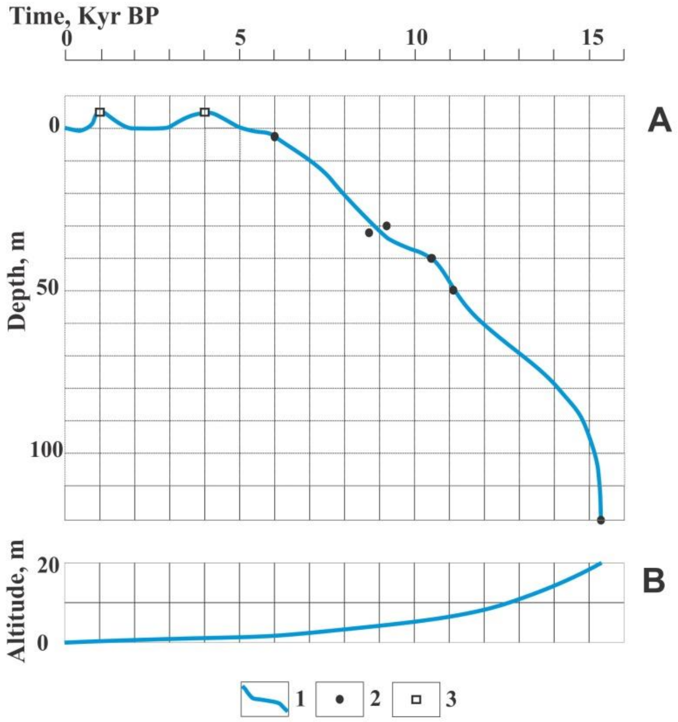
Domains	Subdomains	Areas (landscapes)		Subareas
Periglacial domain	Subaerial	Southwestern shelf	**SW**	Sea depths 0-120 m (contour intervals of average depths at 5, 20, 50, 80 and 100 m)
		Northeastern shelf	**NE**	
	Subaqual (under ice-dammed lake)	Central shelf	**C**	Sea depths 0-80 m
		Estuaries	**E**	
Glacial domain, ice reaching sea bottom	Subaqual (for 7-10 ~~Kyr~~kyr)	**G-1**		Sea depths 0-200 m
Glacial domain, shelf ice, MIS-2	Subglacial-subaqual	**G-2**		Sea depths 200-800 m

Finally, the periglacial areas were divided into subareas according to sea depths which controlled the duration of permafrost formation during regressions and degradation during transgressions: 0-10, 10-35, 35-65, 65- 90 and 90-140 m sea depth intervals with average values of 5, 20, 50, 80, and 120 m, respectively.

The subdomains of ice contacting~~reaching~~ (G-1) or not (G-2) the sea bottom were revealed from seismoacoustic data, with reference to the 1:2 500 000 Map of Quaternary deposits (2010): ~~transparent sequences~~ acoustically transparent deposits (~~sea depths~~ below isobaths 200 m) were considered as glacial-marine. Glaciers in these places were treated as shelf ice.~~were interpreted as subglacial-subaqual (shelf) ice~~. The zones G-1 and G-2 are only shown in Fig. 3 and Table 1 and were not divided further. The modeling we carried out for the G-1 area showed that, to date, the ~~MMPs~~ permafrost formed in the MIS-2 have not survived.

The present permafrost in the region formed under the effect of climate-driven eustatic sea_level change. The sea_level curve for the 125-15 ~~Kyr~~ kyr period was plotted using the eustatic curves of Lambeck and Chappell (2001) and Siddal et al. (2003, 2006). These curves were adapted to the regional specificity (Trofimov et al., 1975; Streletskaya et al., 2009; Shishkin, M.A. et al.~~ The State Geological Map~~, 2015), with regard to Late Pleistocene marine terraces in Yamal interpreted in the context of ice waxing and waning. Special focus by authors was in the recreating on the Late Pleistocene-Holocene transgression (Fig. 4a,b). The Figure 4c shows the scenario on fluctuations of the sea level during the modeling period of 125-15 kyr..





~~Fig. 4. Late Pleistocene-Holocene transgression and shelf flooding (was drawn up by Gavrilov A.V.).~~
~~**A:** *periglacial domain* 1 – sealevel curve, from 15 Kyr BP to Present; 2 – dated bottom sediment cores from Ob' Gulf, Yenisei Gulf, and adjacent offshore (Stein, R. et al., 2009) and Vilkitsky Strait (Levitan, M.A.et al., 2007) sites; 3 – onshore data (Romanenko, F.A., 2012);~~
~~**B:** *glacial domain*.~~
Fig. 4. Scenarios of sea level fluctuations:
for the 15-0 kyr .: A -periglacial domain, B- glacial domain; for the 125-0 kyr: C - periglacial domain.
1 - sea level curve; 2 - dated bottom sediment cores from Ob' Gulf, Yenisei Gulf, and adjacent offshore (Stein, et al., 2009) and Vilkitsky Strait (Levitan.et al., 2007) sites; 3 - onshore data (Romanenko, 2012);

In the method of constructing a scenario of sea level fluctuations for the Kara~~sky~~ shelf, the accounting for glacio-isostatic movements, resulting in the formation of marine terraces (Gutenberg, 1941; Flint, 1957; Bylinsky, 1996), plays a large role. The reason for their formation is the sea flooding of the ~~sea by the end of the glacier~~ ~~lowered~~ glacier bed, with a lag reacting ~~to a rise~~ ~~of~~ to the removal of the glacial load. Therefore, during the reconstructions, post-glacial sea level fluctuations are divided into two categories. In non-glacial areas, sea level rises in relation to the nearest coast, in glacial areas it drops (Lambeck, Chappell, 2001).

In accordance with the above, the scenario is presented in the form of curves for the periglacial (with respect to the continent, Fig. 4A) and glacial (with respect to Novaya Zemlya, Fig. 4B) domains. The periglacial curve was obtained with reference to published evidence on the Laptev Sea (Bauch et al., 2001), and the glacial one was calculated according to data on isostatic subsidence and uplift during glaciation and deglaciation, respectively (Ushakov and Krass, 1972; Nikonov, 1977; Bylinsky, 1996). Figure 4 shows that the calculations for the glacial domain were made taking into account (I) the thickness of the MIS-2 ice sheet (rising 500 m above the m sea bottom subsidence under the ice load; the fall reached 140 m, or 20 m below the global average regression limit (Lambeck and Chappell, 2001).

In postglacial times, the sea level rose during transgression in the periglacial domain but fell in the glacial one as a result of Novaya Zemlya uplift. Thus, the glacial domain was exposed to weaker cooling during the glacial period and became flooded and exposed to permafrost degradation right after ice melting. Unlike this, flooding in the periglacial domain was accompanied by permafrost degradation for as long as 1500 years.

The construction of scenarios of ground~~rock~~ temperature dynamics by the authors during the estimated time is the final part of the paleogeographic materials for the conduction of the numerical modeling. The ground temperatures were reconstructed in several 1D solutions, with reference to paleo-water chemistry (Fotiev, 1999; Volkov, 2006) and oxygen isotope composition of ice wedges (IW, $\delta^{18}O_{IW}$) (Vasil`chuk, 1992), as well as to reconstructed summer air temperatures. The $\delta^{18}O_{IW}$ data were corrected according to the results of Golubev et al. (2001).

We present the paleogeographic scenario as a series of paleotemperature curves adapted to the modeling purposes (Figs. 5, 7). In the following, the plots of mean annual ground temperatures of over the past 125 kyr depending on paleogeographic events (shelf drainage, flooding, glaciation, etc.), and in connection with the existence of latitudinal zoning and meridional sectorality are presented When specifying latitudinal zonality during periods of shelf drying, the authors followed differences in ground temperatures reflected on the Russian Geocryological Map (Yershov ed., 1991). The mean annual ground temperature is 4-6 °C lower in the NE of the region (north of Taimyr) adjacent to the Kara coast, than as for the SW (south-west of Yamal). When zoning the shelf (Table 1, Fig. 3), the southwest (68-71 ° N) and north-eastern (72-77 ° N) areas were distinguished. During the periods of drainage in the periglacial part of the shelf in MIS-2, the following values for the ground temperature were taken: -19 ° C for the north-eastern area, and -15 °C for the south-western one .Altogether thirty such curves have been obtained, each based on four lithological patterns and two heat flux values.

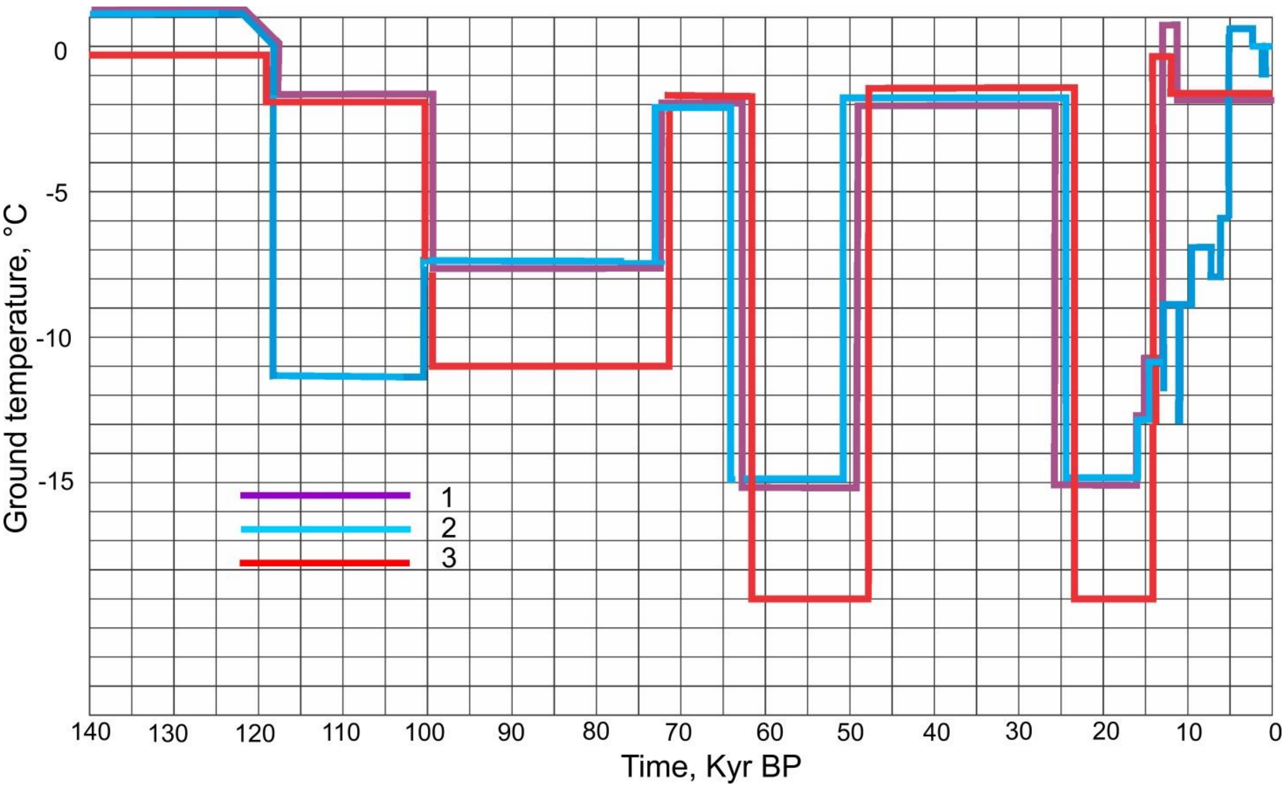
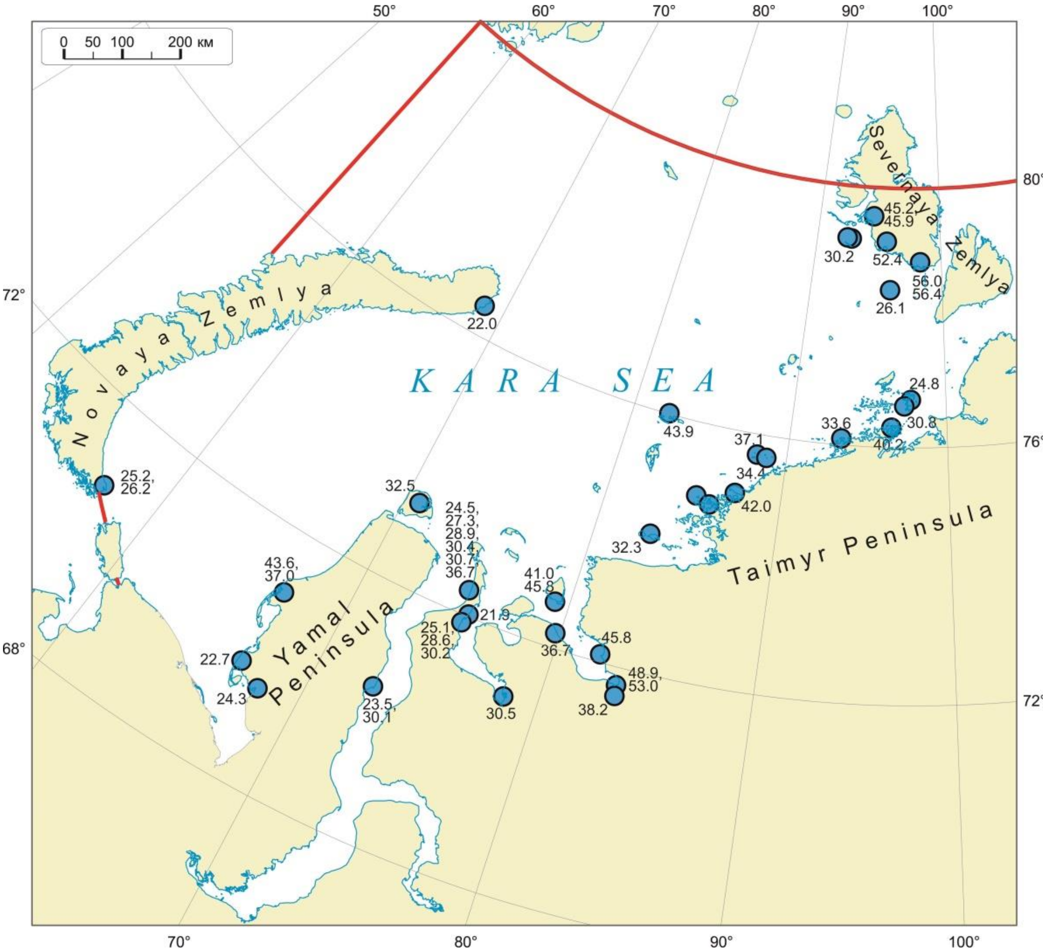


Fig. 5. Paleo-temperature for the periglacial subaerial part of the shelf:
1 = southwestern shelf part (SW), 80 m isobath; 2 = southwestern shelf part (SW), 5 m isobath;
3 = northeastern shelf part (NE), 120 m isobath.

During transgressions in the Holocene, each shelf part stayed for 400-2000 years in the coastal zone where bottom sediments were flooded with saline and warm near-bottom water. It is known that at sea depths from 2 to 7 m in the 1970s (Zhigarev, 1981), up to 10 m in the 2000s. (Dmitrenko) the mean annual temperature of bottom waters in the Laptev Sea stays positive and bottom sediments thaw from above. For the Kara Sea, there are no such data on isobath intervals, but it is known that temperatures are generally lower. Therefore, we assumed that the interval of isobaths with such water temperatures was limited to 5-6 m. Episodes with such water temperatures occurred on the shelf during the postglacial transgression even in its initial periods, since the July temperature is reconstructed for pre-Holocene warming (allered) exceeding 2 ° C the temperature of the 1980s. (Velichko et al., 2000). Therefore, we constructed scenarios for these episodes. To determine their duration, dated data on the absolute altitudes of the sea level during the transgression of the Laptev Sea were used (Bauch et al., 2001). The transgression rate was not the same. The shortest episodes (400 and 375 years) of positive temperatures are determined for periods 15-11 and 10-9 ka respectively. The longest intervals were 11–10, 9–5, and 5–0 Ka with 1000, 750 and >5000 years according to simple calculations. Special mathematical modeling for desalinated coastal zones was not performed due to the relatively small area of their distribution and the specific nature of salinity distribution over the water column. Desalination of waters was taken into account directly when constructing a geocryological map.

The scenarios record alternated cold and warm events accompanied, respectively, by regressions and transgressions (Figs. 5, 7), which created conditions for permafrost growth and degradation. At glaciation peaks, the present sea bottom in the periglacial shelf part was above the shores which subsided under the ice load. This led to the formation of marine terraces, i.e., the sea level fall during cold events (MIS-5b, MIS-4) was smaller than the global average.

The available data, though far incomplete, show that the sea level between 50 and 25 ~~Kyr~~ kyr BP(almost all MIS-3 through) was the same as at present (Fig. 6), in our opinion it is also due to post-Zyryanian uplift (isostatic rebound). On the other hand, the current state of permafrost has been controlled by the ground temperature in the periglacial shelf part and by the presence of an ice-dammed freshwater basin (Fig. 7). In the Holocene, the effect of >0 °C bottom water in the near-shore zone during warm climate events was critical for permafrost degradation from above (Figs. 5. 7). The MIS-2 ground temperature in the glacial shelf part was warmer (Fig. 7, the curve 2) due to thermal insulation by ice.



0 50 100 200 км
50° 60° 70° 80° 90° 100°
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Novaya Zemlya
Severnaya Zemlya
KARA SEA
Yamal Peninsula
Taimyr Peninsula
45.2, 45.9
30.2
52.4
56.0, 56.4
26.1
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30.8
33.6
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34.4
42.0
32.3
25.2, 26.2
32.5
24.5, 27.3, 28.9, 30.4, 30.7, 36.7
43.6, 37.0
41.0, 45.8
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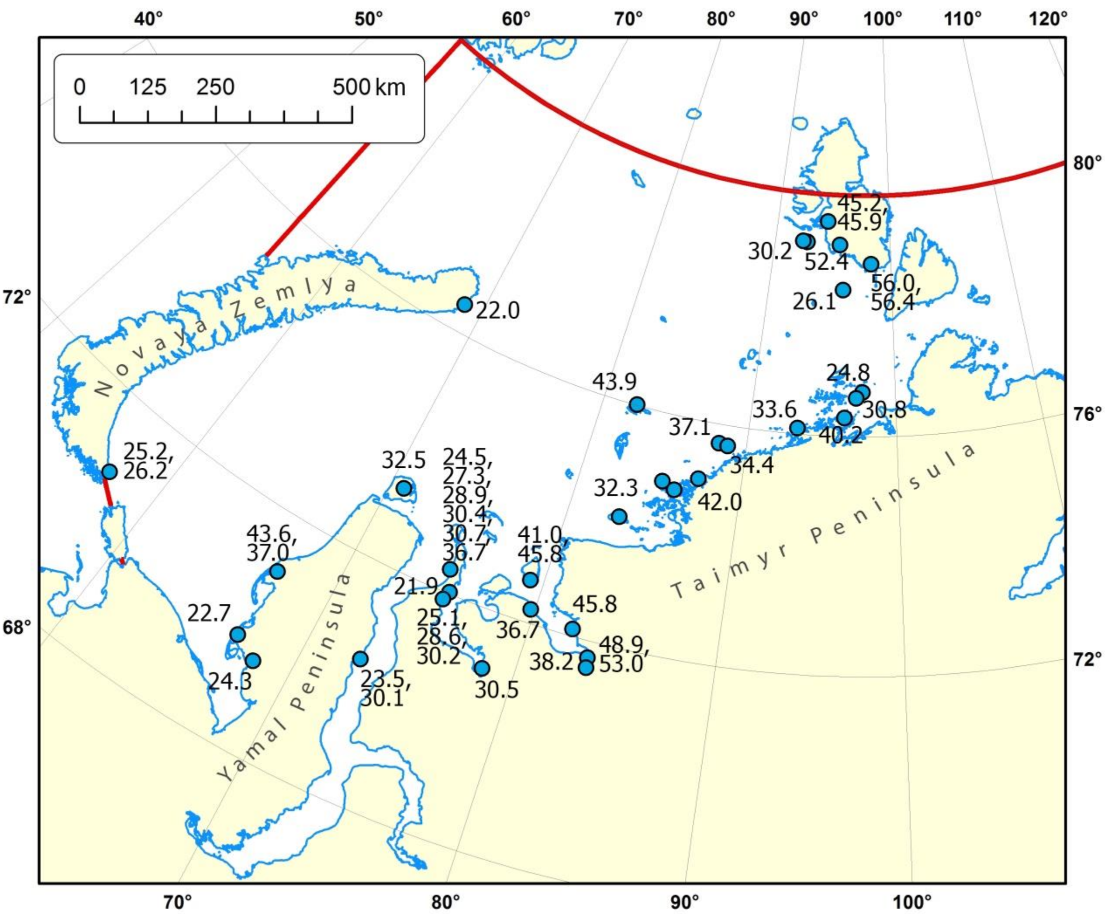

0 125 250 500 km
40° 50° 60° 70° 80° 90° 100° 110° 120°
80° 76° 72° 68°
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Novaya Zemlya
Yamal Peninsula
Taimyr Peninsula
45.2, 45.9
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56.0, 56.4
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24.5, 27.3, 28.9, 30.4, 30.7, 36.7
43.6, 37.0
41.0, 45.8
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25.1, 28.6, 30.2
36.7
45.8
48.9, 53.0
38.2
22.7
24.3
23.5, 30.1
30.5

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Fig. 6. Location of onshore and offshore sections (points) with marine sediments (^{14}C - figures, thousand years ago) of MIS-3 in the Kara Sea shelf, after Gusev et al. (2011; 2012a, b; 2013a, b; 2016 a, b); Baranskaya et al. (2016); Vasil`chuk et al. (1984); Molodkov et al. (1987); Bolshiyanov et al. (2009). The red line is the research region boundary

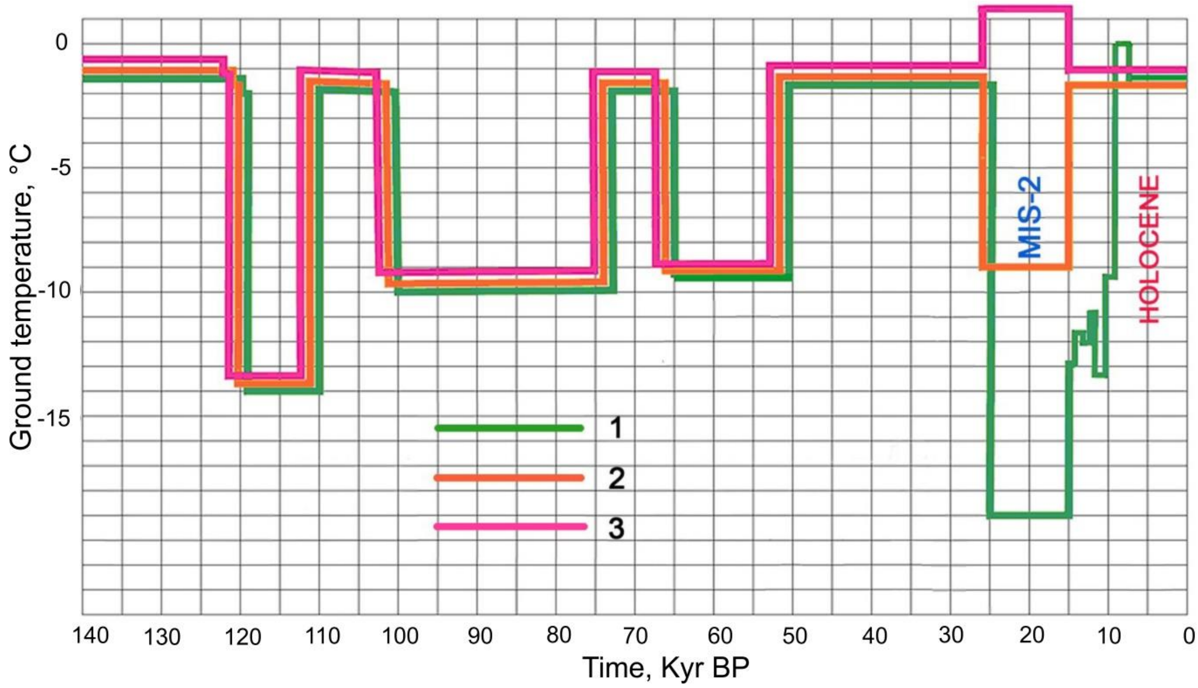


Fig. 7. Paleogeographic scenario for MIS-2 which controlled the present distribution of frozen and cooled ground. Adapted for modeling purposes. A fragment.
1 = periglacial subaerial northeastern shelf part (**NE**); 2 = ice that reached the bottom for 7-10 kyr, **G-1**); 3 = subaqual (beneath damlake) central shelf part, **C**;

The series of cartographic schemes illustrating , the change in surface conditions for the 125 kyr history of the Kara sea shelf is presented in the Fig. 8.

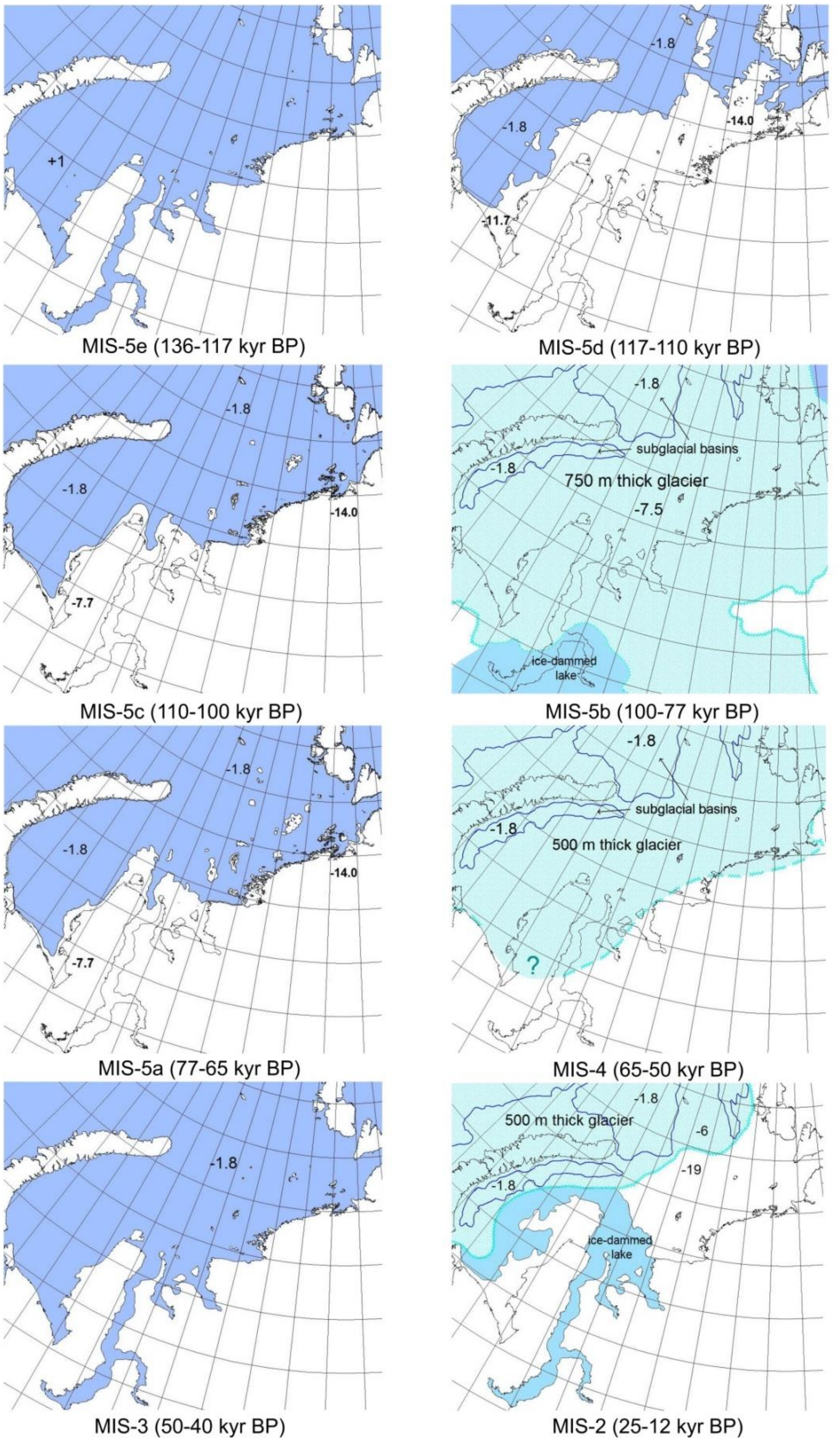


Fig. 8. The series of cartographic schemes illustrating , the change in surface conditions in the Kara Sea shelf for the following moments : MIS 5e (130-120 kyr, MIS 5d (117-110 kyr) MIS 5c (110-105 kyr); MIS 5b (100-75 kyr); 5a (75-65 kyr); MIS -4 (kyr); MIS -3 (50-25kyr); MIS -2 (25-15 kyr)

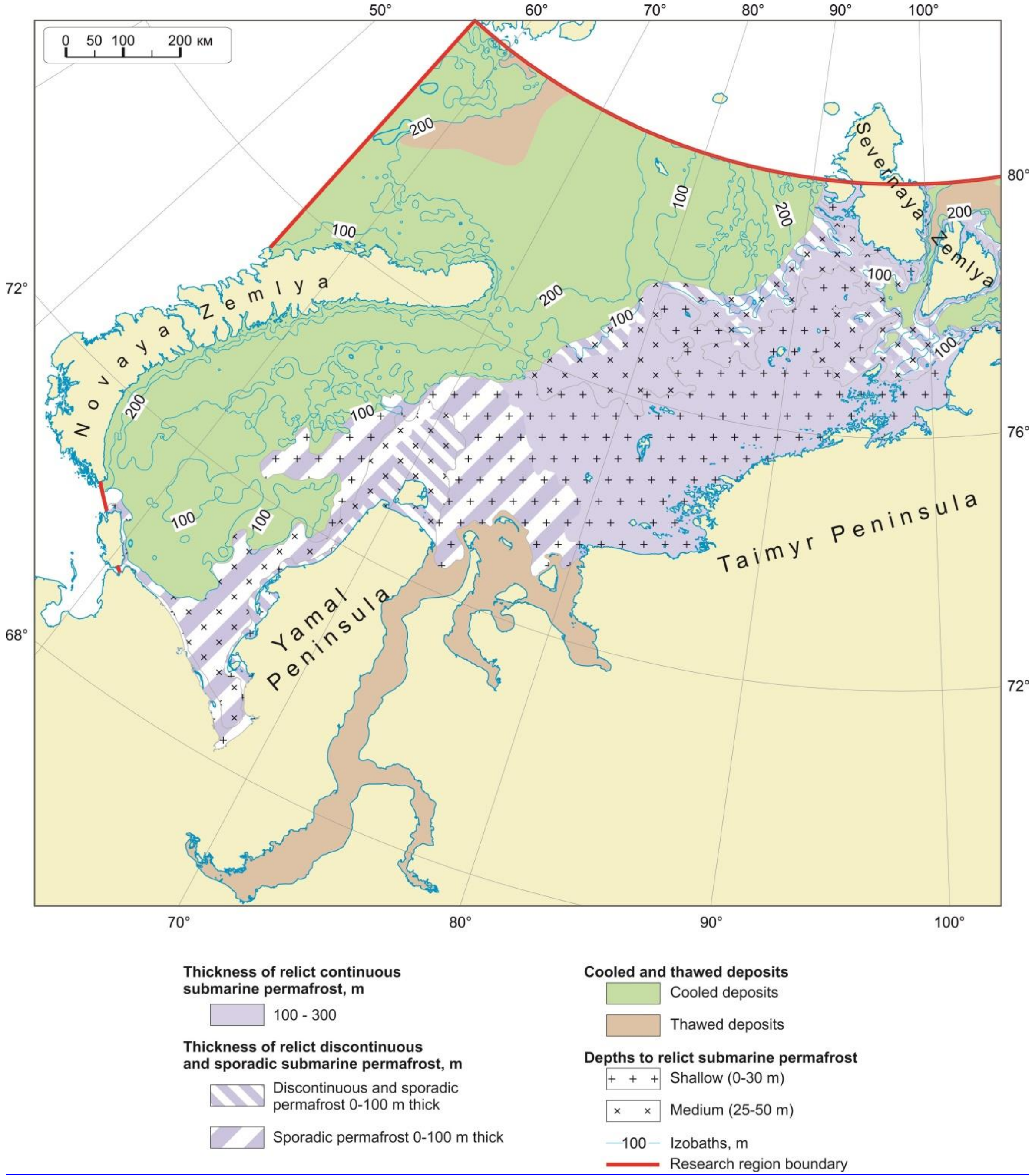
4. Simulation results and regional interpretation

The simulation results show that the distribution of deposits~~of strata of rocks~~ that differ in their state (thawed, cooled, frozen) are associated with the paleogeographic events of the Late Pleistocene-Holocene. In the distribution of permafrost, a particularly close relationship occurs with glaciation in the MIS-2, the ~~glacier~~ postglacial epoch and the Holocene optimum.

4.1. Distribution of frozen, coo~~l~~ed, and ~~unfrozen~~ thawed deposits~~rocks~~

Here we consider the permafrost table (frozen permafrost) corresponds to the -1.8° C isotherm, Therefore further in the text we mean frozen permafrost when talking about «permafrost» and the cryotic unfrozen deposits are «cooled» deposits (marine cryopeg). Permafrost occurs within the areas that were free from MIS-2 ice sheets (SW, NE, C and partly E in Fig. 3; Figs. 8, 9, 10). The present areas of cooled ground were covered with ice that reached the sea bottom during MIS-2 (Fig. 3). ~~Unfrozen rocks~~ Thawed deposits occupy the areas which were open to the ~~input~~ inflow of >0 °C Atlantic waters (Levitan et al., 2009) in early postgalacial time (16-15 k~~K~~yr BP): a part of the G-2 zone (Fig. 3) and a large part of estuaries (E in Fig. 3), except for their northern ends.

Frozen ground is restricted to the periglacial domain. The boundary between the periglacial and glacial domains and, correspondingly, between the frozen, cooled and ~~unfrozen~~ thawed ~~and frozen or cold ground~~ deposits is delineated by the limits of MIS-2 ice that reached the sea bottom and remained in contact with it for 7-10 thousands of years (Fig. 3), and by the 120 m isobath in the northeastern shelf part, within Severnaya Zemlya and the Cheluskin Peninsula (Figs. 3, 8).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Novaya Zemlya
Severnaya Zemlya
Yamal Peninsula
Taimyr Peninsula
100
200
Thickness of relict continuous submarine permafrost, m
100 - 300
Thickness of relict discontinuous and sporadic submarine permafrost, m
Discontinuous and sporadic permafrost 0-100 m thick
Sporadic permafrost 0-100 m thick
Cooled and thawed deposits
Cooled deposits
Thawed deposits
Depths to relict submarine permafrost
Shallow (0-30 m)
Medium (25-50 m)
100 Izobaths, m
Research region boundary

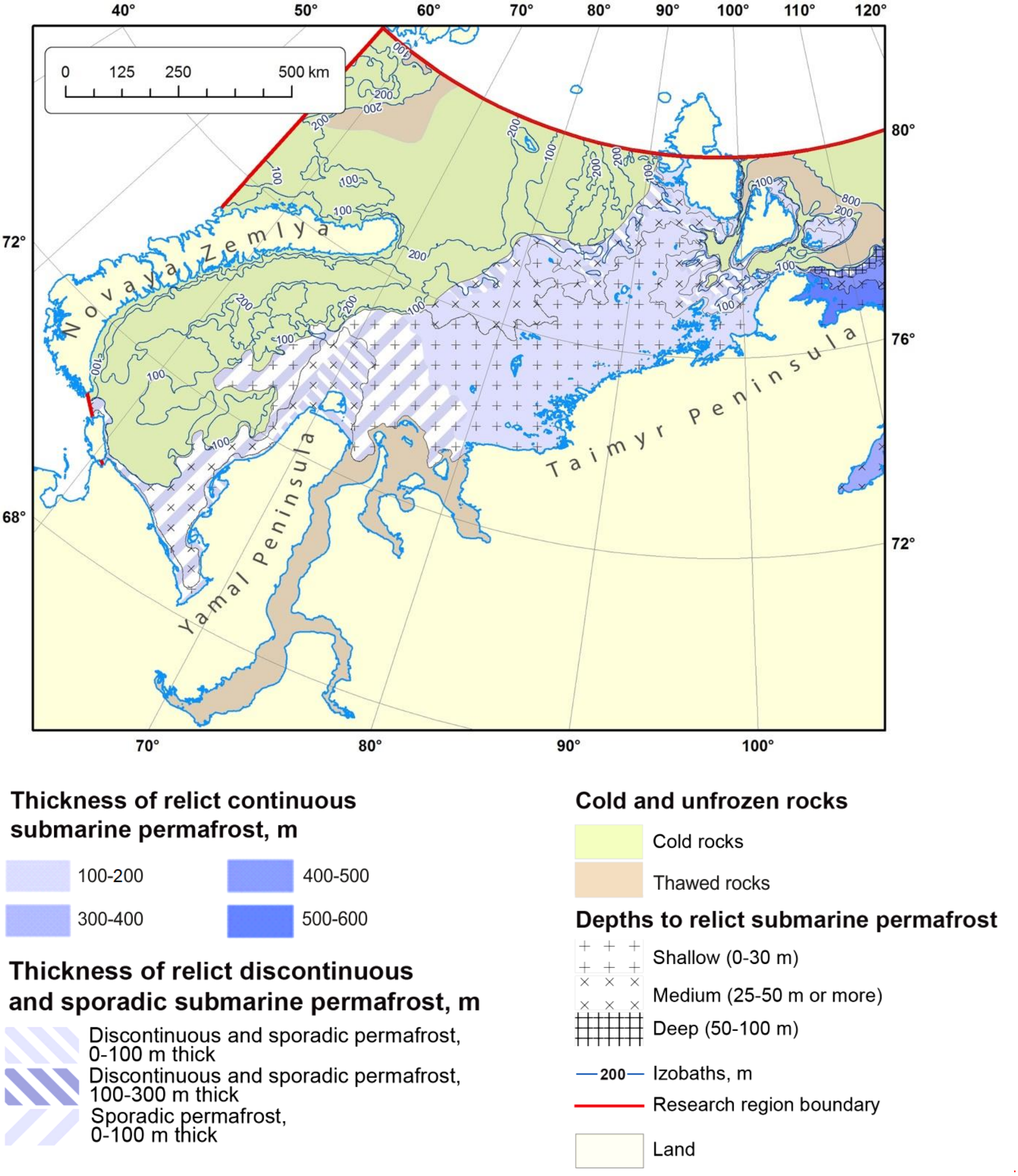

Fig. ~~8~~9. Fragment~~s~~ of the geocryologic map ~~of the permafrost zoning~~ of the Kara Sea and ~~the~~ its legend.

4.2. Distribution of permafrost, its thickness and depth to the ~~top~~ permafrost table

Permafrost becomes more extensive, shallower and thicker from southwest to northeast and from deep offshore toward near-shore shallow waters. This pattern has several controls (Supplementary Figure 1):

(1) latitudinal climatic zonation and division into sectors;

(2) sea depths that affect the duration of shelf drying and flooding (permafrost formation and degradation, respectively);

(3) ice-dammed freshwater basin in MIS-2;

(4) ~~deep~~ geothermal heat flux;

(5) lithology and properties of ~~rocks~~deposits;

(6) sea water and seasonal ice cover (salinity and freezing-thawing temperatures of rocksdeposits);

(7) thermal effect of river waters;

(8) Holocene climate optimum.

The southwestern part of the Kara Sea experienced an impact of warm water inputs (Pogodina, 2009) in the middle Holocene (the Holocene optimum), judging by the distribution of thermophile foraminifera communities with predominant Arctic-boreal species found currently in the Pechora Sea. Therefore, the >0 °C bottom water temperatures common to the present-day Pechora Sea may have existed 7-5 kKyr BP in the southwestern Kara shelf and provided thawing of permafrost from above.

The distribution of permafrost also depends on deep heat flux which may reach 50-60 mW/m^2 over the greatest part of the Kara shelf (Khutorskoi et al., 2013). Temperature logs from deep boreholes in the shelf and coastal gas reservoirs of Yamal give heat flux values of 73-76 mW/m^2. Other controls include lithology, water contents, physical properties, and salinity (freezing-thawing temperatures) of - deposits rocksand sediments.

Tables 2 and 3 lists the most common depths to the permafrost table determined in previous studies and according to our own calculations. They may vary significantly, even within marine geosystems of the same type: according to drilling results, they are 56 m in the near-shore zone at the Kharasavei Cape and as shallow as 5 m in the Sharapov Shar Gulf 50-60 km in the south. The prospective values are 30-40 m below the sea bottom under the Yamal shores and close to the water table under the retreating coast (Baulin et al., 2005). The permafrost thickness was estimated as the difference between the depths to permafrost top table and base

4.2.1. Southwestern periglacial shelf

The southwestern part of the Kara shelf (SW in Fig. 3) is occupied by discontinuous and sporadic permafrost (Fig. 8), as inferred from modeling with reference to field data (Dlugach and Antonenko, 1996; Melnikov and Spesivtsev, 1995; Baulin, 2001; Bondarev et al., 2001; Rokos et al., 2001, 2007, 2009; Baulin et al., 2005; Neizvestnov et al., 2005; Kulikov and Rokos, 2017). According to the modeling results, permafrost can exist in sand at a heat flux of 50 mW/m^2 but is absent in all other lithologies at 75 mW/m^2 (Table 2).

Table 2. Modeling results for depths to permafrost top and base and permafrost thickness, uniform lithology, SW area

Sea depth, m	Lithology	Geothermal h~~H~~eat flux~~ from below~~, mW/m^2					
		50			75		
		Depth to base, m	Depth to top, m	Thickness, m	Depth to base, m	Depth to top, m	Thickness*, m
5	sand	190	50	140	175	55	120
	clay silt	110	45	65	0		
	bedrock	150	45	105	0		
20	sand	180	50	130	140	60	80
	clay silt	75	40	35	0		
50	sand	175	50	125	130	60	70
	clay silt	0			0		
	bedrock	120	60	60	0		
80	sand	165	65	100	82	55	27
120	sand	0			0		
	clay silt	0			0		
	bedrock	0			0		

*the quoted permafrost thicknesses in all tables here and below are current residual values.

Table 3. Modeling results for depths to permafrost top and base and permafrost thickness, alternated sand and clay silt (clay), SW area

Sea depth, m	Alternating layers~~Layered sequence~~, 0.5 and 0.3 volumetric fraction of sand (n_n)	Geothermal ~~Heat~~ heat flux ~~from below~~, mW/m^2					
		50			75		
		Depth to base, m	Depth to top, m	Thickness, m	Depth to base, m	Depth to top, m	Thickness, m
5	n_n=0.5	133	40	93	0		
	n_n=0.3	117	40	77	0		
50	n_n=0.5	132	50	82	0		
	n_n=0.3	124	55	69	0		
120	n_n=0.5	0			0		
	n_n=0.3	0			0		

Table 4. Modeling results for depths to permafrost top and base and permafrost thickness, 50 m of alternated sand and clay silt (clay) lying over bedrock, SW area

Sea depth, m	Alternating layers~~Layered sequence~~, 0.5 and 0.3 volumetric fraction of sand (n_n)	Geothermal ~~Heat~~ heat flux ~~from below~~, mW/m^2					
		50			75		
		Depth to base, m	Depth to top, m	Thickness, m	Depth to base, m	Depth to top, m	Thickness, m
5	n_n=0.5	129	40	89	0		
	n_n=0.3	115	40	75	0		
50	n_n=0.5	130	55	75	0		
	n_n=0.3	127	57	70	0		
120	n_n=0.5	0			0		
	n_n=0.3	0			0		

The quantitative modeling results show (Table 2) that the permafrost state depends on lithology if it is uniform. However, the real shelf sections (e.g., in boreholes of the Leningradskaya and Rusanovskaya fields) consist of different alternating lithologies. Therefore, data listed in Table 2 are applicable uniquely as a check for the role of lithology and ~~rock~~ properties in the formation, distribution and thickness of permafrost, and in depths to its top and base, which were estimated for layered sections.

Along the west coast of the Yamal Peninsula (area of the Kharasavei-Sea field), where the modern frozen ~~rocks~~ deposits ~~make up~~form the upper part of the section, and the~~ir~~ relict ~~rocks~~ ones are underlain, permafrost in the Kharasavei shelf gas and condensate deposit forms three elongate zones: ~0.5 km wide zone of continuous permafrost near the shore (0-2 m sea depth); discontinuous permafrost, 1-3 km wide, sea depths to 5-7 m (Baulin, 2001; Baulin et al., 2005); and sporadic permafrost, which may spread to sea depths of 80 m (our estimate), or 100 m (Kulikov and Rokos, 2017) to 105 m (Vasiliev et al., 2018).

The depths to the permafrost table are variable, especially near the shore, as a result of coastal advance and retreat. Permafrost currently exists in zones of coast aggradation, while permafrost beneath retreating coasts is the shallowest at the shoreline and becomes deeper seaward. Specifically, permafrost was stripped at a depth of 0.5 m below the sea bottom at the geocryological site Marre-Sale, in borehole 16-14 drilled for temperature monitoring 0.5 km far from a retreating coast (Dubrovin et al., 2015) but is deeper (3.5 m) in another monitoring borehole 15-14 located 0.9 km far from the shore, where a 0°C mean annual ground temperature was recorded at 3 m subbottom depth. On the other hand, the permafrost table beneath stable coast may be as deep as 30-50 m (Baulin et al., 2005). Similar depth variations occurred also during the Holocene transgression, i.e., this is a typical feature of local permafrost. However, generally the depths to permafrost increase offshore and depend on its composition and ice content, as well as on the time when it submerged.

Within the sea depths from 2 to 5-7 m, the depth to permafrost varies from 5 to 30-40 m. Similar values were inferred by modeling for the most realistic sections of interbedded sand and clay (40 m at a heat flux of 50 mW/m^2). The calculated most probable permafrost thickness for these lithologies is 75-90 m at 50 mW/m^2. It agrees with 60-80 m reported by Badu (2014) as well as with the estimates 90 m and 70 m by Vasiliev et al. (2018) for the sea depths about 10 m and 35 m, respectively. Permafrost in terrace I of Yamal, which formed from MIS-2 through the Holocene and was not exposed to prolonged subsea degradation, is as thick as 185 m (Trofimov et al., 1975; Yershov, 1989).

According to calculations, on isobaths exceeding 7-10 m, the subsea permafrost table is as deep as 50-80 m (Table 3), which agrees with estimates based on field data (Melnikov and Spesivtsev, 1995). It is most likely beyond the reach of engineering geological drilling (Baulin et al., 2005).

Permafrost is discontinuous to sporadic closer to the shore and sporadic at greater sea depths, with the boundary at the 10 m isobath. The depths to permafrost table are 0-30 in two first zones and 20-50 m in the offshore zone. The permafrost thickness is from 0 to 100 m (Fig. ~~8~~ 9).

Similar distribution and parameters of permafrost are common to other parts of the southwestern periglacial shelf, but they vary slightly as a function of zonal features. Farther in the north, the boundary between discontinuous and sporadic permafrost follows the 20 m isobath. The depths to the permafrost table are 30 to 70 m at sea depths from 0 to 20 m according to field data, and 40 to 70 m according to calculations; the calculated permafrost thickness is mainly <100 m (the estimates in Table 2 are for reference sections and those in Tables 3-4 are real data). In real sections within 20-80 m sea depths, permafrost lies at a depth of 50-55 m and is 70-90 m thick (Tables 3-4).

The permafrost changes form discontinuous to sporadic below the 5 m sea depth south of the Kharasavei deposit and is only sporadic still farther to the south (end of the Baidaratskaya Guba Bay).

4.2.2. Northeastern periglacial shelf

There is no drilling data for this shelf part (NE in Fig. 3; Fig. 8). According to logs from a test well in Sverdrup Island, heat flux, varies from 25 to 60 mW/m^2 as a function of lithology and thermal properties of rocks and sediments at different core depths (Khutorskoi et al., 2013). Modeling results for a heat flux of 50 mW/m^2 predict that the permafrost is continuous at sea depths within 0-80 m and discontinuous to sporadic from 80 to 120 m (Tables 5-7). Cooled rocks may exist at these sea depths mainly in clay sediments, at different heat flux values, though permafrost is predominant (Tables 5-7).

Table 5. Modeling results for depths to permafrost top and base and permafrost thickness, uniform lithology, NE area

Sea depth, m	Lithology	Geothermal ~~H~~heat flux~~ from below~~, mW/m^2					
		50			75		
		Depth to base, m	Depth to top, m	Thickness, m	Depth to base, m	Depth to top, m	Thickness, m
5	sand	270	25	245	175	25	150
	clay silt	130	20	110	0		
	bedrock	190	28	162	0		
20	sand	260	30	230	160	32	128
50	sand	250	35	215	150	35	115
	clay silt	120	35	85	0		
	bedrock	170	40	130	0		
80	sand	230	40	190	105	40	62
120	sand	212	50	162	85	50	35
	clay silt	0			0		
	bedrock	90	50	40	0		

Table 6. Modeling results for depths to permafrost top and base and permafrost thickness, alternated sand and clay silt (clay), NE area

Sea depth, m	Alternating layers~~Layered sequence~~, 0.5 and 0.3 volumetric fraction of sand (n_n)	Geothermal ~~H~~heat flux ~~from below~~, mW/m^2					
		50			75		
		Depth to base, m	Depth to top, m	Thickness, m	Depth to base, m	Depth to top, m	Thickness, m
5	n_n=0.5	221	20	201	107	20	87
	n_n=0.3	190	20	170	75	20	55
50	n_n=0.5	206	35	171	91	38	53
	n_n=0.3	171	35	136	61	37	24
120	n_n=0.5	121	45	76	0		
	n_n=0.3	85	40	45	0		

Table 7. Modeling results for depths to permafrost top and base and permafrost thickness, 50 m of alternated sand and clay silt (clay) lying over bedrock, NE area

Sea depth, m	Alternating layers~~Layered sequence~~, 0.5 and 0.3 volumetric fraction of sand (n_n)	Geothermal h~~H~~eat flux~~ from below~~, mW/m^2					
		50			75		
		Depth to base, m	Depth to top, m	Thickness, m	Depth to base, m	Depth to top, m	Thickness, m
5	n_n=0.5	214	21	193	0		
	n_n=0.3	208	21	187	0		
50	n_n=0.5	195	37	158	0		
	n_n=0.3	188	36	152	0		
120	n_n=0.5	103	43	60	0		
	n_n=0.3	95	40	55	0		

The depth to the top of continuous permafrost is most often from 20-25 m near the shore to 35-40 m at sea depths 50-80 m (Table 6). The permafrost thickness varies from 150 to 200 m in sand-clay sediments depending on lithology and sea depth. Correspondingly, the map of Fig. 8 shows typical depths to permafrost in a range of 0 to 30 m and permafrost thicknesses from 100 to 200 m. Discontinuous permafrost lies at a depth of 40-45 m and is 0 to 100 m thick.

4.2.3. Central area

The central area covers the offshore extension of the Ob', Yenisey, and Gyda rivers (C in Fig. 3; Fig. ~~8~~ 9) in the middle between the southwestern shelf part from the northeastern one. The area was interpreted (Kulikov and Rokos, 2017) as an unfrozen zone (a talik) corresponding to paleo-estuaries and paleo-deltas of the West Siberian rivers. In our view, however, it was rather a lake-like freshwater basin that formed when ice dammed the continuing flow of the large Siberian rivers (Ob, Yenisei, Taz, etc.) during the MIS-2 glacial event. The ice dam caused flooding of the respective shelf part in different periods; the surface area and elevations of the lake table (C in Fig. 3) changed accordingly with the ice sheet contours. Therefore, our map delineates the lake by isobaths from 0 to 80 m.

The Central area is shown in the map as occupied by sporadic permafrost: sea bottom rises within its limits may be frozen (like the cases of Yamal and Ob' Gulf). In fact, permafrost patches beneath the Sartan damlake are scarce as the ~~rocks~~ deposits had stored large heat resources while staying under the ice sheet for thousands of years. The sediments currently occurring within the lake limits were much warmer than the surrounding ~~rocks~~ground during MIS-2: +4 °C against -19 to -23 °C, respectively. The patches of permafrost lie at depths from 0 to 30 m and the permafrost thickness is a few tens of meters.

4.2.4. Estuary (bays)

Permafrost in the quite well documented Ob' estuary (E in Fig. 3) is restricted to a narrow strip along the shore; it is relict permafrost beneath the coast exposed to marine erosion. The total thickness of present and relict permafrost exceeds 20 m within the 1 m isobath, is no more than 10 m at sea depths between 0 and 2-3 m, and pinches out seaward in deeper water; the depth to subsea permafrost within 3 m of water depths is 5 to 15 m or more (Baulin, 2001). Coastal permafrost is traceable as far as the Cape Kamenny at 68°N (Kokin and Tsvetinsky, 2013). The patches of frozen ground are limited to a 100 m wide strip along the shore (less often 300 m).

Seismic reflection profiling reveals numerous gas reservoir zones (Rokos and Tarasov, 2007) and presumably a frozen ~~rock mass~~ deposits at a sea depth of 15 m at 71° N (Slichenkov et al., 2009). The estuaries (south of 71.5° N) are mapped as mainly ~~unfrozen~~ thawed zones with near-shore permafrost at ≤3 m sea depths.

We agree with the previous inference (Melnikov et al., 1998; Badu, 2014~~, etc.~~) that permafrost within gas fields (Rusanovskaya and ~~and~~ other gas-bearing geological structures) does not refer~~s~~ to relict frozen deposits~~rocks~~. Their genesis and cryogenic age is the subject of debate.

5. Conclusions

The present state and 125 ~~Kyr~~ kyr history of permafrost in the Kara shelf has been modeled with reference to the existing knowledge. Since 125 kyr ~~Kyr~~ ago, the parameters of permafrost have been controlled by glacial and isostatic rebound events: frozen ground is present currently in places which were free from ice but is absent from those covered by ice during the MIS-2 glacial.

Degradation of glaciation led to ice rebound and related transgression. As a result, permafrost thawed, partially after the MIS-5b cold event and completely after the MIS-4 event (during the Karginian interstadial, MIS-3).

As a result, the present shelf comprises frozen, cooled, and ~~unfrozen~~ thawed deposits~~rocks~~. Permafrost occurs in the periglacial domain, cooled rocks correspond to areas of MIS-2 glaciation, while thawed~~unfrozen~~ deposits~~rocks~~ occupy the areas that were exposed to the effect of >0 °C Atlantic waters (e.g., the western St. Anna trench) in the early postglacial time (16-15 kyr ~~Kyr~~ BP); thawed deposits~~unfrozen rocks~~ are also found over the overwhelming part of river estuaries in northern West Siberia, except for the river mouths.

The periglacial shelf part is divided into zones of continuous, discontinuous to sporadic, and sporadic permafrost. The geocryological conditions become harsher (continuous, deep, and thick permafrost) from southwest to northeast and from large sea depths to near-shore shallow water.

The distribution and parameters of permafrost have had multiple controls:

(1) latitudinal climatic zonation and division into sectors;

(2) sea depths that affected the duration of regressions and transgressions and the related freezing and thawing of permafrost, respectively;

(3) an ice-dammed freshwater lake that existed during the MIS-2 event;

(4) ~~deep~~ geothermal heat flux;

(5) lithology and properties of ~~rocks~~deposits;

(6) sea water and seasonal ice cover that affect salinity (and hence freezing-thawing temperatures) of ~~sediments~~deposits;

(7) thermal effect from river waters.

The periglacial shelf part is divided into the southwestern, northeastern, central, and estuary areas. The southwestern area comprises two subareas: a zone of discontinuous to sporadic permafrost along the shore, within 20 m sea depths in the north and 5-7 m in the south, which grades seaward into a zone of only sporadic permafrost. In the former zone, the permafrost has its table at depths from 0 to 30 m and is a few tens of meters to 100 m thick; in the latter zones, the depth to permafrost is 20 to 50 m and the permafrost thickness is less than 50 m.

In the northeastern area, continuous permafrost occurs within sea depths from 0 to 80 m and has a thickness of 100-200 m; the depth to its top varies from 0 to 30 m. The 80-120 m sea depth interval is occupied by ≤100 m thick discontinuous to sporadic permafrost with its table at a depth of 20-50 m.

Permafrost in the central area is sporadic; it is within 50 m thick and its top lies from 0 to 30 m deep. ~~Rocks~~ Deposits in the estuaries are mostly unfrozen; relict permafrost is restricted to a 100-300 m strip along the shore.

The studies performed were based on drilling and seismic acoustic data published to date. The study of the shelf by drilling and geophysical methods continues. Therefore, the results of the studies performed by the authors can be used in planning new drilling and in the geocryological interpretation of seismoacoustic profiling.

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