Russian-German Cooperation in the Siberian Shelf Seas: Geo-System Laptev-Sea

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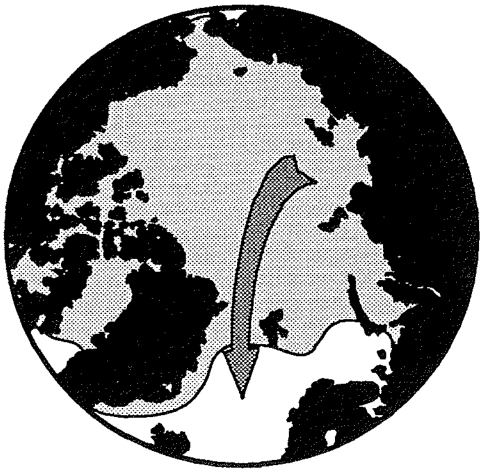

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PREFACE

The workshop 'Russian-German Cooperation in and around the Laptev Sea' was held in May 1993 in St. Petersburg in order to assess (1) the state of knowledge of the Laptev Sea and the adjacent continental margin of the deep Arctic, and (2) to develop a research strategy for the marine geosciences in the Laptev Sea and terrestrial work in East Siberia. The workshop brought together 70 scientists, among them meteorologists, sea ice physicists, oceanographers, biologists, chemists, geologists and geophysicists from various Russian and German research institutions (Fig. 1). The main goal of the workshop was to promote and coordinate scientific collaboration among scientists from Germany and Russia who study the present and past oceanography and climatology as well the ecology of the Laptev Sea and the East Siberian Sea.

The workshop was organized into serveral sessions which followed various themes of the environment of the Siberian shelf seas from their present situation to their geological record:

(I) Oceanography, biology and climatology of the Laptev Sea and the East Siberian Sea
- Oceanography of the Eurasian Arctic shelf seas
- Laptev Sea polynya
- "Dirty" sea ice
- Biology of the Laptev Sea

(II) Paleoceanography and paleoclimatology of the Laptev Sea, East Siberian Sea and the adjacent deep sea
- From Siberia to the Arctic Ocean: the land-sea connection
- Present and past shelf to basin transport
- History of the Arctic sea-ice cover
- Nansen Arctic Drilling Programme: Laptev Shelf - Gakkel Ridge intersection

(III) Coordination of joint future research projects

The scientific content of this workshop is briefly documented in this book containing most of the results and discussions as well as planned joint future research programs.

This publication of this volume serves various purposes. It is primarily a forum for scientists working in the Siberian shelf seas, in which the results of many years of research can be published briefly. In order to provide all the participants in the workshop with the opportunity for presenting their results, a speedy way of publication was chosen. Thus, each individual author has presented his opinions and views as he or she sees them, reflecting the diversity and complexity of the Laptev Sea system. On the other hand, this volume offers many researchers the possibility of acquainting themselves with methods and results of research into the East Siberian seas as carried out in other parts of the world. Finally, it is hoped that this collection of papers will function as a first step toward joint research projects. Many of the papers published identify major scientific problems, thus offering new perspectives for future scientific research in polar regions.

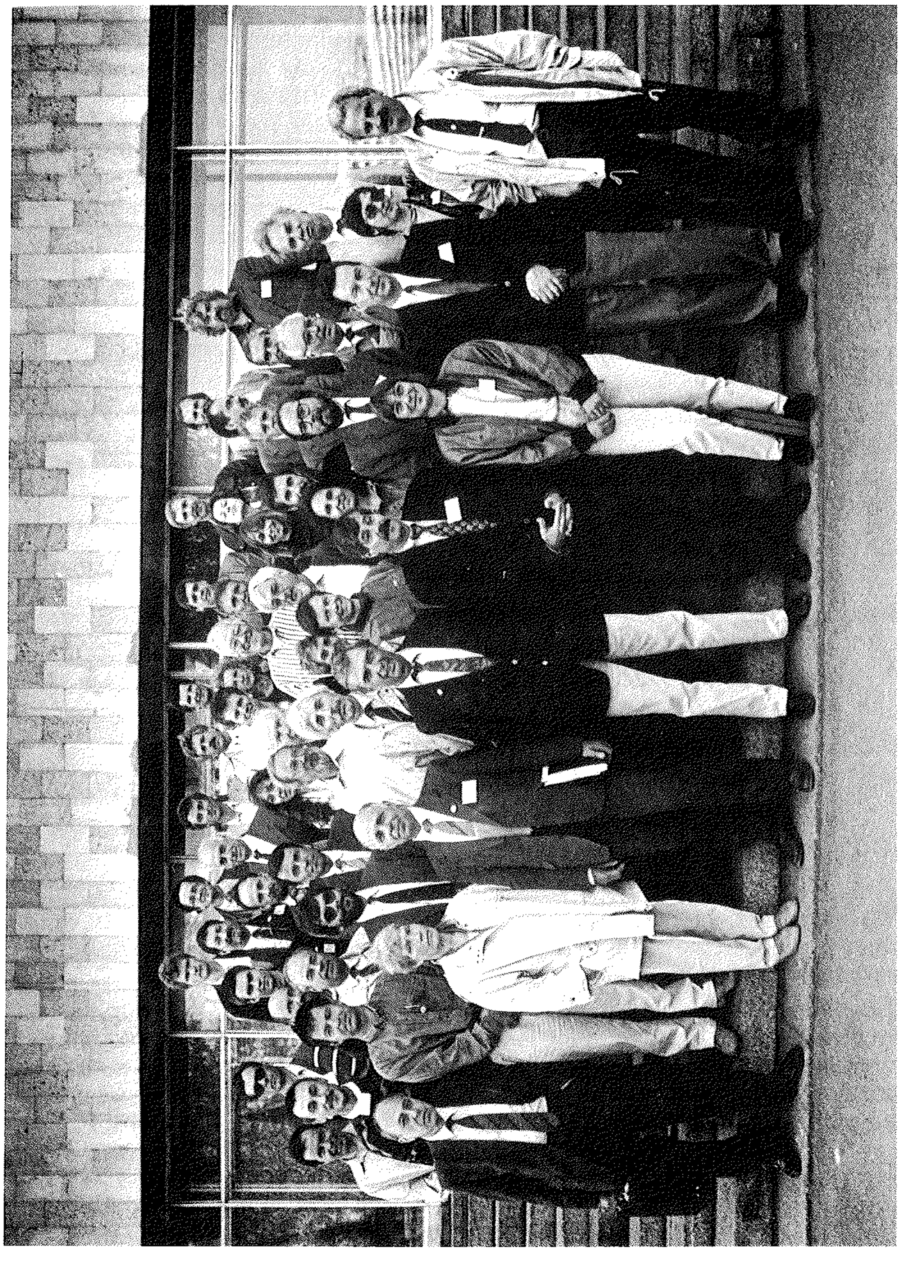

Fig. 1: Participants in the workshop 'Russian-German Cooperation in and around the Laptev Sea' in St. Petersburg, Russia

The nature of the papers, the discussions and the disciplines of the attendees clearly demonstrate that the study of the geosystem Laptev Sea is a multidisciplinary one in an interesting key area involving all branches of the geosciences, such as oceanography, biology and geology, in particular. It thus remains an important example for GLOBAL CHANGE and CLIMATE IMPACT research within international research efforts, e.g., the International Arctic Science Committee (IASC), Arctic Ocean Sciences Board (AOSB) or the Nansen Arctic Drilling Programme (NAD).

The workshop has been sponsored by the German Ministry for Research and Technology (BMFT) and by the Arctic and Antarctic Research Institute in St. Petersburg, Russia, where the meeting was held from the 10th to the 12th of May in 1993. We wish to thank these organizations for their financial and logistic support .

The scientific basis for this workshop was established during the years 1991 to 1993. Two expeditions, AMEIS to Kotelnyy in 1991 and ESARE to Tiksi (Lena Delta) and the New Siberian Islands in 1992, which were carried out in close cooperation with the Arctic and Antarctic Research Institute in St. Petersburg, constituted an important pilot phase of these studies and allowed to build up excellent scientific contacts with our Russian partners. We are extremely grateful for the good cooperation with and the hospitality offered by the Arctic and Antarctic Research Institute in St. Petersburg.

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PROLOGUE AND SCIENTIFIC PERSPECTIVES FOR THE PROJECT 'LAPTEV SEA SYSTEM'

Establishing the properties and variability of our modern global environment as well as their historic changes is one of the great challenges for mankind. Climatic models and prediction provide one necessary base for securing the future of mankind on Earth. Polar regions are responding fast and dramatically to climate change; their climate record and histories are presently studied with great care (1) to decipher the processes controlling climatic changes of the past in great detail, and (2) to monitor ongoing climate changes in real time.

The impact of the polar regions on global climate development was established some time ago. Modern climate models as well as paleoclimatic reconstructions have shown that the waxing and vaning of the continental ice caps and changes in sea-ice distribution influence the renewal of deep and intermediate water masses and, therefore, thermohaline ocean circulation as well. However, our knowledge of the climate impact in the Arctic Ocean, for example, of the influence of climate changes on sea-ice formation, is very limited, thus making it difficult to predict possible future global climate changes. This holds true in particular for the Eurasian shelf seas, which, for logistic and political reasons, have long been inaccessible to the interdisciplinary research. Large amounts of Arctic sea ice are formed here, thus underscoring the central importance of these processes for the climate system. In its role as a source area for the Transpolar Drift and of sediment loaded sea ice, the Laptev Sea is of particular interest (Fig. 2). In this region it may be possible to demonstrate the extent to which global ocean circulation and, as a result, climate development are also influenced by extremely large amounts of fresh water transported into the Arctic Ocean through the Siberian river systems. Current oceanographic models have not yet taken such a direct terrestrial impact on the global climate into consideration.

The Russian scientific community has a long tradition in working on the Eurasian shelf seas because of oil, gas and mineral resources found there and the economic advantages of the Northern Sea Route. Much data and numerous papers about the Siberian shelf seas have been published, but they have appeared primarily in Russian reports or journals which have not easily been available for the Western world. Apart from data from American research programs in the 1960's and some recent results from the Arctic Ocean which clearly point to the Siberian Shelf seas in their central importance for the Arctic, little is known about the complex geosystem of the Laptev Sea.

The workshop under the framework of the Russian-German Cooperation in and around the Laptev Sea held in May 1993 combined a wide variety of researchers covering both marine and terrestrial disciplines. In the meantime this workshop has laid the ground work for a large-scale multi- and interdisciplinary research project to establish the natural properties of the Laptev Sea and of its interaction with the adjacent land areas. The presentations by Russian, American and German researchers established well that the Laptev Sea area is a unique scientific subject which will allow to describe some of the most important properties of the Arctic Ocean. The Laptev Sea is located in a unique position (Fig. 2) to address the following aspects of Arctic Ocean natural history, which will all be represented by the ongoing and planned research activities under the framework of the 'Laptev Sea System':

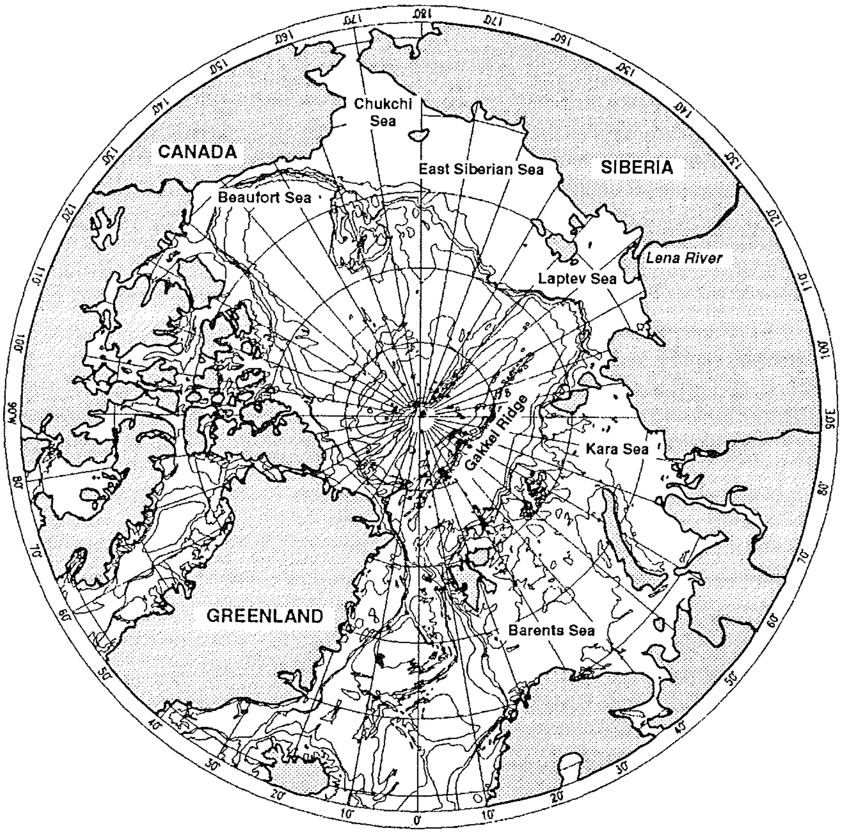

Fig. 2: Bathymetry of the Nordic Seas

1. The Laptev Sea is farthest away from the influence of the Atlantic and Pacific water masses whose properties can be followed both in terms of oceanography and biology from the Barents Sea (Atlantic influence) and the Bering Sea (Pacific). The Laptev Sea is henceforth the most Arctic of the wide Eurasian shelf seas.

2. The Laptev Sea oceanography is characterized by an intensive interaction between the marine water masses of the Arctic Ocean and the river run-off from the Lena River and a number of other large rivers draining the Siberian shield areas and adjacent land regions. Sediments of the Laptev Sea floors should reflect this influence through their variable composition.

3. The Eurasian shelf seas are some of the largest shelf seas of the World Ocean. Because of the peculiar climatice situation of the Arctic Ocean the circum Arctic shelfs are believed to be places of the formation of cold, saline and oxygen rich brines which cascade across the continental margins into the adjacent deep-sea basins, henceforth, influencing the oceanography of the northern hemisphere polar deep-sea basins. These brines seem to influence the morphology and physiography of the deeper parts of the continental margins through gully, channel and canyon formation as well as the deposition of large quantities of tubidites in the Arctic deep-sea basins.

4. The ice margins of the Arctic ice pack and of the coastal fast ice are subject to extreme seasonality. This is particularly well developed under the influence of the seasonally highly variable run-off of the Lena River.

5. The nutrients contributed by the rivers to the Arctic shelf seas are resulting in a considerable biological productivity despite the extreme living conditions which have developed in the Arctic Ocean.

6. Recent investigations of the flaw lead separating the coastal fast ice from the drifting Arctic ice pack have shown that the Laptev Sea is one of the most important "ice factories" of the entire Arctic Ocean. Here new ice is continuously formed which is then contributed to the Trans Polar Drift and which is transporting large quantities of sediment included into the ice due to the peculiar ice-formation processes (frazil ice) in the Laptev Sea.

7. The monitoring of the extent of the Arctic ice cover since the beginning of this century has shown that the global temperature increase during the past decade have seen a response in a reduction of the ice cover. The Eurasian shelf seas, in particular the Laptev Sea, might therefore be excellent objects to monitor the impact of Global Change.

8. The history of the Laptev Sea during the geological past is particularly interesting because this region was properly located to the east of the large north European ice shield. Its paleoenvironmental variability is influenced by the changes of the river run-off from the large Siberian land masses by eustatic sea-level changes and by the impact of tectonics of the young intersection of the active mid-ocean Gakkel Ridge and the underlying continental basement.

The various papers of this volume reflect the presentations and discussion of the workshop in St. Petersburg in May 1993. They also define the scientific perspectives for the project 'Laptev Sea System' which will be one of the major international interdisciplinary research projects addressing a key area of a climatically highly sensitive sub-basin of the World Ocean. Therefore, we all are looking with great interest to the execution of this projects, to the expeditions which have to be organized to study the properties of the 'System Laptev Sea' during the various seasons and we are expecting with excitement the scientific results which will come out of this effort of the Russian-German Cooperation.

J. Thiede and H. Kassens

OCEANOGRAPHY, BIOLOGY, AND CLIMATOLOGY
OF THE
LAPTEV SEA AND THE EAST SIBERIAN SEA

THE ARCTIC SEAS IN THE ARCTIC CLIMATE SYSTEM

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In many respects polar regions are key areas of the global climate system in which strong natural fluctuations in climate characteristics are maintained due to the variations of advective exchange with non-polar parts of this system and to the interaction between the polar system components. The global role of the Arctic is fulfilled, first of all, through the polar ocean, which can change its structure, thermodynamic properties and circulation patterns as a result of variations in the advective exchange of fresh water, salt and heat with the non-polar parts of the global system (ACSYS, 1992). Furthermore, desalinated upper layers and sea ice at the surface are the most active components of the polar oceans (Fig. 1).

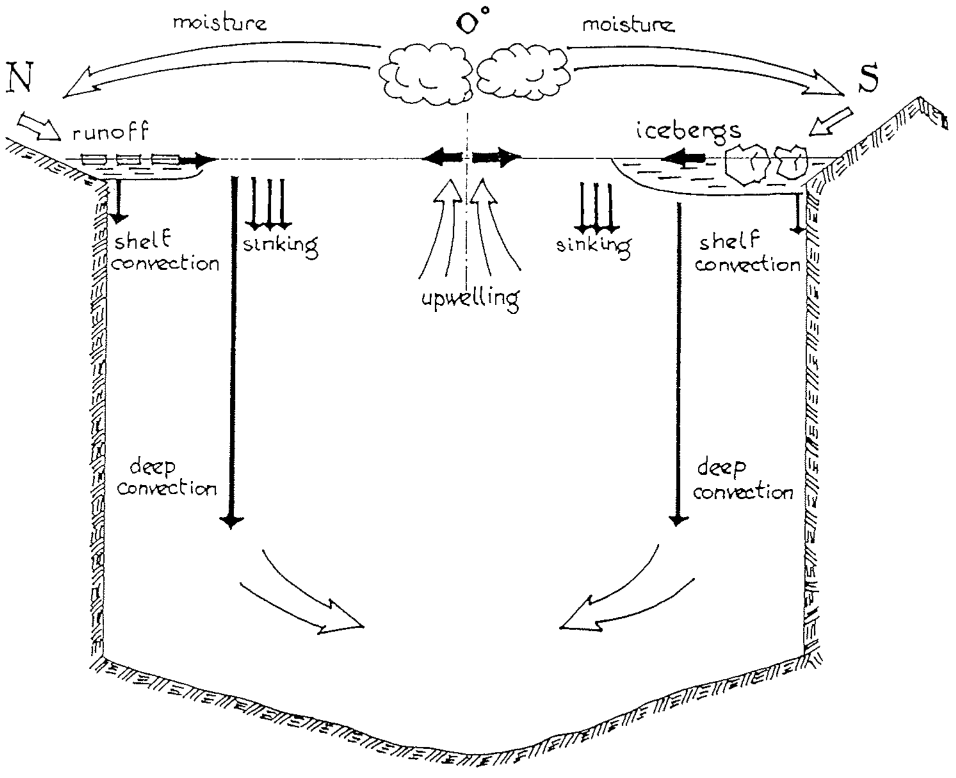

Fig. 1 A diagram of the interaction of polar and extra-polar processes and structures in the global climatic system.

The oceans at high and middle latitudes make a particularly noticeable contribution to the formation of natural climate fluctuations. In addition, they enhance mean annual temperatures in the climatic system through the interseasonal redistribution of incoming heat and the amplitude decrease of mean temperature variations (Alekseev, 1992). Therefore, the oceans of high and middle latitudes play a major role in the formation of a wide range of natural fluctuations in global climate. Certain of these fluctuations are induced through the passive participation of the ocean as an unlimited source of heat and moisture for the atmosphere in winter during short-term variations in atmospheric circulation. Other, long-term variations develop as a result of the activities of the oceans in high latitudes, primarily through changes in the parameters and properties of their upper active layers.

In the Arctic Ocean a shallow upper layer is separated from the lower water mass by a strong halocline. The boundaries of this desalinated "lake" and of drifting ice in the Northern Hemisphere coincide fully with one other and both experience strong interannual variations, particularly in the vicinity of the Atlantic Arctic (Zakharov, 1981). One of the causes for these variations is related to river run-off into the Arctic Ocean from surrounding land areas (Mysak et al., 1990; Savchenko and Nagurny, 1991) This river run-off makes the main contribution to the fresh water balance of the Arctic Ocean (Ivanov, 1976, 1991; Aagaard and Carmack, 1989). This is confirmed by sufficiently coordinated fluctuations of mean annual run-off from the princial Siberian rivers and the ice extent of the Arctic seas (Fig.2).

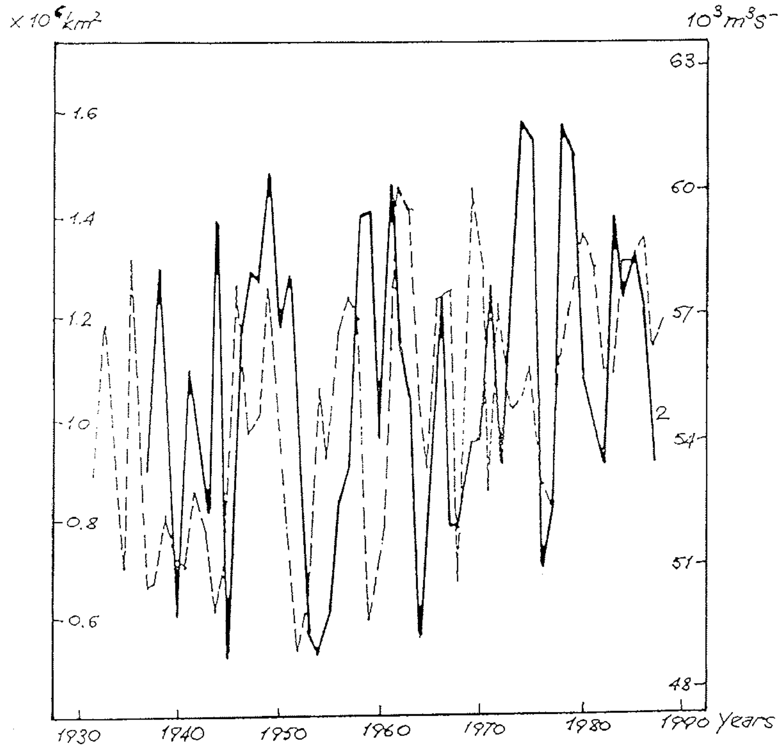

Fig. 2 Changes in sea-ice area in the Siberian Arctic seas in September (Zakharov, 1991) and mean annual run-off of the six principal Siberian rivers (Ivanov, 1991).

An excess of fresh water in the upper layer of the Arctic Ocean is transported in the form of sea ice through the Fram Strait. When this excess is transformed into ice, the main amount of heat, which is transfered through the surface of the Arctic basin to the atmosphere in winter, is released (Alekseev, 1992).

At the same time, another theory states that a large portion of heat lost from the upper layer stems from water of Atlantic origin as it flows into the western part of the Arctic basin. From a generalization of available estimates of water, heat and of salt balance constituents it follows that the thermal contribution of Atlantic water into the upper layer is estimated to be two to three times less than the contribution of ice formation. At the same time Atlantic water serves as the only source for maintaining the salt balance of the Arctic Ocean.

The problem to be discussed, then, concerning the Atlantic water, is the mechanism and location of its entrainment into the upper and lower layers. The earliest perspective on this problem is given by Nansen (1928) and was later shared by Timofeev (1960) and Treshnikov and Baranov (1972). This theory postulates that Atlantic water mixes with river water and, in part, with Pacific Ocean water (in the east) along the shelves of the Arctic seas, thus forming a polar water mass which later accompanies outflowing ice into the North Atlantic.

The bulk of Atlantic water is entrained into deep and near-bottom layers, most likely in the vicinity of the Fram Strait, where the transformation of Atlantic water occurs as it passes through the Fram Strait together with the West Spitsbergen Current and enters into intermediate Atlantic water masses (Aagaard et al., 1987). Following this, all three water masses extend eastward, are gradually transformed and selected by systems of underwater ridges and fill the deep-water basins of the Arctic Ocean (Nansen, 1928; Timofeyev, 1960). This understanding of the formation of the large-scale structure of water masses is also confirmed by recent observations from aboard icebreakers (Anderson and Lönnroth Carlsson, 1991). The suggestion that the considerable contribution of winter cooling processes and water desalination on the shelf to the transformation of deep and bottom waters in the Arctic basin (Aagaard et al., 1981) has not yet been widely supported. At the same time it is obvious that significant volumes of cold and relatively saline winter intermediate waters are formed on the continental shelf slopes and in the troughs of the Barents, Kara, Laptev and also the Chukchi and Beaufort Seas. In some cases, these intermediate waters sink along the continental slope into deeper layers (Nikiforov and Shpaikher, 1980). The literature reports evidence of such sinking along the continental slope (Quadfael et al., 1988, Aagaard et al.,1981). The most promising regions for the formation of deep and near-bottom waters appear to be the continental slopes of the three Eurasian Arctic seas, along which the main water flow of Atlantic origin extends. Modelling of circulation in the Arctic basin (I. Polyakov, 1993, personal communication) shows that the most active vertical shifts in and transformation of the water salinity field occurs there with the participation of tidal motions.

In the Arctic seas into which the principal Siberian rivers flow river and sea waters mix and the formation of new volumes of surface Arctic water takes place. The properties and volumes of these waters are correlated to river run-off volumes and to the state of surface waters far outside the limits of formation regions. Estimates of interannual temperature and salinity changes in the Arctic seas indicate (Fig. 3) that some desalination and warming of water

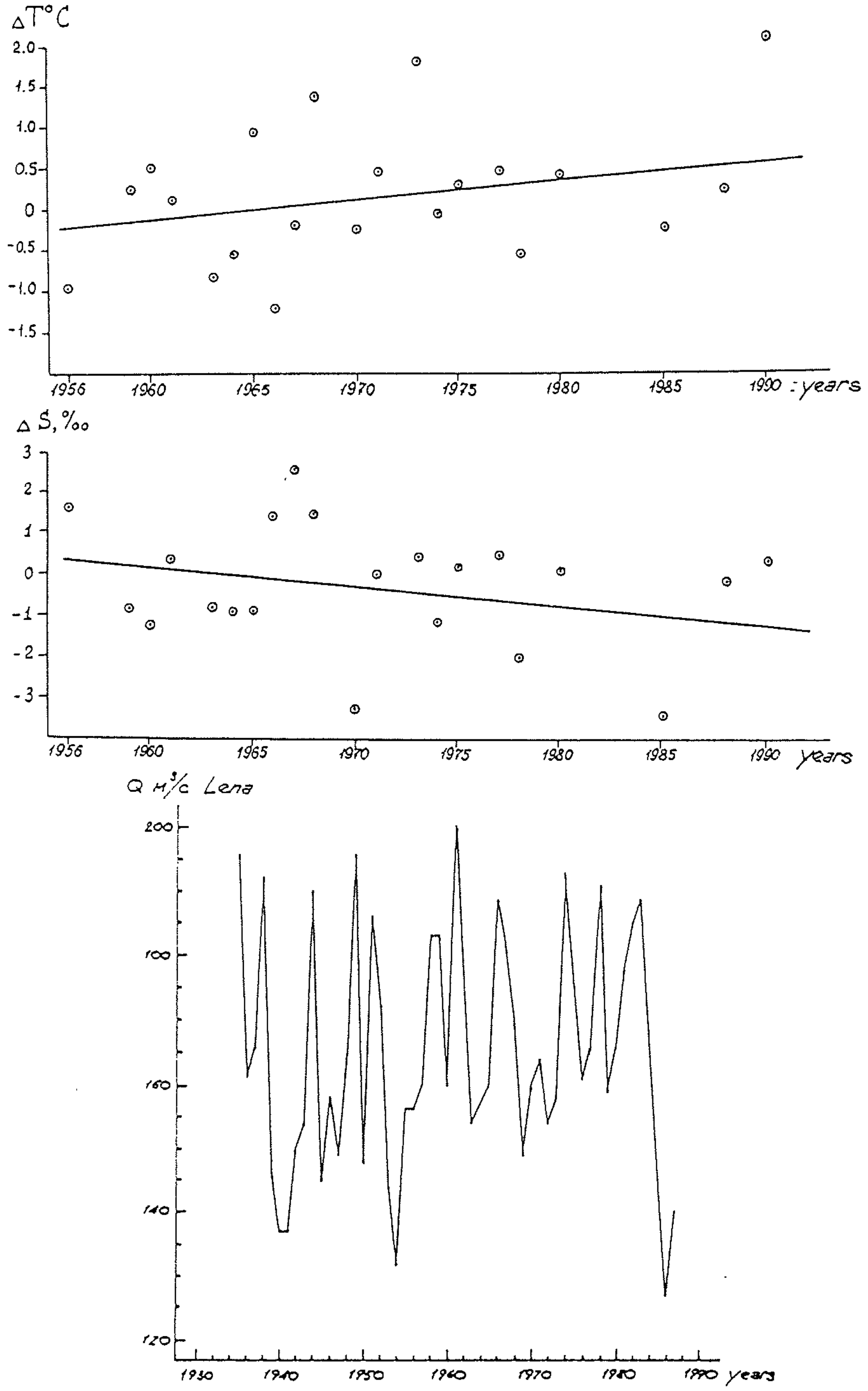

Fig. 3 Anomalies of mean water temperature (a) and salinity (b) in the 0 to 25-m-deep layer in summer in the Laptev Sea (Yanes et al., 1992) and mean annual run-off from the Lena River (b) (Ivanov et al., 1993).

masses takes place in these seas, in keeping with characteristic changes in the upper layer of the Greenland Sea (Alekseev and Korablev, 1993).

Thus, climatically active processes involved in the formation and evolution of desalinated upper layers and of sea ice develop in areas of the Arctic seas showing the active impact of fresh water inflow and energy exchange of Arctic basin water masses and at the continental slope of the Arctic Seas.

The Laptev Sea and its continental slope constitute an important part of the Arctic climate system which significantly contributes to Arctic influence on the climate. In this connection, the main points of investigation are:

- the formation of water masses in the Laptev Sea taking the run-off regime and exchange with the Arctic basin into account;
- the formation of water masses along the continental sea slope and in flaw leads and their contribution to the transformation and circulation of deep and near-bottom waters of the Arctic basin;
- an estimate of the contribution of water circulation and energy mass exchange with the atmosphere to these processes and their modelling;
- monitoring of the climatically active processes in the Laptev Sea. The implementation of these goals includes:
- regular expedition observations of thermohaline water structure during various seasons of the year with the use of vessels, drifting ice stations and fast ice;
- estimates of the seasonal and interannual variability of thermohaline structure;
- modelling of oceanic processes along the continental slope and of the combined circulation of the Arctic basin and the Laptev Sea.

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THE ARCTIC SHELVES: THEIR ROLE IN WATER MASS FORMATION

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Climate research is in recent time increasingly concerned about the role of polar areas in the global climate system. The role of the Arctic Ocean in the climate system is based mainly on two functions:

- its impact on the radiation budget which is controlled by the sea ice
- and cloud cover and
- the transformation of watermasses which are exported from the
- Arctic and which determine the thermohaline circulation of the
- Atlantic.

This paper deals with the second effect.

The thermohaline circulation is considered to be initialised in the North-Atlantic by formation of dense water which sinks to great depths, spreads southwards through the entire Atlantic and enters in to the Indic and Pacific Oceans. Slow upwelling raises the water back to the surface where it returns to the North-Atlantic closing the loop. On its way through subtropic areas the water gets warmer and saltier due to insolation and evaporation. The transportof salty water to the far north is the condition for deep convection which is the controlling process for global circulation. This special role of the Atlanticis determeined to a large extent by the direct connection to the Nordic Seas and the Arctic Ocean where a great part of this deep convection takes place.

The Atlantic Ocean is linked to the Arctic Ocean by the water exchange through the Nordic Seas and Fram Strait. The inflow into the Arctic Ocean is relatively warm and salty in the upper layers, while the deep northward flowing water from the Greenland Sea is relatively cold and fresh. The outflow of the Arctic Ocean through Fram Strait shows a reversed signature: The upper southward flowing water is fresher and colder and the deep water is warmer and saltier than the respective northward flowing waters. This implies a downward flux of heat and salt in the Arctic Ocean.

There are indications that much of the water mass transformation occurs on the shelves. The freshening of the surface waters is due to precipitation, melting of ice and - as most important contribution - to fresh water runoff from the surrounding continents. The increase in temperature and salinity of the deep and bottom water, however, is supposed to be a result of ice formation. The ice extent of the Arctic Ocean doubles from summer to winter and ice as well as meltwater are exported. Most of the ice formation which is needed to balance the loss occurs on the shelf.

When sea ice is formed, very saline and dense brine is released which sinks. During the convection the brine plumes entrain ambient water. Hence, the characteristics of the so formed Shelf Brine Water (SBW) depends not only on the ice formation rate and the surface water salinity but also on the rate and the temperature/salinity structure of the subsurface water which is entrained. SBW accumulates at the shelf bottom (Blindheim, 1989; Midttun,1985) and flows in a gravity current along the shelf bottom towards the shelf edge if the production is high enough. From there it is expected to sink along the continental slopesinto the central basins where it settles at levels that are determined by their relative densities.

It has been suggested by Aagaard et al. (1985) that due to its salt excess SBW could be dense enough to reach the deep-sea bottom. On its way down the continental slope the plume is again exposed to considerable entrainment. Along the Eurasian slope the descending SBW has to pass the several hundred meters thick layer of Atlantic Water which has a similar salinity but a significantly higher temperature. Hence, SBW which starts its descent at freezing temperatures might end up with the temperature of Arctic Ocean Deep Water, -0.7 to -1.0C, and slightly elevated salinity. An indication of a flow of SBW down to the deep sea bottom is given by measurements in the Nansen Basin by Smethie et al (1988): The bottom water below 3000 m shows a distinct increase in salinity of 0.01 at a constant temperature of -.95C. The increasing content of chloroflouromethane towards the bottom shows that the bottom water contains contributions of water which is younger than the overlaying deep water.

Another thermohaline structure of the Arctic Ocean, the Arctic halocline, can be explained by a contribution of SBW as well. It consists of a layer between 50 and 150 m which is characterized by temperatures close to the freezing point and by salinities increasing from 30.0 to 34.5 psu. Due to the strong stability, the halocline isolates the deep waters from the surface water and thus is important for retaining the ice cover.

Because the halocline structure cannot be maintained by mixing between surface and intermediate water,which would require a similar gradient in temperature, it is assumed that the halocline is formed by SBW spreading from the arctic shelves towards the deep basins. Aagaard et al. (1981) estimate for the maintainance of the Arctic halocline that any formation process should provide water with a salinity of 34.75 and temperatures near the freezing point at a rate of 2.5 to 5 * 10^6 m^3s^{-1} over the entire Arctic continental shelf. Recent research in the central basins - specially with the help of chemical parameters such as nutrients - allows for a better localisation of the origin of different halocline types. While the upper halocline, characterized by a nutrient maximum is probably formed in the Chukchi and East Siberian Sea, lower halocline water associated with a minimum of the conservative parameter NO $=[O_2]+9[NO_3^-]$, seems to originate in the Laptev-Kara-Barents Sea (Anderson and Jones, 1992). However, due to the lack of measurements in the shelves seas, these findings remain hypotheses up to now.

The Siberian shelves are rather shallow (100 m) as compared to the Barents- and Kara Sea and the water is rather brackish due to the large inflow of river water. The Barents and northern Kara Sea have a high salinity due to the direct inflow of Atlantic Water. Hence, on the western shelves the initial salinity of the freezing surface water as well as the underlying water entrained to the brine plume is higher than the salinity maximum of the halocline which is about 34.5. Furthermore, the troughs where SBW can accumulate are mostly deeper than 200 m. Hence the Barents and northern Kara Sea are more likely a candidate for Arctic Ocean Deep Water renewal than for the maintainance of the halocline.

In order to study the role of SBW in the Barents Sea, moorings have been deployed south of Svalbard (76°38' N, 19°8' E) from June 1991 to September

1992. Time series of the formation of SBW during winter were obtained (Fig. 1) and the outflow can be estimated from a combination with hydrographic measurements. Close to the bottom there is a continuous southwestward flow which enters into the northern Greenland Sea. At the end of January, when a strong increase of the ice cover occurs in the northwestern Barents Sea, the temperature of this flow reaches almost the freezing point and the average speed increases by more than 100. This strong flow of -1.8° C cold water lasts for about 4.5 months. In this period, the salinity increases from monthly mean values between 34.71 and 34.87 during summer to values between 34.9 and 35.0. Hence, the flow in the bottom layer can be identified as SBW which, however, is not all the time saline enough to maintain the salinity of Arctic Ocean Bottom Water of 34.93. From June 1992 on the cold temperatures become more and more intermittant, indicating a fluctuating drainage of the reservoir through the whole summer period.

Assuming a constant outflowing layer of SBW to be 20 km wide and 25 m thick according to the hydrographic sections in summer, a SBW volume of 300 km3 is drained into the Greenland Sea during the freezing period. This is a fairly large amount as we have to keep in mind that the area of ice production maintaining the observed flow is only a rather small region south of Svalbard.

Sections across the continental slope west and north of Svalbard revealed tongues of low salinity water attached to the bottom at depths of about 800 m. The observation of low salinity values in the SBW time series south of Svalbard and of patches with negative salinity anomalies at the continental slope seems to contradict the postulation that SBW from the western shelves are to maintain the high salinity of Arctic Ocean Deep and Bottom Water. Infact, our results reveal a third role SBW has to play in Arctic Ocean water mass formation. This is on one hand a contribution to the dilution of the warm, saline Atlantic Water core which spreads along the continental slope at the Nansen Basin and secondly the maintainance of the weak salinity minimum between the Atlantic Water and the saline Arctic Ocean Bottom Water. As mentioned above, the characteristics of SBW are dependant on the initial salinity of the freezing water and on the water entrained on its way to the shelf bottom. Both show a strong interannual variability in the Barents Sea (Loeng, 1991) which is strongly related to the variability of the ice coverage. Therefore it is conclusive that both, rate and characteristics of SBW, vary from year to year. A SBW plume at freezing point temperature with a salinity of 34.9 is even after entraining less dense water heavy enough to sink below the Atlantic Water layer and thus decreases instead of increases the deep water salinity. Only in years with high enough salinity of the Barents Sea water, SBW will be able to sink to the deep-sea bottom and to maintain the high salinity of the Arctic Ocean Bottom Water.

Finally we can state that accumulations of cold saline water found in shallow troughs in many regions prove that SBW is likely to be formed on all shelves surrounding the Arctic Ocean. However, depending on the initial surface salinity, the salinity and temperature of the ambient water which is entrained, the depth of shelf depressions where SBW can accumulate and the ice formation rate the role of SBW varies considerably on the different shelves. The SBW of the Barents Sea and the Kara Sea is probably mainly involved in deep water formation because of its higher salinity and greater accumulation depth, whereas SBW of the Siberian shelves is more likely to maintain the halocline. Furthermore, interannual variations in the initial conditions in a certain shelf sea can again alter the impact of SBW on the Arctic Ocean water masses.

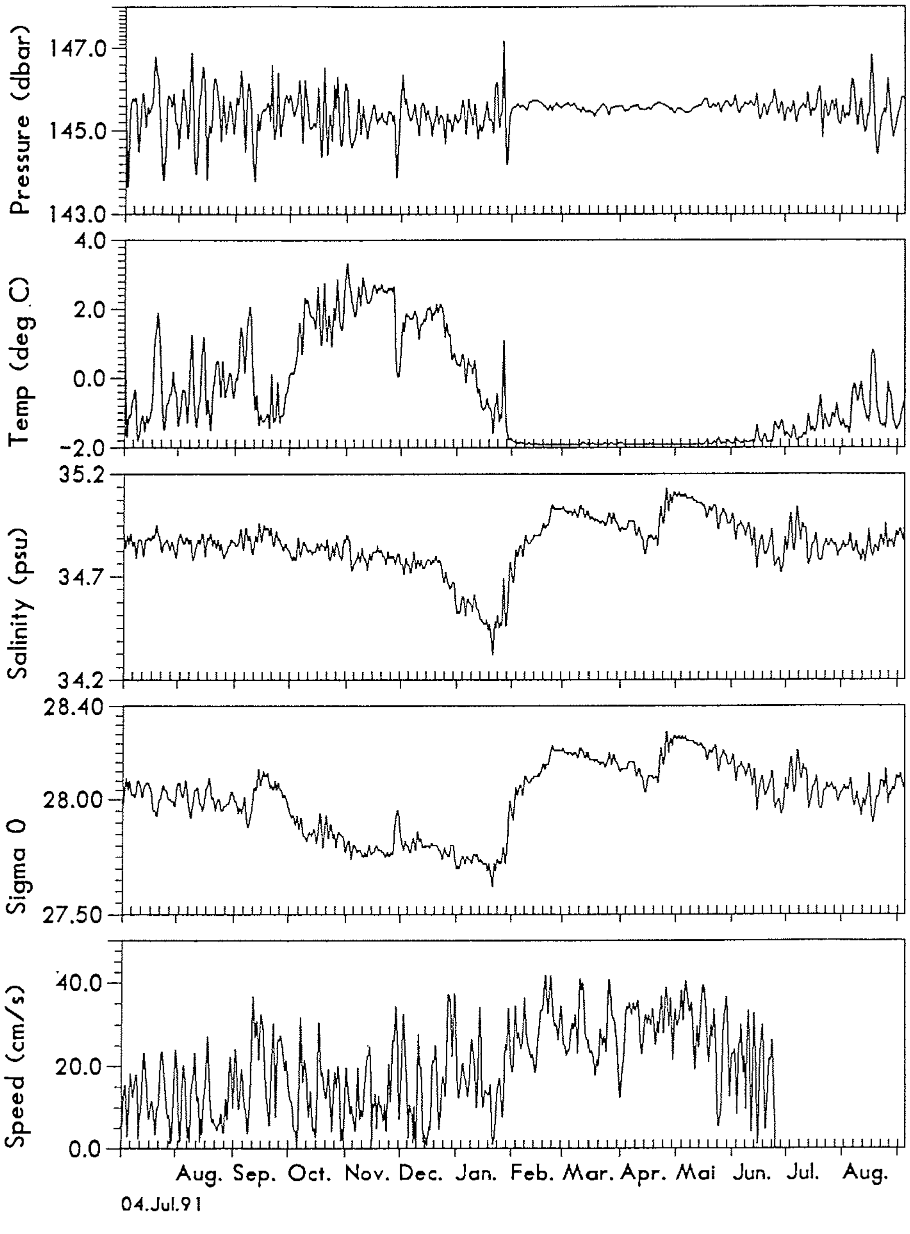

Fig. 1: Records of pressure, temperature, salinity, density and velocity 20 m above the bottom at 76°38' N, 19°8' E. The water depth is 160 m.

Up to date, apart from pilot studies, neither the process and rates of formation and characteristics of SBW on the different shelves nor the mechanisms of the link between shelves and interior basins are known in sufficient detail.

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REGIONAL CHARACTERISTICS OF THE LAPTEV AND THE EAST SIBERIAN SEAS: CLIMATE, TOPOGRAPHY, ICE PHASES, THERMOHALINE REGIME, CIRCULATION

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The Siberian shelf seas have many common features: severe climate, ice cover presence, intensive desalination in summer due to river run-off and ice melt, highly active geochemical processes, fairly low-intensity biochemical processes, attenuated processes of water self-purification and a fragile habitat. In this respect, research in the Laptev Sea constitutes a basis for understanding the features of other water bodies, of the estuaries and of the seas in the northern polar zone. However, there are phenomena in the Laptev and the East Siberian Seas which are particularly pronounced. Here it is possible to speak of the specific and, to some extent, unique character of the environment of this region. Some characteristic features are:

- islands which disappear in a large shallow area of the Laptev Sea. In the late 1950's Semenovsky Island became a sand bank and remained so for 40 years. Previous to that the islands of Vasil'yevsky, Merkurius and St. Diomid, among others, disappeared.
- heavy ice from the Taimyr ice massif in the Laptev Sea and strong ice from the Aion ice massif in the East Siberian Sea act as two large "ice arms", extending either synchronously or asynchronously from the Arctic basin, blocking or freeing the northern sea route in summer.
- the largest amount of sea ice is transported out of the Laptev Sea and into the Arctic basin in winter. For this reason, the Laptev Sea is known as the factory of the Arctic ice.
- the Laptev Sea is an "oasis of life". This is evidenced by the fact that a herd of New Siberian walruses does not leave the sea.
- there are suprisingly quick, long and extensive migrations of polar fox and reindeer extending across the wide fast ice and sometimes across the drifting ice along the coast and in river estuaries to the Northern Land and New Siberian Islands, covering the Laptev Sea with a very rare "ring of life".
- the Laptev Sea is one of the few Arctic seas in which earthquakes are observed.

The geographical location of the Laptev and the East Siberian Seas has the following peculiar features. The seas are not under the direct influence of warm Atlantic and Pacific ocean waters, as for example, the Barents and the Chukchi Seas are. The East Siberian Sea and about 70 % of the water area of the Laptev Sea are the most shallow seas in the Arctic. The seas are widely connected with the Arctic basin. A comparison of the characteristics of the seas of the Siberian shelf is presented in Table 1.

The climate of the seas differs from that of other regions, it can be defined as the Siberian (or Central) climatic region. For comparison, let us note that the Western climatic region includes the Barents Sea, the largest (western) part of the Kara Sea and a significant part of the Arctic basin. The eastern region includes the eastern (smaller) part of the East Siberian Sea, the Chukchi Sea and the Bering Strait.

Table 1: A comparison of the characteristics of the Arctic shelves seas

	Area (km ^{3})	Mean depth (m)	Depth at the shelf edge (m)	Ice volume, end of winter (km^3)	Ice outflow (km^3)	Ice melt, end of summer (km^3)	River run-off (km^3/a)
Barents Sea	1424	222	500	860	40	775	478
Kara Sea	883	111	500	1520	240	930	1347
Laptev Sea	662	53	200	1490	540	650	767
East Siberian Sea	913	54	200	1260	150	960	213
Chukchi Sea	595	71	200	540	10	600	78

The differences between the regions are observed mainly in the cold period, which last from October to April. They are governed by the circulation character and partly by differences in the thermal effect of the underlying surface, which in some places is also stronger in the cold period.

While the western and eastern climatic regions are affected by cyclonic circulation, the Siberian region is characterized by the most continental climate and by the lowest winter temperatures. Mean January air temperature over the sea is -30° to -32°C. Cyclones are rare in winter and come to the region at the filling stage, thus not significantly affecting the climate. The Laptev Sea is jokingly referred to as the cemetery of cyclones by synopticians. Wind speed over the sea is an average 5 m/s, storms occur in the Laptev Sea three to four times and in the East Siberian Sea two to three times monthly. Cloudiness remains slight, and precipitation is also less than in other regions.

Solar radiation, continuously impacting the region during the entire polar day, plays the main role in its impact on climate. In summer, atmospheric circulation is weaker. Sea circulation is characterized by low stable air temperatures of 0° to -1°C in July. Relative humidity reaches 95-98 %, which is why fog is quite frequent, especially in regions with considerable ice accumulation.

The specific features of the Laptev Sea are revealed first of all in its configuration and bottom topography. The bottom of the southern sea presents quite a sloping plain, lowering to the north, cut by canyon-like troughs, which are now only weakly pronounced. These troughs are all located at the mouths of rivers, entering the sea from the south. The underwater troughs appear to be the traces of the river valleys which crossed the low plain many millenia ago (Kotyukh et al, 1990).

The sea bottom is filled by silty deposits with separate lenses of fossil ice. The ice structure of the bottom and the islands appear to be important factors which influence the intensity of geomorphological processes in the basin. However, the extent of spreading, depth and strength of ice formations of the bottom sea bed have as yet been only insufficiently studied.

Repeated measurements of the sea have allowed Kotyukh et al. (1990) to identify the following typical features. At present, the entire continental shoal of the Laptev Sea (the dynamics of the reformation of the underwater relief, coastal band and coast configuration) is characterized by such tendencies: rising of shores and the sea bottom, intensive destruction of shores and smoothing of coastline configuration, depth increase at the continental slope and near retreating shores, a distinct depth increase near islands which disappeared recently and near extensive shoals, general levelling of ice microstructures.

Distinct differences in depth are observed in the Laptev Sea. In its southern part, mean depths are within a 15- to 25-m-span. Near the New Siberian Islands the shallow area extends up to 600 km from the Arctic coast, while the northern sea boundaries pass over the sea bed with depths of more than 2000 m. A sharp continental slope divides the Laptev Sea into its northern and southern parts along a line parallel to the Vilkitsky Strait.

The East Siberian Sea is the shallowest of the Arctic seas, with prevailing depths of 15 to 50 m. The northern sea boundary passes between the isobaths of 100 and 200 m, and only in the northeastern part are depths of more than 1000 m observed.

The seafloor represents a plain, sloping slightly from southwest to northeast, but there are no significant valleys or elevations in the sea (Baskakov et al., 1987). The structure of seafloor and the dynamics of the underwater relief of the East Siberian sea have not been investigated as thorougly as seafloor stucture and underwater relief dynamics in the Laptev Sea.

If the 200-m-isobath is assumed to be the shelf boundary, then shelf zones make up 72 % of the Laptev Sea and 96 % of the East Siberian Sea.

The sea landscape is formed by drifting and stationary ice, zones of ice-free water between ice floes and by significant areas which are free of ice in summer. An understanding of the ice cover extent of the seas in summer can be gained from the investigation of average ice distribution in 1962 and 1968, the coldest and the warmest year, as shown in Figure 1. The extreme years show that oceanographic conditions and the ecological situation in the seas can change considerably from year to year. Let us note that the amplitude of the interannual variability of ice cover extent in the Laptev Sea has been largest in recent decades.

Water temperature and salinity distribution at the sea surface in summer are governed by ice conditions, river run-off and water exchange with adjacent water reservoirs. In general, mean surface water temperature in the Arctic seas decreases gradually northward. In coastal regions, which are under the influence of river run-off from Siberian rivers, surface water temperatures can reach 8 to 10°C and more in summer (Baskakov et al., 1987). The western portion of the Laptev Sea, to which the Taimyr Current transports Arctic basin water, is colder than its eastern part, which, in turn, is affected by warm river water (Fig. 2). The waters of the eastern Laptev Sea, penetrating through the straits of the New Siberian Islands, and the thermal discharge of Indigirka govern the heating of surface waters to temperatures of up to 3 to 4°C. In the eastern part of the East Siberian Sea the impact of Arctic basin water is strongly evident, as is demonstrated by a narrow band of heated water near the coast, which, in spite of the warming influence of the Kolyma water, is much narrower than that in western part of the East Siberian Sea (Baskakov et al., 1987).

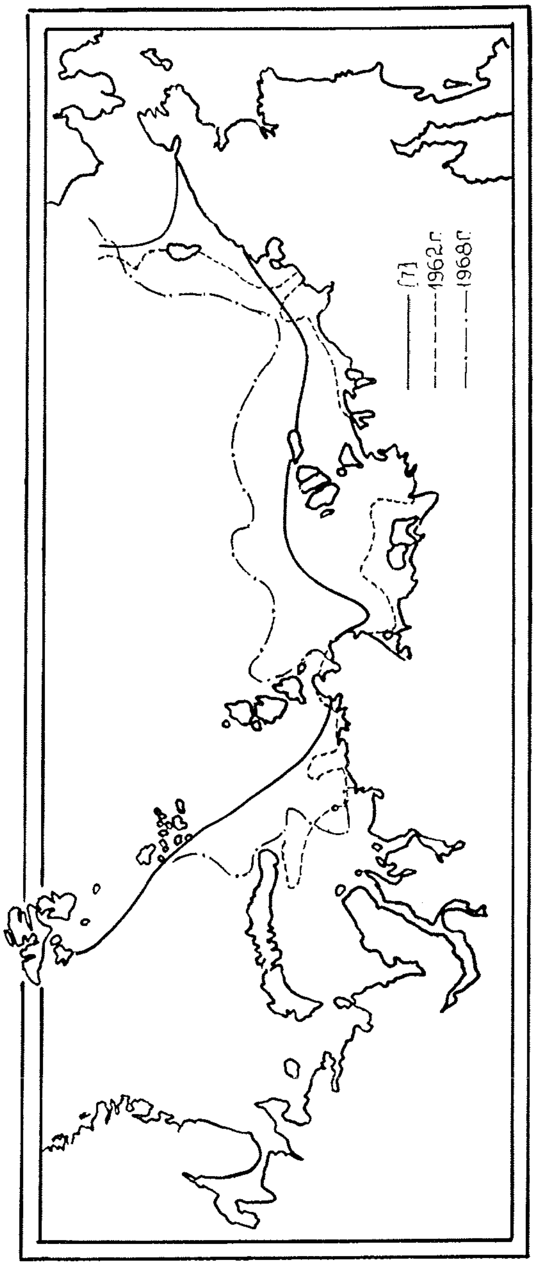

Fig. 1: Ice extend of the Siberian shelves seas during summer

The salinity of Arctic seas stems the influence of the outflow of fresh water from rivers, freshening due to ice melt and the salinating effect of water from the Arctic basin and adjacent seas (Fig. 3).

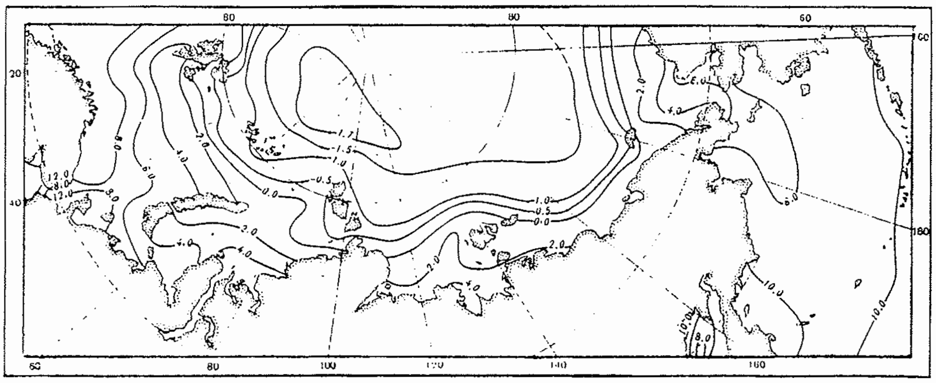

Fig. 2: Surface water temperature distribution of the Arctic seas

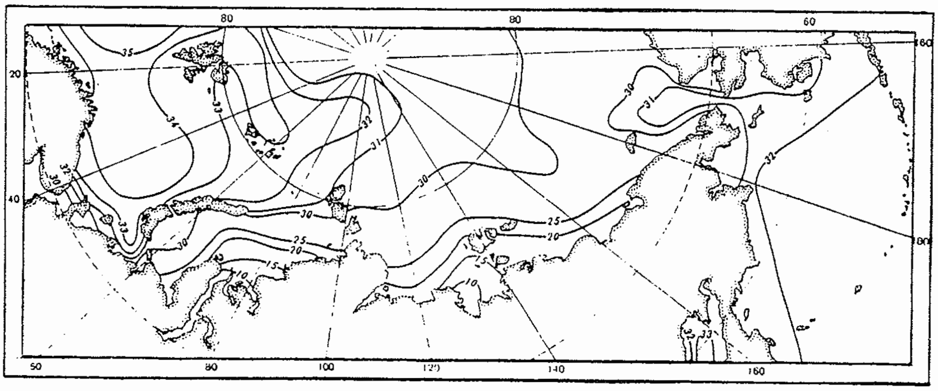

Fig. 3: Surface water salinity distribution of the Arctic seas during summer

The waters of the western Laptev Sea, in which low-temperature water masses with enhanced salinity flow from the north, are significantly more saline than the waters of its eastern part. In the northwestern Laptev Sea salinity reaches 28 % at the surface, while the eastern Laptev Sea is characterized by a decrease in salinity from 25 to 10 %. Similar salinity values are found in the western East Siberian Sea. There, with increasing distance to the north from the mouths of rivers, salinity increases from 10 to 28 % (Baskakov et al., 1987).

In summer, the desalinated layer is generally 5 to 7 m thick. Figure 4 shows vertical salinity distributions from data collected to the north of the Lena River delta.

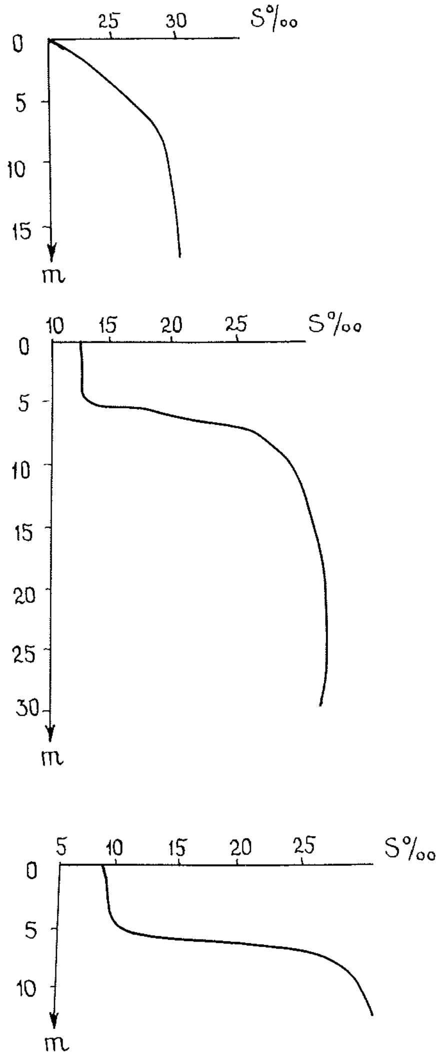

Fig. 4: Vertical salinity distribution in the vicinity of the Lena River mouth

The extent of desalinated water in the sea depends on the intensity of river run-off and the direction of prevailing winds. Frontal divides, which separate desalinated waters, respond rapidly to changes in atmospheric processes. These fresh water areals are, however, to be identified in the climatic context. Three types of desalinated water distribution, namely western, eastern and fan-like, are found in the Kara Sea (Fig. 5). In the Laptev Sea the most frequently obseved types of distribution appear to be a maximum (northward), minimum and eastern extension of desalinated waters (Fig. 5).

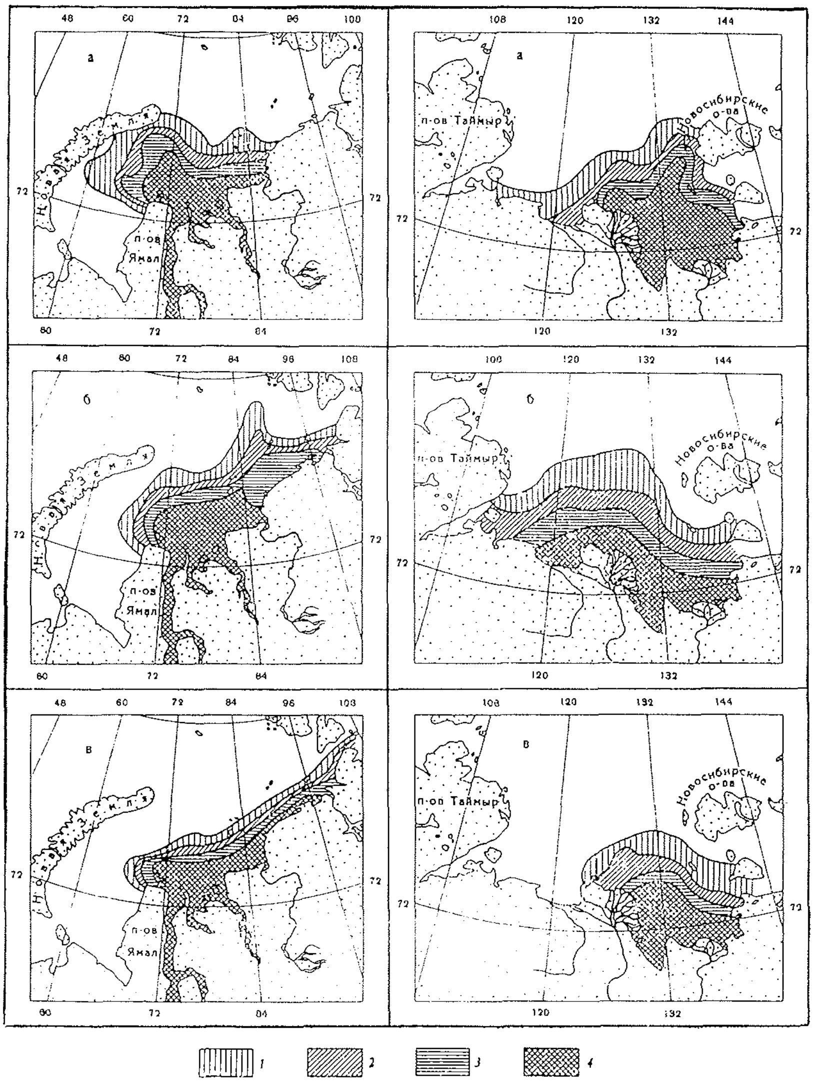

Fig. 5: Types of desalinated river water (1 = 50-70%, 2 = 70-80%, 3 = 80-90%, 4 ≥ 90%)
(I) Kara Sea: a) western, b) fan like, c) eastern
(II) Laptev Sea: a) northern maximum, b) northern minimum, c) eastern

In summer, currents at the Arctic sea surface are closely connected with wind distribution over the seas. But, in spite of a large synoptic variability in these currents, it is possible to identify constant currents in our data. These currents form the water circulation scheme as shown in Figure 6.

As can be seen in Figure 6, two typical features are visible in the circulation of surface water. In the coastal zone, currents are directed eastward along the general direction of the coastline. A general cyclonic water motion is observed in the seas.

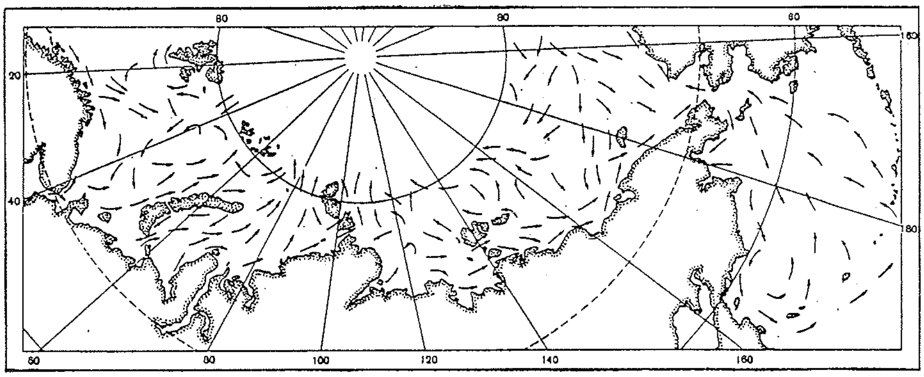

Fig. 6: Surface water of the marginal seas

Very little is known about the deep and near-bottom currents, and measurements of currents at the shelf slope have not been carried out at all by AARI investigators.

Surge-level fluctuations decrease slightly eastward to the western Laptev Sea. They increase up to 2 m and more in the eastern Laptev Sea and in the East Siberian Sea. Further into the Chukchi Sea these surges again decrease. The attenuation of surge-level fluctuations to the north of the mainland coast appears to be the most generally typical feature of the Arctic seas. As a rule, the largest surges are observed in regions of the Laptev and East Siberian Seas with extensive shallow areas. The surge wind effect is reversely proportional to sea depth; the more so, the shallower the sea is. A decrease in surges to the north along the coasts of islands in the marginal seas can be attributed partly to this factor and partly to winds from prevailing directions.

In the Laptev Sea, along the Taimyr Peninsula and the Northern Land, restricting it from the west, and the New Siberian islands, from the east, the observed level fluctuations are a little more than 1 m. As a rule here the surge fluctuations also significantly exceed the tidal fluctuations. Figure 7 shows the values of surge level fluctuations and, for comparison, syzygial values (double amplitudes) of the tides. The prevailing surge fluctuations are particularly noticeable along the mainland coast. Here their values are five to six times greater than fluctuation in tidal level.

In the shallower East Siberian Sea, where the 50-m-isobath passes almost parallel to the mainland shore at an average distance of 550 to 650 km from it and the 25-km-isobath is on the average at a distance of 360 km, a vast shallow area contributes to the strong development of surge level fluctuations. As a result, surge level fluctuations over the entire continental shore of the sea reach level of 2 m and more, while tidal fluctuations are actually absent here.

In the Laptev Sea, tides are induced mainly by waves coming from the Arctic basin and move progressively futher southward. Evidently, due to the deviating force of the Earth's rotation, the tidal value near the right (relative to

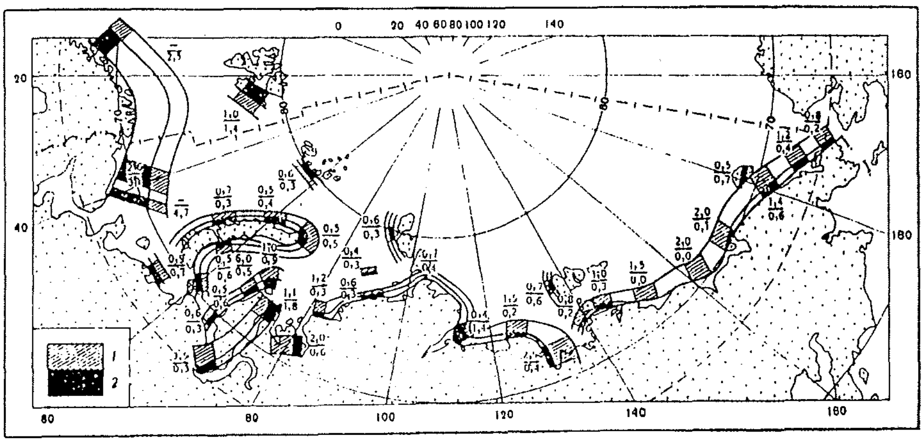

Fig. 7: Surge and syzygial tides level fluctuations (in meter, nominator = value of surge fluctuation, denominator = value of tidal fluctuation)

the direction of wave propagation) shores, in particular, the eastern coast of the Taimyr Peninsula, also increases. Near the entrance to the Khatanga Bay the syzygial tide value exceeds 2 m. In the southeastern Laptev Sea a decrease in tidal values is observed, which is also connected with the shallow features of this area. In the Laptev Sea, tides of a correct semidiurnal character, mainly about 2.5 days old, prevail.

In the East Siberian Sea as well as in other Arctic seas, the tidal wave, propagating from the Arctic basin southward due to a large depth difference at the continental slope, strongly deforms and gradually attenuates in the shallow area with decreasing distance from the shore. Accordingly, the value of the tide decreases from 1 to 1.5 m (in syzygy) in the north (near the New Siberian Islands and Wrangel Island) to 5 to 10 cm in the coastal areas (Bear Islands, Aion Island). The tidal wave, deviating on its way from the north to the right under the influence of the Earth's rotation, also progresses toward the Sannikov and Dmitry Laptev Straits. In turn, for the same reason, a tidal wave penetrates to the East Siberian Sea from the Chukchi Sea in the east through the Long Strait. At a prevailing correct semidiurnal tide in the East Siberian Sea its age here is also equal to approximately 2.5 days.

The dimensions of the waves in the Laptev Sea at winds of constant speeds and directions depend on the dimensions of ice-free water, where they occur and develop. Water acceleration changes on an average from 90 to 100 km in July to 550 to 650 km in September, with maximum accelerations reaching 850 to 1000 km. Waves with a height of more than 3 m are observed more often in fall (in September) than in summer. The most intensive swell develops near the western shores and in the central sea. Waves with a height of less than 1.5 m are more frequent. In summer (July to August) eastern storm winds can create maximum wave heights of 5 m in the Laptev Sea (Fig. 7). In the southeastern sea storm winds from other directions create conditions at which maximum wave heights seldom exceed 4 m. This is due to acceleration conditions at a wind speed of 18 to 10 m/s. The autumn period (September to October) is the stormiest in the Laptev and the Kara Seas. At this time of year wave heights reach their maximum (about 6 m). Along the Laptev Sea navigation route wave heights are usually comparatively small, as navigation routes pass primarily through coastal shallow areas.

In September, when the sea has its lightest ice cover and the speed of storm winds is at most 18 to 20 m/s, the maximum height of waves along the Northern Sea Route does not exceed 4 m, with the exception of stretches near the shores of the Taimyr Peninsula, where easterly winds can create waves with maximum heights of more than 5 m.

As compared with other seas, swell in the East Siberian Sea is weakly developed due to significant ice extent and shallow features.

With the ice edge retreat to the north from July to September, strong swells occur more frequently, reaching a maximum in September. In mid-August in the western East Siberian Sea a comparatively large area of ice-free water appears, where northwesterly winds of up to 20 m/s can create a strong swell with maximum wave heights of up to 4 m. Northeasterly winds in this region create waves with heights not exceeding 2.5 m.

In September, when the ice edge retreats far to the north, the western part of the East Siberian Sea to the meridian of the mouth of the Kolyma River is almost completely free of ice, and the maximum wave heights in these regions can reach 5 m. The maximum wave heights at the navigation route, which passes through the coastal shallow western sea, are about 3 to 4 m. However, sometimes the waves, being even a little less than 2.5 m but coming from the northeastern deep-sea region, become steeper here and, hence, more dangerous for small vessels. While enroute to the north of the New Siberian Islands ships can encounter waves of up to 5 m in height. In the years when the ice edge retreats far north and the western and eastern parts of the sea become ice free, a strong swell develops in the region between the 71° and 73° N parallels. The waves move to this region mainly from the east and southeast, and the height of the waves, which come from the west, remains small.

Ice melting occurs under the effect of solar radiation and air heat. According to calculations, solar radiaton during the polar day is sufficient to melt ice levels of natural growth in all the marginal seas. However, under real conditions, ice melting is delayed for two to three months due to high degrees of ice and snow reflectivity. 10 to 12 % of radiation heat is lost due to ice melt, the remaining energy being reflected into the atmosphere. The opposite is the case for open water, which absorbs large amounts of radiation and accumulates radiation heat well. That is why areas which become free of ice earlier are the centers of ice-cover disappearance in the sea.

The ice cover of the Arctic seas, as is typical of other large reservoirs, is characterized by a significant non-uniformity in time and space. The non-uniformity of this ice cover is to be found in the difference of the main ice characteristics: mobility, age, thickness, ridge amount, destruction extent, compactness, strength, etc.

Massifs, formed by fast ice, appear and persist in the regions with small depths and irregular coastlines. Near the steep shores with a level coastline the fast ice is characterized by a smaller width and by greater strength. For example, in the eastern parts of the Kara and the Laptev Seas, as well as to the west of the East Siberian Sea fast ice extends over hundreds of kilometers from the shore, forming a basis for the Northern Land, Yana and New Siberian ice massifs.

In mid-summer, when the Arctic sea area is, to a large extent, free of ice, the remaining ice is localized in specific places (for example, Novaya Zemlya and

Yana ice massifs). These local massifs are sometimes separated from other massifs by open water or open floating ice areas. By the fall the local massifs often disappear completely.

The branches of the oceanic massifs, extending to the marginal seas from the north, for example, the Taimyr and Aion, are most stable. During most of the year they can be supplemented by heavy ice from high latitudes. In summer these massifs are almost never destroyed completely, only retreating as a result of melting and wind-induced outflow northward.

The processes of ice formation and growth and the formation of ice cover in the Arctic seas occur in the same way. The only differences here are to be found in the scales and intensity of the processes.

The ice forms, first of all, in the place where water is more desalinated, where depths are not large and where water areas are protected from the effect of the winds and waves. That is why in the Arctic seas young ice appears first of all at the edge and among the remaining ice, near the shores, in shallow areas and at the mouths of river mouths. Depending on the hydrometeorological and ice situation formed by the beginning of the fall, the dates of freezing vary to a significant degree. Among the remaining ice patches ice formation can even occur in summer.

A particular role is played by the autumn storms before the onset of ice formation. Strong winds induce an intensive vertical mixing and a rapid cooling of the active layer at negative air temperatures. Immediately after storms rapid ice formation occurs over the large sea areas.

Rapid ice formation and growth after storms should lead to two consequences. In those places where the depths are small, sediment disturbance takes place as a result of wind-induced swell and turbulent mixing. During ice formation, suspended particles are frozen in the ice, thus contaminating it. There are still no experimental data which can confirm the capture mechanism of particles suspended in the water during ice formation. But if this hypothesis is assumed then, in the opinion of Dr. Spichkin, one can explain a more rapid ice melt in spring in the shallow southeastern part of the Laptev Sea by the effect of the inclusion of small particles on the thermal-physical properties of the upper layers of the ice cover.

The second consequence, which also requires additional investigations, is that the quantized formation of ice over the large sea area should "conserve" the redistribution of the water masses at the sea area under the influence of winds preceeding storms. It is likely that further changes in ice-hydrological conditions depend on the direction, strength and duration of storm winds before ice formation. According to Spitchkin, the presence of a correlation between the autumn storms before ice appearance at the open sea surface and subsequent development of ice processes in the Laptev Sea can be an indirect confirmation of such a scenario concerning the development of oceanic processes in the Laptev Sea.

The growth of ice thickness depends on meteorological and oceanographic conditions, which are not uniform in the sea areas. By the end of winter the natural growth of ice causes ice to reach thicknesses of 1.5 to 2.0 m.

A characteristic feature of the ice regime of the Kara, Laptev and East Siberian Seas appears to be the occurrence of large zones of stationary ice in winter. The fast ice extends over large areas due to small depths, highly irregular shorelines and large numbers of islands. Between fast ice and drifting ice, zones of ice-free water or young ice are formed. In certain periods these zones converge, forming especially large flaw leads. Figure 8 shows the position of the polynya. Let us note that the scheme presented for the Laptev Sea coincides with the polynya location in March of 1992 and satellite observation data (Dethlef et al., 1993).

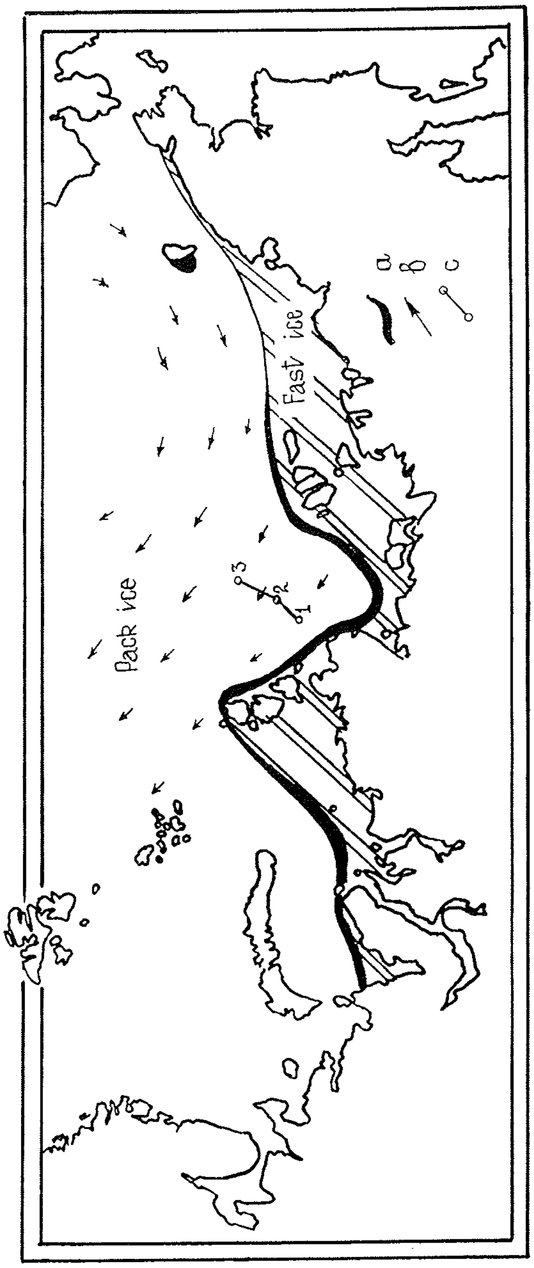

Fig. 8: Ice cover extend of the Arctic seas during winter
(a) polynya, (b) ice drift direction, (c) location of oceanographic stations

Main regular features of the distribution of the ice massifs and recurring polynyas, as well as their regime features, are governed by atmospheric circulation, which has a monsoon character over the marginal seas of the Arctic. As a result of prevailing winds from one direction during the entire winter an ice shift occurs in each sea, which results in weaker ice cover in the outflow area (polynya formation) and ice accumulation in the inflow area (massif formation). Thus, each ice massif in each extensive reservoir has its own respective flaw polynya. For example, in the Kara sea the Amderma and Yamal polynyas correspond to the Novaya Zemlya massif, and the Ob-Yenisey and Northern Land polynyas correspond to the Northern Kara massif. In the Laptev Sea opposite the Taimyr massif there is an extensive Siberian polynya, in the East Siberian Sea a very small Zawrangel polynya corresponds to a large Aion massif.

While the role of winds is recognized by most investigators, the effect of oceanic processes, in particular of vertical convection, on the position and width of flaw polynyas is estimated differently, ranging from a negligible small effect to the prevailing one. Observations in the polynya area have not yet been made in winter.

Let us pay attention to the ice drift diagram in winter in the Laptev Sea in Figure 8: ice outflow from the sea prevails. As estimated by Shpaikher (1976), the largest ice amount is transported from the Laptev Sea (cf. Table 1). Let us note that Zakharov (1966) present a large estimate of the total ice flow from the Laptev Sea - about 910 km for the period from October to April. Such a scattering of values can be attributed both to the interannual variability of ice mass discharge from the Laptev Sea and low reliability of the data on which the formulas for calculating the volume of ice outflow are based. The thicknes of ice at a different development stage is the least accurately determined value. The variability of the ice circulation also unduces fluctuations in the total ice outflow value.

While ice drift can be accurately determined from satellite observation data and from an understanding of ice dynamics, very little data concerning water circulation, especially near the bottom and at the shelf slope, has yet been gathered.

An understanding of surface water circulation and its interannual variability can be obtained from the chart of salinity distribution at the 5 m level in Figure 9. From observations made in April 1978 desalinated waters extend in a wide sleeve from the New Siberian Islands toward the pole. In 1981 desalinated waters were located along the shore from the Lena Delta to the Long Strait. These salinity distribution characteristics are, undoubtedly, connected (or influence or are under the influence of) with large-scale water and ice circulation in the Arctic Basin.

Bathymetric observations provide possibilities for understanding the deep-water circulation. For example, let us mention that cyclonic gyres are often formed in the deeper portions of the northwestern Laptev Sea. Figure 10 gives a vertical temperature and salinity section from the observation data in April 1979 in the points 1, 2 and 3,as shown in Figure 8. The plots of vertical temperature, salinity and density distributions are given in Figure 11. Let us pay attention to an unusual increase in Atlantic water temperature from deep-sea station 3 to station 2, located on the shelf slope. This phenomenon is possibly related to the pulse character of Atlantic water spreading.

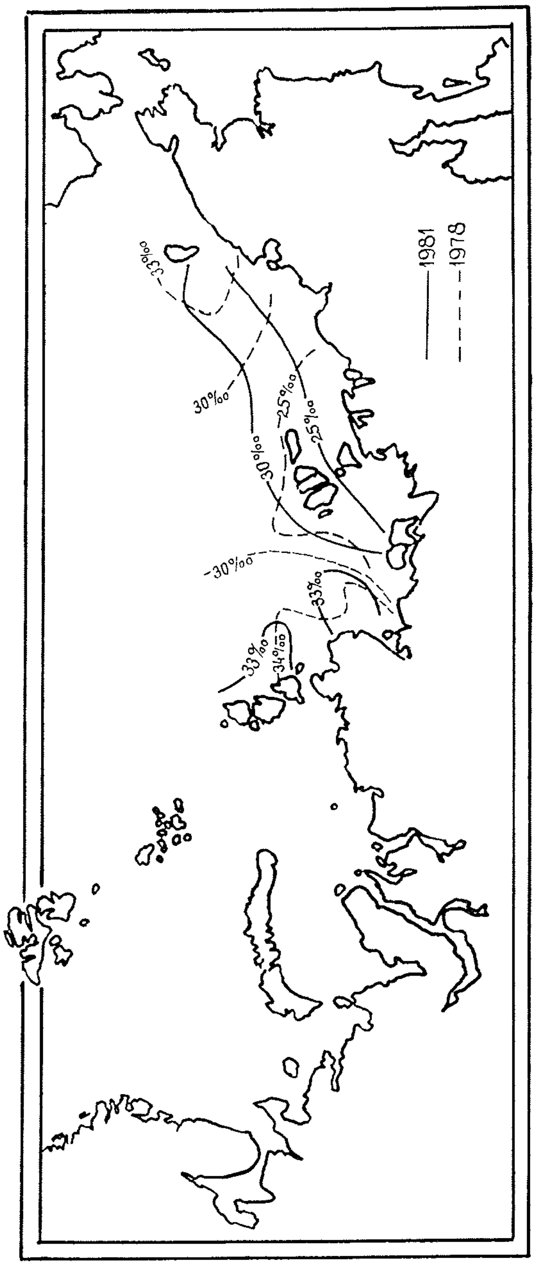

Fig. 9: Salinity distribution at 5 m water depth during winter

Occasional CTD measurements demonstrate the presence of a vertical thin thermohaline structure in the thermohalocline. That is why one can state that the process of double diffusion is one of the mechanisms of heat transfer of Atlantic water to the surface. The absence of detailed observations makes is difficult to more clearly define the role of other mechanisms, for example, the effect of internal wave destruction, including tidal waves, at the shelf slope. Studies of the north--western Laptev Sea are also important, since, according to the estimates of Shpaikher (1976) for the Siberian shelf seas, the largest heat portion is given away by the Atlantic waters to the Laptev Sea.

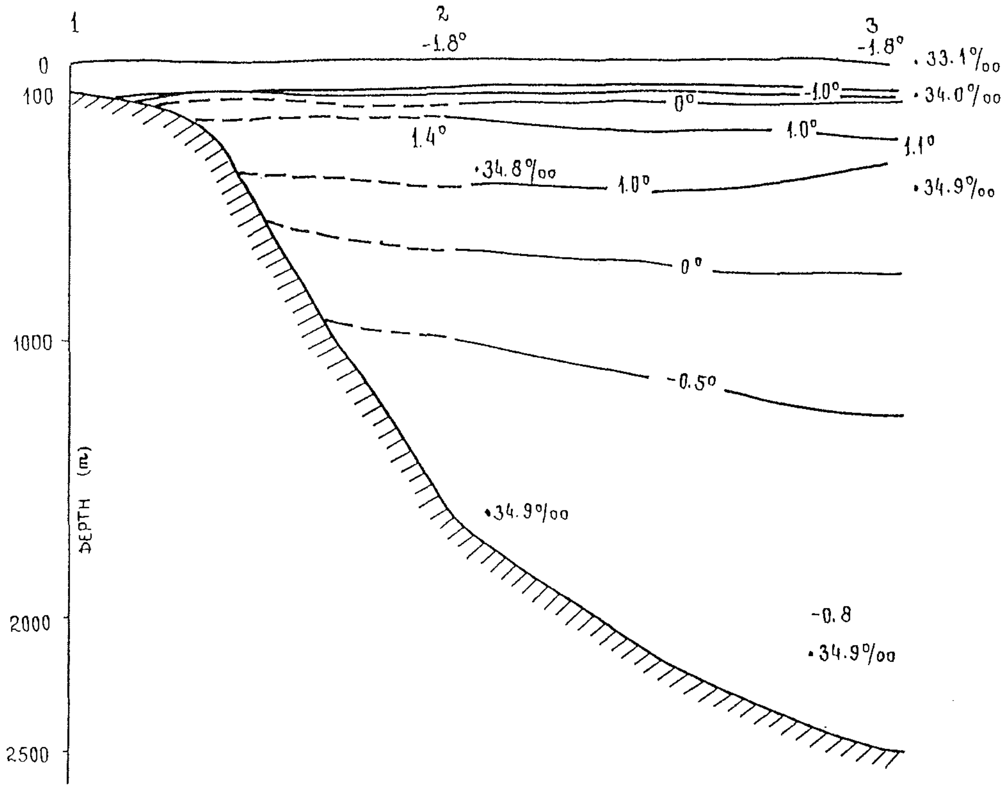

Fig. 10: Vertical temperature and salinity distribution of the Laptev Sea (April, 1979)

The review of the regional features of the Laptev and the East Siberian Seas enables one to speak about the peculiar features of this region, a unique character of some natural phenomena and the close relation of the processes occurring in these seas, with large-scale processes in the Arctic Basin.

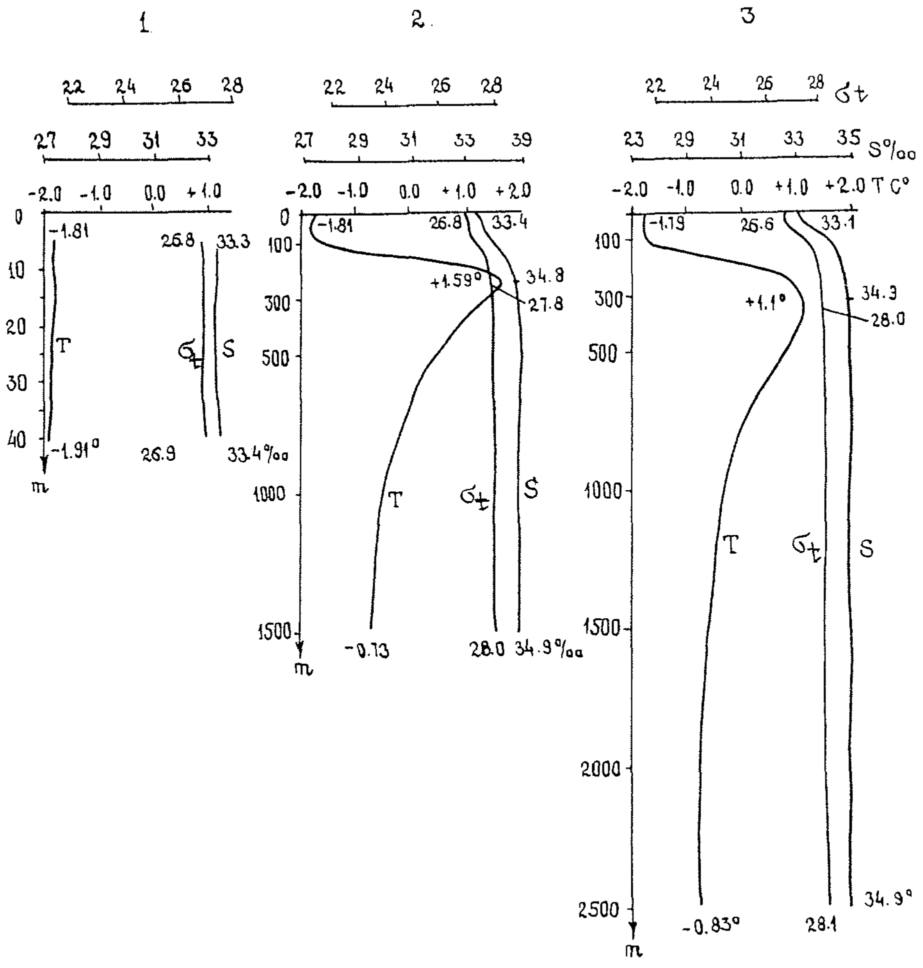

Fig. 11: Vertical temperature (T), salinity (s), and density (σ_t) profiles of the Laptev Sea

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ON THE CHARACTER OF CAUSE AND EFFECT RELATIONSHIPS BETWEEN SEA ICE AND THERMAL CONDITIONS IN THE ATMOSPHERE

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Since the time that it has become known that the climate of our planet undergoes systematic changes, the attention of many specialists has been given to the studies of these changes and their causes. In the first half of this century there was a warming which induced deep changes in the state of the environment, particularly noticeable in areas of perennial natural ice. In some areas permafrost has disappeared. The glaciers of North America, Europe, Greenland and many Arctic islands have retreated. The area of ice cover and its thickness in the Arctic Ocean has become reduced. The dates of ice break up and freezing in the coastal areas have changed. Conditions for ice navigation in the Siberian Arctic waters have improved. It is estimated that this warming trend will continue in the future as well.

In mid-1940s, however, air temperature started to decrease at first in northwestern Greenland and then in the central Arctic, the region of the Canadian Arctic archipelago and in the marginal Arctic seas. Within the eastern Arctic it decreased most strongly in the Kara Sea; its mean annual value in 1961-1965 appeared to be almost 3 degrees lower, than in 1941-1945. The area of ice cover and its thickness increased as well. Ice became a common phenomenon in the places where it is generally not present at all or where it had appeared occasionally. The limits of heavy multiyear ice to the north of the Siberian coast shifted southward and the ice itself was more frequently encountered along navigational routes, making navigation difficult. Sea ice reached the shores of Iceland, making navigation and fishing in coastal waters difficult. One began to speak about the advance of a new glaciation epoch. But at the end of the 1960's cooling stopped. Air temperature started to increase and ice area began to decrease.

The examples mentioned above indicate the existence of quite a close connection between thermal conditions in the atmosphere and sea ice development. The character of this connection seems to be evident: ice area changes in accordance with air temperature changes. But recently collected data indicate that sea ice itself can be the cause of the climate change.

Sea ice is concentrated mainly in the polar regions of our planet. Mean annual areas of sea-ice distribution in the World Ocean is equal to 26 million square kilometers or approximately 7 % of its area. As compared with the Southern Hemisphere, where sea ice forms a wide ring encircling the Antarctic continent over its entire perimeter, in the Northern Hemisphere it forms a compact massif, covering the oceanic area around the geographic pole. The central part of this massif, its core, consists of two-year and multiyear ice. At the external side seasonal ice, which melts completely in summer, is present everywhere, reaching its largest horizontal and vertical extent in February and March. At the border with the Atlantic and the Pacific Ocean this ice forms three tongues, extending meridionally: East Greenland, East Canadian and Pacific-Canadian (Fig. 1). Along the eastern coast of North America sea ice extends in winter sometimes up to 42°30'N, preventing navigation in this animated region. Along the Asian mainland in the Pacific Ocean sea ice extends southward up to 43°N. The freezing of some bays and gulfs along the eastern coast of Korea occurs up to 40th parallel. The fact itself of such deep penetration of sea ice to the south up to the subtropics appears to be particularly unusual, considering that the sea to the west of Spitsbergen below the 80th parallel does not freeze at all. In winter ice is a common phenomenon in the Baltic, Azov, Caspian and Aral Seas and even in some parts of the Black Sea. At the same time there is no ice in the Norwegian Sea, as well as over considerable parts of the Greenland and the Barents Seas, i.e. within the Arctic itself. Along the meridian 5°E in the middle of winter the 80th parallel can be reached by ship without encountering a single ice floe on the way.

Fig. 1: Sea-ice distribution during September and March in the Northern Hemisphere.

The cause of this striking phenomenon is usually related to the character of oceanic circulation. Sea ice in the Atlantic and Pacific Oceans extends southward the farthest along the eastern coasts of the Asian and North American continents, the coasts of which are subject to the effect of cold sea currents. The currents bring ice from the north, creating a strong asymmetry in their distribution between the eastern and western parts of the Atlantic and the Pacific Oceans.

At first glance this explanation appears to be convincing. In reality, the position of the southern edge of sea ice in the northwestern Atlantic in winter can be attributed, as it is usually done, to ice inflow from the Arctic in the Labrador and East Greenland Currents. But what is unusual is that this ice is mainly of local origin. Also the ice of the Bering Sea, Sea of Okhotsk and Sea of Japan forms at the place. Hence, it is clear that ice motion cannot be considered as the main reason for the breaking of the law of latitudinal zonality in its extension in the Northern Hemisphere.

In March, with the increase of solar energy, ice enters the decay phase. The melting wave extends from the south, increasingly covering newer regions. The external ice boundary retreats farther north, ice tongues become shorter and their meridionality, characteristic of winter ice, becomes weakly pronounced by late summer. This fact indicates that the conditions, inducing and maintaining the meridionality in the extension of sea ice in the Hemisphere, are more strongly pronounced in the colder part of the year. That is why particular attention should be paid to the processes which control ice development in the colder part of the year.

Not many investigators pay attention to one important feature of the intra-annual development of Arctic sea-ice cover, namely, the fact that the annual ice extent wave is asymmetric relative to the mean multiyear level. From data as shown in Table I one can see that the ice extent minimum is clearly defined, and takes place in September. The maximum is, in contrast, extended in time: ice extent values in February, March and April are very similar. This feature is typical not only of ice cover in the Hemisphere but of its tongues as well. The area covered by East Greenland ice in February, March and April is actually the same. And the obvious fact that a sharp slowing or even a complete stop in ice-cover increase takes place in the very middle of winter, when surface air temperatures are close to their annual minimum, is very suprising. Hence, it follows that thermal conditions in the atmosphere do not limit ice cover development in the second half of the colder period of the year. Figure 2 demonstrates how the relationship between ice area in the Hemisphere and thermal conditions in the atmosphere, expressed through a sum of degree days of frost in the Arctic, changes.

The curve in this Figure indicates the absence of a rectilinear dependence between thermal conditions in the atmosphere and the extension of sea ice cover in the Hemisphere. This interdependence can be approximated by a direct line in the time interval from the end of September to the mid-January. The effect of breaking is clearly pronounced, i.e., the effect of a sharp slowing and even of the end of ice cover development in the horizontal direction outside this time interval. This phenomenon can be partially explained by the fact that in most regions ice cover reaches its natural boundaries, namely, coasts. However, even at this time in the Arctic Ocean considerable areas of ice-free water persist at the boundary to the Atlantic Ocean, where there are no visible barriers to ice cover development. But then what prevents its growth?

In order to understand this it is necessary to consider the role of the upper desalinated layer in ice cover formations.

The existence of the upper desalinated layer (the so-called surface Arctic waters) is an important feature of the structure of water thickness in the Arctic Ocean. By its physical-chemical characteristics - decreased salinity and temperatures close to the freezing point - they differ distinctly from underlying waters of Atlantic origin, and this, in turn, has a positive temperature and salinity, exceeding 34 %.. Interacting with each other surface Arctic and deep Atlantic waters form a transient layer, the pycnocline, where density rapidly

Table 1: Mean areas of sea ice (x 10^6 km^2) for the period of 1972-1978

	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sept	Oct.	Nov.	Dec.
Northern Hemisphere	14.4	15.2	15.4	15.0	13.9	12.3	10.4	8.75	8.02	9.73	12.0	13.2
East Canadian waters	1.13	1.29	1.3	1.25	1.12	0.87	0.54	0.22	0.07	0.18	0.57	0.89
East Greenland waters	0.75	0.8	0.82	0.8	0.75	0.68	0.58	0.42	0.33	0.37	0.51	0.65
Pacific Ocean	1.44	1.9	2.07	1.75	0.82	0.2	0.03	0	0	0	0.17	0.7

Note:
The East Canadian waters include the Baffin Bay, the Labrador Sea, and the Davis Strait;
The East Greenland waters include the Greenland Sea southward of 80° N up to the parallel of the Farvel Cape;
The Pacific waters include the Bering Strait, the Sea of Okhotsk, and the Sea of Japan.

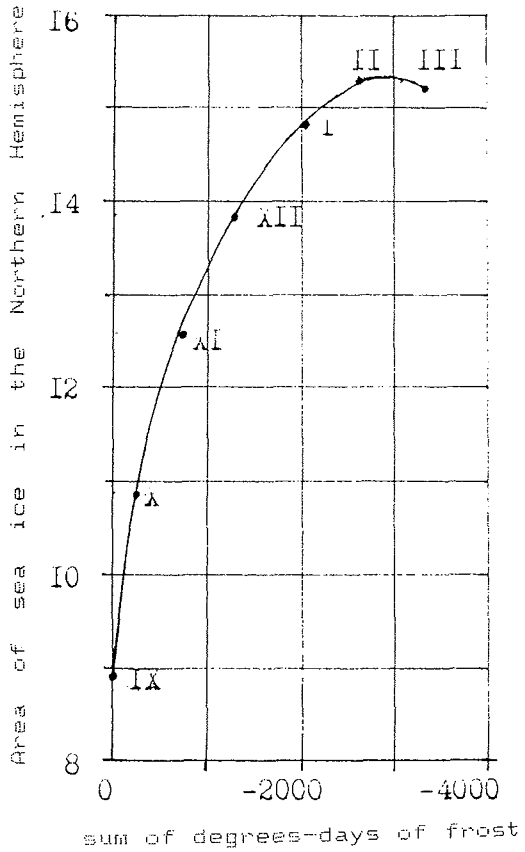

Fig. 2: Area of sea ice in the Northern Hemisphere as a function of the sum of degree days of frost in the latitudinal band of 70° -80° N between 20°W and 160° E. Sea-ice area and sums of degree days of freost are given for the end of each month.

increases with depth. Hydrostatic stability increases with it, as can be seen in Figure 3. Since vertical exchange in the sea decreases with increases in the density gradient, then the pycnocline serves as a screen of some kind, impeding heat flux from Atlantic water to the ocean surface. As a result, heat flux of Atlantic water to the surface in the central regions of the ocean varies by different estimates by 4 to 13 Kj/cm^2 a year. The advective Atlantic heat entering the Arctic basin actually appears to be buried under the layer of desalinated waters and participates very weakly in the energy exchange with the atmosphere.

It is known that ice formation becomes possible only under the condition that heat outflux to the atmosphere from the water surface exceeds its input from deep-sea layers. The heat deficit which is formed in this case is compensated by crystallization heat at the water transition from the liquid into the solid state. From this the important role of conditions which regulate the intensity of heat transfer to the water surface from below is clearly visible. Taking into account that a vertical heat flux of 13 Kj/cm^2 a year is rather insufficient to compensate the heat outflux to the atmosphere from the open

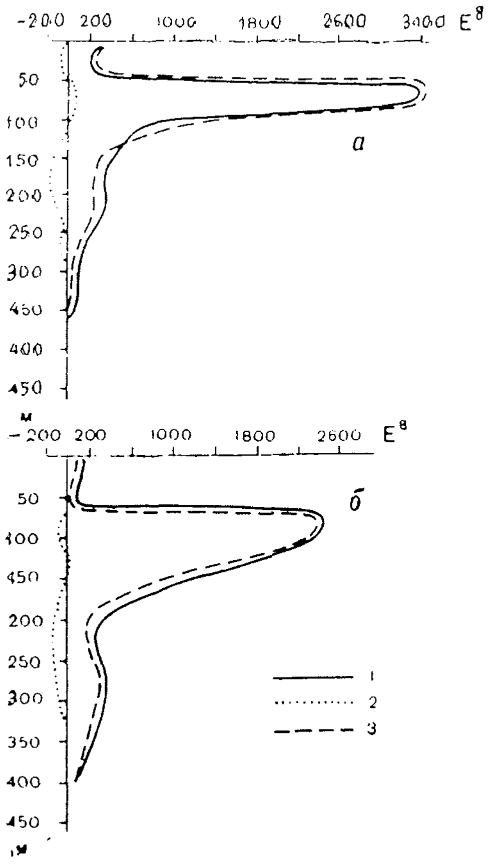

Fig. 3: Change of the vertical stability E in the near Atlantic (a) and near Pacific (b) regions of the Arctic Basin.

water surface, it is necessary to recognize the decisive role of the halocline for the existence of current sea ice in the Arctic.

Genetically, the polar halocline is related to surface Arctic water, forming everywhere, where these waters spread. And they spread over large parts of the Arctic Ocean. They are absent only in the Norwegian Sea and in parts of the Greenland and Barents Seas. Toward the south, these waters spread the farthest of all in the cold Labrador and the East Greenland currents. And everywhere they are accompanied by sea ice, prevailingly of a local origin, and not from the north. One can say that the geographical distribution and the configuration of the ice cover in winter are governed by the features of the geographical distribution of surface Arctic waters and their position at the external boundary. In a manner of speaking, sea ice is a "tracer" of the halocline at the ocean surface. Reaching the halocline boundary the ice cover cannot develop any further in the horizontal direction; its growth ends, in spite of low air temperatures, due to the dramatic increase of vertical heat flux in the ocean outside the halocline limits.

The dependence between the halocline and sea ice allows one to understand the reason for the breaking of the latitudinal zonality law in the

Northern Hemisphere, to account for the breaking phenomenon, to understand why, from time to time, the northern and eastern coasts of Iceland are blocked by ice, and the phenomenon Odden occurs in the Jan Mayen region. In all of these cases the reason is to be found in the features of surface Arctic water spreading and the halocline, connected with it, which blocks as a gigantic screen the heat flux from greater depths to the surface of the ocean and the conditions creates necessary for ice formation. Where air temperatures in winter are lower than those of sea water for a considerable time period these conditions are fulfilled.

Not only the formation and the geographic distribution of sea ice is connected with the polar halocline but its stability as well, i.e., its ability to preserve with the change of the external climate forming factors. Actually speaking, the question of ice stability is to a great extent a question about the preservation of the present structure of the water thickness of polar oceans, presence or absence of the haloclines. The transition from the ice regime of the Arctic Ocean to an ice-free regime occurs as a result of the change of the vertical structure of water thickness, accompanied by the disappearance of the halocline. Advective heat, entering the Arctic Ocean in the system of the North Atlantic current, attains in this case the capability of an unlimited energy exchange with the atmosphere and is not only able to melt existing ice but also to prevent new ice formation. The transition from the ice-free ocean regime to the ice regime which occurred 0.7 mln years ago is governed by the formation of the pycnocline, more accurately speaking, by the formation of the vertical water structure. One can suggest that the formation of the vertical structure, similar to the present one, occurred as a result of the transformation of the Northern Polar Region into the zone of an excessive moistening in the process of natural-historical development. The fresh water excess in this area is a well-known fact. It is hardly possible to change the existing pattern of sea-air moisture exchange at the present time. That is why the change of the vertical water structure in the Arctic Ocean occurs omly very slowly. This means that in the near future Arctic ice is not threatened by a complete disappearance even if a little atmospheric warming takes place due to the anthropogenic impact. It will not lose its ability to recur in the winter time even if slight atmospheric warming is able to melt all ice in the ocean.

These considerations of the stability of the current sea ice are fully confirmed by the calculated results. Also a high value of the coefficient, which can be assumed to be the stability measure, indicates a large stability of Arctic Ice. Such measure appears to be the ratio of its mean annual area to the annual maximum. This measure reflects the capability of the ice cover to withstand seasonal changes of the atmospheric thermal conditions. The latter, as it is known, by their value exceed considerably the variations of other time scales, being comparable only with glacial-interglacial fluctuations. It is sufficient to say that the amplitude of seasonal air temperature changes to the north of 70° N is about 27° C. And still the coefficient of sea-ice stability on the whole in the Hemisphere is 0.80. Ice stability in the main ice tongues and some marginal seas is characterized by the following values of the coefficient: East Canadian ice 0.60, East Greenland ice 0.76, Pacific Ocean ice 0.37, Barents Sea ice 0.66, Kara Sea ice 0.91, Laptev Sea ice 0.77 and East Siberian Sea ice 0.95.

The stable state of sea ice in the Arctic is an important stabilizing factor of the climatic conditions in the Northern Hemisphere. A sharp change in these conditions, inducing a cardinal change of the environment due to natural reasons, appears to be simply impossible during short time intervals.

One more aspect of the problem of the halocline effect on the state of sea ice in the Arctic deserves to be very carefully considered. What is going to happen with it in the event when due to some reasons the horizontal size of the polar halocline is changed? What consequences will, for example, the expansion of surface Arctic water have for the ice-free area of the northern European basin?

The principal possibility for influencing the ice formation regime by means of regulating vertical heat flux in the ocean has already been discussed above. By increasing or decreasing heat outflux to the surface one can shift the dates of ice appearance in the sea or even create the conditions which completely prevent ice formation. It is extremely important that all this can be achieved, leaving all other factors controlling the ice formation process unchanged.

It is quite natural that the horizontal size and the location of the external boundary of the halocline do not remain constant with time. Depending on the factors, the halocline increases its dimensions, extending farther to the south or shrinking and retreating in the opposite direction. What significance can these changes have for the development of the ice cover?

Brooks (1952), in his book devoted to the climate of the past, came to the conclusion about the possible self-development of the sea-ice cover. According to him, after the dimensions of this cover reach some critical value, any further increase of its area should be accompanied by a similar temperature decrease in the atmosphere, which will provide its further development. This development, which is expressed in the shift of the ice edge in the direction of the equator, should continue until the temperature drops due to the cooling effect of the ice cover and is not balanced by its increase, governed by its distance from the pole. When the dimensions of this cover turn out to be less than the critical ones, the cooling caused by the ice is not able to prevent its decay.

An analysis of present winter thermal conditions in the atmosphere allows one to say that these conditions cannot further block the expansion of the Arctic sea-ice cover. The isotherm -2° C in the near water atmospheric layer, which approximately corresponds to the freezing temperature of sea water, is situated in winter southward of the ice edge. In some regions, for example, in the northern European Basin it is hundreds of kilometers from the edge. Over the entire space, limited by the ice edge in the north and by the -2° C-isotherm in the atmosphere in the south, the climate is not a barrier for ice cover development in the horizontal direction.

But this does not occur. A preventing factor in this case appears to be advective heat, coming here from the south with sea currents, which compensates ocean-to-atmosphere heat losses. For ice formation to be possible it is necessary to exclude advective heat from the energy exchange. The manner in which this is best done is shown by the nature itself, i.e., by extending the conditions characteristic of the Arctic at the present time to these areas as well. As it is known, warm Atlantic waters, entering the Arctic Basin to the north of Spitsbergen "dive", sinking under the lighter desalinated surface Arctic waters and are covered by the halocline from above, dramatically limiting vertical heat transfer. Thus, one speaks here about the change of the existing haline structure of the upper ocean layer where thermal conditions cannot prevent ice formation. The disappearance of homohaline conditions existing here and the formation of the halocline near the surface should be accompanied by ice formation without any additional atmospheric cooling.

The idea that ice area increase can be achieved at present by the change of only one haline structure of the upper ocean layer as a result of expansion, flowing of Arctic waters into the warm but more saline waters is confirmed both by calculations and empirical data. In more detail this question is covered by Zakharov (1981), that is why only one example from this book is presented here.

The empirical data, indicating that the sea-ice area increase is preceeded by a change in the haline structure of the upper ocean layer, refer to the region of Iceland. This region is usually free of ice during the entire year. But in the mid 1960's the situation here unexpectedly changed: for several years sea ice started to block its northern coast, making navigation and fishery in coastal waters difficult. The year 1968 was particularly severe, when the ice conditions turned out to be heaviest since 1988. Ice persisted near the shore for about 180 days, interrupting navigation and making it difficult along the eastern and northern coasts of the island.

Clearing out the reason for this phenomenon which frequently occurs in the history of Iceland the scientists of this country found out that signs of the advancing changes were already observed in summer of 1964. They were expressed in a salinity decrease of the upper layer in the region between Iceland and Jan Mayen. For the first time since regular observations began in 1948 salinity dropped lower than 34.7 %., which indicated the increase of the Arctic water content in this region. In winter of 1965 ice appeared near the shores of the island.

Based on these facts one can conclude that the most important reason for climatic changes in ocean ice extent are not the changes in thermal conditions in the atmosphere but changes in the vertical structure of upper ocean layers. These changes are caused by the expansion or retreat of the surface Arctic water mass.

The surface Arctic water mass forms as a result of the mixing of oceanic and fresh waters, entering in the form of atmospheric precipitation and continental discharge. A certain influence on the state of this water mass is also produced by iceberg discharge and fresh water inflow from the northern Bering Sea. It is evident that the volume of the surface Arctic water mass is larger when fresh water income from these sources is higher and ice and surface water discharge outside the Arctic Ocean limits is smaller. That is why the fluctuations of the area of the surface Arctic water mass distribution can be considered as the result of the disturbance of the fresh water balance.

The equation of the fresh water balance of this ocean are described by the equation:

$$F + Q + Q = E + Q$$

where: P - atmospheric precipitation; Q - continental discharge; Q - fresh water inflow from the Pacific Ocean into the Arctic Ocean through the Bering Strait; E - evaporation; Q - fresh water and ice discharge from the Arctic Ocean to the Atlantic.

Today approximate values of each of the components, included into the balance equation for mean multiyear conditions are known: P = 5428 km^3, Q = 5135 km^3, Q = 1800 km^3, E = 3337 km^3, Q = 9026 km^3 a year. The values of the first, second and fourth components are taken from Ivanov (1976). The value of the fresh water equivalent of the Pacific waters is calculated from the known salinity (32 %.) and annual volume (30,000 km^3). The salinity of sea water proper in the Arctic Ocean is assumed to be equal to 34 %. The fresh water volume, ouflown from the Arctic Ocean to the Atlantic is derived as the remaining term of the equation.

The values of some components of the fresh water balance of the Arctic Ocean experience with time irregular variations. The balance is broken. The prevalence during a more or less prolonged time period of the income or outcome balance components changes the volume and geographic distribution of the surface Arctic waters. Unfortunately, at present it does not appear to be possible to test the validity of this statement to its fullest extent; there are no data series on most of the components of fresh water balance. Such series are available only for continental discharge, i.e., for one of the five components. Still attempts have been made to find at least the indications of the relationship between continental discharge and the ice extent in the northern European Basin, i.e., in the Greenland and Barents Seas.

Figure 4 plots two curves: the upper curve shows continental discharge into the Arctic Ocean from Asia and North America from 1940 to 1968 (Timifeyev, 1974), the lower curve shows ice extent in the northern European Basin from 1946 to 1971. The data gap on discharge since 1972 has prevented the extension of the data series up to the present time. Both curves are plotted by mean annual values. The dashed line shows five summer running means.

Comparing the curves, one can conclude that there is a definite relationship between them. A pair correlation was made for a quantitative estimation and the coefficients, characterizing their relation with the time shift of three, four and five years, were revealed under the conditions of the advanced discharge development relative to the ice extent. The values of the coefficients were: at a 3-year-shift 0.33, at a 4-year-shift 0.45 and at a 5-year-shift 0.36. Although all three coefficients appeared to be below the significance level, the latter being 0.51, there are no grounds to state that the continental discharge does not produce any influence at all on the ice state in the northern European Basin. One should not forget that this discharge constitutes only 42 % of the income part of the fresh water balance of the Arctic Ocean. The correlation of the smoothed series with a time shift of two years yielded a coefficient equal to 0.82. This result assures that the increase of the continental discharge from the continents of Asia and North America into the Arctic Ocean in several years will affect the ice extent increase in the northern European Basin. Short data series do not provide sufficient evidence to state explicitly that with the development of the actual base neither the correlation coefficient nor the phase shift change. Vice versa, taking into account a spatial distribution of the continental discharge over the ocean perimeter, its asynchronous fluctuations and temporal differences of the discharge anomaly running up, one can expect that the time shift will change within two to four years. Of principal importance is the fact that the ice state changes at the boundary of the Arctic Ocean with the Atlantic occur several years later after the changes in the continental water inflow are recorded.

On the basis of this fact, as well as on the physical representations considered earlier, one can present the order for the signal transfer in the climatic system in the following generalized manner: atmosphere - ocean - sea ice - atmosphere. Water turnover in nature or, more accurately speaking, the polar branch of the hydrological cycle is a specific expression of this signal. It is this cycle that prescribes the direction to the climatic signal and governs the order of its transfer from one component to the other.

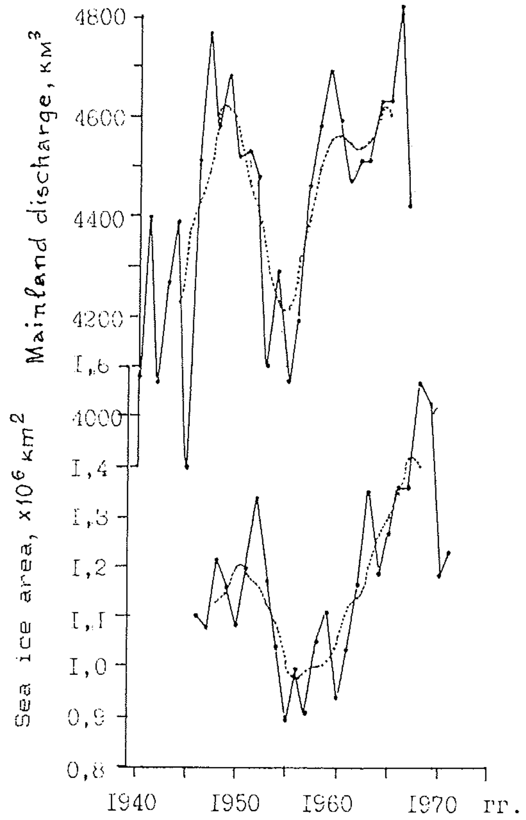

Fig. 4: Mainland discharge from the continents of Asia and North America and ice extent in the Northern European Basin.

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THE LAPTEV SEA SHELF ICE REGIME FROM A WESTERN PERSPECTIVE

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Many arcticles about the Beaufort Sea shelf ice regime, its marine geology, geophysical character, biology, and oceanography, including two interdisciplinary books, have been published in the western literature during the last 20 years (e.g. The Alaskan Beaufort Sea: Ecosystems and Environments, 1984). A recent Russian/German expedition to the Laptev Sea, Siberia (Dethleff et al., 1993) showed a totally different ice regime from that of the Beaufort Sea, implying a very different continental shelf setting in many other respects. Very little is known to western scientists about this shelf and the processes active.

The ice regime on the <80 km wide Beaufort Sea shelf is characterized by compression and shearing, with major grounded, stabilizing pressure ridge systems forming on shoals of the midshelf (Fig. 1, Reimnitz et al., 1978). There are essentially no open-water areas on the shelf in winter. The ice regime of the approximately 500 kilometer wide Laptev Sea shelf, in contrast, is controlled by offshore winds, and is therefore dilational. A perennial polynya borders the hundreds of kilometers wide and very smooth fast ice (Fig. 2). In

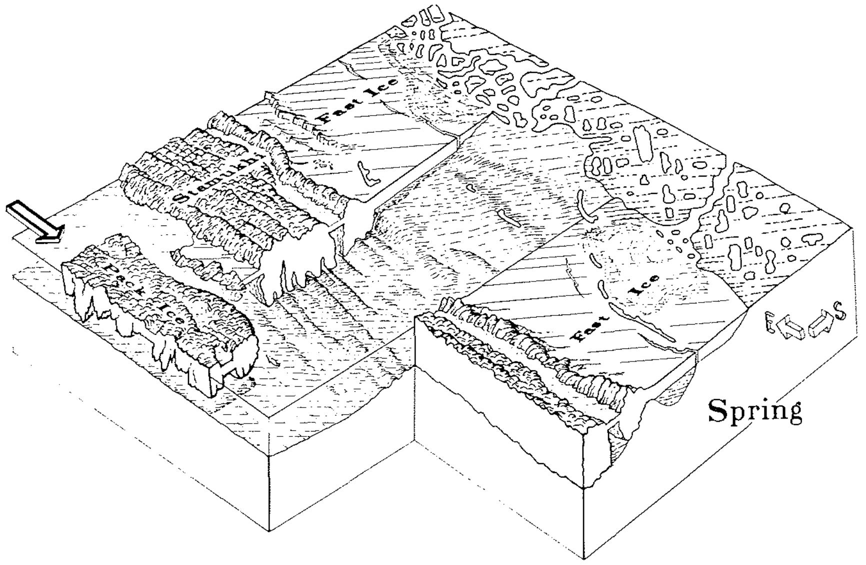

Fig. 1: Three-dimensional diagram of the development of the Beaufort Sea stamukhi zone, protecting and stabilizing the fast ice inshore.

this body of open water, rapidly forming ice is continuously advected offshore, making the Laptev Sea the single major ice factory for the Arctic Ocean and Transpolar Drift. With summer warming, this winter ice factory turns into an area of heat gain, aiding the retreat of the ice edge to a much higher latitude

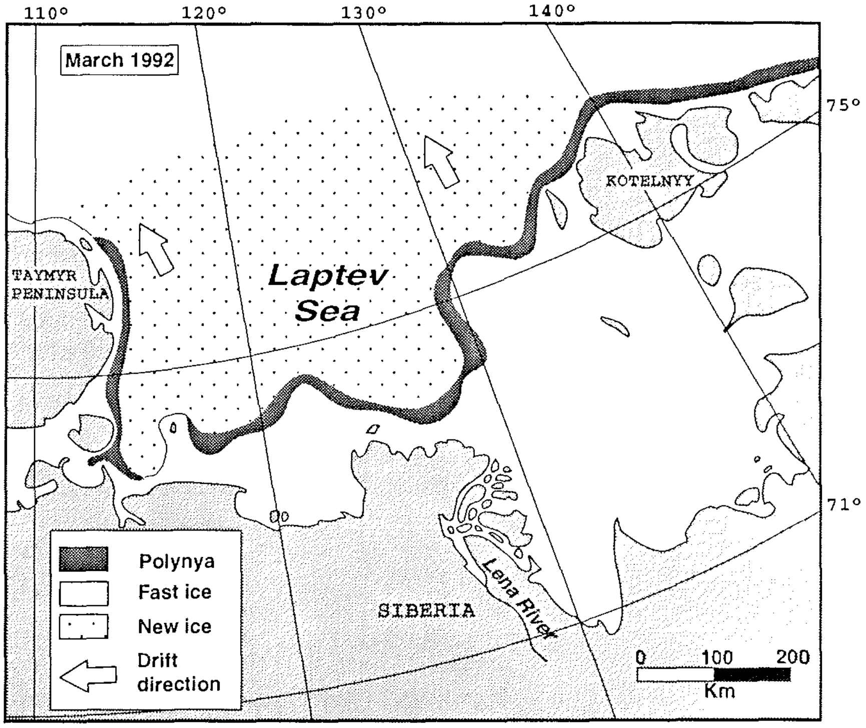

Fig. 2: The fast ice and flaw lead with ice thinner than 15 cm as mapped for the period March 20 to 24, 1992 by the Arctic and Antarctic Research Institute, St. Petersburg.

and greater distance (500 km) from the mainland than in the Beaufort Sea. As a result, the annual freeze-up usually does not incorporate old, deep-draft ice, and with a lack of compression, such deep-draft ice is not generated *in situ,* as on the Beaufort Sea shelf.

At the onset of freezing, as much as 1000 km of fetch can develop and correspondingly large (6 m) waves can form (Timokhov, this volume) on the shallow shelf. The resulting intense fall wave turbulence in shallow water, before the full width of the fast ice is established, make conditions for sediment entrainment by frazil and anchor ice probably much better than in the Beaufort Sea. We expect this to occur yearly. As discussed by Dethleff et al. (1993) and Dethleff (this volume), the flaw lead in December shifts far seaward to the vicinity of the 20- to 30 m isobath, possibly curtailing further sediment entrainment.

Because of a) the distant retreat of the ice edge in the Laptev Sea, and correspondingly long wave fetches during fall, and b) the lack of deep-draft ice required for bottom plowing during winter, we suspect that hydraulic bedforms rather than ice gouges dominate the small-scale morphology of the shelf surface. The different mode of bottom reworking would be another strong contrast from the ice-jammed Beaufort Sea shelf surface, which is re-plowed about every 25 years. In accordance with the large volume of ice produced in the Laptev Sea flaw lead, more brine is thought to be released to the deep Arctic Basin than from the Beaufort Sea shelf. This downslope brine movement possibly is accompanied by sediment transport. Open water on the midshelf provides suitable year-round conditions for walrus which are rare or absent in the Beaufort Sea, in regions located >700 km farther to the south. We suspect that the reduced rate of bottom disruption by ice keels in the Laptev Sea may permit development of benthic communities, which in the Beaufort Sea can thrive only in the protection of barrier islands. Polynya convection currents reaching the sea bed would aerate bottom sediments and thereby also enhance conditions for benthic life, and provide the food source for the Laptev Sea walrus herds.

We could speculate on other consequences of the different ice regimes in the Beaufort and Laptev Seas, but these few examples serve to point out how erroneous our judgement of Arctic shelf settings is when we extrapolate from knowledge gained mainly in the shallow North American Arctic.

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DYNAMICS OF THE LAPTEV SEA FLAW LEAD

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Introduction

The Laptev Sea flaw lead (Fig. 1) and its configuration, presumably controlled by hydrometeorological factors and bathymetry, is a recurring phenomenon first studied in detail and described by Zakharov (1966). During early winter (Oct. to Dec.) the lead apparently lies inshore at 5-10 m water depth (Fig. 1), bordering a narrow belt of coastal fast ice (limited data from

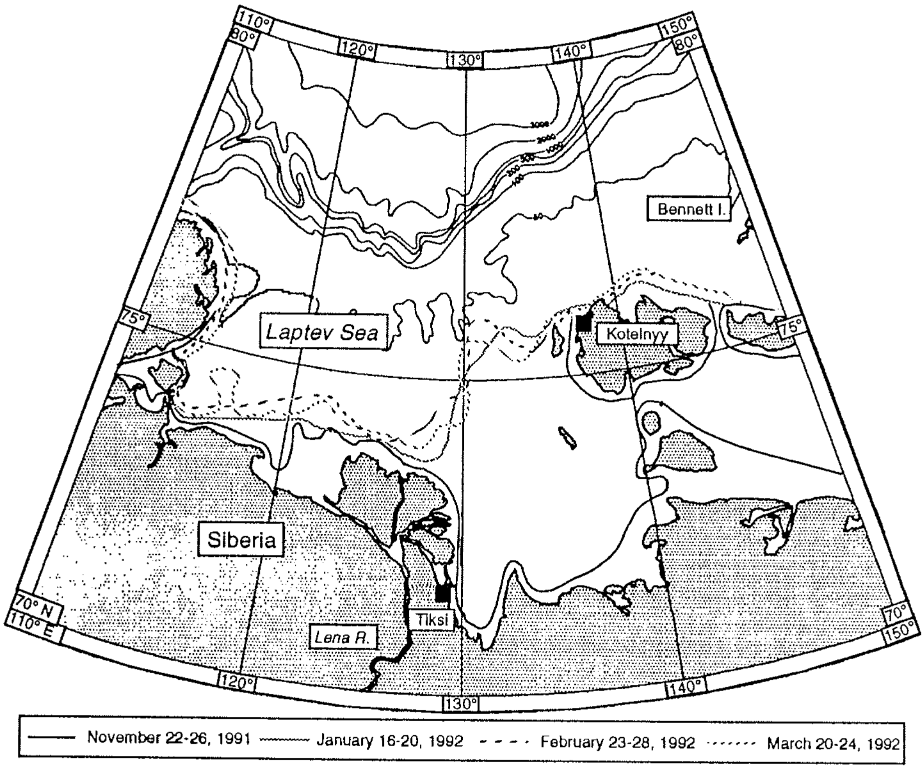

Fig. 1: The edge of fast ice, bordered by the Laptev Sea flaw lead, as prepared from interpretations of satellite images by AARI scientists (also compare Reimnitz, this issue).

AARI unpublished ice charts 1991, and Naval Polar Oceanographic Center 1981, 1983, 1988, and 1989). This period probably provides optimum conditions for re-suspension of bottom material, and thus for sediment entrainment into sea ice by frazil- and anchor ice formation in shallow open water. However, by mid December to mid January at the latest, the regional Laptev Sea ice-cover increases rapidly to as high as 9-10 tenths, and an expanded fast-ice canopy forms within a few days. Thus, the approximately 2,000 km long flaw lead shifts from inshore to water depths ranging roughly between 20-30 m, now separating the edge of fast ice from drift ice locally over 500 km from the main land (Fig. 1). The width of open water ranges between a few hundred meters to 25 km, depending on local and regional on-shore or off-shore winds. Including slush ice, nilas and young ice of up to 70 cm thickness, segments of much more than 25 km and even 100 km width are common (Barnett 1991, Dethleff et al. 1993).

Flaw lead and sea-ice dynamics

The occurrence and maintenance of the flaw lead depends on meteorological impacts such as wind direction and -speed and air temperature and, bathymetric and hydrological (salinity) conditions. The belt of open water is maintained by offshore winds causing huge amounts of oceanic heat loss from the water surface (Zakharov 1966). The newly formed frazil-, slush- and consolidated sea ice is advected offshore and constitutes the Laptev Sea tail end of the Transpolar Drift System (Siberian Branch). Vize (1926) argued that among the Siberian shelf regions the Laptev Sea is the principal source of ice to the polar basin. Zakharov (1966) gives estimates of 910 km^3 new ice produced in the Laptev Sea flaw lead during the cold period from October to April. Temporary changes of wind directions and strenghts apparently cause relatively fast narrowing, closing and re-opening of the flaw lead within few days or even hours (Dethleff et al. 1993).

Flaw lead model profile

The recently gained knowledge and speculations about the Laptev Sea flaw lead is the basis for a hypothetical cross section, showing the main mechanisms active in the water column (Fig. 2). The heat energy released during winter from open water results in formation of small frazil-ice crystals, evident as surface streaks formed in the convergence zones of oppositely rotating pairs of Langmuir circulation cells in the upper oceanic layer (Fig. 3). Such helical vortices are mainly initiated by wind stress and irregular wave fields and continuously clear the water surface for new ice growth (e. g. Martin and Kauffman 1981). The circulation cells are assumed to induce turbulent downward movement of supercooled surface water, enhancing the additional growth of frazil ice in the deeper water column. Furthermore, the water column vortices temporarily can touch the shelf bottom and thus re-suspend fine grained sediments. Toimil and Reimnitz (1979) found herringbone bedform patterns in Leffingwell Lagoon (Beaufort Sea) apparently formed by such three dimensional vortices in the shallow water column.

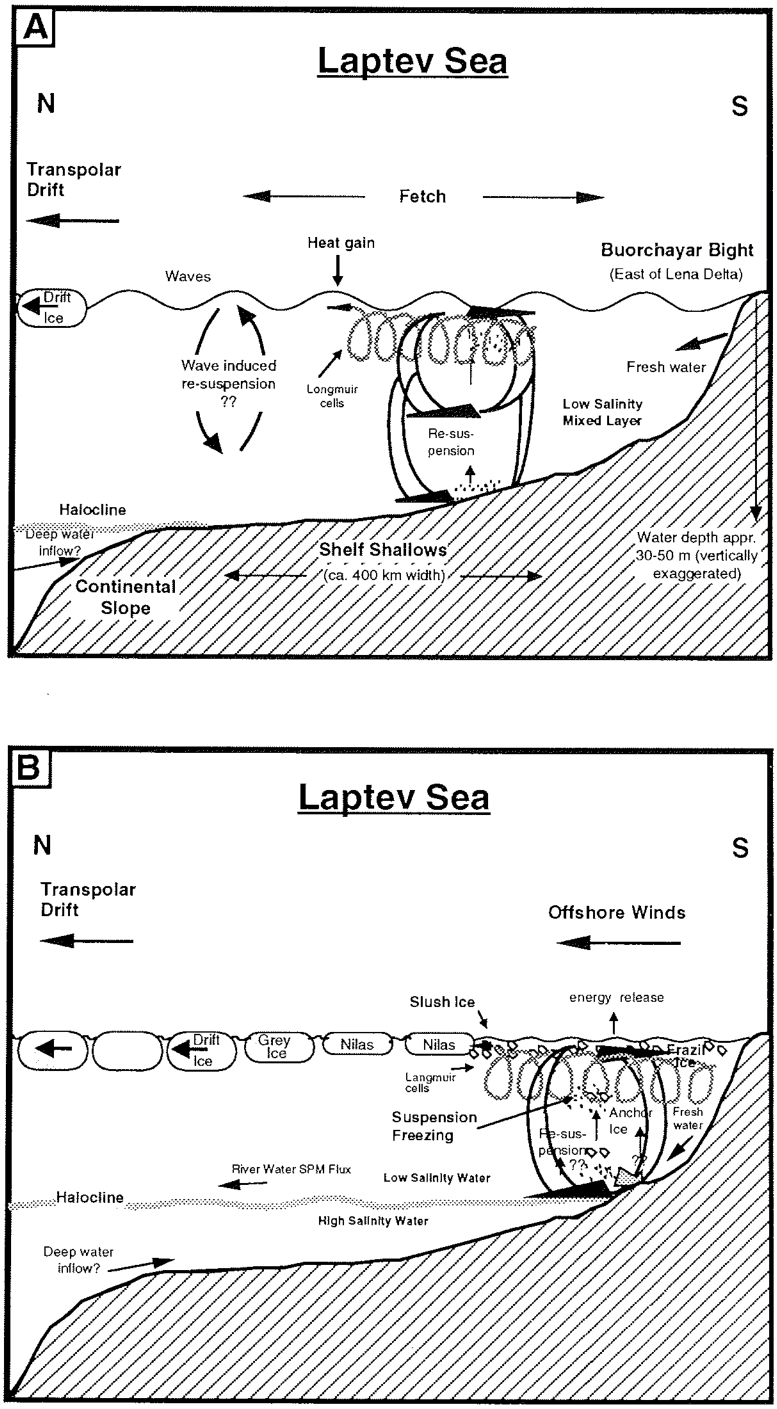

Fig. 2: Hypothetical cross sections of the Laptev Sea flaw lead indicating the seasonal oceanography, possible mechanisms of sediment re-suspension, processes of sea ice formation and the entrainment of particulate matter into newly formed ice. A: Late spring and summer; B: Fall.

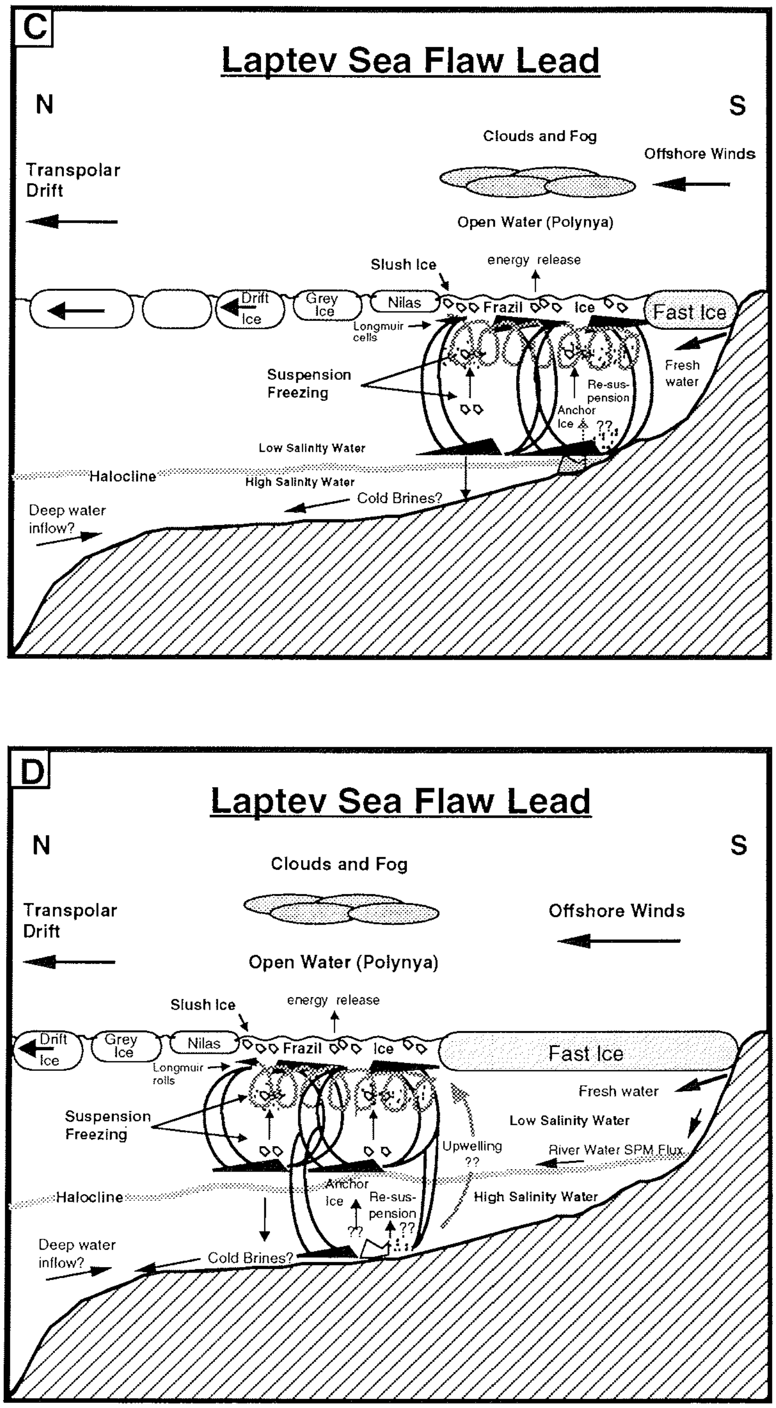

Fig. 2: Hypothetical cross sections of the Laptev Sea flaw lead indicating the seasonal oceanography, possible mechanisms of sediment re-suspension, processes of sea ice formation and the entrainment of particulate matter into newly formed ice. C: Early winter (October-December); D: Winter (January-May).

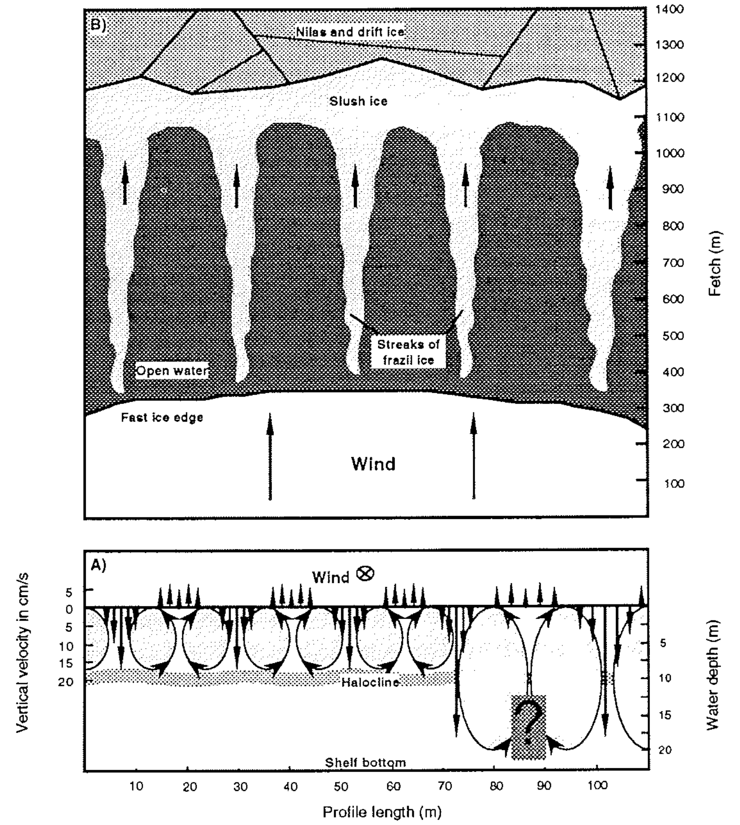

Fig. 3: Hyothetical cross section (A) of Langmuir circulation cells in the Laptev Sea flaw lead as deduced from observed patterns of frazil streaks (B). Vertical section indicates the scale, sense of rotation and speed of the rolls. Note that upward movements presumably have lower velocities (arrows) than downward convection (adapted from Weller et al. 1985).

Vertical and longitudinal transport of mass and energy within the circulation cells can reach water depths greater than 20 m, and vertical and horizontal velocities as high as 20 cm/s occur (e. g. Weller et al. 1985). Buoyant small ice crystals scavenge suspended particulate matter from the water column ("suspension freezing") and consequently incorporate this sediment into the newly formed sea ice of the Transpolar Drift. However, the turbulent downward movement of cold water masses during winter and, subsequent re-suspension of bottom material and formation of anchor ice must be seriously questioned due to the existence of a significant halocline (Fig. 2). In contrast, according to Smagin (pers. com.), upwelling at the fast ice edge is thought to provide the upper water masses with nutrients, which may originate from greater depth or even the shelf bottom and thus, penetrate the halocline.

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SEA ICE VARIATION AND BIOLOGICAL PRODUCTIVITY IN THE POLAR BASIN.

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Introduction

The ice cover on the larger part of the Polar Basin affects the biological productivity significantly. In detail, release of salts during ice formation causes changes in the saline composition of the boundary water layer, which, in turn, influences the convection mixing in the upper and deeper layers. Also the process of photosynthesis is affected since sea ice prevents a large part of the solar energy from penetrating into the water. The impact of this phenomenon is particularly large in spring time when boundary seas are still covered with ice cover. A number of authors underlined the abundance of life in the margin areas and explained it as a result of nutrient input during ice melting.

In general, the impact of sea ice is important both for the development of local and large-scale marine processes including biological aspects.

In this paper we present analysis of temporal and spatial fluctuations of sea ice parameters on the basis of the seasonal development of ice and also an attempt to demonstrate the relationship between interannual variations of ice conditions and parameters of the biological productivity of the Barents Sea.

Field data and area of interest

We used the parameters of ice cover such as the date of stable ice formation, the stage of ice development at the end of a cold period (ice age), the amount of ridges, the stage of destruction and ice area to describe the ice cover. All the data of which most has not been published yet were gained in the Arctic and Antarctic Research Institute with the help of reconnaissance flights during the past fifty years.

The discussed area (shown in Fig. 1) includes Northern Europe Basin, the Siberian shelf seas and the boundary part of the Polar Basin adjacent to Siberian seas.

As for biological productivity data of Arctic seas, the Barents Sea is known best of all, although the amount of data for interannual estimations is insufficient. Herein, I realy completely on the following study (published in the previous year): "Hydrochemical conditions and oceanographical base of biological productivity formation, Barents Sea". From this publication we used material on interannual changes in squid catchings (Todarodes sagittatus) and flat-fish (Plenronectes platessa) in the Barents Sea and data of moiva (Malletus villosus) movement during spawning time to the Murman coast.

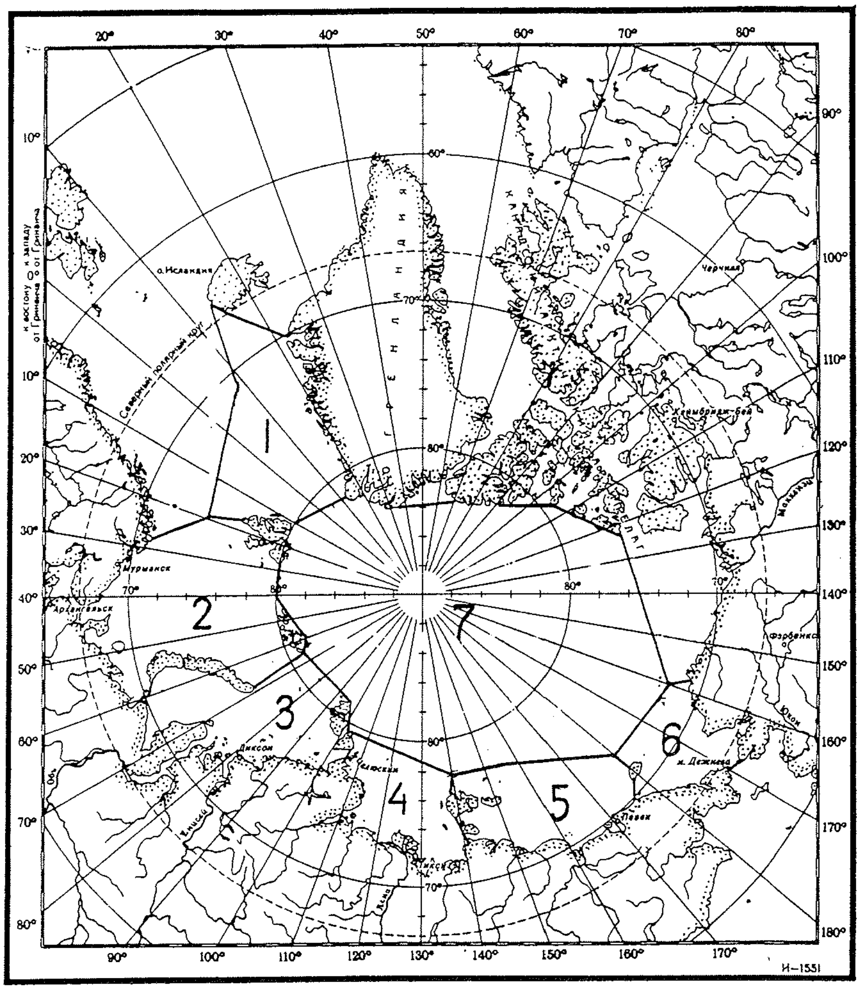

Fig. 1: Margins of the Polar Basin and Boundary Seas
1 Greenland Sea, 2 Barents Sea, 3 Kara Sea, 4 Laptev Sea, 5 East Siberian Sea, 6 Chukchi Sea, 7 Arctic Ocean

Sea ice description

Processes during ice formation have an impact on the entire annual cycle of ice conditions. The date of the formation of stable ice cover marks the end of the upper layer cooling and usually takes place by the end of August or during the first days of September. There is a variety in time of the date of the formation of stable ice cover due to the great extention of the Arctic seas, which are partly affected by the Atlantic Ocean, partly by the Pacific Ocean and river water influx.

Mean interannual dates of stable ice cover formation (for the last forty years) are shown in Fig. 2. The earliest date of ice formation (end of August)

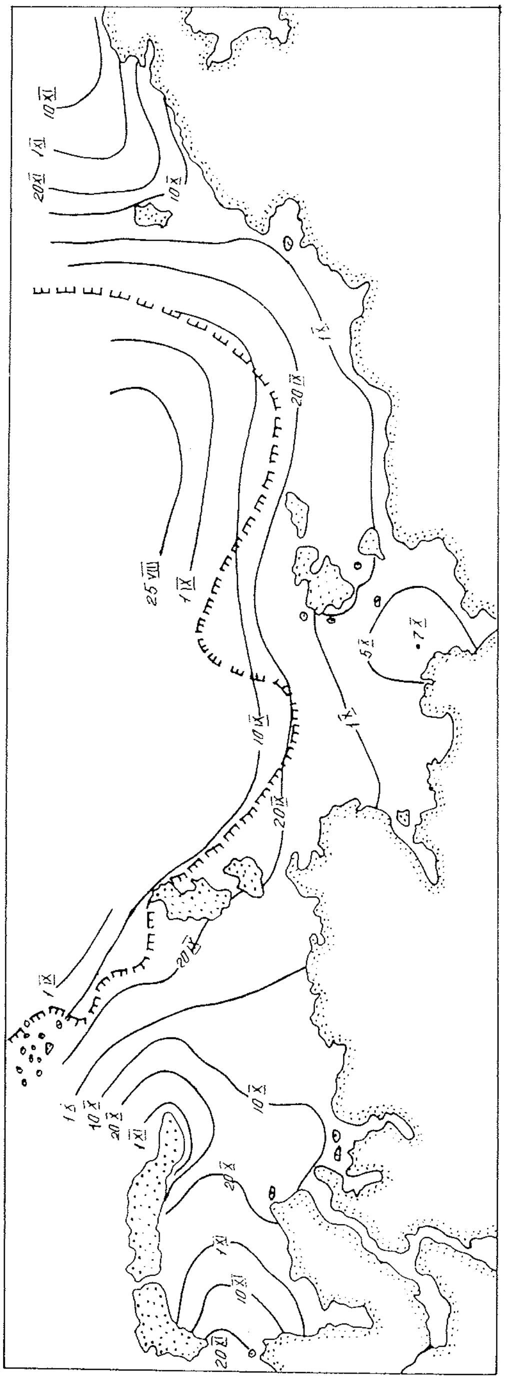

Fig. 2: Lines of equal data of the stable ice cover formation for the Arctic Seas for the period 1940-1980
ππ Mean boundary of the multi year ice

corresponds to the area that is located to the north of Eastern-Siberian Sea and which is mainly occupied by the multi-year ice. In the northern parts of the Kara and the Laptev Seas an ice cover is formed in the first decade of September, and in the Chukchi Sea at the end of the second decade. In the coastal zone and the areas of river water input ice formation starts at the beginning of October whilst the latest dates correspond to the southern areas of the Kara and the Chukchi Seas. In the Barents Sea ice formation occurs all winter because then the upper layer is cooling and the ice margin is spreading southward (Fig. 3).

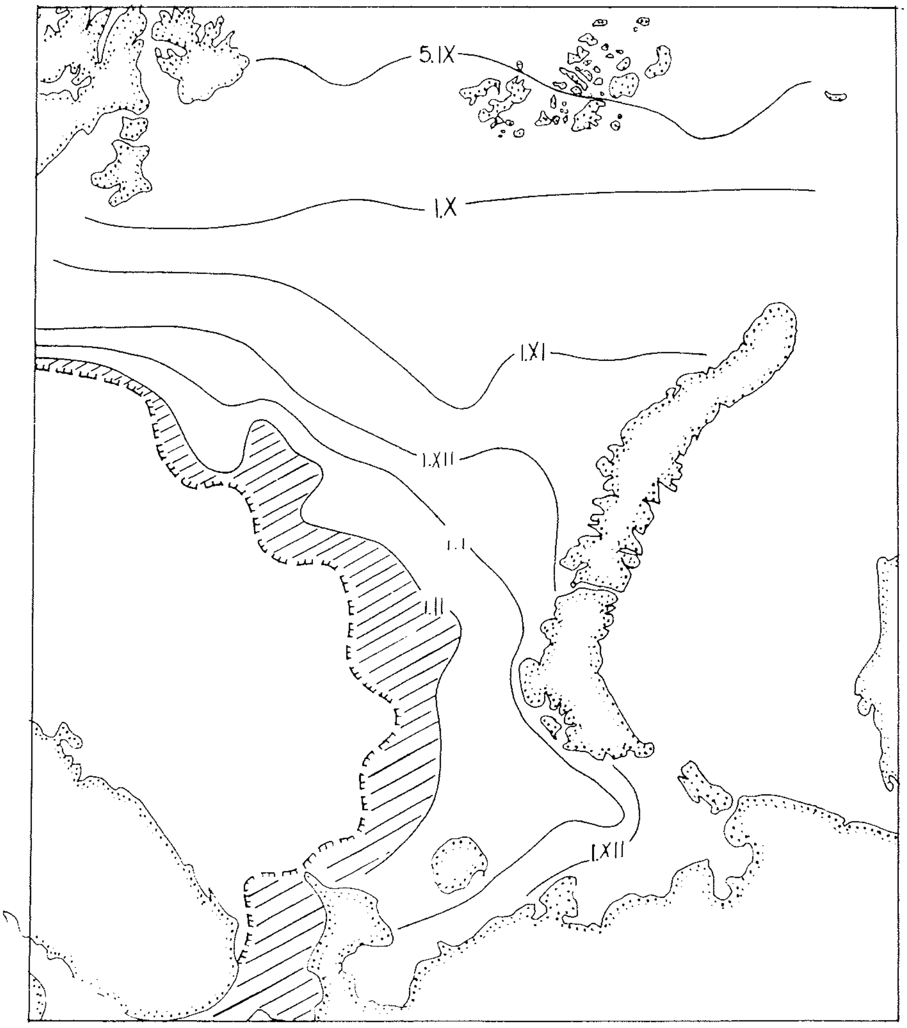

Fig. 3: Lines of equal date of the stable ice cover formation estimated on the base of averaged iinterannual data (shaded-zone: ice formation during March-April)

The wave of ice cover formation in the Arctic seas generally spreads southward at a speed of about 10 miles a day. The Laptev and Eastern-Siberian Seas freeze mainly as a result of the least heat advection.

It is known that the date of the ice formation is subject to interannual fluctuations that are influenced by hydrometeorological and ice processes. The values of mean root square (RMS) for the date of ice formation is shown in a chart of spatial distributions in Fig. 4, displaying the areas of the largest varieties in the parameter discussed. These areas coincide in space with the multi-year ice edge zones and the zones of heat advection by currents. Therefore, maximum values of the RMS parameter are observed in the northern parts of the Arctic seas, in the Kara Gate and the Bering Straits and in the north-eastern part of the Barents Sea. The smallest values of RMS (not greater than 10 days) can be found in the shallow coastal regions.

Results of biological studies reveal that the fish fodder migration ends with the beginning of autumn cooling and stable ice formation.

Stage of ice development and the process of ice ridging

Arctic sea ice is rather unhomogeneous in its stage of development (age or thickness). Multi-year and second year ice is a highly stable (in space and time) share of the ice cover. The margin of this ice is shown in Fig. 5. It closely coincides with the ice edge in September. Ice formation occurring in winter is shown as shaded part in the figure. Common feature of the ice spatial distribution is ,thus, a decrease in the stage of development in direction from the center of the Arctic Basin toward its boundaries. This is also confirmed in Figure 6. In the Barents Sea we can find a decrease in ice thickness toward the ice edge for the first year.

Averaged areas of ice cover of different stages of development at the end of winter are summarized in Tab. 1 (Zakharov, 1981) and were gained by reconnaissance flights to the Arctic in the 50s and 70s. The table shows that at the end of the winter the ice cover consists of 22 percent of multi-year ice, 20 percent of second year ice and 58 percent of the first year and young ice.

The stage of the ice development is indirectly connected with the ice thickness and closely bound up with ice ridging. According to some estimates ice ridging leads to a double and more increase in mean ice thickness. It means the more intensive the ice ridging the greater the thickness and theless the light. Thus, it leads to a change in productivity in the upper water layer.

An attempt to reveal a relationship of interannual fluctuations in ice ridging at the end of the winter with the amount of squid and flat-fish catching seems to be successful. The largest negative values of the correlation coefficient between the discussed parameters vary from 0.4 to 0.7 and coincide in space with the eastern part of the Barents and Pechora Seas. A negative bond means that an increase in ice ridging leads to a decrease in catching.

We can, therefore, conclude that an intensification of ice ridging is unfavorable for the biological productivity of the Arctic seas.

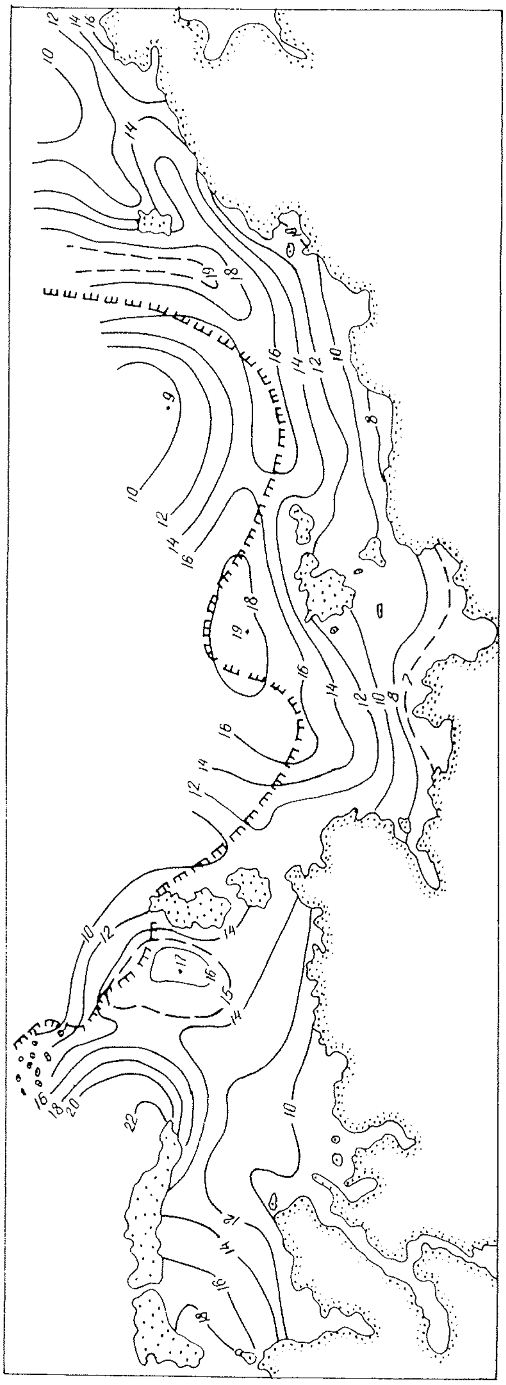

Fig. 4: Root mean square (in days) value for the date of the stable ice cover formation for the Arctic Seas (ππ Mean boundary of the multi year ice)

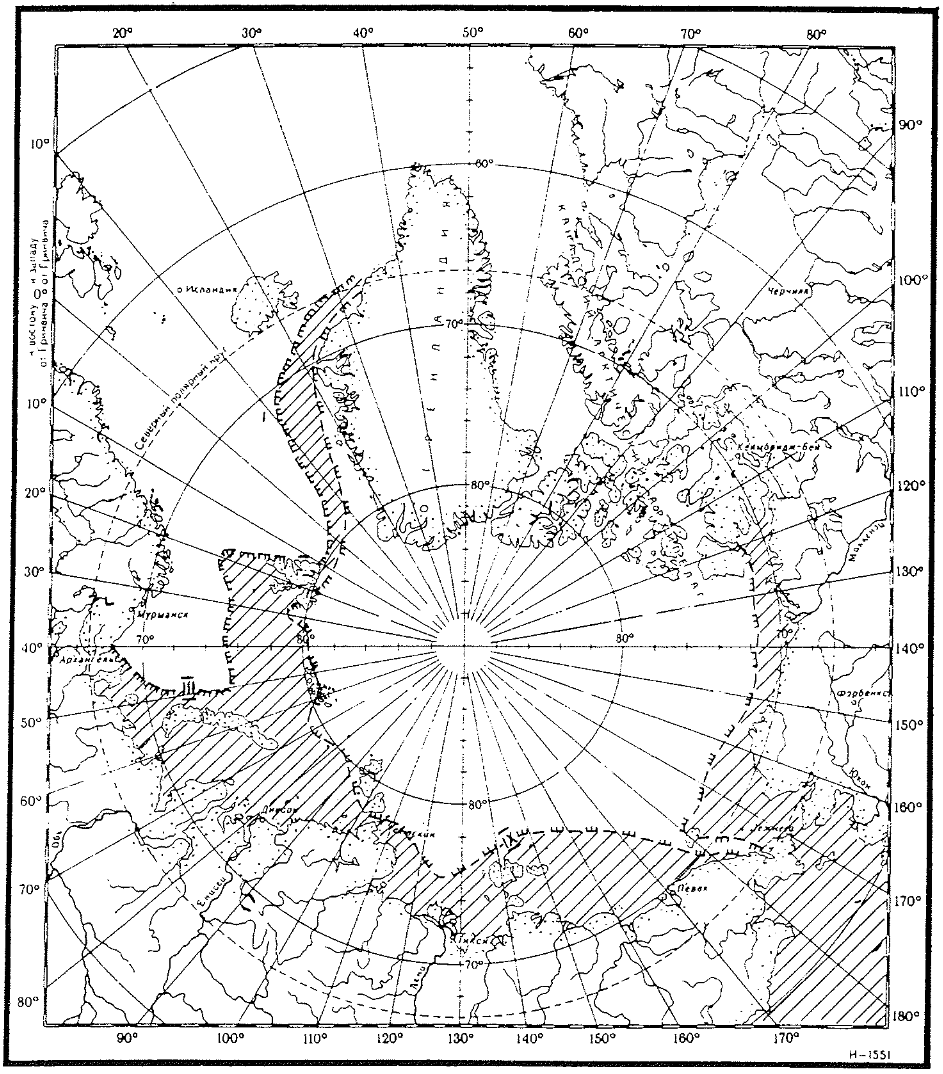

Fig. 5: Position of edges for first year ice in March and multi-year ice at the end of September in the Arctic Ocean (shaded-zone: ice melting during the warm period)

Sea ice destruction

The parameter characterizes the stage of sea ice destruction that occurs mainly due to ice melting. It must have a certain impact on life development in spring time, as the microscopic algae are "sowing the water" in the course of ice melting. Thus, the regions of intensive ice melting, e. g. edges of ice areas and areas of recurring polynyas would receive greater amounts of nutrient and light.

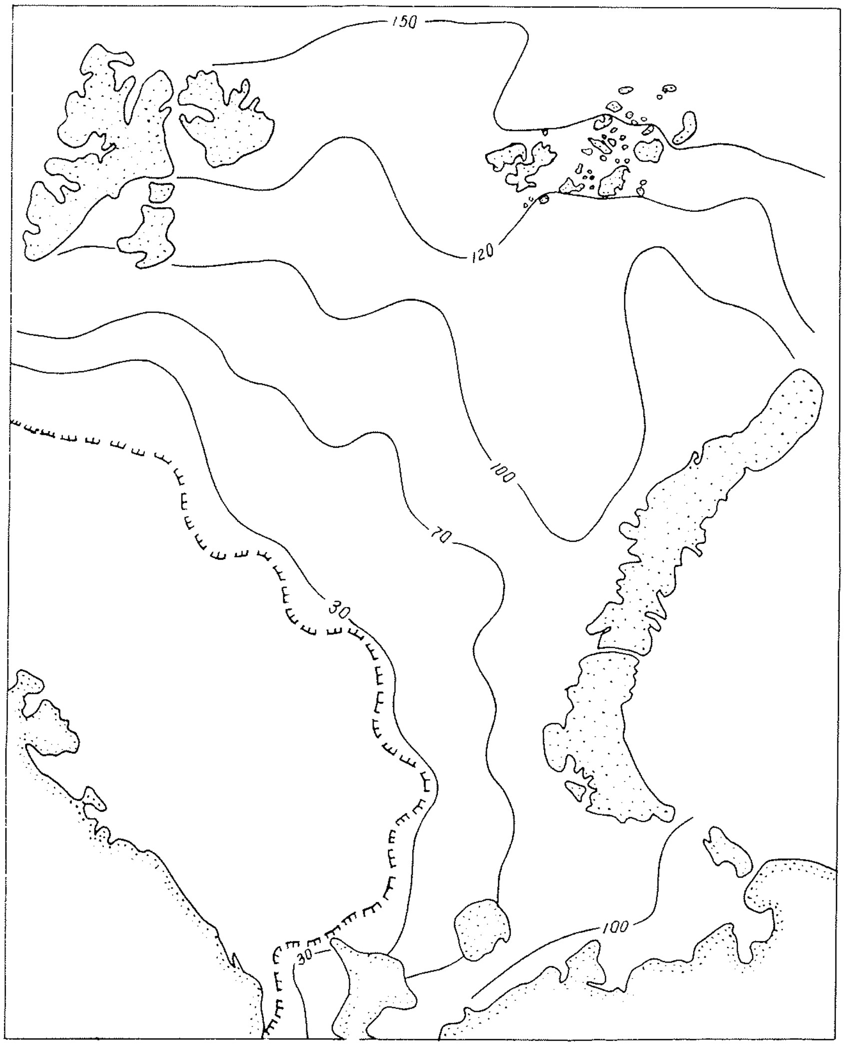

Fig. 6: Ice thickness (in cm) at the time of extreme sea ice propagation at the end of April, estimated on the base of average interannual hydrometeorological data.

For description of the process of sea ice destruction, we used interannual manual aircraft observations made in June, July and August from 1955-1980 that were organized in a grid with spatial resolution of fifty km for the region shown in Fig. 7. The method of principal components was applied for data processing and to determine the areas that are homogeneous in view of ice destruction parameters. Results of the data processing are shown in the same figure (Smolynitsky, 1991).

The first region can be characterized as the area of the important stage of destruction equal to about 5 points according to the five-grade scale. The second region corresponds to an ice destruction level equal to 2 points. Thus,

Table 1: Areas of ice cover of different development stage calculated for the Arctic Basin together with seas: Greenland, Barents, Kara, Laptev Sea, Eastern Siberian,Chukchi, Bofort, Lincoln (Zakharov, 1981)

	Old ice in March		First year and young ice						
	Multi-year	Second year	IX	X	XI	XII	I	I	III
10^6 km^2	3.60	3.22	1.3	2.04	2.12	1.19	1.57	1.04	0.2
%	22	20	8	13	13	7	10	6	1

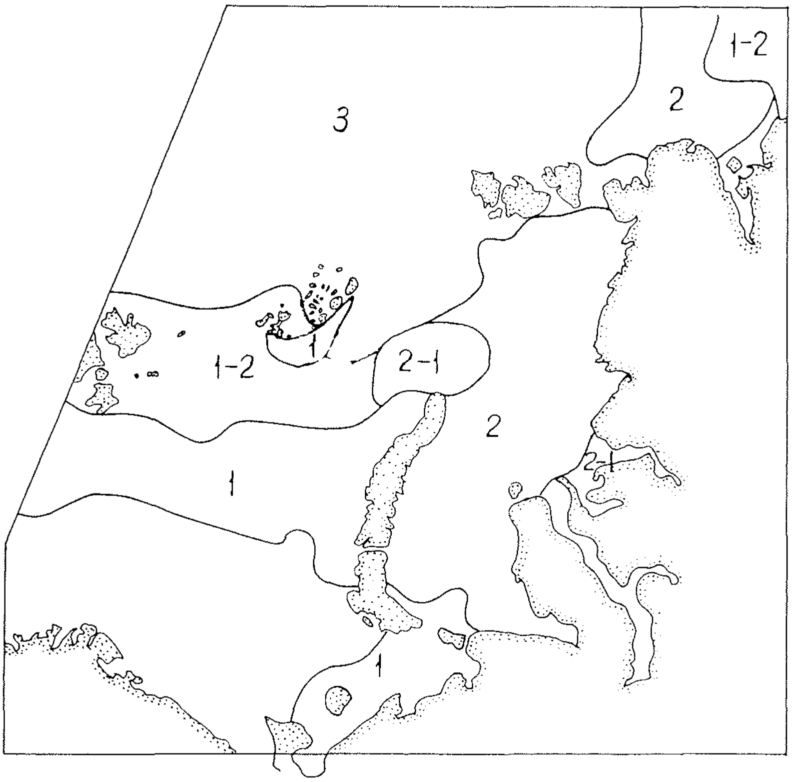

Fig. 7: Pattern of boundaries belonging to regions homogenious in stage of ice destruction during June

this value points to the existence of thaw holes in the sea ice. This region occupies the largest part of the Arctic seas. In summer, the boundaries of the first and the second region spread and expand northward and eastward. The third region is characterized by the least destruction level equal to 1 point. Its boundaries correspond to the pack ice margins. Intermediate regions with mixed destruction properties can be distinguished between the regions mentioned above. We can suggest that the zones of greater destruction provide more favorable conditions for further development of the biological productivity.

Sea ice area

The data of the Arctic ice area are widely used for researches into the climate change. Fig. 8 shows the evolution of the total area of ice cover in the Barents and the Greenland Seas for the 20th century averaged for June-August. These months were chosen because of their longest period of field observations of ice cover propagation. We must note that for the region mentioned the variations in the ice covered area characterize the changes in the ice conditions for the whole Arctic. That fact is supported by a number of authors (Zakharov, 1981). It is, therefore, sufficient to study area variations for the Barents and the Greenland Seas to understand the ice cover fluctuations for the Arctic shelf seas.

From the last figure it is clear that the area of the drifting ice had undergone considerable changes during the last ninety years. Thus, we can observe an area reduction since 1917 with a minimum value in 1960. The amount of reduction (in the area occupied by the drifting ice for the Barents and the Greenland Seas) is equal to approximately 1.0 million of square km. Spreading of the ice cover in the 60s provided an increase in area equal to 0.6 million of square km above the level in 1960. At present the ice covered area of the discussed region is close to its mean interannual value.

In accordance with the presented review we can conclude that a significant change in ice conditions occurred during the discussed period. A study of the temporal and spatial regularities reveals that: a) most considerable changes correspond to areas of the Barents and the Greenland Seas where ice spreading is not limited by a coast line being contrary to the Kara Sea; b) interannual variations in the ice covered area of the whole Arctic Basin are controlled by variations in the ice covered area of these seas. The considered seas provide 79% of the total variation in ice cover (see Fig. 9) That share undergoes insignificant changes during the whole year (see Tab. 2).

Table 2: Share of ice cover variation in Arctic seas in the total dispersion of the ice area for the Arctic Ocean, % (Zakharov, 1981)

Region	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Greenland Sea	46	50	58	49	54	35	21	15	19	19	48	55	39
Barents Sea	54	50	42	51	46	48	36	20	15	17	52	45	40
Kara Sea	0	0	0	0	01	0	24	28	24	37	0	45	10
Laptev Sea	0	0	0	0	0	4	13	23	25	7	0	0	6
East Siberian Sea	0	0	0	0	0	0	3	14	17	16	0	0	4
Chukchi Sea	0	0	0	0	0	3	3	0	0	4	0	0	1

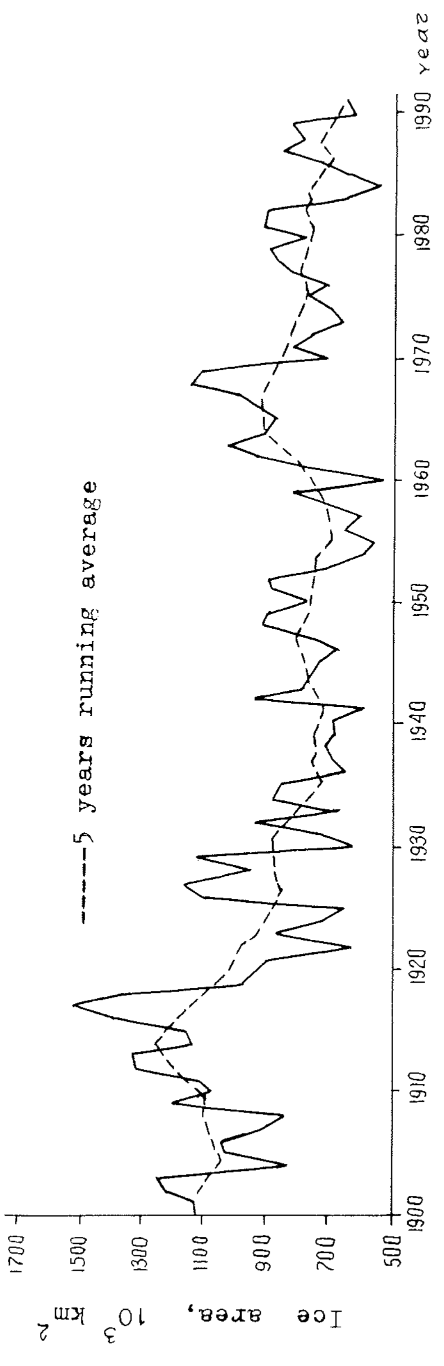

Fig. 8: Fluctuation of the ice cover total area averaged for June-August for Barents and Greenlad Seas for the 20th century.

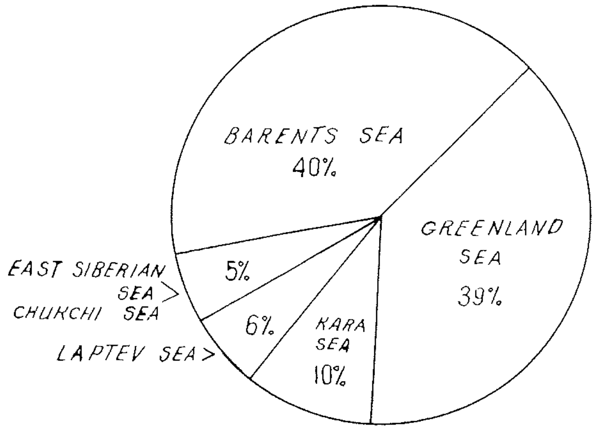

Fig. 9: Annual share of the Arctic seas ice cover area variation in the total ice cover area dispersion for the Arctic Ocean, %.

Therefore, we can assume that the variation of the Arctic ice covered area is controlled by changes in ice conditions in the Barents and the Greenland Seas from November through June. Also, the share of the ice cover variations of the other Arctic shelf seas becomes significant for the period from July up to October. Such results show that the occurrence of changes in the area of the Arctic ice cover observed in our century is due to an increase on the border with the Atlantic Ocean. It is also important to note another peculiarity: in the total variation the share of the Arctic seas diminishes eastward, from the Barents to the Chukchi Seas. Therefore, for the region discussed we can expect a link between a change in the ice covered area or the position of the ice covered edge and biological productivity. If we compare the main locations of moiva fish during cold and warm years (shown in Fig. 10) with the

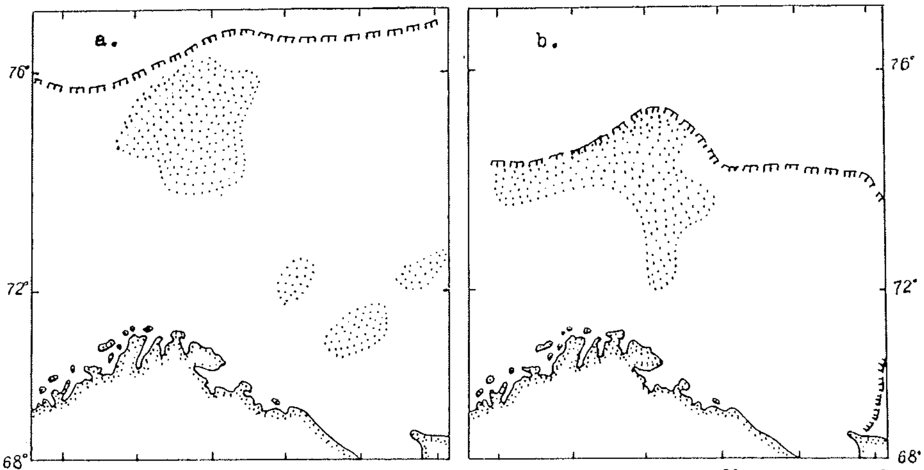

Fig. 10: Position of the main locations of the moiva fish (Mallotus villosus) during June for the warm (a) and cold (b) years. (ππ mean ice edge position at the beginning of June, dotted area: regions of fish concentrations).

position of the ice edge, we will actually see that these locations tend to be displaced northward during years of favorable ice conditions which is contrary to the years of an increased ice covered area. The same result is also shown in Fig. 11. Here a displacement of fish concentrations takes place near Murman coast.

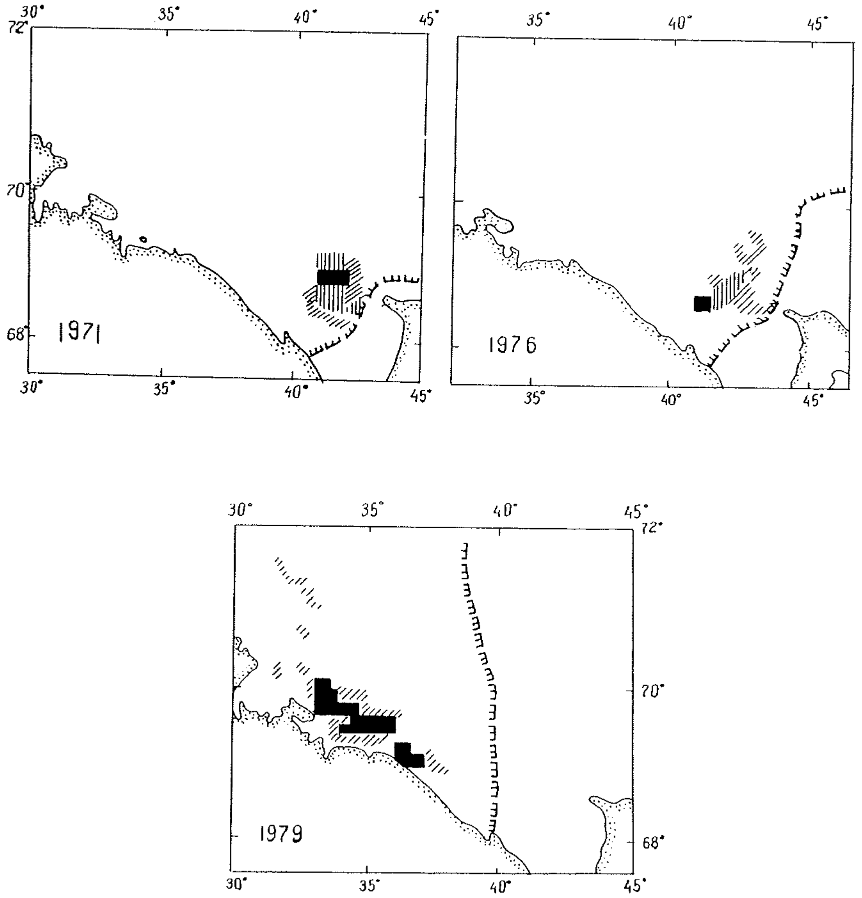

Fig. 11: Catch areas for flat-fish (Plen'ronectes patessa) in the warm 1971 and 1976 years and in the cold 1979 year and ice edge position in the south-eastern part of the Barents Sea at the end of winter (///// less than 3 tonnes for one catch day, IIIIII less than 5 tonnes for one catch day, ■ more than 5 tonnes for one catch day, ⊥⊥⊥ position of the ice edge at the beginning of May.

Conclusion

In summary, the reviewed data testify the existence of the relationship between different sea ice parameters and the productivity of the Arctic seas. The presented facts may largely define the problem and lead to further studies. It especially applies to such poorly studied ice parameters like ice ridging and destruction and multi-year edge displacement, which characteristics are seldom discussed in scientific papers in connection with biological productivity of the northern seas. It is also evident that there is a need for an exchange of data for a fruitful cooperation between sea ice investigators and marine biologists.

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CURRENT KNOWLEDGE ON BIODIVERSITY AND BENTHIC ZONATION PATTERNS OF EURASIAN ARCTIC SHELF SEAS, WITH SPECIAL REFERENCE TO THE LAPTEV SEA

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Introduction

In Russia the study of the fauna of Arctic seas started more than 200 years ago. Already at the end of the 18th century the Zoological Museum of St. Petersburg acquired its first animal collections from the Barents, Kara, and White Sea. Since then Russian scientists have compiled samples from more than 14,000 stations in Arctic seas. Most (10,800 stations) were from the Barents Sea and White Sea. Due to the lower number of stations, however, our knowledge of species composition is considerably less for the Kara, Chukchi, Laptev, and East Siberian Sea (in descending order). The total number of samples is even six times higher than the number of stations. Most of the material (more than 90,000 animal samples from Arctic seas alone, comprising taxa ranging from protozoans to ascideans) has been deposited at the Zoological Institute St. Petersburg (ZISP). A considerable part of these samples has been examined with respect to taxonomy, systematics, zoogeography, and community ecology.

Biodiversity of Eurasian Arctic shelf seas

Currently, a total of 4,296 animal species (excl. Protozoa except foraminifera and a few multicelullar groups) are known from Eurasian Arctic seas. Most of these species (3,746 or 87.2%) are invertebrates, whereas only 550 vertebrate species (12.8%) have been found. Benthic species predominate: 68% and 26% of the species are macrobenthic and meiobenthic, respectively, while planktonic species account only for 6%. Crustaceans predominate the numbers of the known species, especially amphipods with more than 500 species in total, followed, in decreasing order, by foraminiferans, molluscs, nematodes, bryozoans, polychaetes, echinoderms, sponges, and hydroids (Fig.1).

It should be noted, however, that current knowledge varies considerably among taxa. Generally, benthic taxa are not as well studied as planktonic taxa, which are usually less diverse but more widely distributed. Because most faunistic work has always been concentrated on larger organisms, macrobenthic groups tend to be better known than meiobenthic ones as, for instance, nematodes, harpacticoids or ostracods. Foraminiferans, sponges, bryozoans, molluscs, and echinoderms are among the best known taxa (i.e. up to 90% of all species present are believed to be known), whereas turbellaria (25%), nematodes (34%), scyphoid medusae, ascidians, and

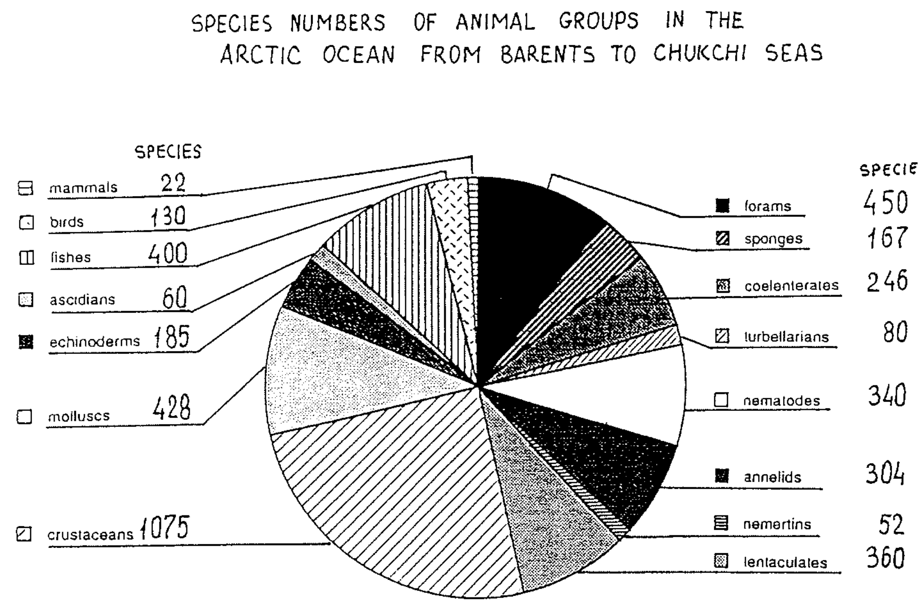

Figure 1: Partitioning of species numbers among taxa in Russian Arctic seas

ostracods (40%) are particularly poorly studied. However, the actual number of species inhabiting the Arctic shelf seas may be inferred from circumstantial evidence. For example: About 1,180 invertebrate species were known for the Kara Sea according to Pergament (1944); since then, 400 additional species have been found. Ushakov (1952) reported 720 species for the Chuckchi Sea; today the species list comprises a total of 950 items. Zenkevich (1963) reported 1,700 species for the Barents Sea; until now 800 species had to be added to this figure. In general, most of these newly reported species were not new to science but had not been found in Arctic waters before. Only a few dozens were new and had to be described. By extrapolation of these trends one can expect that more than 1,800 species (i.e. more than one third of the Arctic invertebrate fauna) are currently unknown. This would mean that a total of 5,600 invertebrate species occur in the Arctic seas.

The variation of species numbers and composition among the various Eurasian Arctic seas reflects their recent zoogeographic relation to the Atlantic, the Pacific, and the central Arctic Ocean (Fig.2). Species numbers are highest in the Barents Sea with about 2,500 invertebrate species. The White Sea fauna, comprising 1,100 species, is basically an impoverished Barents Sea fauna. Species numbers are steadily decreasing eastwards: From the Kara Sea a total of 1,580 species are known, 1,084 from the Laptev Sea, 962 from the East Siberian Sea, and only 946 from the Chuckchi Sea. This obvious trend suggests a notable influence of the Atlantic Ocean on the faunistic composition in the Eurasian seas. In general, Pacific species play a minor role, only in the Chuckchi Sea, Beaufort Sea, East Siberian Sea, and the eastern Laptev Sea they have a considerable share in species numbers and abundances.

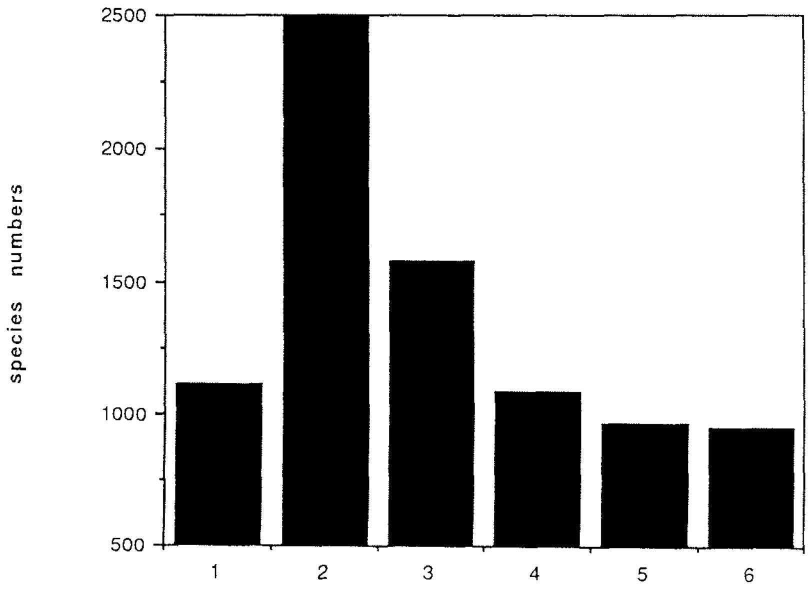

Figure 2: Total species numbers in Eurasian Arctic shelf seas: 1: White Sea; 2: Barents Sea; 3: Kara Sea; 4: Laptev Sea; 5: East Siberian Sea; 6: Chukchi Sea

An assessment of biodiversity on ecosystem level requires quantitative sampling with a relatively high spatial resolution. In Arctic seas, this prerequisite for community studies is hitherto valid only for certain areas of different extent, primarily in the Barents and White Sea, and, to a lesser degree, in the Kara and Chukchi Sea. Even in these cases, the distribution and composition of benthic communities has often to be inferred from samples taken over a long period which sometimes spans up to 50 years. In every respect, the Laptev Sea and the East Siberian Sea are the least studied regions.

History of benthological research in the Laptev Sea

The first studies in the Laptev Sea fauna date back to Nordenskjöld's historic Northeast Passage with the "Vega" in 1878. At this time, the first 16 benthic stations were sampled in this remote shelf sea. The Russian Polar Expedition with the vessel "Zarya" led by Toll in 1901-1902 took samples at approximately the same number of stations. During the "Hydrological Expedition to the Arctic Ocean" of the icebreakers "Taimir" and "Vaigach" 1912-1914 trawl catches were carried out at a total of 48 stations. In 1927, an expedition of the Yakut Commission of the USSR Academy of Sciences with the schooner "Polyarnaya Zvezda" collected organisms from 11 benthic stations in the southeastern Laptev Sea. In 1934, the "Glavsevmorput" expedition to the New Siberian Islands took a total of 6 dredge samples from board of the schooner "Temp". In 1937, "Glavsevmorput" organized a more extensive faunistic inventory covering nearly the whole area of the Laptev

Sea. From three vessels, "Malygin", "Sedov", and "Sadko", benthic samples were collected at a total of 87 stations. An expedition of the Institute of Arctic and Antarctic Research (Leningrad) with the vessel "Litke" gathered interesting benthic material from 33 stations in 1948.

In addition to these Russian expeditions, the Norwegian polar exeditions with the vessels "Fram" (1893) and "Mod" (1924) sampled benthic animals in the Laptev Sea from one station each. In 1963, the American vessel "Northwind" took meiobenthic samples at 106 stations between Bering Strait and the Taimir Peninsula, from which a total of 53 were in the Laptev Sea.

Before 1993, the most recent and comprehensive expedition to the Laptev Sea was organized by the Zoological Institute St. Petersburg of the USSR Academy of Sciences in 1973 (Golikov et al., 1992). From two vessels, "Forvater" and "Zenit", a variety of different sampling techniques (among others, quantitative sampling by SCUBA divers) was employed at each station in order to get a more complete picture of the fauna. A total of 672 macrobenthos, about 400 meiobenthos, and 10 plankton samples were taken at 112 stations, primarily in the eastern Laptev Sea.

Summarizing the biological field studies of the last 100 years, benthic samples have been taken at a total of 338 stations in the Laptev Sea (Fig.3). In spite of the apparently high station density, our knowledge on the benthos is still far from being complete, neither qualitatively nor quantitatively (i.e. with respect to community distribtution and abundances, respectively). The reasons are diverse. The sampling equipment used on most stations, particularly during the expeditions of the 19th and early 20th century, consisted almost exclusively of trawls or similar gears. They provide at best a qualitative impression of the faunistic composition. Quantitative data on the distribution of organisms obtained by means of grab samples or diving are much rarer. Moreover, only a part of the samples was processed to date, some material got lost, and another part is still to be examined. However, our faunistic knowledge has been improved during the last 30 years, especially due to recent efforts of scientists from the ZISP. A total of 311 invertebrate species were reported by Popov (1932) and 473 species by Zenkevich (1963); today, 1,084 species (907 macrobenthic, 142 meiobenthic, and 35 planktonic species) are known from the Laptev Sea. Like in other Arctic seas, crustaceans, particularly amphipods, account for most of the species, followed by molluscs, bryozoans, polychaetes, sponges, foraminiferans, and hydroid polyps. Again, it should be kept in mind that the various taxa have been studied to different extent. We have studied 80% of molluscs, sponges, bryozoans, and some other groups. But we do not have any data of diverse groups such as, for instance, nematodes. This group is assumed to occur in the Laptev Sea with 500 species.

Benthic zonation patterns in the Laptev Sea

A synoptic interpretation of the material collected by the various expeditions permits a general description of the distribution and composition of benthic communities. Popov (1932) summarized the studies of 50 years and delineated three faunistic regions in the Laptev Sea (Fig.4). A "Western Region" basically follows the coastline from the mouth of the Lena River to the northern tip of the Taimir Peninsula. Its fauna is characterized by species with their main zoogeographic distribution in western Eurasian seas. A "Northern

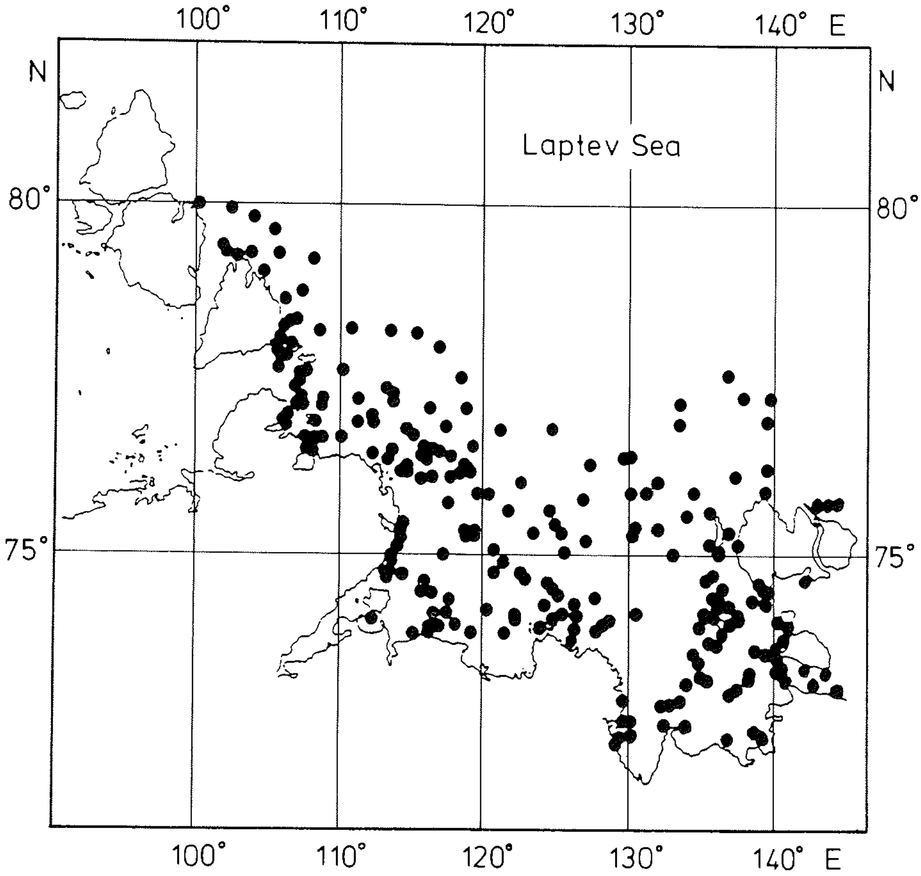

Figure 3: Location of stations in the Laptev Sea where benthic samples have been taken during 1878-1973 (after Smimov and Smirnov, 1990; with additions)

Region" includes the entire shelf north of the latitude of the New Siberian Islands. This region is characterized by the presence of species of eastern origin for which the Laptev Sea constitutes the western boundary of their distribution. The third region encompasses the southeastern Laptev Sea along the coastline from the delta of the Lena River to the New Siberian Islands. Species which prefer the brackish waters off Siberia (so-called "estuarine-Arctic species") predominate the fauna of this region.

According to recent zoogeographic studies of ZISP scientists, this scheme of the benthic zonation of the Laptev Sea needs some refinements. For instance, the distribution patterns of estuarine-Arctic species like the crustaceans *Saduria entomon* and *Gammaracanthus loricatus* or the molluscs *Portlandia aestuariorum* and others suggests that brackish waters predominate not only east of the Lena delta but also west of it. There, the rivers Khatanga, Anabar, and Olenek also discharge large quantities of freshwater into the southern part of the Laptev Sea creating conditions suitable for brackish water species. The coastal areas on both sides of the Lena delta should therefore be treated as one faunistic region. For typically marine stenohaline taxa such as echinoderms and others there is, however, some evidence for a decline in species numbers from the northwestern Laptev Sea southwards and eastwards. With respect to this trend, there is obvious scope for future work.

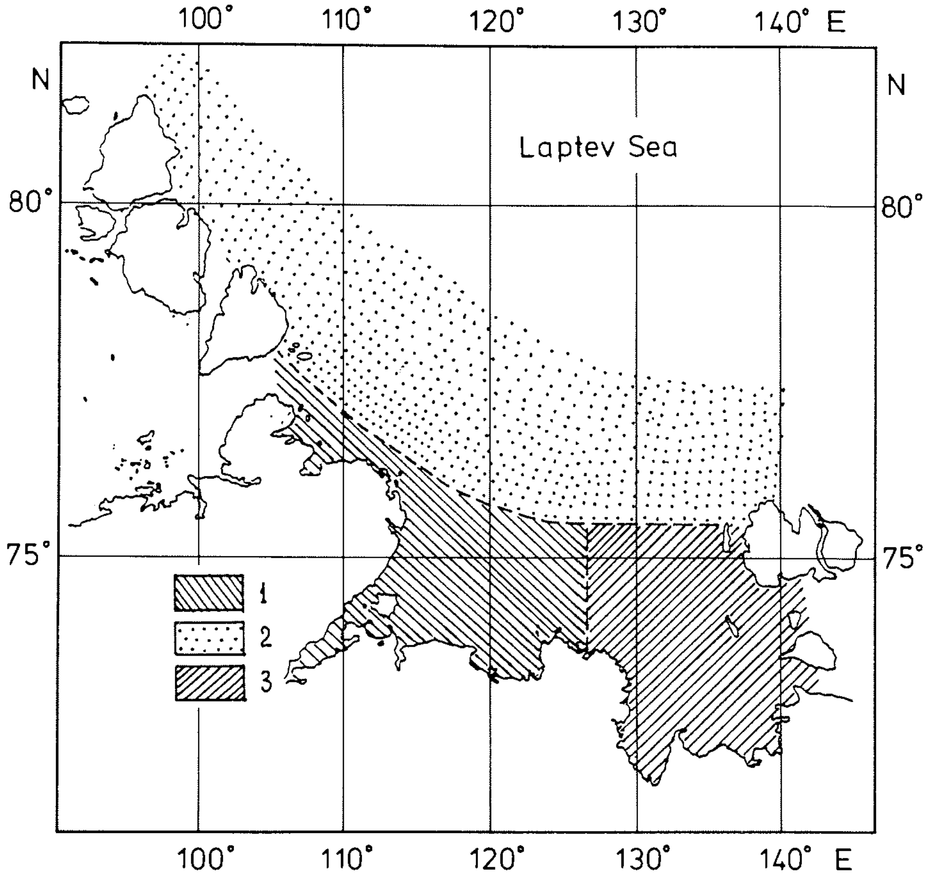

Figure 4: Benthic zonation of the Laptev Sea according to Popov (1932): 1: Western Region; 2: Northern Region; 3: Southeastern Region

During the ZISP expedition in 1973 for the first time SCUBA diving was used to take quantitative samples. It was, thus, also possible to cover the extremely shallow areas between the Lena delta and Bunge Land which had not been accessible before (Golikov et al., 1990). It was proved that a zoogeographic boundary exists off the Stolbovoi Island and Sannikov Strait dividing the southeastern Laptev Sea into two faunistic sub-regions. Southwestwards of this boundary, along the coast between Cape Svyatoi Nos and the Lena delta, estuarine-Arctic species predominate the benthos, indicating the influence of the large freshwater discharge of the Lena. North of Cape Svyatoi Nos, however, off Stolbovoi Island and in Sannikov Strait, there is a significant shift in the dominance pattern, related to a weaker influence of brackish water masses even in small depths: Typical estuarine-Arctic species disappear, and euryhaline marine species, such as sponges, brittle stars, crustaceans (e.g. *Saduria sibirica*, and *S. sabini*) and molluscs (e.g. *Tridonta borealis* and *Portlandia siliqua*), become predominant. Moreover, even typical kelp communities are found between Stolbovoi Strait and Bunge Land in the north. A similar boundary might be expected in the southwestern Laptev Sea, west of the Lena delta, but there is evidence that this boundary is much nearer to the coast than in the eastern Laptev Sea (Fig. 5).

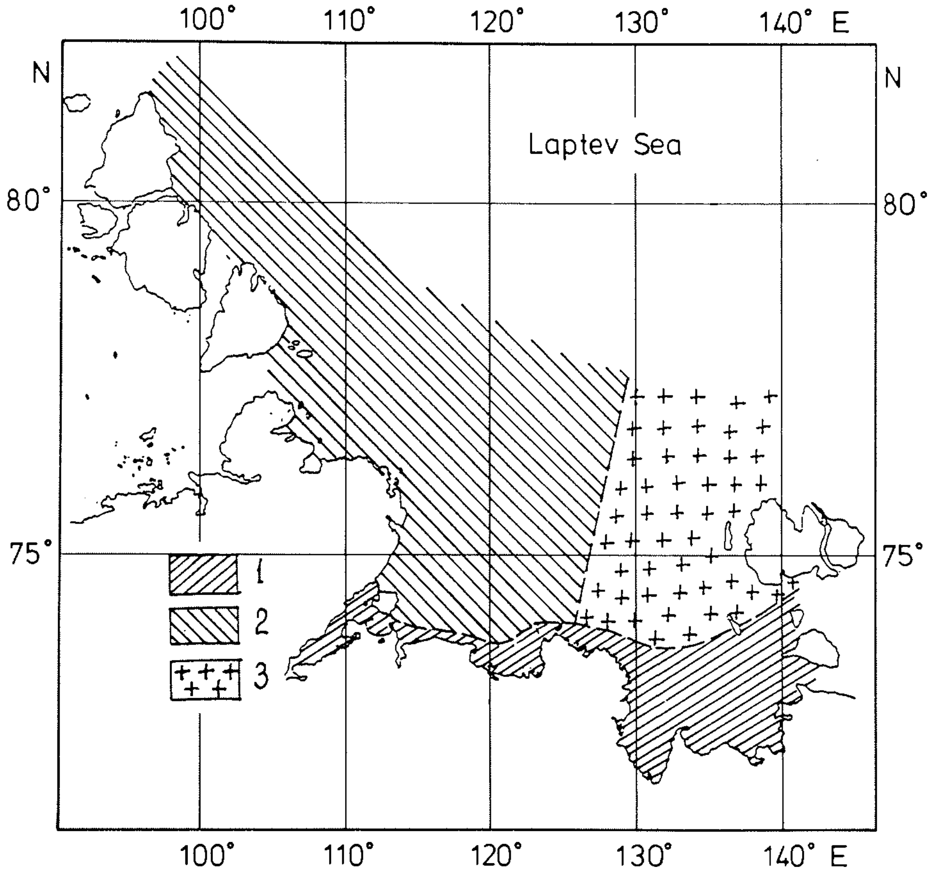

Figure 5: Benthic zonation of the Laptev Sea according to current knowledge (based on Golikov et al. (1990); with some additions): 1: Western Marine Region; 2: Southern Estuarine-Arctic Region; 3: Eastern Marine Region

Another important refinement of Popov's scheme is the division of the northern offshore part of the Laptev Sea, inhabited by true marine organisms, into a western and an eastern sub-region. The boundary between these two faunistic provinces follows approximately a meridian between 130°E and 150°E. This zoogeographic pattern is suggested by the distribution of several species, such as certain bivalves, gastropods, amphipods, cumaceans, and echinoderms. A major part of Atlantic boreal-Arctic species do not spread into the eastern Laptev Sea, and most Pacific boreal-Arctic species do not penetrate further westwards than to the New Siberian Shoals. The distribution of the various zoogeographic species groups primarily reflect the large-scale hydrography. Of special importance is how far water masses of Atlantic origin penetrate from the central Arctic Ocean into the southern and eastern Laptev Sea. Of course, the freshwater discharge of the rivers Lena and Yana is probably also essential for the faunistic composition, especially in the northeastern Laptev Sea.

Perspectives for future work

In the very recent past the developing tight cooperation between Russian and Western scientists has provided new opportunities to continue and even intensify the ecological research in the Laptev Sea. The two-ship expedition of the Russian vessel "Ivan Kireyev" and the German research icebreaker "Polarstern" in the summer of 1993 has yielded extensive new material (Schmid et al., 1994). On both ships, Russian and German biologists collaborated in taking planktonic and benthic samples by using various methods (benthic: dredge, various trawls, box corer, multicorer, seabed imaging; planktonic: phytoplankton net, bongo net, multinet, plankton pump). The station plans of the two ships were complementary: The field studies from board of the "Ivan Kireyev" (performed at 34 biological stations) focussed on the shallow southern Laptev Sea, while the scientists onboard "Polarstern" worked primarily in the offshore northern Laptev Sea. Altogether 60 stations in depths ranging from 10 to 3,000 m were covered, yielding hundreds of new samples.

For the next years, several additional expeditions are planned which will be performed within the framework of the international, multi-disciplinary project "GEOLAPEX 2000". The expected huge amounts of new samples and data will be analyzed with respect to a variety of scientific issues. In terms of faunistics, more details of zoogeographic distribution patterns can certainly be resolved. By comparison with the historic data stored in Russian institutes potential zoogeographic changes on decadal scale - indicating hydrographic and climatic shifts - may be documented and analyzed. It is planned to implement a joint zoogeographic database serving as a versatile tool for these analyses. In addition to the investigations on zoogeography, biodiversity and community patterns, the scientific programme also comprises ecological work on the coupling between benthos, pelagic realm and sea ice biota, as well as autecological studies on the adaptation of abundant species in terms of life cycle and physiology.

The collaboration of the various working groups involved in the joint project will provide a huge body of information on environmental conditions and geological history, serving as a sound basis for the interpretation of zoogeographic and ecological results. It can be expected that our knowledge on the Laptev Sea and adjacent regions will be enhanced considerably by the investigations planned for the next years.

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PALEOCEANOGRAPHY AND PALEOCLIMATOLOGY OF THE LAPTEV SEA, EAST SIBERIAN SEA AND THE ADJACENT DEEP-SEA

CLIMATOLOGICAL SIGNIFICANCE OF ARCTIC SEA ICE AT PRESENT AND IN THE PAST

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Polar sea ice, which covers approximately 10% of the world's oceans, is an important steering mechanism for the global climate system. Acting as a largely impermeable lid and due to its high albedo, sea ice severely controls the energy and gas exchange between ocean and atmosphere.

Climatic models have shown that, due to huge lateral extension in comparison to an average thickness of only 3 m, the Arctic sea-ice cover is expected to react sensitively to environmental changes. One important feature, not considered thus far, of Arctic sea-ice cover is its high - up to 40 t/km^2 - sediment content (Reimnitz et al., 1993). Although the occurrence of dirty sea ice has been known since the beginning of this century (Nansen, 1906) detailed investigations, such as its distribution, characteristics, or entrainment mechanism, were not carried out until the beginning of the 1980's in the region of the Beaufort Gyre (e.g. Barnes et al., 1982; Reimnitz et al., 1987; Reimnitz et al., 1992; Reimnitz et al., 1993) and some years later also in the region of the Transpolar Drift (Pfirman et al., 1989; Wollenburg, 1993; Nürnberg et al., in press.).

In order to study the climatological impact of particulate matter sea ice of the Transpolar Drift, which moves ice from the Siberian shelf seas across the Eurasian Basin to exit through the Fram Strait in an average of 2-3 years (Nansen, 1904, Colony and Thorndike, 1985), field work investigations were performed during several POLARSTERN cruises to the Norwegian-Greenland Sea (Hempel and Thiede, 1991), the Fram Strait, and the central Arctic Ocean (Thiede, 1988) and during two expeditions to the New Siberian Islands (Dethleff et al., 1992). These investigations have shown that sediment inclusions in sea ice are of considerable consequence for previous sediment budget calculations, ablation processes, climate modelling, and remote sensing procedures (e.g. Pfirman et al., 1989; Wollenburg, 1993; Nürnberg et al. in press.). According to rough estimates large parts of the recent sedimentation in the eastern Arctic Basin can be accounted for by sea ice transport (Wollenburg, 1993, Nürnberg et al., in press.). Therefore, modern sea-ice rafting represents a substantial fraction of the total Arctic sediment budget. However, Arctic sea ice does not only transport sediments but also man-made pollutants, making sea ice the 'garbage truck' of the Arctic Ocean (Dethleff et. al, 1993). Furthermore, dirty sea ice can reduce ice albedo and enhance melting during summer (Fütterer et al., in press).

Sea-ice sediment composition in the central Arctic Ocean and most recent investigations in the Laptev Sea have stressed the importance of the broad Arctic shelf areas for dirty sea-ice formation. Above all, the East Siberian shelf seas, which belong to the world's largest and shallowest shelf areas, act as source areas for the largest amount of fine-grained sediments transported to the deep Arctic Ocean (Pfirman et al., 1989, Dethleff et al., 1993, Wollenburg, 1993, Nürnberg et al. in press; Reimnitz et al., in press.).

Suspension freezing, the principal sea-ice sediment entrainment mechanism, requires shallow, open water or thin ice, wind, and low temperatures (cf. Reimnitz, 1993). Under these conditions, frazil and anchor ice forms, and then floats sediments to the surface. The discovery of a 1,800- km-long and 10-to-15-km-wide, recurring polynya in the Laptev Sea, already well known to the Russians (Zakharov, 1966), is thought to answer the question of sediment sources for Arctic sea ice. Thus eolian transport, slumping from cliffs and adfreezing at floe base, seem of minor importance for modern sediment incorporation into Arctic sea ice. The role of river discharge has not yet been estimated. According to ice observations and satellite images, the polynya borders the edge of the fast ice between 10 m and 30 m water depth throughout wintertime, while it is maintained by strong offshore winds (Dethleff et al., 1993; Dethleff, this volume; Reimnitz et al., in press.).

Accordingly, the yearly occurrence of the Laptev Sea polynya is a function of the atmopheric pressure system. Thus changes in climate, sea level, river run-off and other environmental factors will have major impacts on this sensitive polynya system and therefore on ice and brine formation, and finally on sediment incorporation. A lowered sea level, e.g. during glacial periods, has moved the coastline along the steep Siberian continental slope, which in turn would properly lead to a totally different ice regime in the Arctic Ocean. In the Laptev Sea at least five stillstands of sea level may have occurred since about 17,000 yr. B.P. (Holmes and Greager, 1972). Climate models by Lamb (1977) have suggested a reversal of atmospheric circulation over the inner Arctic and hence of modern sea-ice circulation to form a counterclockwise gyre in the Arctic Ocean during the last glacial. However, it still remains an open question, if the Laptev Sea Polynya and/or the Transpolar Drift were still active during such periods.

Evidence for drastic changes in the Arctic ice regime are actually stored in deep-sea sediments - the environmental archive - of the central Arctic Ocean. Today, eastern Arctic Ocean sea ice and surfical deep sea sediments are fine-grained, dominated by silty clays (Wollenburg, 1993; Nürnberg et al., in press.; Fütterer et al., in press.). However, the late Quaternary sedimentary record is characterized by cyclic changes in color and sediment composition and by variations in physical properties, which are thought to reflect distinct environmental changes, such as the variability of sea-ice cover (e.g. Fütterer et al., 1992; Spielhagen and Thiede, this volume).

Remarkable with respect to distinct environmenal changes are sediment cores from the top of the Lomonosov Ridge and the Morris Jesup Rise, areas where sedimentation is clearly dominated by ice rafting. Typical for these sediment cores are frequent layers of "cottage cheese" texture (up to 40 cm thickness), made up of silty to sandy sediment pellets, typically 0.5 to 1 cm in diameter (Fig. 1). Cottage cheese layers with high sand concentrations (up to 40 wt.%) are possibly the document of past climate events, such as deglaciations, when different sea-ice sediment entrainment mechanisms took place to accumulate much more sediment in or on the Arctic sea-ice cover. Heavy sediment-laden ice would further reduce the albedo so that sea ice would have experienced extensive melting. The shallow, exposed, but presumably not glaciated Laptev Shelf (Fütterer et al., in press.), could be a vast source of these sediments during periods of lower sea level. However, the comparison of river load and shelf deposits from the Laptev Sea with sea ice and deep-sea sediments from the Arctic Ocean will give a better understanding of the modern sea-ice and iceberg drift regime.

The continental frame of the Arctic Ocean, its large shelf areas and the various river systems discharging into the Arctic Ocean complicate the search

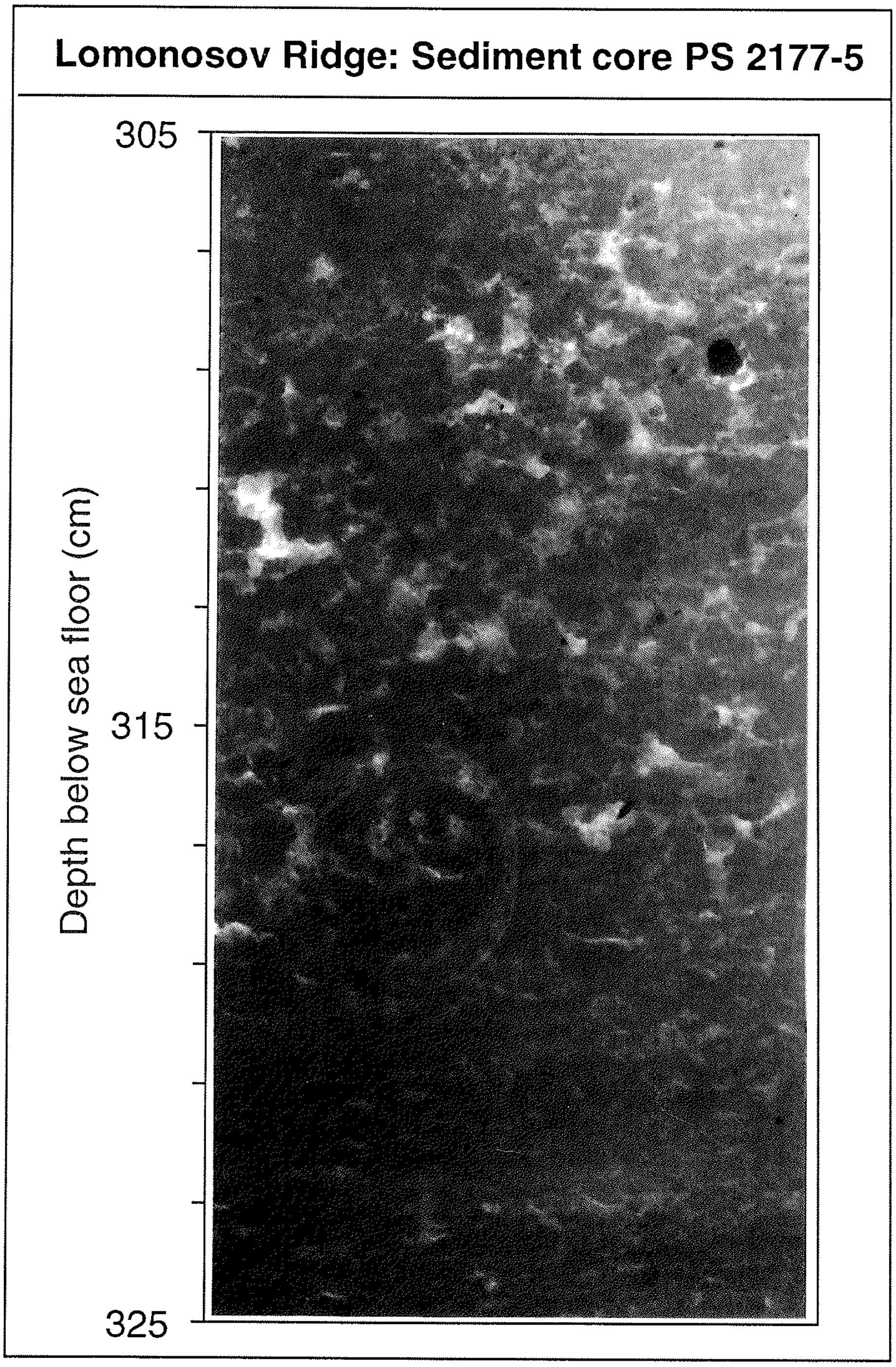

Fig. 1: X-ray record of a typical 'Cottage Cheese Layer' in a sediment core from the top of the Lomonosov Ridge (1399 m water depth).

for source areas of sea-ice sediments. Applying only sedimentological investigations is probably not sufficient enough. Chemical analyses of sea ice, sea-ice and sea-floor sediments as well as of suspended matter in the water column will be the next methodological attempt. Chemical tracers (e.g. CHC) will be identified and traced from the rivers into the deep Arctic Ocean in order to estimate the relevance of single source areas for sedimentation in the central Arctic Ocean. Furthermore, we will attempt to map sea-ice sediments with remote sensing methods.

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SHELF-TO-BASIN SEDIMENT TRANSPORT IN THE EASTERN ARCTIC OCEAN

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Introduction

One of the overall goals of marine-geological research programs in the Arctic Ocean is the high-resolution study of changes in paleoclimate, paleoceanic circulation, paleoproductivity, and sea-ice distribution in the central Arctic Ocean and the adjacent Continental Margin during Late Quaternary times. Of major interest are the significance of the Arctic Ocean for the global climate system ("Global Change"), the correlation of paleoenvironmental data from the different depositional environments (i.e., shelf - slope - deep sea), and the correlation of marine and terrestrial climatic records. To reach these objectives, detailed sedimentological, geochemical, mineralogical, and paleontological investigations have been performed, are in progress, and planned on sediments from the Arctic Ocean and the surrounding continental margin areas. Comprehensive summaries about the present knowledge on Arctic Ocean geology, paleoceanography, and paleoclimate are given by Herman (1989), Bleil and Thiede (1990), and Grantz et al. (1990).

In this context, the characterization and quantification of terrigenous sediment supply from the Eurasian Continent to the marine realm, its transfer from the shelf to the slope and deep sea, and its variation between glacial and interglacial times may give important informations about the history of paleoceanographic circulation patterns, extent of sea ice (and icebergs), and the paleoclimate in Eurasia. Furthermore, the Eurasian shelf areas are an important link between the marine and the terrestrial climate records. Especially the Laptev Sea shelf is believed to be the source area for much of the sediments included in sea ice and transported in the ice by the Transpolar Drift through the entire Arctic Ocean (Fig. 1).

Sedimentary processes in the Arctic Ocean

The terrigenous sediment supply and its shelf-to-basin transport in the eastern Arctic Ocean are mainly controlled by river discharge, sea-ice (and iceberg) transport, turbidity currents, and oceanic currents; aeolian supply are probably of secondary importance (Fig. 2; e.g., Darby et al., 1989). Because contaminants such as heavy metals and organic pollutants are supplied to the Arctic realm through the same pathways, a better understanding of shelf-to-basin transport processes is also of importance for monitoring programmes of the Arctic environment (AMAP, 1993).

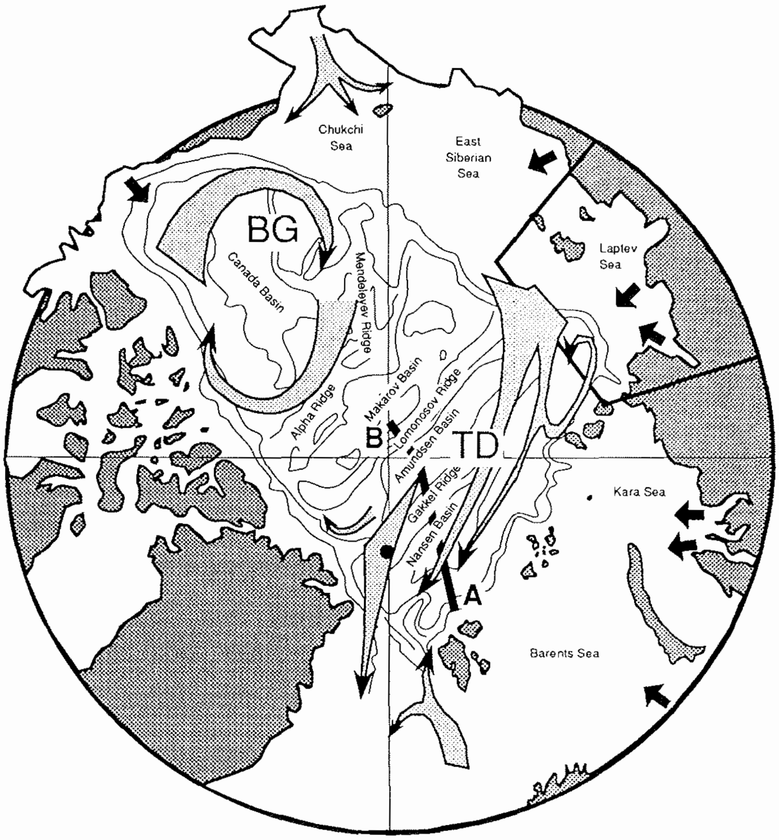

Fig. 1: The Arctic Ocean and major currents systems. BG = Beaufort Gyre; TD = Transpolar Drift. Black arrows indicate major river discharge. Profile A-B is shown in Figure 3; black dot marks position of Core PS2206 (see Fig. 8).

River discharge

Today, the most important contributors are the Siberian rivers Yenisei (603 km^3/yr), Ob (530 km^3/yr), and Lena (520 km^3/yr) (Aagaard and Carmack, 1989). These rivers transport large amounts of dissolved and particulate material (i.e., chemical elements, siliciclastic and organic matter, etc.) onto the shelves where it is accumulated or further transported by different mechanisms (sea-ice, icebergs, turbidity currents, etc.) towards the open ocean. For example, the annual discharge of suspended sediments by the Lena River is already 17.6*10^6 tons (Martin et al., 1993). Thus, river-derived material contribute in major proportions to the entire Arctic Ocean sedimentary and chemical budgets. The Siberian rivers also transport major amounts of anthropogenic pollutants (radioactive elements, heavy metals, etc.) which are trapped in coastal-near sediments and/or transported towards the open ocean.

Factors controlling sedimentation along the Eurasian Continental Margin

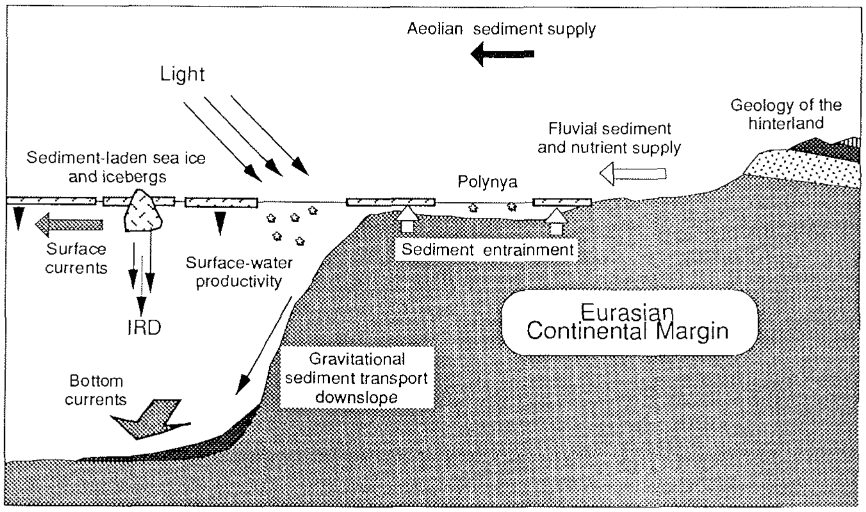

Fig. 2: Summary scheme of factors controlling the sedimentation along the Eurasian continental margin.

Sea-ice and ice-berg transport

Large amounts of the sediment are incorporated into the sea ice in the Laptev Sea shelf area and then transported as ice-rafted debris (IRD) through the central Arctic Ocean via the Transpolar Drift (Pfirman et al., 1989; Wollenburg 1993; Nürnberg et al., 1994; Kassens et al., this vol.). In areas of extensive melting, sediment particles are released and deposited at the sea floor. In these areas, this process may dominate the supply and accumulation of terrigenous material in the polar environment. Icebergs are another possibility for transportation of terrigenous material into the central Arctic, but are very rare today due to the absence of large ice shelves. Source areas for icebergs today are Ellesmere Island, North Greenland, Svalbard, Franz-Josef Land, and Severnaya Zemlya (Sudgen, 1982; Darby et al., 1989).

Turbidity currents

Downslope-transport by turbidity currents may control the sedimentation in the deep basins. For example, major proportions of the Late Quaternary sedimentary columns in the Nansen and Amundsen Basins consist of turbidites (Fütterer, 1992). In the southeastern part of the Canada Abyssal

Plain adjacent to the Canada shelf and the Mackenzie cone, almost 70 % of the cored sediments were deposited by turbidity currents (Champbell and Clark, 1977). Furthermore, the resuspended material (clay-sized siliciclastic material as well as contaminants) may be transported via oceanic (boundary) currents over long distances into the central Arctic.

Oceanic currents

Fine-grained material might be transported from coastal areas into the central part of the Arctic Ocean. In this context, the major boundary currents (e.g., Aagard, 1989) and the downslope flow of shelf-brine waters (Aagaard et al., 1985; Schauer, this vol.) are certainly of great importance.

Aeolian sediment supply

Based on snow samples from the western central Arctic pack ice, the aeolian dust supply may account for a sedimentation rate of about 0.02-0.09 mm/ky (Darby et al., 1989). That means, about 1-10 % of the pelagic sedimentation in the central Arctic may be of aeolian origin.

A detailed study of the composition and grain size of the siliciclastic sediment fractions can give an important key to distinguish between the different source areas and shelf-to-basin transport mechnisms as shown for two examples: (1) clay mineral distributions in the Laptev Sea and the open central Arctic Ocean (for method of clay mineral determination see Stein et al., 1994; cf. also Fig. 3), and (2) bulk mineralogy and heavy mineral distributions in the Laptev Sea (for methods of bulk and heavy mineral determinations see Lapina, 1965; cf. also Fig. 6).

Clay mineral distribution in the Laptev Sea and the eastern central Arctic Ocean

In polar and subpolar regions where physical weathering processes dominate and chemical and diagenetic alterations are negligible, the clay mineral association in marine sediments can be a valuable indicator of sediment sources. That means, the clay mineralogy of Arctic Ocean sediments mainly reflects the source mineralogies of the landmasses and shelf areas surrounding the central Arctic Ocean basins (Darby et al. , 1989 and further references therein). In general, illite is the dominant clay mineral (mostly > 50 %), followed by chlorite and kaolinite (5 to 30 %); smectites are variable, but of minor importance. This general picture is valid for the Amerasian Basin (e.g., Naidu et al., 1975; Clark et al., 1980; Dalrymple and Maass, 1987, Darby et al., 1989) as well as the Eurasian Basin (Fig. 2; Berner 1991; Levitan et al., 1994, Stein et al., 1994a). However when going into details, differences in clay mineral associations between different source areas are obvious and can be used as source rock indicators. For example, potential source areas for kaolinite in Arctic Ocean sediments are Mesozoic and Cenozoic strata along the north coast of Alaska and Canada (Darby, 1975; Naidu and Mowatt, 1983;

Dalrymple and Maass, 1987) and in the Franz-Josef-Land area (Levitan et al., 1994). A major source for smectite is the western Laptev Sea (see below; Silverberg, 1972; Wollenburg, 1993; Nürnberg, et al., 1994).

Sea-ice sediments from the eastern central Arctic Ocean (Profile A-B; Fig. 1) have high smectite contents of 15 to 60 % (Fig. 3). The values are similar to those of surface sediments from the western Laptev Sea shelf which contain up to 45 % smectite (Fig. 4; Wollenburg, 1993; Nürnberg, et al., 1994). Major amounts of the smectite found in the Laptev Sea have probably been transported in the Kathanga River as alteration products and derived from the basalt complex of the Siberian Platform south of the Taymyr Peninsula (Coffin and Eldholm, 1991). This suggests that the western Laptev Sea shelf is a potential source area of the siliciclastic material included in the sea ice. The surface sediments of the Eurasian Basin, however, have only very low contents of smectite (Fig. 3; Stein et al., 1994a). This indicates that sea ice is probably not the dominant transport mechanism for clay-sized material in the Eurasian Basin. Other transport mechanisms such as oceanic and turbidity currents may be more important in controlling the sedimentation in this part of the Arctic Ocean today (cf., Stein et al., 1994a). If terrigenous sediments are delivered primarily by sea ice, on the other hand, then only the coarser (silt- and sand-sized) material is accumulated in place whereas the clay-sized material is transported/winnowed by oceanic currents. In this case, a detailed heavy-mineral analysis of central Arctic Ocean sediments should give more information about the importance of IRD input via the Transpolar Drift than a clay mineralogy study does, because very specific heavy minerals (e.g., epidote, pyroxene, etc.) characterize the source sediments in the Laptev Sea area (see below).

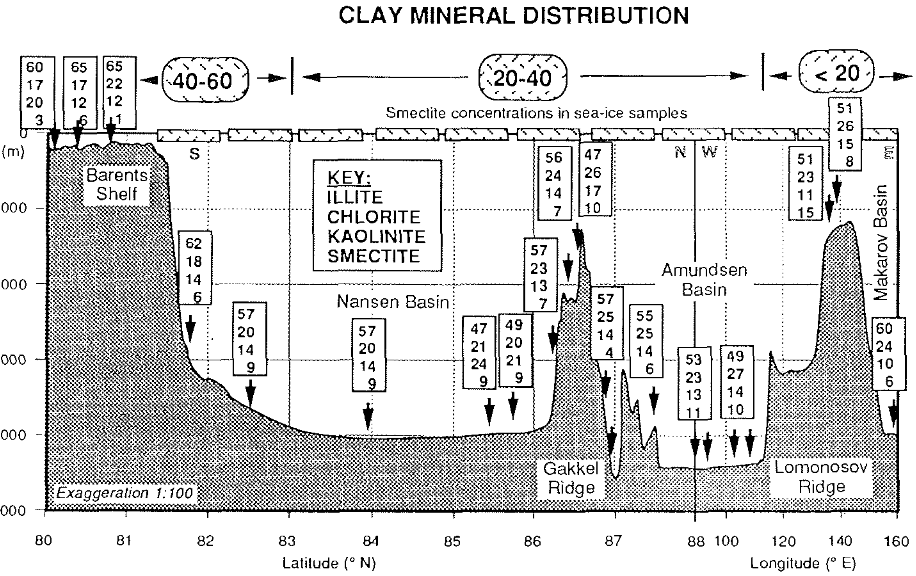

Fig. 3: Profile of clay-mineral distribution in surface sediments in the eastern Arctic Ocean (for position of the profile see Figure 1); data from Stein et al. (1994a). In addition, smectite contents of sea-ice sediments from the same geographic position than the surface sediments are shown (data from Nürnberg et al., 1994). Semiquantitative evaluations were based on peak areas of the four clay minerals smectite (≈ 17 Å), illite (10 Å), kaolinite (7 and 3.57 Å), and chlorite (7 and 3.54 Å) (Biscaye, 1965).

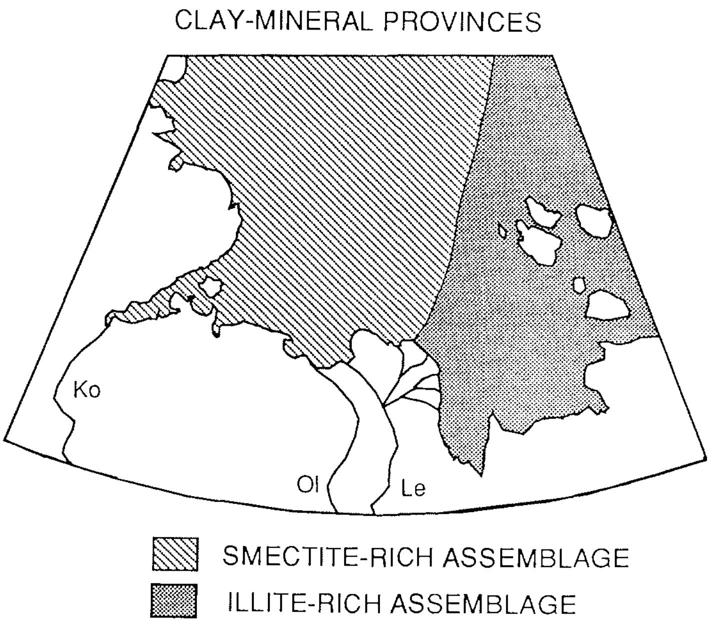

Fig. 4: Major clay-mineral assemblages in surface sediments from the Laptev Sea (according to Silverberg, 1972; Wollenburg, 1991).
Le = Lena; Ol = Olenek; Ko = Kotuy (Kathanga)

Quartz, feldspar, and heavy mineral distributions in the Laptev Sea

Bulk mineralogy (e.g., quartz and feldspar contents; Fig. 5) and, especially, heavy-mineral data (Fig. 6 and 7) can be used to characterize specific source areas. As shown by many authors, the different Arctic Ocean shelf areas show very different heavy-mineral associations which can be used as tracers for reconstructions of the transport path from the source to the deposition area (Lapina, 1965; Holmes, 1965; Lisitzin, 1972; Silverberg, 1972; Naugler et al., 1974; Zauderer, 1982; Darby et al., 1989).

The distribution maps of the different heavy minerals in surface sediments from the Laptev Sea allow the following classification (Fig. 6; Lapina, 1965): The eastern Laptev Sea is characterized by high amounts of epidote and amphibole (Fig. 6A and 6C), transported by the Lena River into the Laptev Sea. The suspension of the Kathanga River, on the other hand, is dominated by pyroxenes (Fig. 6B). The high amounts of ore minerals (ilmenite and magnetite) in the central part of the Laptev Sea, at the coast of the Taymyr peninsula, and south of the New Siberian Islands may indicate erosional processes in very shallow-water environments. Based on the occurrences of the different heavy minerals, three major heavy-mineral provinces can be identified: an epidote-pyroxene-assemblage ("Kathanga-assemblage"), an epidote-amphibole-assemblage ("Lena-assemblage"), and an ilmenite-magnetite-assemblage (Fig. 7; Lapina, 1965).

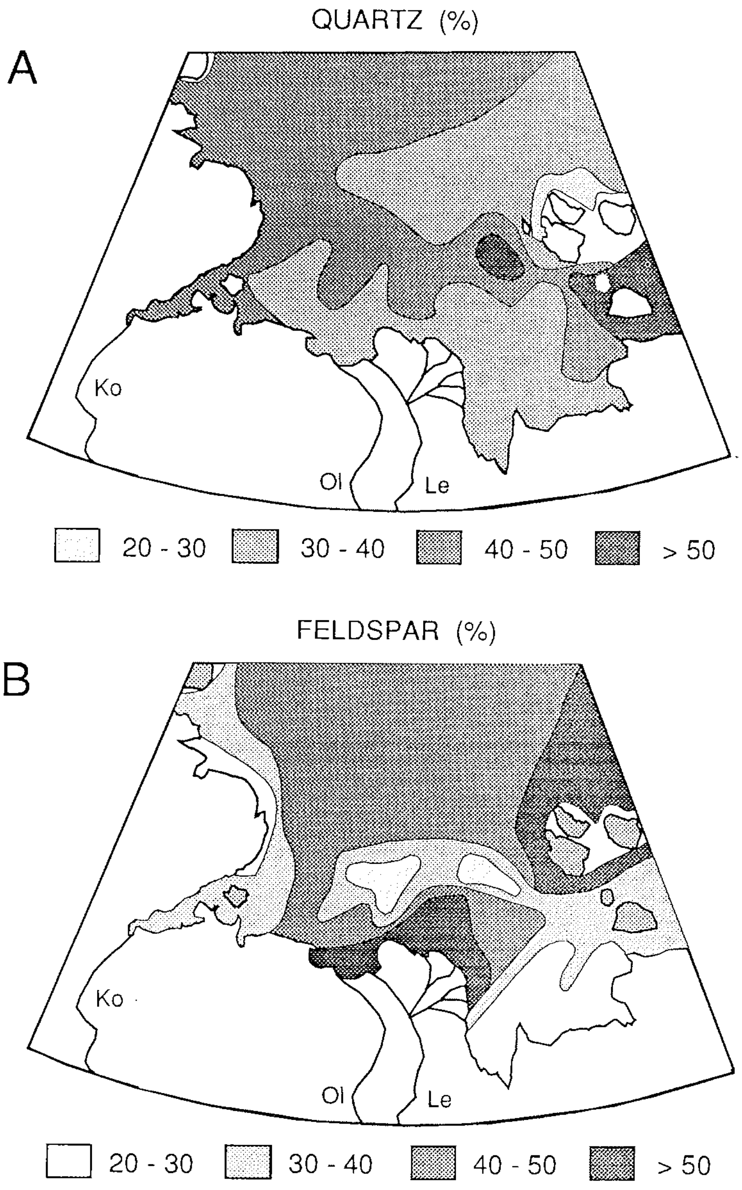

Fig.5: Distribution maps of quartz (A) and feldspars (B) in surface sediments from the Laptev Sea (from Lapina, 1965; cf.also Fig. 6).
Le = Lena; Ol = Olenek; Ko = Kotuy (Kathanga)

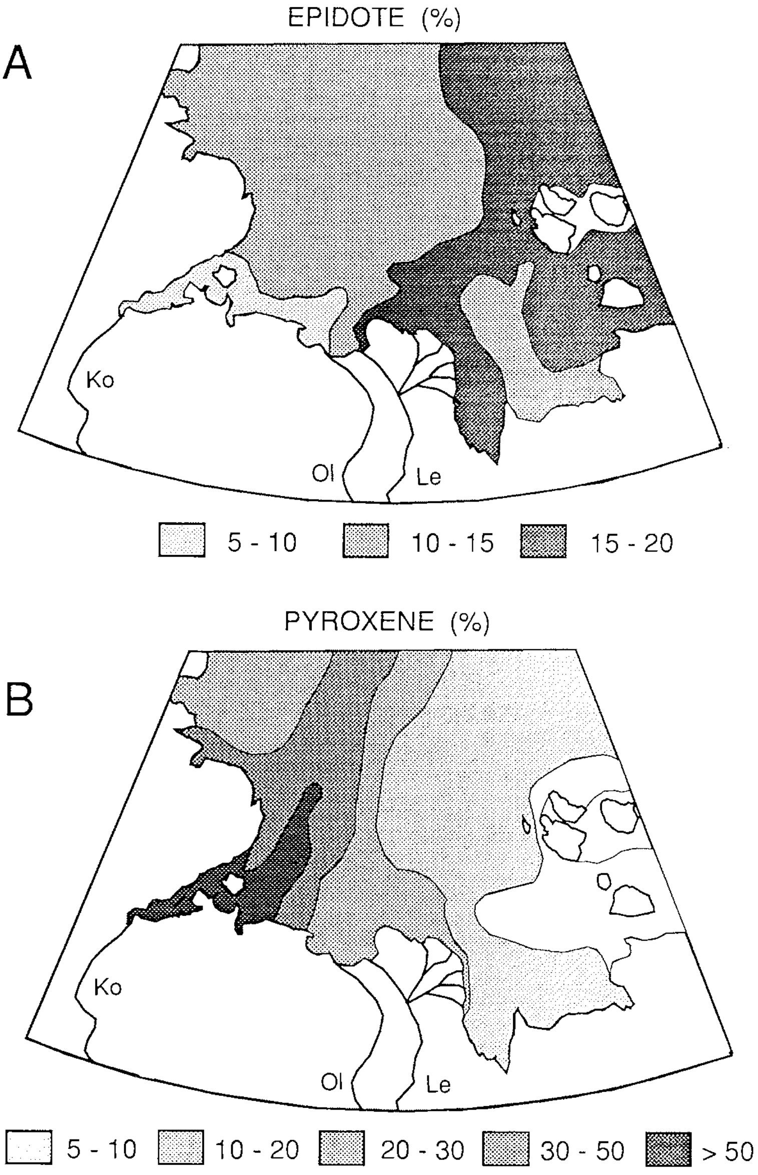

Fig. 6-1: Distribution maps of heavy minerals in surface sediments from the Laptev Sea, epidote (A), pyroxene (B), amphibole (C), and ore minerals (D) (from Lapina, 1965). In the grain-size fraction 0.05-0.10 mm, heavy minerals (density > 2.9 g/cm^3) and light minerals (density < 2.9 g/cm^3) were separated using bromoform. For heavy mineral determinations, about 300 to 400 grains were counted; the results are expressed in percentage values of the total heavy mineral fraction 0.05-0.10 mm. Unfortunately, the data basis of these distribution maps was not available for us. For data source and further details in methods of determinations, see Lapina (1965).
Le = Lena; Ol = Olenek; Ko = Kotuy (Kathanga)

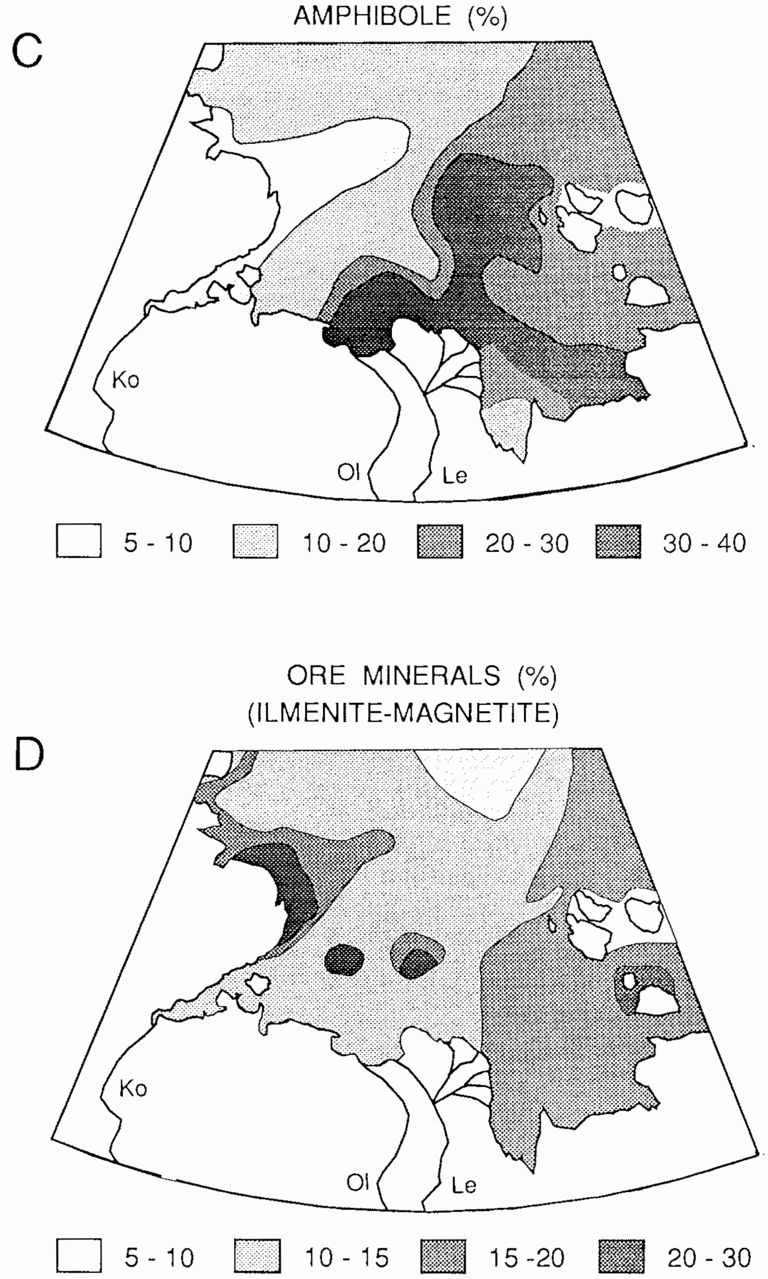

Fig. 6-2: Distribution maps of heavy minerals in surface sediments from the Laptev Sea, epidote (A), pyroxene (B), amphibole (C), and ore minerals (D) (from Lapina, 1965). In the grain-size fraction 0.05-0.10 mm, heavy minerals (density > 2.9 g/cm^3) and light minerals (density < 2.9 g/cm^3) were separated using bromoform. For heavy mineral determinations, about 300 to 400 grains were counted; the results are expressed in percentage values of the total heavy mineral fraction 0.05-0.10 mm. Unfortunately, the data basis of these distribution maps was not available for us. For data source and further details in methods of determinations, see Lapina (1965).
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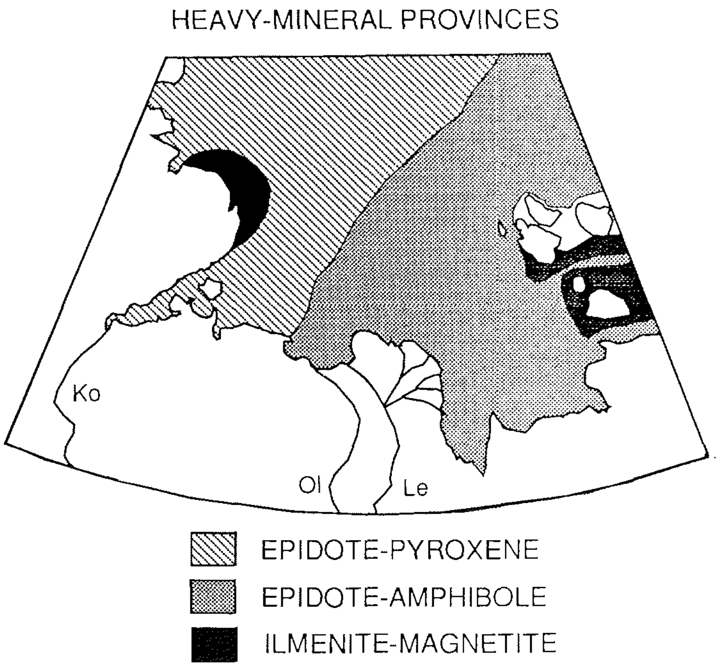

Fig. 7: Heavy mineral provinces in surface sediments of the Laptev Sea (from Lapina, 1965; cf. also Fig. 6). Le = Lena; Ol = Olenek; Ko = Kotuy (Kathanga)

In addition to the heavy-mineral-compostion, the suspensions of the Lena and Kathanga show also differences in the quartz and feldspar contents (Fig. 5). The Lena material appears to contain relatively high amounts of feldspar, whereas the Kathanga material is more quartz-rich.

Since the Laptev Sea is probably a major source of the sediments incorporated in the sea ice and transported via the Transpolar Drift into the central Arctic Ocean (see above), heavy-mineral data should be a very useful tracer to prove this hypothesis. The calculation of the heavy-mineral fluxes (in combination with fluxes of quartz, feldspars, clay minerals, etc.) in the neighbouring continental slope and in the central Arctic Ocean should allow to quantify the terrigenous sediment input via sea ice to the Arctic Ocean sediment budget. This kind of data should be produced from sea-ice sediments as well as the underlying surface sediments.

Late Quaternary changes in terrigenous sediment supply

As based on numerous studies of some hundreds of short sediment cores, distinct changes in sediment composition were recorded in the entire Arctic Ocean during the Quaternary (and late Neogene) (e.g., Clark et al., 1980; Darby et al., 1989; Thiede et al., 1990; and further references therein). These changes are very probably related to glacial/interglacial changes in sedimentary processes, paleoceanographic circulation patterns, and surface-water productivity.

In the eastern central Arctic Ocean, the supply of ice-rafted material was probably increased during glacials. At the same time, a decrease in biogenic carbonate and organic carbon suggest a decreased surface-water productivity due to an extended and more closed sea-ice cover (e.g., Pagels, 1991; Stein et al., 1994b). Clay and bulk mineralogy data also indicate distinct variations in this area, caused by climate-related changes in transport mechanisms and/or source area of the terrigenous material (e.g., Bohrmann, 1991; Berner, 1991; Vogt and Stein, 1993). In the example shown in Figure 8 (Core PS2206-4, western Gakkel Ridge), smectite contents are increased during interglacial stages 1 and 3, and decreased during glacial stage 2. This can be explained by increased smectite supply from the Laptev Sea (as most important smectite source; see above) during interglacials. Dolomite and kaolinite, on the other hand, are relatively enriched during glacial stage 2, suggesting a relative increase in terrigenous sediment supply from the Canadian Arctic and/or North Greenland (which are potential sources for dolomite and kaolinite) (Vogt and Stein, 1993; Vogt, unpubl. data). This preliminary interpretation, however, has to to proved by similar data records from other cores from the eastern central Arctic Ocean as well as by quantitative flux-rate data of clay minerals, quartz, feldspar, detrital carbonates, etc., and - especially (see above) - heavy minerals.

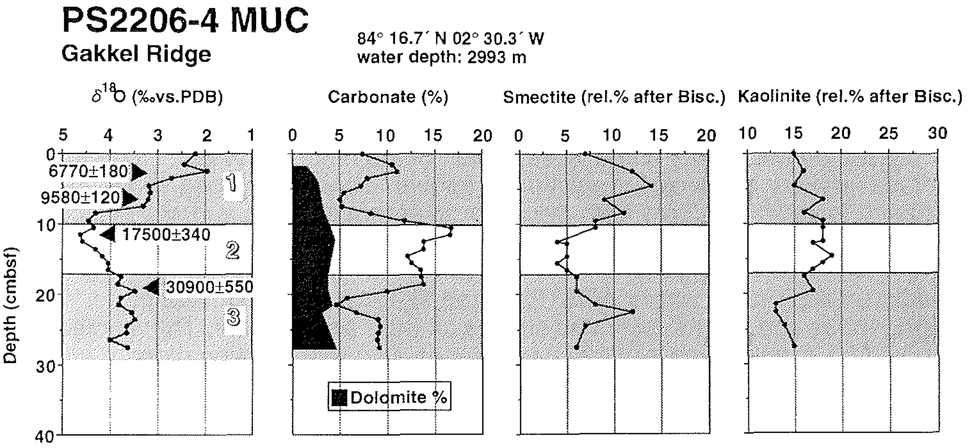

Fig. 8: Stable isotope stratigraphy, carbonate conten (in percent of the bulk sediment), and contents of smectite and kaolinite (in percent of the total clay minerals) of multicorer core PS2206, western Gakkel Ridge (for position see Fig.1) (Vogt and Stein, 1993; Stein et al., 1994b; Vogt, unpubl. data).

Recommended future research objectives

International and multidisciplinary research programs on terrigenous sediment supply along the Eurasian continental margin and its shelf-to-basin transport in the Arctic Ocean are recommended. Key areas are shelf areas of the Laptev Sea (with the Lena and Kathanga river systems), the Kara Sea (with the Yenisei and Ob river systems), and the East Siberian Sea (with the

Kolyma and Indigirka systems), and the neighbouring slope/deep-sea environments. The research programs should include the following major objectives:

(1) Modern sedimentary processes

The quantification and characterization of major river discharge, its accumulation on the shelves, and its transfer into the slope- and open-ocean environment. This study will allow estimates of the importance of riverine input for the Arctic Ocean chemical and sedimentary budgets, identifications of major transport processes, reconstructions of oceanic currents, and estimates of the anthropogenic pollution of the Arctic Ocean environment. Of major interest is a detailed sedimentological, geochemical, mineralogical, and paleontological study of surface sediments from the river itself, the river mouth area, and shelf-slope-basin transects. Methods should include determinations of heavy metals, clay minerals, heavy minerals, microfossil assemblages, organic carbon fractions, etc. Similar investigations should also be performed on river suspension material as well as sea-ice samples. This kind of data is also relevant to the Arctic Monitoring and Assessment Programme (AMAP, 1993).

(2) Glacial/interglacial change in sedimentary processes and its paleoenvironmental significance

Based on the results of the investigation of the modern system, the change of sedimentary processes in relation to (global) climatic changes should be studied in sediment cores from the major river mouth areas and shelf-slope-deep sea transects. Of highest priority is the multidisciplinary investigation of the last glacial-interglacial transition ("Termination I") in areas of very high sedimentation rates where AMS^{14}C-dated high-resolution studies of terrigenous sediment supply and climate change are possible. The studies should be extended on sediment sequences also representing older glacial/interglacial cycles. Methods to be used should be the same used for studies of the modern system.

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LATE QUATERNARY CHANGES IN THE ARCTIC OCEAN ICE COVER

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The Arctic Ocean sea ice cover is not a motionless feature. In the Amerasian Basin, it is rotating clockwise in the Beaufort Gyre (Fig. 1). In the Eurasian Basin, the Transpolar Drift carries ice from the Siberian shelves across the North Pole to the Fram Strait. Presently, the Arctic Ocean ice cover almost exclusively consists of sea ice with an average thickness of 2-3 m. Icebergs are very rare and make up less than 99% of the ice. During expeditions ARK IV/3 (1987) and ARCTIC'91 with RV POLARSTERN, only very few single icebergs have been sighted in the eastern and central Arctic Ocean within a total of four months.

The present situation with a strong dominance of sea ice is reflected in the pelagic eastern and central Arctic Ocean surface sediments. The coarse fraction (>63 µm) makes up less than 10% of these sediments and almost exclusively consists of biogenic particles (mainly planktic and benthic foraminifers). This grain size spectrum is thus similar to that of sea ice sediments, where sand-sized lithogenic particles also are rare (Fig. 2). Rough calculations about sediment transport by sea ice and accumulation rates in the Arctic Ocean indicate that the fine-grained sea ice sediments probably account for the bulk of the young sea floor deposits (Pfirman et al., 1990; Wollenburg, 1993). However, surface sediments occasionally contain gravel or even large rocks, which undoubtedly must have been transported by icebergs and later were released to the sea floor ("dropstones"). A single large dropstone of 25 kg was recovered with a box core from the surface of the Lomonosov Ridge (Station 2186, 88°31'N, 140°29'E) during the ARCTIC'91 expedition and smaller gravel is an occasional feature in all non-turbiditic core sections, indicating present and past rafting by icebergs.

The grain size distributions in three long sediment cores from the Gakkel Ridge in the eastern Arctic Ocean (1524-2), the Yermak Plateau north of Svalbard (1533-3) and the Fram Strait (1535-8) are compared in order to determine changes in the Arctic Ocean ice cover. Coarse ice-rafted detritus (IRD) is present in all investigated samples and implies a continuous history of ice-rafting in the Arctic Ocean and glaciation of at least parts of the circum-Arctic continents during the Late Quaternary. However, the distribution of coarse IRD in the cores is highly variable (Fig. 3). Since lithogenic particles are dominating the fraction >63 µm and exclusive in the fraction >500 µm in almost all samples, the grain size distributions are good indicators of ice-rafting (Molnia, 1972).

In the three analyzed cores, sediments from the last interglacial-glacial cycle and the Holocene (oxygen isotope stages 5-1; 128-0 ka) usually contain 10-15 wt.-% coarse particles. In contrast, older sediments from the glacial stage 6 ("Saalian") contain of 25-40% coarse IRD. Linear sedimentation rates (LSR) at Site 1524 on the Gakkel Ridge decreased drastically after stage 6 (from 1.7 cm/ky to 0.5 cm/ky). In the Fram Strait, the change (from 3.4 cm/ky to 2.7 cm/ky) was less significant. No LSR can be calculated for stage 6 on the Yermak Plateau, because Core 1533-3 did not penetrate into stage 7.

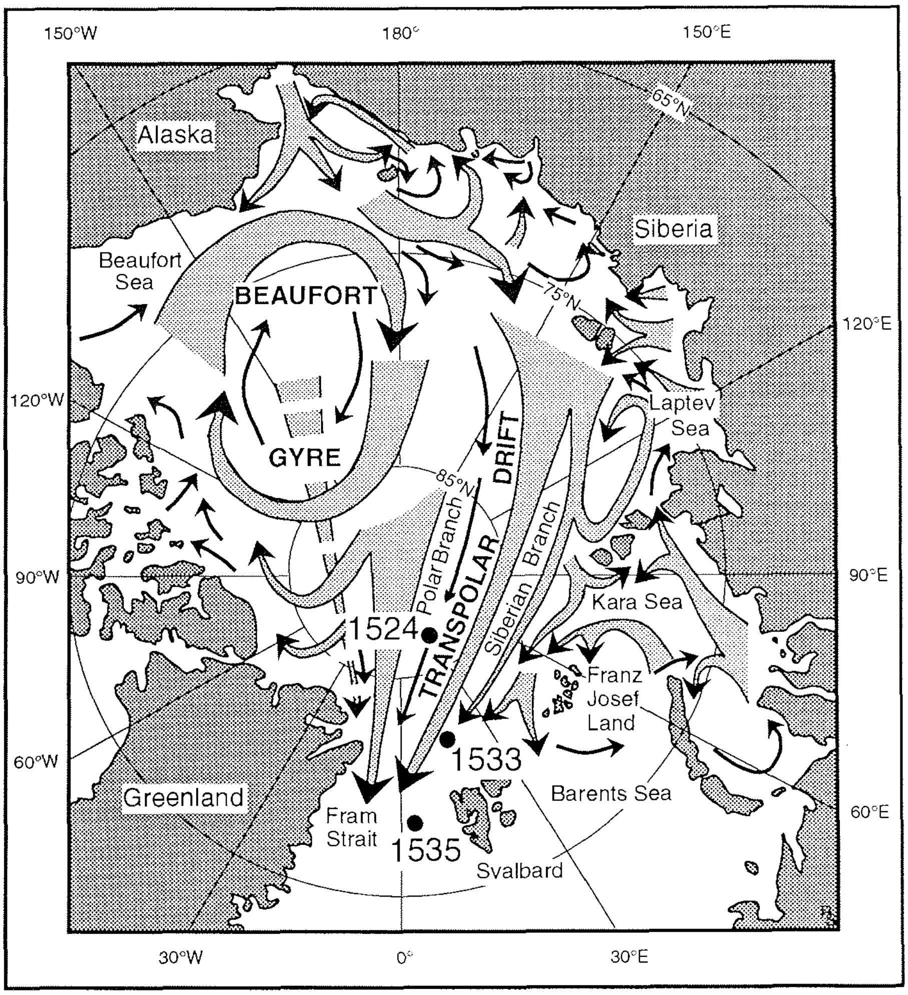

Fig. 1: Ice drift directions in the Arctic Ocean (redrawn after Gordienko and Laktionov, 1969). The locations of investigated cores are indicated.

The changes in coarse fraction contents and linear sedimentation rates indicate corresponding changes in the Arctic Ocean ice cover. The average number of icebergs in the Arctic Ocean during oxygen isotope stage 6 must have been much higher than during the last ca. 128 ky, when it was approximately on the same level as today. This implies a much stronger glaciation of circum-Arctic continents and shelves.

There is evidence that the Transpolar Drift in the Arctic Ocean (Fig. 1) had a similar routing during stage 6 as today (Bischof et al., 1990). Because the lithological composition of the IRD in stage 6 sediments from the Eurasian Arctic Ocean is significantly different from that of the Amerasian Basin, a provenance of the IRD at site 1524 from the Greenland-America area is rather unlikely.

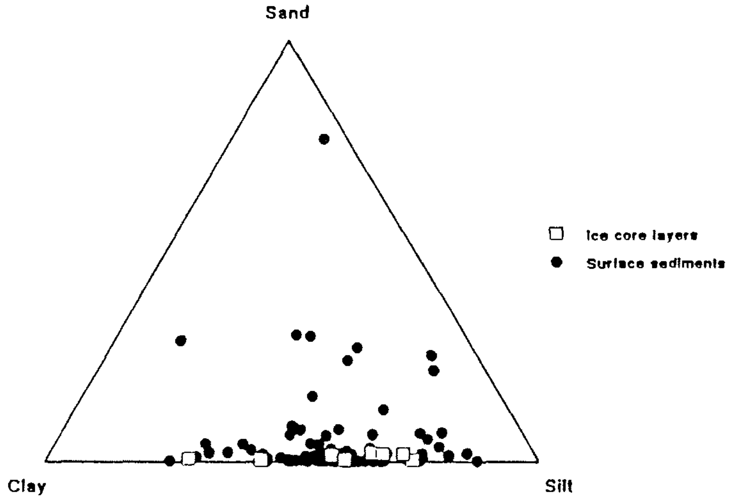

Fig. 2: Grain size distributions of sediments in Arctic Ocean sea ice (from Wollenburg, 1993)

The grain size distribution in the sediments gives further evidence of different sediment sources. In the deposits from oxygen isotope stages 5-1, there is generally a good correlation between the abundances of the fractions >500 µm and >63 µm. This indicates that the material was incorporated into the ice on land in glaciated areas, where particles of all grain sizes were "produced" by glacier erosion of basement rocks. In contrast, in sediments from stage 6 the amount of the fraction >500 µm is comparatively low, although the content of the fraction >63 µm (almost free of biogenic grains) is much higher than in younger sediments. We conclude that the fine-grained sand must have been incorporated into the ice on locations, where comparatively well-sorted sediments were available for uptake by the ice. One possible location could be the Siberian shelves. Shelf sediments are often sandy and well-sorted due to the activity of nearshore currents in shallow water depths. During glacials, the sea level was lowered by up to 130 m and the presently very shallow Siberian shelves (ca. 50 m water depth) must have been dry land. A glacier or ice cap, being fed from remote mountain ridges and overriding such an area, may have incorporated the well-sorted sediments at its bottom. We speculate that during oxygen isotope stage 6, the glacier extension in northernmost Asia must have been significantly greater than during the Weichselian glaciation (stages 4-2). In particular, the glacial ice must have reached the shelf edge at least at one location in the Kara, Laptev or East Siberian seas, from where icebergs could be released into the open Arctic Ocean. These icebergs drifted across the Yermak Plateau to the Fram Strait and continuously released their load of coarse sediment to the sea floor.

It is unclear, why such a scenario did not reappear during the following Weichselian glaciation. The atmospheric moisture supply is the crucial factor for development and evolution of continental ice sheets. Further investigation is needed to find out, why conditions in the Weichselian differred from the Saalian.

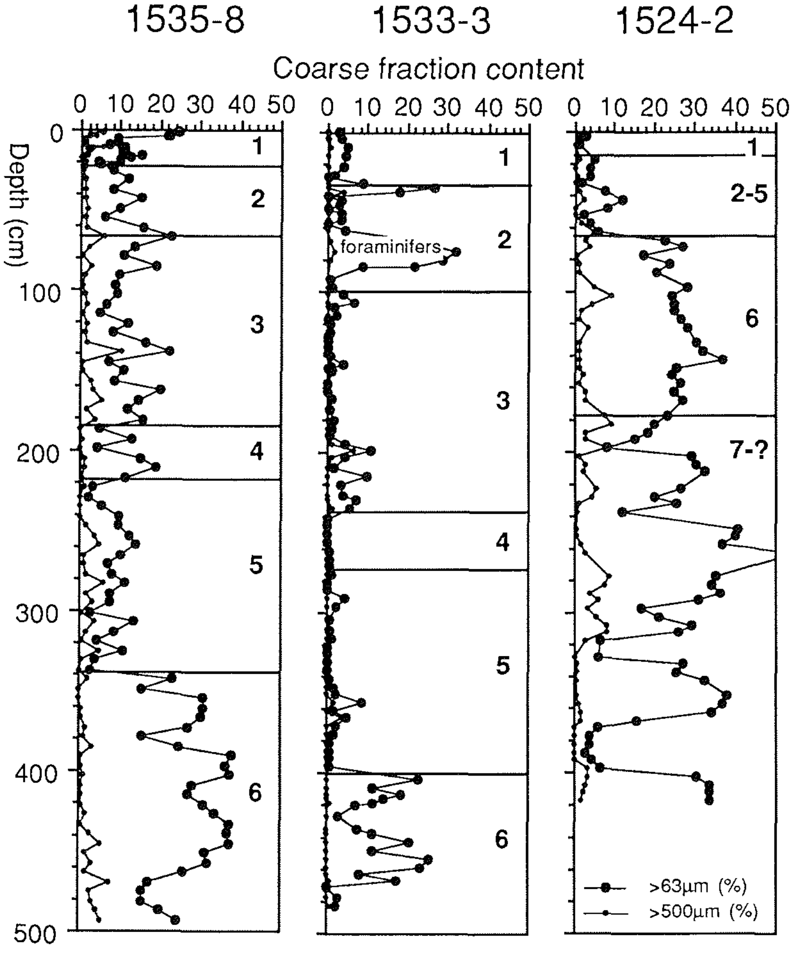

Fig. 3: Grain size distributions in the investigated cores. Stratigraphy is based for 1524-1 on ^{230}Thex and ^{10}Be measurements (Bohrmann, 1991; Eisenhauer et al., in press), for 1533-3 on ^{10}Be and oxygen isotope measurements (Köhler, 1992; Eisenhauer et al., in press) and for 1535-8 on oxygen isotope measurements (Köhler and Spielhagen, 1990). Grain size data of 1524-2 were taken from Pagels (1991). Boundaries of oxygen isotope stages are indicated.

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EVOLUTION PECULIARITIES OF THE LAPTEV SEA GEOSYSTEM AS A KEY REGION IN THE ARCTIC

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Abstract

On the whole, a general object of interdisciplinary investigations is the development of a model of the structural-material evolution of the Laptev Sea geosystem as a junction between the Mid-Oceanic Ridge in the Arctic Ocean and structures of the Eurasian continent.

In a wider sense, the model is to involve different geological components, such as tectonics, sedimentology, biostratigraphy, paleogeography, seismology, the formation of gaseous hydrates, etc., and to be based on a systematic approach.

Research work will include the following:

- theoretic investigations (analysis of existing views and development of a common conceptual base, if possible);
- re-processing and re-interpretation of available information;
- appropriate minimum of extra field investigations, primarily on the northern shelf margin and continental slope;
- laboratory analysis of available and new stony material on an up-to-date level;
- computer data processing and development of mathematical models of processes and objects.

This new line of inquiry is planned as a joint correlation analysis of coeval bottom deposits of the Arctic and the Antarctic, aimed at correlating global natural events and revealing general regularities of sedimentogenesis under polar conditions. This line of research holds great promise for the future; it is, thus, of utmost importance to direct our attention to these questions at the outset.

The geological history of the Laptev Sea

The Laptev Sea shelf has been a key region of the Arctic at all stages of its geological history, during which many global natural objects and phenomena are as though joined. Thus, at the pre-oceanic development stage, structures of the ancient Siberian platform are conjugated here with northeast mesozoids. During the opening of the Arctic Ocean a unique geological situation existed - the mid-oceanic Gakkel Ridge was joined at its end with continental structures. In terms of present-day geography, the Laptev Sea is an intermediate sea between the western and eastern Arctic and is the last sea in which the influence of warm Atlantic waters, whcih have influenced the sea's hydrosphere and biota, can be observed.

Stated differently, the Laptev Sea is a peculiar epicentre of natural phenomena, some of which have been fully explored and the majority of which call for further investigation. Therefore, it is no mere chance that the Institute of Arctic Geology, later reorganized as the VNII Okeangeologiya and its subordinated association "Sevmorgeologiya", at all times considered the Laptev Sea shelf as an object of paramount importance, whose difficult of access position was the only factor restricting large-scale investigations.

Islands fringing the Laptev Sea and the shore have been charted by the Geological Survey on a scale of 1:1,000,000 and 1:200,000. As early as the 1950's, sampling of bottom sediments was begun directly in offshore areas. This collection is still being supplemented, although rather slowly.

From the mid-60's on, air-landing gravimetric observations from ice have been carried out. The whole area has been covered by a small-scale aeromagnetic survey. This gives a first impression of the region's general structure.

The non-anomalous slightly negative magnetic field evident here may point to the total warping of the crust without evidence of developed spreading. The Lena-Taimyr zone of boundary basement uplifts which coincides with a chain of gravitational maximums is clearly discernible in the gravity field. The combined analysis of geophysical data has made it possible to establish a Moho discontinuity beneath the Laptev Sea shelf, bulging up to 30 m and showing an anomalous low boundary velocity (7.5 km/s) which conforms to the dis-consolidated mantle. Such a deep model is typical of development areas of continental riftogenesis.

The structure of shelf sedimentary cover has been studied by seismic survey. DSS and CMRW investigations were performed by polar expeditions of "Sevmorgeologiya" in 1973, 1980 and 1985-86. Most recently, in 1986-90, the Murmansk Expedition conducted on the shelf and resulting in 4200 km of profiles MRW CDP has brought about a revolutionary change in our knowledge of shelf geological structure.

Today we can take for granted that the lower ("pre-oceanic") structural stage shows a lateral-heterogenic structure and represents a junction of large crustal blocks, each representing a continuation of structures from adjacent land masses.

The western block is a pericratonic continuation of the Siberian platform characterizd by an early Proterozoic basement. The total section (Riphean to Cretaceous) of the sedimentary cover is 9-11 km thick; and contains up to 12 refraction horizons. In the northwest early kimmerids with the reduced Jurassic-Cretaceous cover, no more than 2 km in thickness, extend onto the shelf zone of Taimyr.

The eastern block is an offshore continuation of mesozoids of the Verkhoyan-Chukotsk folded area. The sedimentary cover is represented merely by the syn-oceanic complex, 1 to 2 km thick, up to 5 km thick in grabens. Further to the northeast, the so far "enigmatic" Cotelnichesky massif is observed to extend onto the shelf.

The Laptev Sea shelf exists as a single marginal continental plate and as a single sedimentation basin, but at the "syn-oceanic" development stage (Upper Cretaceous-Cenozoic). The ofnset of the formation of this covering ("syn-oceanic") structural stage is coincides with such events as the completion of Late Cimmerian onland folding and the opening of the Eurasian basin.

The corresponding part of sedimentary cover is distributed everywhere, superimposing on different horizons of the sequence below or immediately on the basement. Reflection horizon I (Pre-Paleocene levelling) shows a contrast block structure, whereas overlying reflector II (approximately Neogene foot) is absolutely unaffected by displacements and presents a general pattern of submersion.

As a passive continental margin of the Arctic Ocean, the present-day shelf of the Laptev Sea differs essentially from the classical Atlantic tectonotype. Thus, relatively thin deposits of initial phases of the riftogenesis process and their significantly continental nature are noted. This may be accounted for by the geological "instancy" of the opening of the Arctic Ocean. Other peculiarities may be explained by the structural position of the Laptev Sea shelf relative to the Mid-Oceanic Ridge. The thoroughly studied Atlantic margins are located along expansion axes, whereas, in our instance, the mid-oceanic Gakkel Ridge is situated at nearly right angles to the continental slope of the Laptev Sea. It follows, thus, that block steps (normal faults) parallel to the external shelf margin are absent and that linear disjunctive structures orthogonal to the shelf brow are widely distributed. No less than six or seven large Late Cretaceous-Cenozoic riftogenic grabens are known, where movements with an amplitude up to 2 km have taken place. Signs of buried Cenozoic volcanoes are found inside the grabens. Many trenches are displaced by transverse transform faults which resemble oceanic rifts. It is also interesting to note that, alongside tension structures (normal faults), disjunctive and folded deformations typical of the compression regime are recorded on the shelf.

The straight continuation of the Gakkel Ridge central rift is a locus of the well-defined Omoloi suture zone dividing the platform and folded blocks. The zone's inner structure and pattern of conjugation with the Gakkel Ridge are not as well-understood as are geodynamic relations of the Laptev shelf with the Lomonosov Ridge structure, which, in turn, has developed according to a scenario absolutely different from the spreading one.

An interpretation of translation mechanisms of the crust tension process in the ocean onto the shelf and further onto the continent remains a major scientific problem in the field of the deep geology of the Laptev Sea. The case in point is a rather complicated and ambiguous geodynamic process. This is likewise evidenced by the results of seismologic observations previously made by "Sevmorgeologiya". Within the ocean, the seismic belt is rigorously linear, clearly outlining the well-defined boundary of lithosphere plates, whereas in passing onto the shelf, this belt becomes attenuated and does not join to the continental seismic belt extending from Buor-Haya Bay toward the eastern Taimyr. To obtain a detailed seismological pattern it is necessary to conduct long-term natural observations with bottom seismologic stations arranged directly on the offshore area.

A different line of cognition of the region's geodynamic evolution is to study in detail the syn-oceanic sedimentary cover. This involves revealing inconformities, precise stratification and correlation of some horizons with the global stratigraphic scale, the correlation of shelf sections onland and on the continental slope, analysis of the thickness of some horizons,and the analysis of cover structure by means of correlation of structural maps with major reflectors. The study of the mineralogic composition of sediments will reveal alimentation regions, trends of sedimentation flows, etc.

The evolutionary problem of the geosystem of the Laptev Sea is of great importance not only in terms of geology but in terms of its immediate influence on habitation conditions for humans as well. In spite of a body of information acquired on Cenozoic stratigraphy and paleography, geomorphology, modern tectonics, etc., numerous important problems remain to be solved.

To cite only a few of them:

- existence of covering glaciation in the eastern Arctic (no signs of glacial deposits found in the biostratigraphic scale of the shelf);
- causes of fundamental differences in the bottom relief of the western and eastern Arctic with the simultaneous presence of geomorphological levels;
- discrepancies in dating of temperature optimums on different organism groups and presence of anomalous heat-loving fauna complexes;
- the problem of submarine gaseous hydrates (on evidence derived by VNII Okeangeologiya, the Laptev Sea shelf shows a favorable combination of geological conditions close to that of Beaufort Sea known to show signs of hydrate content).

The key to this and to many other problems lies within a chronicle of events impressed in bottom sediments of the Laptev Sea which need to be further examined by means of high-resolution seismoacoustics, long (3-4 m) bottom corers and precise dating methods, including a determination of absolute age.

THE NANSEN ARCTIC DRILLING PROGRAMME (NAD)

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The Nansen Arctic Drilling Programme (NAD) is a major international research effort designed to understand environmental change in the Arctic and the history of its geological evolution in order to better predict the future of the Arctic basin and its effects on global processes. The NAD programme is developing strategic plans for acquiring long, high-resolution sediment and deep basement cores needed to understand the Cenozoic and Mesozoic paleoceanography, paleobiology, and structural history of the Arctic region. These cores are critical for scientists developing a comprehensive understanding of global change and for industrial researchers assessing the hydrocarbon potential of the Arctic region. This ambitious programme commemorates the pioneering work of Arctic explorer Fridtjof Nansen during the *Fram* expedition, 1893-1896 nearly 100 years ago.

NAD is led by an Executive Committee composed of senior scientists from institutions actively involved in Arctic research. Working with the Executive Committee is a Science Committee of senior-level scientists and a Technical Committee of scientific engineers with Arctic expertise. These committees were inaugurated during the summer of 1989 and NAD now includes representatives from Canada, France, Germany, Japan, The Netherlands, Norway, Sweden, UK, USA, and Russia. Denmark has participated as an observer. A science plan has been published by the German Society of Polar Research (*Polarforschung*, 1992, vol. 61, no. 1).

Executive Summary

The profound influence of the Arctic Ocean on global environment, rapid fluctuations of the Arctic ice cover and its consequences for global change, and unresolved tectonic problems of the Northern Hemisphere have resulted in a growing pressure toward attempting to drill the deep-sea floors of the ice-covered Arctic Ocean. Sediments beneath the Arctic Ocean are a recorder of long and short-term Northern Hemisphere cooling and its linkages to bottom-water renewal and faunal adaption. The underlying basement rocks will reflect the origin and tectonics of the basin and its ridges and plateaus, which are unsampled and of unknown composition.

One of the major unsolved questions in earth sciences is the paleoceanographic and paleoclimatic evolution of the Arctic deep-sea basins. Indentifying greenhouse warming within historical records requires quantifying the magnitudes, frequencies and rates of natural climatic change. Of hundreds of samples collected in the Arctic Ocean, only seven contain sediments that predate the onset of cold climatic conditions. There are no Arctic deep-sea data covering the time span 5-40 Ma when the climate cooled, and thus there is no information available to decipher the forcing functions or time of onset of Cenozoic glacial conditions in the Arctic. Today, dense, cold Arctic surface waters sink and flow southward, filling deep-sea basins of the Atlantic and Pacific Oceans with consequent major climatic implications.

The origin of the Arctic Basin is linked to the evolution of the adjacent basins and continents. An understanding of past and present plate movements in the Arctic is necessary before a complete model of plate motions and paleogeography in the Northern Hemisphere can be constructed. The Cenozoic tectonic history of the Eurasia Basin is relatively well known, since the Eurasia and North America plates have been studied extensively to the south. The basin also contains a well documented and decipherable magnetic lineation history. Little is known about much of the rest of the Arctic Ocean with the evolution of the Amerasia Basin a major unresolved problem.

Scientific Goals

The primary goals of the Nansen Arctic Drilling Programme are to understand:

- the climatic and paleoceanographic evolution of the Arctic region and its effects on global climate, biosphere and the dynamics of the world´s ocean and atmosphere, and
- the nature and evolution of the major structural features of the Arctic Ocean and circum-Arctic continental margins.

Target Areas

The primary target areas in a first phase of drilling in the Arctic Ocean are the rises and plateaus. Here, the sediments are primarily biogenic fallout from the water masses and hemipelagic/pelagic muds. Of these, the Yermak and Chukchi Plateaus are targeted as the initial drill site locations and proposals are being prepared to support the drilling. The advantage of these two sites is that major parts of the Chukchi and Yermak Plateaus are in the marginal ice zone (The Yermark Plateau has recently been drilled as part of ODP Leg 151). A later phase of drilling would give priority to the deep ocean basins where the water depth is 4,000 m or greater and the sediment thicknesses are greater than 1 km. A major part of all plateaus and ridges would be accessible with a water depth capability of 1,500 m except for Alpha Ridge. From the available seismic reflection records it appears that 500 m of penetration would reach basement on all plateaus and ridges as well as the major unconformity on the Lomonosov Ridge.

A step-wise drilling approach will be pursued: Proposals will be prepared to drill marginal plateaus and sections of the continental margins in the marginal ice zone which can be reached with commercial drillships (up to 600-700 m water depth and 2,000-3,000 m penetration). The following areas were selected (Fig. 1):

- Laptev Sea (intersection Mid-Ocean Ridge and continental margin),
- Yermak Plateau,
- Chukchi Plateau and other potential areas along the North America and Eurasia continental margin,
- Other areas, with Alpha-Mendeleyev and Lomonosov Ridges given the highest priority.

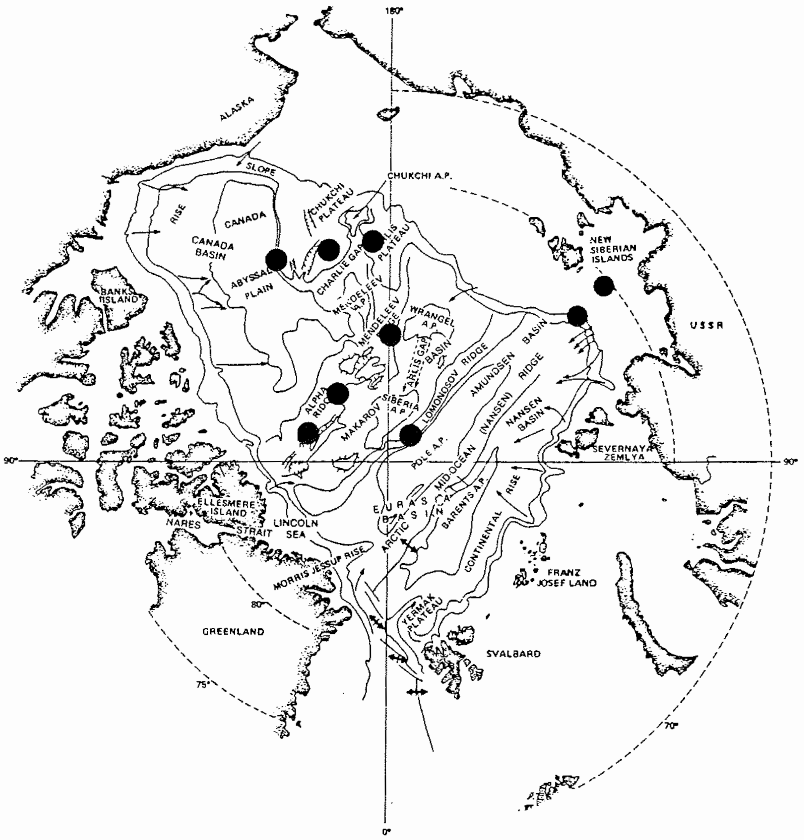

Fig. 1: Proposed drill site location for the Nansen Arctic Drilling Programme

STRUCTURE AND PLATE TECTONICS OF LAPTEV SEA SHELF: DRILLING OF THE GEOLOGICAL RECORD

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The Laptev Sea Shelf is a key region to understand tectonics and evolution of the eastern Arctic. On one hand, it occupies joint areas between the Siberian craton, Early Mesozoic Taimyr fold belt and Late Mesozoic Novosibirsk-Chukchi and Verfhoyansk-Kolyma fold belts. This poorly known structural ensemble underlying Laptev Sea Shelf sedimentary basin was formed in Late Mesozoic orogenic event. On the other hand, a unique situation of the direct penetration of the oceanic spreading axis (Gakkel Ridge) into continental passive margin is situated here. The spreading of oceanic lithosphere is transforming into the stretch of the continental one. This process caused the origin and development of Laptev Sea Shelf Cenozoic rift system which is a perfect object to study an initial break-up of the continent.

The present-day knowledge of Laptev Sea Shelf geology is based on seismic reflection and gravity data by LARGE (Laboratory of Regional Geodynamics) and MAGE (Murmansk Arctic Geologic Expedition). According to these results the Laptev Sea Shelf can be divided into two large structural and seismic stratigraphy provinces. One of them occupies the central and eastern parts of Laptev Sea Shelf. The Cenozoic rift system comprises from the west to the east Ust-Lena graben, Central uplift, Omoloi graben, East-Laptev uplift and Bel´kov-Svyatoi Nos graben. We suppose that the entire rift system was formed mainly during Late Cretaceous to Eocene and underlain by the Late Mesozoides. The age of the basement was well-demonstrated for East-Laptev uplift by geologic data on Stolbovoi I., but is more questionable for the elements located to the west. The MAGE´s scientists believe that the western side of the rift system is underlain by Laptev cratonic block and a graben-filling that consists of the Riphean and Phanerozoic sequences including Cenozoic ones. The total cover thicknesses are 0.5-2.5 km on the uplifts and 5-10 km within axial parts of the grabens.

Another structural province is located between the Lena River Delta and Taimyr Peninsula. It was intersected by three MAGE´s seismic lines only and comprises the graben-like South-Laptev basin which is separated from LAPTEV SEA SHELF rift system by the Trofimov linear uplift and from Siberian craton by the Lena-Taimyr fold zone. The thickness of sediment cover is 7-12 km. The higher seismic velocities into lower horizons of cover (5.5-6.2 km/s) can characterize Riphean and Lower Paleozoic carbonate rocks. Possibly this province is the northeastern edge of Siberian craton. Therefore the south Laptev Basin can be considered as a foredeep basin in front of a Late Mesozoic fold belt. The proposed seismic stratigraphy model of Laptev Sea Shelf sedimentary basin is supported by detailed geologic and paleogeographic data on continental and islands frame.

Laptev Sea Drilling Plans

The primary program objectives are to understand both environmental changes in the Arctic and its geologic evolution. By obtaining Artic sediment cores, scientists will be able to unlock the natural history of the region and better predict the future of the Arctic Basin and its effect on the global climate, the biosphere, and the dynamics of the world ocean and atmosphere. These studies will include:

- detailed history of sea ice cover;
- detailed history of changes in ice sheets;
- detailed history of organic carbon flux, productivity and CO_2;
- history of river influx;
- establishment of the relationship between high-resolution seismic records, physical properties and paleoenvironmental parameters;
- tectonic conditions and rates of sediment accumulation, preservation and diagenesis;
- role of the Arctic in the global transition from the Eocene "greenhouse world" to present day "icehouse world";
- improving drill techniques and scientific equipment for the nature experiments in this complicated environment;
- study gas hydrate areas to better understand the gas hydrate formation process.

The Laptev Sea Shelf plays a key role for recognition and explanation of the oceanographic conditions, climate, ecology, geology and paleoenvironment of the Arctic. Geological and geophysical data show that the Laptev Sea shelf continental margin was formed under the influence of the Eurasia basin opening and penetration of the Gakkel Spreading Ridge into a continental area. The major stages of Arctic history were imprinted in the Laptev Sea Shelf sedimentary record. It is possible here to find the areas of very high sedimentation rate that will allow the examination of Arctic variability on time scales of tens and hundreds of years.

The available seismic reflection data collected by Murmansk Arctic Geological Expedition (MAGE) and Moscow Laboratory of Regional Geodynamics (LARGE) supplemented by other geological, geophysical and oceanographic data by VNIIOkeangeologia (St. Petersburg), Arctic and Antarctic Research Institute (St. Petersburg), and P.P. Shirshov Institute of Oceanology (Moscow) will be used to determine prospective drilling areas within major structural elements of the Laptev Sea Shelf rift system. Major elements are e.g. the Omoloi and Belkov-Svyatoi Nos rifts subsided continuously during the Cenozoic.

SEDIMENTATION IN THE NORWEGIAN-GREENLAND BASIN AND IN THE REGION OF ICELAND

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The Norwegian-Greenland Basin and the region of Iceland are of particular interest, especially in the Tertiary and Quaternary periods of historical development. The processes of volcanogenic, terrigenous and glacial sedimentation were combined. Numerous results of investigations have been summarized by Bott et al. (1983). At the same time, Soviet marine geological expeditions were organized between 1969 and 1990. In the Norwegian-Greenland Basin and in the region around Iceland bottom sediments from different stations, including one hundred cores up to 6 and 8 m in length, were collected and investigated, lithological-geochemical maps were compiled, summaries concerning the problems of sedimentation and geological history were published during these years (Emelyanov, 1977, 1982, Kharin, Emelyanov, 1987). Studying the sea-floor sediments we payed much attention to the mineralogy of sandy-aleuritic fractions and to the distribution of chemical components in sediments. This has permitted us to avoid repetitions and to complete research conducted in other countries (Kellog, 1980, Eisma, van der Gaast, 1983). Most of our work was published in Russian and is practically inaccessible for many researchers who do not have a command of the language. Therefore, the aim of this paper is to make up for a difficiency. The following topics will be addressed:

1. a brief description of Recent and late Pleistocene sediments is given;
2. the principal indicators are revealed:
   a) pyro- and volcanoclastic materials of Iceland, Jan Mayen and the Faroe Islands;
   b) the products of land denudation without volcanic rocks;
   c) ice and iceberg material which enters the Norwegian-Greenland Basin and the region of Iceland;
3. some questions of paleography in the late Quaternary period are dealt with.

The materials of this work are samples of Soviet marine expeditions and samples from the region of the sunken atomic submarine "Komsomolets", which were recovered with the assistance of the expedition on R/V "Academic Mstislav Keldysh" (1990-1992).

Recent and Late Quaternary sediments

Recent pyro- and volcanoclastic sediments: They contain more than 50 % pyro- and volcanoclastic material of basaltic composition and are distributed around Iceland, Jan Mayen and the Faroe Islands (Fig. 1). In the region of Iceland volcanogenic sediments surround Iceland from all sides, stretching 100 to 150 km into the open ocean and 2185 km down. The square of volcanogenic sediments is about 250,000 km^2. According to their granulometric composition they are usually represented by sands, aleurites (silts) and aleuritic-pelitic (silty) muds. They consist of no more than 70 % of

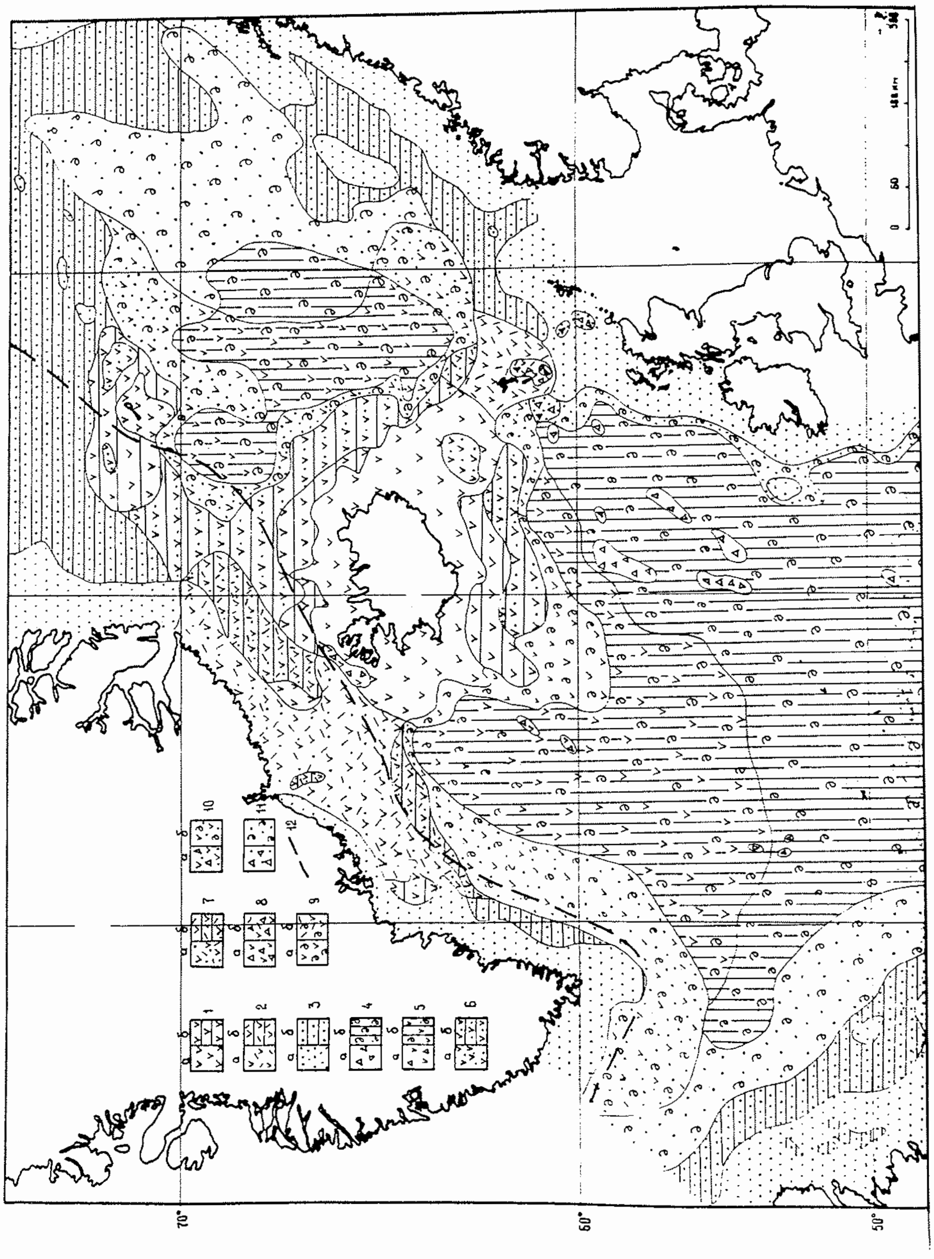

Fig. 1: Distribution of recent sea-floor sediments (uppermost layer, 0-5 cm).

1) Pyroklastic, 2) vulcanoclastic, 3) terrigeneous, 4) biogenic carbonate, 5) biogenic carbonate and pyroclastic, 6) pyroclastic terrigeneous, 7) volcanoclastic terrigeneous, 8) biogenic and pyroclastic, 8a) biogenic and volcanoclastic, 9) volcanoclastic-foraminiferal ooze, 10) pyroclastic-terrigenic-foraminiferal ooze, 11) biogenic-terrigenic calcareous, 12) ice edge.

fraction <0.01 mm. In the light subfraction (0.1 to 0.5 mm) of sediments, volcanic glass (colorless and green-brown), opaque ash particles and feldspar predominate. The heavy subfraction (>2.9 mm) is represented by clinopyroxene, brown volcanic glass, ash particles, magnetite and titanomagnetite (Fig. 2). Transparent cement in ash particles is represented by pyroxenic matter and glassy mass. Pyroclastic particles (pyroxenes, glasses) are usually oxygonal, fresh without signs of roundness and weathering. Clayey minerals are represented by montmorillonite, hydromica and chlorite.

In volcanoclastic sediments of separate grains of garnet, common green hornblende, rutile, epidote, quartz are connected with their supply from Greenland; they are either completely absent or present in small quantities in the sedimentary material of Iceland.

Pyroclastic sediments are divided into non-calcareous (less than 10 % $CaCO_3$), low calcareous (10 to 30 % $CaCO_3$) and calcareous-pyroclastic (30 to 50 % $CaCO_3$). Carbonaceous material is represented by mollusc shells (pelecypods, gastropods, neogastropods, scaphopods or their remains). Moss animals (bryozoa), stellerideans, ophiuroids, benthic foraminifers occur rarely. Planktic foraminifers predominate in muds.

The content of SiO_2am is 0.20 to 8.15 % in pyroclastic sediments. High content of SiO_2am (> 3 to 5 %) in pyroclastic sediments is not connected with volcanic products but with sponge spicules and diatom skeleton accumulation in sediments and to a lesser degree with radiolarians and silico-flagelates.

The high content of Fe (up to 11.85 %) and Ti (up to 1.86 %) is significant for pyroclastic sediments in the region of Iceland. The maximum content of these elements increases up to 12.88 and 2.36 % respectively calculated on clastic material (or CFB) (Fig. 3). It is maximum content of Ti of Atlantic Ocean (Emelyanov et al., 1976). Fe and Ti are genetically common and represented by the same minerals (opaque and transparent ashy particles, clinopyroxenes, titanomagnetite, etc.). Therefore, a clear direct connection exists between them. The content of Mn (up to 0.41 %) is increased in pyroclastic sediments, too. In contrast to Fe and Mn is not connected only with firm pyroclastic and volcanogenic-terrigenous materials, but with hydroxides of the element which is dispersed in the mud strata. The content of P in pyroclastic sediments is approximately the same as in basalts and ashes in Iceland. The phosphate minerals of authegenic origin were not discovered. The content of Cr, Zr is slightly high (up to 0.16, 0.033 and 0.040 % respectively) and also Al2O3 in pyroclastic sediments in comparison to sedimentary rock.

The high content of Al_2O_3, Fe_2O_3, TiO_2, MnO, P_2O_5, V, Cr, Zr and their mineralogical composition indicate a close genetic similarity between pyroclastic sediments with basalts and tuffs of Iceland (Kharin, Emelyanov, 1987). The role of products which are going to the ocean on account of the destruction of acid and intermediate rock is not rich in composition of sediments. As far as moving off from Iceland the content of shown chemical components (especially Fe, Ti, P, V, Cr and Zr) decreases considerably.

Volcanogenic sediments in the region of Jan Mayen cover the bottom round the islands at a distance of 50 to 100 km and the depth of it reaches 3,2000 m. According to their granulometric composition the sediments are the same as in the region of Iceland. The sandy-aleuritic (1 to 0.01 mm) fraction is represented by oxygonal fragments of brown volcanic glass (N=1.850 to 1.585), opaque and semi-transparent ashy particles and fragments of lava (Emelyanov et al., 1976). To a lesser quantity diopside-hedenbergite

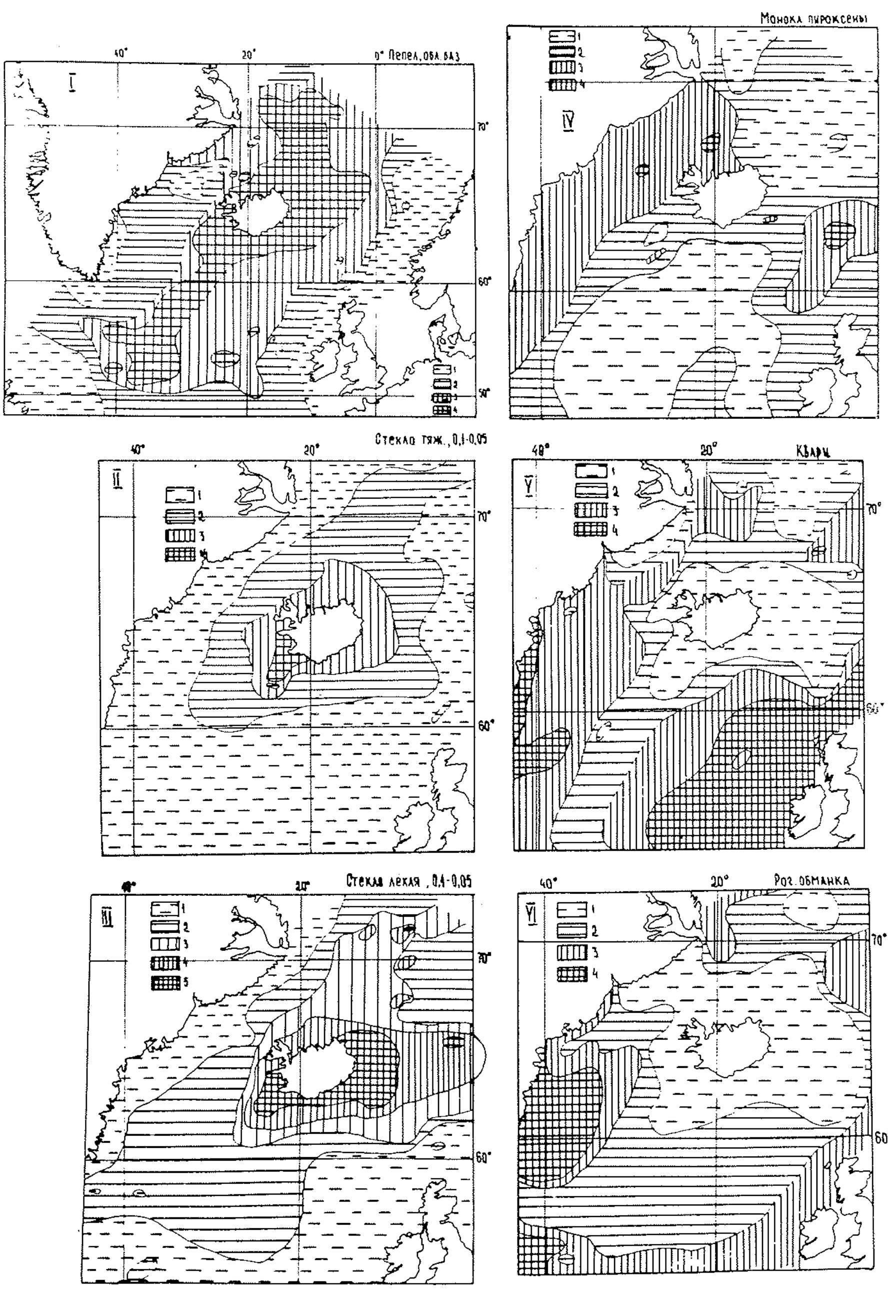

Fig. 2: Distribution of pyroclastic and most characteristic minerals in the fraction 0,1-0,05 mm of surface sediments (0-5 cm).

I) Opaque ash particles: 1. 1-10 %, 2. 10-30 %, 3. 30-50 %, 4. >50 %; II) volcanic glass in heavy subfraction: 1. 1-10 %, 2. 10-30 %, 3. 30-50 %, 4. >50 %; III) volcanic glass in light subfraction: 1. <1 %, 2. 1-10 %; 3. 10-30 %, 4. 30-50 %, 5. >50 %; IV) clynopyroxene: 1. 1-10 %, 2. 10-20 %, 3. 20-40 %, 4. >40 %; V) quartz: 1. 1-10 %, 2. 10-30 %, 3. 30-50 %, 4. >50 %; hornblende: 1. 1-5 %, 2. 5-10 %, 3. 10-20 %, 4. 20-30 %.

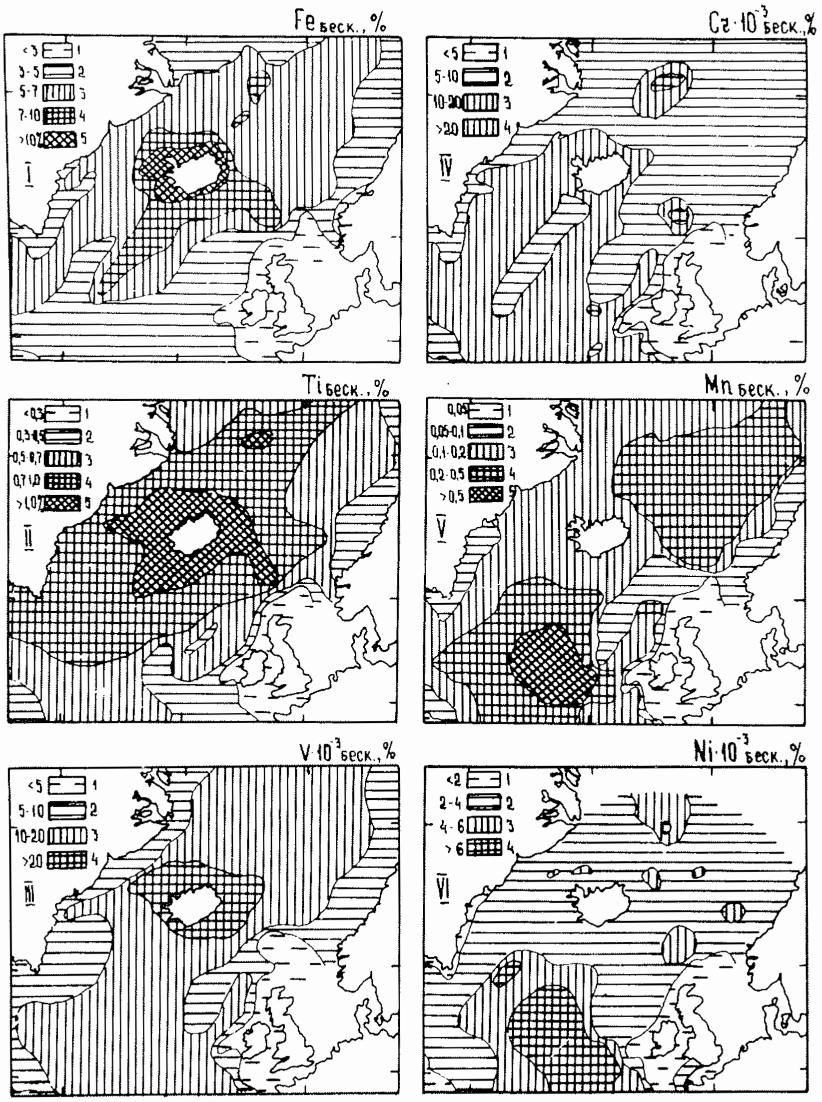

Fig. 3: Distribution of chemical elements in recent surface sediments (0-5 cm).
I) Iron; II) titanium; III) vanadium; IV) nickel.

(Ng=1.694 to 1.702) was discovered. As single average and basic grains of plagioclase, olivine and magnetite are found. Some ashy particles and fragments of lava are oxygonal.

In the area of the Faroe Islands volcanoclastics (at depths up to 595 m) were formed on account of destroyed Tertiary plateau basaltic products of Faroe Islands. There are sands and coarse aleurites (silts). Plagioclases, opaque ash particles, clinopyroxenes prevail in the sediments. To a lesser quantity brown and colorless glass are in the sediments (Emelyanov, 1977).

In comparison to Iceland considerable admixture of terrigenous minerals is contained in these sediments. There is poor content of Fe, lesser of Ti, Mn; V, but the content of Cr is higher (Fig. 3).

Close to the eastern shore of Greenland volcanoclastics are widely spread at depths of up to 1.2000 m (50 to 100 km from the shore). In general, these are coarse aleuritic and fine aleuritic (silty) muds. To a smaller extent these are sands, aleuritic-pelitic sediments. Principal minerals are plagioclasts and clino-pyroxene. To a lesser quantity weathered grains, transparent ashy particles, brown and colorless volcanic matter are contained in sediments. All these things are the products of plateau basalt destruction of central Greenland. To a lesser extent it is pyroclastic material of Iceland volcanoes. Generally, sediments of eastern Greenland on account of sharp plagioclases and clino-pyroxenes are different from Iceland sediments. They are different from each other on account of considerable admixture of terrigenous material in it (weathering products of acid erupted and metamorphic rocks of northern and southern Greenland). Great amounts of ice and iceberg rafted material of Greenland were discovered in sediments of the given province.

Volcanogenic-terrigenous sediments of Faroe-Iceland still consist of volcanogenic (opaque ashy particles, plagioclases, common hornblende, epidote, garnet and zircon) materials. Mixed mineral composition of sediments causes low content of Fe, Ti, Mn, P and trace elements in it.

Sediments of Kolbeinsey Ridge, Iceland plateau, Norwegian Trench occur at depths from 490 to 1900 m. These sediments are driven back by pyroclastics from volcanic islands by mixed volcanogenic-foraminiferal sediments from the shore to the center of the sea. The areal of spread of these sediments approximately coincides with areals of the western part of the central Norwegian mixed mineralogical province. The coarse part of clastic sandy-aleuritic sediments is characterized by considerable volcanogenic admixture of volcanogenic materials of Iceland and Jan Mayen (opaque ashy particles, plagioclases, brown and colorless glass, clino-pyroxenes). The terrigenous part is represented in general by minerals of the northern Greenland province (quartz, plagioclases, hornblende, garnet, zircon and micas). Sometimes zeolite is found. Considerable admixture of volcanogenic material stipulates different chemical composition from typical terrigenous composition. Heightened amounts of Fe, Ti, P and V are contained in it.

Pyroclastic-shelly sediments were found near Iceland and the Faroe Islands. These are sands with great amounts of molluscs foraminifers and bryozoans remains. The clastic part of sand consists of more than 50 % of opaque ashy particles, brown glass and clino-pyroxenes. The content of Fe, Mn and P are considerably higher as a result of it. According to mineral and chemical composition the remains of pyroclastic-shelly deposition will correspond to volcanoclastic sediments if we do not take into consideration the diluting influence of biogenic material.

Foraminiferal and coccolithic-foraminiferal oozes (with considerable admixture of pyroclastic) are spread on the Iceland Plateau and in the Norwegian Basin at depths from 1475 to 3060 m. Mineral composition of clastic part of sediments (sandy-aleuritic) is mixed. On the one hand there were many materials which were brought from Scandinavia and Greenland, on the other hand volcanic pyroclastics of Iceland and Jan Mayen. As a result, the content of many elements is increased, especially Fe (calculated on carbonate-siliceous free basis), Ti, Mn, Ba and Ni.

Foraminiferal and coccolithic-foraminiferal ooze with pyroclastics are also spread in the region of the Reykjanes Ridge. Sandy-aleuritic part of muds is represented by pyroclastics of Iceland, volcanoclastics (plagioclases, clinopyroxenes, remains of volcanogenic rocks) of Central Greenland and terrigenous materials having brought by ice and icebergs from southern and northern Greenland. A lesser part of the sediments is represented by sponge spicules.

Foraminiferal ooze is spread in the eastern part of the Norwegian Basin and in the North Atlantic. Muds from the Norwegian Basin contain from 50.1 to 64.1 % of $CaCO_3$. According to their granulometric composition they correspond to coarse aleurites, fine aleuritic and aleuritic-pelitic muds. According to their mineral composition of clastic part of foraminiferal sediments belong to the mixed volcanongenic-terrigenous province off Central Norway. Among terrigenous materials the denudation products of acid and erupted metamorphic rocks of Scandinavia prevail. These are quartz, plagioclases, micas, hornblende, epidote, garnet and zircon. Volcanogenic material is represented by pyroclastics of Iceland.

Terrigenous sediments lie to the north of Jan Mayen, Scandinavia, Labrador, Newfoundland and at the southern tip of Greenland (Fig. 4). Sediments are enriched in ice-rafted material in the last of these regions. The atomic submarine "Komsomolets" lies at a depth of 1700 m on greenish grey terrigenous muds. The submarine has sunk into these muds up to a depth of 2 m.

Late Quaternary sediments: The same volcanogenic and volcanogenic-terrigenous sediments are spread in the region of Iceland as on the surface of bottom (Fig. 4). Intercalation of volcanogenic terrigenous minerals which are typical for Greenland exist in volcanoclastic Pleistocene sediments. These data show that ice-rafted material for Iceland province which was intensively brought by Greenland icebergs in separate periods of the late Quaternary.

At station 50 (Danish Strait, Fig. 6) late Quaternary sediments are represented by volcanogenic sands, coarse aleurites and fine aleuritic muds. Their mineral composition is the same as the composition of surface sediments at the coast of the Iceland Sea. Fe content is 11.8 %, Mn content is less than 0.15 %. Therefore these are low terrigenous and terrigenous-volcanogenic sediments.

At station 59 volcanogenic sediments alternate with volcanogenic-terrigenous deposition which were formed during the Late Pleistocene as a result of large mass material removal from Greenland, including products of plateau basalt destruction from central Greenland.

In the region of the Reykjanes Ridge, typical volcanogenic and mixed volcanogenic-terrigenous volcanogenic-foraminiferal muds and also foraminiferal ooze are spread. Volcanogenic muds prevail in the northern part. Mixed muds prevail in the central part of the Ridge, especially on its flanks. Foraminiferal sediments with pyroclastic material admixture are generally spread in the central and southern parts of the Ridge and also on the flanks of the northern sections. Sediment units with thicknesses of up to 335 cm (station 779-1 and 780-3, Fig. 5) are found in stripes in the northwestern parts of the Ridge. Late Pleistocene sediments which are represented by dense, almost "dry" greenish grey clay, fine aleuritic and aleuritic-pelitic muds containing considerable admixtures of brown volcanic and separate grains of colorless acid glass. There are many palagonites and zeolites in muds (clay). There are layers of pyroclastics in bluish-grey volcanogenic-terrigenous mud or in "dry" late Pleistocene clay in the northwestern part of the Ridge. Sandy-aleuritic parts of muds and clays are represented by poorly rounded quartz grains, foraminifera, palagonite, ore grains (magnetite and titanomagnetite), hornblende, sometimes glauconite, acid and brown (basaltic) volcanic glasses, zeolites (including fibious) are found. Terrigenous minerals show that the main part of these sediments was brought from Greenland to this region when upper Pleistocene sediments were being formed. Some interlayers of volcanogenic-terrigenous sediments contain heightened amounts of volcanoclastic materials (especially palagonite), which came from Iceland.

The upper layer of sediments (Holocene) is represented by nanno-foraminiferal ooze in cores AK-1333, -1335, -1336, -1337 (Figs. 5 and 6). Late Pleistocene sediments in core AK-1333 are represented by terrigenous and volcanogenic-terrigenous muds with interbeds of coarse aleurites and sands. Abiogenic parts of sediments are generally represented by terrigenous material which was brought by ice and icebergs from Greenland. There is much volcanogenic material from Iceland (brown glass, clino-pyroxenes, opaque ash particles, etc.). Increased quantities of Ti are contained in interbeds which are enriched in pyroclastics.

Core AK-1335 at all depths is represented by nanno-foraminiferal ooze with contents of CaCO3 of up to 66.29 %. Interbeds of foraminiferal or terrigenous sands and coarse aleurites are often found in muds. The abiogenic parts consist of ice-rafted material from Greenland. Quartz, plagioclases and micas prevail among minerals. There is little volcanogenic material.

Core AK-1336 consists of nanno-foraminiferal ooze, which is mixed with terrigenous low calcareous muds. Sometimes thin interlayers of terrigenous and foraminiferal aleurites and sands are also found here. Quartz, plagioclases and amphiboles are typical of Greenland. They prevail among minerals. Separate interlayers of muds are enriched in pyroclastic material from Iceland's volcanoes. Gravelly (ice) material is found everywhere. There is much ice material from Greenland in core AK-1334 of Pleistocene sediments. Volcanogenic material of Iceland is found everywhere in low quantities (brown glass, opaque ash particles, clino-pyroxenes).

In the Faroe Island Ridge (core AK-1383, 616 cm long) late Pleistocene sediments are represented by terrigenous and volcanogenic-terrigenous sands, coarse aleurites and fine aleuritic muds which are interbedded by each other. Interlayers of sands, aleurites are usually distinct, but sometimes interlayers with rough boundaries are found. This supports the supposition that the slumps of the sediments and erosion by near-bottom currents were possible here. There is much ice material (gravel, rubble) in sediments. The interlayers found in some muds and aleurites with dense consistency resemble sub-aerial terrigenous (morainic) deposition (sandy loams, loams, etc.). In a low part of core there is strong interbedding of terrigenous, very moist sand (254-580 cm). The clastic sandy-aleuritic part (1 - 0.01 mm) is represented generally by terrigenous minerals with are typical of Scandinavian rocks. But separate interbeds are enriched in volcanogenic material from Iceland. Therefore, ice-rafted material which was brought from Scandinavia plays the main role in the formation of late Quaternary (late Pleistocene) sediments. Volcanogenic material from Iceland was also brought here.

In cases when the role of pyroclastics increases, the content of geochemical indicators of volcanogenic matter (Fe up to 7.49 % and Ti up to 1.29 %) increases noticeably as well. In the region of the Jan Mayen Ridge (region of

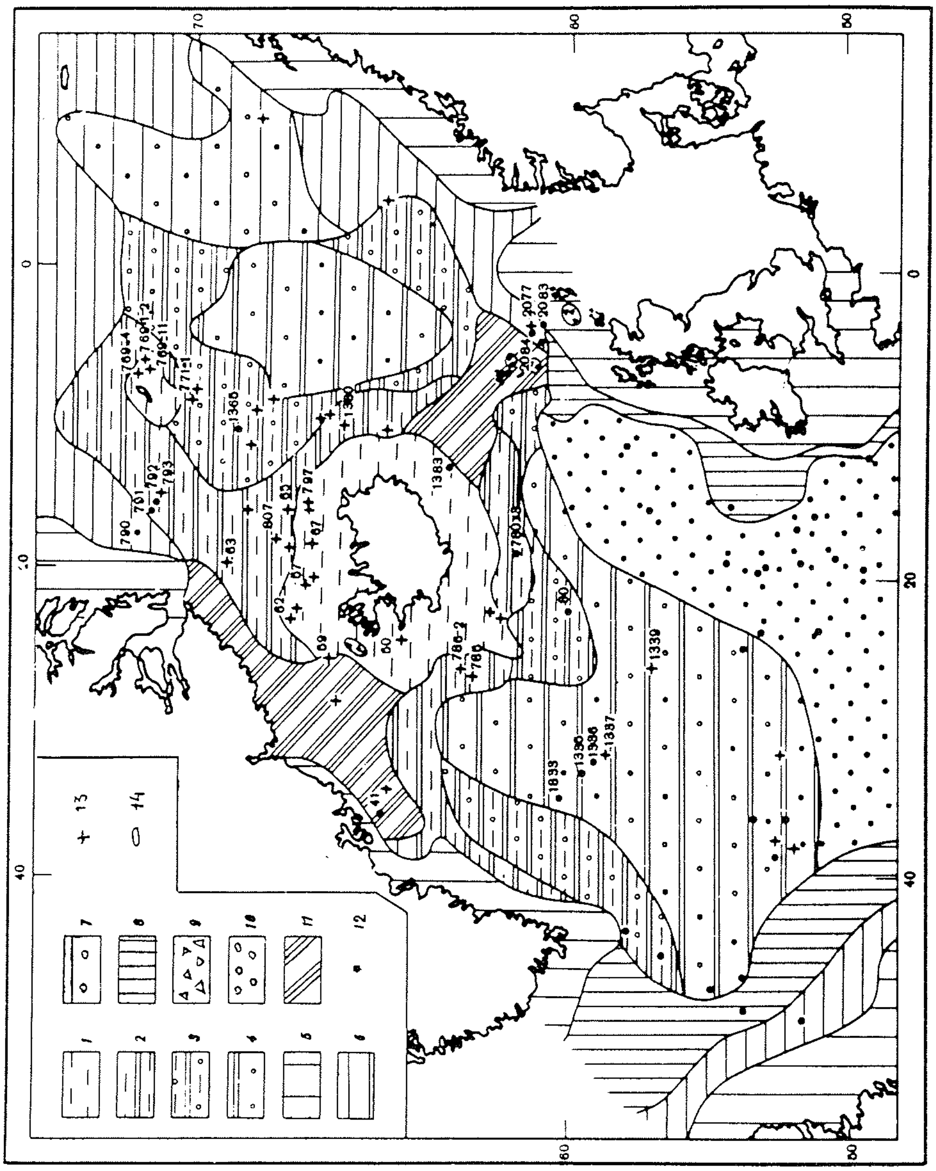

Fig. 4: Late Quaternary sediments in the Norwegian-Greenland Sea.

1) Volcanogenic, 2) volcanogenic-terrigeneous mud with ash layers, 3) volcanogenic-foraminiferal-terrigeneous mud with ash layers, 4) foraminiferal-terrigeneous mud with ash layers, 5) terrigeneous sand and silt, 6) terrigeneous mud, 7) terrigeneous low calcareous mud, 8) terrigeneous low calcareous clayey mud, 9) foraminiferal-terrigeneous mud, 10) carbonate shelly, 11) volcanogenic-terrigeneous sand and silt with Tertiary sediments, 12) with ash, 13) without ash, 14) location of the submarine "Komsomoletz".

station AK-779-3, Fig. 5) volcanogenic sediments containing different amounts of volcanogenic material are interbedded with foraminiferal mixed volcanogenic-terrigenous rocks. Interlayers of pure volcanoclastic sands and fine aleuritic muds are thin (1 - 10 cm). Many of them are sorted. They were stored during redeposition of material which occurred at the top and slope of mountains (core AK-799-3 was chosen at the foot of one of them). One of the peculiar features of volcanoclastic sediments from the Jan Mayen Ridge is the marked predominance of acid glass over basaltic and acid plagioclases over average and basic plagioclases in it. This is stipulated by ashy material supply from volcanoes of Hekla and Askja. We cannot exclude the presence of underwater volcanoes with acid volcanoclastic products in the region of the Jan Mayen Ridge.

In the Jan Mayen Trench some cores were gathered (station AK-769-1, -2, -3, -4, -11). In general they are represented by volcanogenic and volcanogenic-terrigenous sediments which are enriched in Fe, Ni, Mn and P. Rather clear stratification is noticeable, which is expressed either in the stratification of different grain-size distributions or in colors replacement. In general, sandy-aleuritic interlayers are represented by products from the destruction of basaltic rock. These are fragments of basalt, grains of plagioclases and clino-pyroxenes. To a lesser extent, fresh and oxygonal grains of brown glass (N = 1.580 - 1.585), semi-transparent ashy and palagonitic particles of irregular shape, colorless and greenish clino-pyroxenes (Ng about 1.690 - 1.700), separate grains of magnetite and olivine are present here. The interlayer in core AK-769-1 is 74 to 77 cm. It consists of fresh brown volcanoclastic glass (95 to 97 %). Separate grains of brown and yellow biotite, chlorite, chloritized grains of calcite and some other minerals are found in sediments from Scandinavia and Greenland.

At station AK-769-11 (270 m depth) late Quaternary sediments are represented by dense, almost "dry" terrigenous (< 10 % $CaCO_3$) clay with admixture of aleuritic material. The color of the clay is brown-grey. Traces of tectonic action are distinctly observed on account of the presence of gliding and fracture surfaces. At station AK-769-3 (3600 m depth) grab brought angular, weakly rounded grains of argillite and aleurites measuring from 1 to 15 mm. The color of the grains is yellow-grey, brown-grey (with rust). There are also separate grains of basaltic rock gravel. At station AKL-769-15 (1480 m depth) volcanogenic-terrigenous sediments apparently low-calcareous, aleuritic-pelitic muds with great amounts of basalt fragments were lifted by dredge. There was much ice-rafted material which was brought from Jan Mayen and Greenland in trench sediments.

The upper layer (Holocene) of the Iceland Plateau core is represented by nanno-foraminiferal oozes. Their low parts are noticeably different from each other. Core AK-1397 is represented by terrigenous and volcanogenic-terrigenous muds and coarse aleurites. Sediments from Scandinavia (station AK-1379) are enriched in pyroclastics more of less (also Fe and Ti) but only in separate small interlayers especially in intervals 111 to 155 cm. Typical minerals for Scandinavia and for northern Greenland prevail.

In core AK-1363 late Quaternary brown-grey terrigenous low-calcareous muds with interlayers of foraminiferal coarse aleurites at horizon (89 to 106 cm) lie und layers of Holocene foraminiferal ooze (0 to 16) up to 26 cm. Light grey clay lies in layers (126 to 194 cm). The complete absence of $CaCO_3$ and very low contents of Corg are typical of this. Then, downwards (up to 245 cm) is brown, very dense argillite (Miocene) containing up to 12.92 % of Fe and up to 17 % of Mn (Emelyanov et al., 1976). Cemented rock (argillite) lies (251 to 259 cm) and then weakly cemented aleuroliths with inclusions of

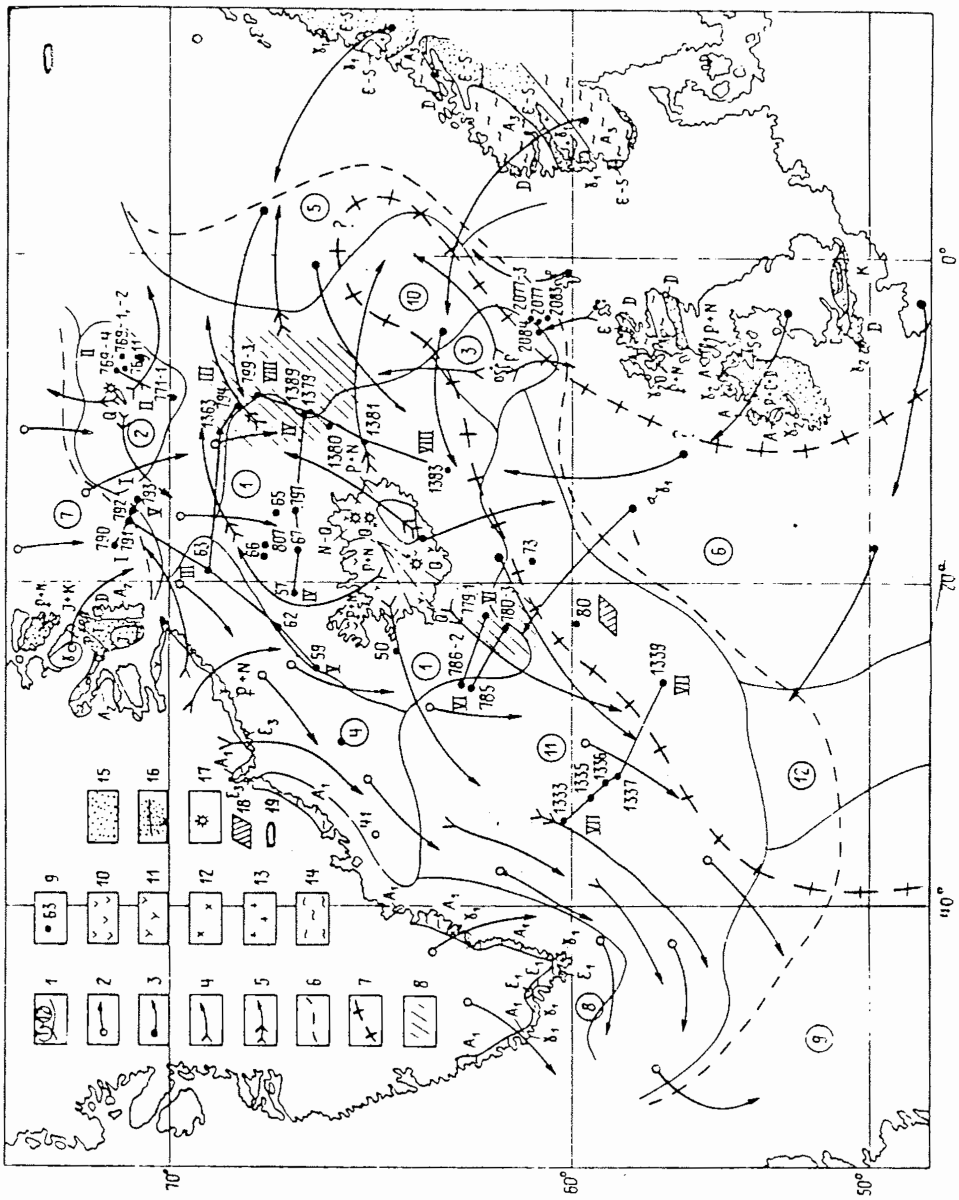

Fig. 5: Recent terrigeneous-volcanogenic mineralogical provinces and pth ways of clastic material to the ocean.

1) Numbers of the mineralogical provinces, 2) acid and metamorphic rocks from S and E Greenland, 3) clastic material from Europe, 4) volcanoclastic material, 5) pyroclastic material from Iceland and Jan Mayen, 6) distribution of ash layer, 7) Pleistocene ice limit, 8) distribution of acid volcanic glass, 9) stations, 10) tholeitic basalts and djlerites, 11) basalt, 12) zhyolite, 13) granit, 14) acid magmatites, 15) terrigeneous rocks, 16) carbonate-terrigeneous rocks, 17) volcanic sources of acid tephra.

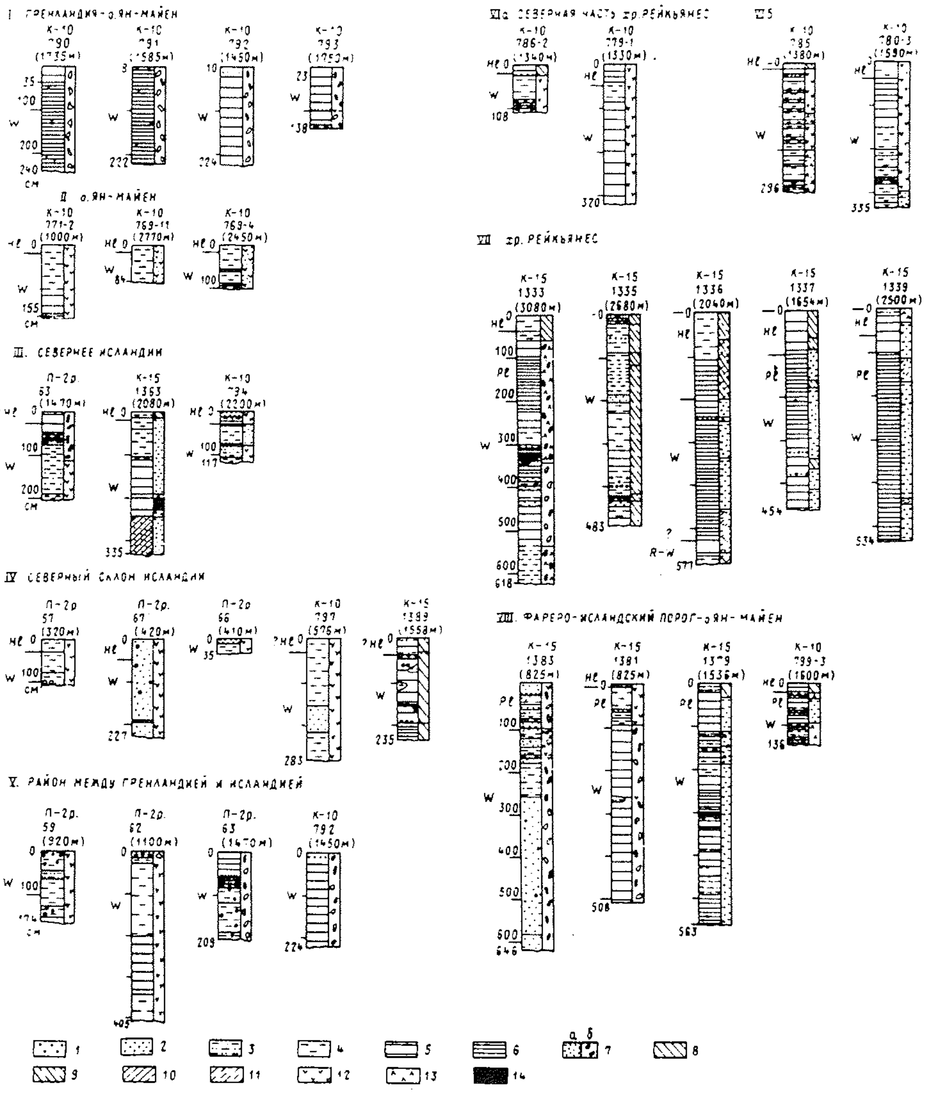

Fig. 6: Lithology of Late Pleictocene sediments in the Norwegian-Greenland Sea.

1) Gravel, 2) sand, 3) aleurite, 4) silty mud, 5) aleuritic-pelitic mud, 6) pelitic mud, 7) glacial marine, 8)biogenic, 9) biogenic-terrigenous (30-50 % carbonate), 10) biogenic silicous, 11) biogenic-terrigenous (10-30 % SiO_2), 12) pyro and volcanoclastic, 13) 10-50 % ash content, 14) maganese-iron deposits.

cemented argillite lie in layers at depths of 251 to 259 cm.

Marine-glacial terrigenous (iceberg) and terrigenous-volcanogenic sediments are spread in the Iceland-Greenland Trench and on the Kolbeinsey

Ridge. At cores AK-63, -790, -792 (Fig. 5) material which was brought by ice and icebergs from northern Greenland (probably from more distant regions, from the Arctic Basin) prevail. However, there is also a noticeable admixture of volcanoclastic material. These are opaque ashy particles, plagioclases, clinopyroxenes and brown glass. Probably in the late Quaternary period they were brought here from central Greenland. The chemical composition of the core sediments is closer that of terrigenous than of volcanogenic sediments. At core AK-793, which was selected almost on the top of the Kolbeinsey Ridge, high contents of Fe, Ti, Mn and P are found. This corresponds closely to sediments which are typical of volcanogenic deposits from Jan Mayen and Iceland.

Mineralogical and geochemical indicators of different supplying provinces

According to descriptions of sediments for different genetic types their own indicators are typical.The following basaltic composition is typical of the Icelandic pyroclastic province:

Opaque ashy particles, brown volcanic glass, basic plagioclases, clinopyroxenes, smectite (saponite). Palagonite and zeolite - in Pleistocene sediments. The ratio of quartz to feldspar is 4 to 100. High contents of Fe (7.0 - 13.5 %), Ti (0.7 - 2.49 %), V (0.015-0.051 %), increased Mn (average 0.16 %), P (average 0.14 %) and Cr, Zr, Ba and Ni are typical. The significance of the ratio of (Ti and Fe)/Al is 3.0, (Fe and Mn)/Ti - 4.8 to 9.4. According to the high contents of the minerals listed (Fig. 2) and of chemical elements (Fig. 3) the region of distribution of erupted products from Iceland and Jan Mayen is easily delimited (Fig. 1). The borders of areal distribution more or less precisely coincides with the contents of the isolines: 7 % Fe (clastic or CFB), 1.0 % Ti (clastic), 0.20 % V (clastic). This regularity is expressed less in Cr. The distribution of Ti, Fe, V and Cr in late Quaternary sediments subordinates to the same regularities as in the upper layer of sediments, i.e. it stipulates by pyroclastics (volcanoclastics) quantity, granulometric composition and biogenic material admixture.

We point out that in the past 1100 years Iceland's volcanoes have erupted about 10.1 km^3 of tephra and 19.6 km^3 of lava (Torarisson, 1967). Approximately half of these products (5 km^3 of tephra and 15 km^3 of lava) have come to the Earth's surface during the last 250 years. Therefore, about 20 million m^3 of tephra have erupted each year (about 50 million tons per year) and about 60 million m^3 of lava (about 180 million tons per year). Let us assume that all these products are uniformly distributed all over Iceland (103,000 km^3) and to the zone which was covered by volcanoclastic sediments around Iceland (about 25,000 km^2). We calculate that in the span of 100 years about 57 kg of volcanoclastic products were deposited on each m^2. Excluding lava and taking into consideration only tephra (45 km^{3}for 250 years). We have calculated that about 140 kg/m^2 was deposited during the course of 1000 years. This corresponds to loose sediment accumulations with rates of approximately 6 cm for 1000 years.

The content of the second group of elements (Mn, Ni, Co, Cd and Ba) in basalts, in products of basalt destruction and in pyroclastic material of basic composition is considerably higher that in sedimentary rocks: volcanogenic material is one of the main sources. However, the elements of the second group are more flexible in contrast to Ti, Fe, V and Cr. This is why they are contained in increased quantities in volcanogenic sediments on the one hand, therefore close to volcanoclastic islands. On the other hand, in pelagic (terrigenous, volcanogenic-terrigenous and foraminiferal) muds, which lie further from the sources of volcanogenic material, but are characterized by considerable admixture of fine pyroclastics (Fig. 3). This can be traced according to the ratios of Mn/Ti and Mn/Fe. In general, the distribution of the second group of elements (including Mn) is determined by the mineral composition of clastic and clayey material, but with the help of chemical and physical factors. Their potential does not play a large role because of this consistently low potential. Considerable admixture of authigenic minerals have not been observed in sediments in which a large number of one or the other of the elements may be concentrated. The content of P, which is an element of the third group, reaches 0.19 % in volcanogenic and up to 0.20 % in clastic sediments. The distribution of P according to its types and to the squares of surfaces resembles distribution patterns in the second group of elements.

Where ancient volcanogenic provinces, such as those with paleogenic tuffs in the Faroe Islands and in the eastern part of Greenland, are found slightly different compositions are formed. Active volcanism stopped here in the Eocene. The source of volcanogenic (volcanoclastic) material is found in the products of the distribution of Tertiary plateau basalts. The predominance of plagioclases and clino-pyroxenes is typical of central Greenland (province 4, Fig. 5). There is some brown glass in sediments. These differences help us to more accurately distinguish the numerous volcanogenic materials accumulated and which come from different volcanogenic provinces.

Among clayey materials, smectite (saponite) and chlorite which were formed as a result of basalt weathering usually prevail (Zangalis, Kharin, 1976) in volcanoclastic sediments of the Faroe-Iceland Ridge (including Faroe Island sediments). There is much feldspar and quartz in the thin fraction (< 0.01 mm). Zeolites (clinoptilolite) are present. Latters in Recent sediments are probably of terrigenous origin (they were brought with the products of weathered basalts which contain zeolites). The same basalts and tuffs are wide-spread on the Faroe Islands. In cores which were taken close to the Faroe Islands and to Greenland show great amounts of very changed pelliterized grains, which were formed due to the changing of feldspars, opaque ashy particle and brown glass are found. Hydrous-ferric oxide sometimes non-sulfide is found in sediments. Volcanoclastic sediments near the Faroe Islands consist of small quantities of V, considerably less Fe, Ti and Mn than sediments found near Iceland, but contain more Cr and P (Fig. 3).

The most typical mineral indicators of products of denudation from Scandinavia are quartz, common hornblende (Fig. 2), acid plagioclases, potassic feldspar, epidote-zeolite, garnet, zircon, illite and large quantities (more than 60 %) of quartz and silicate SiO_2 (Emelyanov and Lisitzin, 1977). Mixed (volcanogenic-terrigenous) composition with various admixtures of biogenic carbanaceous or siliceous material characterize the sediments which lie between typical pyroclastic and terrigenous sediments.

Marine-glacial sediments are spread near the sea coast of western Greenland. However, in the late Pleistocene period the spread of these sediments was widest. They were spread as far as the southern part of the Reykjanes Ridge. In general, they are aleurites, aleuritic-pelitic muds, weakly or poorly sorted with large amounts of rudaceous ice or iceberg material. In the region of the Faroe Island Ridge marine-glacial sediments are practically not covered with Holocene sediments and are subjected to erosion by strong benthic currents (cf. station AK-1383, AK-1381). Clastic sandy-aleuritic parts of these deposits are generally represented by terrigenous minerals which are typical of the Scandinavian petrological province. This points to the fact that ice material coming from Norway played the main role in the late Pleistocene formation of sediments.

The distribution of amorphous silica in sediments and some paleo-geographic questions

In recent sediments from the North Atlantic and the Norwegian-Greenland Basin increased quantities of diatom skeletons and sponge spicules are found (Fig. 7). Pleistocene muds are enriched in these remains. They are compacted and look like "dry" clay. Inclusion of gravel and rubble is often found.

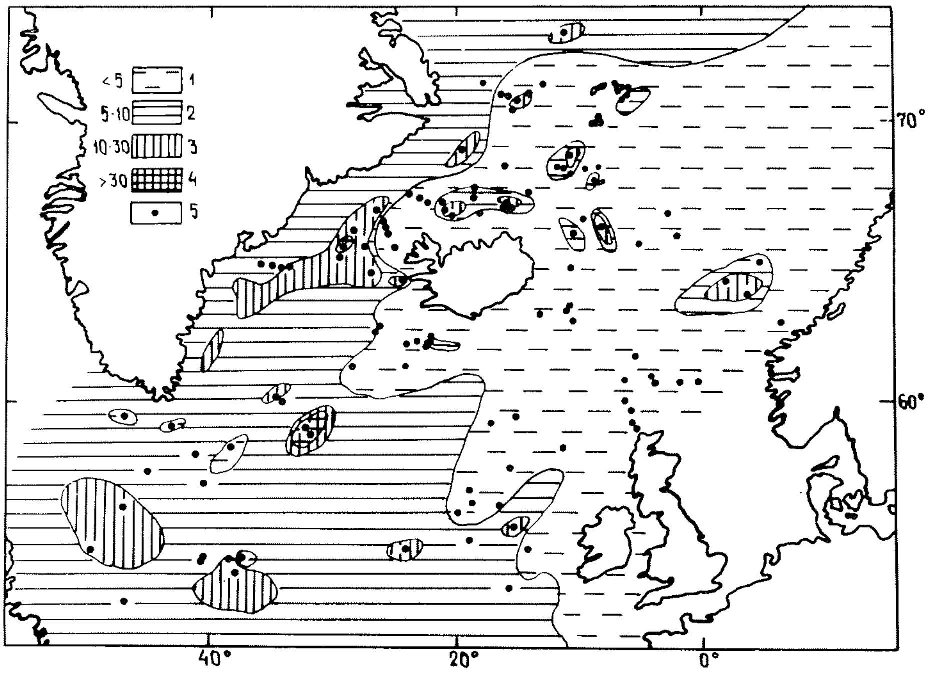

Fig. 7: Biogenic siliceous particles in the light 0.1-0.05 mm fraction of surface sediments (0-5 cm).

The content of amorphous silica is from 0.84 up to 12.87 %. If we take into consideration that the chemical method gives us reduced (lowered) results approximately in 1.6 times (Emelyanov et al., 1978), therefore, the real content of this component will increase to 10.59 % (Fig. 8). Such quantities of SiO_2 are found at horizon 540 to 550 in core AK-1336. Low siliceous muds of this horizon are also cocollithic-foraminiferal. They contain 55.04 % of $CaCO_3$, 0.54 % of C_{org}, 1.01 % of Fe, 0.06 % of Mn, 0.27 - 0.38 % of Ti and 0.04 - 0.05

% of P (Fig. 8).

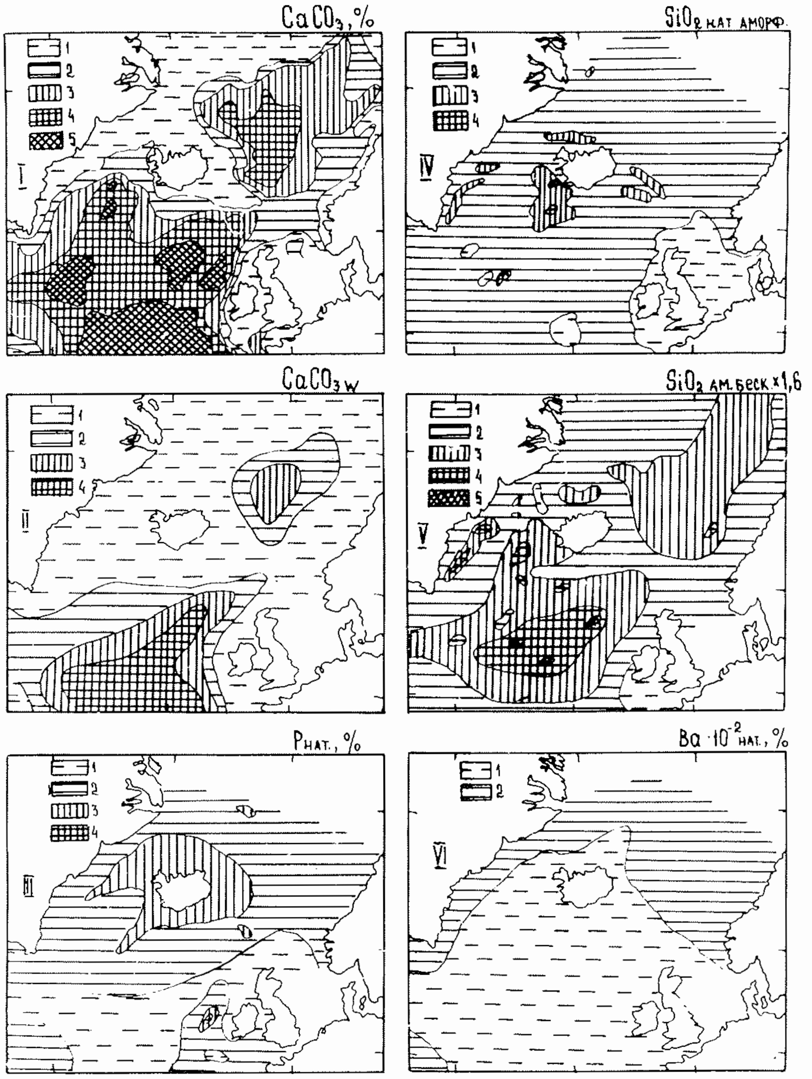

Fig. 8: Chemical components of surface sediments.
I) $CaCO_3$: 1. 1-10 %, 2. 10-30 %, 3. 30-50 %, 4. 50-70 %, 5. >70 %; II) $CaCO_3$ content of glacial sediments (about 18-20 ky ago): 1. 1-10 %, 2. 10-30 %, 3. 30-50 %, 4. >50-70 %; III) phosphorus: 1. >0,05 %, 2. 0,05-0,1 %, 3. 0,1-0,2 %, 4. >0,2 %; IV) amorphous silica: 1. <1 %, 2. 1-3 %, 3. 3-5 %, 4. 5-10 %; V) amorhous silica (on carbonate free basis): 1. < 1 %, 2. 1-5 %, 3. 5-10 %; 4. 10-20 %, 5. > 20 %; IV) barium: 1. < 0,05 %, 2. 0,05-0,1 %.

In cores of section VVI there are many shells of foraminifera and, as a result, muds turn into mixed foraminiferal-terrigenous, glacial-marine or even foraminiferal. Therefore, in core AK-1335 $CaCO_3$ content fluctuates within the limits of 34.27 - 68.29 % , in core AK-1336 within 21.51 - 59.04 %, in core AK-1337 from 18.51 to 50.78 % and in core AK-1333 from 5.75 to 31.77 %. The content of amorphous silica is increased in Pleistocene sediments in the northern part of the Reykjanes Ridge. Core AK-779-1 ranges from 4.32 to 7.22 % of SiO_2, core AK-786-2 ranges from 5.80 to 6.16 % of SiO_2. Thus, vast zones of increased silica accumulation existed in the North Atlantic (south of Iceland) in the late Pleistocene. In this connection sediments enriched by SiO_2 were foraminiferal at the same time (they contain up to 60 % $CaCO_3$). This points to the fact that in the region of the Reykjanes Ridge a considerable rise in abyssal water and strong hydrofronts took place. This prompted the supply of nutrients from the "below". Therefore it carries on the rise of biogenic productivity. Given zone is something like the Atlantic zone of divergence, where mixed diatom and foraminiferal muds are presently being accumulated.

The question is then, what kind of indicators are typical for Arctic Ocean ice material which is supplied through the Fram Strait to the Norwegian-Greenland Basin? What is its value? These question should be solved in following international expeditions.

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