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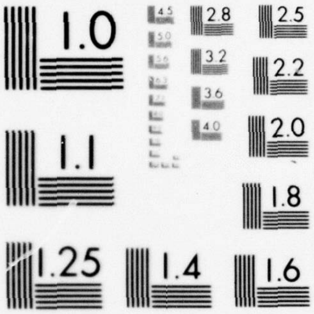
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SUBSEA CRYOLITHOZONE OF THE ARCTIC OCEAN

F.E. Are

May 1978

U.S. ARMY CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Draft Translation 686	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SUBSEA CRYOLITHOZONE OF THE ARCTIC OCEAN		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) F.E. Are		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE May 1978 13. NUMBER OF PAGES 26p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

PERMAFROST DEPTH
PERMAFROST DATING
PERMAFROST DISTRIBUTION
PERMAFROST ORIGIN
SEA LEVEL
ICE ISLANDS
BIBLIOGRAPHIES
ARCTIC CLIMATIC
USSR--ARCTIC OCEAN

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In this chapter, the cryolithic zone is the designation for a zone of the Earth's crust having a negative temperature; the frozen rocks are rocks which contain ice; the cold (frost) rocks are rocks whose temperature is below zero but which do not contain ice. It is reliably known that a cryolithic zone is extensively developed below the bottom of the Arctic Ocean and its fringe seas. However, the geocryological study of the sea bottom is extremely deficient. Reports about the distribution, properties and

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developmental principles of rocks of the sea bottom cryolithic zone have already long been necessary to support navigation through the northern maritime routes and for the construction of ports. Their requirement has sharply increased in connection with the initiated conquest of natural resources of the Arctic shelf. The enormous practical significance, poorly studies nature and poor access of the subsea cryolithic zone render its investigation one of the most interesting and pressing problems of modern cold research.

DRAFT TRANSLATION 686

⑭ CRREL-TRANS-686

ENGLISH TITLE: ⑥ SUBSEA CRYOLITHOZONE OF THE ARCTIC OCEAN

FOREIGN TITLE: (O SUBAKVAL'NOI KRIOLITHOZONE SEVERNOGO LEDOVITOGO OKEANA),

AUTHOR: ⑩ F.E./ Are

⑪ May 78

⑫ 30p.

㉑ Trans. of

SOURCE: YAKUTSK, YAKUTSKOE KNIZHNOE IZDATEL'STVO, 1976, p.3-26.

CRREL BIBLIOGRAPHY NO. 32-322

(USSR) p3-26 1976.

Translated by Sam Blalock Inc., Kingsport, Tennessee for the U.S. Army Cold Regions Research and Engineering Laboratory, 1978, 26p.

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REGIONAL AND THERMOPHYSICAL INVESTIGATIONS OF FROZEN SOILS (ROCKS) IN SIBERIA

By: F. E. Are

From the Academy of Sciences of the USSR, Siberian Branch, The Order of Labor
Red Banner Institute of Cold Research, Published by: the Yakutsk Book Publishing
House, Yakutsk, 1976

The Subsea Cryolithic Zone of the Arctic Ocean (F. E. Are)

In this chapter, the cryolithic zone is the designation for a zone of the Earth's crust having a negative temperature; the frozen rocks are rocks which contain ice; the cold (frost) rocks are rocks whose temperature is below zero but which do not contain ice.

It is reliably known that a cryolithic zone is extensively developed below the bottom of the Arctic Ocean and its fringe seas. However, the geocryological study of the sea bottom is extremely deficient. Reports about the distribution, properties and developmental principles of rocks of the sea bottom cryolithic zone have already long been necessary to support navigation through the northern maritime routes and for the construction of ports. Their requirement has sharply increased in connection with the initiated conquest of natural resources of the Arctic shelf. The enormous practical significance, poorly studied nature and poor access of the subsea cryolithic zone render its investigation one of the most interesting and pressing problems of modern cold research.

The report of A. Ye. Nordenshel'd is among the first information about the presence of frozen rocks on the bottom of the Arctic seas (1880 a). The reports notes that the sandy bottom in one of the bays of the eastern part of the Chukotsk Sea shoreline is cemented by ice.

The monograph written by V. Yu. Vize et al. (1946) states that on the bottom of the Dmitriy Laptev Gulf ice has been detected which is not subject to thawing due to the sub-zero water temperature. There are no verifying data.

The factual data about the permafrost below the bottom of the Arctic seas, until recently, were available solely for the coastal shallows. These data were chiefly obtained at the Permafrost Institute of the Siberian Department of the Academy of Sciences of the USSR by N. F. Grigor'yev (1966), who made a great contribution to studying the subsea cryolithic zone. Beginning in 1953, under his supervision, a large number of boreholes were drilled and these boreholes encountered permafrost or cold rocks at the receding shores of the open sea and in the shallows of sea gulfs to a distance of several hundred meters from the coast, as well as in the mouth debouchment areas of the Yana and Indigirka rivers to a distance of up to 25 km from the outer edge of the delta. In all cases, the water depth was less than 2 m. V. A. Usov (1965) and M. S. Ivanov (1969) participated in these investigations.

In 1962 - 1972, under similar conditions, Ye. N. Molochushkin (1973) studied the permafrost and cold rocks near the outcropping shores of Mostakh Island in Buorkhaya Gulf and in the Van'kin Gulf of the Laptev Sea, as well as in the near-mouth salt water part of the Lena River in the region of the Oleneksk tributary.

The first reports of the presence of subsea cryolithic zones outside the limits of the 2 m water level were obtained by V. M. Ponomarev (1960, 1961) for Kozhevnikov Bay and Khatangsk Gulf, where many boreholes revealed permafrost and cold rocks. At one of the drilling points a distance of 3 km from the shore at a water depth of 3 m, the thickness of the permafrost was in excess of 66 m. V. M. Ponomarev also points out that V. F. Zhukov and N. I. Saltykov encountered permafrost at a water depth of less than 2 m in the coastal zone of the Ob' Gulf.

In 1970, Ye. N. Molochushkin (1973) detected permafrost during sampling of bottom deposits of the Ebelyakhsk Gulf and the Dmitriy Laptev Bay in several locations at distances of up to 30 km from the coast in the lower parts of extracted cores during the use of a vibropiston tube.

According to the report of L. A. Zhigarev and I. R. Plakht (1974), heavily iced permafrost friable rocks lie in the submarine part of Van'kin Gulf of the Laptev Sea 10 km from the shore. Water depth was not indicated.

The discovery of oil in the region of Prudhoe Bay in Alaska in 1968 gave a powerful impetus to the development of research of the Arctic regions of the USA and Canada. The National Academy of Sciences of the USA recognized that the modern level of geological study of the Arctic does not correspond to its economical potential (polar research, 1970).

In 1969 the first report appeared about the presence of permafrost below the bottom of Disepshen Bay in northern Quebec, Canada (Samson, Tordon, 1969). According to an oral report made by B. R. Pel't'ye in 1970, fresh water ice was extracted from the bottom of the sea in the northwestern part of the Canadian archipelago between the Prince Patrick Islands and Borden at a water depth of 10 m (Mackay, 1972).

In the Spring of 1970, in the southern part of the Beaufort near the Canadian coast, between Herschel Islands and the Liverpool Bay, ice cores and frozen loose deposits were extracted from four boreholes in the process of drilling the bottom for oil. These cores were investigated in detail by D. R. Mackay, 1972. The boreholes were located at a distance of 3 to 25 km from the coast in points with a water depth ranging from 8 to 17 m.

In the Summer of 1970, a frozen core with a lens of fresh water ice was obtained by the Canadian Geological Service from the bottom of the Beaufort Sea 30 km north of Cape Baterst at a water depth of 37 m (Yorath et al., 1971; Reimnitz et al., 1972).

Hence, it was factually established that permafrost is encountered below the bottom of the Arctic Sea at distances of several tens of kilometers from the coast and at a water depth of several tens of meters.

Based on general concepts and extremely limited factual material, I. Ya. Baranov (1958, 1960) identified two zones of subsea permafrost layers. The first of these zones extends over the entire Arctic shelf of Asia to an isobat of 100 m. The second lies in the coastal zone of the Karsk, Laptev and Eastern Siberian Seas to an isobat of 20 m. These strata were formed in the Pleistocene and partly in the Holocene, when the shelf was dry. The first zone was converted to the subsea position as a consequence of marine transgression. The second underwent this process as the result of abrasion at a constant sea level. Today, the subsea permafrost strata are degrading, in the opinion of I. Ya. Baranov.

I. Ya. Baranov's basic tenets were further developed in the works of N. F. Grigor'yev (1966); Ye. N. Molochushkin (1970), F. E. Are and D. N. Tolstyakov (1970), and S. V. Tomirdiaro (1974) also extended their scope. Certain ideas about the extent of the subsea cryolithic zone and calculations are available in the works of A. N. Lachenbruch (1957); M. C. Brewer (1958); J. R. Mackay (1972); R. I. Lewellen (1973), and others.

The possibility and necessity of a prolonged existence of the submarine cryolithic zone are due to the constant negative temperature of the near-bottom layers of sea water over a large part of the territory of the Arctic Seas and the Arctic Ocean (AANII, 1954; Nordenshel'd, 1880, b; Timofeyev, 1957; Sovetskaya Arktika, 1970; Neizvestnov et al., 1972; Chekhovskiy, 1972; Brewer, 1958; Collin, 1960; Lachenbruch, Marshall, 1968; Lewellen, 1973 and others). Thermal aspects of the Arctic waters have been studied in quite detailed fashion. Therefore, today, it is quite possible to construct a diagram of distribution of the submarine cryolithic zone, as, for example, was done by A. L. Chekhovskiy (1972) for the Karsk (Kara) Sea shelf. But it is much more complicated to determine the thickness of rock with a negative temperature, and still more to explain the morphology of the permafrost strata. Drilling deep boreholes on the bottom of the Arctic Seas is only beginning, and making geothermal measurements within them presently remains a matter for the future. Geophysical methods are inadequately developed for the examined conditions and cannot provide reliable data without confirmation by drilling (Reimnitz et al., 1972).

Today, the concept of the morphology and nature of the submarine cryolithic zone can only be devised on the basis of approximate calculations. The chief factor that must be taken into account in this case is the contemporary temperature of the near-bottom water layers (the sea bottom). But one should bear in mind that under continental conditions the surface temperature correlates poorly with the thickness of the cryolithic zone (Balobayev, 1973; Gold, Lachenbruch, 1973). Obviously, this is also valid for the submarine cryolithic zone of the shelf, where the surface temperature of the bottom in the recent geological past changed many times, rapidly and extremely significantly as a consequence of the alternation of transgressions and regressions of the sea. In this connection, a consideration of the developmental history of the Arctic shelf has primary significance.

No less important are reports about the paleoclimate, under whose direct influence the cryolithic zone of dry land formed and upon which the temperature of the sea water depended. An important factor affecting the thickness of the cryolithic zone is the stream of intraground heat. It is entirely necessary to take into account the degree of mineralization of the sea water and subterranean waters of the shelf, since the phase state of water in rock pores depends not only on its temperature, but also its mineralization. It is known that rocks are widespread in the coastal zone of the Arctic Seas which are saturated with mineralized water and are frozen (Vittenburg, 1940; Ponomarev, 1950, 1960; Grigor'yev, 1966; Govorucka, 1968; Molochushkin, Gavril'yev, 1970; Neizvestnov, Semenov, 1973; Pinneker, 1973; Brewer, 1958).

In order to estimate the possible thickness of the submarine cryolithic zone, one must know the geological structure of the sea bottom in order to use it as a basis for an approximate determination of the thermophysical properties and moisture content of the rocks.

It is also necessary to take into account the abrasion process and erosion washing of the bottom by sea currents which can reduce thickness or cause destruction of the equilibrial state of the cryolithic zone. The accumulation of bottom sediments can lead to limestone formation in the sea and to the formation of a new or increased thickness of an earlier existing cryolithic zone.

Hence, among the most important factors which affect the formation of the submarine cryolithic zone one should include the following: relative sea level and dry land level; climate and temperature of the sea bottom; the intraground heat flux; mineralization of the near-bottom layers of water and subterranean waters of the sea bottom; properties of rocks which underlie the bottom; processes of abrasion and accumulation of bottom sediments.

We shall examine each of the listed factors in greater detail.

Relative changes of sea and dry land level cause transgression and regression of the sea and, consequently, the filling or drying of the ground surface, which fundamentally alters the thermal regime of the rock and the hydrogeological conditions of rock development. A vast number of scientific investigations whose results in many cases are contradictory have been devoted to a history of the marine transgressions either directly or indirectly in the geological past of the Earth.

It is now widely recognized that the alternation of shorelines represents phenomena resulting from the complex interaction of tectonic and glaciostatic motions of the lithosphere and glacioeustatic fluctuations in the level of the World Ocean. The process which is most large-scale in time and against whose background all other processes development is the unidirectional tectonic uplift of dry land and the warping of the bottom of oceans over the course of the entire Quaternary period. In the opinion of P. A. Kaplin (1973), the level of the World Ocean relative to dry land has dropped 100 m over the course of the last million years. More rapid glacioeustatic fluctuations in the level of the World Ocean have occurred against the background of this process. Their range in the Quaternary period, according to the calculations of I. A. Suyetova (1968) was about 120 m.

On the subject of the intensity and scope of the glaciostatic (glacioisostatic) motions, the views of various researchers sharply diverge. In a number of works recently published, it is pointed out that the most recent vertical motions, at least in certain regions of the Soviet Arctic coast, have been chiefly caused by tectonic factors and not by glacioisostatic ones (Kiryushina et al., 1961; Lazukov, 1961; Lazukov, 1965, b). Most investigators agree that total vertical motions of the lithosphere in the coastal zone of the Arctic Seas during the Pleistocene and Holocene developed extremely unevenly in a regional regard, reaching several tens of meters in certain tectonic structures (Markov et al., 1965; Grosval'd et al., 1973; Koshechkin et al., 1973), and even hundreds of meters according to certain data (Ionin et al., 1961).

With the appearance of the radioactive carbon dating method of determining the absolute age of rocks, success was achieved in quantitatively studying the course of the eustatic changes in World Ocean level over the last 30 thousand years. The age of rocks was investigated in tectonically quiet regions of the coasts of different continents. Relative dates were determined by traditional geological methods while absolute ones were determined according to C^{14} (Markov, Velichko, 1967; Grosval'd et al., 1973). Kh. Godvin, R. Feyrbridzh and a number of other investigators used this method to show that in the period between 17 thousand and 6 thousand years ago a eustatic uplift of the World Ocean level by 100 m occurred. This developed relatively uniformly at an average rate of about 9 m every 1 thousand years. During the last 6 thousand years, the level of the World Ocean underwent eustatic fluctuations in a range of no more than 10 m (Serebryanyy, 1961; Kaplin, 1973). In the period of intensive transgression, variable fluctuations in the level of the World Ocean also existed, but it is presently impossible to give a reliable explanation of their chronology and amplitude (Karrey, 1968).

Approximate calculations made according to the formulas of V. T. Balobayev (1966), D. V. Redozubov (1966), and D. N. Tolstyakov (Are, Tolstyakov, 1970) and modelling on the hydrointegrator (Molochushkin, 1970) show that a quantitative estimate of the possible modern extent of the cryolithic zone beneath the bottom of the Arctic Seas necessitates clarification of the dynamics of motions of the coastline in time and space over the last 20 - 30 thousand years.

It is obvious that unidirectional regression of the World Ocean in the Pleistocene can be ignored if it was only 2 - 3 m over the examined period of time. Inasmuch as the glacioeustatic fluctuations of ocean level have been relatively well studied, the primary task is to explain the glacioisostatic and neotectonic changes.

Analysis of the results of investigations carried out up to now shows that on the Arctic coast of the USSR in the upper Pleistocene and Holocene an uplift of dry land predominated whose magnitude diminished to the east of the Kola peninsula and Franz-Joseph Land to the coast of the Laptev and Eastern Siberian Seas. Further it again slightly rises in the direction of the Chukotsk peninsula (Zenkovich et al., 1960; Kaplin, 1973).

The history of development of the coastline and shelf have been best studied for the western regions, but even for these less detailed diagrams with an absolute chronology have been developed for no more than 10 - 11 thousand years. In the easterly direction, the level of study decreases. The least investigated is the marine region of the Laptev, Eastern Siberian and Chukotsk Seas.

The structure of the coastlines of Franz-Joseph Land, Navaya Zemlya and the northern part of the Kol'sk peninsula is determined by ascending motions (Zenkovich et al., 1960). Detailed diagrams of the dynamics of these regions are available in the works of K. K. Markov et al. (1965), M. G. Grosval'd et al. (1973), and P. A. Kaplin (1973). Individual questions are discussed in the works of V. D. Dibner (1965), M. V. Klenova (1933), A. S. Ionin et al. (1961), M. G. Kiryushina et al. (1961) and others.

One can conclude on the basis of the listed works that over the course of the entire Holocene the modern shelf of the Barents Sea was not dry. According to the data of K. K. Markov et al. (1965), relating to vertical motions of the Baltic crystalline shield, the level of the Barents Sea at the end of the upper Pleistocene was below that of modern times.

The works of M. A. Lavrova and S. L. Troitskiy (1960), M. A. Lavrova (1965; 1969), and B. I. Koshechkin et al. (1973) are devoted to the White Sea coast. The southern part of the Kola peninsula underwent an uplift in the Holocene with gradually diminishing fluctuations. The sea level for the entire time was somewhat below the modern level (Koshechkin et al., 1973). The other shores, according to M. A. Lavrova were subject to multiple transgressions in postglacial time. P. A. Kaplin (1973) considers the constructions of M. A. Lavrova to be inadequately reliable. One can assume on the basis of the listed works that the White Sea formed approximately 12 thousand years and that since that time its contemporary bottom has not experienced significant constriction.

The histories of development of the Kara Sea coast is the subject of the works of G. I. Lazukov (1961; 1964; 1965, a; 1965, b; Markov, Lazukov, Nikolayev, 1965). According to the scheme the above-authors developed, in the northwestern part of the Western Siberian lowlands, beginning in the middle Pleistocene, a transgression existed for nearly the entire time. The contemporary coastline formed in the mid-Holocene and has not significant changed since that time. Transgressions did not occur in the Pleistocene in the northeastern part of the Western Siberian lowlands, in the opinion of G. I. Lazukov.

Unlike G. I. Lazukov, V. N. Saks (1948), N. N. Kulikov, and V. T. Martynov (1961) and S. A. Strelkov (1961) feel that multiple regressions of the Kara Sea occurred in the upper Pleistocene to modern depths of 250 and 100 m. The scheme of G. D. Rikhter (1963) also significantly differs from the constructions of G. I. Lazukov. G. I. Lazukov, S. A. Strelkov, and I. L. Kuzin et al. (1961), as well as A. L. Chekhovskiy (1972) are agreed that at the beginning of the Holocene the Kara Sea shelf had constricted to the contemporary depth of 15 - - 20 m. G. D. Rikhter himself feels that a lowering of sea level occurred throughout the entire course of the Holocene.

There are practically no data on the development of the Taymyr and northern land parts of the Kara Sea coast. Evidently, the shelf did not constrict beginning with the Middle Pleistocene near the shore of Novaya Zemlya.

S. A. Strelkov (1961, 1965) drew-up the most detailed scheme of development of the shelf of the Laptev Sea. In the opinion of Strelkov, during the Zyryansk glaciation the entire shelf was dry. Yu. P. Baranova and S. F. Biske (1964) and L. S. Govorukha (1968) adhere to the same opinion. In Karginsk's time, a transgression existed. The result of this is that the coastline on Taymyr approximately coincided with the modern one, was 50 - - 100 km further at sea from Anabar to the Lena, and further to east ran in the direction of the northern end of the Novosibirsk Islands. V. N. Saks, Yu. P. Baranova and S. F. Biske hold about the same point of view.

At the beginning of Sartansk's time, the sea level dropped about 50 m, and at the end of that period briefly rose 15 - 20 m higher than the contemporary level. According to V. N. Saks, this uplift conprised about 10 m. The given rise in sea level seems improbable, at least for the eastern half of the Laptev Sea coastline. Here are widespread, strongly icy loose deposits which formed no later than the middle of the Upper Pleistocene (Alekseyev, 1970; Ivanov, 1970). These are easily eroded by the sea and therefore traces of a coastline which formed when the sea level rose in Sartansk time should have been preserved. However, there are no such traces.

By the beginning of the Holocene, according to the S. A. Strelkov scheme, the sea level once again sank below the contemporary one by 20 m. According to general opinion, in the course of the first half of the Holocene a transgression developed which terminated at the contemporary level 5 thousand years ago. The latter figure is confirmed by certain zoogeographic, and particularly, archeological data found in the works of V. G. Dibner and K. N. Nesis (Govorukha, 1968).

The developmental history of the Eastern Siberian Sea shelf is discussed in less detail in the literature than that of the Laptev Sea. According to the data of N. A. Belaz and N. N. Lapina (1962), in Zyryansk time the level of the Eastern Siberian Sea was 100 m below the contemporary level. According to S. A. Strelkov and Yu. P. Baranova and S. F. Biske, the sea level was 50 - 40 m lower. S. A. Strelkov feels that sea level rose approximately 15 m in Karginsk time, while in Sartansk time it dropped 50 m. Subsequently, events developed as in the Laptev Sea.

In the opinion of Yu. P. Baranova, S. F. Biske and S. A. Strelkov, the Chukotsk Sea shelf dropped to a depth on the order of 40 - 50 m in Zyryansk time. In this case the coastline ran somewhat north of Wrangel Island. The Bering Straits did not exist. According to S. A. Strelkov, in Karginsk time the coastline nearly reached the contemporary one (1961). Chukotka was separated from Alaska.

D. M. Hopkins (Strelkov, 1965) feels that in Zyryansk time the sea level in the region of the Bering Straits was 100 m lower than now, that it rose to the 40 m isobat in Karginsk time, and at the beginning of Sartansk time again dropped by 10 - 30 m. In the opinion of D.M. Hopkins (1965), the contemporary sea level in Alaska was established about 5 thousand years ago. O. M. Petrov (1965) feels that this occurred at the very end of the Pleistocene. Later, S. F. Biske (1967) concluded that the complex relationship of the eustatic and neotectonic factors in the late Quaternary era is not subject to consideration at all on the Ckukotka coastline.

Such is a brief survey of the contemporary ideas about the relative changes in the level of Arctic Seas of the USSR in the Upper Pleistocene and Holocene. Its analysis shows that today there are no more or less reliable quantitative data on this subject. Therefore, when constructing a scheme of movements of the shoreline in time and space on the basis of available materials for any part of the shelf, even in the Holocene, large errors are possible which are measured by the thousands of years in time and hundreds of kilometers in space.

Climate and primarily climatic thermal characteristics and their changes in time determine the development of the cryolithic zone. It is widely known that in the Quaternary period climate changed many times and extremely significantly. One can consider it proven that within general aspects these changes developed synchronously throughout the entire Northern Hemisphere (Vinogradov et al., 1961; Markov, Velichko, 1967; Bouen, 1969; Nikiforova, 1969; Kind, Sulerzhitskiy, 1970), and possibly developed synchronously over the entire Earth (Emiliana, 1955; Flint, 1963). But during a detailed examination, one detects certain displacements of the climatic events which were caused by local factors. For example, the Karginsk warming in Western Siberia and on Chukotka, obviously occurred at different times (Serebryanyy, 1965). In the opinion of M. A. Belov and N. N. Lapina (1970), the modern warming in Eurasia began 1 thousand years later than in Amerasia, etc.

The chief tendency of the Pleistocene consists in the general cooling of the climate, against whose background smaller-scale fluctuations developed (Markov, Velichko, 1967; Nikiforova, 1969; Ravskiy, 1969, and others). In the general opinion, in periods of warming the climated was similar to the modern one or somewhat milder, while during cooling the climate was somewhat more severe (Kind, 1965; Shvartsbakh, 1965; Flint, 1963; Serebryanyy, 1965; Bouen, 1969; Belov, Lapina, 1970; Kind, Sulerzhitskiy, 1970). G. I. Lazukov (1961) and D. Clark (1974) assert that the Arctic climate in the Pleistocene was never warmer than it is today. There is reason to assume that over the course of the entire Pleistocene and Holocene climatic conditions on the coast of the Arctic Seas ensured the continuous existence of a cryolithic zone (Markov, Velichko, 1967). Ye. M. Katasonov came to the same conclusion on the basis of cryolithological investigations (1973). In all probability, during the Holocene climatic optimum there was a partial degradation of the cryolithic zone (Baulin, 1963; Serebryanyy, 1965), but it did not introduce fundamental changes into the permafrost landscapes of the Arctic coast (Kayyalaynen, 1970).

The modern level of knowledge is inadequate for a reliable foundation of the quantitative characteristics of the paleoclimate of the Quaternary period. Therefore, most investigators limit themselves to cautious approximate comparisons of climates of the past with the modern climate.

One of the most detailed quantitative schemes of changes of the average yearly air temperature was drawn-up by E. I. Ravskiy (1969) for the southern half of Eastern Siberia over the last 75 thousand years. This scheme corresponds to the data of R. Bouen (1969) regarding climatic changes of the mid latitudes of the Northern Hemisphere in the Upper Pleistocene and the Holocene. However, the author himself points out the poor study of the question. K. K. Markov and A. A. Velichko (1967) have drawn-up a similar scheme for Central Yakutiya based on studying a section of the Mamontovaya Mountains. It significantly differs from that of E. I. Ravskiy.

The quantitative estimates of the mean annual air temperature of the periglacial zone of Central Europe for periods of the glaciations, made by various investigators, diverge extremely significantly: from 0°C to -6°C (Aseyev, 1974), but the predominant opinion of recent years pertains to the fact that the mean annual temperature was an average of 10°C below the modern one (Shvartsbakh, 1955; Flint, 1963; Aseyev, 1974; Bouen, 1969).

The climatic conditions of the Arctic coast in Sartansk time, certainly, were more severe than now, chiefly because the sea level was 100 - 140 m below the contemporary one and access of warm Atlantic waters into the Arctic basin was significantly reduced (Belov, Lapina, 1961; Govorukha, 1968). In this case the climatic conditions of the Arctic should have approximated the conditions of the contemporary Antarctica (Pomirdiaro, 1970). At present, the mean annual air temperature at the South Pole is -48.5°C, and is -56°C at the inaccessible pole (Soviet designation for a spot in Antarctica) (Atlas Antarktika, Vol. I, 1966). The vertical temperature gradient for Antarctica has not yet been established (Atlas Antarktidy, Vol. II, 1969). The mean annual temperatures reduced to sea level on the basis of the average terrestrial vertical gradient of 0.5°C/100 m (Alisov et al., 1952) will be -34.5°C for the South Pole and -37.4°C for the inaccessible pole. Probably, the mean annual air temperature at the North Pole during the marine regression was no higher than the indicated values, i.e., 15 - 18°C below the contemporary temperature of -19°C (Kalesnik, 1955). In this case, based on the latitudinal temperature gradient (Kalesnik, 1955), one can assume that on the Arctic coast of Asia at that time the mean annual air temperature was no higher than -25°C.

The bottom temperature or the temperature of the near-bottom water layers is required for calculations of the parameters of the subsea cryolithic zone. The basic modern method of studying the paleotemperatures of the oceans is the so-called carbonate thermometer method, which is based on isotope oxygen analysis of planckton Foraminifers from deep water cores of bottom deposits. The author of the well known temperature curve for the equatorial regions of the Atlantic Ocean, K. Emitiani (1955), in one of his latest works (1974), asserts that the temperature which he calculated with an accuracy of up to 1°C is correct, while the accuracy of the geochronological scale of several percentages is correct at least for the last 175 thousand years. However, it is evidently impossible to employ K. Emitiani's curve to determine the paleotemperatures of water on the Arctic shelf.

There are very few data for the Arctic Ocean and what data there are are contradictory. J. Van Donk and G. Met'yu (1974), based on a study of bottom deposit cores from the deep water part of the Arctic basin, concluded that the water temperature of the ocean has not changed over the last 25 thousand years. One should bear in mind that study of the Foraminifers gives clear information only about the temperature of the surface layers of the water. The results are less certain with regard to the near-bottom temperatures (Flint, 1963).

In the opinion of R. F. Flint, beginning with Oligocene and through the present, a drop in the temperature of the near-bottom water of the oceans has been occurring with certain fluctuations. This process is due to the low temperature of surface waters in the polar regions (Emiliana, 1955).

There are practically no data about the paleotemperatures of Arctic shelf waters. One can only recall that in the opinion of P. M. Borisov (1970), the temperature of surface waters of the Arctic basin during the Holocene climatic optimum was 2.0 - 2.5°C higher than the modern one. However, the opinion predominates that air temperature during this optimum increased by 2°C only in comparison with the modern one (Bouen, 1969; Ravskiy, 1969, and others). Taking into account the high thermal inertia of water masses in comparison with air (Shpaykher, 1973), one should consider that P. M. Borisov's estimate is too high.

The modern temperature of the near-bottom water in the shelf seas of Asia has been studied well. As a rule, it is below zero at any time of the year. An exception is the zone of the warming effect of rivers and the eastern part of the Chukotsk Sea (Sovetskaya Arktika, 1970). Inasmuch as the Arctic climate during the regression was certainly more severe than the modern one, one can assume that the temperature of the near-bottom water was near the freezing point.

<u>The geothermal heat flux</u> has an effect on the thickness of the cryolithic zone. Being relatively uniform within limits of the homogeneous geological structures, it basically varies on the continents within limits of 0.035 to 0.070 kcal/(hr · m^2), i.e., it can differ twofold for different large regions, while in individual cases it can be greater (Lyubimova, 1966; Gold, Lachenbruch, 1973). On the geothermal map of the USSR on the scale of 1:5 million (1972), a large part of the Arctic coast is characterized by a value of the geothermal flux ranging from 0.04 to 0.06 kcal/(hr · m^2). On the north coast of Alaska, the flux is equal to 0.050 kcal/(hr · m^2) (Gold, Lachenbruch, 1973).

Investigations of the geothermal flux through the bottom of oceans were initiated in 1952 (the thermal regime of the depths of the USSR, 1970). A number of measurements were made in the Arctic Ocean. The submarine ridges of the Soviet sector of the Arctic proved to be a zone of elevated thermal activity. For example, within limits of the Lomonosov ridge, the thermal flux varies from 0.05 to 0.10 kcal/(hr · m^2) (Lyubimova, 1968; Lyubimova et al., 1969; Lyubimova et al., 1973). These same authors cite quite high values of the flux for the Makarov depression as well (from 0.05 to 0.07 kcal/(hr · m^2).

In the North American Arctic sector, the values of the geothermal flux are significantly lower. In the Canadian basin, the flux is approximately 0.05, while in the transitional zone from the Abissal plain to the shelf it is even 0.04 kcal/(hr · m^2). In the straits between islands of the Canadian archipelago, the value of the flux is nearly 0.05 kcal/(hr · m^2) (Lachenbruch, Marshall, 1969). According to the data of G. Simmons and K. Horai (1968), the flux is 0.015 - 0.060 kcal/(hr · m^2) in MacClure straits.

There are no data on the value of the geothermal flux on the shelf of the Arctic Seas. This is due both to technical and methodological difficulties. The temperature gradient graphs which have been successfully employed to determine the heat flux in deep water ocean basins are unsuited to shallow water shelves, where the temperature of near-bottom water layers is variable. Even at a water depth on the order of 1 km, the interpretation of data obtained with the aid of the temperature gradient graph can encounter great difficulties in individual cases (Lachenbruch, Marshall, 1968).

Analysis of the presented data with consideration of modern concepts about geological structure and the developmental history of the Arctic shelf shows that the value of the flux of geothermal heat within limits of the shelf is probably similar to the value on the coast, i.e., is approximately 0.05 kcal/(hr · m^2) with possible deviations of at least ±14%. Much more significant anomalies are also possible, whose value is hard to predict, for example, in the tectonically active regions.

Mineralization of sea water and subterranean water has a great effect on the phase state of rocks which underlie the bottom of the shelf seas. The subterranean waters which are highly mineralized prevent freezing of the intervening rocks and form super-, inter-, and subpermafrost water tables. Their extent on the shelf is unknown and the principles of formation and interaction with permafrost strata have been very poorly studied.

At the interface of the mineralized water table with the frozen layer at a temperature below zero, above the freezing point of the threshold solution, a fusion of ice which fills the pores of the rocks occurs. The intensity of fusion under natural conditions is unknown, but it is so slight that it is not identified by direct observations. An increase in mineralization of the threshold solution near the boundary of permafrost is necessary for development of the process of fresh water ice fusion and occurs through the medium of ion migration under the effect of the concentration gradient which diminishes proportional to the development of the process. Hence, in the absence of pressure filtration the process automatically slows. Therefore, the mineralized fresh water tables and permafrost layers can evidently coexist without significant movements of the freezing boundary over the course of geologically significant periods.

All of the above also fully pertains to the interaction of sea water with permafrost which underlies the bottom of the sea. In the opinion of V. M. Ponomarev (1961), a solution of ice can only penetrate into the pores of rock under the effect of sea water at a depth of several meters. This is also indirectly confirmed by laboratory experiments conducted at the Permafrost Institute of the Siberian Department of the Academy of Sciences of the USSR by L. V. Chistotinov and L. G. Rogovskaya, who showed that melting of ice saturated dispersed rocks in contact with mineralized water at a temperature below zero slows with the increase in depth of thawing and the degree of dispersion of the rock, as well as with the decrease in mineralization of the water.

In Dmitriy Laptev Gulf and Ebelyakhskaya Bay of the Laptev Sea, Ye. N. Molochushkin used a vibrating piston tube to detect non-saline melt as well as frozen bottom deposits a distance of 25 km from the coast, where the submarine conditions have been predominant for thousands of years. Evidently, the bottom is made up of rocks which were under continental conditions until the last transgression in such areas.

It is known that the length of the cores obtained from the bottom of the Arctic shelf by various samplers does not exceed 6 m (Govorukha, 1968), and basically comprises tenths of a meter (Neizvestnov, Semenov, 1973). In Dmitriy Laptev Gulf and Ebelyakhskaya Bay, the piston sampling tube is immersed by nor more than 3.5 m on the bottom (Molochushkin, 1973). Evidently, in many cases the depth of sinking the samplers is limited by the deposit depth of the frozen layer. Hence, it is improbable that a thinner layer of frozen deposits could form on the shelf due to the fusion of subterranean ice under the effect of the saline sea water.

In the zone of the contemporary accumulation of sediment in the Laptev Sea, cold bottom deposits have been detected and studied which are not cemented by ice at a temperature up to -6°C (Molochushkin, Gavril'yev, 1970; Molochushkin, 1973). An interesting feature of such deposits is the fact that mineralization of their threshold solution is significantly above the mineralization of sea water (Marchenko, 1966; Molochushkin, Gavril'yev, 1970; Neizvestnov, Semenov, 1973). The causes of this phenomena are unclear. The presence of saline, non-ice cemented sediments on the bottom of the Arctic shelf seas has been the subject of certain investigators' efforts to postulate the possibility of existence of frozen rock (permafrost) a significant distance from the coast (Govorukha, 1968; Neizvestnov, Semenov, 1973). However, the factual data cited at the beginning of the article negate this opinion. The cold state of the bottom deposits on the Arctic shelf, as a rule, indicates that these are contemporary marine sediments.

The properties of rock which underlie the bottom of the Arctic Ocean and which must be taken into account in the thermophysical calculations of cryolithic zone parameters have almost not been studied. Their characteristic values can be assigned only on the basis of general concepts about the geological structure of the sea bottom and approximate assumptions. One can visualize what this leads to on the basis of the example of the heat conductivity coefficient. According to investigations of the Geothermal Laboratory of the Permafrost Institute of the Siberian Department of the Academy of Sciences of the USSR, the heat conductivity coefficient of the most prevalent rocks of Yakutiya varies from 1.5 to 4.5 kcal/(hr · m · °C), i.e., can vary by a factor of 3. The equilibrial thickness of the cryolithic zone is directly proportional to the value of this coefficient. Consequently, depending upon the choice of the magnitude of the heat conductivity coefficient, the calculated thickness of the cryolithic zone can differ three times.

Processes of erosion and accumulation in the coastal zone of the sea certainly have had and do have a significant effect on the development of the cryolithic zone of the shelf. This phenomenon has been described in detail by N. F. Grigor'yev (1966). Therefore, we shall only dwell on certain details.

Within limits of the coastal lowlands of Eastern Siberia, the contemporary sea level evidently was established in the Middle Holocene, i.e., 5 - 6 thousand years ago. Over the course of this time thermal abrasion intensively developed. Based upon the modern observations, one can assume that subsidence of the shores under the effect of thermal abrasion occurred at an average rate of at least 4 - 6 m per year (Are, 1973). And this means that in the second half of the Holocene, in many areas with an unchanged sea level, the shore subsided by at least 20 - 36 km. Certainly, in individual areas (capes extending far out to sea, small islands in the open sea), the subsidence of the coastline was somewhat greater. S. V. Tomirdiaro (1974) feels that the coast receded 400 - 500 km under the effect of temperature abrasion, i.e., the greater part of the shelf formed as the result of thermal abrasion development. However, in order to contour the zone of thermal abrasion erosion one has no factual data at one's disposal.

As the result of thermal abrasion, the continental frozen layers of great thickness proved to be below the bottom of the sea. Their subsequent fate significantly depended upon the zone of prevalence of the warm and fresh water effect of rivers. For large rivers, the arael extent of this zone has been studied in great detail. It is also known that river waters do not descend to a depth greater than 20 m on the shelf (Vize, 1926; Vize et al., 1946; Gorbatskiy, 1970; Sovetskaya Arktika, 1970). Under the effect of river water, which has an above-freezing temperature, the continental-submerged permafrost layers were degradated. The approximate calculations of Ye. N. Molochushkin (1970) demonstrate that the frozen layer could either totally thaw or still be maintained at a certain depth from the surface of the sea bottom depending on distance from the shore and the rate of recession of the coast in such areas, by now.

Outside the limits of the zone of effect of rivers, near the surface of the bottom, a freezing (below zero) temperature constantly predominated which was significantly higher than on dry land. In the given case, a partial degradation of the frozen layer occurred from below with an increase in its temperature to an equilibrial state corresponding to the temperature of the near-bottom water.

In the zone of accumulation of the contemporary bottom deposits, new permafrost layers can form. Their formation strongly depends on mineralization of the sea water. In the near-river mouth inlets, where the water is fresh or mildly saline, permarfrost bottom freezing begins when water depth decreases to approximately 1.5 m (Grigor'yev, 1966).

Outside the limits of the zone of influence of the rivers, a still greater decrease in depth is necessary for the beginning of permafrost freezing. The precise shallow depth depends on salinity of the sea water and bottom deposits. In this case one should emphasize that the decrease in water depth with any mineralization of the sea water possible under natural conditions and any threshold solution of the bottom deposits lead to permafrost freezing of the bottom, since upon the shallow's reaching sea level the mean annual temperature of the surface drops to -10 - -12°C and the freezing point of sea water with a salinity of 30% is -1.7°C according to N. N. Zubov (1944). In Winter, in the closed coastal shallows, the salinity of the water increases proportional to the increase in thickness of the ice cover and reaches an anomalously high level, for example, on the order of 74% (Molochushkin, 1969). But even this water freezes at -4.4°C. Even if one takes into account that salinity of the threshold solution of the bottom deposits can be 1.5 times higher than salinity of the near-bottom layers of the water, it should be recognized that freezing of bottom deposits under ordinary marine conditions is unavoidable at temperatures of -10 - -12°C.

<u>The cryolithic zone of the Arctic basin</u>. One can identify two zones on the bottom of the Arctic basin: a deep water zone washed by water at a temperature below zero (AANII, 1954; Sovetskaya Arktika, 1970), and a zone within limits of depths from 200 to 900 m, washed by Atlantic waters with a temperature above freezing (AANII, 1954; Timofeyev, 1957; Sychev, 1960; Coachman, Barnes, 1963).

In the Abissal depression, located between Lomonosov ridge and the Barents-Kara shelf, the temperature of deep water is -0.7 - -1.0°C. On the other side of Lomonosov ridge, water temperature is 0.35°C. It is obvious that a cryolithic zone exists below the bottom of the depressions which is in an equilibrial state. On the bottom lie loose marine deposits whose thickness is usually several hundred meters (Leont'yev, 1963). The coefficient of heat conductivity of such deposits is about 1.5 kcal/(hr · m · °C). The flux of geothermal heat is from 0.05 to 0.07 kcal/(hr · m^2). The thickness of the cryolithic zone of 15 - 30 m in the Nansen trough and of about 10 m in the Beaufort trough correspond to the indicated data. It is obvious that bottom deposits are in a frozen state within the confines of the cryolithic zone.

In the zone of submarine ridges, the sedimentary cap can be absent in places. The coefficient of heat conductivity and the deep heat flux here should be relatively high. Under such conditions, the thickness of the cryolithic zone is on the order of 25 m. Its maximum value can reach 70 m.

Atlantic waters enter the Arctic basin along the western shores of Spitzbergen and move in a layer 550 - 800 m thick within limits of depths ranging from 200 to 900 m, extending throughout the entire territory of the basin. These waters execute a circular motion in the Arctic basin in a counterclockwise direction and return to the Atlantic Ocean along the coasts of Greenland. Their distinguishing aspect is a positive temperature, which these waters maintain over the entire territory of the basin. Over the course of several years that are necessary for completion of the circular cycle of motion, the Atlantic waters are cooled on the average from +1.5°C to +0.2°C. They primarily wash the continental slope, as well as the bottoms of lobes and deep water portions of the Arctic Seas.

It is obvious that within the zone of prevalence of the Atlantic waters that bottom deposits have an above-freezing temperature. The features of this zone in the plan are easily established on the basis of the results of investigations conducted in the USSR. The question arises of whether a relic cryolithic zone could be preserved here at a certain depth from the bottom surface.

As was already stated above, today it is widely recognized that in periods of glaciations the Arctic shelf dried as a result of a drop in the level of the World Ocean. In this case the influx of Atlantic waters into the Arctic basin either terminated or diminished to a small level (Govorukha, 1968), and consequently, the temperature of waters of the Arctic basin was below zero throughout their entire volume. Approximately, the value of the negative temperature of near-bottom layers of water in the zone of modern extent of Atlantic waters beyond limits of the effect of the river flow could be equal to the temperature of freezing of sea water with a salinity value on the order of 30%, i.e., -1.7°C.

The coefficient of heat conductivity of rocks of the continental slope in the zone of prevalence of loose marine sediments (greater depths, gentle slopes) can be on the order of 1.5 kcal/(hr · m · °C), and in the zone of outcroppings of bedrock to the surface (the upper part of steep slopes with an upthrust structure) - up to 4.5 kcal/(hr · m · °C). The flux of geothermal heat is from 0.04 to 0.10 kcal/(hr · m^2). The equilibrial thickness of the cryolithic zone with the indicated determined parameters can range from 25 to 190 m.

An increase in the temperature of near-bottom water in the examined zone could have begun together with the last transgression, i.e., 17 thousand years ago. The contemporary temperatures were established about 6 thousand years ago.

One can assume that the permafrost over the greater part of the bottom presently washed by Atlantic waters has always been absent, since the cap of sedimentary deposits on the continental slope apparently formed under marine conditions, and consequently, the threshold solution has a level of minearlization at which freezing is impossible under submarine conditions. Therefore, during bottom heating by the Atlantic waters phase transitions did not occur.

A simple calculation according to known formulas shows that with the indicated thermophysical parameters and thickness of the cryolithic zone, no more than 100 years is required for its degradation. Hence, presently the cryolithic zone is obviously absent under that part of the sea bottom washed by Atlantic waters.

<u>Conclusion</u>. Analysis of the presented data shows that the submarine cryolithic zone extends over the greater part of the Arctic shelf of Asia and North America, as well as the Arctic basin. It is absent in the upper part of the continental slope and in the deepest water parts of the Arctic Seas (depths of 200 - 900 m), and is also possibly absent in the zone of the

thawing effect of large rivers at a depth of less than 20 m.

The permafrost layers are widespread in the coastal strip of the shelf up to 40 km wide if the strip entered the submarine position under the effect of thermal abrasion. These strata could also exist in that part of the shelf which dried in the recent geological past. Outside the limits of these territories the rocks of the submarine cryolithic zone are in the cold state.

The thickness of the cryolithic zone in the deep water part of the Arctic basin between the Barents-Kara shelf and Lomonosov ridge is on the order of 15 - 30 m and is 10 m on the other side of the ridge.

There are very few factual data which characterize the submarine cryolithic zone in separate points or regions. Its morphology, temperature and other properties are basically determined by the relative changes of sea level and the level of dry land, as well as climate in the recent geological past, by the contemporary temperature of near-bottom layers of sea water, the magnitude of the geothermal heat flux, properties of rocks, the degree of mineralization of the subterranean waters of the sea bottom and the sea water, and by processes of abrasion and accumulation of bottom deposits.

In principle, parameters of the submarine cryolithic zone can be determined by calculation, taking into account the listed determinative factors. However, these factors have been little studied in a quantitative regard. For example, it is widely recognized that the Arctic shelf of Asia in the Upper Pleistocene partly dried, but the absolute chronology and magnitude of displacements of the shoreline have not been reliably established. Mutually exclusive points of view exist with regard to this problem.

Climatic conditions on the Arctic coast of Asia ensured a continuous cryolithic zone over the course of the entire Pleistocene and Holocene. Partial degradation of the cryolithic zone occurred during the Holocene climatic optimum. However, the quantitative characteristics of the paleoclimate of the Arctic coast and paleotemperatures of water of the Arctic Seas are practically absent.

It is now only possible to make very crude approximate calculations of the morphology of the submarine cryolithic zone, whose degree of reliability is impossible to estimate. Evidently, it is expedient to make calculations for two extreme combinations of initial data. Then the actual parameters of the cryolithic zone proved to be within limits of the two extreme values. The latter will provide a concept about the accuracy of the calculations as well.

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