Modern and Late Quaternary Depositional Environment of the St. Anna Trough Area, Northern Kara Sea

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Preface

Preface

THE JOINT RUSSIAN-GERMAN KARA SEA PROJECT (1995-1998)

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The terrigenous sediment supply and its shelf-to-basin transport in the eastern Arctic Ocean is mainly controlled by river discharge, oceanic currents, sea-ice (and iceberg) transport, and down-slope transport; aeolian supply is only of minor importance. Furthermore, most of these mechanisms also influence biological processes in the water column as well as at the sea floor (i.e., surface-water productivity, particle fluxes through the water column, benthic activities at the sea floor, organic carbon export and burial, etc.). In this context, especially the St. Anna Trough is of major interest. The St. Anna Trough is the connection between the Kara Sea shelf and the open Arctic Ocean and thus (1) an important pathway for the water exchange between the shelf and the open ocean and (2) an important pathway for the sediments supplied by the major rivers Ob and Yenisei onto the Kara Sea shelf and transported through the trough towards the central Arctic.

Within a joint Russian-German research project funded by the German Ministry for Education, Science, Research and Technology (BMBF), detailed sedimentological, mineralogical, geochemical and micropaleontological investigations were performed on sediments from the St. Anna Trough area. Major objectives of these studies were (1) the characterization and quantification of the terrigenous sediment input, (2) the identification of source areas and transport pathways of the terrigenous matter, and (3) the reconstruction of the depositional environment and its change through late Quaternary times.

This special issue of "Berichte zur Polarforschung" presented results of the joint investigations performed at AWI Bremerhaven, IORAS Moscow, MMBI Murmansk, and VNIIOkeangeologia St. Petersburg. It is divided into three main chapters.

Chapter 1 includes two papers dealing with a short review of the history of (mainly Russian) geological research activities in the Barents-Kara-Sea area, beginning from the 16th century. Of course, these papers could not include all of the numerous investigations performed in this area by the different institutions. Furthermore, the two papers partly strongly emphasize the research activities of the author´s home institutions, VNIIOkeangeologia St. Petersburg and MMBI Murmansk, respectively. Within a review of Russian geological research in the Kara Sea, one should mention, however, at least also the work performed at the Shirshov Institute of Oceanolgy Moscow under the guidance of A.P. Lisitzin. During the multidisciplinary Kara Sea Expedition of RV "Dmitry Mendeleev" in 1993 (Lisitzin and Vinogradov, 1995), for example, numerous new data and concepts on sedimentary processes and the ecosystems of the Kara Sea as well as the Ob and Yenisei estuaries were obtained and published (e.g., Lisitzin, 1995, and numerous other papers in the special issue of Oceanology, English Translation, Vol. 34, No. 5, 1995). In 1997, a joint Russian-German expedition was carried out into the area of the Ob and Yenisei estuaries with RV "Akademik Boris Petrov" to study the biological, geochemical and geological processes related to the freshwater, contaminant, and sediment supply by the Siberian rivers Ob and Yenisei and its impact on the environment of the inner Kara Sea (Matthiessen and Stepanets, 1998; Matthiessen et al., 1999). These studies will be extended during a second joint Russian-German Kara Sea Expedition with "Akademik Boris Petrov" in 1999.

Chapter 2 contains papers dealing with modern processes in the St. Anna Trough area, including very different and complex aspects. Oceanographic topics, aerosol input, composition and fluxes of suspended matter, and plankton and benthos data are presented and discussed as well as sediment data on clay minerals, heavy minerals and physical properties.

Chapter 3 includes three papers dealing with results from investigations of upper Quaternary sedimentary sequences from the St. Anna Trough. Grain-size data and heavy mineral data as well as organic carbon data are interpreted in terms of changes in terrigenous sediment supply and depositional environment during this time period.

I would like to mention that we made an effort to edit the manuscripts by the Russian authors to make them easier to read. I hope that we have not changed the meanings of the original papers. The papers contained in this issue do not necessarily reflect the opinion of the editors.

Acknowledgements

We would like to thank the German Ministry for Education, Science, Research and Technology (BMBF) for financial support.

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History of Russian Research in the Barents - and Kara Seas

THE HISTORY OF INVESTIGATION OF BOTTOM SEDIMENTS OF THE WESTERN ARCTIC SHELF: THE BARENTS AND KARA SEAS

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The history of investigations of the Barents and Kara seas can be divided into three main periods: (1) from the 16th to the beginning of the 20th century, (2) from 1921 to 1941, and (3) from 1945 to the present time.

Period from the 16th to the beginning of the 20th century

In the 16th century the study of the hydrological region of the Barents Sea was carried out in connection with fishery activities. During navigation as well as hydrological and meteorological observations the character of grounds was recorded. These observations, however, were single and not systematical. In 1552, the Russian diplomat and scientist D. Gerasimov still talked about the possibility to sail to China through India and the Northern seas. In 1553, the English people sent several ships for searching the North-Eastern passage, but without success. At the end of the 16th century the Dutch sailors started the navigation to the Arctic Ocean. The expedition of V. Barents in 1594-1597 became the most famous.

At the end of the 16th century and the beginning of the 17th century the Russian inhabitants of the coast familiarized the sea way along the coast of the Barents, Pechora, and Kara seas and recorded the character of sediments during navigation.

In 1734 - 1738, the Great Siberian Expedition under the leadership of S. Muraviev, M. Pavlov, S. Malygin, A. Skuratov, and A. Suhotin performed the description of the coast and also registered the character of bottom sediments at single points. The pieces of information about the seafloor were recorded on navigation maps in sailing directions. Information about the character of bottom sediments were also included in maps of the English Admirality and in German fishery maps of that time.

In 1764 - 1766, the expedition of V. Ya. Chichagov reaching 80°30′N for the first time, was organized by M.V. Lomonosov. During the 16th and 17th centuries none of the expeditions penetrated so far to the north. As result, new valuable scientific data both on the shelf seas and partly the central part of the Arctic Ocean were obtained.

In the 19th century, P.F. Anzhu, D.P. Vrangel, and F.P. Litke proved that the Arctic Ocean was not covered by permanent ice and that the ice regime varied from year to year.

The first detailed description of sediments of the Barents Sea was done by F.P. Litke in 1821 - 1824 during sailing to the shores of Novaya Zemlya. F.P. Litke, together with M.F. Reineke, compiled sailing directions on which they marked information about shoals, reefs, and the character of bottom sediments.

In 1824 - 1825, N. Shcheglov and D.I. Sokolov studied marine nodules.

Between 1876 and 1896, information about the sediments and the seafloor relief was also obtained during several expeditions from other countries. In 1876 - 1878, the Norwegian North Atlantic Expedition,. although mainly collecting and studying recent sediments in the Greenland Sea, obtained several bottom sediment samples in the western part of the Barents Sea. The Russian-Swedish "Vega" Expedition under the leadership of A.E. Nordensheld (1878 - 1879) and the Dutch "Varka" Expedition (1882 - 1883) recovered first information about sediments and iron-manganese concretions in the southern Kara Sea. In 1893 - 1896, the most famous Norwegian "Fram" Expedition into the Arctic Ocean under the leadership of F. Nansen took place. In 1904, F. Nansen compiled the first bathymetry map of the Barents Sea shelf area.

In 1899, the research vessel "Andrey Pervozvany" was built on the initiative of N.M. Knipovich. On May 25, 1899, RV "Andrey Pervozvany" started her first scientific cruise into the Barents Sea. From 1899 to 1902 N.M. Knipovich and collaborators conducted complex explorations of stations and transects crossing the North Cap Current. According to the results of these investigations the Russian Geophysics Society issued the fundamental work "The bases of hydrology of the Arctic Ocean" by N.M. Knipovich in 1906. In this issue, the author suggested that the Barents Sea bottom was a vast river valley which in the recent geological past dropped below sea level and had been filled by Atlantic waters. The troughs existing today are the fragments of ancient valleys. In 1902, the expedition was headed by L.L. Breitfus, the assistant of N.M. Knipovich, who continued the complex investigations as a result of which a series of large works was published. In 1904, however, the expedition was obliged to stop working and the steamship "Andrey Pervozvany" was sold to the marine department.

In 1901, a famous Russian expedition with the icebreaker "Ermak" under the leadership of admiral S.O. Makarov took place, reaching 81°29'N and the archipelago of Svalbard and Novaya Zemlya. In 1903 and 1913 the hydrographic expeditions of B. Vilkitsky with the ships "Taimyr" and "Vaigachi" built especially for navigation in Arctic seas, opened the way to the islands of North Land. During these expeditions, parallel to the hydro-meteorological observations, the selection of rock samples on land and sediment samples in the Arctic seas were accomplished.

In 1913 - 1914, the least accessible part of the Barents Sea shelf was explored by the "St. Foma" expedition under the leadership of G. Sedov.

The expeditions of the end of the 19th and beginning of the 20th centuries still payed little heed to study bottom sediments. Furthermore, the investigations were carried out mainly in the most accessible southern parts of the Arctis seas. The obtained samples of bottom sediments were often studied by different methods, and the results were not correlative between each other. There were no fundamental generalization on the character and distribution of bottom sediments.

Period from 1921 to 1941

The serious systematical exploration of bottom sediments of the Russian Arctic seas began in 1921. On March 21, 1921, the Chairman of Sovnarkom (the government of the Soviet Union at that time) V. I. Lenin signed a decree about the creation of the "Floating Marine Research Institute (Plavmorin)". The scientific works in geology were conducted under the guidance of Ya. Yu. Samoilov and M. V. Klenova. In this context, the important contributions in studying bottom sediments of the Barents and Kara seas by T.I. Gorshkova, P.S. Vinogradova, V.P. Zenkevich, M.M. Ermolaev, and M.V. Klenova should be mentioned. M. V. Klenova who participated in ten cruises of RV "Persey" between 1925 and 1933, became the "Honary Scientist of Russia".

T.I. Gorshkova who participated in 50 expeditions mainly in the Barents Sea, compiled several maps of sediment composition and distribution. V.P. Zenkevich compiled the first geomorphological map of the Barents Sea. The shelf bottom sediment samples of the western Arctic seas are stored in the archives of PINRO and VNIRO.

In 1930 - 1931, the data on chemical and mineralogical studies of the Barents and White seas were published in papers by T.I. Gorshkova. At the same time with investigations carried out by PINRO and VNIRO since 1932, an intensive and systematic study of the Arctic seas (mainly of the Kara Sea and western Arctic) was accomplished during oceanological expeditions of the Arctic Research Institute (ANII). The expeditions of the research vessels "Sibirakov" (1932 and 1939), "Sedov" (1932), "Malygin" (1935), and "Sadko" (1935-36) were the most important ones. Papers devoted to grain-size distributions as well as lithological and chemical compostions of bottom sediments collected during these expeditions, were published by M.M. Ermolaev, Z.N. Neyasova, G.F. Ul and others. In 1937, a paper devoted to radioactivity of iron-manganese concretions and composition of bottom sediments in the northern Kara Sea was published by M.M. Ermolaev and L.M. Kurbatov. Based on the study of mineral and chemical compostion of bottom sediments, the content of certain rock-forming and accessory minerals and the content of certain chemical elements were plotted in maps. Charts of mineralogical provinces and geochemical maps of bottom sediments for the Barents and Kara seas, however, were not compiled.

In 1941, all Russian Arctic seas and partly the Greenland and Norwegian seas as well as certain regions of the Arctic Basin were embraced by explorations. During the Second World War scientific investigations of the western Arctic shelf seas were not carried out.

Period from 1941 to present times

After the Second World war, the exploration of bottom sediments of Arctic seas was resumed by several organisations. The main organizations were ANII, VNIRO, PINRO, the Hydrogeographical Survey of MMF, the Research Institute of Arctic Geology, and the Murmansk Marine Institute of Kola Branch of the Russian Academy of Sciences.

In 1946, the expedition with the icebreaker "Severny Polus" carried out studies in the eastern Arctic. Since 1948 annual air expeditions began, and since 1950 regular expeditions on the drifting ice station "Severny Polus (SP)" started to work. At that time, also systematical investigations of the Arctic seas were initiated by annual oceanological studies (ice patrol) in which the selection of bottom sediments both in the western and eastern Arctic was accomplished.

Since 1948 all samples were treated according to unified methods in the lithological laboratory of NIIGA under the guidance of N.N. Lapina. During this period the issue of "Geology of the Sea" (1948) by M.V. Klenova was published as fundamental work. Based on this work, "Marine Geology" became an independent branch of geological sciences.

In 1952, the first monograph on "Conditions of formation of bottom sediments in Arctic seas of the USSR" by V.N. Saks was published. In this work the characteristics of the geological structure of the seafloor and shores of Arctic seas are given, the processes of sedimentation examined, and the geological history of basins restored. In 1953, the monograph "Sediments of the Kara Sea" by A.A. Kordikov was published. This work having generalized material and data of Arctic institutes obtained during previous expeditions, however, only gave relatively brief characteristics of bottom sediments.

In 1956, the group marine geologists at NIIGA took part in annual expeditions on RVs of ANII and the Hydrogeographical Survey of MMF, on drifting ice stations and in "Sever" expeditions. This group of scientist consisted of N.N. Lapina and other geologists such as N.N. Kulikov, Yu. P. Semenov, A.S. Zelenko, Yu.N. Ustinov, K.P. Samsonov, Yu.N. Komarov, V.Z. Melenitsky, G.S. Filishkin, O.N. Kuleshova, and S.V. Tamanova. Since 1963, long sediment cores could be recovered by means of gravity and piston corers, allowing to study not only the Holocene, but also late Pleistocene sediments.

In 1960, the monograph by M.V. Klenova on the "Geology of the Barents Sea" including the first seafloor chart of the entire Barents Sea, was published. In 1961, the monograph by N.A. Belov and N.N. Lapina on "Bottom sediments of the Arctic Basin" was published, presenting the characteristics of bottom sediments of the Barents and Kara seas.

From 1956 to 1972, investigations of the Kara Sea were performed under the guidance of N.N. Kulikov. In 1964, he and others finished the generalized work about the character of Kara Sea bottom sediments and the peculiarities of their formation. The work was based on more than 3000 sediment samples and contained more than 20 maps of the scale 1:5000000 with data on granulometric, mineral, and chemical composition and other characteristics of surface sediments of the Kara Sea. Furthermore, results of detailed investigations of long sediment cores obtained in the St. Anna Trough, the Novozemelskoe Hollow and other regions, were presented.

In the following years, huge amounts of material from bottom sediments of the western Arctic shelf was treated and generalizied by V.I. Gurevich, D.S. Yashin, and V.L. Kosheleva. Detailed chracteristics of bottom sediments of the Arctic seas including the Barents and Kara seas were published in the monograph "Geology of the USSR" (edited by B.V. Tkachenko and B.Kh. Egiazarov, 1970) in papers by N.N. Lapina, N.A. Belov, N.N. Kulikov, Yu.P. Semenov, and M.A. Spiridonov. In 1971, maps compiling mineralogical provinces were published for the first time. Three types of maps were distinguished: (1) maps of mineralogical provinces based on 2-3 minerals, (2) maps of terrigenous mineralogical provinces of rock-forming minerals, and (3) maps of terrigenous mineralogical provinces of accessory minerals.

The 70s were a new stage in shelf studies. Geophysical investigations including the methods of reflection and refraction seismic, deep seismic sounding, and seismo-acustic profiling were introduced.

During the 80s, a large number of deep wells were drilled in the Barents Sea down to depths of 250 m below seafloor by the Arctic Murmansk Government of Exploration Drilling (AMURB) and PO "Arcticmorneftegazrazvedka". At the same time, the Arctic Marine Engineer-Geological Expedition (MMIGE) carried out drillings from RV "Bavenit" and RV "Kimberlit", which allowed to study the Cenozoic sedimentary cover of the shelf in detail.

In 1981, the "Atlas of grounds of the Arctic Ocean" was issued which was rewarded with a "State Premium of the USSR" in 1983. Within this atlas, the manifold characteristics of bottom sediments of the Arctic Ocean, including maps of mineralogical provinces, geochemical divisions into districts of provinces, and physiochemical properties of bottom sediments, were compiled.

From the beginning of the 80s, the surveys performed by the Marine Arctic Geological Exploration Expedition of NPO "Sevmorgeologia" embraced the southern and central regions of the Barents Sea shelf. The systematic study of the Barents Sea seafloor was carried out by the Geological Survey of Shelf (GSSh) on the scale of 1:1000000 (V.G. Lopatin, V.I. Gurevich, 1990).

V.I. Gurevich and E.E. Musatov recently published a paper on "The history of the study of Barents and White seas shelf" in which a map of "Recent deposits of the western Arctic shelf" as well as a list of literature of Russian and foreign scientists are enclosed.

At the present time, the "Atlas of bottom deposits of the World Ocean" is prepared for publication. The second part of this atlas is devoted to the Arctic Ocean including the Arctic seas, and contains 44 maps of the scale 1:15000000 to 1:45000000, part of them characterizing the bottom sediments.

Since the beginning of the development of oil and gas fields the Arctic shelf of Russia is coming into particular importance as object of national economy. In this context environmental investigations of the shelf are evidently urgent. Thus, multidisciplinary studies of seafloor environments and geoecology in the western part of the Arctic were started in 1991 under the scientific supervising of VNIIOkeangeologia. During 1991-1994 VNIIOkeangeologia, together with branches of the research-industrial association "Sevmorgeologia" (MAGE and PMGRE) conducted four multidisciplinary cruises into the Kara Sea with the research vessels "Academik Alexander Karpinsky (1991), "Geolog Fersman" (1992, 1993), and "Professor Logachev" (1994). Furthermore, in 1993 the Kara Sea Expedition of RV "Dmitry Mendeleev" took place (see R. Stein, Preface, this vol.).

The multidisciplinary character of these expeditions consisted in stuying all main links within the geosystem: aerosols, sediment flux, suspended matter, water column (salinity, temperature), bottom sediments (grain size, bulk minerals, clay minerals, total and organic carbon, major and minor elements), benthos (taxonomy, abundances, species composition, community structure, biomass), and various pollutants in bottom waters, benthic organisms, and sediments (polychlorinebiphenyls-PCBs, hexachlorocyclohexane-HCH, oil hydrocarbons, phenols, heavy metals, radioactivity).

A reference list of selected main papers by Russian scientists, dealing with the history and characteristics of bottom sediments of the western Arctic shelf, is given below.

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THE HISTORY OF RUSSIAN GEOLOGICAL INVESTIGATION OF BOTTOM SEDIMENTS IN THE BARENTS AND KARA SEAS (WITH SPECIAL EMPHASIS ON MMBI STUDIES)

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The results of work of marine geologists are reflected in the monographs by M.V. Klenova "Geology of the Sea" (1948) and "Geology of the Barents Sea" (1960) where data on the composition, occurrence, and formation of bottom sediments are reflected and presented. It should be mentioned that some of the conclusions by M.V. Klenova are subjected to revision, but the facts remain valid due to the thoroughness of natural observations and high quality of laboratory analyses.

After a clear decrease during and directly after the Second World War, geological research activties began to rise in several organizations: the Polar Scientific and Research Institute of Fishing Economy and Oceanography (PINRO) by P.S. Vinogradova, V.M. Litvin, G.G. Matishov, A.I. Dmitrienko and others (Vinogradova, 1957; Matishov, 1974); the Murmansk Marine Biological Institute (MMBI) by V.I. Gurevich, G.A. Tarasov, L.G. Pavlova, T.V. Yakovleva and others; the All-Union Geological Institute by M.A. Spiridonov, A.E. Rybalko and others; the Scientific and Research Institute of Arctic Geology by V.D. Dibner, V.E. Melnitskiy, E.N. Shkatov; the Institute of Oceanology by A.I. Blazhchishin and others.

In the 60s - 70s world-wide geological studies allowed to develop a detailed chronostratigraphical classification of bottom sediments on the basis of paleomagnetic (first attempts in the Barents Sea were carried out by T.I. Linkova), radioisotopic and micropaleontological investigations instead of purely lithological descriptions. The basis of modern palynostratigraphy has been established by R.M. Khitrova, N.N. Kulikov, E.A. Spiridonova, E.S. Malyasova, L.M. Ivanova and others, based on the international scale of Blitt-Serander. Foraminifera analysis established for the Barents Sea by Z.G. Schedrina (1958) and L.A. Digas (1969) was carried out during the following years by micropaleontologists: I.I. Burmistrova, S.V. Tamonova, V.Ya. Slobodin, T.S. Troitskaya, O.F. Baranovskaya, L.A. Tverskaya, L. Polyak, T.A. Khusid, I.A. Sakharova, N.V. Belyaeva, N.I. Druzhinina, and S.A. Korsun. Foraminifera data, in combination with geochemical data, gave information about the stratigraphy of sedimentary sequences s well as the paleoecology and paleoenvironment (e.g., paleotemperature, paleosalinity) of the Barents Sea.

In the 70s, with the beginning of the use of micropaleontological, paleomagnetic and radioisotopical data within lithological analyses, it was possible to replace the old binary division of Barents Sea sediments into "glacial ancient clays" and "post-glacial sandy-silty sediments" by a more detailed classification into not less than four units: (1) upper Pleistocene-upper Dryassic, (2) lower Preboreal-Boreal, (3) middle Atlanticum, and (4) upper Holocene-Subboreal-Boreal. In long sediment cores taken with piston corers, it was sometimes even possible to distinguish of all the ten subdivisions according to the international Blitt-Serander scale.

In the 70s - 80s many expeditions were conducted to the World Ocean, allowing to consider the geology of glacial shelves in a view of global oceanology. As a result papers with new ideas and wide range of generalization appeared. For the first time, G.G. Matishov put forward conceptionally a new notion and direction: "Oceanic periglacial" (Matishov, 1982). Generalizing papers by G.G. Matishov have been issued to physiography, geomorphology, morpho-structures, and morpho-tectonics of glacial shelves of the Norwegian-Greenland Sea and the Barents Sea (Matishov, 1977, 1980, 1984).

In 1979 based on data obtained onboard RV "Academician Kurchatov", paleomagnetic analyses were carried out the results of which gave first doubts concerning the Late Pleistocene age of the ancient clays (Blazhchikhin et al., 1979). In 1978, the monograph by V.D. Dibner "Morphostructure of the Barents Sea shelf" was published. V.D. Dibner paid special attention to the origin of the ancient clays considering them as a direct proof of continental glaciations during the Pleistocene. As a matter of fact, questions on the Quaternary glaciations became the subject of sharp discussions during the following years. Two extreme hypotheses divided the Quaternary scientists into "glaciologists" and "marinists":

The American scientists G. Denton and T. Hughes can be considered as extreme "glaciologists" (Denton and Hughes, 1981). These scientists based on their own experience of investigations in Antarctica, assumed a large ancient Panarctic glaciation, embracing the whole basin of the Arctic Ocean and the adjacent continental areas. The supporter of the pan-glacialism ideas of Denton and Hughes in Russia was I.G. Grosswald (Grosswald, 1983). Extreme "marinists" were those who deny the existence of extended Arctic ice sheets, suggesting that the majority of Quaternary sediments are marine and glacial-marine sediments. Among the "marinists" working on the Quaternary geology of the Barents Sea region, the most important ones were O.V. Suzdalsky, V.Ya. Slobodin, I.D. Ganilov, R.B. Krapivner and I.I. Gritsenko. Other scientists represented an intermediate position. They identified both glacial and marine deposits in the Quaternary sedimentary sequences and suggested that local centers of glaciation existed in Scandinavia, Novaya Zemlya etc. during several Pleistocene glacial periods, which disappeared during the interglacials in between (Velichko, 1973, 1979; Matishov, 1976, 1982).

The second half of the 70s became the object of oil-gas exploration in the Barents Sea shelf area. First only one organisation of the Ministry of Geology (MAGE) carried out eploration, then organizations belonging to other ministries (Scientific Production Association "Arcticmorneftegazrazvedka") joined. The detailed knowledge of the Quaternary marine geology became necessary for the construction of basements of drilling platforms, pipelines at the seafloor, and other engineering constructions. Since the beginning of the 80s, due to the efforts of engineers and geologists, serious and substantial new data on the stratigraphically older deposits of the Barents Sea region have been obtained from investigations of drill holes.

Since 1980, a regular geological survey of the shelf began to be carried out by MAGE specialists, first on the Kola shelf, then this survey was extended towards the southern and eastern Barents Sea. As bottom sampling was accompanied by complex geophysical investigations, a large number of maps of different content was also compiled, e.g., the main geological map of Quaternary deposits on the scale 1:1000000.

In the 80s MMBI received the new research vessels "Dalnie Zelentsy" and "Pomor" and increased activities on the sampling of bottom sediments and the level of their processing under the leadership of G.G. Matishov and G.A. Tarasov. Macro- and micro-faunistical approaches began to be widely used. V.V. Alekseev and E.K. Zamilatskaya investigated malako-fauna; I.A. Pogodina and S.A. Korsun studied foraminifera, L.V. Rasumovsky diatoms, and A. Yu. Sharapova pollen and spores. In addition, specialists from the Geological Institute Kola Scientific Center (Apatity), the Geological Institute RAS (Moscow), the Moscow State University (Moscow), and the Rostov-on-Don State University participated in these expeditions. The cooperation between these institutions carrying out fundamental investigations, influenced positively the processing and generalizing of the data. Thus, works of Murmansk geologists headed by Yu.A. Lavrushin established a detailed lithogenetical typification of bottom sediments. Generally, three main groups (glacial, glacial-marine, and ice-marine) were distinguished, subdivided in further different sediment types and sub-types. In particular in the glacial-marine group two types are genetically different. The first one is connected with melting of the moraine substance from the foot of the glacial cover (sub-aquatic ablation moraine), the second one is related to glacial-turbidite deposits formed by muddy flows at the seafloor with subsequent gradational sedimentation. Thus, the purely glacial origin of the "ancient clays" was subjected to doubts.

During the 80s, hundreds of drillings were carried out in the Barents and Kara seas by the State Enterprise AMIGE using the drilling vessels "Bavinit" and "Kimberlit", and continuous sections of Quaternary deposits were recovered. New data on thicknesses, composition, and age of these deposits were obtained. Seismo-stratigraphical approaches were used as the basis of stratigraphical sectioning of the sedimentary sequences (Gritsenko, 1986; Krapivner et al., 1988; Gritsenko and Krapivner, 1989). Sedimentological-seismostratigraphical complexes were connected with five regional cycles corresponding in age to the Late Miocene-Middle Pliocene, Middle Pliocene-Late Pliocene, Early Pleistocene-Late Pleistocene, Late Pleistocene, and Late Pleistocene-Holocene.

At the beginning of the 90s, marine expeditions directed previously more in the western Barents Sea and in the North Atlntic, were conducted in the north and in the east. A geological survey was carried out in the Kara and Laptev seas. At MMBI where bottom sediments were traditionally investigated for the purpose to solve problems of the reconstruction of the western Arctic glacial shelves during the last 20000 years BP, quite simultaneously investigations of bottom sediments from a geoecological point of view (levels, distribution, and dispersial of heavy metals and radionuclides) started (Matishov et al., 1992, 1993, 1994, 1995).

The interest to the Arctic seas increases more and more recently. New perspectives for the next ten years are constructed. The Decree of the Kola Scientific Center of the Russian Academy of Sciences decided in 1995 to establish the Center of Marine Geology of the Arctic in Murmansk to investigate fundamental questions of marine geology and paleoceanology. G.G. Matishov and F.P. Mitrofanov are the initiators of establishing this center.

For further information about the history of Russian geological investigations in the Barents - Kara seas see Kulikov et al. (this vol.) and Stein (this vol.).

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The Modern System

THE COMPOSITION OF AEROSOLS IN THE MARINE BOUNDARY LAYER OVER THE ST. ANNA TROUGH AND THE BARENTS SEA

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Introduction

In August-October 1994 19 atmospheric aerosol samples were collected by the mesh technique in the marine boundary layer over the St. Anna Trough and the Barents Sea during the 9th cruise of the RV *Professor Logachev*, and 10 aerosol samples were taken simultaneously by filtration of air through AFA-HA filters. The electron microscope studies have shown that the large (>1 μm) non-salt particles mainly consist of mineral grains and organic matter (plant fibres, pollens, and diatoms). The most abundant minerals in the crystalline phase are quartz (in average 31 %), illite (average 29 %), and the sum of chlorite and kaolinite (average 28 %). In general, our data do not indicate a considerable anthropogenic aerosol pollution above the St. Anna Trough and the Barents Sea in August-October 1994. Enrichment of aerosols by many chemical elements has mainly been caused by natural processes.

Aerosols in the Arctic are of importance for atmospheric chemistry and climate (Rahn, 1981; Lannefors et al., 1983; Barrie, 1986, 1996; Barrie and Barrie, 1990; Pacyna, 1991; Leck et al., 1996; Maenhaut et al., 1996). There is much evidence that atmospheric inputs contribute significantly to the chemical budget of marine areas (Duce et al., 1991; Lisitzin, 1996). Up to now, aerosols of the Russian sector of the Arctic were studied only to a small extent. Measurements of the elemental composition of Arctic aerosols were carried out on Wrangel Island, the Severnaya Zemlya Archipelago, in the Lena River delta, and on the Franz-Jozef-Land Archipelago (Rovinsky et al., 1995; Vinogradova and Polissar, 1995; Kuusk et al., 1996; Vinogradova, 1996). We began aerosol research in the marine boundary layer over the seas of the Russian Arctic in 1991; first results have been published elsewhere (Shevchenko et al., 1995, 1997 a, b; Smirnov et al., 1996; Ivanov et al., 1997; Serova and Gorbunova, 1997). In this paper we present and discuss new data on the elemental composition of the St. Anna Trough and the Barents Sea aerosols.

Material and Methods

During the 9th cruise of the RV *Professor Logachev* in August-October 1994 19 samples of atmospheric aerosols were collected by nylon meshes, and 10 samples were taken nearly simultaneously by filtration of air through AFA-HA filters in marine boundary layer over the St. Anna Trough and the Barents Sea (Tables 1 and 2; Fig.1). In order to collect the aerosols, 10 nylon meshes (1 m^2 each; pore 0.8 µm) were raised on the mast above the bow of the ship. After 5 - 48 hours the meshes were fetched down, and we removed the particles by washing the meshes in bi-distilled water. Then the water with the particles was passed through Nuclepore filters (0.45 µm), and the filters were dried at 40-45 °C. With this method, salt particles were removed, whereas non-salt particles larger than 1 µm were precipitated on the filters. This sampling method is described in more detail elsewhere (Chester and Johnson,1971; Aston et al., 1973). By the second sampling method, 65 - 525 m^3 of air was pumped through AFA-HA filters. To exclude contamination from the ship, sampling was interrupted when the relative wind direction was not opposite to the ship movement. No samples were collected during rain and snow falls. Sampling periods, co-ordinates of the start and end of sampling, as well as wind speed and direction are given in Tables 1 and 2.

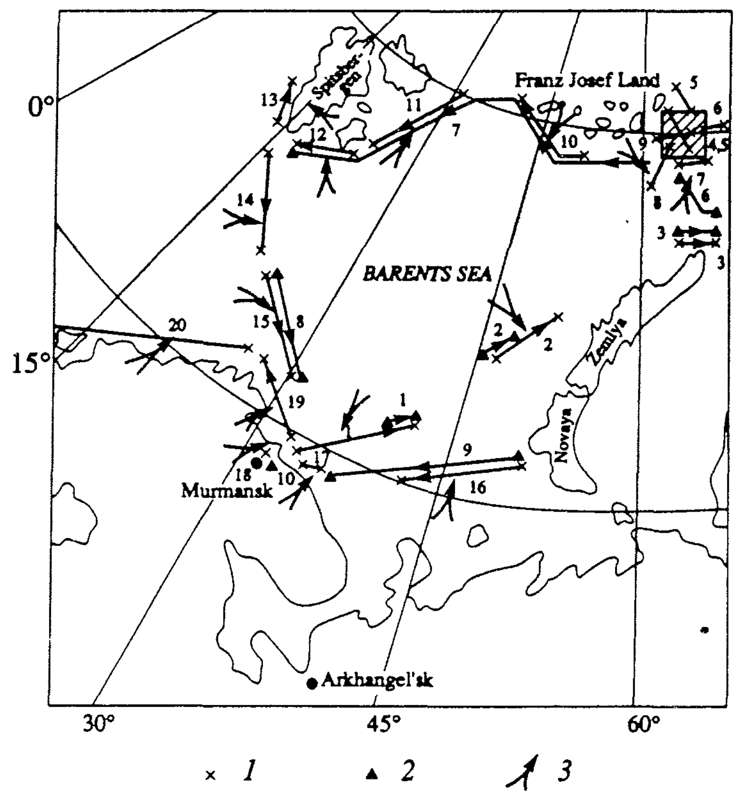

Fig. 1: Scheme of aerosol sampling during the 9th cruise of the *RV Professor Logachev* (August-October 1994): 1 - mesh samples, 2 - filtration samples; 3 - wind direction during sampling.

Table 1: Mesh method sampling periods, coordinates and atmospheric concentrations of insoluble aerosol particles larger than 1 mm in the marine boundary layer over the St. Anna Trough and the Barent Sea in August-October 1994

Sample	Date, time UTC	Co-ordinates start/end		Wind (average)		Conc. (mg/m^3)
	start/end	Latitude (N)	Longitude (E)	Speed (m/s)	Direction (°)	
1	05.08-19.10	69°35.0'	34°18.7'	5.6	25	0.16
	06.08-18.20	72°06.5'	42°11.9'			
2	07.08-13.55	73°48.4'	46°10.7'	7.7	305	0.29
	08.08-09.50	75°36.8'	53°11.5'			
3	09.08-10.50	77°03.7'	66°47.2'	3.7	185	0.57
	09.08-17.20	77°00.0'	70°00.2'			
4	10.08-16.45	79°25.2'	69°59.7'	9.5	245	0.30
	11.08-08.25	80°54.5'	68°00.2'			
5	13.08-01.00	80°39.8'	69°59.9'	3.2	255	0.31
	13.08-14.45	81°58.2'	67°30.2'			
6	18.08-11.10	80°00.0'	77°36.5'	3.6	240	0.21
	18.08-20.00	79°59.8'	71°29.7'			
7	21.08-08.30	79°15.0'	71°40.0'	3.2	205	0.49
	21.08-14.35	79°19.8'	67°21.3'			
8	02.09-03.30	78°17.4'	63°59.2'	7.5	300	0.51
	02.09-21.00	79°35.7'	67°18.2'			
9	03.09-12.25	80°00.0'	70°31.0'	4.8	330	0.27
	04.09-11.10	79°59.9'	64°55.1'			
10	06.09-09.25	78°51.6'	52°35.8'	2.4	5	0.16
	07.09-06.00	80°35.5'	42°25.6'			
11	08.09-12.15	79°59.1'	36°46.8'	0.5	230	0.14
	09.09-10.50	77°35.4'	25°31.6'			
12	09.09-12.00	77°26.8'	24°58.2'	3.3	170	0.27
	10.09-00.45	76°29.2'	18°41.2'			
13	10.09-08.00	76°38.8'	15°20.0'	5.0	100	0.39
	10.09-24.00	78°00.8'	13°03.7'			
14	13.09-17.25	75°50.0'	17°32.4'	8.0	240	0.13
	14.09-16.50	73°16.1'	25°02.8'			
15	14.09-17.45	73°09.8'	25°19.6'	7.5	250	0.18
	15.09-20.00	70°59.5'	32°07.2'			
16	02.10-09.20	71°22.1'	51°52.7'	11.0	185	0.55
	03.10-16.00	70°12.1'	42°05.7'			
17	04.10-09.30	69°26.8'	36°08.7'	9.0	190	0.97
	04.10-14.10	69°18.4'	34°23.7'			
18	06.10-10.30	69°01.0'	33°02.5'	5.5	230	0.14
	08.10-11.00	69°01.0'	33°02.5'			
19	08.10-20.00	69°40.2'	33°28.5'	9.5'	220	0.40
	09.10-15.15	71°20.0'	27°59.4'			

Table 2: Filtration method sampling periods, coordinates and volume of pumped air in the marine boundary layer over the St. Anna Trough and the Barents Sea in August-October 1994.

Sample NN	Date, time UTC	Co-ordinates start/end		Wind (average)		Pumped air (m^3)
	start/end	Latitude (N)	Longitude (E)	Speed (m/s)	Direction (°)	
1	06.08-16.00	71°54.0'	41°18.8'	5.5	20	64.6
	06.08-21.25	72°24.1'	43°22.8'			
2	07.08-12.55	73°42.3'	45°45.3'	8.1	350	104.6
	08.08-01.25	74°48.9'	49°51.1'			
3	09.08-10.50	77°03.7'	66°47.2'	4.0	180	77.3
	09.08-16.00	77°04.1'	69°14.3'			
4	10.08-10.20	79°10.7'	70°00.0'	4.6	240	150.5
	13.08-14.30	81°56.7'	67°30.1'			
5	16.08-13.15	80°42.9'	71°28.9'	3.1	210	524.0
	23.08-16.00	80°00.0'	65°43.0'			
6	29.08-08.00	77°26.3'	72°00.3'	6.0	320	458.9
	04.09-11.10	79°59.9'	64°55.1'			
7	05.09-08.20	79°35.0'	64°26.8'	2.1	170	496.5
	09.09-24.00	76°25.5'	19°04.5'			
8	14.09-08.00	74°14.1'	22°22.3'	7.5	250	462.7
	15.09-20.15	70°58.3'	32°11.8'			
9	02.10-09.35	71°21.5'	51°46.6'	10.0	185	151.7
	04.10-14.10	69°18.4'	34°23.7'			
10	06.10-10.45	69°01.0'	33°02.5'	5.5	230	110.4
	08.10-14.00	69°01.0'	33°02.5'			

Morphology of the particles collected by mesh method was studied by scanning electron microscope JSM-U3 of Jeol (Tokyo, Japan) with maximum magnification of 10000 times. Mineral composition of these samples was studied by X-ray diffractometry with a DRON-2 devise described in more detail by Serova and Gorbunova (1997). The elemental composition of both mesh (non-salt particles larger than 1 μm) and filtration samples (i.e., all particles, including salt particles) was studied by the instrumental neutron activation analysis (INAA). In preparation for the INAA, the samples and standards (KH, ST, SGD, FFA, RUS-1) were irradiated in the heat channel of the nuclear reactor of Moscow Institute of Engineering Physics (neutron flux 2.8 x 10^{13} neutrons $cm^{-2}s^{-1}$) for 15-20 h. Their activity was measured three times by germanium detectors with 4096-channel high-resolution pulse analysers (LP-4900, Nokia, Finland and NUC-8192, FMG, Hungary).

Results and Discussion

In August-October 1994 the mass concentration of the coarse fraction of non-soluble aerosols over the St. Anna Trough and the Barents Sea varied from 0.13 to 0.97 mg/m^3 (0.34 mg/m^3 in average) (Table 1). These values are similar to those measured in the North Atlantic (Duce et al., 1991). The highest value of concentration was registered in the mesh sample N 17 near the Kola Peninsula during strong wind blowing from the land.

The scanning electron microscopy has shown that the large (> 1 µm) non-salt particles mainly consist of mineral grains 1-10 µm in size (some of them up to 20 µm) and organic material (plant fibres, pollens, and diatoms). The main sources of these particles are soils and plants from the surrounding land and islands. In the crystalline phase the most abundant minerals are quartz (its content ranges from 16 to 66 %, average 31 %), illite (8-46 %, average 29 %), and the sum of chlorite and kaolinite (16-41 %, average 28 %); feldspars and montmorillonite appear as secondary minerals (Table 3; Fig.2). Data of aerosol studies in southern Barents and Kara seas carried out in August-October 1993 during 49th cruise of RV *Dmitry Mendeleev* show that the content of quartz ranges from 15 to 56 % (33 % in average), feldspars - from 4 to 20 % (12 % in average), illite - from 12 to 38 % (23 % in average), chlorite plus kaolinite - from 12 to 48 % (31 % in average) (Shevchenko et al., 1998). The high variability of mineral composition can probably be explained by the different origin of the air masses.

Table 3. Mineral composition of insoluble aerosol particles collected by the mesh method in the marine boundary layer over the St. Anna Trough and the Barents Sea in August-October 1994

Sample	Quartz	Feldsp.	Illite	Chlorite+ kaolinite	Montmoril	Quartz/ feldsp. ratio
1	66	7	8	16	3	9.4
2	46		22	22	10	
3	38	13	29	20		2.9
4	35	10	28	18	9	3.5
6	24	5	36	35		4.8
7	47	7	12	25	9	6.7
8	42	4	19	30	5	10.5
9	27	2	28	41	2	13.5
10	42	6	22	22	8	7
11	27	5	35	27	6	5.4
12	17	3	36	37	7	5.7
13	30	3	28	33	6	10
14	30	4	33	30	3	7.5
15	21	5	37	37		4.2
16	17	20	27	36		0.9
17	23	3	43	31		7.7
18	22	11	46	21		2
19	16	5	41	35	3	3.2
average	31	6	29	28	6	5.2
st. dev.	13	4	10	7	3	
S. Barents and S. Kara seas, Aug.-Oct. 1993*	33	12	23	31		2.8

*Shevchenko et al., 1998.

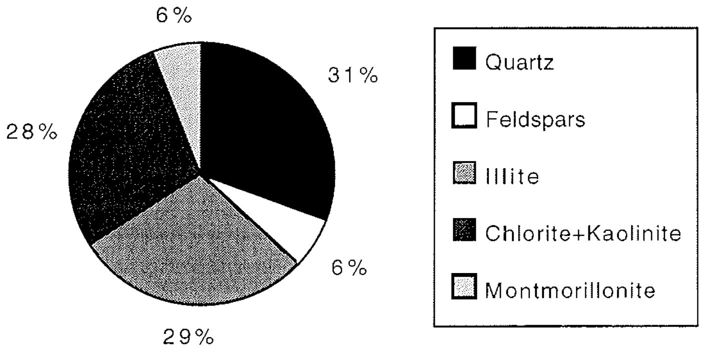

Fig. 2: Average mineral composition of aerosol samples collected by mesh method over the St. Anna Trough and the Barents Sea in August-October 1994.

High content of organic material was not typical for samples collected during the RV *Professor Logachev* expedition in August-October 1994, but in some other expeditions in the Arctic (Shevchenko et al., 1995, 1997 a, b). In the Arctic plant fibres and pollens of land plants are transported for hundreds of kilometres. Diatoms 5-50 μm in size are also common in aerosols of the marine boundary layer; they are carried away by wind from the sea-water surface microlayer. A number of investigations carried out during the recent years confirm that organic matter is one of the main components of the atmospheric aerosols (Isidorov, 1990; Matthias-Maser and Jaenicke, 1995).

In most mesh samples fly ash particles both porous of 5-50 μm in size and smooth spheres of 1-10 μm in diameter have been detected. The main part of porous particles comes from industrial blow-outs and, to a lesser degree, from forest fires. The spherical fly ash particles are called "combustion spheres ". Their main sources are high-temperature processes in smelters (Van Malderen et al., 1996). The amount of these typically anthropogenic particles increased in the direction of industrial regions (towards Murmansk) and with the air mass drift from the Kola Peninsula side.

Table 4 presents data on atmospheric concentrations of chemical elements in marine boundary layer over the St. Anna Trough and the Barents Sea in August-October 1994; average concentrations are compared with the literature data of long-term observations in Spitsbergen and Severnaya Zemlya (Maenhaut et al., 1989; Vinogradova and Polissar, 1995) in Table 5.

Table 4. Atmospheric concentrations of chemical elements, average (avg), standard deviatio (std) and geometric mean (g.m.) over the St. Anna Trough in August-October 1994 (Filtration method, ng/m^3)

NN	Na	Ca	Sc	Cr	Fe	Co	Ni	Cu
1	6600	620	0.0015	7.74	93		35.6	0.33
2	3600	220	0.0038	7.65	86	0.34	0.1	0.01
3	560	375	0.0026	7.77	194	1.11	0.1	0.13
4	280	53	0.002	3.65	47	0.31	0.1	0.05
5	490	100	0.0038	2.1	36	0.01	0.2	0.09
6	1650	100	0.0026	3.27	83		2.8	0.02
7	490	200	0.0012	4.43	32	0.09	0.4	0.03
8	3080	230	0.0019	3.24	106	0.32	38.7	0.47
9	760	530	0.0066	8.57	363		1.3	0.01
10	135	400	0.0072	8.15	308	0.78	2.7	0.24
avg	1760	283	0.0033	5.66	135	0.42	8.2	0.14
std	2080	192	0.0021	2.52	116	0.39	15.3	0.16
g. m.	930	220	0.0028	5.09	98	0.22	1.0	0.06

NN	Zn	As	Br	Sb	Cs	La	Ce	Nd
1	53	0.01	0.39	0.003	0.011	0.005	0.005	
2	33	0.03	0.164	0.062	0.073	0.016	0.046	0.023
3	101	0.01	0.021	0.047	0.009	0.048	0.129	0.084
4	43	0.43	0.029	0.11	0.014	0.129	0.193	0.044
5	22	0.01	0.016	0.114		0.038	0.071	0.026
6	36	0.28	0.068	0.065		0.029	0.058	0.019
7	11	0.28	0.02	0.006	0.001	0.005	0.005	0.003
8	27	0.01	0.191	0.116	0.004	0.114	0.149	0.025
9	59	0.04	0.087	0.003	0.009	0.12	0.191	0.05
10	45	0.44	0.026	0.113	0.01	0.145	0.249	0.072
avg	43	0.15	0.101	0.064	0.016	0.065	0.110	0.038
std	25	0.18	0.119	0.048	0.023	0.056	0.085	0.026
g. m.	37	0.053	0.057	0.033	0.0088	0.037	0.062	0.028

NN	Sm	Eu	Tb	Yb	Lu	Ta	Au	U
1	0.0011	0.0003	0.0002	0.0005	0.00011	0.0031	0.0019	0.076
2	0.0068	0.0021	0.0011	0.0018	0.00029	0.0143	0.0016	0.001
3	0.0269	0.0082	0.0045	0.0101	0.00155		0.0093	0.239
4	0.0112	0.0033	0.002	0.0047	0.0008	0.0385	0.0041	0.03
5	0.0063	0.002	0.001	0.0019	0.00029		0.0003	0.002
6	0.0054	0.0004	0.0002	0.0008	0.00013	0.0092	0.0001	0.002
7	0.001	0.0003	0.0002	0.0003	0.00004		0.0005	0.002
8	0.0043	0.0006	0.0003	0.0006	0.00009		0.0005	0.001
9	0.0111	0.0019	0.0009	0.002	0.00033	0.0343	0.0018	0.046
10	0.017	0.0024	0.0013	0.0029	0.00045	0.0299	0.0063	0.007
avg	0.0091	0.0022	0.0012	0.0026	0.00041	0.0216	0.0026	0.041
std	0.0079	0.0024	0.0013	0.0030	0.00046	0.0146	0.0030	0.074
g. m.	0.006	0.0013	0.0007	0.0015	0.00025	0.0159	0.0013	0.0082

Table 5. The average composition of atmospheric aerosol in the St. Anna Trough and the Barents Sea (this paper) in comparison with other Arctic areas (ng/m^3)

Element	St. Anna Trough and Barents Sea; summer-autumn 1994, n=10 samples*	Spitsbergen, summer 1984, n=46 samples**	Severnaya Zemlya, spring 1985, 1986, 1988; sea is covered with ice; n=22 samples***
Na	1760	66	90
Ca	283	7.3	180
Sc	0.0033	0.0012	0.014
Cr	5.66	0.56	1.6
Fe	135	5.6	30
Co	0.42	<0.004	0.075
Ni	8.2	<0.2	6.2
Cu	0.14	<0.3	3.8
Zn	43	<0.15	5.6
As	0.15	0.01	1.8
Br	0.10	0.73	4.1
Sb	0.064	0.0024	0.19
Cs	0.016	0.003	
La	0.065	0.005	
Ce	0.11	<0.02	
Sm	0.0091	0.0007	
Eu	0.0022	<0.001	
Au	0.0026	<0.00015	0.066

In Spitsbergen the sampling was carried down by filtration air through Whatman-41 filters at a 1-km distance from the coast in summer; the samples were analysed by the INAA method (Maenhaut et al., 1989). In Severnaya Zemlya air was filtered through AFA-HA filters and samples were also analysed by INAA method (Vinogradova and Polissar, 1995). The studies in Severnaya Zemlya were carried out in spring, when the Arctic seas were covered with ice and the supply of sea salt was practically excluded. In August and October 1994 the contents of most elements were higher in the St. Anna Trough than in Spitsbergen and Severnaya Zemlya. This may be explained by the substantial contribution of sea salt particles during our sampling; in spring the role of the sea as a source of aerosol particles was minimal in Severnaya Zemlya, as well as at the coastal station in Spitsbergen. In the marine boundary layer sea salt particles comprise about 85 % of the aerosol matter (Savenko, 1994). The higher Br and Cu concentrations in Severnaya Zemlya are probably related to the maximum pollution of the Arctic atmosphere with some elements at the end of winter and the beginning of spring (Sturges and Shaw, 1993; Barrie and Barrie, 1990).

In order to estimate the sources of the elements in filtration samples, enrichment factors (crustal) (EF) were calculated for each element:

$EF=(El./Sc)_{sample}/(El./Sc)_{Earth\ crust}$

where Sc is the concentration of scandium (as terrigenous source indicator) and El. is the concentration of the given element in the sample and in the Earth crust

(Taylor, 1964), respectively. EF are shown at the Figure 3.

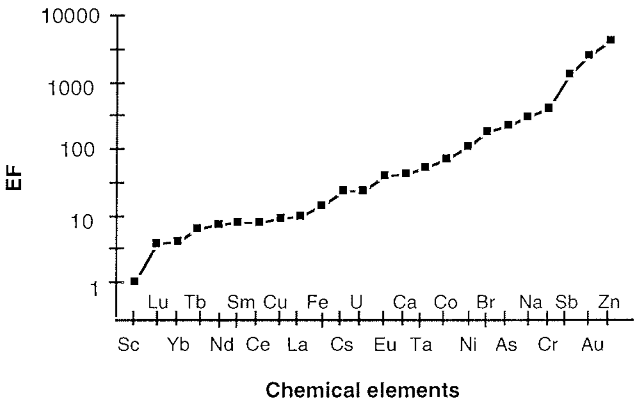

Fig. 3: Enrichment factors (crustal) of filtration samples of aerosols collected over the St. Anna Trough and the Barents Sea in August-October 1994.

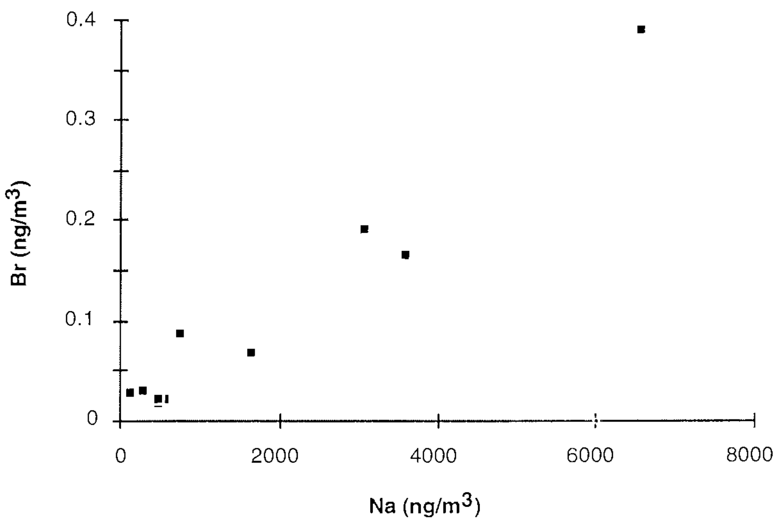

Fig. 4: Relationship between atmospheric concentrations (filtration method) of Br and Na over the St. Anna Trough and the Barents Sea in August-October 1994.

Rare earth elements (REEs) and Cu have relatively low enrichment factors in the filtration samples (Fig. 3). For Lu, Yb, Tb, Nd, Sm, Ce, La, and also for Cu average

EF are <10, and we suggest that they have mainly a terrigenous, crustal origin in our samples. Aerosols are slightly enriched by these elements likely due to fractionation of elements in the marine surface microlayer and generation of sea-salt aerosol particles by bubble bursting in this microlayer (Duce et al., 1991; O'Dowd and Smith, 1993). For Fe, Cs, U, Eu, Ca, Ta, Co, Ni, Br, As Efs grow from 14 to 230 and we suppose an increase of the role of marine source. For Na, as a typical sea salt element, EF is 306. Br has relatively close EF values (178), and a strong correlation between Na and Br exists (Fig.4). The correlation coefficient is equal 0.98 (n=10 samples). This may suggest that the main source of Br is marine.

As it was mentioned above, Ni also comes mainly from marine sources; correlation coefficient between Na and Ni is equal to 0.78 (n=10 samples), but in samples NN 1 and 8 both concentrations (Table 4) and EFs of Ni are very high. Cu having mainly a terrigenous source, also demonstrates very high values both of concentrations and EF in samples NN 1 and 8. Thus, we could assume that filtration samples NN 1 and 8, collected near Kola Peninsula during winds blowing from the land, contained much anthropogenic aerosols. The Kola Peninsula is a region of intense atmospheric pollution by iron, nickel, copper, zinc, lead mostly by Severonikel and Pechenganikel smelters (Vilchek et al., 1996). For Cr, Sb, Au, and Zn Efs are > 390, suggesting a dominantly anthropogenic.

Conclusions

In the marine boundary layer over the St. Anna Trough and the Barents Sea during end of summer and in autumn, large (>1 μm) non-salt particles mainly consist of mineral grains and organic matter (plant fibres, pollens, and diatoms). The most abundant minerals in the crystalline phase are quartz (in average 31 %), illite (average 29 %) and the sum of chlorite and kaolinite (average 28 %). In general, our data do not indicate a considerable anthropogenic aerosol pollution above the St. Anna Trough and the Barents Sea in this time.

Acknowledgements

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OCEANOGRAPHIC INVESTIGATIONS IN THE ST. ANNA TROUGH, KARA SEA

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Abstract

In the course of a joint multidisciplinary Russian-American-Norwegian expedition during August-September 1994 the Association Sevmorgeologia investigated the physical oceanography of the St. Anna Trough. The hydrophysical data allow to characterize the oceanographic field conditions and to determine the character of geostrophic (density) circulation as well as peculiarities of water and heat exchange in the St. Anna Trough and adjacent water bodies. The thermodynamic regime of the region is primarily determined by submeridional transfer of the warm Atlantic-derived water (ADW). The inflow of warm ADW from the north is confined to the bottom layer (about 120 m - bottom). The maximum heat content is observed in the northern part of the study area. The dynamic structure is characterised by two main currents. The first one is connected with the ADW entering from the north and forming the cyclonic circulation with its center above the deep part of the St. Anna Trough. The second one is the Barents Sea branch of the ADW, which enters from the Barents Sea and follows the eastern slope of the canyon as a strong jet to the Arctic Ocean.

Introduction

Since the beginning of oil and gas field development, the Russian Arctic shelf became an important object for national economy. In this context the need of complex geoecological investigations is quite evident.

The new scientific focus recently developed at VNIIOkeangeologia and called "ecogeochemical sedimentology" (Ivanov et al., 1996) considers the geoecology of shelf areas as a science regarding the relationship between technogenesis and sedimentogenesis of the modern stage of the Earth's evolution. The major attention is given to the analysis of supply, migration, transformation and accumulation of pollutants.

On this basis the determination of the spatial variability of the hydrophysical fields and their hydrodynamic, physico-chemical and biogeochemical barriers was the most important component of geoecological studies implemented during 1992-1994.

Data and Research methods

The scientific-industrial Association "Sevmorgeologia" performed a joint Russian - Norwegian - American expedition to conduct a multidisciplinary environmental investigation in the St. Anna Trough area (Fig.1). The investigations included studies of aerosols, sediment fluxes, suspended matter, water column, bottom sediments (Ivanov et al, 1995). The main scientific goals were to study the oceanographic field structures and dynamics and to determine mass and heat exchanges.

Hydrophysical observations were carried out by means of a hydrophysical measuring system ("Neil Brown") consisting of a submergible device CTD/ACM-2 and shipboard MK III. The available hydrophysical system included the standard deep-water CTD with an acoustic counter of currents (ACM-2), and sensors to determine dissolved oxygen and transmission (Table 1).

Table 1: Character of measurenment canels of CTD/ASM-2

Parameter	Unit of measurenment	Range of measurenment	Error (accuracy)	Resoltuion
Pressure	dB	0 - 6500	+/- 6.5	0.1
Temperature	C°	-32 - +32	+/- 0.005	0.0005
Specific electric **conductivity**	mCm/cm	1 - 65	+/- 0.005	0.001
Oxygen				
Current	mA	0 - 2.047	+/- 0.001	0.0005
Temperature	C°		+/- 0.256	0.128
Stream				
Rate	cm/c	-250 - 250	+/- 1.0	0.15
Direction		0 - 360	+/- 2.0	
Light passing	%	0 - 100	+/- 0.5	0.024

Hydrophysical data were recorded on computer hard disks in a real time scale (30 measuring cycles/sec). The secondary processing was made on a personal computer (Pentium-100) by the "Zond" routine (PMGRE). Algorithms of secondary hydrophysical parameters calculation are based on the salinity scale and equation of state of sea water (EC-80) and correspond to the recommendations of UNESCO International Oceanographic Commission (IOC). Processing of the hydrophysical information allowed to obtain the following parameters: depth of CTD (m); water temperature (°C); electric conductivity (mCm/cm), salinity ‰); sound velocity (m/sec); dissolved oxygen saturation (%),dissolved oxygen absolute concentration (ml/l); coefficient of the light attenuation (l/m); potential density (kg/m^3).

Rough estimates of the baroclinic current direction were derived by means of traditional dynamic methods (Fomin, 1964), taking into account the recent results of ADCP measurements in the St. Anna Trough (Schauer et al., 1997) for choosing the appropriate "zero-speed" reference level.

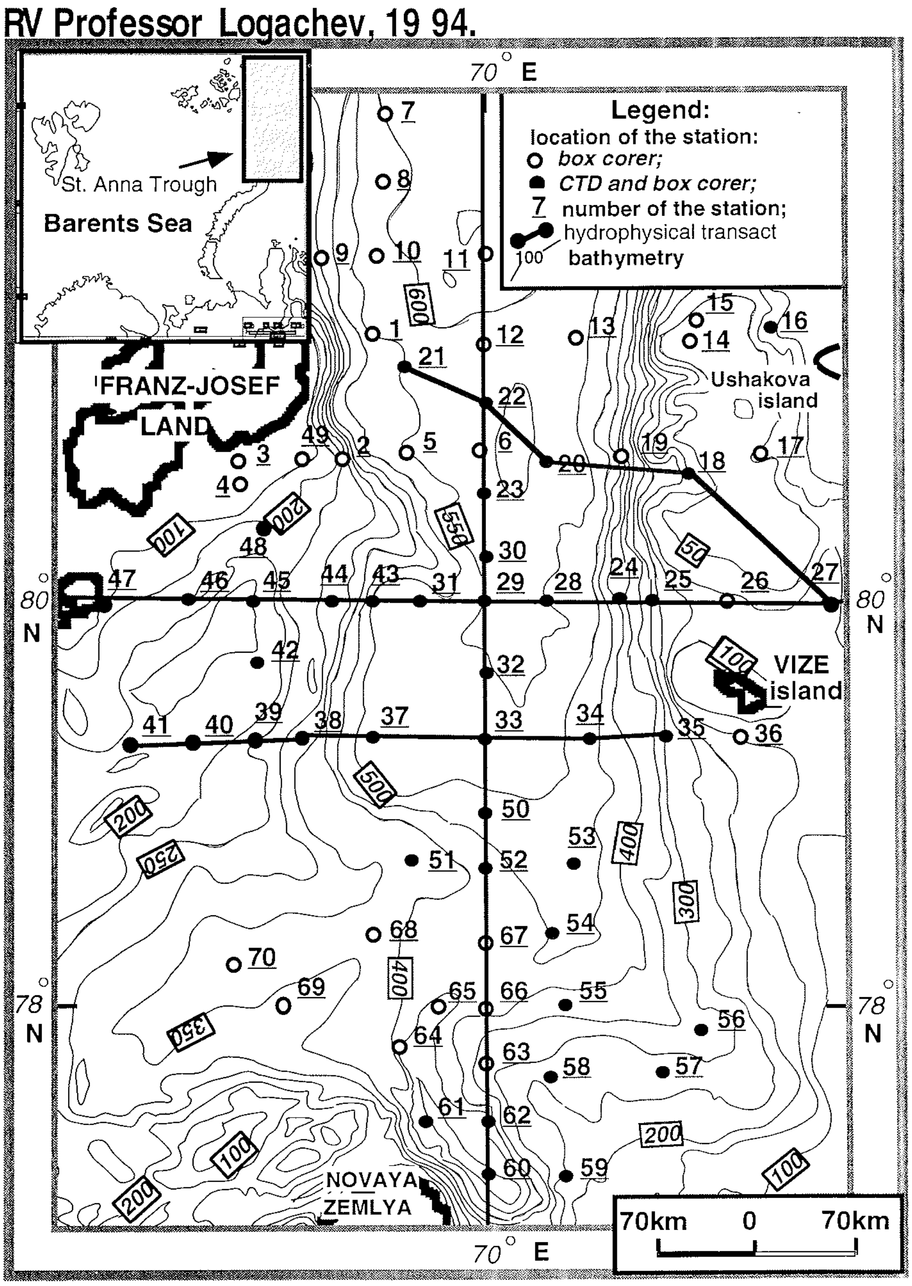

Fig.1: Location of hydrophysical stations and cross-section carried out in St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

Results

The data processing and analysis were performed for several conditional lines stretched in submeridional and sublatitudinal directions and crossing the major morphological features of the trough floor and hydrological boundaries (Fig.1).

The background of hydrophysical field structures in the study area is the interaction between the water masses of different origin (Ivanov and Korablev, 1997; Schauer et al., 1997). However, in different structure zones the signature of specific processes can prevail. Additionally, the summary effect of external exchange of properties between ocean and atmosphere determines the specific features of the upper quasi-homogenous layer. Incoming solar radiation and turbulent heat flux provide the enthalpy increase and quasizonal temperature distribution near the surface. Zonation disappeared at depths of > 30 m where heat advection becomes dominant.

The vertical structure of the temperature field (Figs. 2 to 5) is represented by the following components: upper heated layer, seasonal thermocline, residual cold ("winter") layer, main thermocline, Atlantic-derived water (ADW).

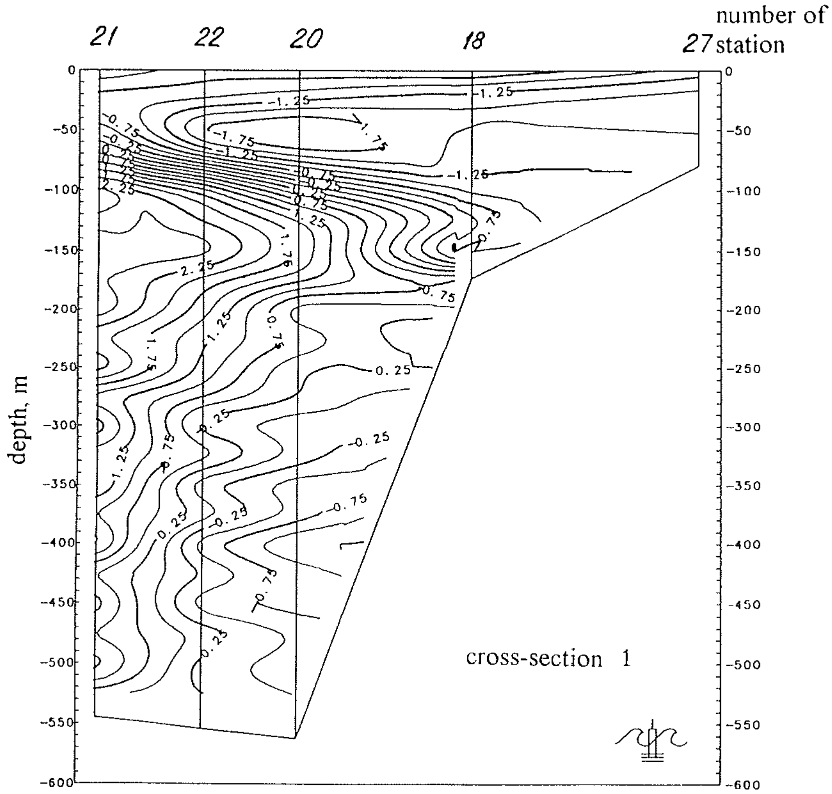

Fig.2: Distribution of temperature (in °C) on the cross-section N 1 in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

The upper heated layer is characterised by positive temperatures in the southern (up to 2.473 °C) and in the central (up to 1.254 - 0.118 °C) parts of the polygon. On the contrary, to the north and north-east the temperature is negative, varying from -0.088 to -1.205 °C (Fig. 6).

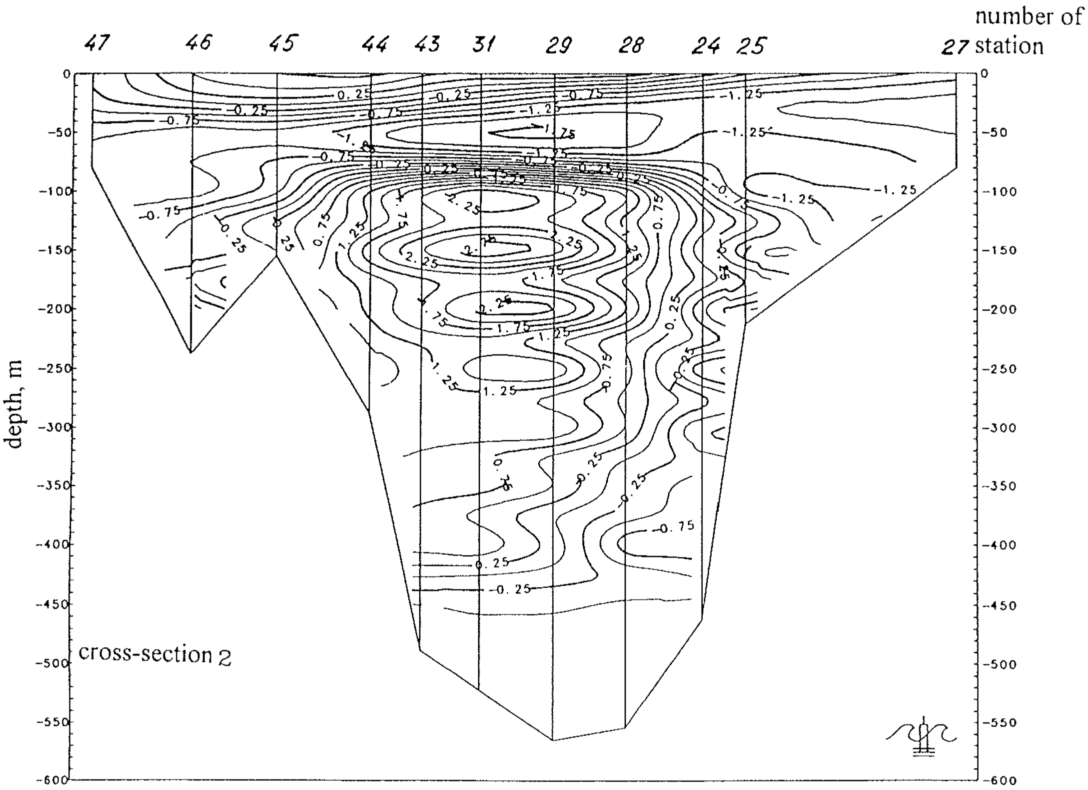

Fig.3: Distribution of temperature (in °C) on the cross-section N 2 in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

In the transition zone between the Barents and Kara seas in the southern part of the polygon (stations 59, 62) the upper heated layer extends down to depths of 80-100 meters (Fig. 5). The observed intermittent structure with temperature variations up to 0.30-0.40 °C is likely caused by intensive mixing at the boundary between water masses with different properties. Besides, in the course of measurements the sea surface cooling started. The latter follows from the temperature increase with depth in the upper 20-meter layer.

The seasonal thermocline is characterised by temperature variations from 0 to -1.251-1.734 °C and a vertical gradient module up to 0.050 to -0.069 °C/m

(Fig. 3). For the most part of the study area the seasonal variability is expresses in the existence of a residual cold ("winter") layer at the depths 25-100 m just below the upper heated layer. The temperature in the cold layer decreases to -1.405 to -1.830 °C. Maximum temperature decrease is observed to the north and to the north-east of the polygon where warm ADW is absent (Fig. 2). The thickness of this layer gradually increases eastward where the lower boundary of cold water reaches the depth of 120-130 m (Fig. 4).

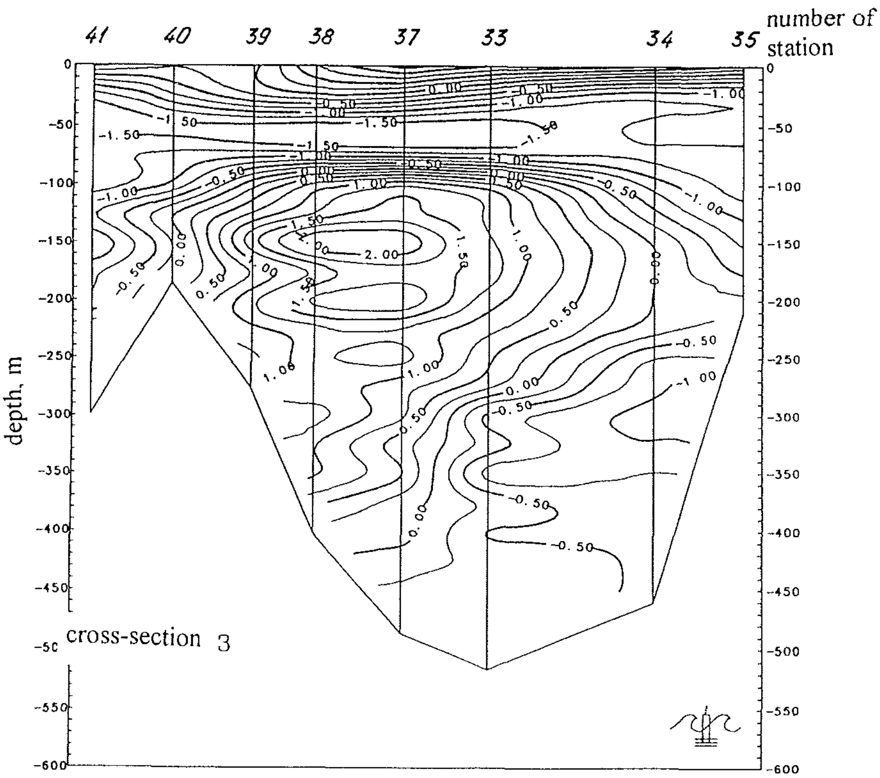

Fig.4: Distribution of temperature (in °C) on the cross-section N 3 in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

The main thermocline is the transition zone between the cold intermediate layer and the warm ADW entering from the north. The temperature increase in the thermocline reaches 3.5-4.0 °C with a vertical gradient module as high as 0.070-0.084 °C/m (Figs. 3 and 4). The layer is characterised by a fine structure, comprising a combination of micro-discontinuities and quasi-homogeneous intermediate layers (Figs. 7 and 8). The origin of such pattern is presumably connected to flow instabilities, leading to inversions which induce double-diffusive convection (Rudels et al., 1994, 1996).

The ADW layer with positive temperature is observed at the depths from 100-125 m to 200-450 m. This water forms a "mushroom-shaped" cloud on the western side of the trough (Figs. 2 to 5). Thus, in the layer 125-200 m ADW (conventional boundary goes along the isotherm 0 °C) penetrates along the latitude 80° N to the east up to 73° 30´ E, in the layer 250-300 m to 72°30´ E, nad in the layer 400 m to 70°30´ E (Fig. 2). At the level of maximum extension (layer 130 m) the ADW can be traced at the latitude 77°30´ N. At the 200 m depth level the boundary is located near 78°10´ N, at the 300 m depth level near 78°30´ N, and at the 400 m depth level near 79°20´ N (Fig.5).

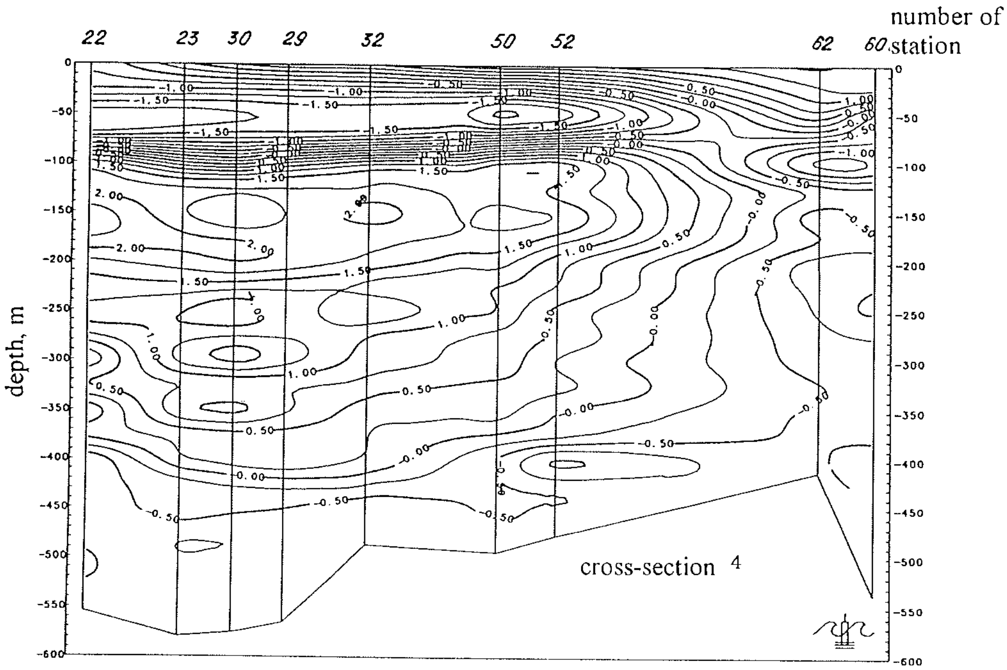

Fig.5: Distribution of temperature (in °C) on the cross-section N 4 in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

The warm water is characterised by a pronounced fine structure. It is expressed in alternation of high-gradient intermediate layers, homogenous layers and inversions of different scales (Figs. 6 and 7). Fine-structure genesis in the ADW is typical for frontal interfaces with enhanced processes of vertical and horizontal mass and momentum exchange. The maximum inversion frequency and relative temperature variations corresponds to zones with extreme velocity gradients and hence, developed shear turbulence.

At the upper halocline boundary (approximately 25 m depth) the highest salinity values are detected in the eastern part of the polygon (34.40 - 34.58 ‰). The increased salinity values are also observed in the western part of the polygon (34.01 - 34.13 ‰). In the centre of the polygon the salinity decreases down to 33.08 - 33.33 ‰, and in the southern part to 33.85 - 33.62 ‰. A similar salinity field structure is revealed at 50, 75 and 100 m depths, taking into account the salinity increase with depth.

From the horizon of 125 m (i.e. the level of warm layer upper boundary) the salinity field structure is reversed: minimum salinity corresponds to shallow waters at the trough sides, while its maximum corresponds to the deep part. Below the horizon of 125 m the salinity increases. At the 175 m depth level (Fig. 8) near the trough axes, salinity reaches 34.93 - 34.88 ‰, manifesting the vicinity of the ADW core. To the east it decreases to 34.74 - 34.77 ‰, and to the west to 34.78 - 34.80 ‰. In the southern part of the polygon the salinity is 34.75-34.81 ‰.

At 350 m depth the warm water in the north part of the polygon is characterised by maximum salinity values, about 34.93 ‰, typical for the ADW core (Ivanov and Korablev, 1997). To the south salinity reduction, due to mixing of ADW with freshened water, is observed. The general features of the salinity field remain constant from the 350 m depth to the sea floor (Figs. 9 and 10).

Water density in the upper quasi-homogeneous layer has non-zonal distribution with minimum values in the eastern part and maximum values in the western part of the polygon. Interstructural heterogeneities, caused by non-stationary energy exchange across the ocean-air interface are universally present. Their dimensions correspond to mesoscale variability (Fig. 6-7, 9-10). The absolute density minimum is noted in the south of the polygon, in the zone of Kara Sea water carrying freshwater of river origin (Ob) to the north.

Freshening and heat influx reduce the density of surface waters to 1022.83 kg/m3 whereas at the 50 m horizon it increases to 1027.10-1027.85 kg/m3. Such strong stratification totally excludes the possibility of convective mixing and essentially complicates the exchange of properties by the wave turbulence.

The specific features revealed in the distribution of the dissolved oxygen (Figs. 6, 7, 9 and 10) are as follows. Absolute maximum of the dissolved oxygen concentration (7.83 - 8.54 ml/l) is observed in the layer 10-40 m. Obviously, it is correlated with cold "winter" interlayer. At the surface values of dissolved oxygen concentration vary from 3.10 ml/l (near Franz Josef Land) to 3.62-3.74 ml/l (over the eastern side of the trough) and 8.13-8.34 ml/l (over the shallow waters of the Central Kara uplift).

Below the 50 m depth the concentration of dissolved oxygen decreases, and horizontal heterogeneity of the field declines. Thus, at the 50 m horizon the content of dissolved oxygen varies in the range of 5.94 to 7.12 ml/l, at the 100 m horizon in the range of 5.06 to 6.39 ml/l, at the 150 m horizon in the range of 4.87 to 5.84 ml/l, at the 200 m horizon in the range of 4.80 to 5.70 ml/l, at the 300 m horizon in the range of 4.85 to 5.56 ml/l, and at the 450 m horizon in the range of 4.92 to 5.62 ml/l. Concentration of dissolved oxygen increases eastward, in the area of the colder waters.

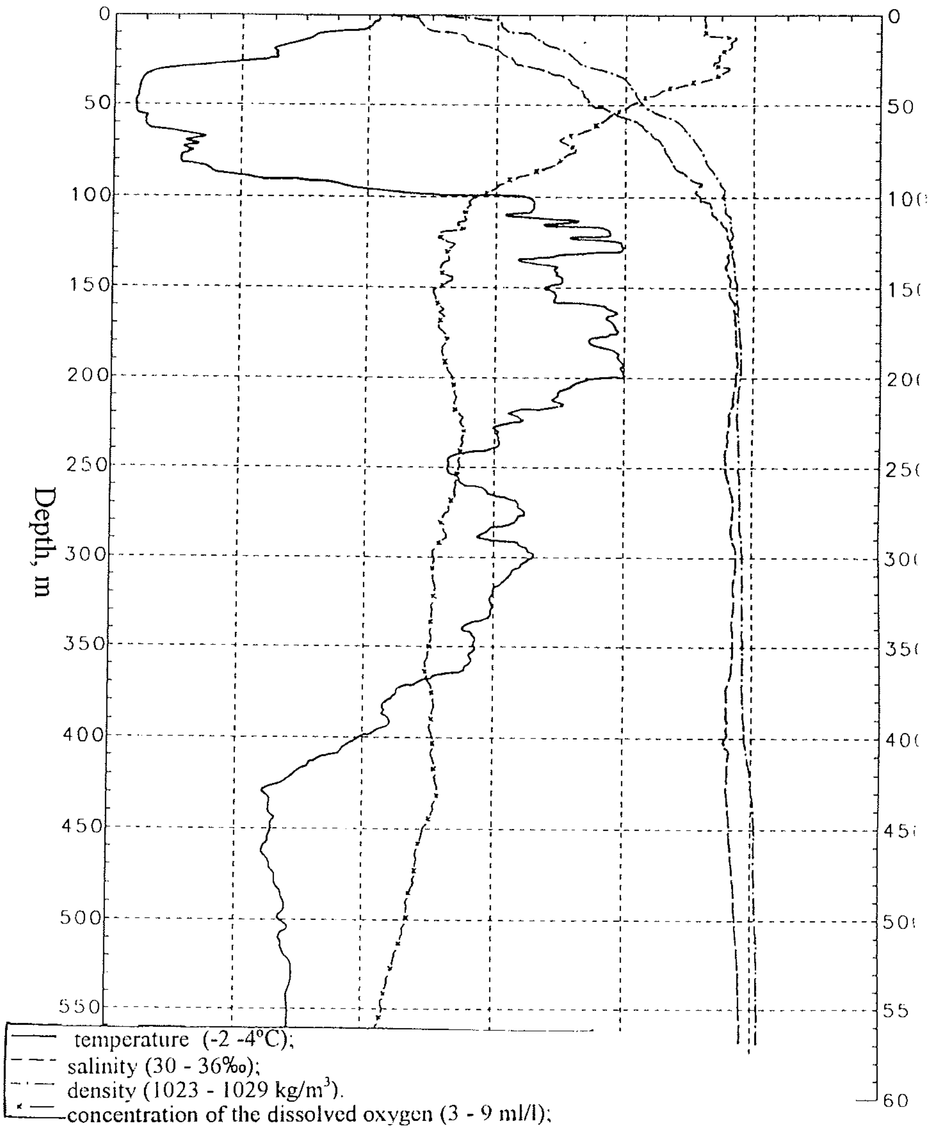

Fig.6: Vertical distribution of temperature (in °C) on the station N 30 in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

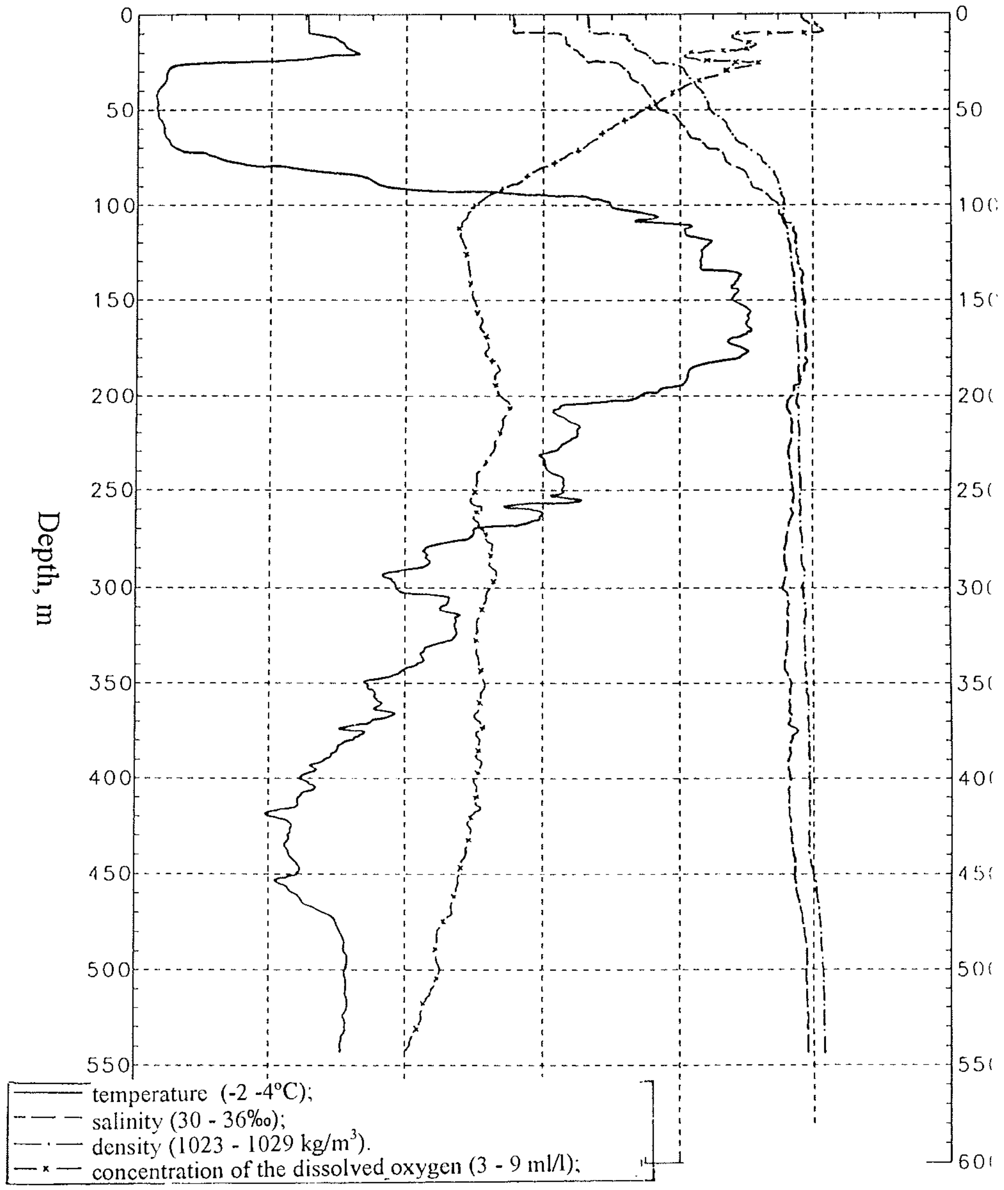

Fig.7: Vertical distribution of temperature (in °C) on the station N 22 in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

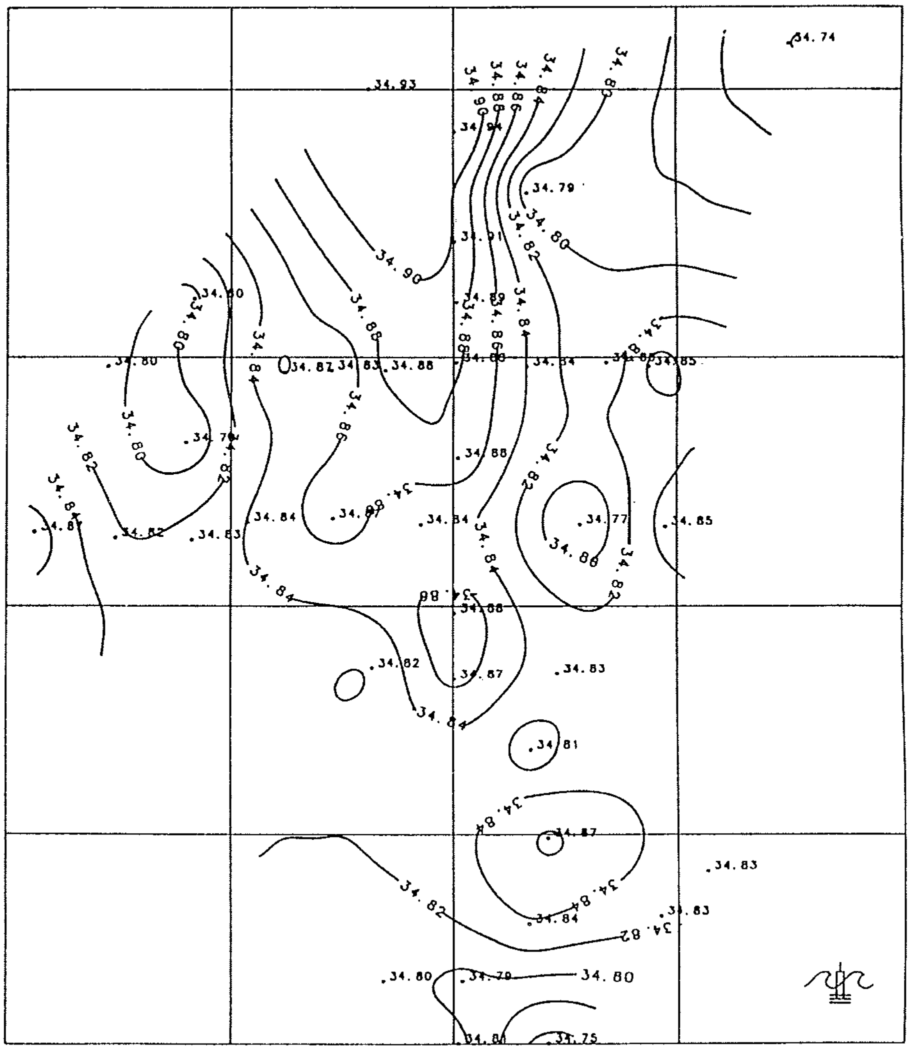

Fig.8: Distribution of salinity (in (‰) of waters at the horizon 175 m in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

The dynamic structure in the St. Anna Ttrough area is characterized by two main opposing flows, both bringing Atlantic-derived water (Schauer et al., 1997). The first flow enters the Kara sea from the north at the intermediate depth (150-450 m) coming from the Fram Strait along the Eurasian continental slope. This water is the main heat source of the Arctic Ocean and Siberian seas. The other one enters the Kara Sea from the west (Loeng et al.,1993). It comprises the water of the North Cape Current, modified while in the Barents Sea due to strong atmospheric cooling and freshening when mixing with the shelf origin water and the water of the Norwegian Coastal Current (Rudels et al., 1994). Within the St. Anna Trough these branches meet and interact with each other as well as with the water masses of local origin, forming a rather complicated dynamical structure.

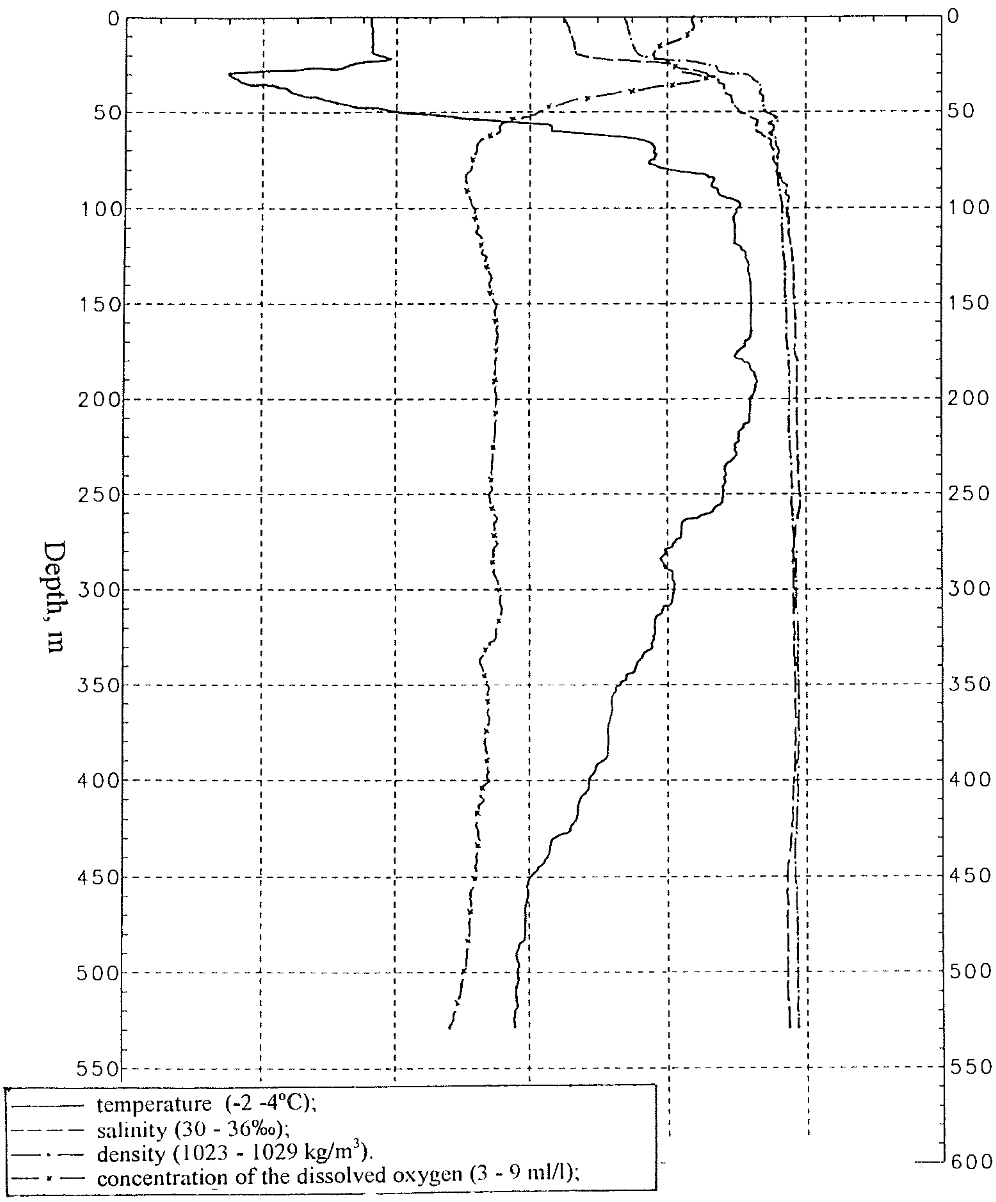

Fig.9: Vertical distribution of temperature (in °C) on the station N 21 in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

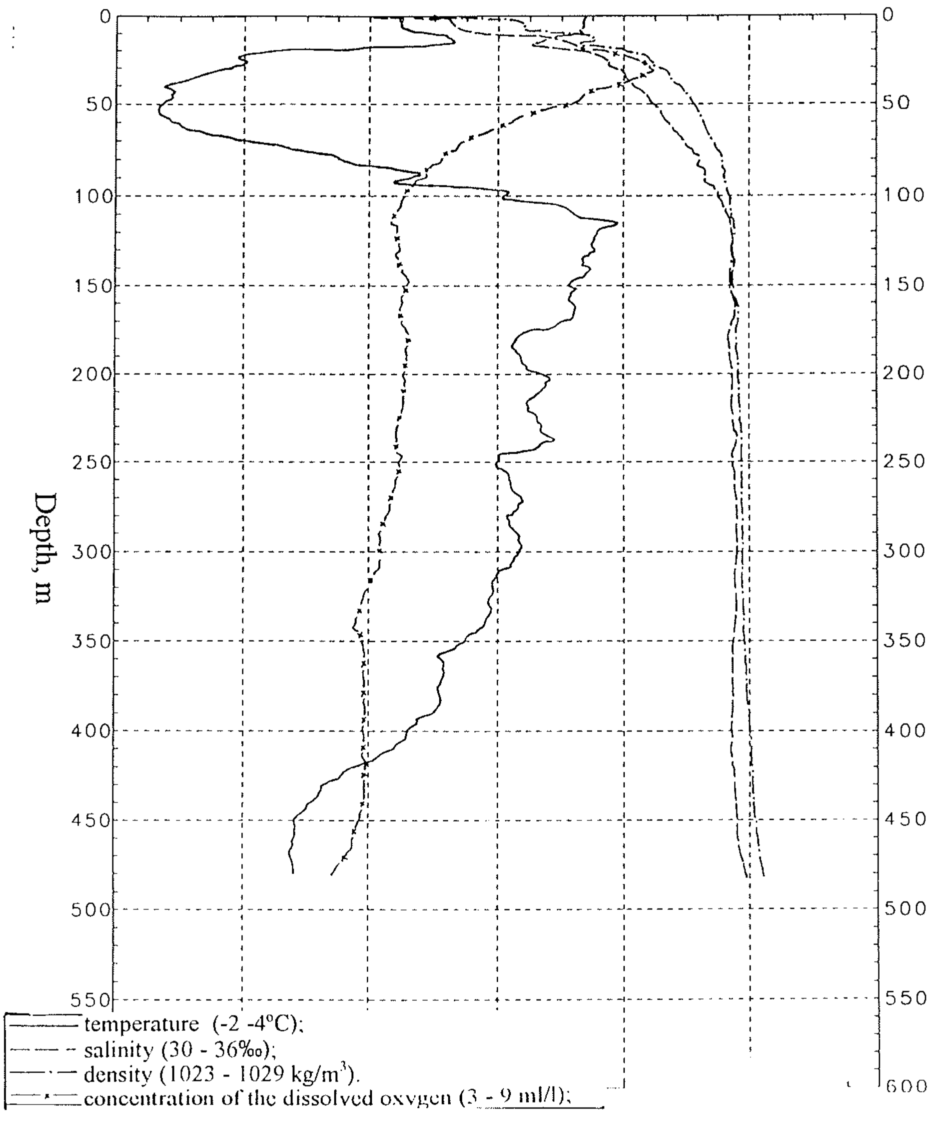

Fig.10: Vertical distribution of temperature (in °C) on the station N 43 in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

Earlier attempts to calculate the dynamic topography of the Kara Sea (Garcia, 1969; Hanzlick and Aagaard, 1980) were unsuccessful due to the problem of valid reference level choice. Recent ADCP measurements carried out onboard the German research icebreaker "Polarstern" (Augstein,1997) in the northern part of the St. Anna Trough, demonstrated the velocity increase towards the bottom (Schauer et al.,1997). Hence, the attempt to include the reference level in the upper part of the water column seems quite reasonable. As the maximal northward current was measured at the eastern slope of the trough near the bottom (Schauer et al.,1997), the velocity values, calculated from the upper horizons should be closer to the actual ones than if referring to the bottom. The dynamical calculations from the surface (Schauer et al.,1997) and from 75 m depth (Ivanov and Korablev, 1997) have shown a reasonable structure of a baroclinic velocity field, consistent with the distribution of thermohaline parameters, ADCP measurements and conventional views about water mass motion in the St. Anna Trough.

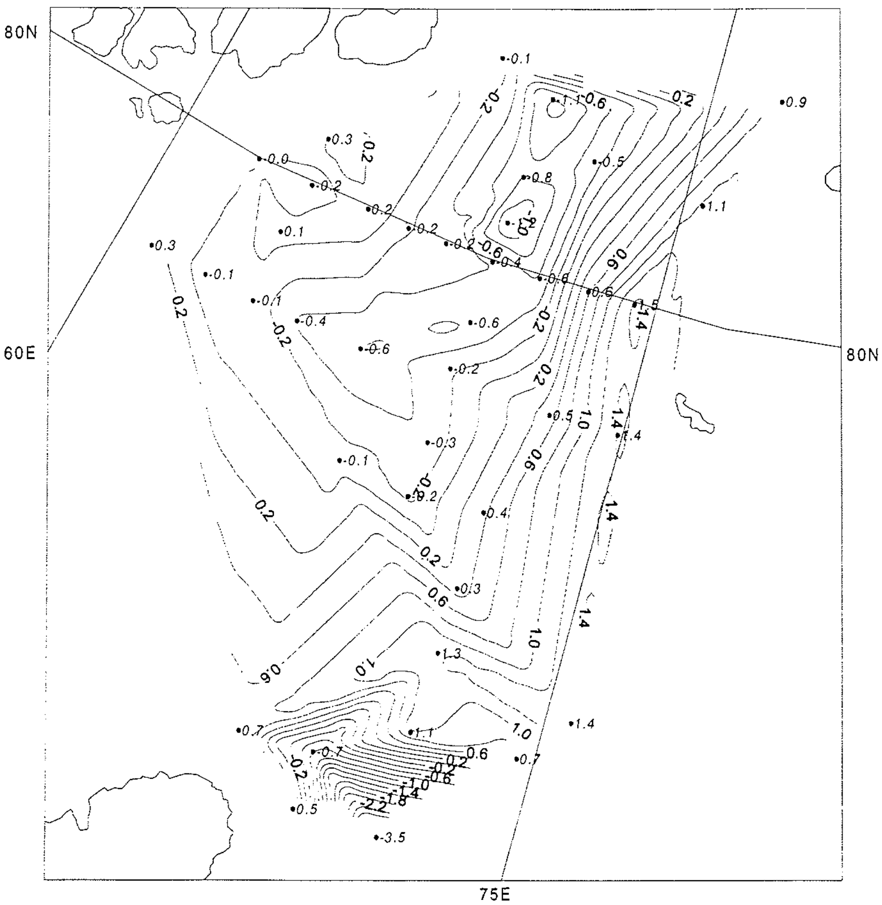

Fig.11: Denivillation (cm) of 150 db geopotential surface relative to 50 db reference level.

In the present study the 50 db surface was chosen as the reference level for geostrophic current simulations. According to completed analyses of thermohaline field structures, this level corresponds to the mean spatial location of cold (winter) layer core. Presuming that the surface water moves mostly northward (in correspondence with prevailing ice drift direction), while the underlying ADW moves southward, the subsurface cold layer is likely to be the most stable in comparison with other parts of the water column. It should be stressed that such choice of reference level is still rather arbitrary.

The denivillation of the 150 db geopotential surface relative to 50 db reference level is presented in Figure 11. This depth is the most appropriate for revealing the dynamic pattern due to strict manifestation of ADW and possibility to calculate values at shallower stations which cannot be done for deeper geopotential surfaces.

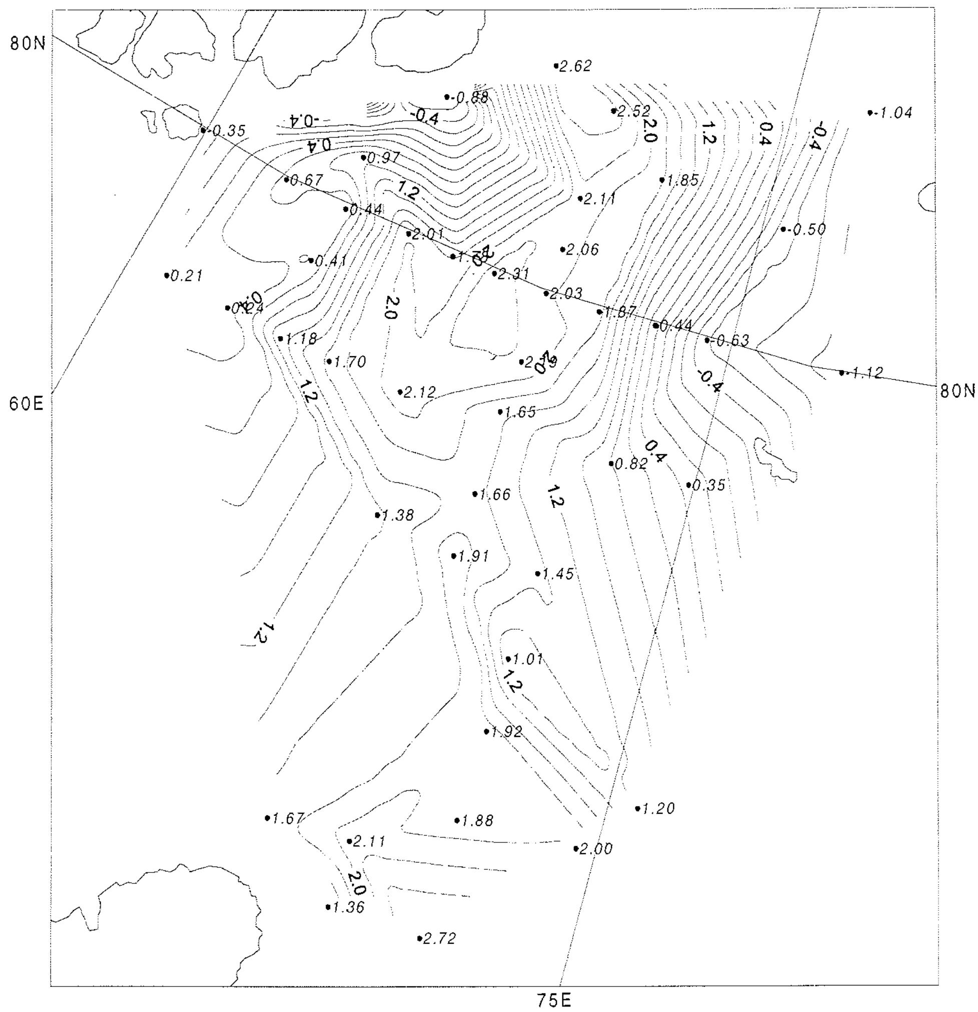

Fig.12: Distribution of maximum water temperature (in °C).

The central part of the trough is occupied by a cyclonic gyre (depression), stretched in meridional direction. At the western slope of the canyon the current direction corresponds with southward inflow of the ADW. Two local eddies are present above the deepest parts of the trough. The northern one (with the center at station 22) looks rather artificial. It is probably a result of interpolation, caused by lack of data to the north. The intensive northward stream is embedded in the eastern part of the canyon. It brings water from the south-west which is presumably the Barents Sea branch of ADW (Rudels et al., 1994; Schauer et al., 1997; Ivanov and Korablev, 1997). The origin of the anticyclonic gyre is presumably in the eastern part of the polygon (above the Central Kara uplift). In the far south of the polygon the intensive stream from the estuarian part of the Kara sea is revealed.

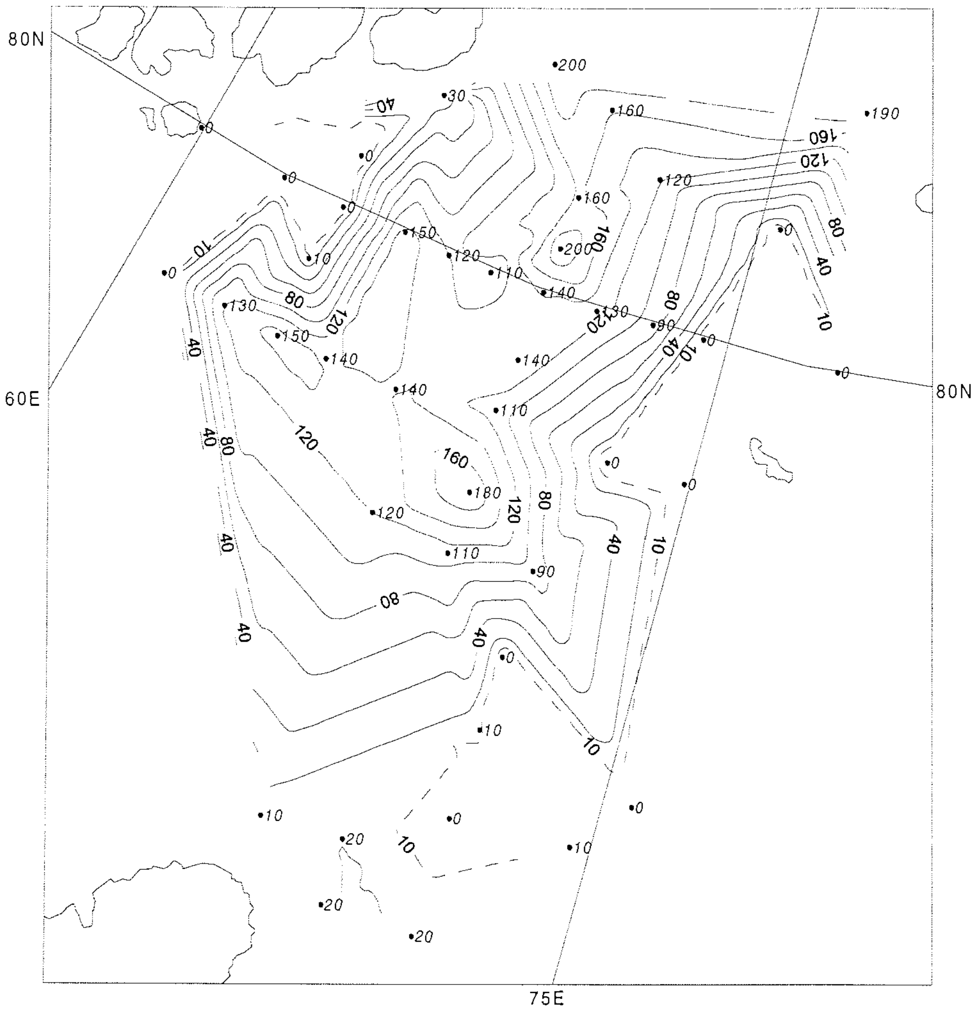

Fig.13: Distribution of depth (m) of maximum water temperature.

The results of dynamical estimates were validated against the distributions of maximal water temperature (Fig. 12) and the depth of this maximum (Fig. 13). There are two cores of maximal temperature > 2 °C within the polygon. However, their origin differ essentially. The high temperature zone, covering the central and northern parts is obviously associated with the ADW inflow. Hence the depth of this temperature maximum lies within the limits 120-200 meters (compare with Figs. 2 to 5). On the dynamic map (Fig. 11) this zone corresponds with cyclonic circulation, where the ADW inflow occurs at the western slope of the trough. The southern periphery of this cyclonic gyre is marked by a sharp front in the distribution of the maximum temperature depth. Between stations 50 and 54 the depth of temperature maximum raises from 170 to 10 meters. Although the values of maximum temperature at these stations are practically the same, the origins of temperature maximum at station 50 and to the south of it are quite different. The shallow temperature maximum is connected with the inflow of the warm surface water from the south and south-west. Hence the temperature maximum here is embedded in the surface or close to it. Advection of warm water from the south also governs the depth of temperature maximum in the eastern part of the polygon, corresponding with the calculated direction of the flow (Fig. 11). Obviously the value of surface temperature maximum diminishes while moving northwards. Thus, it can be concluded that dynamic calculations in the subsurface layer compare well with temperature field and expected dynamical structure.

Conclusions

Analysis of the hydrophysical fields structure in the area of the St. Anna Trough allows to conclude the following:

The thermodynamic regime of the region is primarily determined by submeridional transfer of the warm ADW. Heat influx from the north is dominating within the depths from 120-150 m down to the sea floor. The maximum heat content is observed in the northern part of the polygon.

The structure of hydrophysical fields in the research area possesses features typical for the frontal interfaces with strong horizontal and vertical velocity shear:

- contact between waters of different origin forms frontal zones with increased gradients of properties (better expressed in temperature and salinity fields);
- heterogenities in form of sharp steps and inversions are typical for the observed fine structure. It is presumably caused by intense turbulent lateral mixing in frontal zones;

The dynamic structure is characterised by two main streams. The first one is connected with ADW entering from the north and forming the cyclonic circulation with its center above the deep part of the St. Anna Trough. The second one is likely the Barents Sea branch of the ADW, which enters from the Barents Sea (Loeng et al.,1993) and follows as a strong jet to the Arctic Ocean along the eastern slope of the canyon.

The decisive factor of interzonal exchange in the area of the St. Anna Trough is advective transfer of heat, salt and various passive impurities (including pollutants). The stability of circulation is essentially governed by the bottom topography. Low temporal variability of the tracer transport mean that the distribution of pollutants and the structure of biological communities both on the sea floor and in the water column are essentially governed by water dynamics.

Acknowledgements

The authors would like to express their gratitude to the master and crew of RV "Professor Logachev" for providing the possibility to carrying out field work at high latitudes.

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VERTICAL PARTICLE FLUXES IN THE ST. ANNA TROUGH AND IN THE EASTERN BARENTS SEA IN AUGUST-SEPTEMBER 1994

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Abstract

Vertical particle fluxes in the St. Anna Trough and in the Eastern Barents Sea were studied in August - September 1994 during the 9th cruise of the RV *Professor Logachev*. In the central part of the St. Anna Trough the fluxes of total particulate matter were equal to 19.5 - 27.9 mg $m^{-2}d^{-1}$ and particulate organic carbon (POC) fluxes were equal to 1.64 - 4.65 mg $m^{-2}d^{-1}$ which is typical for oligotrophic areas. Diatoms played an important role in the sedimentation here. In the eastern Barents Sea near the Novaya Zemlya Archipelago high values of total fluxes (up to 656 mg $m^{-2}d^{-1}$) and POC (up to 55.2 mg $m^{-2}d^{-1}$) were measured, resulting from resuspension of bottom sediments.

Introduction

In the Ocean particle fluxes from the surface waters to the bottom represent a significant link in geochemical cycles of carbon and many other chemical elements. The values of particle fluxes, along with the particulate matter composition, allow us to apply quantitative methods to biogeochemical, sedimentological, and ecological problems. Studies of particle fluxes in the Arctic region are of special significance. Large Siberian rivers and shelf seas serve as major sources not only of mineral particles, but also of organic carbon (C_{org}), accumulated in the Central Arctic Ocean (Stein et al., 1994; Walsh, 1995). Particle fluxes have been studied in detail in the western Barents Sea, the Norwegian Sea, the Greenland Sea and in the Fram Strait (Honjo, 1990; Wassmann et al., 1990, 1994; Bauerfeind et al., 1994, 1997; Bodungen et al., 1995; Andreassen et al., 1996; Lukashin et al., 1996; Ramseier et al., 1997; Kohly, 1998). The first studies of particle fluxes in the Kara Sea and in the Ob and Yenisey estuaries were carried out in September 1993 during the 49th cruise of RV *Dmitry Mendeleev* (Lisitsyn et al., 1995; Shevchenko et al., 1997).

Material and Methods

Vertical particle fluxes were studied in the St. Anna Trough in August 1994 and in the eastern part of the Barents Sea in September 1994 during the 9th cruise of the RV *Professor Logachev* (Ivanov et al., 1997; Shevchenko et al., 1997, 1998). We used small cylindrical sediment traps (vinil plastic cylinders, 118 mm in diameter, with a 490 mm high working part and bafflers installed in the upper part). Bafflers are installed in the upper part to eliminate turbulent whirls and to prevent the washing out of particles settled into the trap (Gardner, 1980). The lower part of the trap terminates as a cone with a screwed-in 100-ml plastic flask for collection of particulate matter. Prior to sediment trap deployment we poured into the flasks 5 ml 40% formaline to eliminate bacterial activity and to prevent the settled particles from being eaten by zooplankton (Gardner et al., 1983). The scheme of sediment trap deployment at the buoy sedimentological station N 3 is shown on Figure 1. In detail the construction of sediment traps and the methods of their deployment are presented elsewhere (Lisitsyn et al., 1995). The buoy stations were positioned at the moment the anchor touched the bottom, using the GPS navigation system.

Immediately after buoy station recovery flasks with samples were unscrewed, closed by lids, and stored in a refrigerator until further processing. One parallel sample from each depth was studied microscopically in Bogorov and Naumann chambers. To estimate the sedimentary matter fluxes, the second sample from each horizon was filtered using previously weighed Whatman GF/F filters. After drying at 55°C for 24 hours the samples were weighed and the sedimentary matter fluxes were calculated. One fourth of each filter was then used for the organic carbon (Corg) analysis. Parts of filters were studied using scanning electron microscope JSM-U3.

Coordinates and time of sediment trap deployments and the particle flux values are given in Table 1, the position of the stations is shown on Figure 2.

Table 1: Coordinates and exposure time of buoy sedimentological stations and vertical particle fluxes in the St. Anna Trough and the eastern Barents Sea in August - September 1994.

Stat.	Coordinates		Date		Expo-sure (days)	Water depth (m)	Depth (m)	Flux (mg $m^{-2}d^{-1}$)		C_{org} (%)
	Lat. N	Long. E	deploy-ment	reco-very				Total	POC	
3	79°23.4'	69°58.4'	10.08	20.08	9.54	515	55	23.0	4.65	20.2
							205	19.7	2.28	11.6
							405	19.5	1.68	8.6
							465	27.9	2.67	9.6
5	72°56.8'	51°26.9'	24.09	30.09	5.77	135	35	62.9	7.61	12.1
							95	42.5	4.05	9.5
6	73°01.2'	52°53.9'	25.09	30.09	4.72	40	15	314	34.8	11.1
							20	656	55.2	8.4

Results and Discussion

At the central St. Anna Trough Station 3 total particle flux decreased from 23 mg $m^{-2}d^{-1}$ at 55 m to 19.5 mg $m^{-2}d^{-1}$ at 405 m in August 1994, and then increased to 27.9 mg $m^{-2}d^{-1}$ at 465 m; particulate organic carbon (POC) fluxes decreased from 4.65 mg C $m^{-2}d^{-1}$ to 1.68 mg C $m^{-2}d^{-1}$ and then increased to 2.67 mg C $m^{-2}d^{-1}$ at the same depths (Table 1; Fig. 3). Relatively low fluxes of organic carbon in the St. Anna Trough testify the oligotrophy of this area at the time of our expedition. Low values of total particulate matter and POC fluxes were also registered in western Kara Sea in August 1993 (Lisitsyn et al., 1995). At Station 4382 (Fig. 2) total flux and flux of POC at 60 m were equal to 25 mg $m^{-2}d^{-1}$ and 5.54 mg C $m^{-2}d^{-1}$; respectively. At Station 4396 flux values at 20 m were equal to 22.9 mg $m^{-2}d^{-1}$ and 1.51 mg C $m^{-2}d^{-1}$, respectively. For comparison, in the Sargasso Sea (as a typical oligotrophic region) the minimum flux of POC at the depth of 3200 m was 1.81 mg C $m^{-2}d^{-1}$ (Deuser et al., 1981). An increase of particle flux at 465 m is likely related to sedimentation of particles from benthic nepheloid layer widely spread over the shelf and upper continental slope (Gardner et al., 1985; Biscaye and Anderson, 1994; Rutgers van der Loeff and Boudreau, 1997). Optical and scanning electron microscopy shows that in sediment trap material from this depth contents of mineral grains increased.

At all horizons of Station 3 particulate matter collected by sediment traps is mainly represented by amorphous aggregates ("marine snow"). These aggregates contain many diatoms (both colonies and individual cells) of the genera *Thalassiosira* (*Th. antarctica*, *Th. gravida*, *Th. nordenskioeldii*), *Chaetoceros* (*Ch. atlanticus, Ch. concavicornis, Ch. furcellatus, Ch. septentrionale*), *Melosira* (*M. arctica*), *Navicula*, *Licmophora, Amphora.* It has been shown, that in the Arctic diatoms often dominate the sedimented phytoplankton (Bauerfeind et al., 1997; Kohly, 1998). Relatively high contents of *Th. nordenskioeldii, Ch. septentrionale, M. arctica,* i.e., species known to grow underneath the ice in the Arctic Ocean (Usachev, 1949; Poulin, 1990), indicate that a major proportion of the setting particles was released from melting sea ice in this area.

Table 2: Diatom fluxes in the water column of the St. Anna Trough and some other regions

Region	Coordinates		Depth (m)	Time interval (mean)	Diatom flux (valves*10^5 $m^{-2}d^{-1}$)	Source
	Latitude	Longitude				
St. Anna Trough	79°23.4'N	69°58.4'E	55	10.-20.08.94	3.6	This study
			205	-//-	10	-//-
			405	-//-	6.2	-//-
			465	//-	7.2	-//-
Greenland Sea	72°00.7'N	7°02.5'W	500	20.-31.07.91	77	Kohly, 1998
				08.91 - 07.92	1	-//-
	72°34.8'N	10°30.5'W	500	09.88 - 04.89	0.07	Bauerfeind et al., 1994
				05.-06.89	14.4	-//-
Norwegian Sea	69°41.2'N	0°27.8'E	500	08.91	3	Kohly, 1998
				01.-04.92	1	-//-
Benguela upwelling	20°02.8'S	09°09.3'E	599	29.05.-16.06.89	353.1	Treppke et al., 1996
				18.03.89 - 13.03.90	54.7	-//-

At 55 m depth diatom flux was 3.6 x 10^5 valves $m^{-2}d^{-1}$ during the sampling period (Table 2; Fig. 4). The highest flux values (10 x 10^5 valves $m^{-2}d^{-1}$) were observed at 205 m, which may indicate release of diatom valves from sinking amorphous aggregates. At 405 m diatom flux was 6.2 x 10^5 valves $m^{-2}d^{-1}$, at 465 m 7.2 x 10^5 valves $m^{-2}d^{-1}$. With increasing depth contents of living (chloroplast-containing) cells decrease. As shown in Figure 4, the ratio of living to dead diatom cells decreases from 21 to 1. It could be explained both by degradation of organic matter during the sedimentation from the euphotic zone and by resuspension of bottom sediments in which no living diatoms occur.

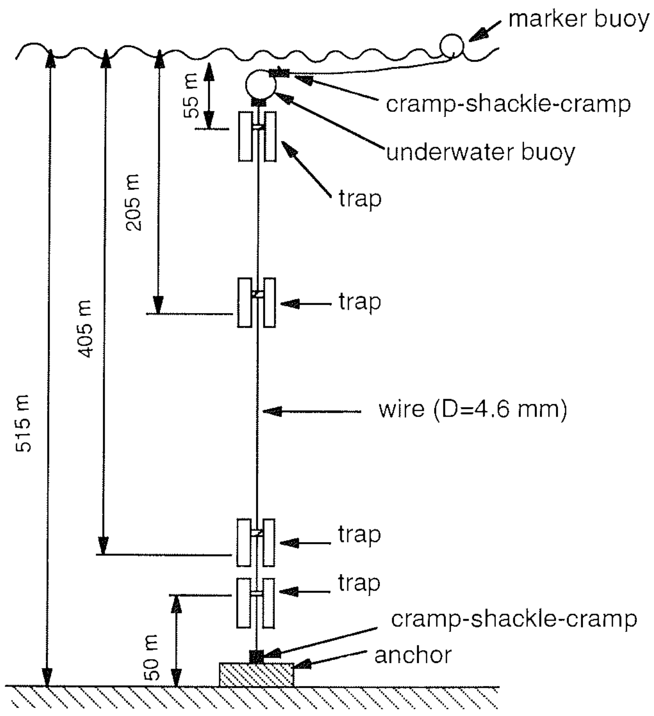

Fig. 1. Scheme of sediment trap deployment at Station 3 during the 9-th cruise of RV "Professor Logachev".

During the sampling time from 10 to 20 August 1994 diatom fluxes in the St. Anna Trough are slightly higher than diatom fluxes in the Greenland and Norwegian Seas during the year (approx. 1 x 10^5 valves $m^{-2}y^{-1}$), but much lower than fluxes at times following the diatom bloom in the Greenland Sea (77 x 10^5 valves $m^{-2}d^{-1}$) and in the high-productive Benguela upwelling area (up to 353.1 x 10^5 valves $m^{-2}d^{-1}$; Table 2; Kohly, 1998; Treppke et al., 1996).

At the end of September in the eastern Barents Sea near the Bezymyanaya Bay (Southern Island of the Novaya Zemlya Archipelago) (Fig. 2) total flux at the Station 5 (depth 135 m) was equal to 62.9 mg $m^{-2}d^{-1}$ at 35 m and 42.5 mg

$m^{-2}d^{-1}$ at 95 m (Table 1). POC flux here was equal to 7.61 mg C $m^{-2}d^{-1}$ and 4.05 mg C $m^{-2}d^{-1}$ at the same depths correspondingly. Particulate material consisted mainly of amorphous aggregates. Dinoflagellates *Dinophysis rotundata* and *Ceratium arcticum* play important role in formation of these aggregates. Only few diatoms *Thalassiosira sp.* were found in samples at this station.

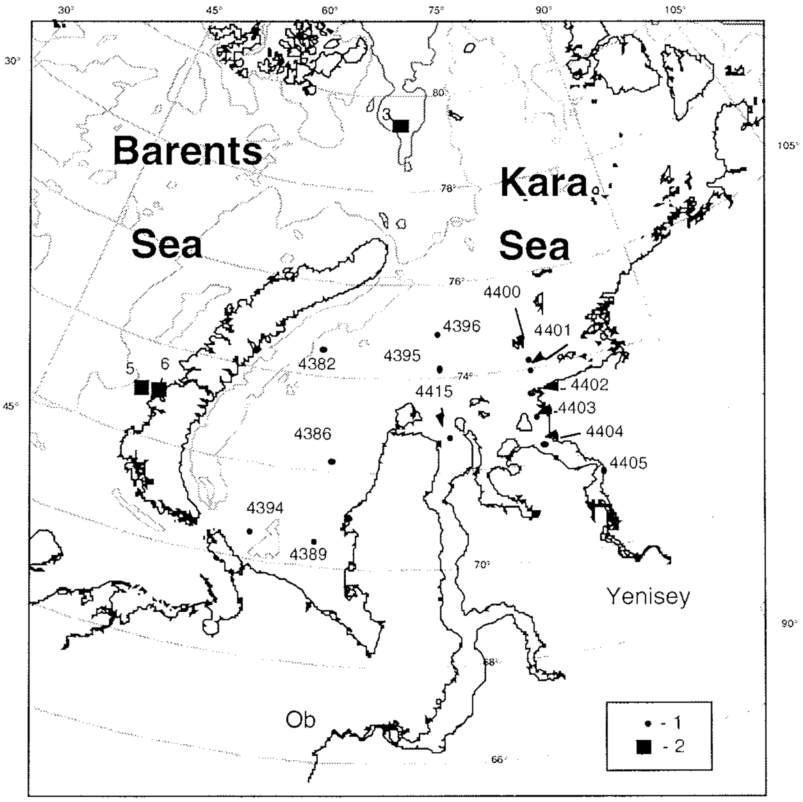

Fig. 2. Location of sediment trap stations: 1 - in the 49-th cruise of the RV "Dmitry Mendeleev" (Lisitsyn et al., 1995; Shevchenko et al., 1997); 2 - in 9-th cruise of RV "Professor Logachev" (this work).

At Station N 6 situated closer to the shore (depth 40 m) total flux was equal to 314 mg $m^{-2}d^{-1}$ at 15 m and 656 mg $m^{-2}d^{-1}$ at 20 m and POC flux was equal to 34.8 and 55.2 mg C $m^{-2}d^{-1}$ at 15 m and 20 m correspondingly (Table 1). Mineral particles are the main component of particulate matter at this station. Both large values of fluxes and the composition of particulate matter show that in this case we register fluxes of resuspended material.

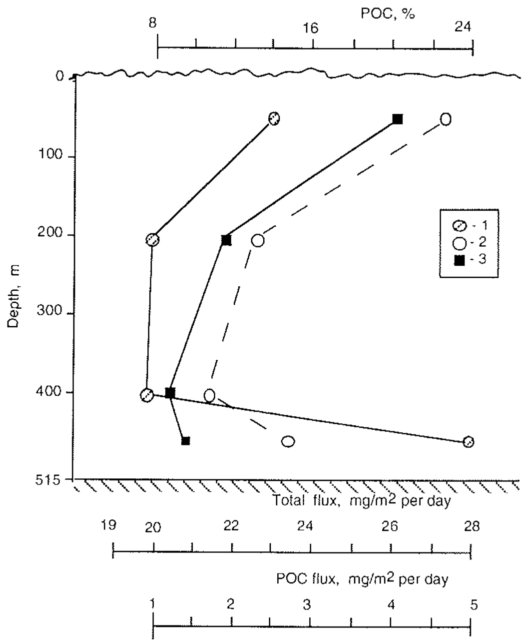

Fig. 3. Particle fluxes at Station 3 in the St. Anna Trough from 10 to 20 August 1994: 1 - total flux; 2 - POC flux; 3 - POC contents in sedimentary material.

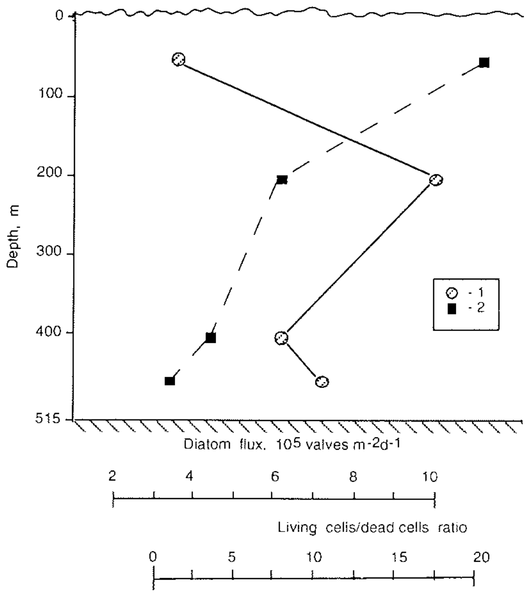

Fig. 4. Diatom fluxes at Station 3 in the St. Anna Trough: 1 - total diatom flux; 2 - living cells/dead cells ratio.

Conclusions

Low vertical fluxes of particulate organic carbon in the central part of the St. Anna Trough testify oligotrophy of this area even in summer. Amorphous aggregates formed around diatom colonies and cells play important role in sedimentation. High values of total particulate matter and particulate organic carbon fluxes near the Novaya Zemlya Archipelago in the eastern Barents Sea are the result of resuspension of bottom sediments in the shelf zone.

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THE DISTRIBUTION OF TOTAL SUSPENDED MATTER AND PARTICULATE ORGANIC CARBON IN THE ST. ANNA TROUGH AND IN THE BARENTS SEA

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Abstract

The distribution of total suspended matter (TSM) and particulate organic carbon (POC) in the St. Anna Trough and in the Barents Sea was studied in August-October 1994 during 9th cruise of RV *Professor Logachev*. 210 samples of of TSM and 85 samples of POC were collected. In the surface layer (0-1 m) of the St. Anna Trough concentrations of TSM varied from 0.11 to 1.74 mg/l and concentrations of POC from 27 to 401 µg C/l. In the north-eastern part of the St. Anna Trough they increased towards to the marginal ice zone. In the Barents Sea lowest contents of TSM (0.07 mg/l) and POC (41 mg C/l) were noted in the north-western part, in the western Barents Sea TSM content varied from 0.09 to 0.41 mg/l and POC content from 43 to 135 µg C/l, and in the south-eastern Barents Sea they varied from 0.15 to 1.58 mg/l and from 57 to 134 µg C/l, respectively. In general, these data indicate low primary production and low input of suspended matter from other sources in August-October 1994.

Introduction

The study of suspended particulate matter in the Ocean is necessary for understanding of modern sedimentation processes and for the ecological assessment of the state of waters. In this context the Arctic seas are studied insufficiently. In the Kara and Barents seas the distribution of total suspended matter (TSM) were studied by Medvedev and Potekhina (1986, 1990 a, b). These authors, however, used membrane filters from the Mytishinskiy plant, which distort the results of suspended matter concentration measurements. Particulate organic carbon (POC) was studied in the Barents Sea by Romankevich et al. (1982). Particulate matter studies in the Kara and the Barents seas using modern methodics were carried out in 1993-1997 (Dai and Martin, 1995; Shevchenko et al., 1996 a, b, 1997 a, b; Aleksandrova and Shevchenko, 1997; Jambers et al., 1997; Lukashin and Rusakov, 1998). In this paper we present preliminary data on the distribution of TSM and POC in the surface waters (0-1 m) of the St. Anna Trough and new data for the Barents Sea.

Material and Methods

In August-October 1994 210 samples of TSM and 85 samples of POC were collected during 9th cruise of RV *Professor Logachev*. Sampling of water from surface layer (0-1 m) was carried out by a 5-l plastic bucket and from depth by bottles. For TSM studies the filtration of water samples was carried out through Nuclepore filters 47 mm in diameter (pores 0.45 μm) and for POC studies - through precombusted Whatman GF/F filters. After filtration filters were washed with distilled water, dried at 55-60 °C, packed in Petry cups and then sealed in plastic envelopes for later analyses in the home laboratory. In more detail working procedures are described elsewhere (Shevchenko et al., 1996 b). POC content was measured by coulonometric method (Lyutzarev and Smetankin, 1980).

Results and Discussion

In August 1994 in the surface layer (0-1 m) of the St. Anna Trough lowest contents of TSM and POC were registered in the western part of this area: <0.25 mg/l of TSM (Appendix Table 1; Fig. 1) and < 100 mg C/l of POC (Appendix Table 1; Fig. 2). The contents both of TSM and POC increase to the NE, i.e., forwards the marginal ice zone, where the highest values of TSM concentations (up to 1.74 mg/l) and POC (up to 401 mg C/l) were found. This could be explained by high productivity in marginal ice zones at the end of summer described elsewhere (Smith, 1987; Sakshaug and Skjoldal, 1989).

In Figure 3 the distribution of TSM is shown in the cross-section from Ob estuary to the northern part of the St. Anna Trough, using data from two expeditions (49th cruise of RV *Dmitry Mendeleev*, August-October 1993 and 9th cruise of RV *Professor Logachev*, August-October 1994) collected in same season (Lisitsyn and Vinogradov, 1995; Shevchenko et al., 1996 b, 1997 b; Ivanov et al., 1997). In this cross-section the highest contents of TSM (varying from 11.7 to 115.3 mg/l) with a observed in the upper part of the Ob estuary (Shevchenko et al., 1996 b, 1997 b), where salinity was <1 ‰ (Burenkov and Vasil'kov, 1995). In the zone of Ob marginal filter (Lisitsyn, 1995) in the salinity range from 5 to 10 ‰ the contents of TSM sharply decrease to less than 5 mg/l. In the open Kara Sea it is in the range of 1 to 5 mg/l. In the outer part of the Kara Sea concentrations of TSM are very low (less than 0.5 mg/l). Only in upper 15-20 m of water depth near marginal ice zone in the St. Anna Trough they increase again up to 0.5-1 mg/l.

In the NW part of the Barents Sea, in the Franz-Victoria Trough, contents of TSM (Appendix Table 1; Fig.4) and POC (Appendix Table 1; Fig. 5) are very low: 0.07-0.16 mg/l and 41-72 mg C/l, respectively. Only at St. 74 (Appendix Table 1) located in the marginal ice zone concentration of TSM was 0.19 mg/l and POC 124 mg C/l. In the transect from Spitsbergen to the Kola Peninsula TSM contents varied from 0.1 to 0.37 mg/l, with higher values in the North Cape Current area (Loeng, 1991) and in near-coastal waters (Fig.4). Content of POC at this cross-section varied from 44 to 266 mg C/l; the highest value was found in the coastal waters of the Kola Peninsula (Appendix Table 1; Fig. 5).

Concentrations of TSM and POC in the surface waters of the Barents Sea in August-October 1994 were relatively low, resulting from low primary production and insufficient input of particulate matter from other sources.

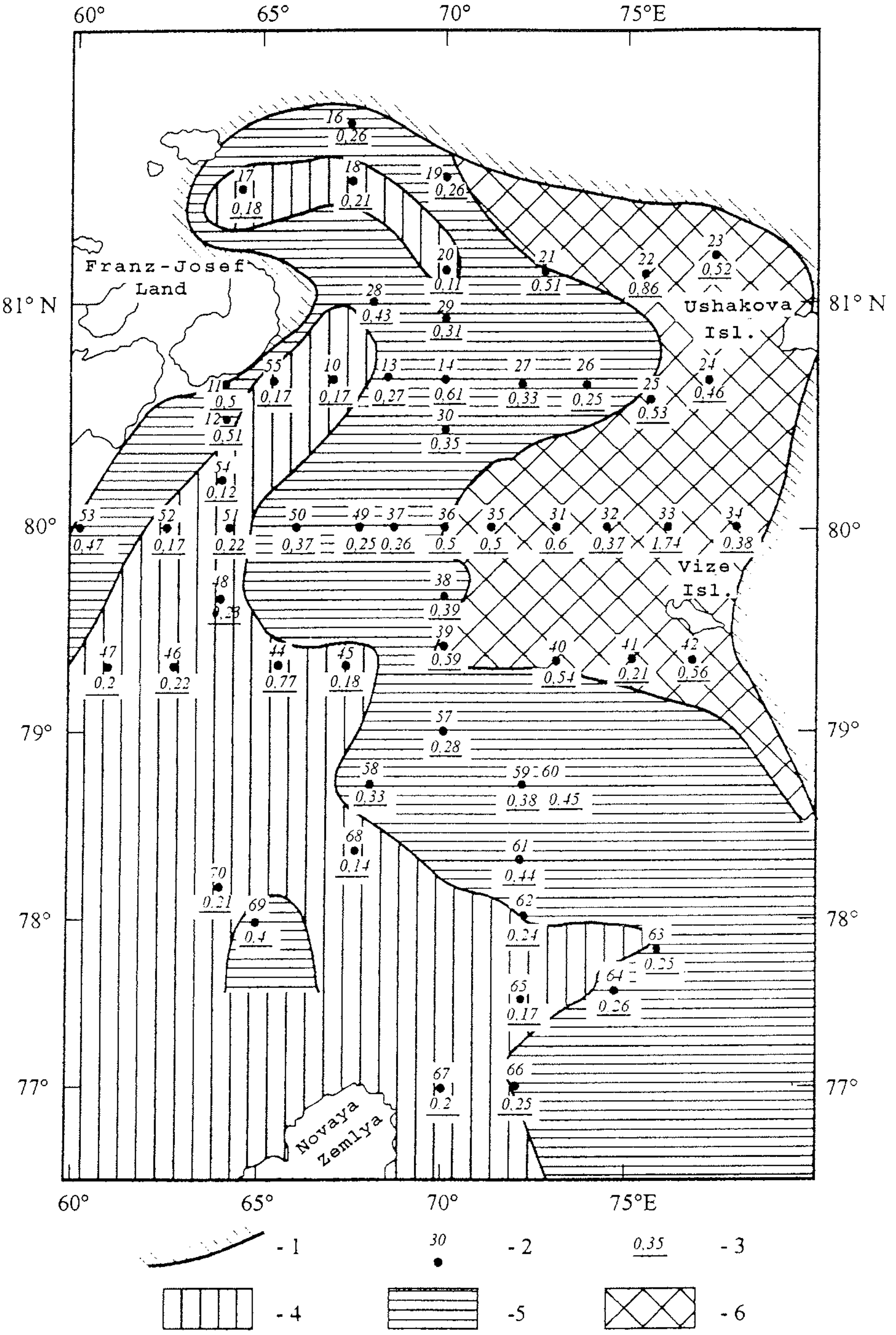

Fig. 1: Distribution of total suspended matter (TSM) in the surface (0-1 m) layer of the St. Anna Trough in August 1994: 1 - ice edge; 2 - station number; 3 - content of TSM (mg/l), 4 - <0.25 mg/l; 5 - 0.25 - 0.5 mg/l; 6 - > 0.5 mg/l.

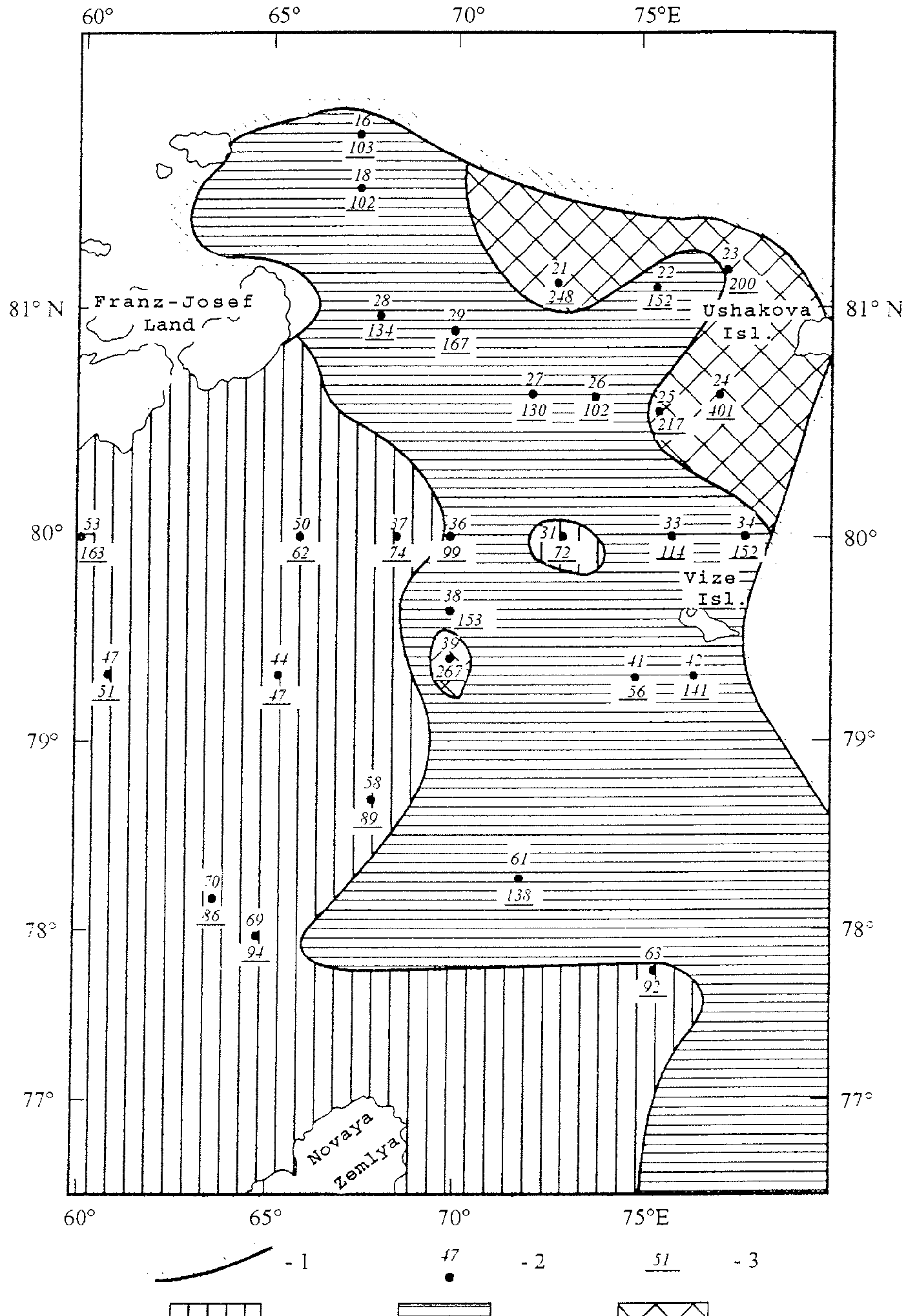

Fig. 2: Distribution of particulate organic carbon (POC) in the surface (0-1 m) layer of the St. Anna Trough in August 1994: 1 - ice edge; 2 - station number; 3 - content of POC (mg C/l); 4 - <100 mg C/l; 5 - 100 - 200 mg C/l; 6 - > 200 mg C/l).

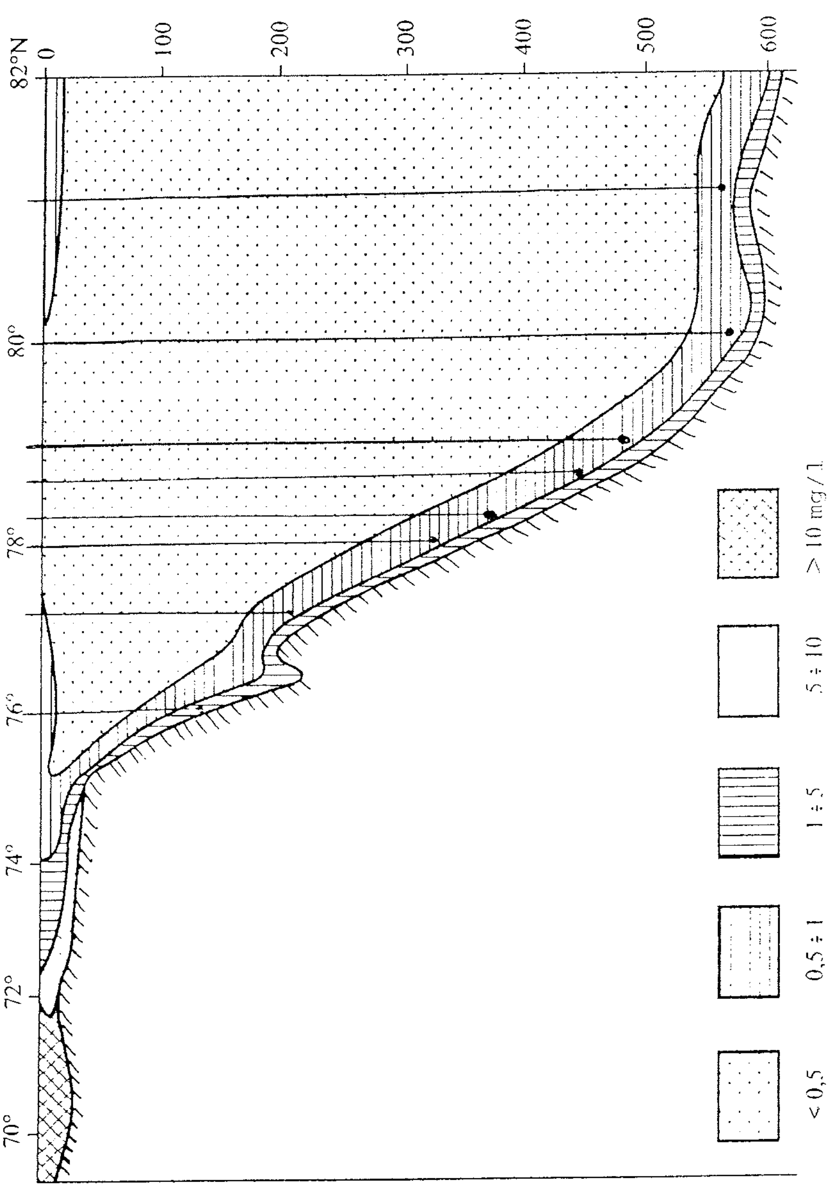

Fig. 3: Distribution of total suspended matter in a cross-section from the Ob estuary to the St. Anna Trough end of August/beginning of September.

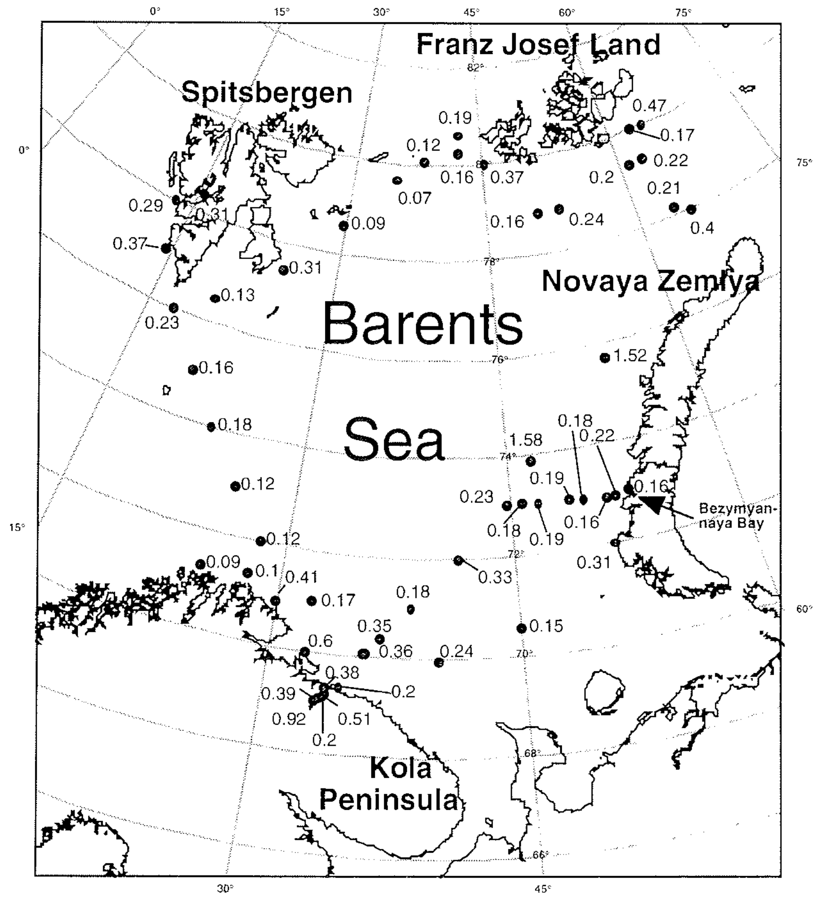

Fig. 4: Distribution of total suspended matter (mg/l) in the surface (0-1 m) layer of the Barents Sea in August-October 1994.

On 26-27 September 1994 the distribution of total suspended matter was studied in Bezymyannaya Bay at the western side of the Southern Island of the Novaya Zemlya Archipelago. In the inner part of the bay the TSM content was > 3 mg/l, decreasing towards the open sea, where concentrations are < 1 mg/l (Appendix Table 1; Fig. 6).

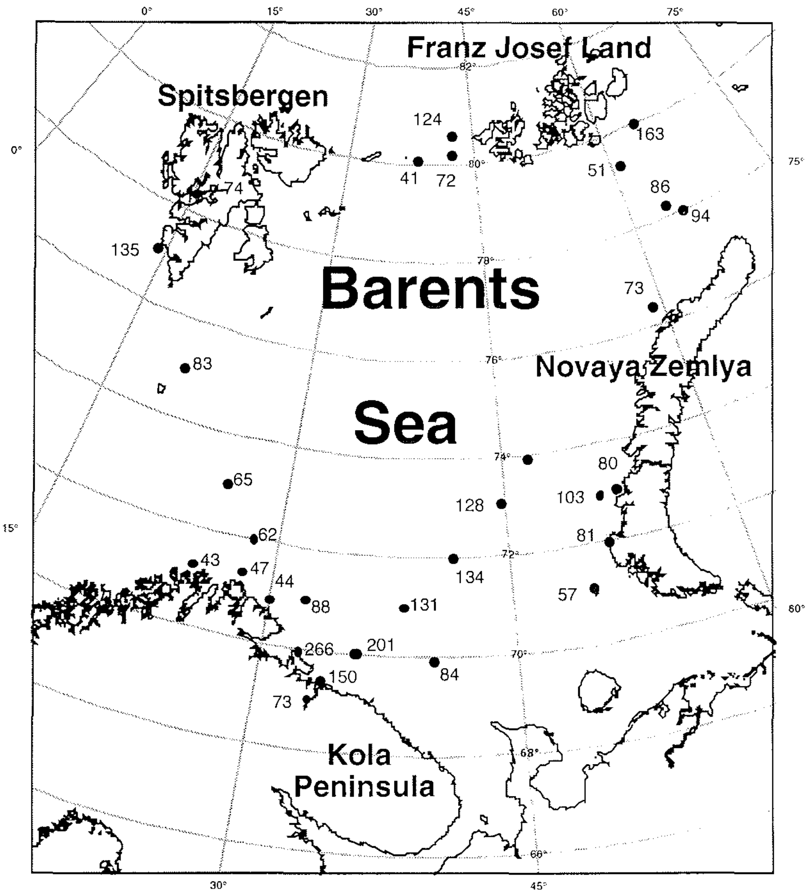

Fig. 5: Distribution of particulate organic carbon (mg C/l) in the surface (0-1 m) layer of the Barents Sea in August-October 1994.

Nearly the same pattern of TSM distribution has been described in the the fjord near Pavlov Glacier, Northern Island of Novaya Zemlya Archipelago (Shevchenko et al., 1996 a). Unfortunately, we had no possibility to take samples from the main tributary of the bay, Bezymyannaya River, but the TSM content in mouths of small tributaries in the NE part of the bay is low (from 0.11 to 0.53 mg/l). We could assume that the coastal abrasion was the main source of suspended matter in the Bezymyannaya Bay during our expedition and that most part of this suspended matter deposits in the outer part of the bay and does not reach the open sea.

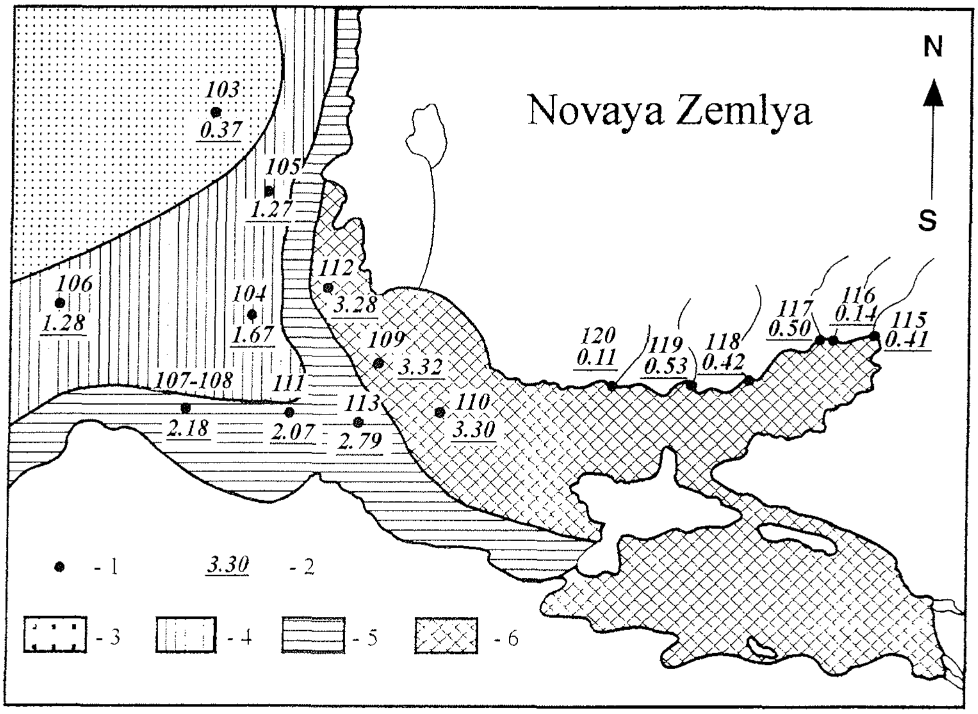

Fig. 6: Distribution of total suspended matter (TSM) in the surface layer (0-1 m) of the Bezymyannaya Bay (the Barents Sea side of the Southern Island of the Novaya Zemlya Archipelago) in September 1994: 1 - station number; 2 - content of TSM (mg/l); 3 - <1 mg/l, 4 - 1-2 mg/l, 5 - 2-3 mg/l; 6 - >3 mg/l.

Conclusions

In August-October 1994 concentrations of total suspended matter in the St. Anna Trough and in the Barents Sea were generally low, due to low biological productivity and reduced river discharge during this season. The increase of suspended matter contents took place only near the ice marginal zone due to high productivity.

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Appendix (Shevchenko et al.)

Table 1: Time and coordinates of suspended matter sampling sites in August-October 1994 in the St. Anna Trough and in the Barents Sea and concentrations of total suspended matter (TSM) and particulate organic carbon (POC) in the surface (0-1 m) layer.

Station	Data- time (UTC)	Coordinates		TSM	POC
		Latitude (N)	Longitude (E)	(mg/l)	(mg/l)
1	05.08-16.40	69°17.90'	33°32.18'		150
3	06.08-02.00	70°24.02'	36°27.83'	0.35	
6	07.08-15.15	73°55.19'	46°37.80'	1.58	
7	08.08-10.50	75°42.53'	53°34.51'	1.52	
8	08.08-21.50	76°23.09'	58°59.91'		73
10	11.08-23.48	80°40.02'	66°50.41'	0.17	108
11	12.08-07.44	80°39.94'	63°59.65'	0.50	129
12	12.08-12.00	80°29.78'	63°57.94'	0.51	102
13	12.08-18.33	80°40.15'	68°19.40'	0.27	64
14	12.08-21.16	80°40.30'	69°59.15'	0.61	84
15	13.08-15.15	81°59.98'	67°28.96'	0.19	89
16	13.08-21.00	81°46.08'	67°29.73'	0.26	103
17	14.08-03.37	81°29.66'	64°30.21'	0.18	74
18	14.08-10.13	81°29.84'	67°26.57'	0.21	102
19	14.08-14.04	81°29.68'	70°03.58'	0.26	
20	14.08-22.09	81°08.84'	70°00.33'	0.11	
21	15.08-02.03	81°09.16'	72°43.83'	0.51	248
22	15.08-07.53	81°09.08'	75°24.15'	0.86	152
23	15.08-12.54	81°12.04'	77°18.86'	0.52	199
24	15.08-21.00	80°40.34'	77°07.35'	0.46	401
25	15.08-23.46	80°35.33'	75°35.29'	0.53	217
26	16.08-05.00	80°40.31'	73°49.07'	0.25	102
27	16.08-09.17	80°39.71'	71°59.82'	0.33	130
28	16.08-21.00	80°59.78'	68°00.07'	0.43	134
29	17.08-00.40	80°52.99'	70°00.00'	0.31	167
30	17.08-09.00	80°27.70'	69°59.40'	0.35	
31	17.08-17.07	80°00.19'	72°58.06'	0.60	72
32	17.08-23.25	80°00.30'	74°21.60'	0.37	
33	18.08-04.51	79°59.85'	76°00.63'	1.74	114
34	18.08-09.18	80°00.10'	77°59.20'	0.38	152
35	18.08-20.00	79°59.80'	71°29.72'	0.50	
36	19.08-00.20	80°00.32'	70°04.70'	0.50	99
37	19.08-15.00	80°00.14'	68°30.98'	0.26	74
38	19.08-21.17	79°39.87'	69°58.64'	0.39	153
39	20.08-04.00	79°24.05'	69°52.82'	0.59	267
40	20.08-12.36	79°20.18'	72°55.49'	0.54	
41	20.08-20.15	79°20.22'	74°53.51'	0.21	56
42	20.08-22.33	79°19.95'	76°38.19'	0.56	141
43	21.08-15.30	79°19.91'	67°22.80'	0.18	
44	21.08-21.30	79°20.11'	65°30.02'	0.77	47
45	22.08-04.45	79°19.65'	64°10.33'	0.16	64
46	22.08-09.52	79°20.10'	62°40.36'	0.22	
47	22.08-15.00	79°20.13'	60°59.32'	0.20	51
48	22.08-23.13	79°42.50'	63°59.81'	0.23	
49	23.08-08.30	79°59.63'	67°19.28'	0.25	
50	23.08-12.46	79°59.99'	66°00.12'	0.37	62

Table 1: cont. 1

51	23.08-18.30	79°59.85'	64°13.38'	0.22	
52	23.08-22.50	79°59.76'	62°29.45'	0.17	
53	24.08-05.25	80°00.56'	64°02.41'	0.47	163
54	24.08-15.22	80°15.00'	64°02.41'	0.12	
55	24.08-22.13	80°39.91'	65°24.58'	0.17	
56	25.08-10.30	81°02.36'	65°33.13'	2.48	325
57	26.08-16.50	79°00.19'	69°59.56'	0.28	
58	26.08-16.50	79°00.19'	69°59.56'	0.33	89
59	27.08-06.20	78°45.15'	72°00.71'	0.38	
60	27.08-11.10	78°45.33'	72°02.72'	0.45	
61	28.08-04.00	78°20.64'	71°58.68'	0.44	138
62	28.08-12.00	77°59.60'	72°01.52'	0.24	
63	28.08-18.45	77°50.19'	75°38.29'	0.25	92
64	29.08-00.20	77°35.04'	74°36.01'	0.26	
65	29.08-07.00	77°33.43'	71°58.90'	0.17	
66	29.08-12.00	76°59.40'	72°01.72'	0.25	
67	29.08-18.50	77°00.00'	70°00.00'	0.20	
68	01.09-12.40	78°24.89'	67°30.20'	0.14	
69	01.09-20.35	77°59.91'	65°00.00'	0.40	94
70	02.09-02.00	78°12.53'	63°42.58'	0.21	86
71	06.09-09.25	78°51.56'	52°35.82'	0.24	
72	06.09-12.40	78°51.45'	50°14.57'	0.16	
73	07.09-00.01	79°58.61'	44°59.96'	0.37	
74	07.09-07.00	80°37.57'	42°13.50'	0.19	124
75	07.09-13.50	80°12.70'	42°01.02'	0.16	72
76	07.09-21.05	80°05.00'	38°04.00'	0.12	41
77	08.09-15.50	79°39.30'	34°56.10'	0.07	
78	09.09-01.30	78°35.10'	29°57.20'	0.09	
79	09.09-12.00	77°26.80'	24°58.20'	0.31	
80	09.09-22.18	76°29.10'	20°02.30'	0.13	
81	10.09-12.00	77°01.50'	14°10.70'	0.37	135
82	10.09-23.50	78°00.01'	13°03.85'	0.29	116
83	11.09-09.35	78°23.42'	15°19.57'	0.31	74
84	13.09-16.00	75°58.90'	17°04.10'	0.23	
85	14.09-02.00	74°59.40'	20°20.00'	0.16	83
86	14.09-10.05	73°59.90'	23°02.70'	0.18	
87	14.09-19.10	72°59.30'	25°45.90'	0.12	65
88	15.09-04.00	72°00.90'	28°16.20'	0.12	62
89	15.09-20.00	70°59.50'	32°07.20'	0.17	88
90	16.09-20.00	69°57.38'	32°12.29'	0.60	266
91	22.09-10.30	70°02.50'	35°31.50'	0.36	201
92	22.09-19.05	71°00.40'	38°12.70'	0.18	131
93	23.09-04.00	72°00.40'	41°13.70'	0.33	134
94	23.09-16.45	73°04.01'	44°37.28'	0.23	128
95	23.09-20.46	73°02.98'	45°42.42'	0.18	
96	24.09-02.30	73°02.04'	46°50.90'	0.19	
97	24.09-08.81	72°59.86'	48°55.30'	0.19	124
98	24.09-13.15	72°58.31'	49°55.99'	0.18	
99	24.09-18.45	72°56.80'	51°27.20'	0.16	103
100	25.09-01.17	72°56.07'	51°59.87'	0.22	
101	25.09-05.40	73°00.67'	52°33.08'	0.12	
102	25.09-16.45	73°00.20'	52°53.61'	0.16	
103	26.09-08.35	72°57.51'	53°01.76'	0.37	80
104	26.09-09.35	72°55.31'	53°03.07'	1.67	
105	26.09-11.00	72°56.60'	53°03.19'	1.27	
106	26.09-12.24	72°55.53'	52°56.79'	1.28	166

Table 1: cont. 2

107	26.09-12.37	72°54.49'	53°01.22'	2.29	
108	26.09-13.41	72°54.45'	53°01.21'	2.07	
109	26.09-14.25	72°54.05'	53°07.86'	3.32	214
110	26.09-14.47	72°54.48'	53°04.34'	3.30	
111	26.09-15.39	72°54.45'	53°04.28'	2.07	
112	26.09-16.03	72°54.94'	53°05.82'	3.28	
113	26.09-16.56	72°54.13'	53°07.94'	2.79	
114	26.09-17.40	72°54.25'	53°10.29'	2.38	173
115*	27.09-10.00	72°55.20'	53°24.00'	0.41	85
116*	27.09-10.30	72°55.00'	53°22.80'	0.14	
117*	27.09-10.55	72°54.80'	53°21.10'	0.50	
118*	27.09-11.20	72°54.70'	53°20.70'	0.42	
119*	27.09-12.00	72°55.20'	53°13.30'	0.53	
120*	27.09-12.30	72°54.40'	53°13.40'	0.11	
121	30.09-08.00	73°01.22'	52°53.91'	0.17	80
122	30.09-21.45	71°59.50'	51°19.50'	0.31	81
123	02.10-14.25	71°09.18'	50°00.69'		57
124	03.10-03.10	70°32.50'	44°59.60'	0.15	
125	03.10-22.45	69°56.12'	39°59.10'	0.24	84
126	04.10-16.00	69°19.10'	34°18.75'	0.20	56
127**	05.10-22.05	69°11.70'	33°31.80'	0.20	73
128**	08.10-14.00	69°01.00'	33°02.48'	0.92	
129**	08.10-14.45	69°04.09'	33°11.17'	0.39	
130**	08.10-15.25	69°07.48'	33°26.11'	0.51	
131**	08.10-16.40	69°17.38'	33°32.00'	0.38	
132	09.10-10.00	70°53.30'	29°58.90'	0.41	44
133	09.10-15.15	71°20.00'	27°59.40'	0.10	47
134	09.10-22.00	71°16.30'	24°58.40'	0.09	43

*Mouths of rivers, flowing into Bezymyannaya Bay
**Kola Bay

THE COMPOSITION AND DISTRIBUTION OF THE MICROPLANKTON COMMUNITY IN THE SAINT ANNA TROUGH AREA

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Abstract

The composition and distribution of microplankton were studied on a transect across the Saint Anna Trough during RV *Polarstern* expedition ARK XII in July 1996. Flagellated protists (including dinoflagellates) dominated the community allong the transect at all depths. Diatoms were of some significance only in the upper 20-40 m of the pelagic zone. The most prominent features of the distribution of microplankton in the study area were (1) preferential occurrence of microplankton in the uppermost water column (polar mixed layer and upper halocline), and (2) much higher densities of all microplanktonic organisms in the western portion of the transect adjacent to Franz Josef Land. Two structural compartments may be distinguished in the microplankton community: (1) an obligate autotrophic assemblage consisting largely of diatoms and some photosynthetic flagellates, and (2) a mixotrophic-heterotrophic assemblage predominated by flagellates.

Introduction

At present our knowledge on patterns of the spatial distribution and seasonal cycle of the microplankton communities in the open Arctic Ocean is very scarce and fragmentary (for review, *see*, e.g., Guillard, Kilham, 1977; Heimdal, 1989) due to the extremely restricted accessibility of the polar regions covered with perennial sea ice. Moreover, most of the plankton studies focused on the ice algae and the „classic“ phytoplankton (largely diatoms) while ignoring nearly entirely the heterotrophic components of the microplankton community. This causes a gap in understanding the patterns of pelagic sedimentation and cycling of new and regenerated organic matter production in the Arctic Ocean.

The present study attempts to outline the holistic „structural image“ of the Arctic microplankton inhabiting the pelagic zone in the Saint Anna Trough area. The pelagic protists of 2-200 µm size range (nano- and microplankton) including a wide variety of taxonomic and ecophysiological groups of planktonic organisms. are an objective of our study. Of course, there is not possible to give a full inventory of plankton in this size fraction as there is no universal method for their counting and taxonomic identification. Therefore, most of the smallest protists have remained unidentified, and therefore we can only work with some size categories of the microplankton. Without special experimental research, the trustworthy identification of a prevailing type of metabolism (auto-, mixo-, phago- or osmotrophy) was also impossible within the limits of the methods used. However, our data on the „macrostructure“ (on group an d genus level) of the community and patterns of its distribution over the water column would serve as a preliminary basis for further advanced field and experimental studies in this direction. Below we deal only with the data on diatom and flagellate assemblages. Planktonic ciliates will be considered elsewhere (Druzhkov, Druzhkova, 1998).

Material and methods

Sampling of the protist microplankton (2-200 μm) was carried out during the ARCTIC'96 (ARK XII) expedition of RV *Polarstern* to the eastern Arctic Ocean (July - September 1996) (Augstein et al., 1997).The stations 3 to 18 were located along a transect across the northern Saint Anna Trough (24 - 28 July) (Fig.1).

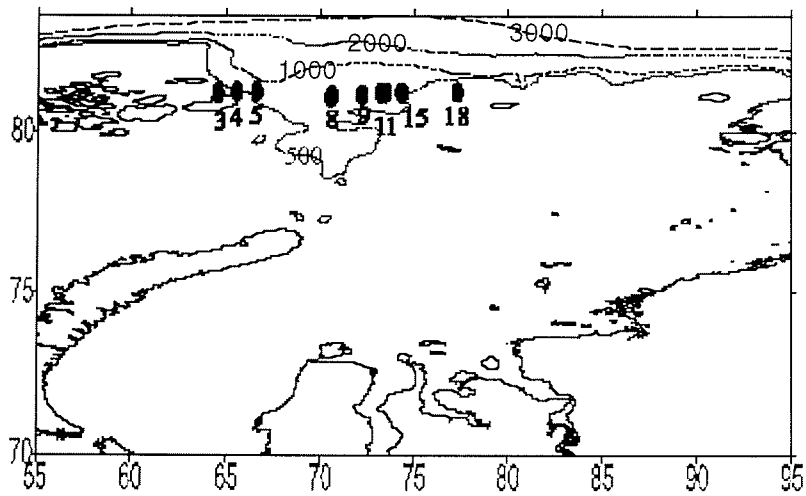

Fig.1: The study area: location of the stations on the transect and bathymetry.

The water samples (200ml) were taken from the rosette sampler and preserved with 1% Lugol solution. After 3 days of sedimentation (Edler, 1971) the samples were concentrated to a volume of 2-3 ml (Sukhanova, 1983). Identification and enumeration of microplanktonic organisms larger than 15 μm were carried out in the 0.1 ml counting chamber (Druzhkov, Makarevich, 1988) under the Amplival (Zeiss) microscope at a magnification of 200x (for details of the procedures, *see* Fedorov 1979).

Cell dimensions of most microalgae were measured individually with the ocular micrometer at a magnification of 400x, and then biovolumes were calculated using the recommended systems of approximation to simple geometric bodies (Edler, 1979; Plinski et al., 1984). All biovolumes were calculated as the means of individual cell volumes (Clarke et al. 1987). The mean biomasses of some dominant diatom species were adopted from the literature sources (Makarevich et al., 1993). Microplanktonic organisms smaller than 15 μm were counted and measured at a magnification of 400x in the same counting chamber. Some large and rare microplankton taxa were enumerated and identified in the entire sample volume of the Bogorov chamber under the stereomicroscope MBS-10 (magnification 32x).

Results and discussion

1. The taxonomic composition

The pelagic protist community in the study area was rather diverse. Although most smaller flagellates were not identified, 134 microplankton taxa were recorded in the samples. Of these, the diatoms accounted for 39 % of the total number of species (52 taxa). Centric and pennate diatoms were encountered on parity basis (26 taxa in each group). The bulk of the diatom assemblage consisted of taxa of the early-spring and cryophilic arcto-boreal flora dominated by the genera *Chaetoceros* (11 species), *Nitzschia* (9 species), *Navicula* (5 species), and *Thalassiosira* (9 species).

Somewhat more diverse were dinoflagellates (60 taxa) making up 45 % of the total species number. Most of them were unarmoured forms from the order Gymnodiniales (36 species). The gymnodinioid populations of *Amphidinium* spp. (8 species), *Gymnodinium* spp. (11 species) and *Gyrodinium* spp. (8 species) dominated in the study area, and were distributed all over the water column.

As stated above, most smaller flagellates were taxonomically not identified as their identification requires special methods. Only 22 taxa of flagellates were recognised in our material which belong to a number of classes of microalgae and zooflagellates (Choanoflagellidea - 2 species, Chrysophyceae - 2, Cryptophyceae - 3, Dictyochophyceae - 3, Euglenophyceae - 3, Kinetoplastidea - 3, Prasinophyceae - 2, Prymnesiophyceae - 2, and Raphidophyceae - 2 species). However, even this extremely reduced „selection" of randomly identified taxa reflects the potential complexity and diversity of the taxonomic structure of the nanoflagellate assemblage in the study area.

2. The basic structure of the microplankton community

In general, flagellated protists dominated in the study area. The contribution of diatoms to the community biomass was remarkable only in the upper 20-40 m layer of the pelagic zone. In the most productive, western part of the transect, diatoms accounted for 10-65 % of the total microplankton biomass (on average, about 20%), while in the eastern part, closer to Severnaya Zemlya, their percentages were significantly lower ranging from 5-25 % (usually about 10%). Below 50 m the biomass of diatoms rarely exceeded 5 % of the total microplankton biomass.

Correspondingly, in the rest of the water column there was an absolute predominance of flagellates. In the upper 50-100 m, dinoflagellates made up from one third to half of the total biomass of flagellates. Their biomass increased in the lower pelagic zone, where they accounted for up to 80-90 % of the flagellate biomass. This shift in dominance was largely due to the almost complete disappearance of photosynthetic nanoflagellates such as

Plagioselmis spp., *Ochromonas* spp., *Phaeocystis* spp., and *Chrysochromulina* spp.

3. The distribution in the pelagic zone

The most prominent features of the distribution of microplankton in the study area were (1) preferential concentration of the populations in the uppermost water column (the polar mixed layer and upper halocline), and (2) much higher densities of all microplanktonic organisms in the western part of the transect nearest to Franz Josef Land (Fig.2 and 3). The areas west of Severnaya Zemlya were most depleted with respect to both microplankton and major nutrients. The first pattern is quite understandable and characteristic of the whole Arctic Ocean: it is due to the thin surface layer where the water column stability and light climate is favourable for photosynthesis (Anderson, Dyrssen, 1989; Jones et al., 1990; Harrison, Cota, 1990; Smith, Sakshaug, 1990; Anderson, 1995).

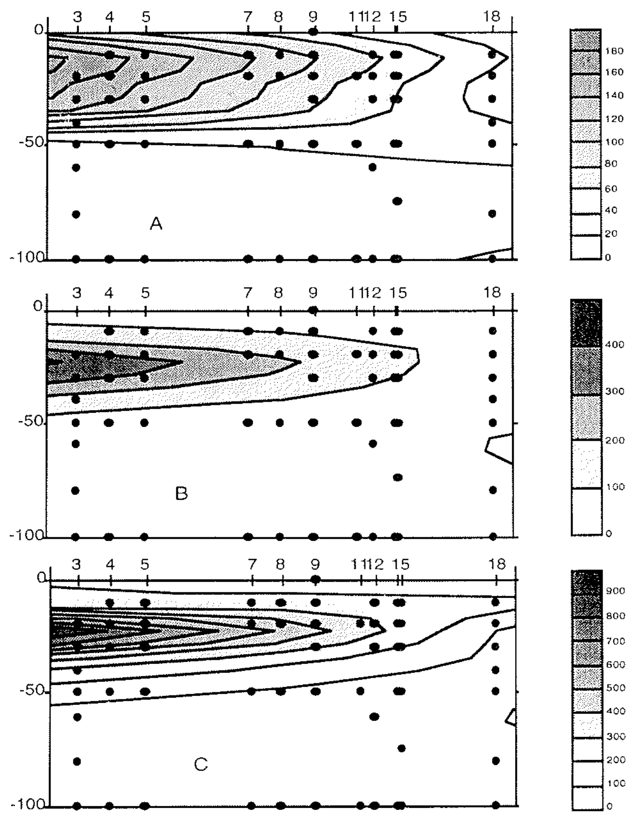

Fig.2: The distribution of the microplankton biomass (mg dm^{-3}) in the upper 100 m pelagic zone. A - diatoms, B - dinoflagellates, C - total flagellates (vertical scale - depth, m; horizontal scale - numbers of the stations).

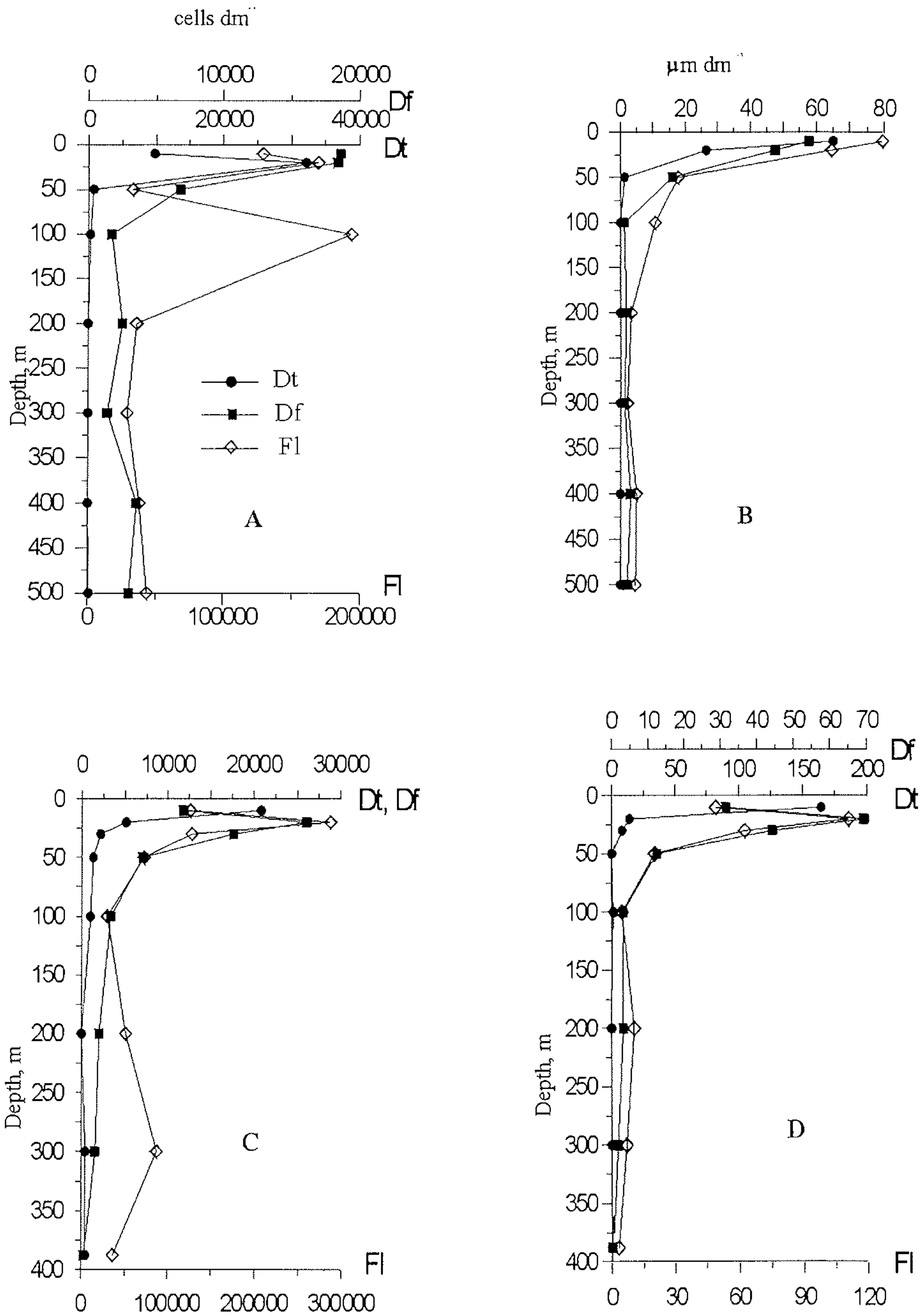

Fig.3: The vertical distribution of microplankton on the selected stations of the Saint Anna transect: St. 7 (A, B) and St. 4 (C, D). A, C - density (cells dm^{-3}); B, D - biomass (mg dm^{-3}). Vertical scale - depth, m. Designations: Dt - diatoms, Df - dinoflagellates, Fl - total flagellates.

An explanation of the second feature is not so easy since the circulation patterns in the study area are rather complicated and poorly known (Tantsyura, 1959; Andrew, Kravitz, 1974; Loeng et al., 1993, 1995). Such a distributional trend may originate from the sea ice conditions and surface circulation features. The surface outflow of nutrient depleted shelf water (after the spring bloom) from the Kara Sea occurs largely along the eastern slopes of the Saint Anna and Voronin troughs extending into the northern part of the basin. Although surface waters in the western portion of the transect flow to the open ocean (Andrew, Kravitz, 1974; Dobrovolsky, Zalogin, 1982), the observed patchiness of the phytoplankton bloom may be formed by fuelling the phytoplankton growth (and as a consequence, mixotrophic and heterotrophic activities of the microplankton community) with nutrients entrained into the upper pelagic zone with melt water from the large polar archipelagos (Novaya Zemlya and Franz Josef Land) located west of the study area. Recently, such entrainment has been demonstrated for the phytoplankton community of the northernmost areas of the south-western Kara Sea (Makarevich et al. 1997). Much more severe oceanographic, sea ice and meteorological conditions near Severnaya Zemlya archipelago located at the boundary between the Kara and the Laptev seas (Dobrovolsky, Zalogin, 1982), do not favour intense ice and snow melt there, thus not allowing the formation of proper light climate and entrainment of nutrients to the depleted top layer of the ice-covered pelagic zone. This might result in the observed impoverishment of the microplankton community.

The Atlantic water located below 100 m water depth tended to be most impoverished with respect to the microplankton. In contrast, the density and biomass of flagellates usually slightly increased in the cold near-bottom water (Fig.3) being apparently the outflow from the Kara Sea (*see* Andrew, Kravitz, 1974), and this increase was accompanied by reappearance of elevated concentrations of particulate matter (visual estimates).

4. Functional structure of the microplanktonic community

In general, the whole microplankton community of the uppermost Arctic pelagic zone may be subdivided into two functional, „metabolic“ compartments closely interrelated in space and time but differing essentially in a functional sense. Indeed, there is also some spatial separation between them (Fig. 2 and 3). The first compartment occupies primarily the polar mixed layer and uppermost portion of the halocline. This compartment is related to the ice habitats, the ice-driven thin top layer of the pelagic zone, and to marginal ice zones. It consists of obligate autotrophic forms represented primarily by diatoms and, possibly, by some flagellates such as *Phaeocystis* spp. and *Chrysochromulina* spp. The principal environmental function of this compartment is the production of new particulate and dissolved organic matter replenishing the top pelagic zone. These plankters therefore promote conditioning and structuring the environment for maintenance and active proliferation of the components of the second compartment.

This second compartment which is located in the water column slightly below the first one migrates to the upper halocline and consists of mixotrophic and obligate heterotrophic taxa belonging to a wide variety of flagellated microalgae and zooflagellates. About half of their biomass is formed by the abundant and diversified dinoflagellate assemblage. This group of microplankton is primarily dependent on the new (and also recycled) organic matter introduced into the top pelagic zone by the different groups of autotrophs. However, members of this compartment also photosynthetic using a number of mixotrophic metabolic strategies. Pelagic protists are used as model objects for studying different modes of mixotrophy. Their own chloroplast-based photosynthesis combined with phago- and/or osmotrophy, retention of live chloroplasts from prey organisms, and photosymbiosis of different modes are most usual means to gain energy from the pelagic environment and biota (Sanders, Porter, 1988; Stoecker et al., 1989; Taylor, 1990; Pierce, Turner, 1992).

The representatives of the autotrophic compartment may be only accidentally found in the lower pelagic zone, while the components of the mixotrophic-heterotrophic community are found down to the bottom. Of course, their diversity and abundance rapidly decrease with depth, but even in the bottom waters the flagellate populations (including dinoflagellates) reach traceable biomass levels (up to 8 mg dm^{-3}). Anyway, the identifiable part of the community is extremely impoverished due to the absence of light and low levels of processible organic matter. Only few species are common in the intermediate and bottom waters of the pelagic zone. These are *Gyrodinium flagellare*, *Gymnodinium wulffii*, *G. blax*, *G. micrum*, and sometimes *G. veneficium*. These populations thrive on (together with the bacterioplankton and the smallest flagellates) sinking organic matter. At least, the layers of somewhat elevated densities of flagellates in the lower water column (often located near the bottom) are correlated (visual estimates) with higher concentrations of particulate matter. Their participation in conditioning the particulate matter which enters the bottom habitat seems to be a major environmental function of these microplanktonic organisms.

In conclusion, our results allow to consider the microplanktonic community inhabiting the deep pelagic zone of the high Arctic from a holistic point of view, thus mitigating, to some extent, the hypnotic influence of „pure" phytoplankton on most of the earlier microplankton studies carried out in the Arctic Ocean. Further intense research on the role of the microplankton community in forming particulate matter sedimenting from the pelagic zone would significantly increase our understanding of the ecological processes related to the pelagic sedimentation in the Arctic.

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BIOMASS OF LARGE FORAMINIFERA IN THE ST. ANNA TROUGH

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Abstract

The abundance of large agglutinated tests has suggested that high biomasses of foraminifera occur in troughs on the western Arctic Eurasian shelf. To verify this, we measured foraminiferal biomass (protoplasmic volume) at seven stations close to 80°N in the St. Anna Trough, a shelf depression open to the Arctic Basin. The abundance of arenaceous tests was high owing to good postmortem preservation in the surface sediment. Foraminiferal biomass was moderate (range = 0.06 - 1.7 g/m^2) compared with common shelf values and increased with water depth. The foraminiferal contribution to the biomass of the benthic community was negligible on the slopes of the trough but below 500 m water depth, where the macrofauna is scarce, the foraminifera:macrofauna ratio reached 0.3. The bulk of the foraminiferal biomass consisted of specimens approximately 2 mm in diameter. The volume of cytoplasm in tests of the dominant foraminiferan *Reophax pilulifer* increased in response to the summer pulse of organic detritus.

Introduction

Benthic foraminifera, a group of meiofauna (Snider et al. 1984), are thought to play an important role in nutrient cycling owing to their high biomass which occasionally exceeds that of macrofauna (Lipps 1983; Altenbach and Sarnthein 1989; Gooday et al. 1992). Nevertheless, only one previous internationally published study reports biomass values for this group of organisms in the Arctic (Paul and Menzies 1974) and we therefore present new data on foraminiferal biomass from a high Arctic area.

Large agglutinated foraminifera are a visually conspicuous deposit in the St. Anna Trough and in many other deeper areas of the Barents-Kara shelf. The abundance of large tests has inspired a hypothesis that very high biomasses of foraminifera might exist in these areas (Mesyacev 1929; Zenkevitch 1963; Pogrebov et al. 1995; Kuznetsov 1996). The aim of the present study was to investigate (1) whether the abundance of large tests in the St. Anna Trough reflected a high foraminiferal biomass and (2) whether the biomass of foraminifera exceeded that of macrofauna.

Study area

The St. Anna Trough is ice covered most of the year. Gloersen et al. (1992) reported that during a ten years period (1978-87) only six summers were ice free and only then for one to two months. During the sampling period (22-24

August 1995) the sea-ice margin was situated within several kilometers north of the route (Fig. 1B).

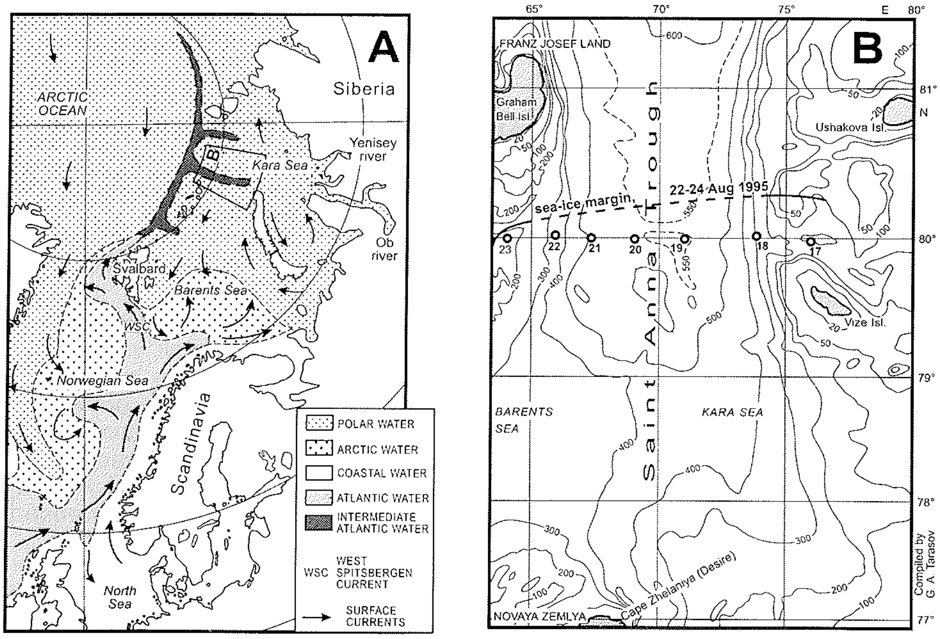

Fig. 1: Maps showing location of the sampling stations. A. Major surface water masses of the Barents-Kara and adjacent seas after Mosby (1968) and Hopkins (1991) and the main stream of intermediate Atlantic Water with the study area framed. B. Bathymetry of the St. Anna Trough and location of the sampling stations.

A stream of warm Atlantic Water deepens north of Svalbard and reaches the St. Anna Trough as an intermediate water mass within 1.5 to 2 years (Timofeev 1962; Coachman and Aagaard 1974). All published hydrographic surveys of the St. Anna Trough show a western positioning of Atlantic Water (Hanzlick and Aagaard 1980; Milligan 1981; Hald et al. in prep.) which suggests Coriolis-forced advection from the north. By contrast, the transport of Atlantic Water to the St. Anna Trough across the Barents shelf has been recently suggested (e.g. Rudels et al. 1994; Schauer et al. 1995). This hypothesis has not been supported with empirical evidence.

During the sampling period a layer of Polar Water (Coachman and Barnes 1962) with a very low temperature (<-1.5°C) and a decreased salinity (33.5-34.5‰) occupied an interval of 20 to 60 m depth in the western part of the transect (Fig. 2, Korsun 1996). A warm body of surface water in the eastern part of the transect (Fig. 2) probably corresponded to the main northward extension of Continental runoff, emanating from the Ob and Yenisey estuaries (Hanzlick and Aagaard 1980; Milligan 1981). Atlantic Water (temperature > 0°C) occured below 75-100 m at the western flank of the trough. The core of Atlantic Water had a temperature above 2°C and high salinity (34.85 - 35.0‰). Arctic Bottom Water relatively warm (ca. -0.6°C), with a high salinity (34.8 - 34.9‰) occupied the lower part of the water column at the eastern slope (Fig. 2). Cold (ca. -1.7°C) bottom water, an inferred result of brine rejection (McClimans and Nilsen 1990), was not found in the trough.

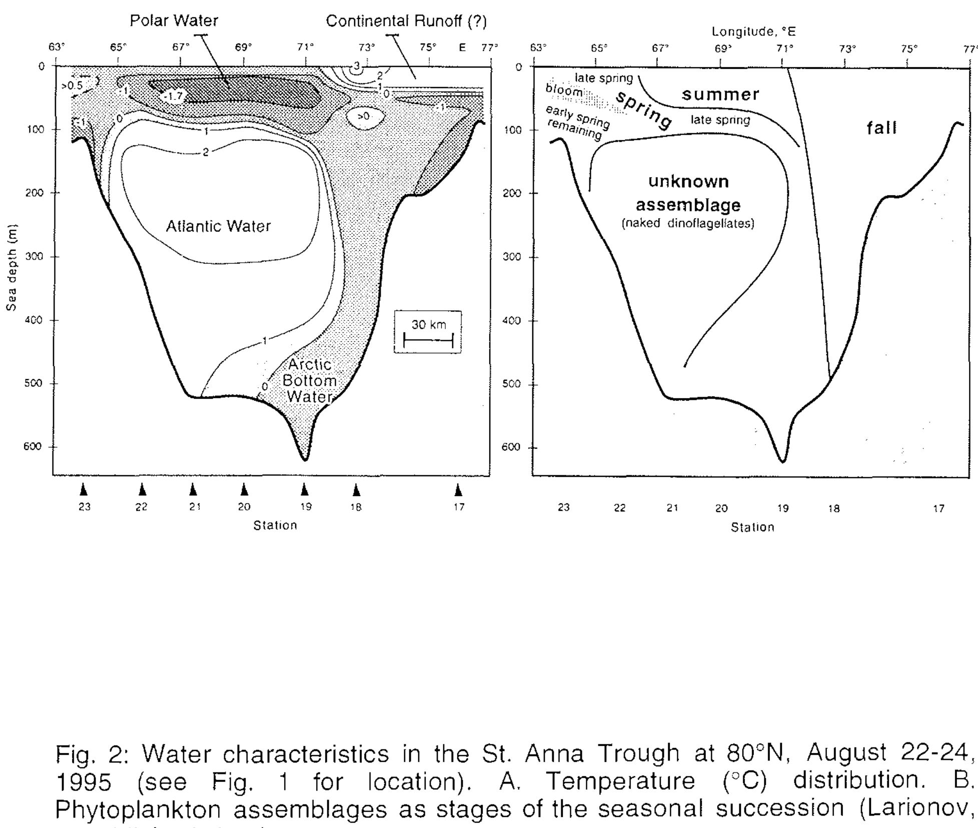

Fig. 2: Water characteristics in the St. Anna Trough at 80°N, August 22-24, 1995 (see Fig. 1 for location). A. Temperature (°C) distribution. B. Phytoplankton assemblages as stages of the seasonal succession (Larionov, unpublished data).

Fine grained sediments dominate the trough. An upper oxidized layer is brown reflecting a high concentration of MnO_2 (> 0.5%; Gorshkova 1957; Gurevich 1995). This "brown mud" (Klenova 1960), which covers all shelf depressions in the Kara Sea and in the northern Barents Sea (Klenova 1960; Gurevich 1995), reaches its greatest thickness (20-30 cm) in the St. Anna Trough (Andrew and Kravitz 1974).

Organic carbon in the surface sediment, which is possibly delivered by a northbound current from the Ob and Yenisey estuaries, reaches relatively high concentrations (>1.6%) along the eastern slope of the St. Anna Trough (Andrew and Kravitz, 1974). The lowest values of organic carbon (<1%) occur in the northwestern part of the trough where the Atlantic Water advection is maximal.

Vinogradov et al. (1995) characterized the Kara Sea area as oligotrophic based on analysis of phyto- and zooplankton. Macrofaunal biomass in the St. Anna Trough, like all areas of the Barents-Kara shelf covered with brown mud, is low (ca. 10 g/m^2; Zenkevitch 1963).

The phytoplankton community aged eastward in the trough (Fig. 2B). At the western station, a pronounced bloom was dominated by the diatoms typical of late spring in the northeastern Barents Sea (Larionov 1995). The bloom deepened and weakened to the east, though still presents with densities numbering thousands of cells per liter. A summer mixo-heterotrophic assemblage occupied Polar Water. In the eastern, warmest part of the transect, the phytoplankton community was degraded showing a late stage of the seasonal succession. The assemblage found in deeper parts of the western side of the trough consisted of small (12 to 20 μm) naked dinoflagellates with densities of 105 cells per liter. This assemblage, previously unknown from the Barents and Kara seas, was presumably transported by incoming Atlantic Water. The relative abundance of organic detritus was highest in the central part of the trough, in and under Polar Water, and distributed throughout the water column.

Methods

Samples were collected in August 1995 along a transect of seven stations across the St. Anna Trough at 80°N lat. (Fig. 1B) during an expedition of the Murmansk Marine Biological Institute. Two stations (no. 17 and 18) characterize the eastern slope, three (19, 20, 21) the central flat area and two (22, 23) the western slope. The distance between the stations ranged from 25 to 50 km.

Sediment

Sediment was retrieved with an "Ocean-50" grab, 0.25 m^2 at a penetration of 15-30 cm. Samples for the lithological analyses were taken from the upper 1 cm of the sediment. Boundaries between the grain size fractions were 0.002, 0.063 and 2 mm. A Leco induction oven was used to quantify the content of total and organic carbon by measuring acid (HCl) treated and non-acid treated samples, respectively. The proportion of calcium carbonate was calculated as %CaCO3 = 8.33 * (%TC %TOC), where TC = total carbon and TOC = total organic carbon.

Macrofauna

Two or three full grab samples at each station were processed for the macrofaunal analysis. The sediment was washed through a 0.5 mm sieve and macrofauna were picked from the residue, identified and wet weighed to 0.01 g before being stored in 4% formalin. Complete faunal lists are presented in Korsun (1996) or available on request.

Foraminifera

Large foraminifera (>1.0 mm) comprise at least 90% of foraminiferal biomass from the size fraction >0.1 mm in muddy sediments in the Barents Sea (Korsun et al. 1994). Sediment samples (whole grab) were therefore washed on a 0.5 mm screen and we assumed that the underestimation of foraminiferal biomass due to omitting the fraction <0.5 mm was negligible.

Foraminifera and macrofauna were analyzed in the same samples. After removal of metazoans the >0.5 mm residue of the grab samples was fixed in 4% formalin and then transferred within one week to Bengal Rose stain (1 g/l) in 70% ethanol. The stain and ethanol were removed before counting by washing on a 0.5 mm screen. Appropriate sample sizes were obtained with a wet micro-splitter. Foraminifera were identified and counted in water under a dissecting microscope with transmitted and incident light. With one exception (station 23) two samples were processed per station. Results from each pair of replicates were combined and mean values were used in the analysis of data.

The biomass of foraminifera was estimated after determination of protoplasmic volume (Saidova 1967). The shape of the intratest protoplasmic body in each specimen was approximated as a sphere or a cylinder, as appropriate, and was then measured with an ocular micrometer. The details of the technique are given in Korsun et al. (1998).

As the grab penetration depth was 15 to 30 cm, it is safe to assume that all living foraminifera, even deep infaunal, were sampled. Consequently, we expressed the density of living foraminifera as standing crop, i.e. the number of specimens per unit area, where our standard area was 10 cm^2 (Murray 1991).

Results

Sediment

The surface sediment in the study area was a brown oxidized mud. At station 23 it was 2 cm thick and underlain by reduced grey sediment. At the other stations the thickness of the brown mud exceeded the penetration of the grab. The CaCO3 concentration was <2.7% at all stations (Table 1). The organic carbon content showed two peaks of 1.5% in the shallow area southeast of Franz Josef Land and under the eastern slope of the trough (Fig. 3H).

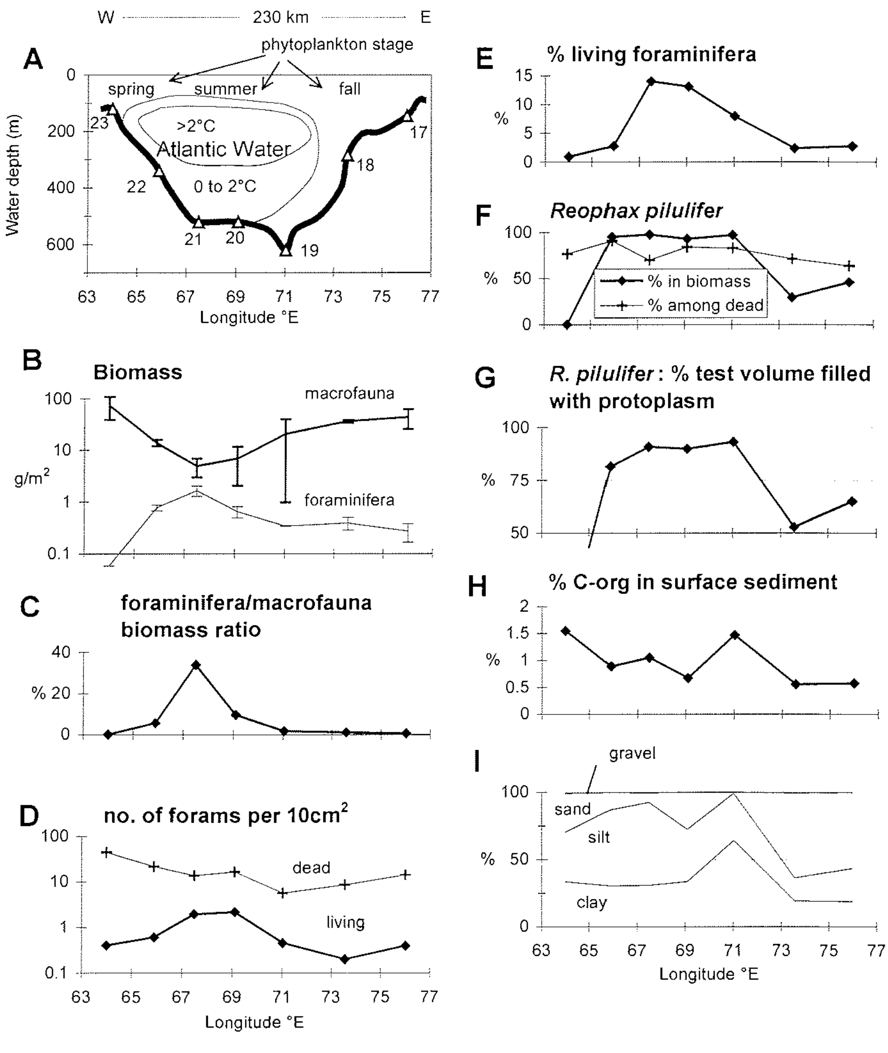

Fig. 3: Distribution of selected parameters across the St. Anna Trough, 80°N, in August 1995. A. Bottom profile, sampling site location, position of Atlantic Water and phytoplankton assemblages. B. Biomass of macrofauna and foraminifera (error bar = ±1 standard deviation). C. Foraminifera:macrofauna biomass ratio. D. Foraminiferal density. E. % living foraminifera. F. *R. pilulifer* contribution to foraminiferal biomass and to dead foraminiferal density. G. Proportion of *R. pilulifer* intratest volume filled with protoplasm. H. % organic carbon. I. Grain size distribution.

Table 1: Station list and sediment characteristics.

Stat.	Position		Sea depth	Grain size %				$CaCO_3$ %	C-org %
no.	N	E	m	clay	silt	sand	gravel		
23	79° 59.7´	64° 00´	95-110*	33.6	36.7	29.0	0.7	0.7	1.5
22	80° 01.2´	65° 54´	305-315	30.5	56.6	12.8	0.2	1.4	0.9
21	80° 00.3´	67° 30´	530-530	30.9	61.5	7.3	0.3	1.6	1.1
20	79° 59.0´	69° 06´	520-520	33.6	38.8	27.6	0.1	2.7	0.7
19	79° 59.0´	71° 02´	620-630	64.1	35.0	1.0	0	0	1.5
18	80° 01.3´	73° 34´	280-285	19.2	17.1	63.2	0.5	1.1	0.6
17	79° 59.2´	76° 01´	135-140	18.9	24.5	56.3	0.3	0.7	0.6

* Depth range due to ship drift

Macrofauna

Macrofaunal biomass was greater at the flanks (ca. 50 g/m^2) than in the central deep part of the trough (<10 g/m^2). Lowest values (minimum 5 g/m^2) were recorded under the western slope (Fig. 3B).

Foraminifera

Nineteen species of >0.5 mm foraminifera were present (Table 2). No living (stained) specimens of *Reophax nodulosus*? and *Hyperammina elongata* were found.

The dead fauna at all the stations was dominated by Reophax pilulifer (Table 3A, Appendix). Macrofaunal studies in the Kara and Barents seas following Stschedrina (1949) have identified the species as *Hormosina globulifera* Brady (e.g. Zenkevitch 1963; Kuznetsov 1996). Reophax scorpiurus *and Astrorhizoides polygona* also occurred throughout the transect but at lower frequency. *Cribrostomoides subglobosum* was present in the central deep. *Rhabdammina abyssorum*, *Hyperammina elongata*, *Saccorhiza ramosa*, *Astrammina* sp., *Reophax nodulosus*? and *Labrospira crassimargo* occurred only on the slopes of the trough. There was no asymmetry in the distribution of dead foraminifera across the trough.

Foraminiferal biomass was distributed asymmetrically with a maximum of 1.7 g/m^2 under the western flank of the trough (Fig. 3B). Biomass consisted mostly of R. pilulifer (Table 3B, Appendix) which, in the central part of the trough, showed a very high (90%) index of protoplasm filled intratest volume (Fig. 3G). The occurrence of living foraminifera increased to 14% in the central deep (Fig. 3E). The size distribution of the foraminiferal standing crop was bimodal (Fig. 4). The first peak consisted of small foraminifera including *C. subglobosum*, *R. scorpiurus* and *L. crassimargo*. The second peak consisted mainly of *R. pilulifer*. Foraminifera with an external test diameter >1 mm accounted for 37% of the >0.5 mm foraminiferal standing crop and 93% of the >0.5 mm foraminiferal biomass.

Table 2: List of all foraminiferal taxa (size fraction >0.5 mm) in the sediment samples from the St. Anna Trough.

1	Allogromiina gen. sp.	
2	*Astrorhizoides polygona*	(Heron-Allen & Earland, 1934)
	(= *Astrorhiza arctica*)	Stschedrina, 1964
3	*Rhabdammina abyssorum*	M. Sars, 1868
4	*Hyperammina elongata*	Brady, 1878
5	*Saccorhiza ramosa*	(Brady, 1879)
6	Astrammina sp.	
7	*Reophax pipulifer*	Brady, 1884
8	*Reophax nodulosus*?	Brady, 1884
9	*Reophax atlantica*	(Cushman, 1944)
10	*Reophax scorpiurus*	Montfort, 1808
11	*Labrospira crassimargo*	(Norman, 1892)
12	*Cribrostomoides subglobosum*	(G. O. Sars, 1872)
13	*Cornuspira foliacea*	(Philippi, 1844)
14	*Quinqueloculina seminula*	(LinnE, 1758)
15	*Miliolinella subrotunda*	(Montagu, 1803)
16	*Planispiroides bucculentus*	(Brady, 1884)
	(= *Miliolinella subrotunda var. trigonia*)	(Weisner, 1931)
17	*Pyrgo williamsoni*	(Silvestri, 1923)
18	*Elphidium bartletti*	Cushman, 1933
19	*Nodosaria flintii*	Cushman, 1923

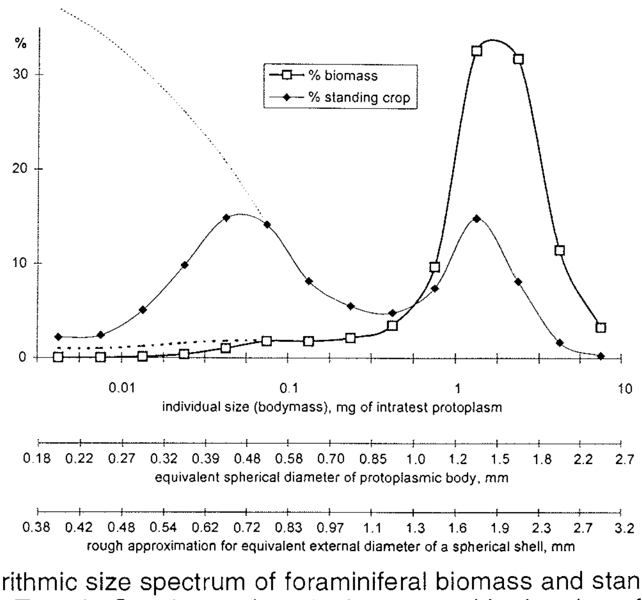

Fig. 4: Logarithmic size spectrum of foraminiferal biomass and standing crop in the St. Anna Trough. Specimens (n = 416) measured in the sieve fraction >0.5 mm are separated into size classes with a logarithmic increment of 100.25 mg (cf. Gerlach & al. 1985). The x-axes are plotted in alternative scales. The curves show the contribution of each size class to foraminiferal biomass and standing crop. No smoothing has been applied. Large specimens, ca. 2 mm in external diameter, make up the bulk of foraminiferal biomass. The dashed curves show the probable contribution to the foraminiferal biomass and standing crop by specimens <0.5 mm which were omitted from the sieved fraction.

Discussion

The abundance of large arenaceous tests

Zenkevitch (1963) showed that the weight of large foraminiferal tests in the Kara Sea can be as large as 0.6 kg/m^2. Several authors have predicted the primacy of foraminiferal biomass in the benthic systems of the deeper Barents-Kara shelf owing to the reported abundance of large foraminiferal tests (Mesyacev 1929; Zenkevitch 1963; Pogrebov et al. 1995; Kuznetsov 1996). The studied assemblage of large foraminifera from the St. Anna Trough contains few living specimens (1 to 14%) indicating that the abundance of foraminiferal tests is a result of good postmortem preservation. Our measurements show that the biomass of foraminifera in the St. Anna Trough is only moderate (0.06 to 1.7 g/m^2) compared with common shelf values, consistent with the notion of oligotrophy of this area.

Dense accumulations of large arenaceous foraminifera typically occur along continental margins (Gooday et al. 1997). When these abundant occurrences have been examined for live specimens they have appeared to consist largely of dead tests (Gooday 1983; Linke and Lutze 1993). The studied assemblage from the St. Anna Trough also belongs to this type of cemetery-like accumulations.

Foraminifera and macrofauna

The foraminifera:macrofauna ratio in the St. Anna Trough increased with increasing water depth (Fig. 3C). The contribution of foraminiferal biomass was negligible on the slopes and accounted for approximately only 1% of macrofaunal biomass. Deeper in the trough, however, foraminiferal biomass was comparable to that of the major macrofaunal groups, Polychaeta, Echinodermata, and Bivalvia, and reached 34% of the total macrofaunal biomass (Table 3C, Appendix). Thus, in the deeper parts of the St. Anna Trough, foraminifera were an important benthic group in terms of biomass. Considering that benthic foraminifera are able to maintain energy-turnover rates comparable to those of bacteria (Linke 1992), we predict that in the deeper parts of the St. Anna Trough the role of foraminifera in the benthic community energy flux is likely to be at least as large as that of the total macrofauna.

The distribution of foraminiferal biomass was inverse to that of macrofauna (Fig. 3B). Such an inverse relationship between meiofauna (foraminifera included) and macrofauna is common for marine biocoenoses and the meio:macrofauna ratio normally increases with water depth (e.g. Golikov and Averincev 1977; Thiel 1983; Shirayama 1984; Gooday et al. 1992; Graf 1992). It is generally thought that the meiofauna thrive wherever conditions for the macrofauna are unfavourable, probably reflecting predator pressure, the destructive effect of bioturbation or trophic competition (Buzas 1978; Cedhagen 1993; Golikov and Averincev 1977).

Size spectrum

Most of the biomass consisted of a few large specimens (Fig. 4), reflecting the fact that the diameter-volume relation is allometric. The volume of a spherical object is a 3rd power function of its diameter; a two-fold difference in diameter between two specimens will therefore correspond to an eight-fold (23) difference in volume and, hence, mass.

Two size groups (mean test diameter approximately 0.7 and 2.0 mm) were most frequent in the foraminiferal fauna (Fig. 4). The discontinuity between the two peaks occurred at a test diameter of approximately 1 mm which roughly corresponds in the size spectrum of marine benthos to the boundary between the meio- and macrofauna (Fenchel 1969; Gerlach et al. 1985; Warwick and Joint 1987). Confirmation of this bimodal frequency distribution in other regions would provide a solid biological basis for the separation of foraminifera into meio- and macrofauna (e.g. Gooday 1990).

Short-term foraminiferal response to the summer organic pulse

Short-term processes in benthic foraminiferal populations have been increasingly acknowledged as important in the utilization of organic pulses on the ocean floor (Gooday and Turley 1990; Altenbach 1992; Graf 1992; Linke 1992; Pfannkuche 1993; Linke et al. 1995). The volume of foraminiferal cytoplasm declines during periods of starvation and increases within a few days, filling up the intratest cavities, when food becomes abundant (Linke 1992).

Describing an extremely abundant occurrence of the large tubular foraminiferan *Hyperammina crassatina* (Brady) on the East Greenland shelf, Linke and Lutze (1993) noted that the few live specimens (1-6 individuals per 10 cm^2) were associated with a high level of metabolic activity. Gooday et al. (1997) predicted that some of the large agglutinated species can undergo rapid growth when food becomes sufficient.

The percentage of the intratest volume filled with cytoplasm in the dominant foraminiferan *R. pilulifer* changed substantially across the trough (Fig. 3G). High cytoplasm filling (ca. 90%) in specimens from the central part of the transect suggested good trophic conditions in this area.

In the Kara Sea the seasonal succession in the phytoplankton community is reduced to a single bloom which occurs at the beginning of the short ice-free period and which produces most of the annual phytoplanktic biomass (Savinov and Bobrov 1995). At the time when the samples in this study were collected, the bloom had crossed the trough from east to west (Fig. 2B). An increased concentration of suspended organic detritus observed in the central part of the transect (see the Study Area) was probably sinking residue of the bloom. We interpret the increased cytoplasm filling in *R. pilulifer* from the central deep (Fig. 3G) as a response to the pulse of fresh organic detritus.

Conclusions

The abundance of large foraminiferal tests in the brown mud does not reflect a high biomass but only good postmortem preservation of arenaceous tests. Foraminiferal biomass in the St. Anna Trough is moderate (0.06 to 1.7 g/m^2) compared with common shelf values and does not exceed the total macrofaunal biomass (5 to 75 g/m^2).

Foraminifera are an important benthic group in the deeper parts of the St. Anna Trough where macrofauna is scarce. In the deeper trough, foraminiferal biomass values are comparable to those of the major macrofaunal groups, including Polychaeta, Echinodermata and Bivalvia.

A total of 19 benthic foraminiferal species >0.5 mm in size, including 17 living and 7 calcareous forms, occurred in the sediment. Arenaceous forms dominated in terms of both biomass and the density of dead tests. *Cribrostomoides subglobosum* was common in the central deep (>500 m) whereas *Rhabdammina abyssorum*, *Hyperammina elongata, Saccorhiza ramosa*, *Astrammina* sp., *Reophax nodulosus*?, and *Labrospira crassimargo* occurred only on the slopes. Most of the foraminiferal biomass was *Reophax pilulifer.* This species also dominated dead assemblages throughout the transect.

Most of the foraminiferal biomass consisted of large specimens (ca. 2 mm in external diameter).

The population of *Reophax pilulifer* seemed to respond to the summer pulse of organic matter, resulting in an increase in the cytoplasmic volume.

Acknowledgments

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Appendix (Korsun et al.)

Table 3: Foraminifera and macrofauna in the St. Anna Trough, size fraction >0.5 mm. Each value is averaged from two or three subsamples (SD--standard deviation)

Station	23	22	21	20	19	18	17
A. Foraminiferal density							
living forams/10cm2	0,4	0,6	2,0	2,2	0,5	0,2	0,4
dead forams/10cm2	45	22	14	16	6	9	14
% living	1	3	14	13	8	2	3
A. Dead foraminifera (% no.)							
Allogromiina gen. sp.	<1			<1			
Astrorhizoides polygona	6	1		<1	1	1	<1
Rhabdammina abyssorum	1	5				<1	<1
Hyperammina elongata	<1	<1				<1	<1
Saccorhiza ramosa	<1	<1				1	1
Astrammina sp.	<1					<1	<1
Reophax pilulifer	77	91	70	84	83	71	64
Reophax nodulosus?	<1	<1				1	<1
Reophax atlantica	<1						<1
Reophax scorpiurus	9	<1	2	2	1	7	19
Labrospira crassimargo	7	1			1	19	16
Cribrostomoides subglobosum		3	27	9	14		
Cornuspira foliacea	<1	<1	1	<1			<1
Quinqueloculina seminula		<1	<1	2	<1	<1	
Miliolinella subrotunda				<1			
Planispiroides bucculentus	<1	<1		1			
Pyrgo williamsoni		<1					<1
Elphidium bartletti				<1		<1	
Nodosaria flintii						<1	
other five species	<1	<1		<1		<1	<1
no. of dead forams counted	112	109	114	206	100	129	146

Table 3: cont.

Station		23	22	21	20	19	18	17
B. Foraminiferal biomass, %								
Allogromiina gen. sp.		9			1			
Astrorhizoides polygona		60	<1			<1	37	
Rhabdammina			<1				10	1
Saccorhiza ramosa			2				<1	21
Astrammina sp.		7				<1	1	1
Reophax pilulifer			95	98	93	97	29	68
Reophax atlantica		2						<1
Reophax scorpiurus		12	<1	<1	1	<1	7	1
Labrospira crassimargo						1	9	6
Cribrostomoides			<1	1	3			
Cornuspira foliacea		10		<1				1
Quinqueloculina seminula			1	1	2	1		
Miliolinella subrotunda					<1			
Planispiroides					1			
Pyrgo williamsoni			1					<1
Elphidium bartletti							1	
Nodosaria flintii							5	
other seven species		11	1		2		6	1
no. of forams measured		20	37	107	50	68	105	29
C. Biomass of foraminifera and major macrofaunal groups, g/m2								
Foraminifera		**0,06**	**0,77**	**1,66**	**0,65**	**0,34**	**0,39**	**0,27**
	±SD	N/A	±0,10	±0,38	±0,16	±0,00	±0,11	±0,10
Bivalvia		**5,04**	**0,86**	**0,99**	**0,03**	**2,63**	**3,02**	**0,92**
	±SD	±7,01	±0,48	±1,11	±0,05	±1,37	±1,16	±0,45
Echinodermata		**15,0**	**0**	**0**	**0**	**10,4**	**9,20**	**13,6**
	±SD	±9,33				±18,1	±3,96	±19,2
Polychaeta		**29,3**	**12,6**	**3,24**	**6,26**	**3,55**	**3,21**	**25,9**
	±SD	±39,4	±1,47	±1,43	±4,02	±3,25	±0,55	±2,86
macrofauna total		**73,4**	**13,7**	**4,91**	**6,80**	**20,3**	**36,0**	**43,3**
	±SD	±34,6	±1,90	±1,92	±4,74	±19,4	±2,49	±17,9
forams/macrofauna ratio,		0,1	6	34	10	2	1	1

THE LIPID COMPOSITION OF PARTICULATE MATTER FROM THE TRANSITIONAL ZONE BETWEEN KARA AND LAPTEV SEAS

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Introduction

The lipid composition of particulate matter in oceanic environments can provide informations on the nature and origin of the organic matter as well as on their transformation processes. Molecular characteristics for lipids in the Arctic environment have been used as indicators of the sources and transformation of organic particulate matter (Smith et al., 1997; Fahl and Stein, 1997, 1999). However, the features of the lipid composition of particulate matter in the Arctic with its high seasonality of ice cover and primary productivity has been studied insufficiently.

Lipids are one of the most important compounds of organic matter. On the one hand, the composition of lipids is a result of the variability of biological sources (phyto- and zooplankton, higher plants, bacteria etc.). On the other hand, the lipid composition of particulate matter is undergone significant alteration during vertical transport. The organic matter balance in the Arctic marginal seas, such as the Kara and Laptev seas, is characterized by the significant supply of dissolved and particulate material by the major Eurasian rivers - Ob, Yenisei and Lena (Cauwet and Sidorov, 1996; Gordeev et al., 1996, Martin et al., 1993). In relation to the world's ocean the primary productivity values are lower in the Arctic seas due to the ice-cover. However local increased values of primary productivity can be connected with the melting processes inducing increased phytoplankton growth near ice-edge (Nelson et al., 1989; Fahl and Stein, 1997) and enhanced river supply of nutrients. These features can influence the proportion of allochtonous and autochtonous components of the organic matter in the Arctic marginal seas (Fahl and Stein, 1997; Stein and Fahl, 1999). Furthermore, increased lipid contents in aquatic environments were found near density discontinuities (Parish et al., 1988). Although being less informative than lipid studies on the molecular level the character of lipid composition analysis on the group could also be used for studying of particulate organic matter and its transformation in sedimentation processes in the Arctic. In this paper the investigation of the characteristics of lipid composition performed by Alexandrova and Shevchenko (1997) in Arctic seas was continued.

Methods

The samples from the transitional zone between the Kara and Laptev seas were taken during the RV "Polarstern" expedition ARK-XI/1 (Rachor, 1997) in September 1995 (Fig.1). The sampling was carried out by means of Niskin bottles attached to a CTD-sonde (conductivity, temperature, depth). At 7 stations in the Laptev and Kara seas 7 to 10 litres were filtered through Whatman filters (GF/F, diameters 47 mm). Samples were stored at -30 C until further treatment.

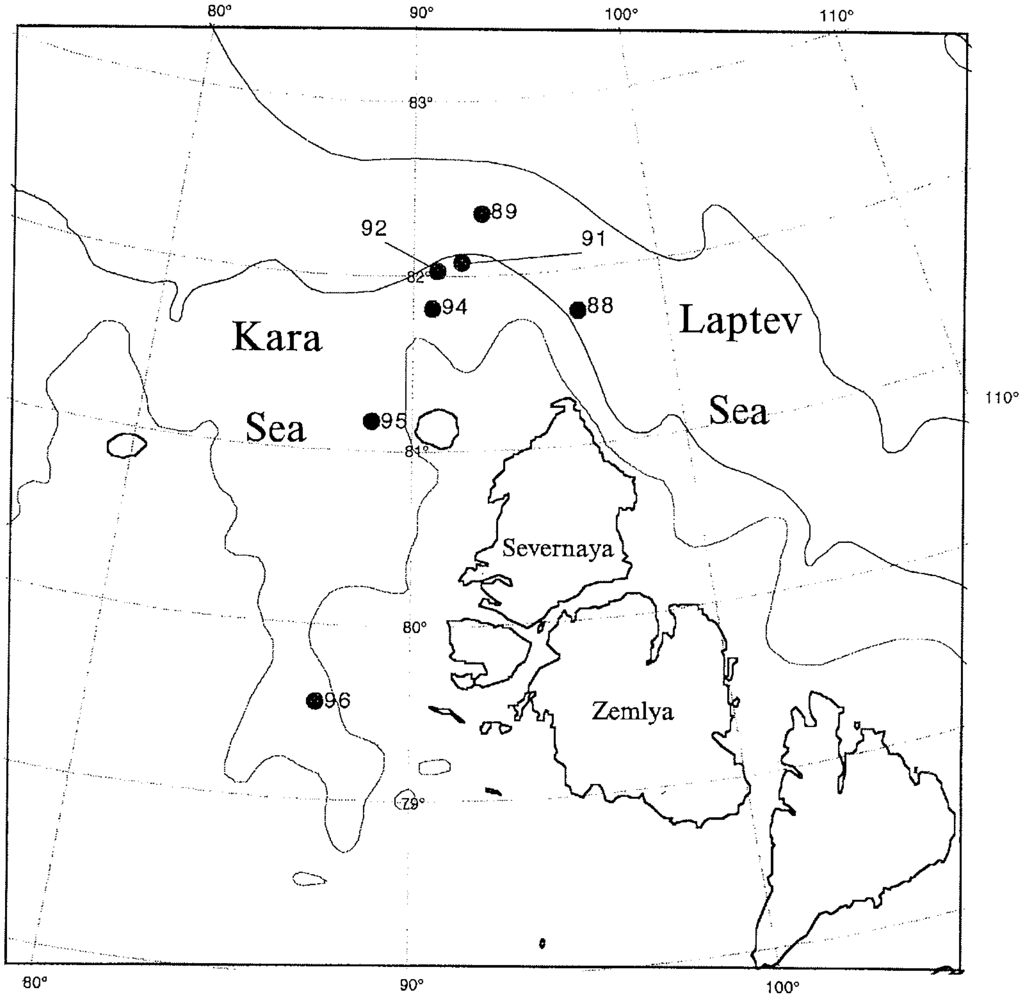

Fig. 1: Position of particulate lipid samples in the transitional zone between the Kara and Laptev seas in September 1995.

Lipid analysis

The extraction was carried out using chloroform-methanol (2:1, by vol.) as solvent (Bligh and Dyer, 1959). The different lipid classes were separated by thin-layer chromatography with flame ionization detection (IATROSCAN TH-10 Mark III) using hexane:diethyl ether:formic acid (85:15: 0.04, by vol.) as solvent. For qualification and quantification of hydrocarbons, wax esters, sterols esters, fatty acid esters, triacylglycerols, free fatty acids, sterols and polar lipids a standard mixture (Sigma Chemical Co., USA) was used.

Results and Discussion

The most important factors controlling lipid distribution in the Arctic seas are (1) surface water productivity, (2) preservation grade of lipids mainly depending on sedimentation rates and (3) supply of terrigenous matter.

To elucidate some of the most important processes determining lipid distribution in the marginal Arctic seas (such as Laptev and Kara seas) the lipid composition within the transitional zone between the Kara and Laptev seas was investigated and compared with data from the Ob estuary - Kara Sea transect (Alexandrova and Shevchenko, 1997).

Lipid concentrations of particulate matter along the shelf transect (stations 92, 94-96) are significantly lower than those along the continental slope (stations 88, 89, 91) near Severnaya Zemlya Islands (Fig.2, Table 1, Appendix). This difference is extremly high in the surface water. High lipid contents in the surface water layer are well correlated with the position of the ice edge which presumably caused an increasing primary productivity (Eicken et al., 1997; Fahl and Stein, 1997).

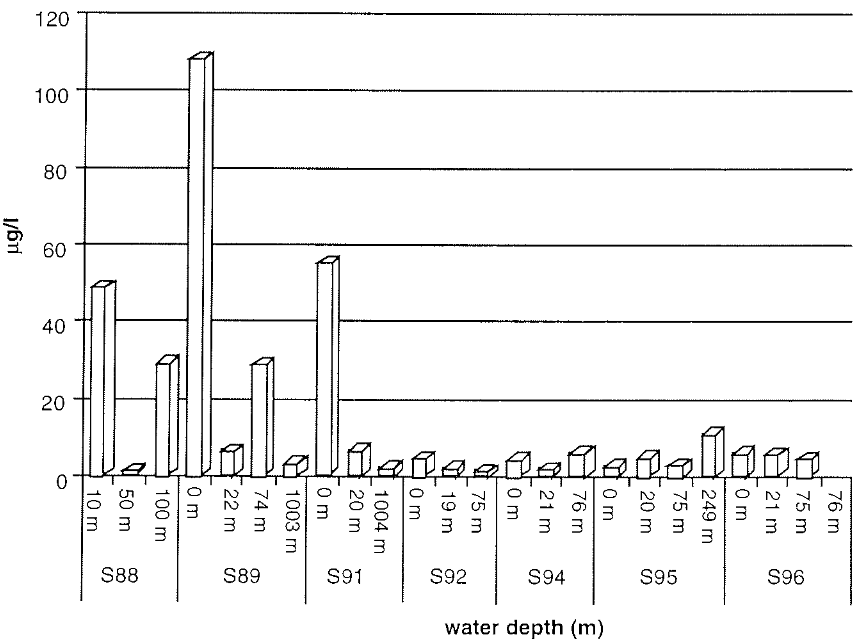

Fig. 2: Total lipid content in particulate matter (µ/l).

Due to mixing processes indicated in the hydrological profiles (see Rudels et al., 1997) at the stations located on the shallow shelf, the lipid distribution of the particulate matter is rather monotonous. The distribution along the continental slope is characterized by two maxima: the surface maximum already mentioned above and a maximum at the depth interval from 74 to 100 meters. Increased lipid concentrations of particulate matter within this layer can be explained by the occurrence of the pycnocline at this depth (Rudels et al., 1997). Thus, the more cold and dense water masses keep the particles back from sinking.

In general, hydrocarbons and polar lipids are the main components in all samples from the transitional zone between Kara and Laptev seas (Table1, Figs. 3 and 4). In comparison, the lipid composition of the Ob estuary - Kara Sea transect is very similar, except for the relatively high contents of wax esters and sterols esters originating from zooplankton which synthezise this energy-rich lipid classes (Alexandrova and Shevchenko, 1997). Triacylglycerols are of minor importance in the Ob estuary - Kara Sea transect. High contents of triacylglycerols, however, were found in the surface water layer near Severnaya Zemlya Islands as well as in the deeper waters along the shelf transect (Fig. 5).

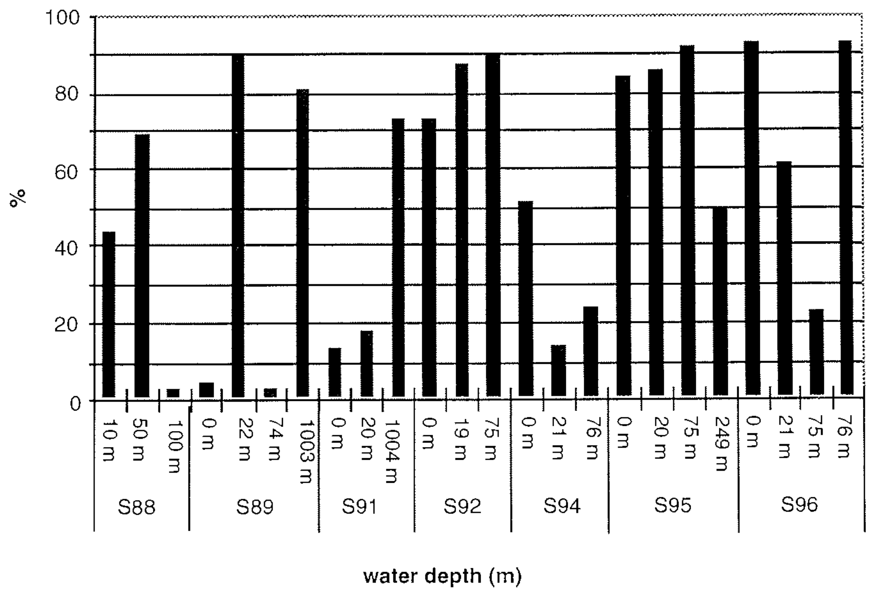

Fig. 3: Percentage of hydrocarbons in total lipids.

The hydrocarbons contents in transitional zone between Kara and Laptev seas vary from 0.26 to 21.4 µg/l (3.2 to 92.3 % of the total lipids) (Table 1, Appendix, Fig.3). At the stations located on the shallow shelf the percentages of hydrocarbons are significantly higher (in average 63.7 % of total lipids) in comparison with the stations along upper continental slope. This fact (considering similar absolute concentrations of hydrocarbons within both groups of stations) allows supposing the higher grade of lipid transformation on the shallow shelf.

In general, the polar lipid contents are low (Table 1, Appendix, Fig.4). This is probably caused by low primary productivity values, which is one of the main source of polar lipids (Parrish, 1988). It is well established that polar lipids are mostly membrane lipids of different organims (Belyaeva and Romankevich, 1976). In marginal seas (such as the Kara and Laptev seas) characterized by an high fluvial supply, the polar lipids may be supplied by the rivers as a biopolymers of terrigenous origin like those found in soils (Amblez et al., 1991). Of some interest, however, is the distribution of polar lipids, particularly along the upper continental slope. Concentrations of polar lipids in the pycnocline layer significantly decreases approximately by one order of magnitude with respect to the surface values at stations 88 and 89). The increased content of polar lipids in the surface layer at these stations is probably caused by phytoplankton bloom and/or recycling by microorganisms (Saliot et al., 1996) as well as grazing by zooplankton (Volkman and Maxwell, 1986. The high concentrations of polar lipids also occur in the depth interval from 74 to 100 meters at the stations near the Severnaya Zemlya Islands (stations 88 and 89). This can be related to the keeping back of organic matter within the pycnocline layer of enhanced sea-water density, where the activity and number of microorganisms significantly increase (Mitskevich and Namsaraev, 1994). This, however, is only a hypothesis, which has to be proved by further analyses of polar lipid composition.

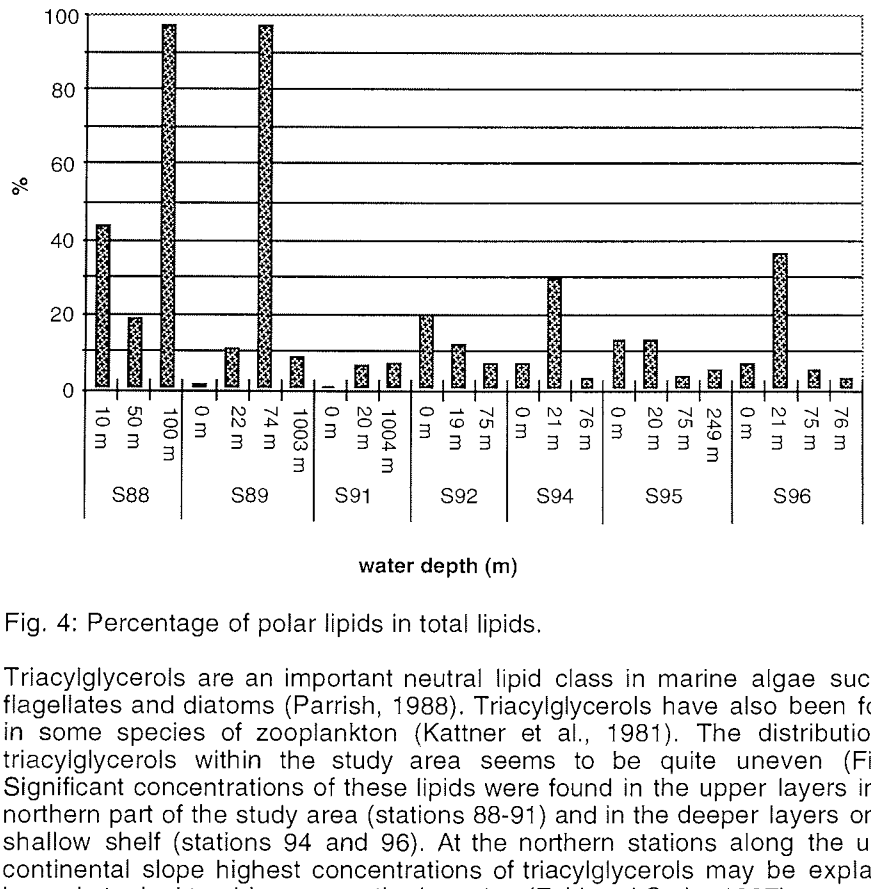

Fig. 4: Percentage of polar lipids in total lipids.

Triacylglycerols are an important neutral lipid class in marine algae such as flagellates and diatoms (Parrish, 1988). Triacylglycerols have also been found in some species of zooplankton (Kattner et al., 1981). The distribution of triacylglycerols within the study area seems to be quite uneven (Fig.5). Significant concentrations of these lipids were found in the upper layers in the northern part of the study area (stations 88-91) and in the deeper layers on the shallow shelf (stations 94 and 96). At the northern stations along the upper continental slope highest concentrations of triacylglycerols may be explained by a phytoplankton bloom near the ice edge (Fahl and Stein, 1997).

Fatty acid esters, sterol esters, wax esters and free fatty acids are of minor importance in the transitional zone between Kara and Laptev seas (Table 1, Appendix).

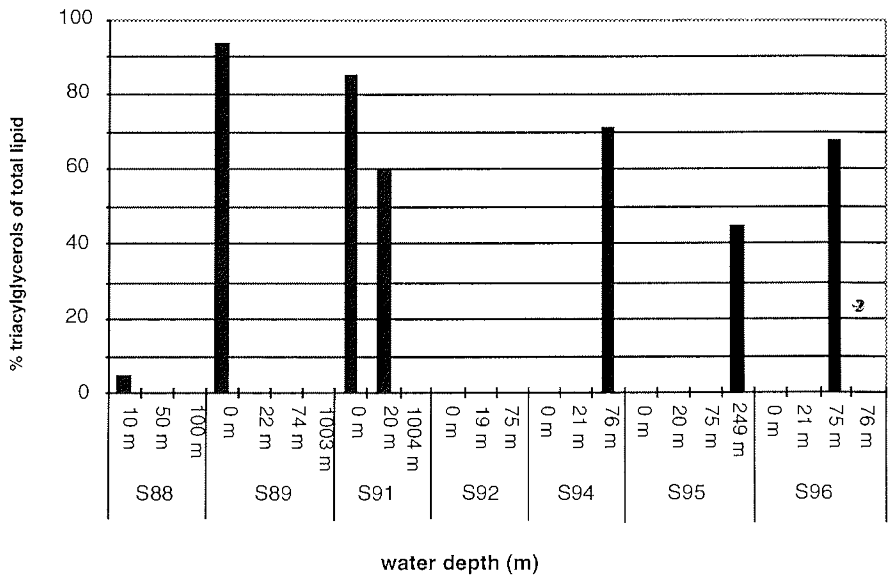

Fig. 5: Percentage of triacylglycerols in total lipids.

Conclusion

*The total lipid content and the distribution of most lipid classes (dominated by hydrocarbons and polar lipids) in the particulate matter from the transitional zone between Kara and Laptev seas were comparable to results obtained along the Ob River - Kara Sea transect.

*The lipid composition of particulate matter within transitional zone between Kara and Laptev seas is characterized by high contents of triacylglycerols in the upper layers of water column near Severnaya Zemlya Islands. The distribution of the triacylglycerols is correlated with the sea-ice distribution. The highest amounts of the triacylglycerols were found near the ice edge, probably caused by increased primary productivity.

*The distribution of total lipids and polar lipids is related to the water column stratification within the transitional zone between the Kara and Laptev Sea. Due to the pycnocline presence the maximum of total lipids (in particular polar lipids) occur at the depth interval from 74 to 100 meters along the lower continental slope. Thus, the pycnocline acts as a barrier for the sinking of lipid-containing organic matter from the surface to the depth.

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Table 1: Lipid composition of particulate matter in the transitional zone between Kara and Laptev seas. TLC/FID analyses.

Stat.	depth	hydro-carbons		wax esters		sterols esters		fatty acid esters		triacyl-glycerols		fatty acids		polar lipids		total lipids
	m	µg/l	%	µg/l	%	µg/l	%	µg/l	%	µg/l	%	µg/l	%	µg/l	%	µg/l
S88	10 m	21.4	44.0	0.0	0.0	0.0	0.0	3.6	7.5	2.3	4.8	0.1	0.5	21.1	43.9	48.6
	50 m	0.5	68.9	0.1	6.4	0.0	0.0	0.1	6.4	0.0	0.0	0.0	0.0	0.1	18.9	0.7
	100 m	0.9	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.9	96.7	28.8
S89	0 m	4.5	4.2	0.0	0.0	0.0	0.0	0.3	0.3	101.0	93.6	0.0	0.0	2.1	1.9	107.9
	22 m	5.6	88.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	11.1	6.2
	74 m	0.9	3.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.7	96.7	28.6
	1003 m	2.5	80.2	0.0	0.7	0.0	0.0	0.3	9.9	0.0	0.0	0.0	0.0	0.3	9.1	3.1
S91	0 m	7.5	13.5	0.0	0.0	0.0	0.0	0.1	0.2	46.9	85.3	0.0	0.0	0.5	0.9	55.0
	20 m	1.2	18.1	0.0	0.0	0.2	3.6	0.8	12.1	3.9	59.6	0.0	0.0	0.4	6.6	6.5
	1004 m	1.5	72.6	0.1	2.7	0.1	0.0	0.1	5.3	0.0	0.0	0.2	9.7	0.2	7.2	2.0
S92	0 m	3.2	73.0	0.1	3.2	0.1	2.4	0.1	1.6	0.0	0.0	0.0	0.0	0.9	19.8	4.4
	19 m	1.8	87.4	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	11.9	2.1
	75 m	1.1	90.2	0.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	7.3	1.2
S94	0 m	2.1	51.5	0.0	0.0	0.8	19.7	0.0	0.0	0.0	0.0	0.9	21.8	0.3	7.0	4.1
	21 m	0.3	14.6	0.0	2.4	0.7	39.2	0.0	2.4	0.0	0.0	0.2	12.2	0.5	29.3	1.8
	76 m	1.4	23.9	0.1	1.9	0.0	0.0	0.0	0.0	4.3	71.1	0.0	0.3	0.2	2.9	6.0
S95	0 m	2.1	83.8	0.0	0.0	0.1	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	13.3	2.6
	20 m	4.0	86.1	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	13.4	4.6
	75 m	2.7	91.8	0.0	0.0	0.1	3.1	0.0	1.0	0.0	0.0	0.0	0.0	0.1	4.1	2.9
	249 m	5.4	49.4	0.0	0.0	0.0	0.2	0.0	0.0	5.0	45.1	0.0	0.0	0.6	5.2	11.0
S96	0 m	5.5	92.3	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.4	7.1	6.0
	21 m	3.3	61.5	0.0	0.0	0.1	2.1	0.0	0.0	0.0	0.0	0.0	0.0	1.9	36.4	5.3
	75 m	0.9	22.7	0.0	0.0	0.2	3.9	0.0	0.0	2.8	67.6	0.0	0.0	0.2	5.8	4.2
	76 m		92.8		0.0		4.4		0.0		0.0		0.0		3.0	

DISTRIBUTION OF HEAVY METALS IN THE WATER COLUMN OF THE ST. ANNA TROUGH.

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Abstract

During the joint Russian-American-Norwegian expedition in August-September 1994 the Association Sevmorgeologia performed a multidisciplinary investigation in the St. Anna Trough. The data of hydrogeochemical measurements allowed to analyze the heavy metal distribution in the different levels of the water column (surface, thermocline, Atlantic-derived, and bottom waters). Lateral diversity of Pb, Zn, Cu, and Cd, presented in 12 distribution maps of heavy metal contents, revealed the following regularities: (i) washing-out of rocks of the Central Kara Rise and their supply by the Kara Sea waters is the major source of Cd in the trough waters; (ii) Atlantic-derived water masses are the source of Pb, Cu and Cd; (iii) zones of anomalously high values of Pb, Cu and Cd at different horizons in the inshore shallow zone of the Ushakov Island may indicate the existence of a local endogenic source.

Introduction

The distribution of heavy metals in marine systems is affected by many factors, such as the presence of sources of pollution substances, the influence of hydrographic parameters and biological productivity. The input of pollution substances by Atlantic waters and river discharge are the main sources of heavy metal supply into the Arctic seas.

The level of heavy metal content in waters of the Russian Arctic is explored insufficiently (Israel and Tstiban, 1989). It is still unknown for many heavy metals which physico-chemical form of their occurrence is dominant in natural waters. Their toxicity and biological activity depend on its specific physico-chemical form rather than on element concentration. Free ions of heavy metals are considered to be toxic. The complexes of metals or metals connected with colloid particles are toxic to a lesser extent, although lipid complexes of cadmium or copper, for example, are as toxic as free ions due to their capability of fast penetration into the biological medium with further dissociation and release of free ions (Kravtzov, 1991).

Material and methods

During the joint Russian-American-Norwegian expedition in August-September 1994 the SIA „Sevmorgeologia" performed multidisciplinary investigations in the Saint Anna Trough (Fig. 1) including studies of aerosols, sediment fluxes, suspended matter, water column, bottom sediments, pore waters and benthic communities (Ivanov et al., 1995,1996, 1997).

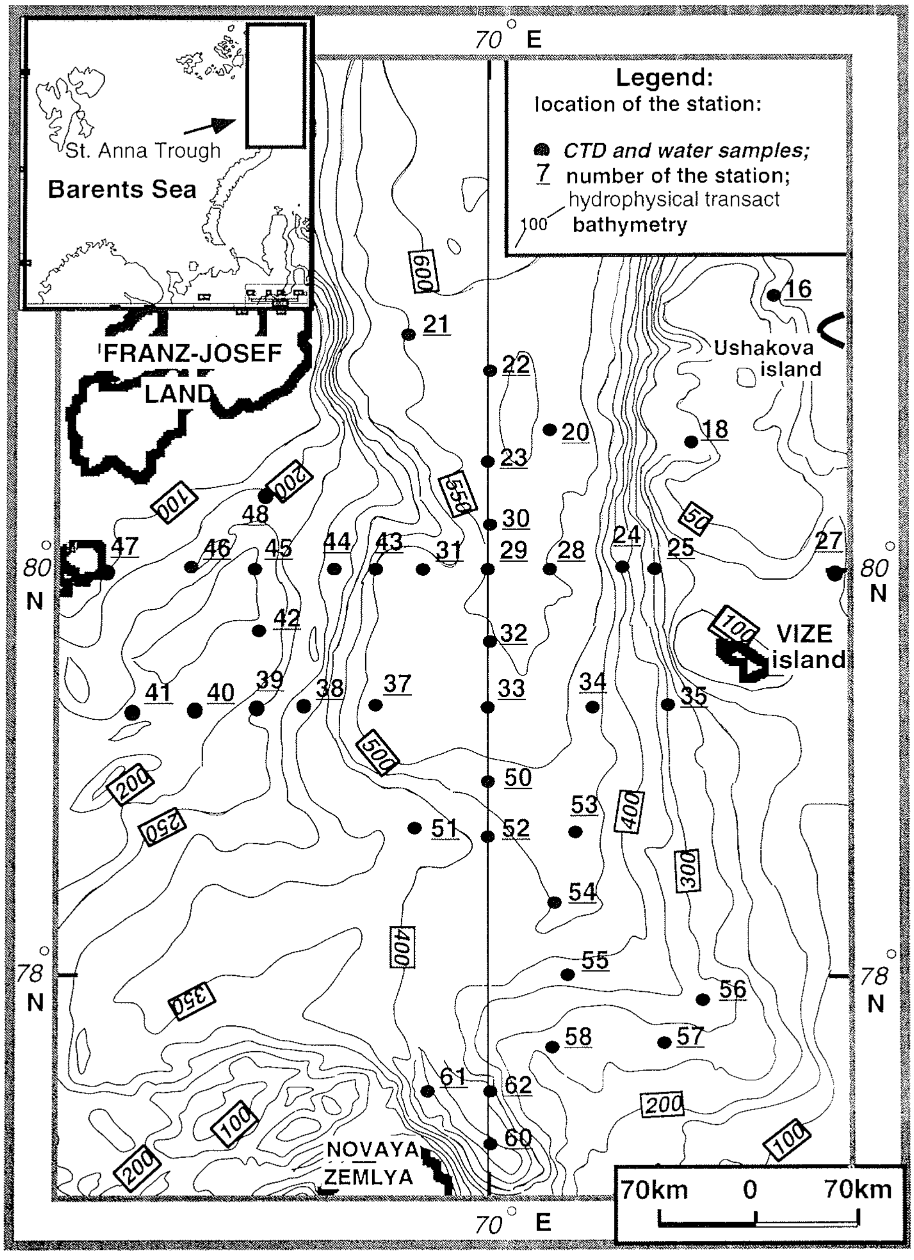

Fig. 1: Location of sampling stations carried out in the St. Anna Trough (RV Professor Logachev, Cruise 9, 1994).

Water for hydrochemical analyses was sampled by a 10 l bottle at 70 stations (Fig. 1). Whenever possible, we tried to sample surface, thermo-(halo-)cline, Atlantic-derived, and bottom waters (Ivanov and Nechsheretov, 1998). The measurement of heavy metal contents (Pb, Zn, Cu, Cd) was performed using a "IVA-1M" analysator (Kalvoda, 1987) and the method of inversion volt-amperometry (Brainina et al., 1988; Kravtzov, 1991). The method was worked out at the Sverdlovsk Institute of National Economy and testified by the All Union Research Institute of Metrology, Experiments and Standardization of Instrument Making (VNIIMISI, 5.12.1989).

The lower detection limits are 0.2 μg/l for Zn and 0.5 μg/l for Cd, Pb and Cu. For the construction of maps the original methods developed at VNIIOkeangeologia were used (Ivanov, 1991).

Results and discussion

The distribution patterns of heavy metals in sea water is controlled by the sources of heavy metals, oceanological parameters of the water column, and biological productivity. The variability of concentrations of the four most toxic elements of the first group of metals (Cu, Pb, Zn, Cd) was studied within the St. Anna Trough. Studies were carried out in four major layers: surface-water layer (SL), "thermocline layer" (TCL), „Atlantic-derived water" layer (AL) and bottom-water layer (BL). Table 1 shows the main statistic parameters of the heavy metal distribution in these layers. It is obvious that the average contents of all four elements increase at the transition from the SL to the AL and to the BL (Fig. 2). An important feature of the heavy metal distribution of the four elements is the distinct enrichment (to anomalous values) in the TCL. It should be hold in mind, however, that this layer was not sampled in detail, only two samples were collected. Nevertheless, this fact has to be taken into account when carrying out future works in this region.

Another important feature of the waters is their enrichment in Cd; the average concentration is 0.29 μg/l (Mart et al., 1982; Ivanov et al., 1997) which is 3.5-4 times as high as that in the bottom and surface waters of the Black Sea (Shimkus et al., 1994) and Arctic Ocean (Crane and Pfirman, 1994; Melnikov, 1991). Average concentrations of Pb (0.49 μg/l) and Cu (0.98 μg/l) are comparable with those of bottom waters of the Arctic marginal seas (Table 2, Brugmann, 1988; Kremling and Peterson, 1984; 1989; Ivanov et al., 1997; Melnikov, 1991; Melnikov et al., 1994).

Surface-water layer (SL)

The statistical parameters of heavy metal contents in the SL are listed in Table 1. The comparison of average values with those of surface layers of the Black Sea (Shimkus et al., 1994) suggests that St. Anna Trough waters are undersaturated with Pb, Zn, Cu and highly enriched (by almost one order of magnitude) in Cd. A sharp increase of all heavy metal concentrations in the SL of the St. Anna Trough waters compared with average values given for coastal waters, is obvious (Israel and Tsyban, 1983). The exception is provided by Pb. Pb concentrations are lower than average values determined in waters of the Baltic and Northern seas (Kremling and Peterson, 1984).

The analysis of lateral variability of heavy metal contents in the surface layer is shown in Figures 3 to 6. Two zones of anomalously high Pb concentrations are distinctly pronounced at the eastern flank of the trough (Fig. 3).
Table 2 Levels of content of heavy metals in water of different seas.

Region	comment	Cd	Cu	Pb	Zn
Baltic Sea[1,2]		0.027	0.661	0.016	0.992
North Sea[2]		0.033	0.925	0.148	-
Kara Sea[5]	surface water, winter-spring	0.05-0.14	0.1-0.79	0.05-0.09	0.5-7.9
Barents Sea[3]	bottom water	0.02	0.1	0.3	1.1
Kara Sea[4]		-	8	1	57
Arctic seas[4]	surface water	0.03-0.3	0.05-0.3	0.05-0.30	0.6-3.0
Arctic Basin[4]	surface water	0.02-0.2	0.03-0.40	0.02-0.25	0.5-1.1
Eastern Arctic Ocean[4]	surface water	0.0008	0.0015	0.009	-
Central Arctic Ocean[4]	surface water	0.012	0.028	0.015	-
Mean concentration in water of the Arctic seas[5]		0.35	0.31	2.34	
Black Sea[6]	surface water	0.058	1.75	0.9	8.48
Black Sea[6]	bottom water	0.087	1.23	0.58	8.52

[1]Brugmann, 1988
[2]Kremling and Peterson, 1984; Mart et al., 1982; Israel. Tstibaní, 1989
[3]Ivanov et al., 1997
[4]Melnikov, 1991
[5] Melnikov et al., 1994
[6]Shimkus et al., 1994

One is located in the north (1.2 μg/l), the second in the south (1.1 μg/l). A zone of relatively Pb-depleted waters, most likely supplied from the Voronin Trough, is located between them. A submeridional zonation can be generally distinguished. Waters of the western flank of the trough have lower concentrations compared to the eastern one.

A similar distribution type is characteristic for Cu (Fig. 4). Zones with high values are located approximately in the same regions of the eastern flank of the trough reaching 1.45 and 4.0 μg/l at the southern and northern parts, respectively. As for Pb, zones of high values are separated by an area of relatively Cu-depleted waters supplied from the Voronin Trough through the bay between Ushakov and Vise islands.

The type of Zn distribution is somewhat different from the Pb and Cu distribution patterns (Fig. 5). A zone of increased values is fixed in the south-eastern (9.5 μg/l) and western (10.4 μg/l) parts of the trough. The south-eastern part generally coincides with similar zones revealed for Pb and Cu (Figs. 3 and 4). The increased concentrations are most likely caused by the supply from the Kara Sea. The submeridional zonation of the western part is associated with heavy metal supply from the Barents Sea.

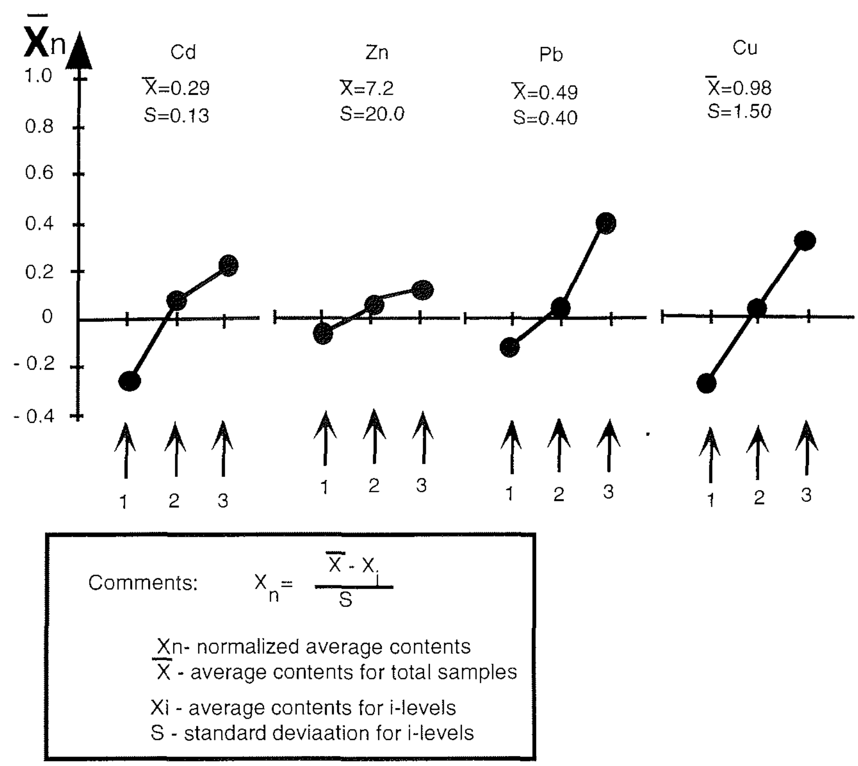

Fig. 2: Scheme of distribution of heavy metals in different levels of the water column in the St. Anna Trough. (1- surface water; 2- Atlantic water mass, 3- bottom water).

The distribution of Cd distinctly differs from that of the other elements (Fig. 6). The zone of increased values (up to 0.55 µg/l) is located in the eastern part of the trough. It should be noted that maximum contents occur in the bay between Ushakov and Vise islands and surrounding shoals. This may suggest that bottom sediments of the Central Kara Uplift represent the source of Cd supply to waters. The second area of relatively high Cd contents is located in the south-western part and can be associated with Cd supply from the Barents Sea. Along with this, the south-eastern flank of the trough connected with the Kara Sea, has relatively low concentrations indicating low Cd concentrations in the surface waters of the Kara Sea.

The structures of the correlation links of the chemical elements are characterized by the tendency of positive linear dependence for Pb and Zn (Table 1, Fig. 7a).

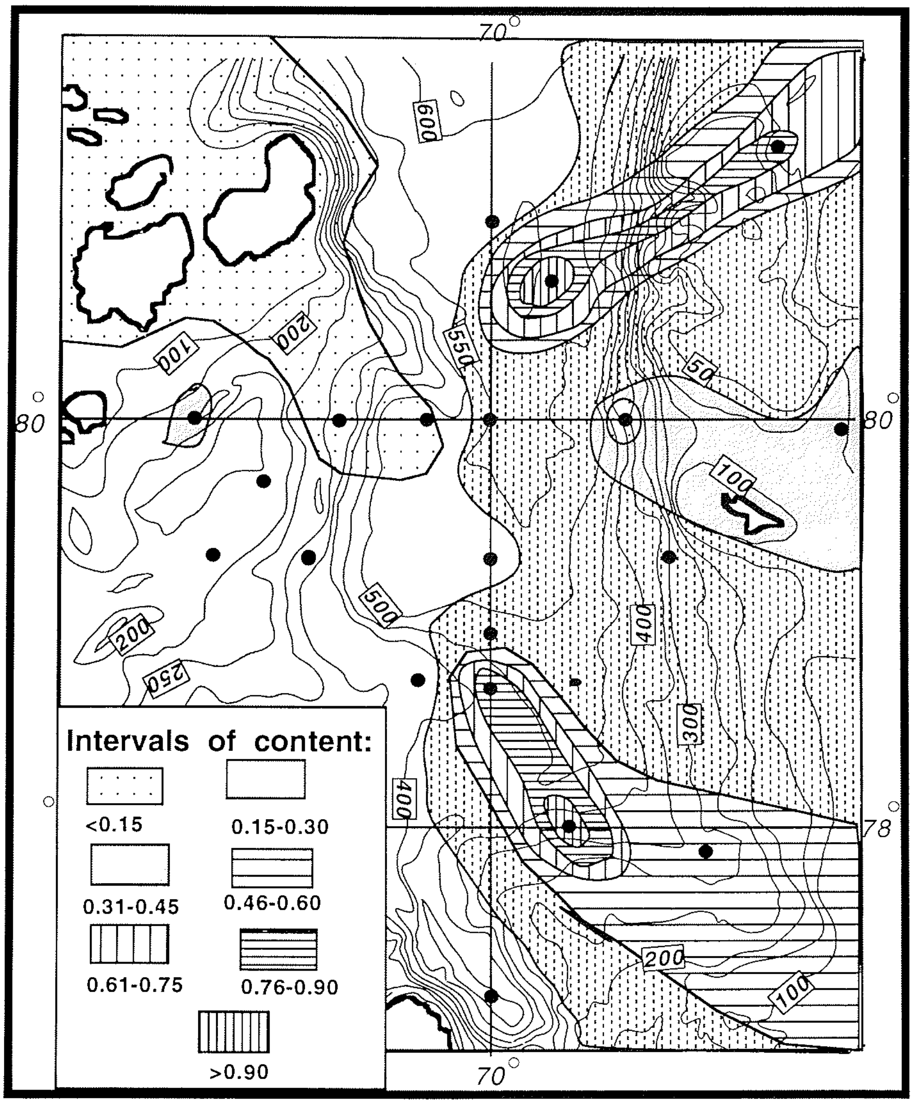

Fig. 3: Distribution of Pb (µg/l) in the surface water in the St. Anna Trough.

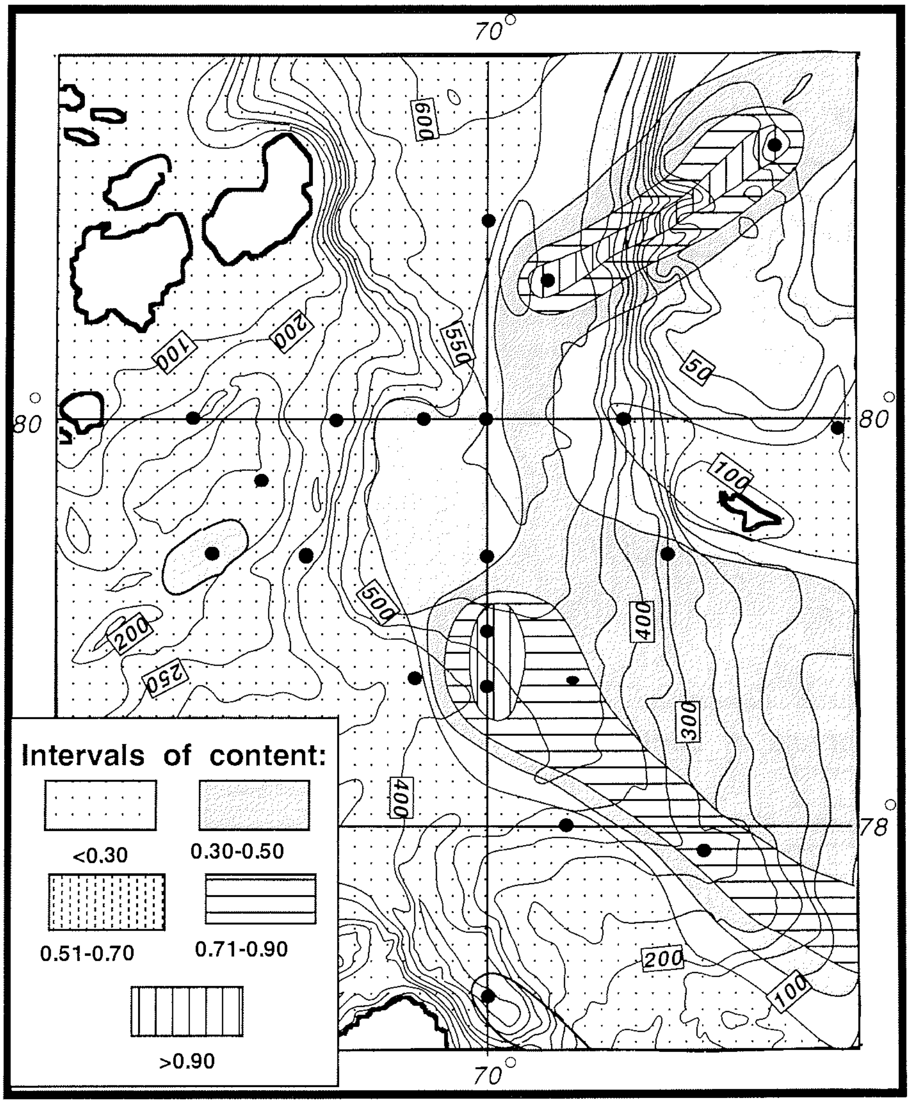

Fig. 4: Distribution of Cu (µg/l) in the surface water in the St. Anna Trough.

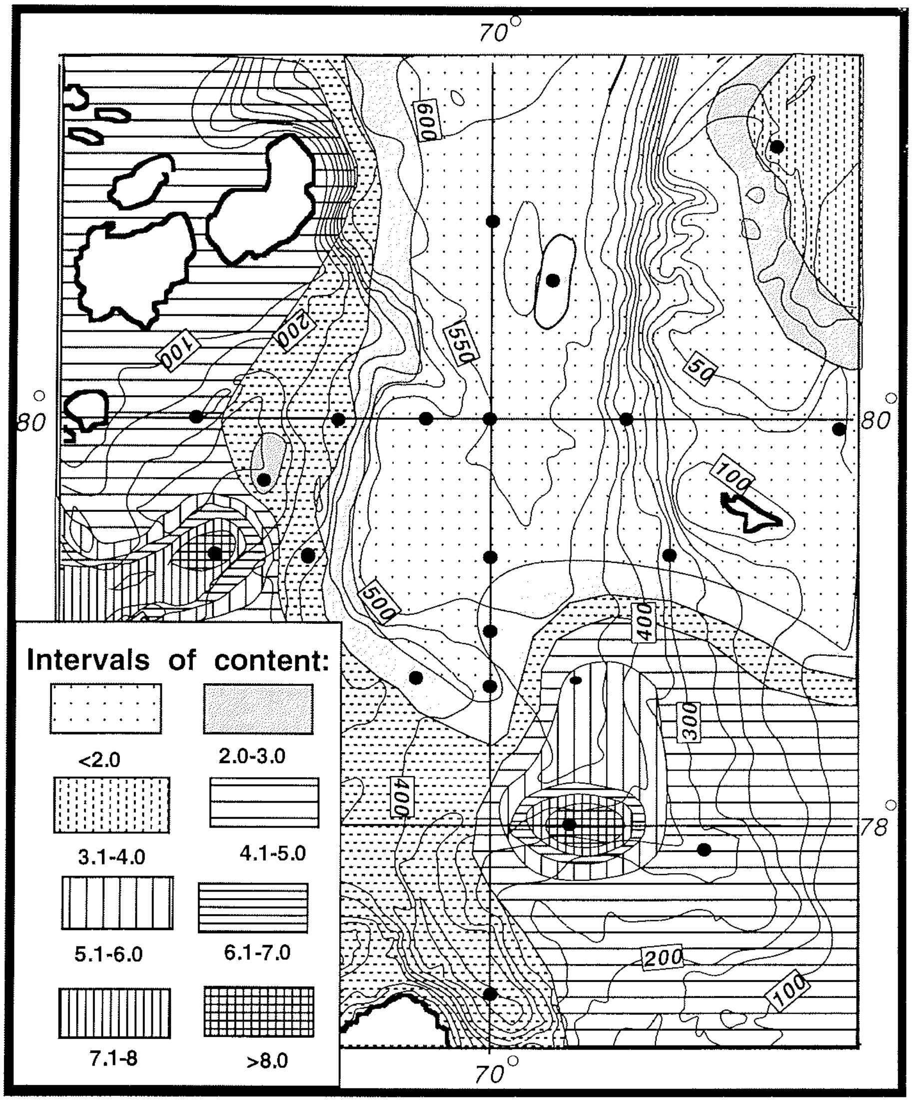

Fig. 5: Distribution of Zn (µg/l) in the surface water in the St. Anna Trough.

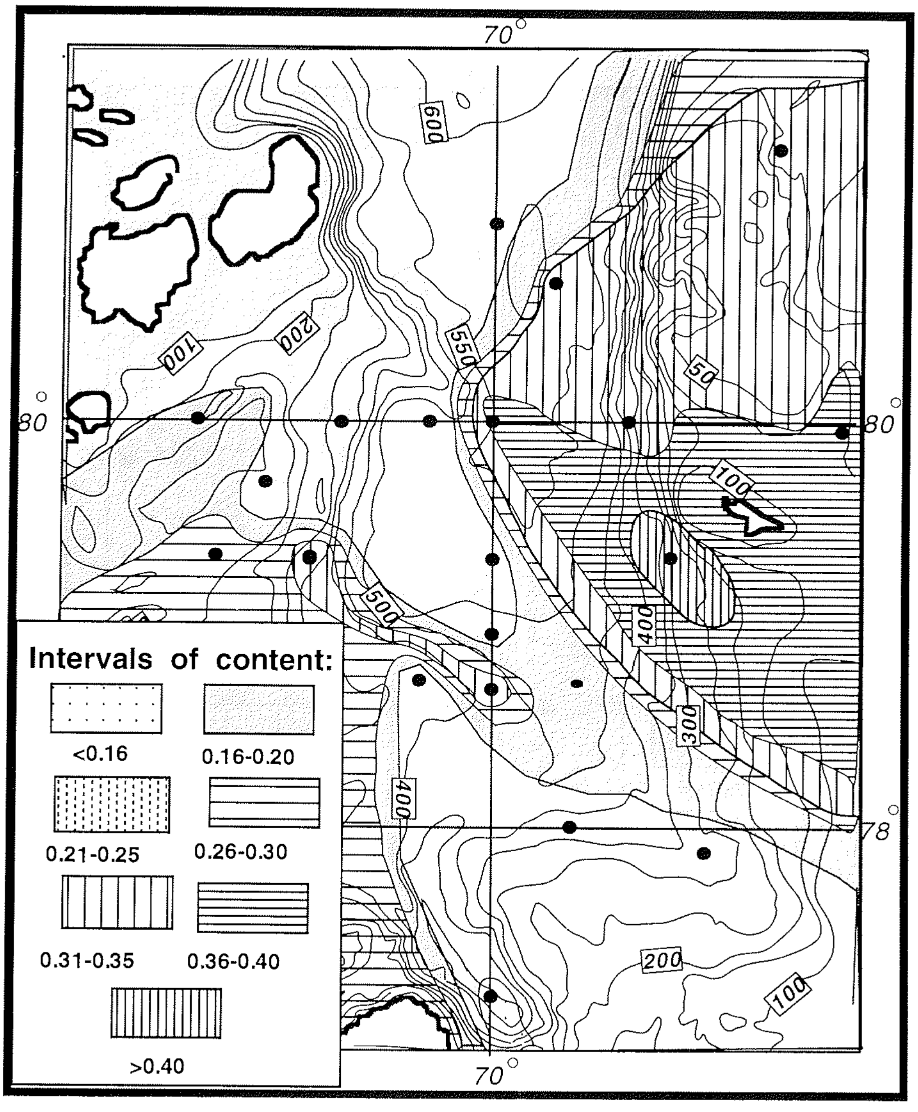

Fig. 6: Distribution of Cd (µg/l) in the surface water in the St. Anna Trough.

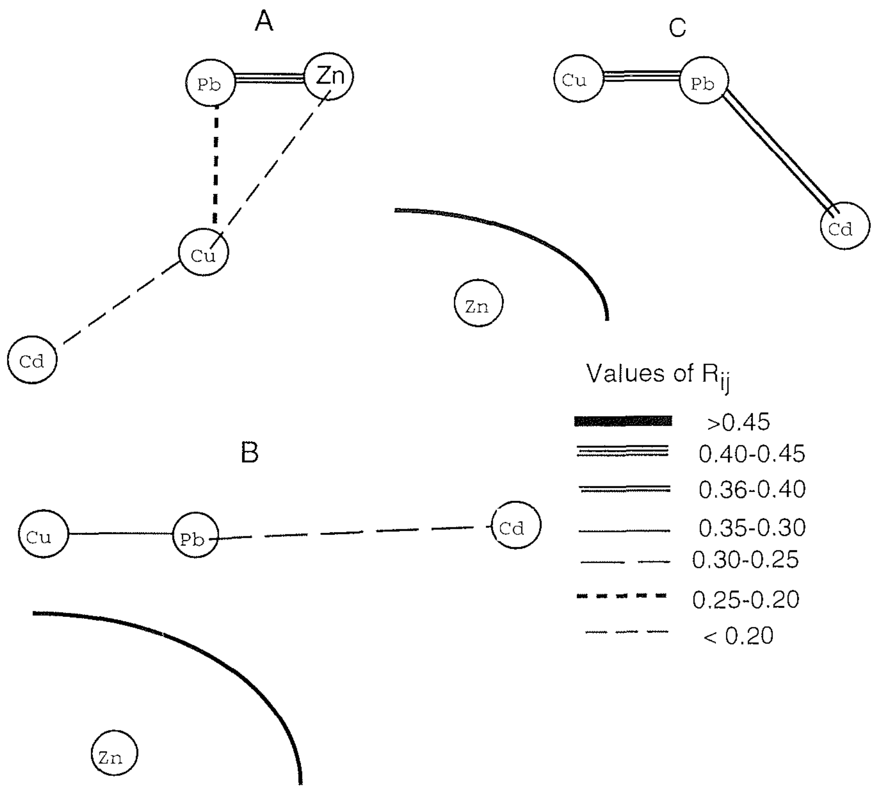

Fig. 7: Scheme of correlation links between heavy metals at different levels of water column in the St. Anna Trough. (A- surface water; B- Atlantic water mass, C- bottom water).

Atlantic-derived water layer (AL)

Average concentrations of heavy metals in the AL are comparable with those of both near-bottom and surface layers of the Black Sea (Shimkus et al., 1994) and significantly exceed concentrations in the inshore oceanic waters (Israel and Tsyban, 1983). Significant correlation dependencies between PB, Zn, CU and Cd are absent (Table 1, Fig. 7 b).

Figures 8 to 11 show the distribution patterns of element concentrations in the AL. One should note, that the structure of the AL is rather complicated (Ivanovet al., 1998, this volume), and the selection of the intervals of water sampling was carried out on the base of temperature curves for each station, regardless of the lateral variability. Different horizons were sampled at each station.

Maximum Pb values are located in the north-western and south-eastern parts of the trough (Fig. 8). The north-western part is characterized by a high gradient of variability from 1.2 to 0.5 μg/l. This is most likely caused by the influence of "Gulf Stream contaminated waters". Further southward, on the western flank of the trough, concentrations decrease to 0.15-0.2 μg/l (Fig. 8).

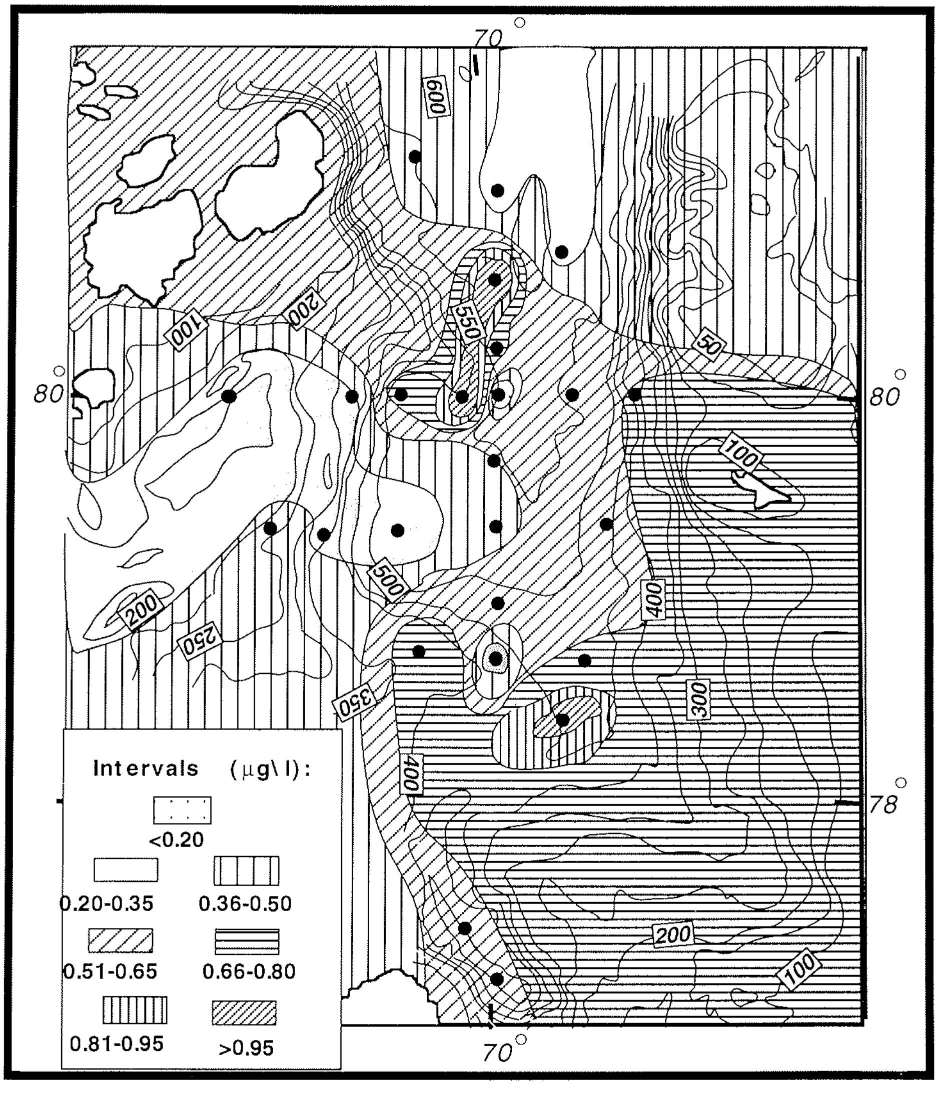

Fig. 8: Distribution of Pb (µg/l) in the Atlantic water mass in the St. Anna Trough.

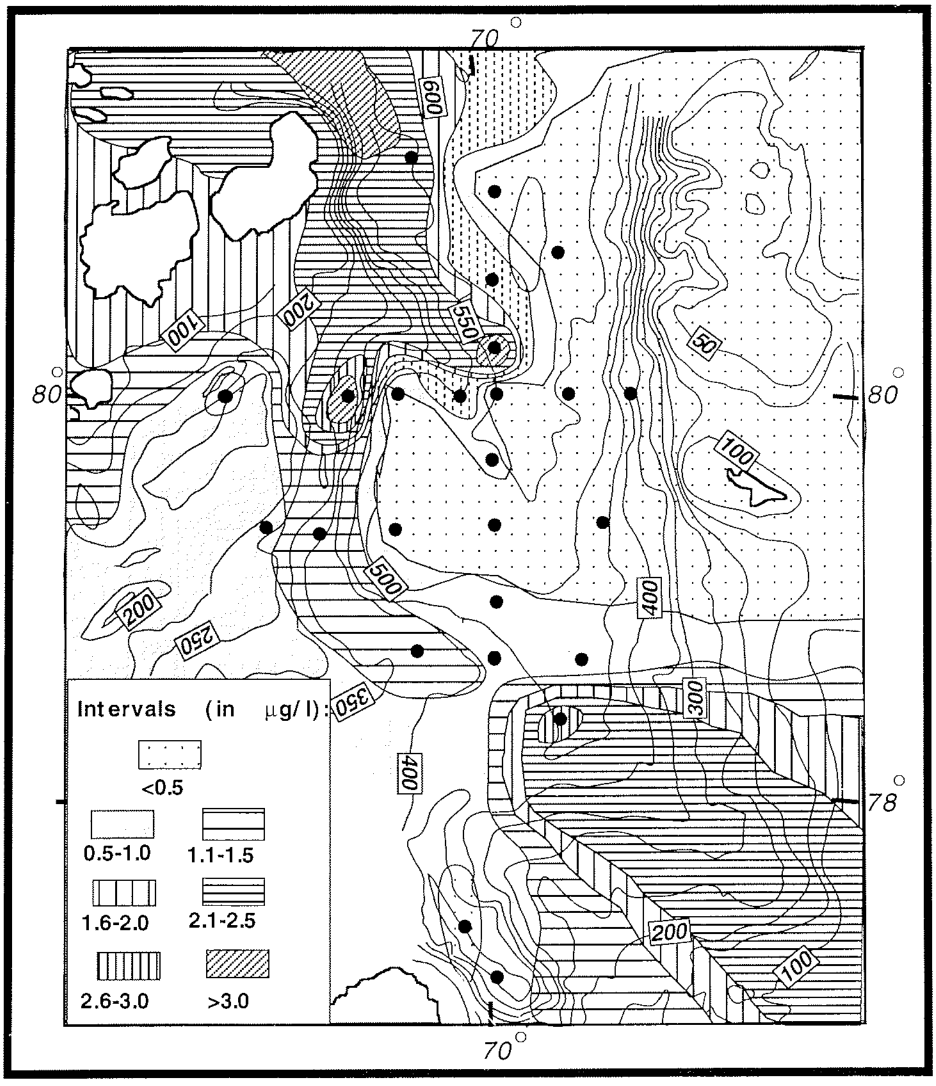

Fig. 9: Distribution of Cu (µg/l) in the Atlantic water mass in the St. Anna Trough.

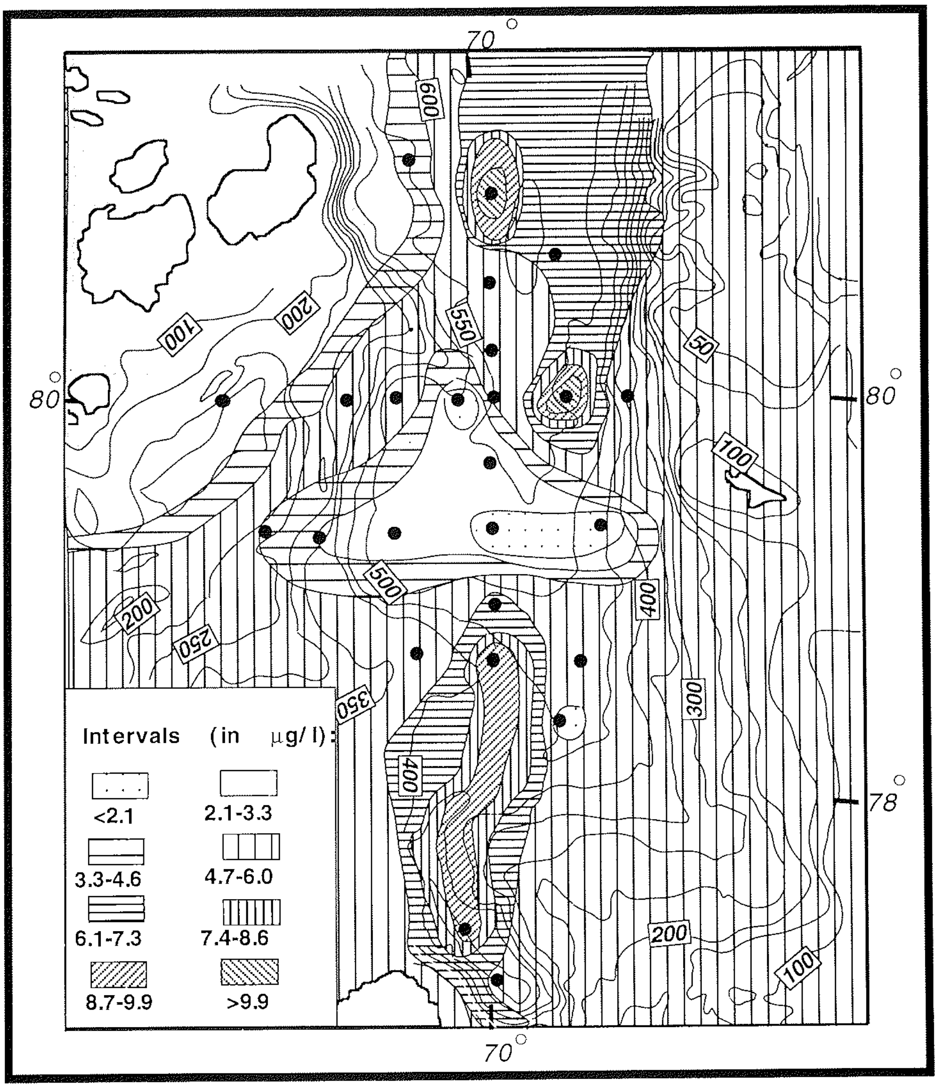

Fig. 10: Distribution of Zn (µg/l) in the Atlantic water mass in the St. Anna Trough.

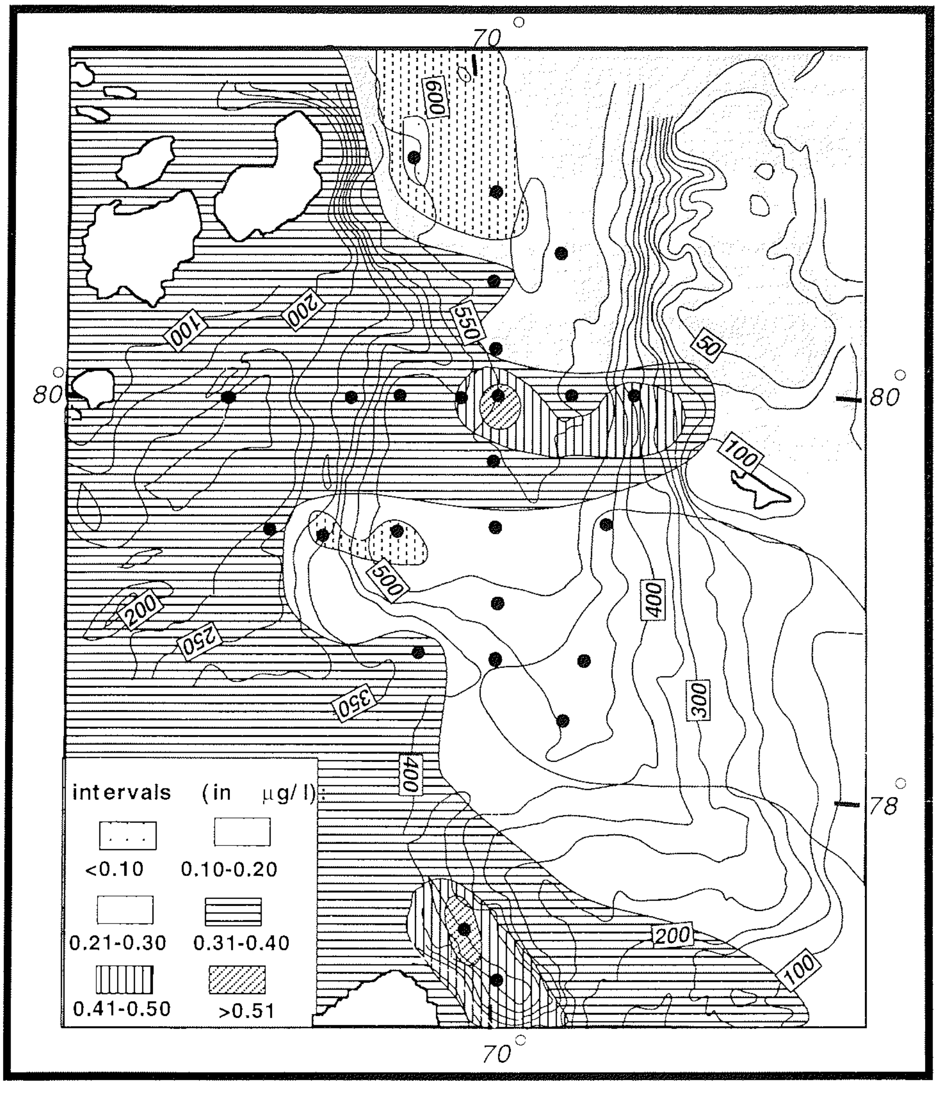

Fig. 11: Distribution of Cd (µg/l) in the bottom water in the St. Anna Trough.

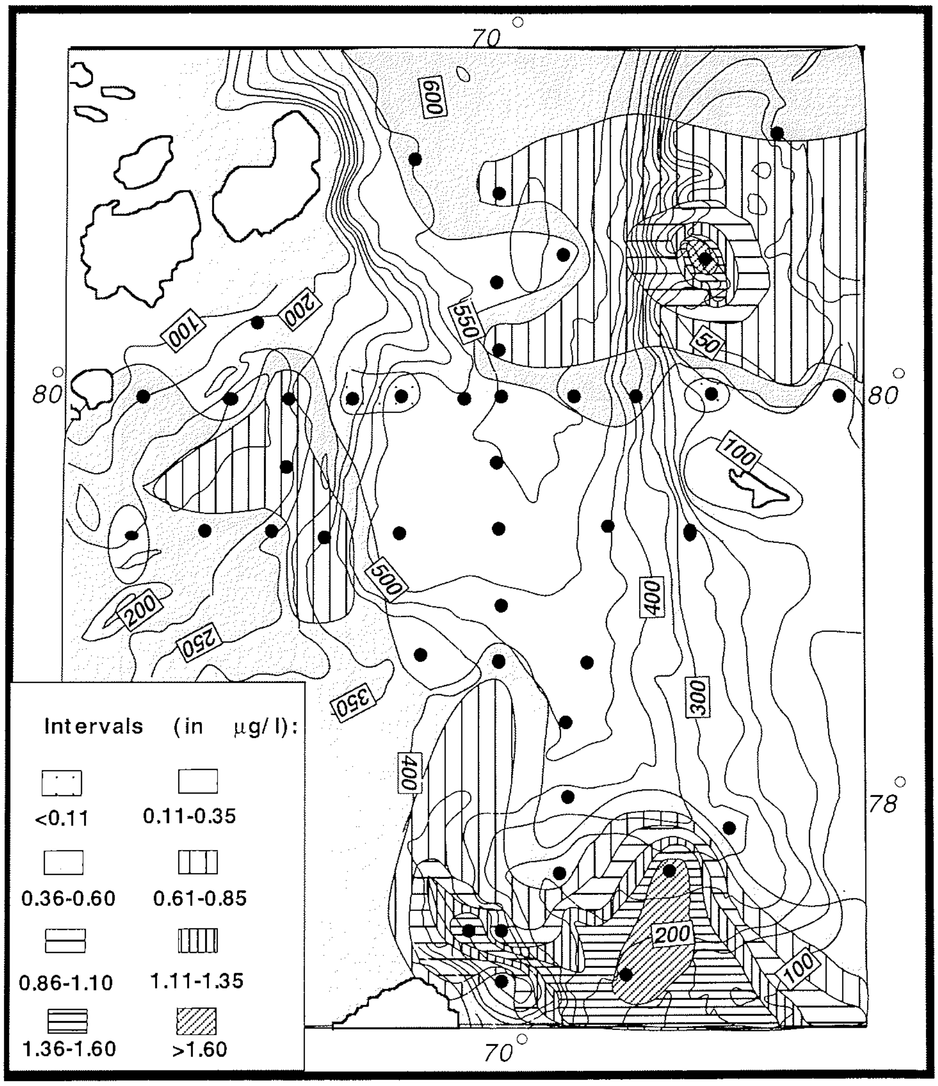

Fig. 12: Distribution of Pb (μg/l) in the bottom water in the St. Anna Trough.

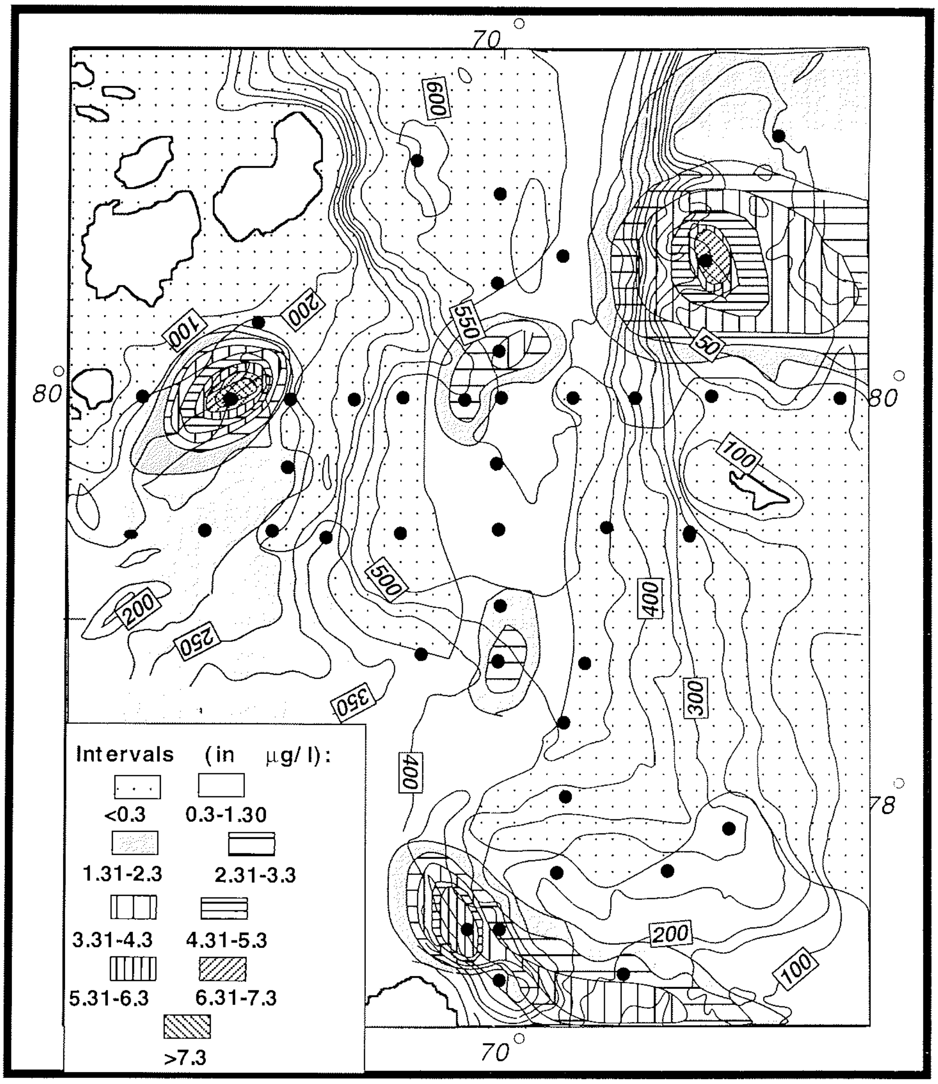

Fig. 13: Distribution of Cu (µg/l) in the bottom water in the St. Anna Trough.

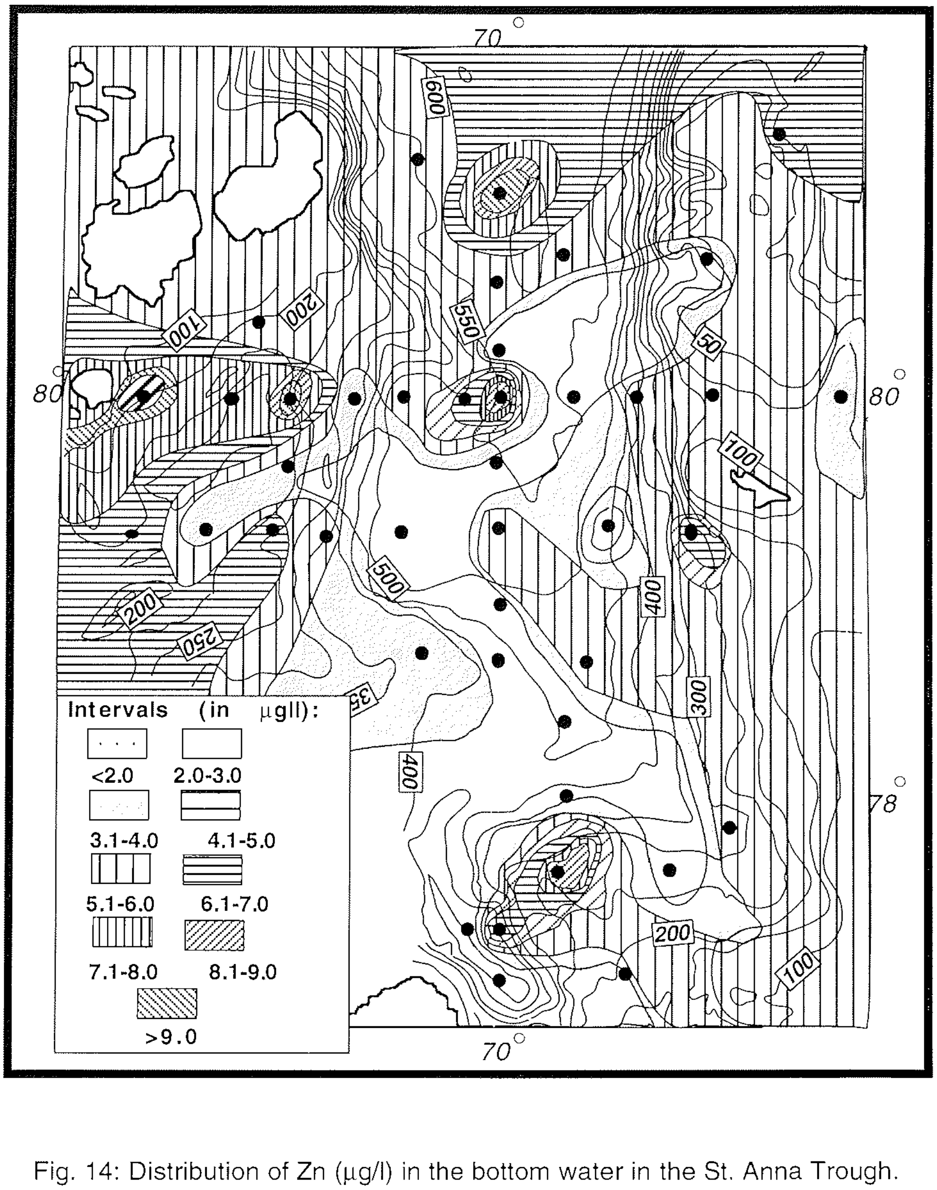

Fig. 14: Distribution of Zn (µg/l) in the bottom water in the St. Anna Trough.

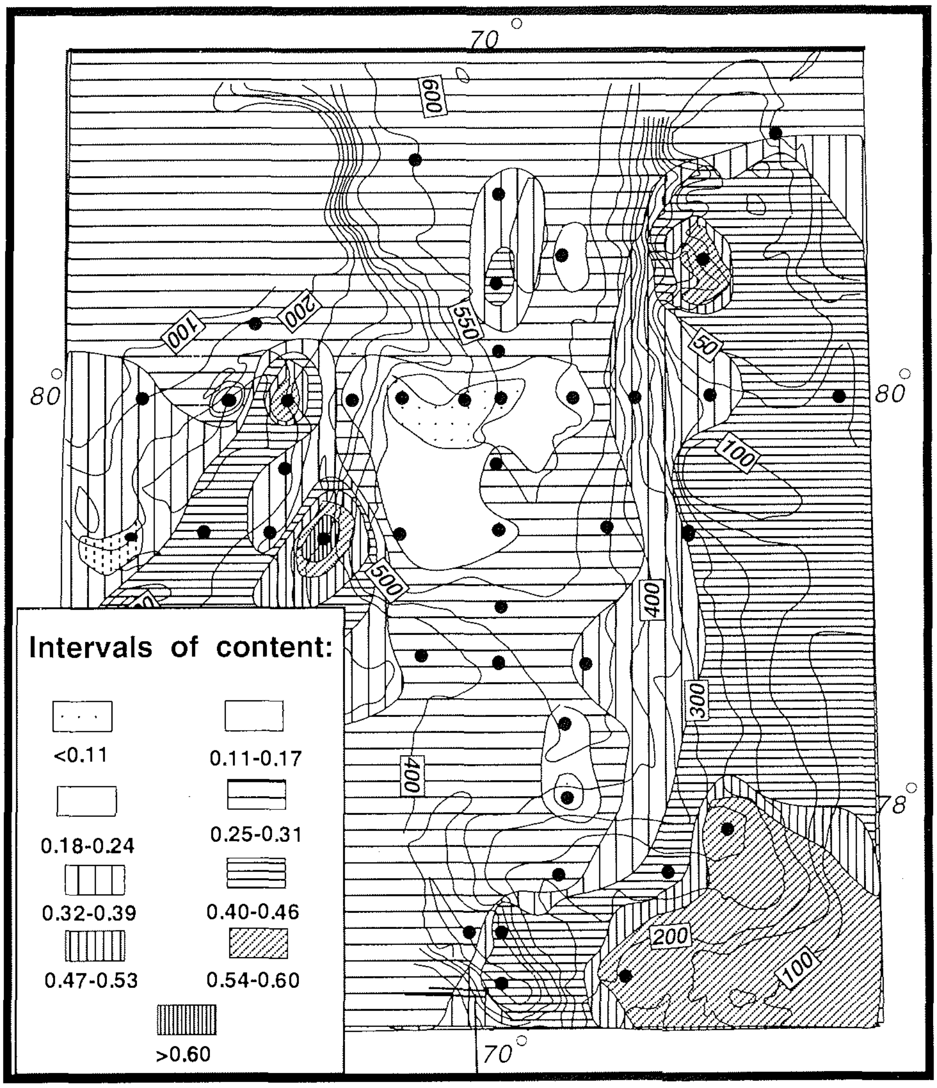

Fig. 15: Distribution of Cd (µg/l) in the bottom water in the St. Anna Trough.

The south-eastern part is characterized by high Pb contents (up to 1.1 μg/l), but the variability gradient is significantly lower. A relationship between high Pb values and water supply from the Kara Sea is suggested.

A similar distribution is obvious for Cu (Fig. 9). Zones of high values are located in approximately the same areas of the north-western and south-eastern parts of the trough reaching values of 3.50 and 2.90 μg/l, respectively. Zones of high values are separated by areas of Cu-depleted waters (< 0.3 μg/l).

The Zn distribution pattern differs from the Cu and Pb patterns described above (Fig.10). In the central deep-water part of the polygon anomalously high values occur (up to 11.5 μg/l). Zones of high content in the central part are separated by the zone of minimum values (1.5 μg/l). Generally, the eastern slope of the trough has higher concentrations than the western one.

The lateral Cd variability (Fig. 11) is close to distribution described for Cu and Pb. The same zones with increased values are identified in the north-western and south-eastern parts of the trough. The distinctive feature of Cd distribution is the submeridional zonation expressed in the regular increase of Cd contents from the east to the west.

Bottom-water layer (BL)

Statistic parameters of heavy metal distribution patterns in the BL are listed in Table 1. The comparison of the average values with those of waters from other basins (Black Sea, Baltic Sea, Barents Sea, Pechora and Kara seas) are shown in Table 2. The lateral variability of heavy metal contents in the BL is presented in Figures 12 to 15.

Two zones of anomalously high Pb contents can be clearly distinguished in the south-eastern and north-eastern part of the trough (Fig. 12). In the south-eastern part the contents reach 2.1 μg/l, gradually decreasing to background values (0.20-0.35 μg/l). The north-eastern zone of increased values located in the shoals near Ushakov Island, is characterized by a higher gradient of variability. The zones are separated by a distinct zone with minimum values of 0.1-0.35 μg/l. Waters of the western slope of the trough have lower Pb concentrations compared to the eastern slope. In the center of the western flank of the trough, however, a zone of relatively increased values (0.75 - 0.85 μg/l) occurs, possibly associated with Pb supply caused by washing-out of the seafloor sediments as suggested from mineralogical and micropaleontological data (Djinoridze et al., 1999; Ivanov et al., 1998, this volume).

A similar distribution type is characteristic for Cu (Fig. 13). As for Pb, zones of high values are separated by an area of Cu-depleted waters (< 0.3 μg/l). It should be noted, However, that the zone of minimum Cu values does not cross the deep-water part of the trough where increased Cu contents relative to the eastern and western flanks occur. Moreover, the zone of anomalously high Cu values (9.8 μg/l), surrounded by minimum values from all sides, is revealed in the western flank.

The Zn distribution differs from the Pb and Cu distributions (Fig.14). Anomalously high values (up to 165 µg/l) occur in the northern part of the polygon opened to the ocean. Zones of high Zn contents are located in the south-eastern (8.3 µg/l) and western (10.4 µg/l) parts of the trough. The south-eastern area generally coincides with analogous zones revealed for Pb and Cu, and, most likely, is caused by the supply of elements from the Kara Sea. The zonation in Zn contents at the western flank is connected with heavy metal supply from the Barents Sea.

The distribution of Cd is different from the other elements (Fig. 15). A zone of increased contents (to 0.55 µg/l) is located on the eastern flank of the trough. One should note that maximum contents are observed in the south-eastern part connected with the Kara Sea and in the shoals of the Ushakov Island. This proves earlier conclusions which suggest that bottom sediments of the Central Kara Uplift are the source of Cd for the trough waters. The second area of relatively high Cd contents is observed in the western part and can be associated with washing-out of basement rocks.

A positive correlation is obvious for Pb with Cu and Cd (Table 1, Fig. 7c). This fact is evidence of the availability of other sources of heavy metals and mechanisms of their accumulation which are different from those assumed for the SL and AL.

Conclusions

1. Statistical analysis of heavy metal contents in the St.Anna Trough waters shows:

* an increase in average contents of all elements at the transition from surface waters to „Atlantic" waters to near-bottom waters;
* a distinct enrichment (up to anomalous values) of Pb, Zn, Cu and Cd in the thermocline layer;
* increased Cd contents in all four layers; and
* average concentrations of Pb, Zn and Cu which are comparable with those measured in other Russian Arctic seas.

2. Analysis of correlation links revealed various releationships between the chemical elements at three different levels that allows to identify various sources of heavy metal supply.

3. Analysis of the lateral heavy metal variability in the four layers revealed the following regularities:

* washing-out of rocks of the Central Kara Uplift and their supply by the Kara Sea waters is the major source of Cd in the trough waters;
* „Atlantic waters" are the source of increased values of Pb, Cu and Cd. Zones of anomalously high values of Pb, Cu and Cd in the inshore shallow zone of Ushakov Island suggest the existence of a local endogenic source.

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Appendix (Ivanov and Andrianova)

Table 1: Statistic parameters of metals content (mg/l) and correlation matrix for different levels of water column in the St. Anna Trough.

	Surface layer				Halocline layer				"Atlantic" water				Bottom water			
	Cd	Cu	Pb	Zn	Cd	Cu	Pb	Zn	Cd	Cu	Pb	Zn	Cd	Cu	Pb	Zn
N OF CASES	28	28	28	28	2	2	2	2	25	25	25	25	54	54	54	54
MINIMUM	0.05	0.15	0.05	1.1	0.35	1.4	0.67	1.90	0.05	0.15	0.15	1.5	0.10	0.15	0.05	1
MAXIMUM	0.55	6.00	4.10	10.4	0.55	2.4	1.80	11.20	0.60	3.50	1.20	100.0	0.65	9.80	2.25	165
MEAN	0.26	0.51	0.44	3.58	0.45	1.90	1.24	6.55	0.30	1.00	0.51	8.50	0.32	1.45	0.66	8
STANDARD	0.11	0.45	0.31	2.44	0.14	0.7	0.80	6.58	0.14	1.0	0.30	19.2	0.14	1.93	0.56	22
C.V.	0.42	0.89	0.70	0.68	0.31	0.37	0.65	1.00	0.47	0.98	0.58	0.96	0.44	0.92	0.85	0.89

	Cd	Cu	Pb	Zn
Cd	1.00			
Cu	0.16	1.00		
Pb	0.05	0.20	1.00	
Zn	-0.01	0.16	0.42*	1.00
n=28				

	CD	CU	PB	ZN	CD	CU	PB	ZN
CD	1.00				1.00			
CU	-0.23	1.00			0.11	1.00		
PB	0.28	0.34	1.00		0.43*	0.39*	1.00	
ZN	-0.13	-0.21	-0.20	1.00	0.06	-0.13	0.01	1.00
	n=25				n=51			

Comments: 0.42* - Marked correlations are significant at $p < 0.05$

THE GRANULOMETRICAL STRUCTURE OF SURFACE SEDIMENTS IN THE ST. ANNA TROUGH AREA

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Introduction

The shelf north of the Barents-Kara Seas region, an area adjacent to the modern glaciers of the Franz-Josef Land and Novaya Zemlya archipelagoes is covered with ice more than 10 months a year. Its bottom relief is extremely diverse and forms stretched trenches cut deeply. Taking into account that these circumstances directly influence the modern sedimentogenesis, it is important to distinguish the principal natural processes which criteria might be used for the sediment genesis typification.

Although scientific interest in this high-latitude Arctic region is large, This region remains poorly known due to natural reasons - short Arctic summer and difficult ice conditions. Since the development of the Biological Station of the Murmansk Marine Biological Institute at Guker Island (Franz-Josef Land) in 1990, however, expeditions in this region have become annual. Preliminary results from these expeditions were recently published (Complex International Expedition, 1992; Matishov et al., 1993; Nürnberg and Groth, 1993; Tarasov et al., 1993; Alekseev et al., 1993; Matishov et al., 1994). Modern sedimentation processes in the St. Anna Trough area can be found in Ivanov et al. (1995, 1997).

Material and methods

More than 350 samples of bottom sediment were taken during the expeditions of the scientific research vessels "Dalnye Zelentsy" (1992, 1996), "Academician Golitsyn" (1994), "Yasnogorsk" (1995). The locations of the stations are shown in Figure 1. During the joint Russian-American-Norwegian expedition in August-September 1994 the Association Sevmorgeologiya perfomed multidisciplinary investigations in the northern part of the Kara Sea (Ivanov et al., 1995). 70 complex stations were carried out (Fig.2). The sampling of bottom sediments (to 30 cm depth) was performed by "Box-corer", "Multi-corer" and by grab "Ocean-50", and sediment cores of 2-3 m length were obtained by percussion subsoil tube. The primary processing of samples was carried out on board including visual lithological description of sediments and selection of samples for laboratory studies of sedimentary structure and microfauna. Further analytical investigations were performed at laboratories of VNIIOceangeologia and at the laboratory of marine geology of Murmansk Marine Biological Institute. To determine the grain-size distribution, standard methods were used, wet sieving for the coarse (sand) fractions and water mechanical analyses for the fine fraction < 0.065 mm.

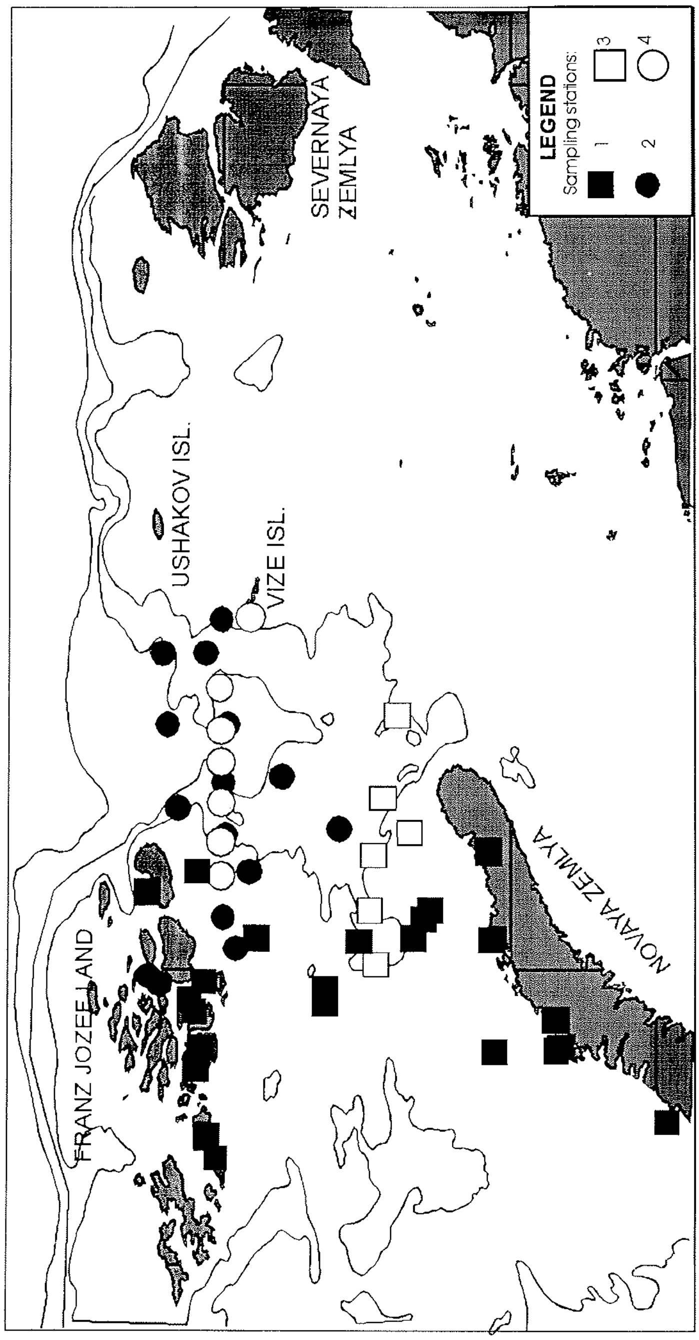

Fig.1: Map showing locations of the stations sampled in 1992 to 1996: 1. RV "Dalnie Zelentsy" (1992), 2. RV "Akademic Golitsyn" (1994), 3. RV "Yasnogorsk" (1995), 4. RV "Dalnie Zelentsy" (1996).

The following sizes of fractions of gravel-sand-silt-clay sediments were defined: more than 1.6 mm; 1.6-1.0 mm; 1.0-0.5 mm; 0.5-0.25 mm; 0.25-0.125 mm; 0.125-0.063 mm; 0.063-0.032 mm; 0.032-0.002 mm; less than 0.002 mm.

Results

Our investigation of the surface sediments from the Barents-Kara Sea has shown that fine aleurite and clayey muds of green-yellow, light brown and light grey colours predominate. Based on grain-size data, the studied part of the Barents-Kara Sea region may be divided into two areas: the coastal-insular zone and the open-sea zone.

1. Coastal-insular sediments.

At a first view the modern coastal-insular sediments do not differ from those in the open-sea regions. Their composition is very similar; some difference is only recorded in grain packing and sedimentogenesis rates. It has been observed that in fjords and bays with calm hydrodynamics the pronounced sedimentation of the terrigenous matter takes place without apparent treatment of the particles. The influence of the sediment transport by rivers and springs originating from the modern outlet glaciers in fjord heads is of most importance. This flow of thaw water is greatly enriched with moraine mineral suspension. Figure 3 based on satellite photography data, shows the pattern of the suspended mineral matter transportation in the Nordenshield Bay (west coast of the Northern Island of Novaya Zemlya archipelago) on July 22, 1990. Here the thaw water flow enriched with terrigenous suspension expands from the bay into the open sea for more than 20 to 30 km. According to Medvedev and Potekhina (1990) suspension concentration makes up to 304.2 mg/l in the Nordenshield Bay head, 49.0 mg/l just before outlet to the sea, and 6.1 mg/l at 10 km from the coast line. Consequently, most part of the mineral suspension falls out in the limits of the bay and only insignificant parts enter the open sea. The amount of transported terrigenous matter and transportation distance from the outlet glacier border depend on the glaciers melting rate and, consequently, on the summer temperature conditions. In warmer summers amount of transported matter is greater than in colder summers.

The modern sedimentogenes in the Novaya Zemlya bays is similar to other regions, for example, West Svalbard outlet glaciers in the Hornsoonn fjord (Tarasov et al., 1993). Different processes are observed in bays and sounds of the Franz-Josef Land archipelago. Here the climate is more severe, the summer is very short (July-August), and glaciers are "colder". The mentioned peculiarities together with geological and geomorphological specific features of the Franz-Josef Land archipelago and bottom geomorphology of the adjacent shelf determine the main features of the modern sedimentogenes and promote formation of the atypical fine-granular sediments (like open-sea sediments). Cores of maximal length were obtained in bays and sounds protected against the bottom currents (Col-12, 13, 14; DZ-14, 19, 20, 29). They are composed of grey and deep-grey homogenous fine aleurite muds enriched with hydrotroilit. The aleurite fraction predominates in the granulometric composition. Thus, at the station Gol-13 (234 m water depth, Austria Strait) aleurite concentration ranges from 41.8 % to 73.6% (averages 50%) in a 1 m long core. The middle aleurite fraction predominates.

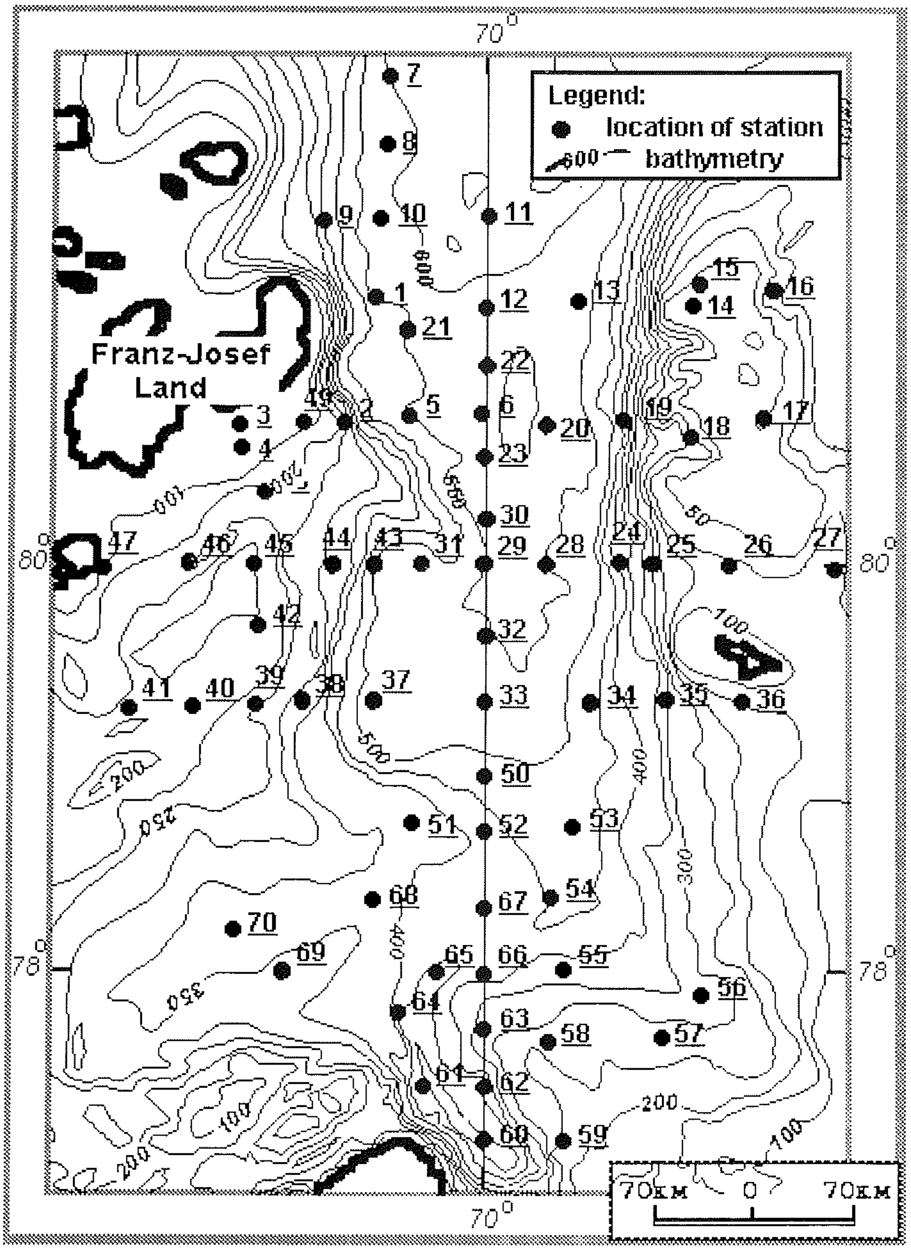

Fig.2: Locations of sampling stations carried out in St. Anna Trough with RV "Professor Logachev", Cruise 9, 1994.

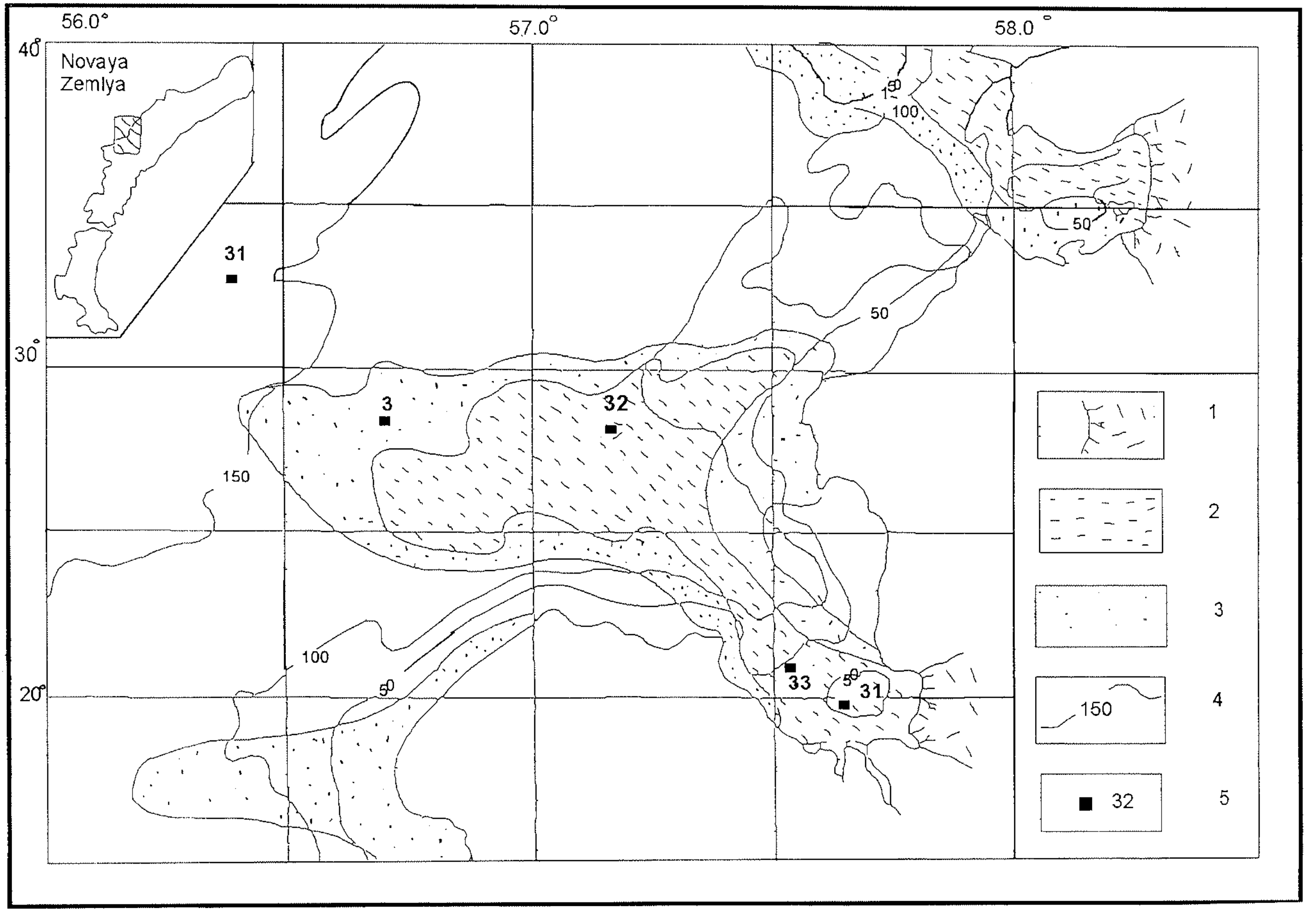

Fig.3: Tracing of the suspension in the under-glacier thaw water flows in the Nordenschleld Bay (Novaya Zemlya archipelago). 1. active outlet glacier, 2.-3. zone of more (2) and less (3) concentration, 4. isobaths, 5. sampling sites.

The content of gravel-pebble matter originating from rough pieces of the coastline rocks is rather small. It may reach 10% in some samples and is distributed more or less evenly over the entire core. This distribution of gravel and pebbles in bottom sediments points to their constant dispersion due to ice drift and melting during summer seasons.

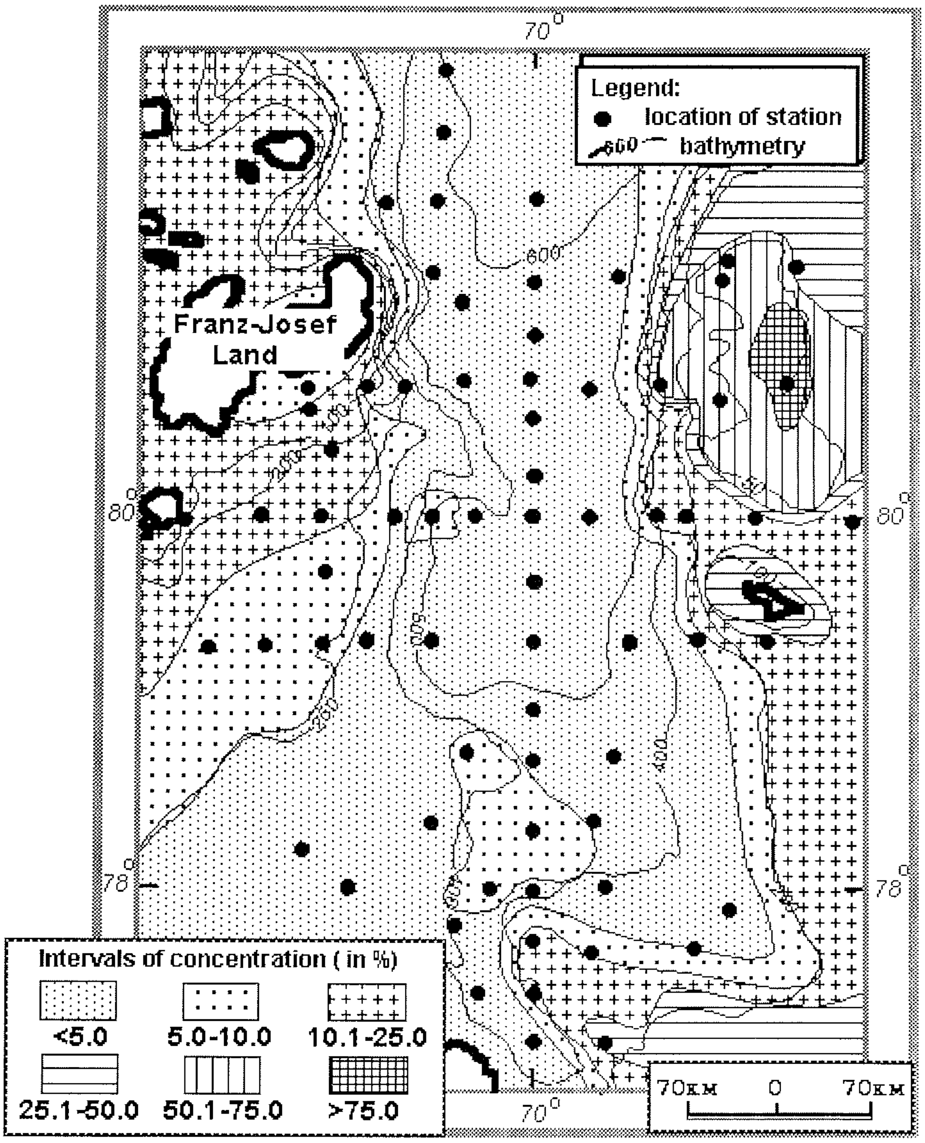

Fig.4: Distribution of sand fraction (>0.1 mm) in surface bottom sediment in the St. Anna Trough.

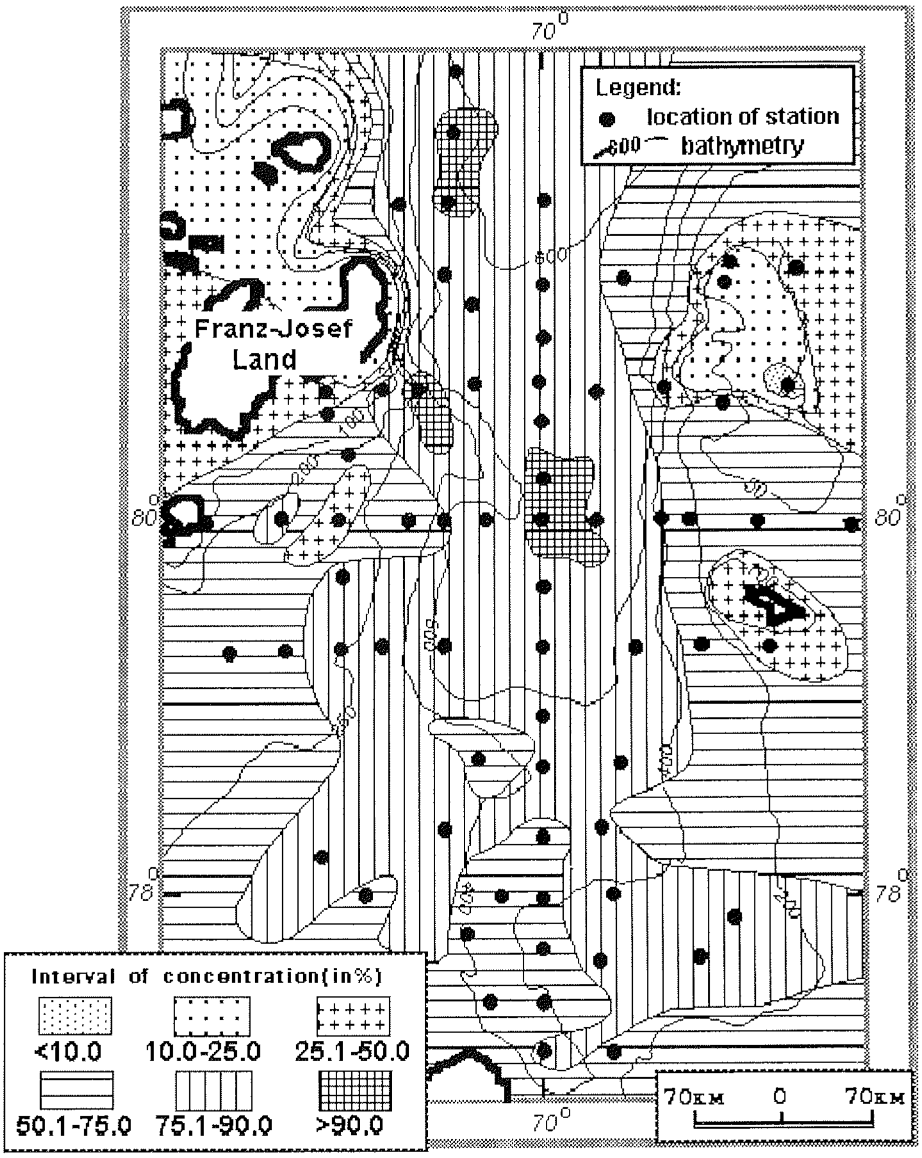

Fig.5: Distribution of clay fraction (<0.01 mm) in surface bottom sediment in the St. Anna Trough.

2. Sediments in the open sea.

The grain-size distribution in surface sediments from the open-sea zone shows a relationship to bathymetric position and bottom geomorphology. Sandy deposits represented by fine and middle sands, occur in water depths < 120 m (Fig.4). As a rule, they are located in the shelf zone and are connected with coastal shallow waters or bottom elevations. In wet condition they are of grey and grey-green colour, in dry condition they have green-grey, olive and grey-green colours. The specific feature of the sandy deposits is the permanent presence of coquina matter (up to 8%). The sands are sized to the high and intermediate degree. The sorting index ranges from 1.7 to 3.5.

In the deeper parts fine-grained sediments (fine aleurite and aleurite-clayey muds) are dominant (Fig.5). In wet condition the sediments are semi-liquid whereas with drying they become more solid. They are of grey-green colour with blue shade and with ochre-brown spots. Light brown and brown inclusions are also recorded. The clayey muds are constituted by homogenous fine-granular (hydromica-peach or hydromica) matter containing aleurite and fine sand admixture. Usually, they are lacking of carbonates and contain an insignificant amount of organic substances.

Laminar sediments are typical for under-water slopes of the archipelagoes (Stations DZ-12, 13, 16, Gol-1, 2, 3 - Franz Josef Land; DZ -1, 6 - the Novaya Zemlya) and for elevation slopes in the open sea (St. DZ - 9, 10; Gol - 6, 8). The surface layer (0 to 3 cm) is mainly brown, green-yellow, soft, sometimes semi-liquid and is composed of fine-aleurite or aleurite-clayey stiff mud. The transition to the underlying layer is marked by the apparent stiffness of the deposit. The next layer is dark-grey or dark-green, thin (15 to 40 cm) and fine aleurite mud (sometimes also clayey or sandy-clayey mud) with large amounts of gravel matter. The lowest layer is represented by dark-grey stiff diamicton-like deposits ("ancient clay").

Discussion

The data of the study of bottom sediment show a regular variability of the sedimentogenesis processes in the past. First of all, it results from climate fluctuations: repeating of warm and cold periods both in the annual cycle (short-term climate fluctuations) and the long-term ones covering tens and hundreds of years. In their turn, increase of the modern island glaciers, their steady state or drop degradation took place. The climate fluctuations are connected with dynamic peculiarities of the sea-ice cover in high latitudes areas. Glaciers and ice enriched with terrigenous fragments are main sources of the sediments in the sea.

In the northern area of the Barents-Kara Sea region in summer drifting icebergs, fast ice and sometimes Arctic pack ice melt quickly and cover the bottom with sediments. The melted ice gives place to receipt of new ice masses. This process continues during the short Arctic summer and becomes slower with formation of new ice. In the zone of drifting ice thick loose deposits mainly composed of fine grains containing gravel and pebbles arise. Transporting of large fragments of coastal rocks can not be ruled out. During the RV "Academician Golitsyn" expedition in the Austrian Sound (Franz-Josef Land archipelago) we observed ice fields or icebergs containing big stones. Bottom sediments resulting from ice transport can be devoid of laminar structure. As during winter transportation of material becomes slower under ice cover, the semi-liquid layer is formed at the bottom owing to suspended matter. However, this process may be hampered or stopped due to water currents removing deposits from the bottom surface. This is only recorded in some places and depends on many reasons. The usual amount of deposits of ice origin of the next year passes easily through the winter semi-liquid layer and joins the old layer. In such cases we record no laminar structure. This pattern is recorded not in all parts and depends on many factors.

Sediments sharing thin layers with apparently annual cyclicity were occasionally recorded. In some cores these thin layers display regular thickness whereas in others an unregular alternation of thick and thin layers was observed. Probably, the latter results from drastic changes in both amount and rate of sediment matter transported from year to year. Consequently, during warm summers ice melting and glaciers decrease take place more intensively than during colder summers. Thus, the transportation of sediments is increased. In general, the distribution of lamination in a core and their thickness and composition are determined by the stability of climatic conditions.

In the regions of the modern glaciers. sedimentogenesis is greatly influenced by under-glacier flows of thaw water enriched with terrigenous material. Near the outlet glaciers this factor becomes prevalent and transforms sedimentogenesis into "avalan- ice" processes. The influence of thaw water on the total rate of sedimentogenesis decreases with increasing distance from the coastline. Nevertheless, this factor plays an important role for the modern sedimentogenes.

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DISTRIBUTION OF LIGHT MINERALS IN SURFACE SEDIMENTS OF THE ST. ANNA TROUGH

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Introduction

Among the numerous methods of investigations of sedimentation processes and depositional environments in the seas and oceans mineralogical analysis plays a very important role. Mineralogical data may help to identify source areas and transport pathways of terrigenous matter of the marine sediments.

In the given paper the authors present results of investigations of the mineral composition of the light fraction of surface sediments from the St. Anna Trough and discuss the data in relationship to the peculiarities of sediment accumulation and sources of these minerals.

Materials and methods

The mineralogical analysis was performed on surface sediments sampled during the expeditions of the R/V «Academician Golitsyn» (MMBI, 1994) and «Professor Logachev» (AUSRO, 1994) (Fig. 1). The investigation of roundness of quartz in the sand fraction (500-250µm) was carried out according to the 5 grades scale, suggested by A.V. Khabakov. Completely non-rounded particles with sharp edges are marked by grade 0, maximum grade of roundness 4 indicates that the quartz particles are completely round with completely smooth surface. To determine the average roundness of quartz the roundness of 100 grains was estimated according to the above-mentioned scale, then the number of grains in each group was multiplied by the correspondent grade, and the sum of all the products was divided by the total amount of grains measured.

The preparation of the samples for mineralogical analyses was carried out at the Alfred Wegener Institute of Polar and Marine Research (AWI, Germany) in cooperation with the P.P. Shirshov Institute of Oceanology, RAS (Moscow).

The mineralogical analysis was carried out using two different methods of preparation. Differences between these methods are the way of separation of fractions into light and heavy sub-fractions and the use of different chemical reagents. In the first method for separation of the light and heavy minerals bromoform with the specific weight of 2.89 g/cm^3 was used. The investigation of minerals was performed in immersion liquids. The second method of separation of minerals was carried out using the heavy liquid sodium metatungstate with a specific weight of 2.8 g/cm^3 and liquid nitrogen.

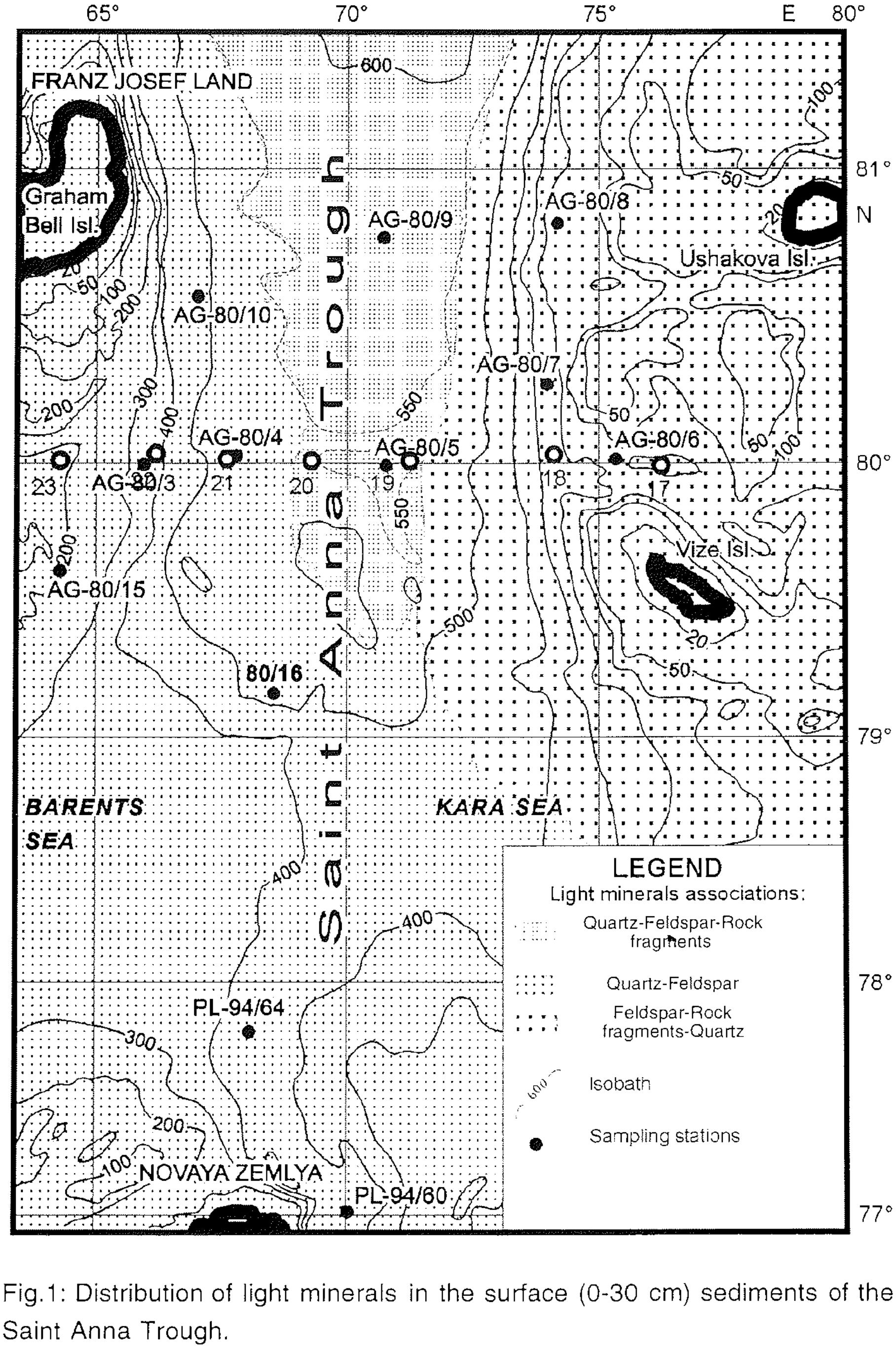

Fig.1: Distribution of light minerals in the surface (0-30 cm) sediments of the Saint Anna Trough.

The specimens for mineralogical analysis were prepared using "Meltmount" as resin. It melts during heating at temperatures of 64-100°C on the glass slide and into this solution the grains of minerals were added immediately. The results of mineralogical analysis performed on samples prepared by the two different methods do not differ principally.

For mineralogical analysis 300 grains of minerals of the light fraction were counted.

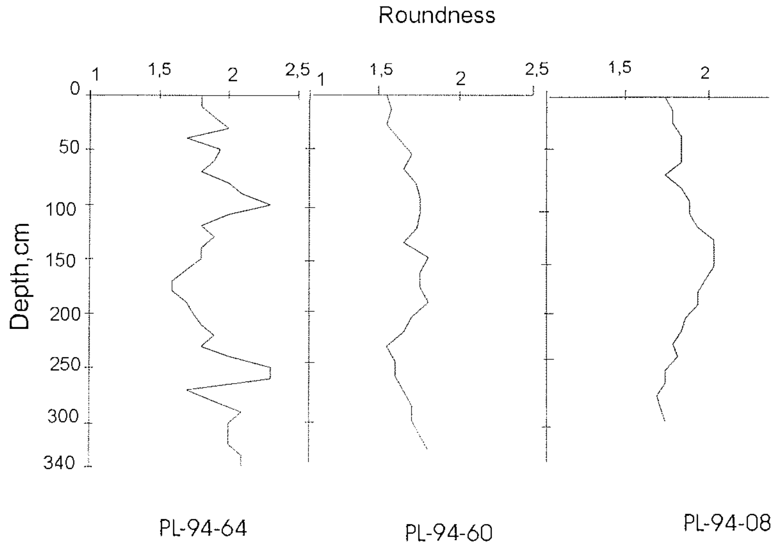

Fig.2: Graphics of quartz grain roundness of grain-size fraction 500-250 µm (RV „Professor Logachev", 1994).

Results

The results of the investigation of the mineral of the large aleurite fraction indicate the dominance of light minerals reaching 78%-99%. The main minerals of the light fraction are: quartz (30-67.7%), plagioclase (8-15.6%), soda-potash feldspar (9.4-19.5%), and muscovite. The presence of large amounts of rock fragments (up to 30%) is observed very often. These fragments are epidote- chloritic, sericite- chloritic, quartz-silicic. In the northern part of the trough (station PL94-08) grains of biogenic carbonate are observed. In the surface sediments of stations PL94-64, PL94-60, and 80/9 the dominant particles (up to 70%) are clayish fusiform aggregates, the contents of quartz decreases to 8%. In the southern part of the St. Anna Trough increased contents of organic remnants of bivalves, parts of sea weed and the foraminifer *Neogloboquadrina pachyderma* are observed.

Quartz is the main mineral, its average content is 40.4%. The highest contents are determined at station PL94-8 (up to 63%). At the station PL94-64 the quartz contents range from 19%-56.3%.

Feldspars are represented by plagioclases and soda-potash feldspars. Plagioclases are often of milky-white colour, their form approximates the lamellar prism form. The acid and basic plagioclases are the most abundant. Their contents vary between 3 and 19%. Soda-potash feldspars are intensively pellitilized and have numerous inclusions, some grains are gray in colour. Basic plagioclase, quartz and biotite are often the inclusions in the soda-potash feldspar. The contents of the soda-potash feldspar is approximately 10.8%.

Muscovite has the form of irregular scales of yellowish colour. It is probably epimagmatic developing on plagioclase. Muscovite is observed very seldom (0.2-2%). Chlorite is the mineral of the mica group which is observed most often; its content varies from 0 at station PL94-60 to 17% at station PL94-8. The form of the grains is foliar, they are of light green to grayish-green colour with high relief and average shagreen surface.The peculiarity of the sediments at station PL94-08 is the predominance of chlorite over muscovite and the increased content of chlorite in the fraction of light minerals.

Quartz-silicic aggregates are of rounded form. They are light yellow and their optic properties similar to those of chalcedony and zeolite. It differs from chalcedony by its positive prolongation and from zeolite by its larger refraction.

Opal and volcanic glass are also observed very often as bubbles or fragments of bluish-gray or light yellow colour. To distinguish between opal and volcanic glass the index of refraction was used. In some samples the contents of volcanic glass is 2%.

It should be mentioned that rock fragments and products of chemical degradation (clay aggregates of the hydro-mica type) are observed in large amounts in some samples. Epidote-chlorite shales and quartz-silicon rocks are observed most often among the rock fragments.

Quartz grains display a better roundness in sediments from the central trough in comparison to those from the flanks. Index of roundness varies between 1.6 and 2.2 (Fig. 2). Ideally round quartz grains (4 degrees) with a smooth surface are observed extremely seldom. Quartz is practically without any inclusions, clear and transparent.

Discussion

The St. Anna Trough is situated in the north-west of the Kara Sea in the triangle between the archipelagoes Franz Josef Land and Novaya Zemlya and the under-water North Kara elevation with Vise and Ushakov islands. It is obvious to suppose that these three sources of ablation situated in the vicinity of each other but different by their geological structure, play a very important role for the sediment supply into the trough. In the central part of the Franz Josef Land low- chalky trap strata are overlain by the under developed thin cover of Quaternary deposits. In the east (islands Gram Bell) Triassic and Jurassic terrigenous complexes are exposed, characterized by a predominance of aleurites and sandstones with silicic and carbonate cements (Dibner, 1970). The northern island of Novaya Zemlya is composed of metamorphosed aleurites of Lower Paleozoic age (Romanovich and Zagorskaya, 1970). The Vise and Ushakov islands consist of terrigenous rock strata of Lower Cretaceous, represented by the sandy and clayey grayish- black aleurites with inter-layers of sand of feldspar composition (Dibner and Zakharov, 1970).

Based on the mineral composition of the studied light fraction and quartz/feldspar ratios (Q/FS) three associations can be distinguished. The first (in the order of increase) is composed of quartz, feldspars, rock fragments and a Q/FS ratio of 1.6. This association occupies the deepest (more than 550 m water depth) central part in the north of the trough. The second association has a quartz-feldspar composition; the Q/FS ratio $\leq$ 1.0. This association is typical for the eastern flank of the trough. The third association is composed of feldspars, rock fragments and quartz grains of variable contents. The Q/FS is $\geq$ 0.5 (Fig.1).

Conclusions

Based on the mineral composition of the coarse aleurite fraction Franz Josef Land, Novaya Zemlya and the northern Kara elevation can be identified as main source areas of the terrigenous sediments in the St. Anna Trough.

The main source of quartz and rock fragments is Franz Josef Land, that of feldspars the northern Kara Sea elevation. Sediment transport in the west and southwest of the study area is probably related to iceberg activity mainly concentrated in this area.

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HEAVY MINERAL COMPOSITION IN SURFACE SEDIMENTS OF THE ST. ANNA TROUGH

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Introduction

Studies of bottom sediments of the Arctic seas including the Kara Sea, were started by the Research Institute of Arctic Geology (NIIGA) in 1949. Since this time, extensive information was accumulated and included in the "Ecoshelf" database (Ivanov et al., 1997). One of the first generalising studies on the Soviet Arctic region was published in 1961 by N. Belav and N. Lapina, containing data on the distribution and types of bottom sediments, their mineralogical and chemical composition, sedimentation conditions and a summarising paleogeographic scale for the last 105 ka. In the following period, numerous publications (e.g. Kulikov, 1961; Lapina 1959; Lapina et al., 1970; Kosheleva, 1988; Aksyonov, 1987; Levitan et al., 1994; Kosheleva and Yashin, 1996) specified the compilations made in this work.

Interest in the investigation of the St. Anna Trough sediments is attributed to several factors. First, this area is a large transition zone between the Arctic Ocean and the Barents and Kara seas. Second, the Novaya Zemlya and Franz Josef Land (FJL) archipelagos are the largest ice-sheet centers. Finally, this area is the main transportation pathway of terrigenous sediments supplied by the large rivers Ob and Yenisei. Thus, data derived from sediments of this region allow reconstructing of the oceanic circulation patterns, river discharge and influence of sea-ice transport.

A joint Russian-German research program, performed on sediments from the Kara Sea, included detailed sedimentological investigations, i.e. the determination of the bulk and clay mineral composition, grain size and heavy minerals distribution. The main targets of this program were to characterise and quantify the terrigenous matter supply and to identify the source areas and transportation pathways (Stein et al., 1996). Bottom sediments of the St. Anna Trough are predominantly terrigenous in origin. Therefore, their mineralogical analysis allows to identify different source areas and the ways of migration and sedimentation (Ivanov et al., 1997). As shown by different studies on the heavy mineral distribution in sediments of the Kara Sea (Kordikov, 1953; Gorshkova, 1957; Belov and Lapina, 1961; Kulikov, 1961; Gurevich, 1989; 1995; Levitan et al., 1994; Ivanov et al., 1994) these data are a valuable indicator of sediment sources and transport pathways.

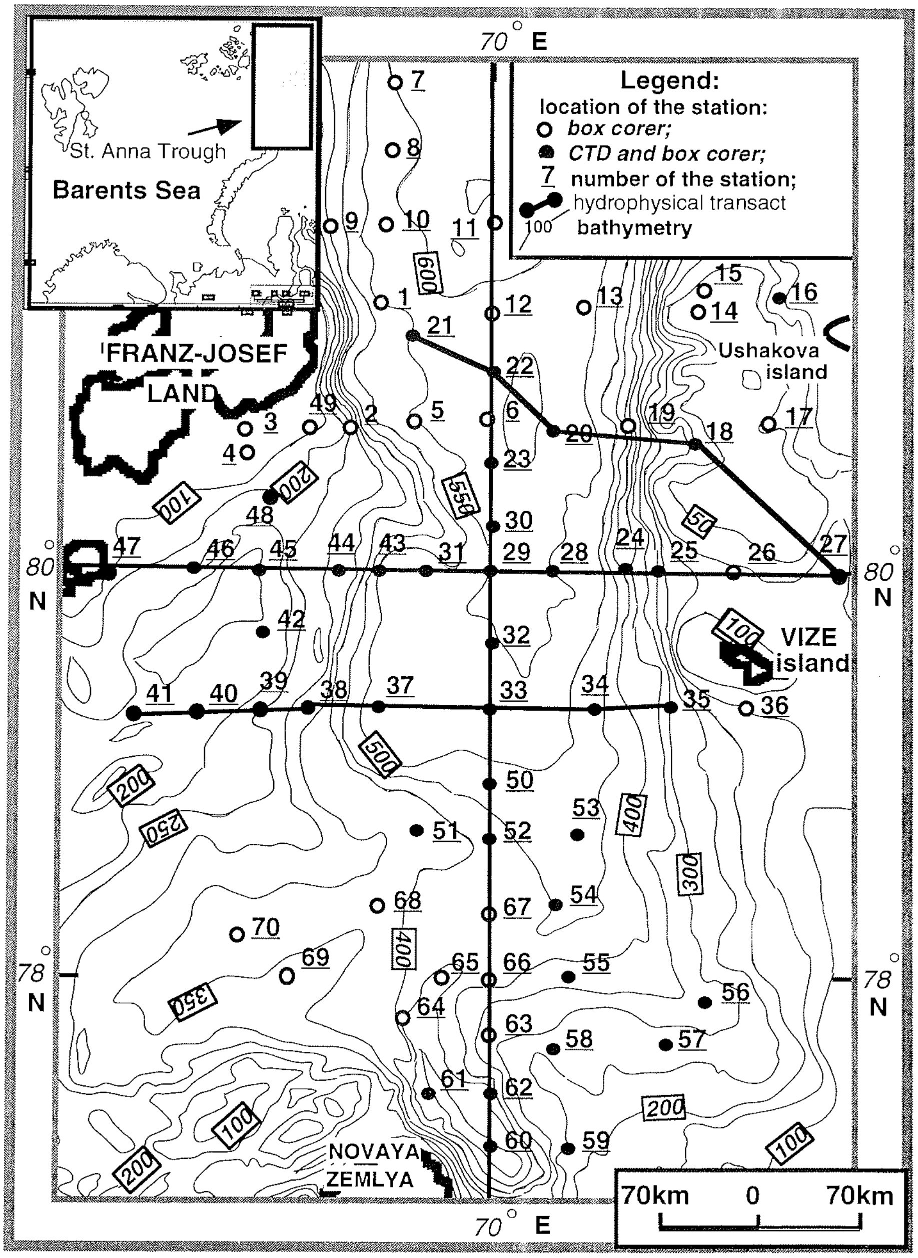

Fig.1: Location of sampling stations carried out in St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

Data and Methods

A joint Russian-American-Norwegian expedition to the St. Anna Trough was performed in August-September 1994 under the auspices of the Association Sevmorgeologia (Ivanov et al., 1995). During the cruise 70 stations (Fig. 1) were sampled. Grain size analysis and separation were performed as described by Lapina (1977) and based on the method of Petelin (1967). After a pre-separation with bromoform (specific weight 2.82g/cm^3), heavy and light minerals were analysed in the 0.1-0.05 mm fraction using immersion microscopy (immersion liquids N 1.637, N 1.702 and N 1.544, respectively). If possible, 500-600 grains of the heavy fraction were used for mineralogical analysis, but in case of lower yields all grains were used. In the light fraction, 300-400 grains were subjected to microscopic analysis. Based on the obtained data set, distribution maps were plotted using the method described by Ivanov (1991).

Results and discussion

The distribution and statistical parameters of the heavy minerals in the sandy-silt (0.1-0.05 mm) fraction in bottom sediments of the St. Anna Trough are given in Table 1 (Appendix). In general, heavy minerals show a polymictic composition and about 30 various minerals and mineral groups could be identified. Among the dominating minerals, which occur in all of the investigated samples, are pyroxene (27.6%, average of all samples), "black ore" minerals (25.9%), amphiboles (14.1%) and minerals of the epidote-zoisite group (11.7%). In lower contents, garnet (5.4%), zircon (5.3%) and titanous minerals (4.7%) have been identified. Although occurring in all investigated samples, the following minerals are represented only in low amounts: iron (ferric) hydroxides (2.3%), apatit (1.8%), rutile (0.8%) and tourmaline (0.4%). A number of other minerals (e.g. staurolite, kyanite, sillimanite, biotite etc; for details see Table 1, Appendix) were also recognised, but did not occur in all of the investigated samples. Therefore, in the following attention is paid only to minerals found ubiquitous in the investigation area.

Heavy mineral fraction yields

The yields of the heavy mineral subfraction ranged from 0.4 to 24.4%, averaging at 2.3%. Maximum yields (24.4%) of the heavy mineral fraction determined at some stations, are associated with bottom sediments affected by intensive re-washing. The lateral variability of the heavy mineral fraction yields is shown in Figure 2. Maximum contents (> 3.0%) are observed in the central and south-eastern part of the St. Anna Trough. On the eastern flank of the trough, the yields of the heavy mineral fraction are slightly lower (2.5-3.0%). In the coastal parts of Ushakov and Vize islands, this fraction accounts for 2.0-2.5%, whereas between the islands the amounts decrease to 1.5-1.0%.

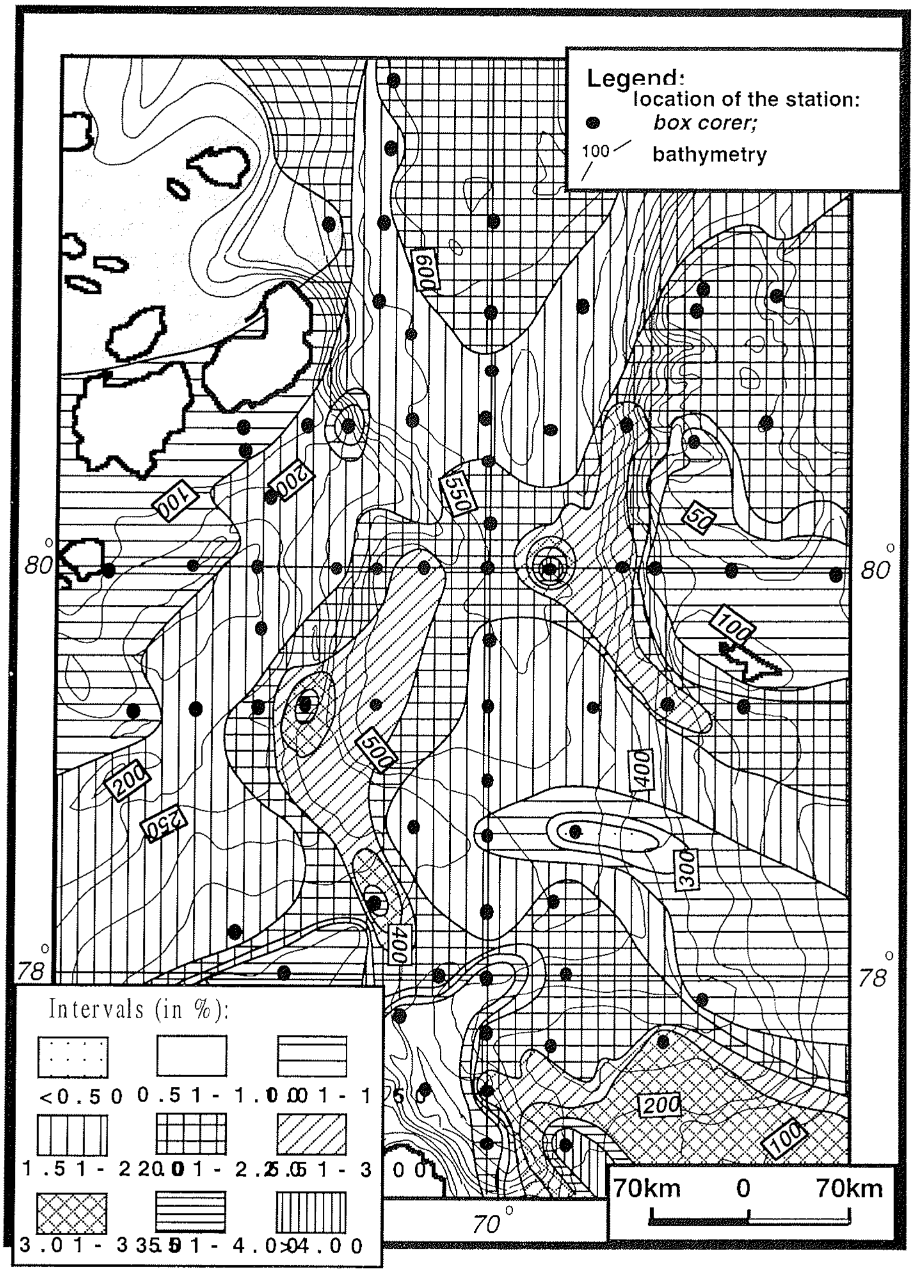

Fig.2: Distribution of heavy fraction minerals yield in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

Pyroxene minerals

Minerals of the pyroxene group are dominated by monoclinic pyroxene (clinopyroxene) and account for 95-98% of this group. In addition, rhombic pyroxenes (orthopyroxene, 15% of the stations) and Aegirin (12% of stations) have been identified but usually occurred only as individual grains. Clinopyroxene is represented by semi-rounded to angular-rounded grains. Different brownish shadings indicate that they often contain ore dust. Grains of diallages of augite are extremely rare.

Clinopyroxene contents span a wide range from 1.1 to 57% with an average of 27.4%. However, a relatively insignificant coefficient of variation (C.V.) of 0.4 (40%) has been determined for this mineral. The distribution of Pyroxene contents is given in Figure 3 and revealed a distinct zonation. Highest values, averaging at 35.6% (Table 2, Appendix), are found on the western flank of the St. Anna Trough (coastal parts of FJL Archipelago and north-eastern part of Barents Sea), and the maximum value of 57% also derives from stations in this part of the study area. In contrast, the eastern part of the trough is characterized by relatively low pyroxene contents (< 20%). The average value within this area is 13.4% (Table 2, Appendix) and a regular decrease towards the east is obvious (Fig. 3). Consequently, the coastal areas surrounding and between Vize and Ushakova Island have pyroxene contents <5%. In the central part of the trough, intermediate values (25-40%) have been encountered. Within this region, slightly increased (30-40%) values are characteristic for the northern and southern part.

The distribution of pyroxenes is explained by the bedrock composition of the islands surrounding the St. Anna Trough. High pyroxene contents in the western part of the basin are related to the erosion and weathering of Cretaceous, volcanogenic formations with a basic composition (plateau basalt, after Dibner, 1970). Rocks composing Ushakov and Vize island are dominated by volcanogenic formations of acidic and intermediate composition. In the south-eastern part of the St. Anna Trough (east off Novaya Zemlya), where contents of up to 40% have been detected, the clinopyroxene most likely is associated with sedimentary supply from the Kara Sea, where bottom sediments have comparable pyroxene contents (Kulikov, 1961).

"Black ore" minerals

The second most abundant fraction of heavy minerals are the so-called „"black ores", represented by magnetite and ilmenite and ranging from 12.6 to 60.5%. Their average content (mean of all stations) of 25.9% is only slightly lower than that of the pyroxenes (27.6%, Table 1, Appendix). In Figure 4, the distribution of the "black ore" minerals is depicted. The shallow water sediments surrounding Ushakov island form a distinct area where maximum values of up to >35% occur.

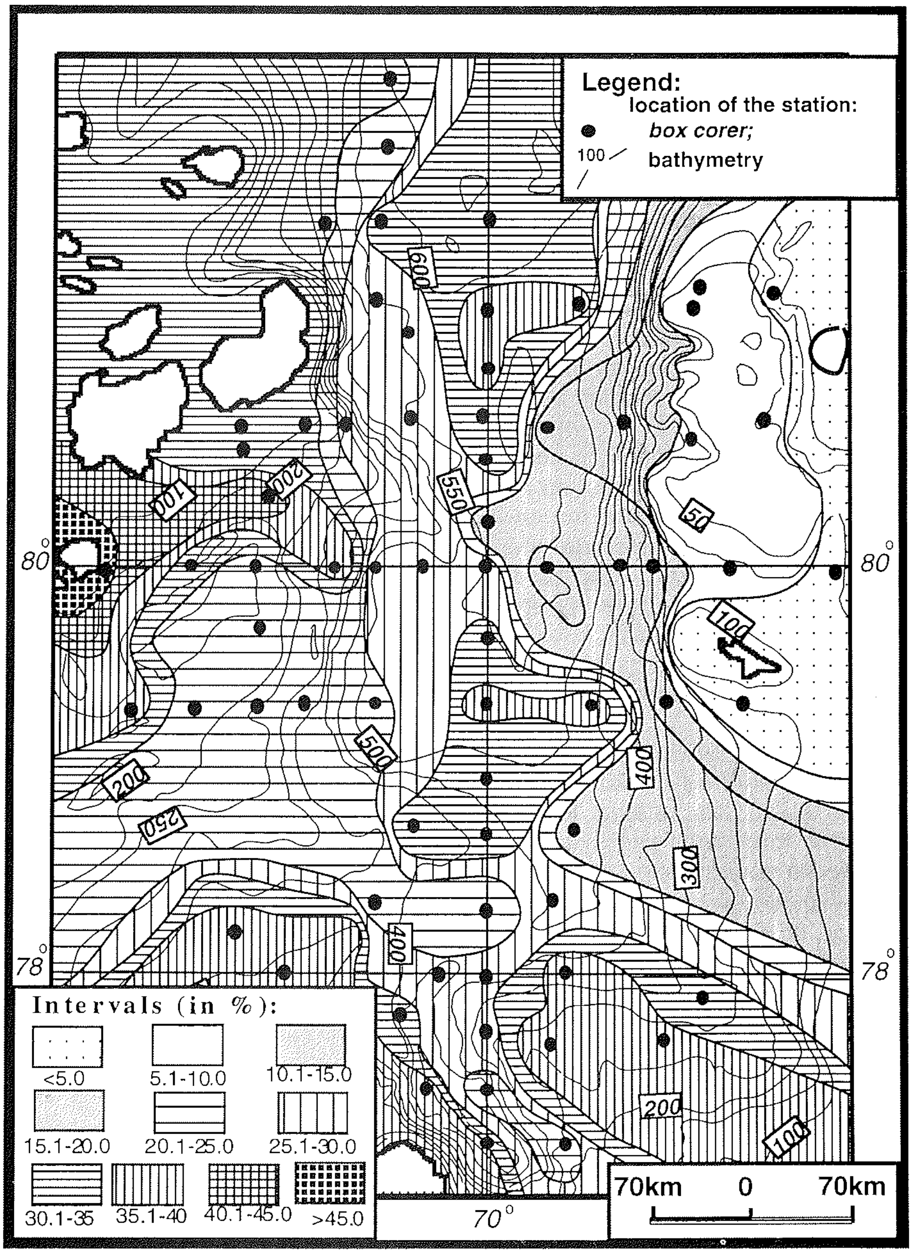

Fig.3: Distribution of monoclinic pyroxene in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

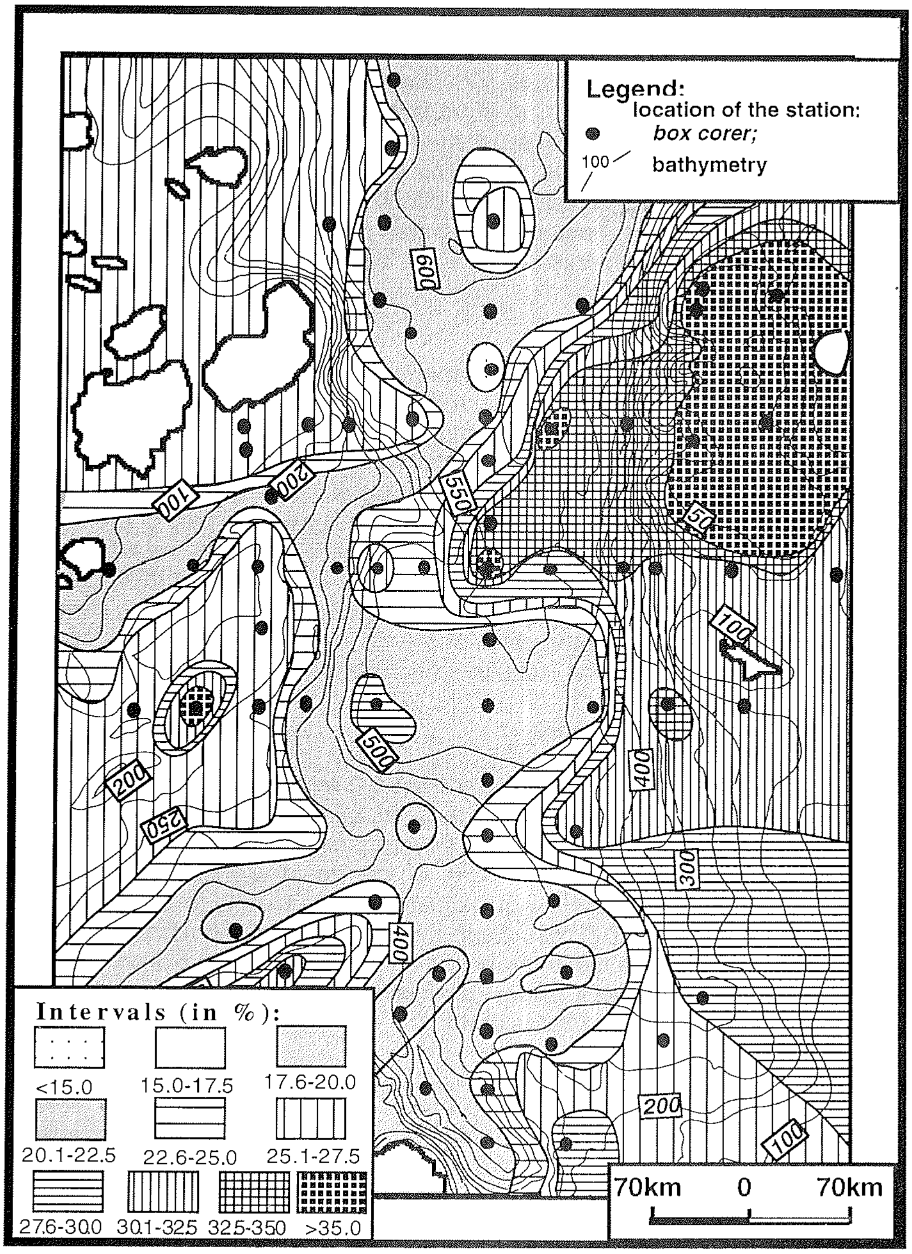

Fig. 4: Distribution of "black ore" minerals in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

Towards the west and in direction to the deepest part of the St. Anna Trough, the "black ore" contents slightly decrease to 32.5-35%, but local maxima (stations 20 and 29) still reach >35%. The distribution of "black ore" minerals in the vicinity of Ushakov indicates that this island is an important source area and also that from this region magnetite and ilmentite is transported towards the central St. Anna Trough. However, elevated values (>27.6%) towards the south indicate that "black ore" minerals are also transported in direction to the Kara Sea plateau. In comparison, the western and central deep-water parts of the investigation area are characterized by lower contents (20-22%) of "black ore" minerals.

Amphibole minerals

The relative contents of amphibole group minerals average 14.1%, with minimum and maximum values of 0.8 and 56%, respectively. They are dominated by hornblende, actinlolite and tremolite (grammatite). Actinolite and Tremolite only occurred in low amounts (0.2 – 0.4 %, av. 0.3%) and thus only the contents of hornblende are given in Figure 5 and discussed. The zone of maximum hornblende contents is located in the southern to south-western part of the trough (Fig. 5). In contrast, the shallow waters of Ushakov and Vize Island, as well as the coastal areas surrounding the Islands of Franz Josef Land, are characterized by minimum hornblende contents (< 4.0%). In general, hornblende contents increase towards the deeper water parts of the St. Anna Trough, which can be explained by gradual fractionation (relative enrichment?) during transportation.

Minerals of the Epidote-Zoisite group

Minerals of the epidote-zoisite group vary from 0.2 to 30.2%, with an average content of 11.7% (Table 1, Appendix). The distribution of the relative amounts (Fig. 6) reveals highest values in the shallow waters around Vize Island (>21.5%) and in the central and south-western parts of the basin. Zones with minimum values are located in the surrounding of Ushakov islands (< 4%) and in the south-eastern part of the trough (4.0-6.5%). Even though the Vize and Ushakov Island are not distant, they show the minimum (<4%) and maximum (>21.5%) contents of epidote-zoisite minerals. These sharp distinctions can be explained by the composition of the rocks forming the islands.

Garnet distribution

The garnet contents in the sediments varied from 1.0 to 18.3% and average at 5.4% (Table 1, Appendix). Figure 7 shows the garnet distribution. The area of maximum values (>11.9%) is located on the eastern flank of the trough, in the shoals of the Vize and Ushakov islands. Intermediate garnet contents (6.3-7.7%) are observed on the western flank, in the area of the Vilchek and Salm islands. The south-eastern and south-western part of the trough is characterized by minimum garnet concentrations (< 2.1%).

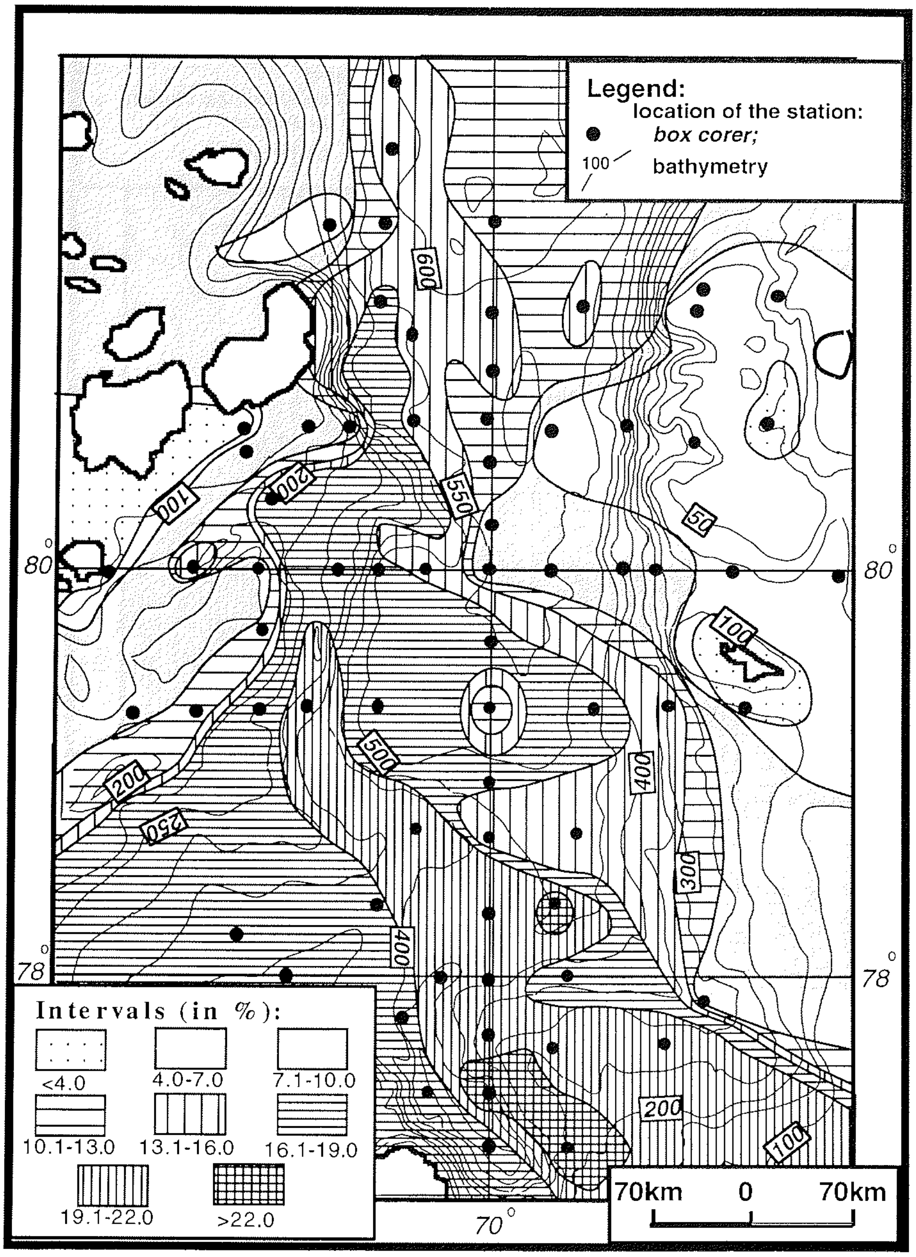

Fig. 5: Distribution of hornblende in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

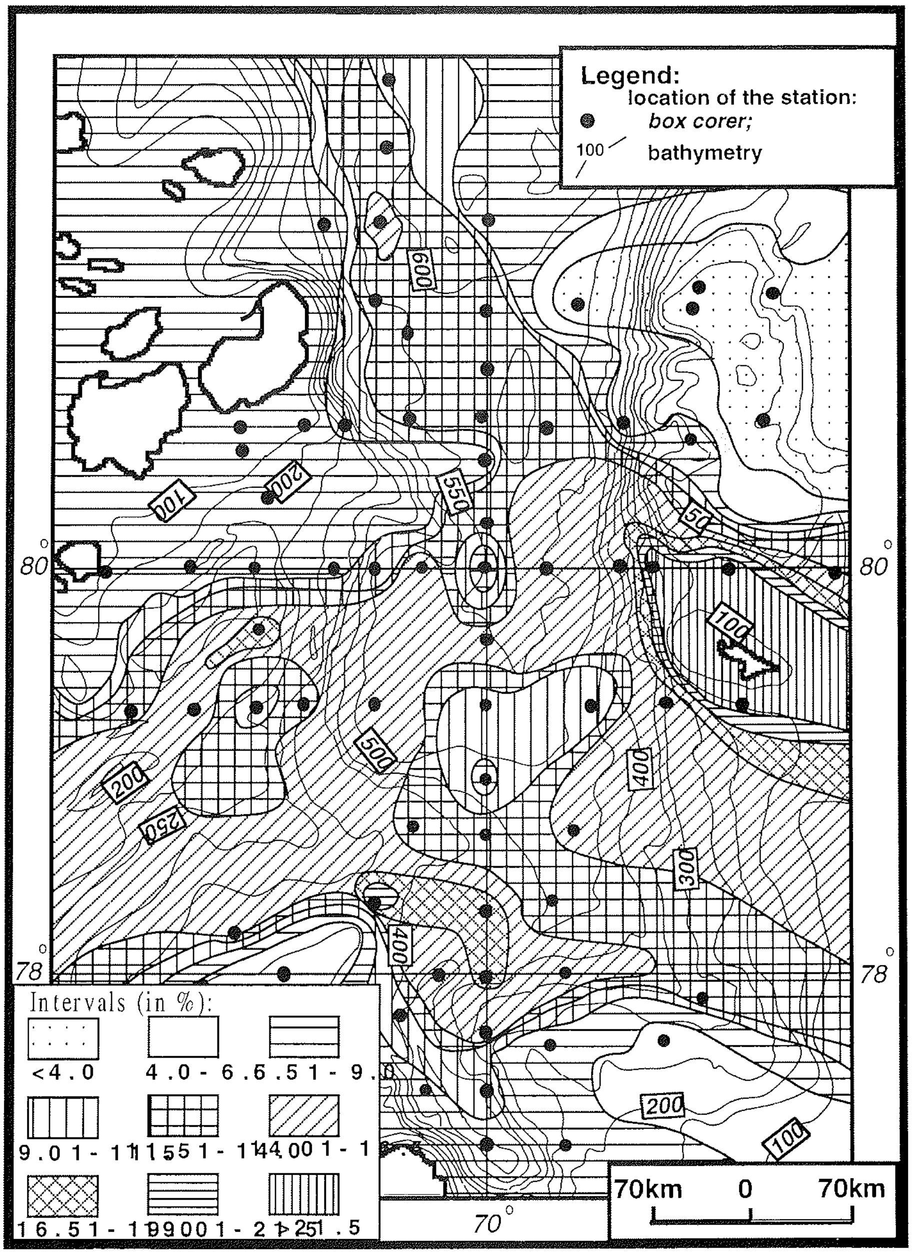

Fig. 6: Distribution of epidote-zoisite mineral group in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

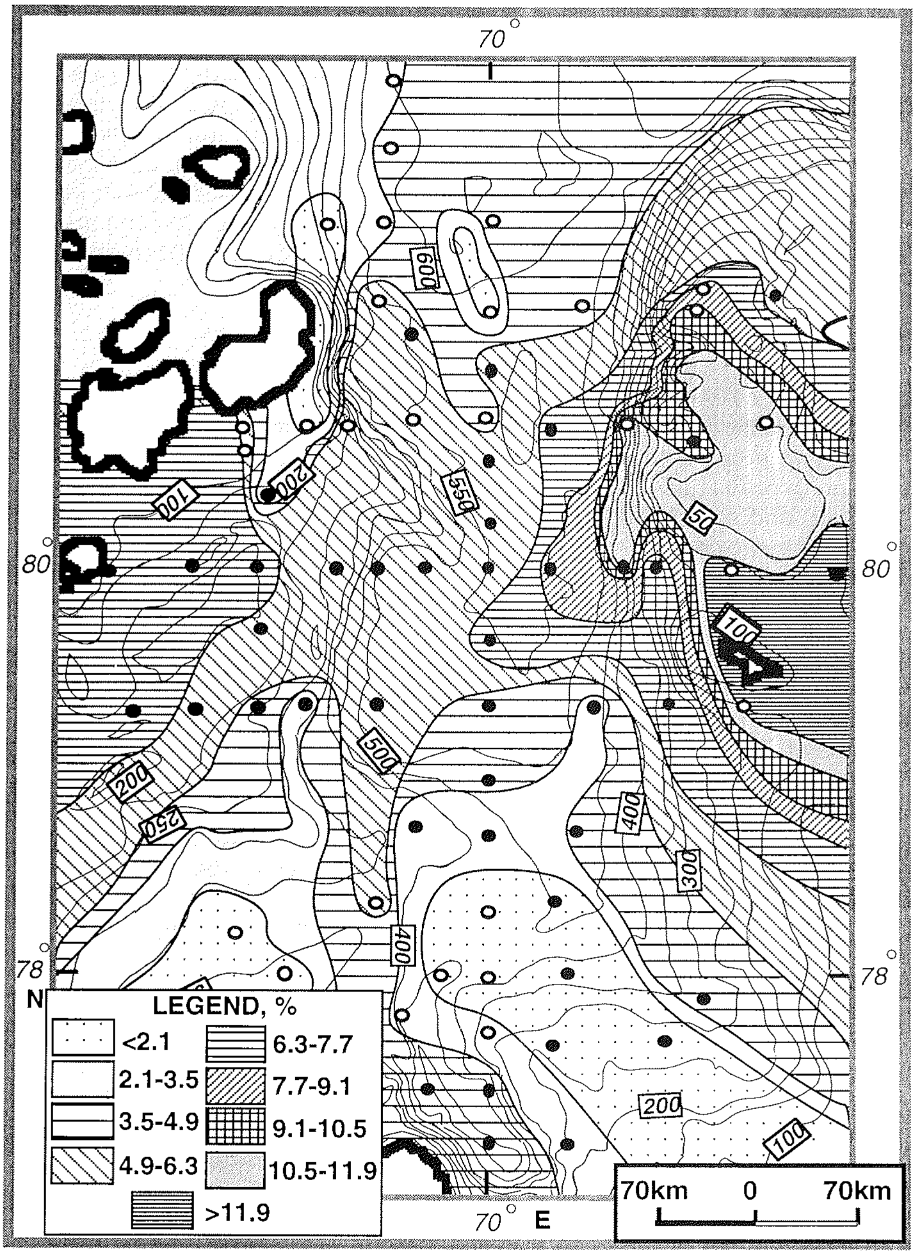

Fig. 7: Distribution of the garnet in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

Titanous minerals

Titanous minerals average 4.7% and vary from 0.4% to 12.0% (Table 1, Appendix). High concentrations of titanous minerals are located in the northern part of the trough (Fig.8), whereas the southern investigation area in general is characterized by lower contents. Within the northern part, the shallow water areas in the west (Vilchek and Graham-Bell islands, > 8%) and in the east (shoals of the Ushakov Island, > 10%) are relatively enriched in titanous minerals, compared to the deeper water parts in-between. Minimum values (< 2.1%) are observed in the south-eastern part of the trough.

Ferric hydroxides

Ferric hydroxide contents average 2.3% and range from 0.3 to 9.4%. Figure 9 displays the distribution of ferric hydroxide concentrations in the surface sediments. Two areas of maximum contents are distinguished in the central part of the trough (> 5.4%) and in the northwest (> 4.6%). In contrast, large areas in the south-eastern and south-western parts of the trough only show low contents (< 1.4%) of ferric hydroxides.

Apatite distribution

Apatite contents, averaging at 1.8% and varying from 0.5 to 4.8%, are in general lower than the above-described mineral groups. The variation of the apatite concentrations (Fig.10) shows that zones of maximum concentrations are located in the shoals of Vize (> 3.0%) and Ushakov (> 2.2%) islands. Zones of increased apatite contents are also observed within and in the surrounding of the FJL Archipelago (> 2.2%) and in the southwest of the investigation area. The latter region, situated in the vicinity of a submarine ridge, is suggested to be an area where washing-out of basement rocks occurs. The similar contents of apatite in the different above-mentioned zones indicate a similarity in the composition of the island-forming rocks and the rocks in the south-western submarine erosion area.

Tourmaline distribution

Although tourmaline concentrations were the lowest encountered, this mineral was found in all samples. In average, tourmaline concentrations reach 0.4%, with variations from 0.2 to 1.1% (Table 1, Appendix). In general, tourmaline concentrations (Fig.11) show a gradient from highest values in the east to lower values in the west. Maximum tourmaline contents on the eastern side of the trough are located in the surrounding of Ushakov (0.8%) and Vize (0.6%) islands. As seen for the apatite contents, an additional area of increased tourmaline concentrations (0.5%) is recognised in the south-western part, and as already suggested for apatite, is probably related to submarine erosion of basement rocks.

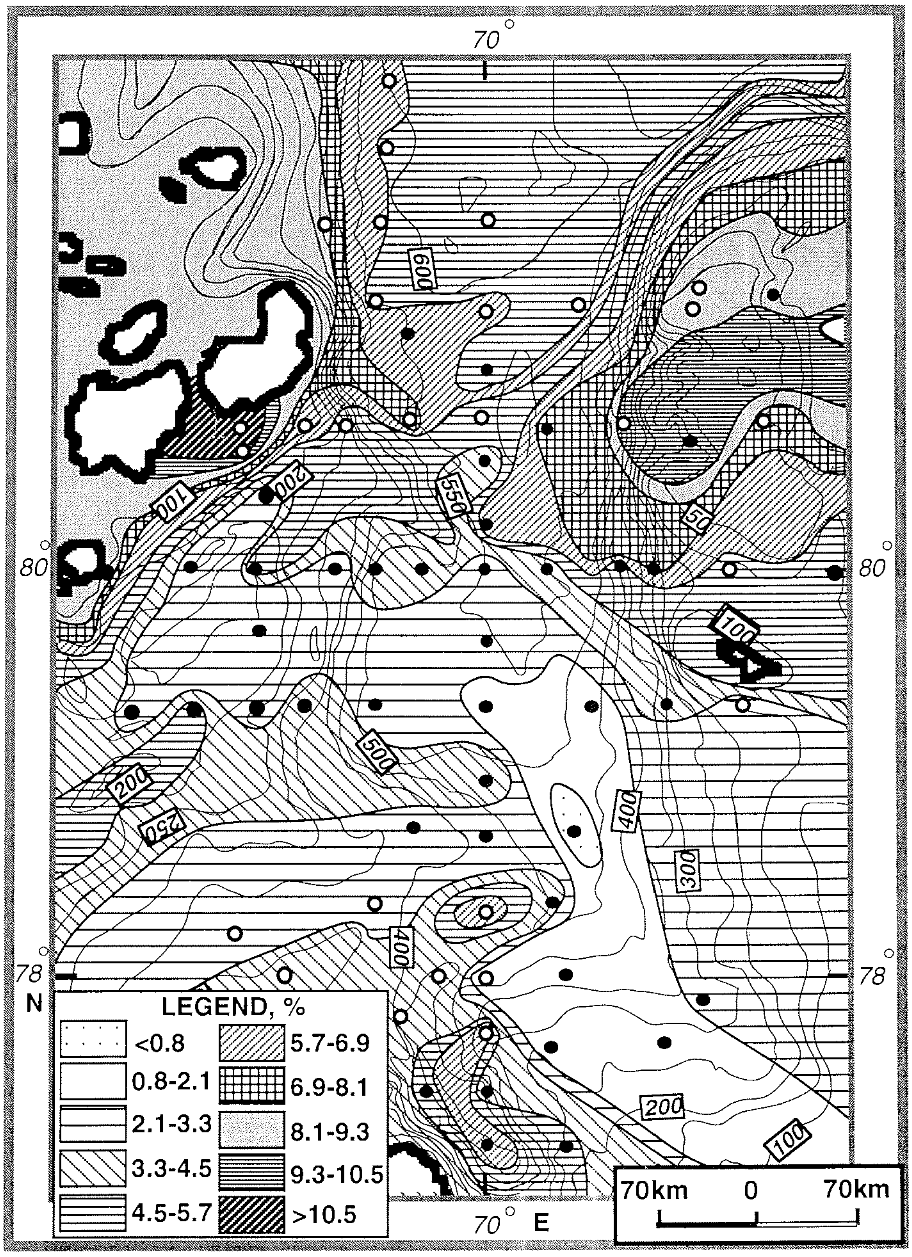

Fig. 8: Distribution of titanous minerals in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

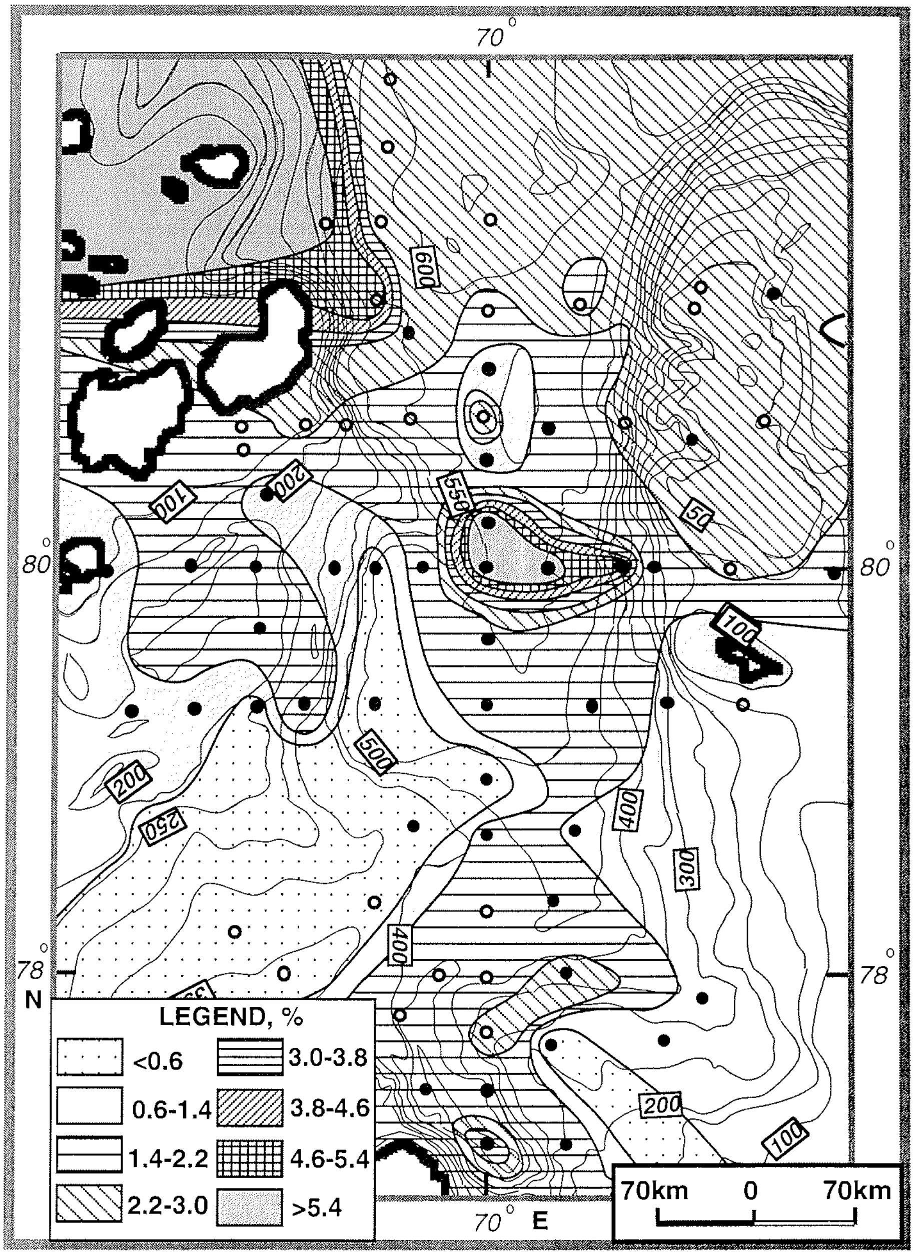

Fig. 9: Distribution of ferric hydroxide minerals in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

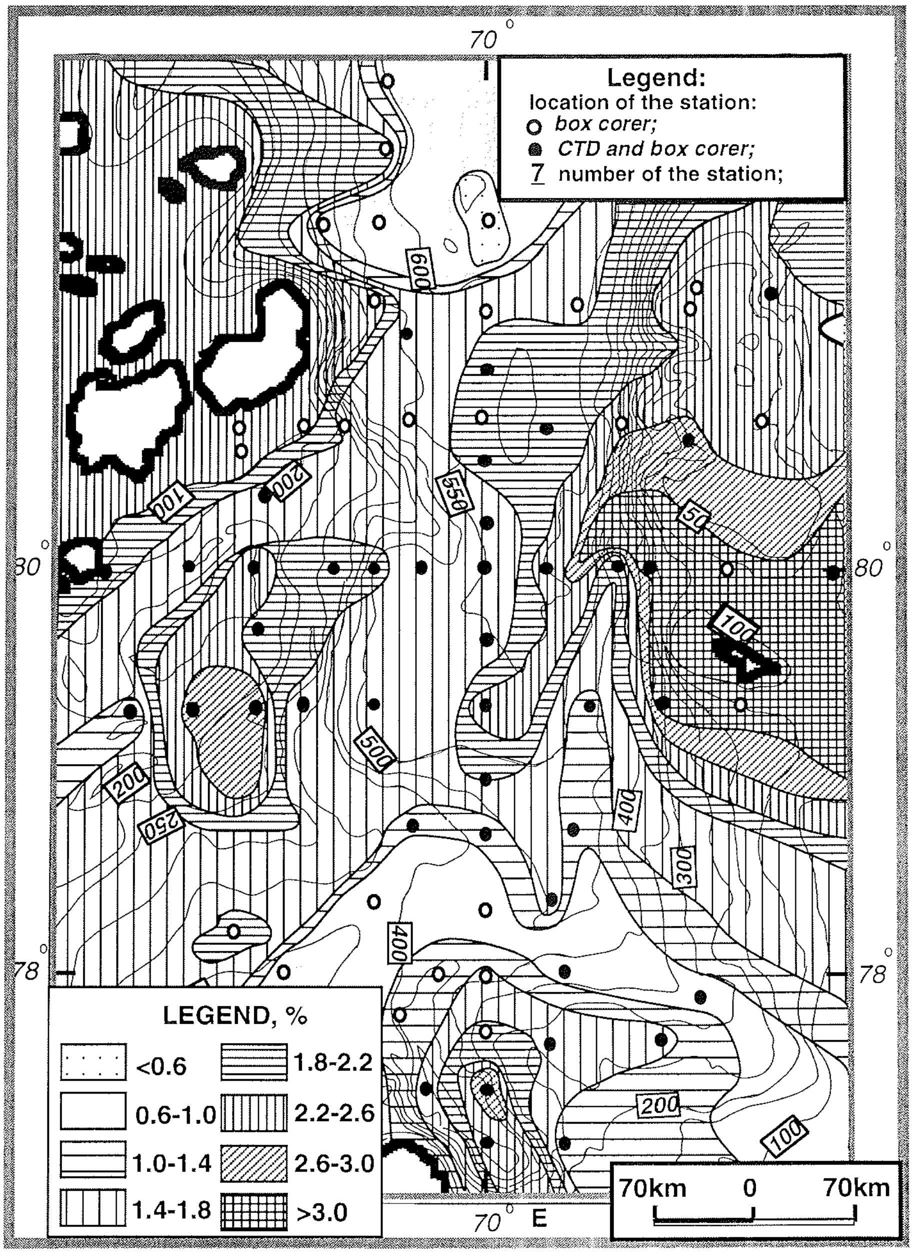

Fig. 10: Distribution of apatite in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

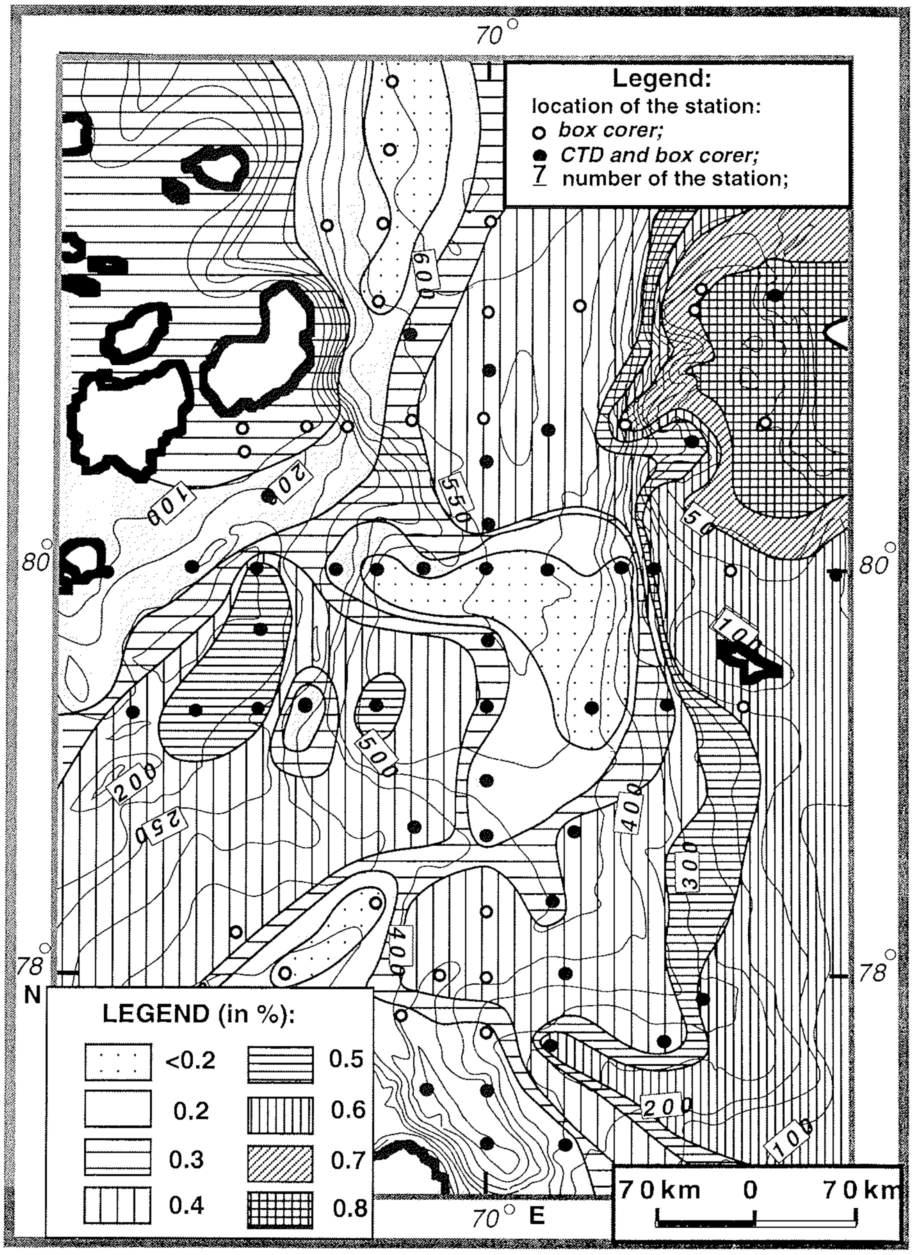

Fig. 11: Distribution of tourmaline in surface bottom sediment in the St. Anna Trough (RV "Professor Logachev", cruise 9, 1994).

Heavy mineral zonation in the St. Anna Trough

In the map of terrigenous-mineralogical provinces of the Arctic Basin, the study area is referred to as ore-epidote-pyroxene province (Belov, Lapina, 1961) and the coastal part of the FJL Archipelago is regarded as a pyroxene subprovince. Despite some minor variations, the average mineralogical composition of the heavy mineral fraction given by Belov and Lapina (1961) is in agreement with our data. However, "black ore" and pyroxene contents are somewhat higher (this study: 25.9% and 27.4%, respectively) than the 16.95 and 21.8% obtained by Belov and Lapina (1961). On the other hand, amphibole and epidote-zoisite contents are comparable (11.5% and 13.2%, this study, *vs.* 14.1 / 11.7%, Belov and Lapina, 1961).

Based upon our data, we can distinguish 8 regions in the study area, each characterised by a distinct heavy mineral association. The average heavy mineral contents of these 8 areas are given in Table 2 (Appendix).

Maximum average hornblende contents (19.5%) are found in the south-eastern part of the St. Anna Trough, whereas low amounts are typical for the areas offshore Vize Island (0.8%) and the southern (3.1%) and northern (4.2%) offshore region of Ushakov Island. The high hornblende contents observed in the south-eastern part of the trough can be explained by export from the Kara Sea (Kulikov, 1961).

The western part of the trough, adjacent to the FJL Archipelago, is characterised by maximum pyroxene contents (average 35.6%). In the shallow waters off Ushakov and Vize islands, average pyroxene contents are lowest (1-2%). However, in the strait between Ushakov and Vize islands, the pyroxene contents significantly increase up to 11.9% (see Table 2, Appendix). This suggests that the islands are not the source region of the pyroxenes found inbetween the islands. Therefore, these increased pyroxene contents most likely reflects the hydrodynamic regime. Additionally, highest contents of ferric hydroxides (4.0%) are typical for this area. The shallow waters surrounding Vize-Island are furthermore characterized by maximum contents of epidote-zoisite minerals (30.2%), garnet (14.6%), zircon (12.5%) and apatite (3.6%). In contrast, in the surrounding of Ushakov Island, epidote-zoisite contents are lowest (4.2 – 4.8%), but in the northern part off Ushakov Island, maximum values of titaneous (9.0%) and "black ore" minerals (55.2%) are found. The southern part off Ushakov Island is also characterised by high "black ore" mineral contents (49.6%). Somewhat lower values were obtained for the shallow waters off Vize Island (32.0%) and in the bay between the two islands (29.2%). No maximum value of a distinct heavy mineral was found for the eastern part and the central deep part of the St. Anna Trough. In general, the central deep part shows heavy mineral contents comparable to the mean amounts of all stations investigated and thus most likely is an accumulation area of deposit where mixing and deposition of all heavy mineral sources surrounding the St. Anna Trough occur.

Conclusions

The heavy mineral distribution and their relative contents in surface sediments allow to distinguish different zones of heavy mineral assemblages within the St. Anna Trough. The main factors controlling the heavy mineral accumulation and distribution are different source areas, the distance from the source area, water depth, (bottom) water currents and thus transport pathways. According to the presented data, the following main source areas are suggested to deliver heavy minerals into the St. Anna Trough: Franz Josef Land (FJL), the islands of Vize and Ushakov and, additionally, sediment export from the Kara Sea.

Acknowledgements

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Appendix (Ivanov et al.)

Table 1: Average contents of minerals of heavy subfraction in surface sediments in St. Anna Trough (in %).

	clinopyroxene	orthopyroxene	Egyrin	Pyroxene	Hornblende	Actinolite-Tremolite	amphiboles	Epidote-Zoisite	Orthite	Apatite	Tourmaline	Garnet	Zircon	Monazite	Sphene	Rutile	Ti - minerals	Biotite	Chlorite	Staurolite	Kyanite	Sillimanite	Chloritoid	Black ore minerals	Fe-hydroxide	Siderite	% heavy subfraction
N OF CASES	65	10	8	65	66	16	66	65	11	66	55	65	66	5	28	66	66	34	19	43	28	8	17	66	64	29	66
MINIMUM	1.1	0.2	0.2	1.1	0.8	0.2	0.8	0.2	0.2	0.5	0.2	1.0	2.0	0.2	0.2	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0.2	12.6	0.3	0.2	0.4
MAXIMUM	57.0	0.2	0.2	57.0	25.8	0.4	56.0	30.2	0.4	4.8	1.1	18.3	31.0	0.2	0.5	3.4	12.0	2.0	1.0	2.1	0.8	0.3	1.0	60.5	9.4	4.3	24.4
MEAN	27.4	0.2	0.2	27.6	13.3	0.3	14.1	11.7	0.2	1.8	0.4	5.4	5.3	0.2	0.2	0.8	4.7	0.3	0.3	0.5	0.3	0.2	0.3	25.9	2.3	0.8	2.3
STANDARD DEV.	10.4	0.0	0.0	10.5	6.4	0.1	8.2	5.3	0.1	0.9	0.2	3.6	3.8	0.0	0.1	0.6	2.6	0.3	0.2	0.5	0.2	0.0	0.2	8.0	1.9	1.0	2.9
C.V.	0.4	0.0	0.0	0.4	0.5	0.4	0.6	0.5	0.3	0.5	0.5	0.7	0.7	0.0	0.4	0.8	0.6	1.0	0.7	1.0	0.5	0.2	0.6	0.3	0.8	1.2	1.2

Table 2: Average contents of minerals of heavy subfraction in different parts of St. Anna Trough (in %).

South-Eastern part	29.9	0.2	0.2	29.9	19.5	0.3	19.6	10.9	0.3	1.5	0.4	2.1	4.7		0.2	0.6	3.8	0.2	0.2	0.3	0.5	0.2	0.3	22.3	1.8	0.4	2.1
Offshore of Vize Island	1.1			1.1	0.8		0.8	30.2	0.3	3.6	0.6	14.6	12.5		0.2	0.5	2.4							32.0	1.0		2.2
straigt between Ushakova & Vize Is.	11.8	0.2	0.2	11.9	7.1	0.3	7.2	17.0	0.2	2.8	0.5	12.2	6.1	0.2	0.2	0.8	5.1	0.2	0.2	0.4	0.2	0.2	0.2	29.2	4.0	0.2	2.1
southern part off-shore of Ushakova Is.	9.0	0.2		9.2	3.1		3.1	4.8		1.8	0.8	10.6	8.6	0.2		2.4	5.0	0.2		1.4	0.6	0.2		49.6	3.0	0.8	12.8
northern part off-shore of Ushakova Is.	2.2	0.2		2.4	4.2	0.2	4.4	4.2		2.2	0.8	6.1	6.0			2.8	9.0	0.4		1.8		0.2		55.2	2.5	2.0	2.3
Eastern part of trough	13.2	0.2	0.2	13.4	7.5	0.3	7.6	14.1	0.2	2.5	0.5	10.4	6.3	0.2	0.2	1.2	5.6	0.4	0.2	0.6	0.3	0.2	0.2	31.9	3.4	0.5	1.8
Western part of trough	35.6	0.2	0.2	35.7	11.2	0.2	11.3	8.0	0.2	1.7	0.3	4.7	4.1	0.2	0.2	0.7	5.7	0.3	0.2	0.5	0.4	0.2	0.5	23.1	2.2	1.8	1.5
central deeply part of trough	29.2	0.2	0.2	29.3	13.8	0.3	13.9	12.0	0.2	1.9	0.4	4.5	4.8	0.2	0.3	0.7	4.2	0.4	0.4	0.3	0.3	0.2	0.3	23.9	3.0	0.4	2.0

PROVENANCE OF KARA SEA SURFACE SEDIMENTS, BASED ON HEAVY MINERAL DATA

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Introduction

There are a number of traditional methods and approaches to distinguish source provinces and study the pathways and mechanisms of sediment supply in recent and/or ancient sedimentary basins. Among these methods are: the study of heavy, light and clay minerals; detailed investigation of mineral typomorphism and crystallochemical peculiarities; the chemical composition of bulk sediments, individual grain-size fractions; the isotopic composition of bulk sediment and/or monomineral samples (e.g., $^{87}Sr/^{86}Sr$, $^{18}O/^{16}O$, etc.); investigation of absolute age of individual minerals (e.g. zircon, apatite) etc. The term „terrigenous-mineralogical province" was introduced by V. P. Baturin in 1937 (Baturin, 1937) and describes parts of recent and ancient sedimentary basins characterized by sediments having the same mineral assemblage. In numerous studies, heavy minerals are used to determine the provenance of sediments.

Materials and methods

In a number of publications, the heavy mineral distribution has been used to determine the sedimentary provenance of recent sediments in the Kara Sea (Kordikov, 1953; Belov and Lapina, 1961; Kulikov, 1961, 1971; Andrew and Kravitz, 1974; Kosheleva, 1988; Gurevich, 1995; Levitan et al., 1996). Based on these publications, in this paper we add new data on the heavy mineral composition of surface sediments in the Kara Sea southwards of 76°N (49-th cruise of R/V „Dmitry Mendeleev", 1993) and of the St. Anna Trough (9-th cruise of R/V „Prof. Logachev", 1994). Sediment sampling locations of the „Dmitry Mendeleev" cruise are shown elsewhere (Levitan et al., 1996), whereas the sampling sites within the St. Anna Trough are shown in Figure 1. From both cruises, surface (0-2 cm) sediments were analyzed. These samples were obtained either by means of grab samplers, box corers and by gravity corers.

In order to get a comparable data set of the heavy mineral composition, the same method has been used by analysts of Shirshov Institute (V. P. Kazakova, A. N. Rudakova, M. V. Bourtman) and VNIIOkeangeologia (L. S. Smirnova). Briefly, the grain-size fraction 0.05-0.1 mm was separated and then subdivided in a heavy and light fraction by means of bromophorm. The heavy minerals were studied by microscope, using immersion liquids. Usually, 300-600 grains were counted.

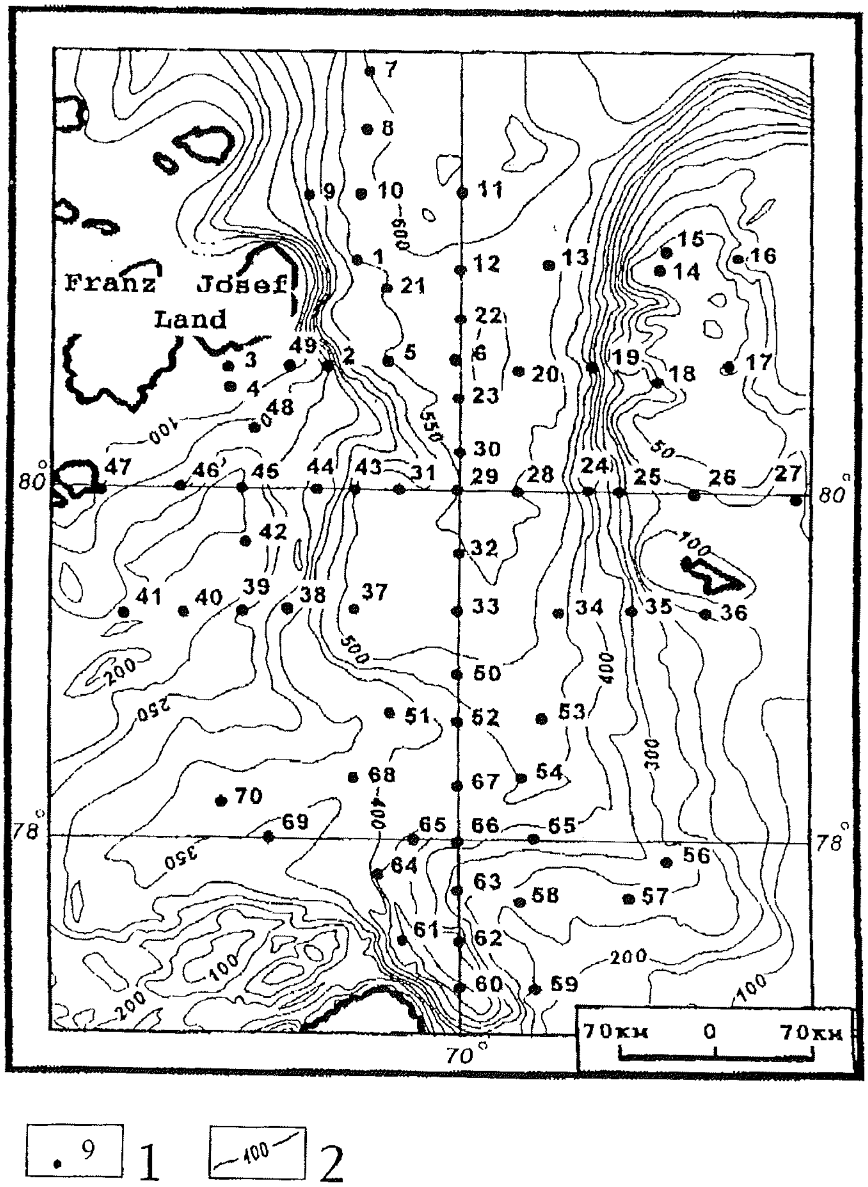

Fig.1: Location of R/V "Professor Logachev" geological stations in the St.Anna Trough area. 1 - number of station; 2 - isobaths (in meters).

Results and discussion

A total number of ca. 30 minerals were encountered. The percentage of heavy minerals in the analysed fraction (0.05-0.1 mm) usually does not exceed 2.0-2.5 % but can increase up to 4.7-11.5 % in coastal areas. In general, clastogenic minerals dominate, but low amounts of authigenic minerals (pyrite, iron carbonates) and undetermined grains exist as well. The percentages of heavy minerals discussed in this paper are given as a percentage of the identified clastogenic minerals. The names of terrigenous-mineralogical provinces represent the most common (>10%) heavy minerals and within the names (e.g. amphibole-epidote–clinopyroxene), distinct minerals are sorted by increasing abundances.

Dominating heavy minerals in Kara Sea surface sediments are: pyroxenes (mainly clinopyroxenes, augite), amphiboles (mainly normal hornblende), minerals of epidote-zoisite group, black ore minerals (ilmenite, titano-magnetite and, in lower amounts, magnetite). At distinct locations, garnets and iron oxides/hydroxides are also common. Sporadically, accessory minerals (e.g. apatite) can occur in higher relative concentrations.

The distribution of amphiboles, black ores, epidote and clinopyroxenes in the Kara Sea surface sediments southward of 76°N was shown earlier (Levitan et al., 1996) but it was not described in detail. Based on these data, the following conclusions are possible:

1) Black ore, epidote and clinopyroxene contents are highly related to inputs from adjacent landmasses, whereas for amphiboles such a relation is not obvious. Amphiboles are typical for sediments located in some distance from source provinces, i.e., for environments where fluxes of other minerals supplied from the land are reduced. The same conclusion was made earlier by Kosheleva and Yashin (1996).
2) The main sources of black ores and epidote are the Paleozoic sedimentary sequences of the Novaya Zemlya Archipelago and the Yamal Peninsula where Quaternary sediments represent erosion products of Mesozoic-Cenozoic sequences (Ronkina and Vishnevskaya, 1977). Increased epidote amounts are mainly related to the South Island of Novaya Zemlya.
3) Clinopyroxene inputs into the Kara Sea mainly derive from the river Yenisey. The eastern Yenisey tributaries drain the Tungusskaya Syneclise (East Siberia), where thick Permian-Triassic trapp-basalts are enriched in clinopyroxenes. Quite definite supply of clinopyroxenes is also made by the river Ob. The Ob receives major sedimentary inputs from erosion of Westsiberian Mesozoic-Cenozoic sedimentary sequences, which got these minerals from Permian-Triassic trapp basalts (including West Siberian ones). Furthermore, high contents of clinopyroxenes reported in bottom sediments northward from the Taimyr Peninsula derive from the same Permian-Triassic trapp-basalts (Kulikov, 1971).

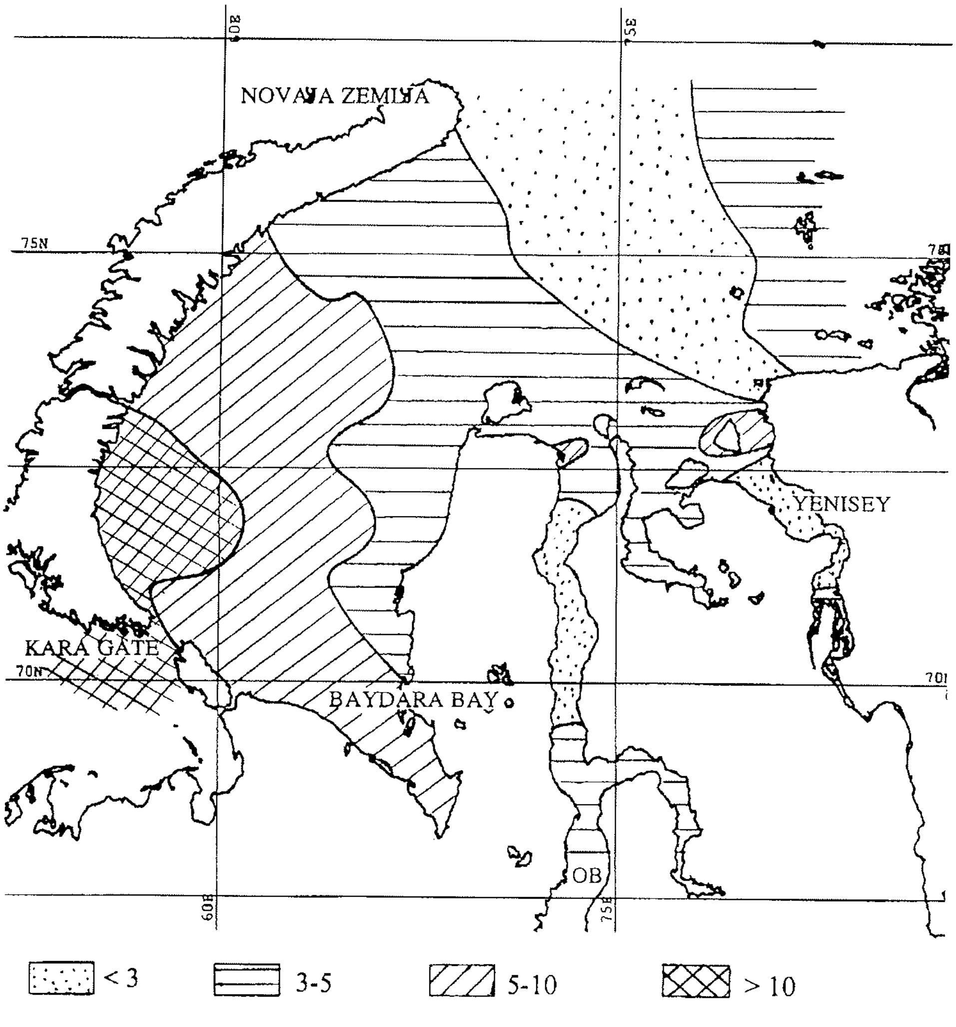

Fig.2: Distribution of garnet (%) in the Kara Sea surface sediments

For most of the recent marine sedimentation areas of the Kara Sea, epidote/clinopyroxene (Ep/ClPx) ratios indicate contributions of Ob and Yenisey discharge. According to our data (Levitan et al., 1996), the mean Ep/ClPx ratio for western Kara Sea sediments is 1.7, for Ob transect sediments 0.6, and for Yenisey transect sediments 0.2.

The garnet distribution (Fig. 2) shows that the main source of this mineral is the South Island of Novaya Zemlya. Minor local enrichments of garnet where also recorded in sediments off the northwestern Yamal Peninsula and northwards the Yenisey Bay. The distribution of heavy mineral assemblages (Fig. 3) indicates a sharp difference between the Ob/Yenisey and Western Kara facies zones (Levitan et al., 1996): clinopyroxenes dominate the sediments in the Ob and Yenisey zone, whereas epidote is enriched in the Western Kara Sea. Besides the dominating amounts of garnet and epidot, it seems that additional proportions of hornblende and black ores indicate areas of enhanced erosion of bottom sediments.

Additional information with regard to the above-mentioned problems is obtained by means of factor analysis.

Distribution of heavy minerals is a multi-factor process. The first 5 factors determine 80,70 % of obtained results, and the first 8 factors - 90.88 %. We consider just the first 5 factors. Coefficient of variation for factor 1 is 40.06 %, for factor 2 - 16.79 %, for factor 3 - 10.08 %, for factor 4 - 8.61 %, and for factor 5 - 5.14 %.

The analysis of normalized factor loadings allowed to assume the leading role of hydrodynamic regime as the explanation of these factors. Thus, factors 1 and 2 can be interpreted as the manifestation of active hydrodynamics in the nepheloid layer (including bottom erosion and transportation by means of brines). Factor 1 is connected mainly with the Ob- Yenisey facial zone, and factor 2 with the western Kara facial zone. Factor 3 explains the transportation in the surface water layer of buyoant minerals such as biotite and chlorite. Factors 4 and 5 are related to calm hydrodynamic environment, and we can suppose (based on indirect data) that factor 4 reflects biotransportation mechanisms of heavy minerals on the sea floor, and factor 5 mechanisms of ice sedimentation.

Factor analysis allowed to distinguish 7 main heavy mineral associations and to explain their probable origin:

1) *Iron oxides/hydroxides – garnet – rutile – staurolite – tourmaline - chromspinel*; resistent remnants of metamorphic rocks, enriched in areas of intensive reworking of bottom sediments
2) *Clinopyroxenes - chloritoid*; erosion products of Siberian trapp basalts, transported into the Kara Sea by the rivers Ob and Yenisey
3) *Rhombic pyroxenes - anatase - spinel - andalusite*; comparable to association 1.), but less resistant to transportation and reworking processes
4) *Black ore minerals*; enriched by gravitation in coastal areas or regions of active erosion of bottom sediments
5) *Biotite - chlorite*; transported for long distances by surface currents

6) *Leukoxene - epidote - apatite - sphene - disthene*; remnants of low-grade metamorphic granitoids and/or sedimentary rocks lying underneath
7) *Magnetite - hornblende - actinolite/tremolite - glaucophane*; supplied from erosion of rocks belonging to the amphibolit facies and, partly also from rocks of low temperature/high pressure metamorphism.

Characteristics of heavy mineral distribution in surface sediments of the St. Anna Trough

Pyroxenes, epidote, hornblende and black ores are the most prominent heavy minerals in the bottom sediments of the St. Anna Trough. The clinopyroxen distribution (Fig. 4) shows, that in the southeastern area off Franz-Josef Land this mineral contributes >40% to the heavy mineral fraction. Moderate amounts of ClPx (30-40 %) are also typical for: 1) the region adjacent to the northern Island of Novaya Zemlya; 2) the southeast of the studied area (extension of Ob - Yenisey facies zone?) and 3) large areas in the central and northeastern part of the St. Anna Trough.

In average, contents of epidote are higher in the southern part of the study area than in the north (Fig. 5). Highest amounts (>19 %) are located near the Vise Island. Moderate amounts (14-16.5 %) in the southwestern part of the region are probably related to an input from the Barents Sea. Local areas of same amounts (up to 19 %) in the northwest and south of the trough are probably related to the erosion of underlying epidote - enriched rocks.

According to Figure 6, input of hornblende into the St. Anna Trough takes place from the southwest and southeast. It seems that the large area with hornblende contents >16% in the southwest of the Kara Sea is linked to comparable hornblende abundances in the Barents Sea (Levitan et al., 1996).

The average amount of black ores in the St. Anna Trough is about 20 %. Local enrichments of black ores are found in the Northern Kara Rise area (up to 30%) and maximum values (up to 60%) occur around Ushakov Island. The surrounding of Ushakov Island is further characterized by high amounts of iron oxides/hydroxides (up to 20 %), zircon (6-11 %) and rutile (up to 3.1 %). North off the Island Novaya Zemlya, black ores (mainly ilmenite) comprise 25-30% of the heavy mineral fraction. In the vicinity of Vise Island, high amounts of garnet (10-15 %) have been found.

Even though we have not yet completed the mapping of terrigenous - mineralogical provinces, we can distinguish several areas with specific heavy mineral associations in the St. Anna Trough. The association of ilmenite and augite characterizes sediments around the eastern Islands of Franz-Josef Land. The surrounding of the northern Kara Rise is defined by the clinopyroxene - black ore assemblage and high amount of accessories (including garnet near Vise Island). Most of the southern St. Anna Trough is comprised by sediments with amphibole - epidote - clinopyroxene, whereas in the north ilmenite - epidote - clinopyroxene dominates.

With respect to the sources and processes controling the composition of the above-mentioned heavy mineral associations, we can only make preliminary conclusions.

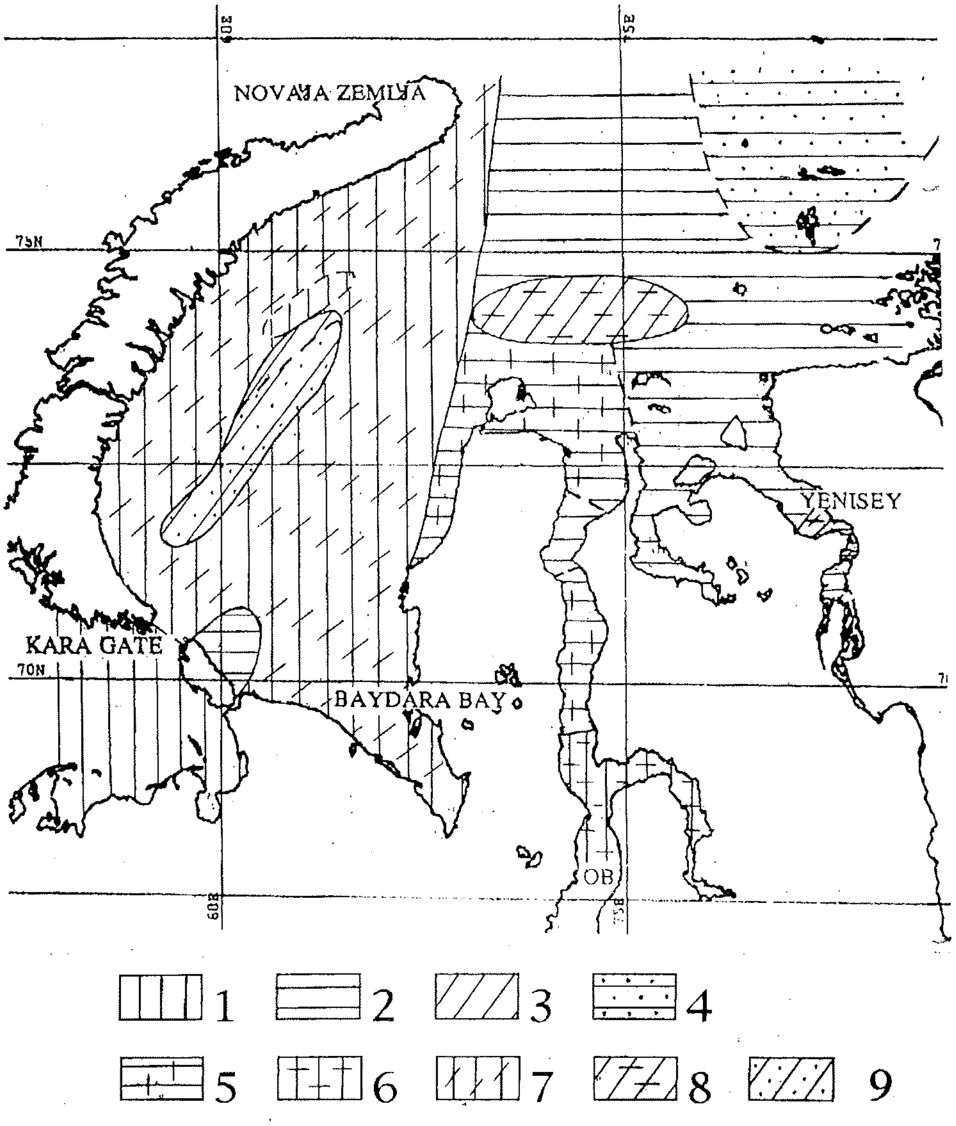

Fig.3: Distribution of heavy mineral assemblages in the Kara Sea surface sediments. Assemblages: 1 - epidote; 2 - clinopyroxene; 3 - black ore minerals; 4 - hornblende-clinopyroxene; 5 - epidote-clinopyroxene; 6 - clinopyroxene-epidote; 7 - black ore-epidote; 8 - clinopyroxene-black ore; 9 - hornblende-black ore.

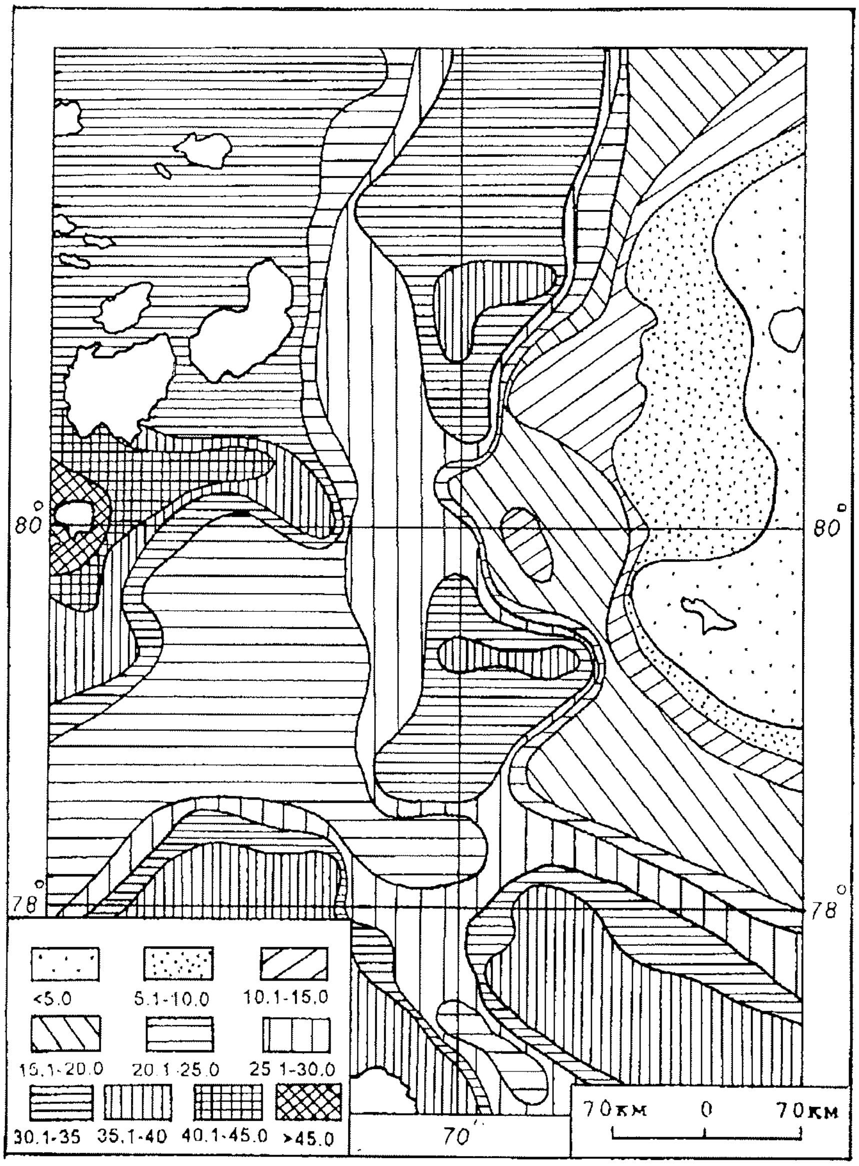

Fig.4: Distribution of clinopyroxenes (%) in the St.Anna Trough surface sediments.

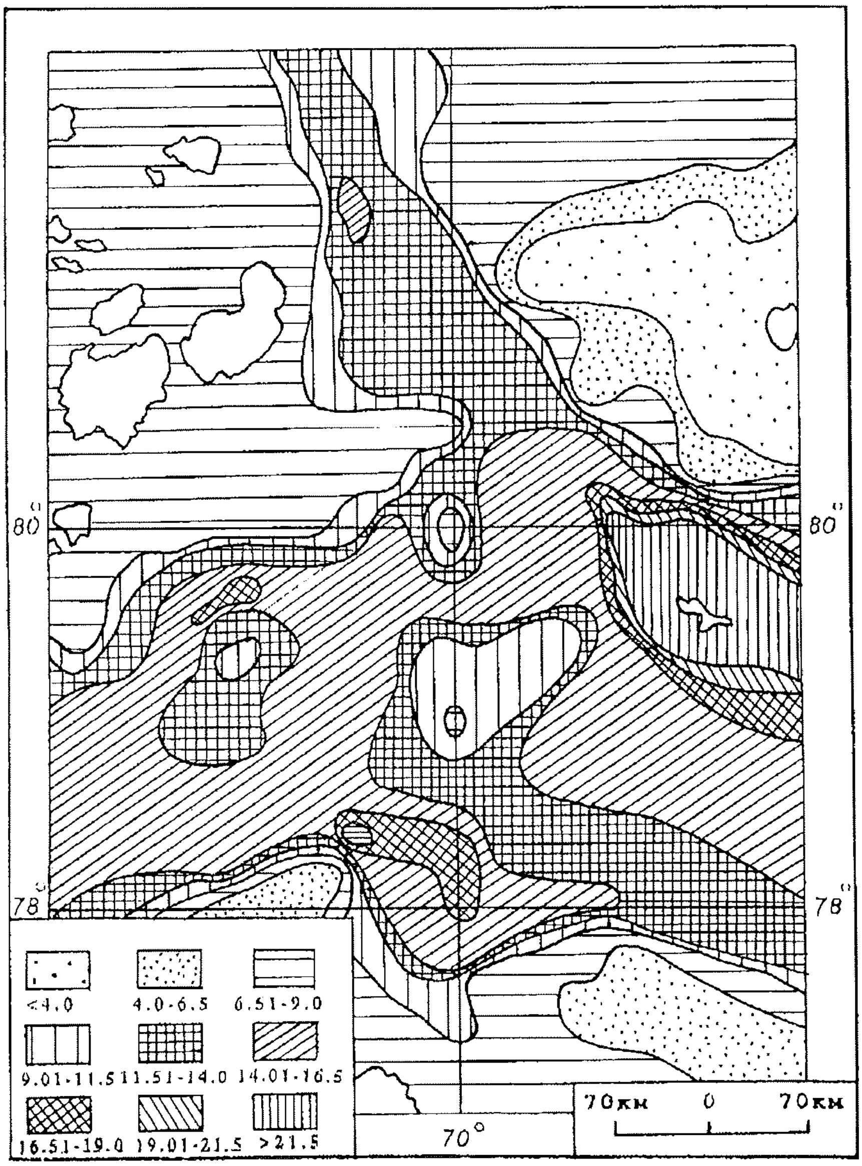

Fig.5: Distribution of epidote (%) in the St.Anna Trough surface sediments.

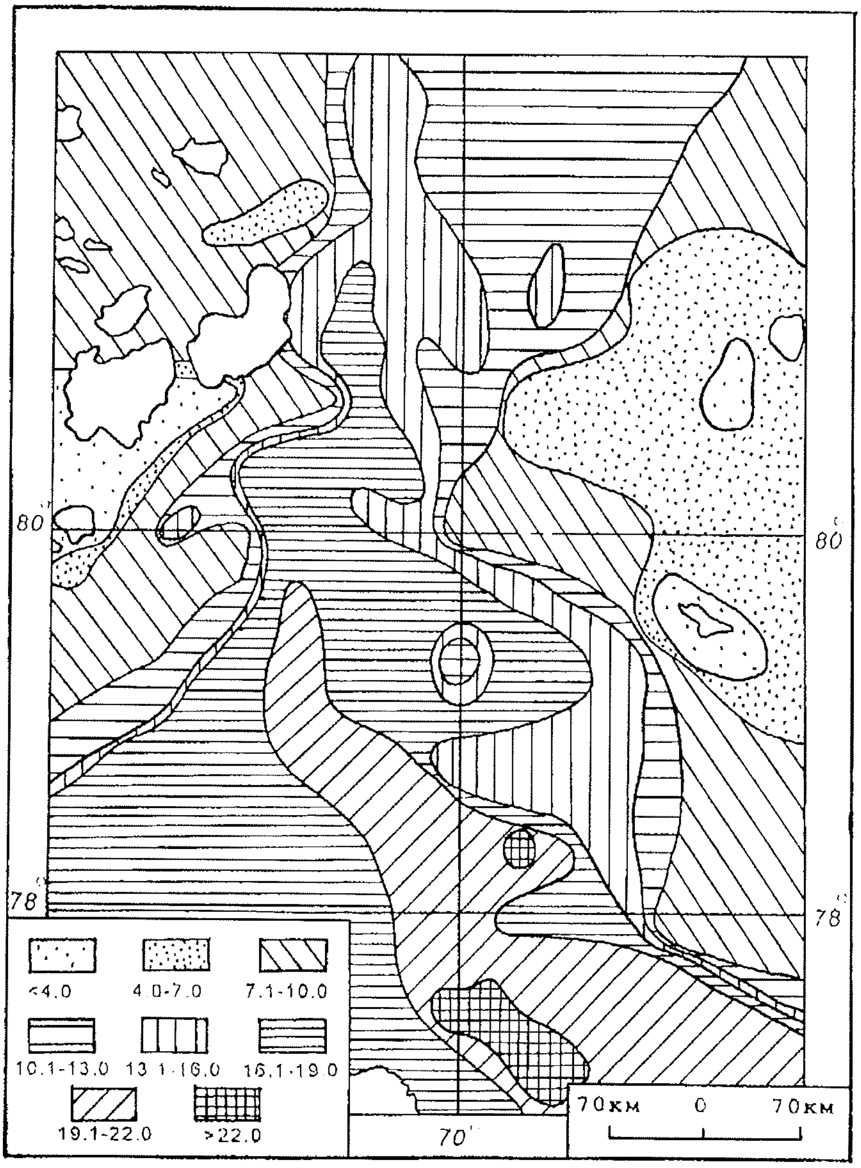

Fig.6: Distribution of hornblende (%) in the St.Anna Trough surface sediments.

For example, we can not exclude that high amounts of iron oxides/hydroxides, black ores and several accessories (garnet, zircon, etc.) in the Northern Kara Rise sediments are due to rather deep reworking of bottom sediments (including Pleistocene sediments), and not only due to the composition of source province rocks.

The main agents of reworking and transportation of heavy minerals in the study area are waves, bottom currents (including brines) and slope processes. Transportation of heavy minerals by sea ice has also to be considered, but this has to be studied in detail. However, as most of the iceberg production and concentration occurs in the southwestern part of the study area, we suppose that transportation by icebergs contributes also to clinopyroxene maxima (Fig. 4) near the southeastern islands of Franz Josef Land and northwest of Novaya Zemlya. Local amphibole (and epidote?) maxima in the St. Anna Trough as well as in more southern regions of the Kara Sea could possibly reflect bottom erosion.

Conclusion

Clinopyroxenes, epidotes, amphiboles and black ores are the main heavy minerals in the Kara Sea sediments. Ratios of individual heavy minerals allow to distinguish a number of mineral assemblages and to reveal source provinces and main transportation pathways. The epidote/clinopyroxene ratio is a good indicator for the influence of river discharge into most parts of the Kara Sea (besides of the St. Anna Trough). In the St. Anna Trough mixing of sediment matter from local (regional) sources and from the Barents and Kara Seas is observed.

Clinopyroxenes supplied to the Kara Sea derive from multiple sources: Permian - Triassic trapp basalts from Siberia and Yamal, and Jurassic-Cretaceous plateau basalts of Franz Josef Land. Epidote is mainly supplied from the South Island of Novaya Zemlya, from Yamal Peninsula and Vise Island. Enrichments of amphiboles in bottom sediments indicate areas of enhanced bottom erosion. Black ores and iron oxides/hydroxides are supplied mainly from adjacent land areas and as a result of gravitational differentiation are also concentrated near these sources.

Acknowledgments

We sincerely are thankful to V. P. Kazakova, A. N. Rudakova and L. S. Smirnova, who provided data on heavy minerals. We are grateful to E. G. Gurvich who performed the factor analysis.

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DISTRIBUTION OF CLAY MINERALS IN SURFACE SEDIMENTS OF THE ST. ANNA TROUGH

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Introduction

As shown by several investigations on clay minerals in the Arctic Ocean (Dalrymple and Maass, 1987; Clark et al., 1989; Darby et al., 1989; Stein et al., 1994; Elverhoi et al., 1995; Nürnberg et al., 1995; Wahsner et al., 1999), the clay mineralogy can be a valuable indicator of sediment sources and transport pathways. This is of special importance in polar and subpolar regions, where physical weathering processes are dominant and chemical and diagenetic alteration are negligible. In general, the clay mineralogy of Arctic Ocean sediment reflects the source mineralogy of the landmasses and shelf areas surrounding the central Arctic Ocean basins (e.g., Darby et al., 1989; Wahsner et al., 1999). Thus, in order to understand the sediment supply and transport into the deep ocean it is also important to investigate the clay composition of the shelf sediments surrounding the Arctic Ocean.

Within a joint Russian-German research program detailed sedimentological investigations i.e., determinations of bulk and clay minerals, heavy minerals as well as grain size distributions, were performed on sediments from the St. Anna Trough (Fig. 1) to characterize and quantify the terrigeneous supply and to identify source areas and transport pathways of the terrigeneous matter. The sediment samples were taken during a joint Russian-American-Norwegian expedition performed by the Association Sevmorgeologia in August-September 1994 (Ivanov et al., 1995).

This paper re-examines the clay-mineral data obtained and published by Wahsner et al. (1996, 1999), extending the discussion of data in terms of sediment sources and transport pathways. The general distribution pattern of the different clay minerals presented in Figures 2 to 5, however, is similar to the distribution pattern published by Wahsner et al. (1996). For the analytical procedure of sample preparation and clay-mineral analysis as well as the evaluation of analytical results we refer to Wahsner et al. (1996).

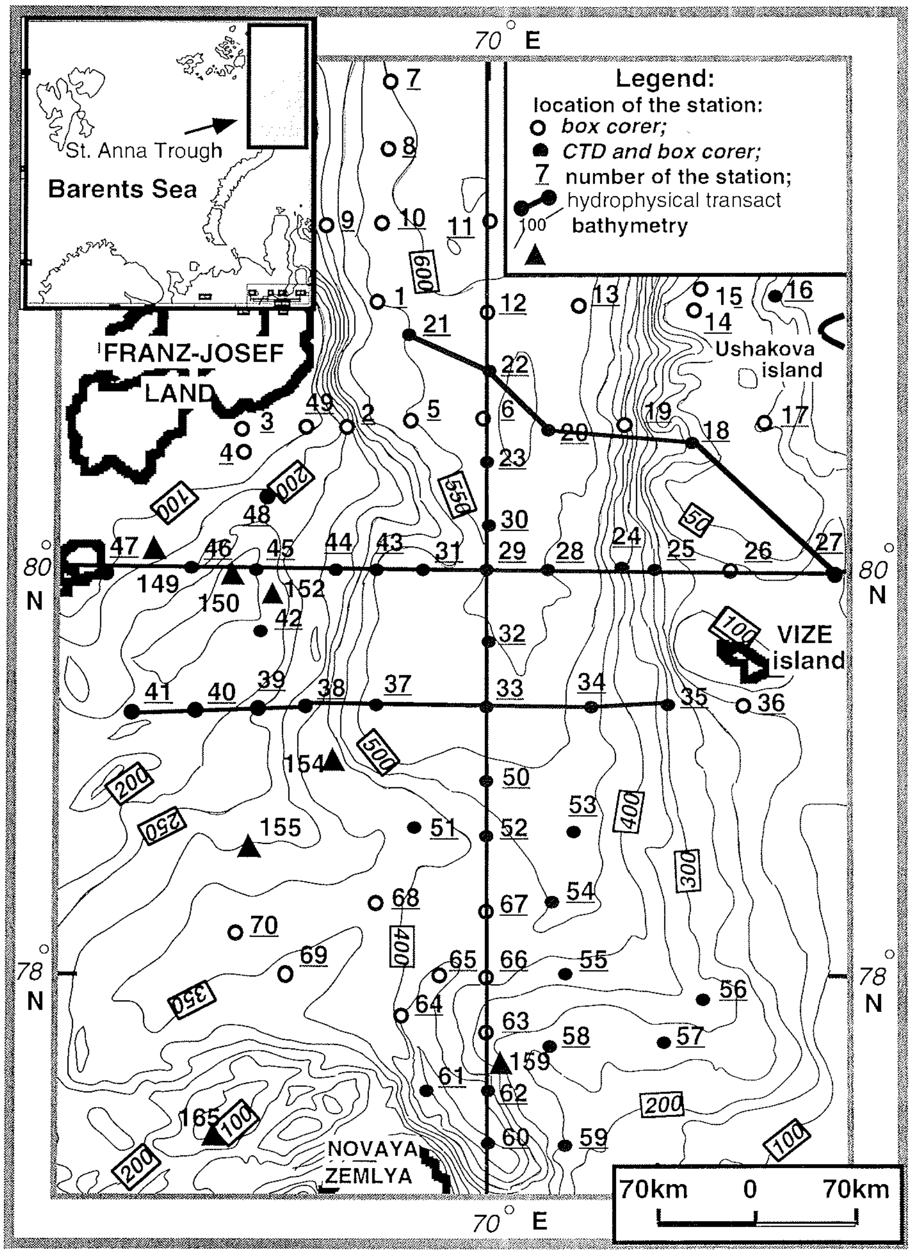

Fig. 1: Location of sampling stations carried out in the St. Anna Trough (RV "Professor Logachev" Cruise 9, 1994, and RV "Geolog Fersman" Cruise 12, 1992).

Results and discussion

The statistic parameters of the major clay-mineral-groups in the surface sediments of the St. Anna Trough are given in Table 1 (Appendix). Illite is the most dominant clay mineral with an average concentration of 39 % (range 26-56 %). The average contents of smectite, chlorite, and kaolinite reach values of 23 % (range 6-37 %), 22 % (range 16-32 %), and 16 % (range 5-35 %), respectively.

The distribution maps of illite, chlorite, kaolinite and smectite based on the data of Wahsner et al. (1996, 1999) were compiled to indicate the lateral variability of the different clay minerals (Fig.2-5).

In the northern part, the illite distribution pattern reflects a submeridional zonation. The western flank of the trough is characterized by minimum illite contents of < 35 %; concentrations regularly increase eastward up to 45 % (Fig. 2), suggesting an illite source at the eastern flank of the trough. Maximum concentrations of illite occur in the south-eastern part of the trough which is open to the Kara Sea. These are values similar to average illite contents in bottom sediments of the inner Kara Sea (Nürnberg et al., 1995). This may point to an illite supply into the St. Anna Trough from the southern Kara Sea.

The chlorite distribution shows a similar lateral variability (Fig. 3). Minimum concentrations of < 20 % occur on the western slope of the trough. Both westward and eastward the content slightly increases up to 25-30 %. In the southern part maximum concentrations of up to 40 % are observed, possibly indicating a supply of terrigenous material from both the Kara Sea and the Northern Island of the Novaya Zemlya Archipelago.

The variations of kaolinite concentrations are also submeridional. Maximum concentrations of up to 35 % occur in the coastal part of Franz Josef Land Archipelago. Towards the east, concentrations continuously decrease to 7-8 %. The south-eastern part of the trough is also characterized by minimum concentrations (5-6 %). Two potential source areas of kaolinite are assumed: the Franz Josef Land Archipelago and the area of Ushakov Island. The maximum kaolinite concentrations south of Franz Josef Land are associated with local uplifts with water depths ranging from 350 to 100 m. Most probably the erosion of seafloor basement rocks which have a composition similar to the rocks composing the adjacent islands of the Franz Josef Land Archipelago, caused the kaolinite enrichment (c.f., Wahsner et al., 1996, 1999).

The smectite distribution is more complicated. The zone with maximum concentrations of up to 37 % is located at the western slope of the trough, in the segment having the steeper dip angles. The zone is extended submeridionally and is well consistent with the scheme of water mass circulation (Ivanov et al., 1997). Towards the west, concentrations gradually decrease reaching 6 % in the coastal part of Graham-Bell Land. Eastward, the decrease is less significant, down to 18 % in the near-coastal zone of Ushakov Island and down to 19 % near Vise Island. Concentrations increase up to 28 % between the islands.

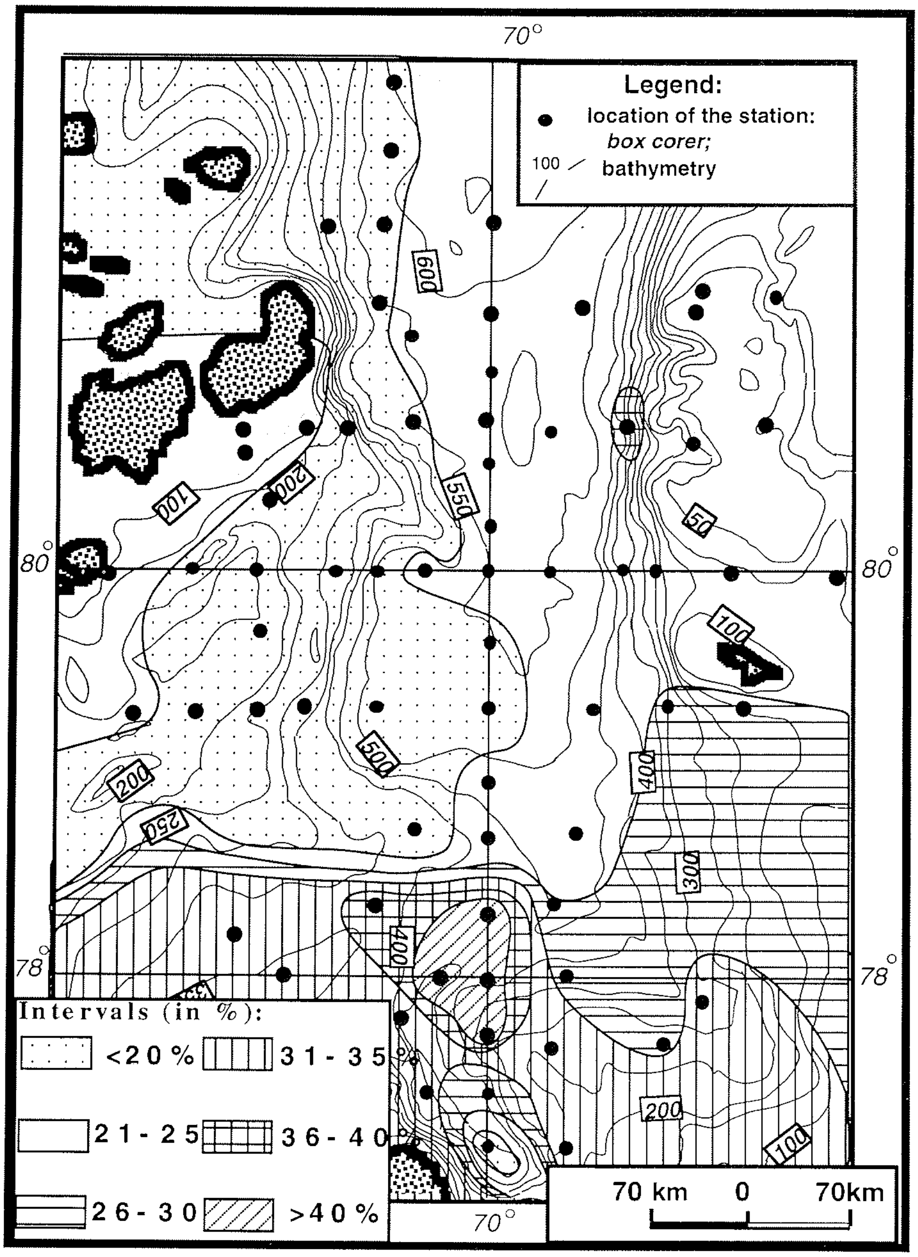

Fig. 2: Distribution of illite in surface sediments in the St. Anna Trough (Based on the data of Wahsner et al. (1996, 1999).

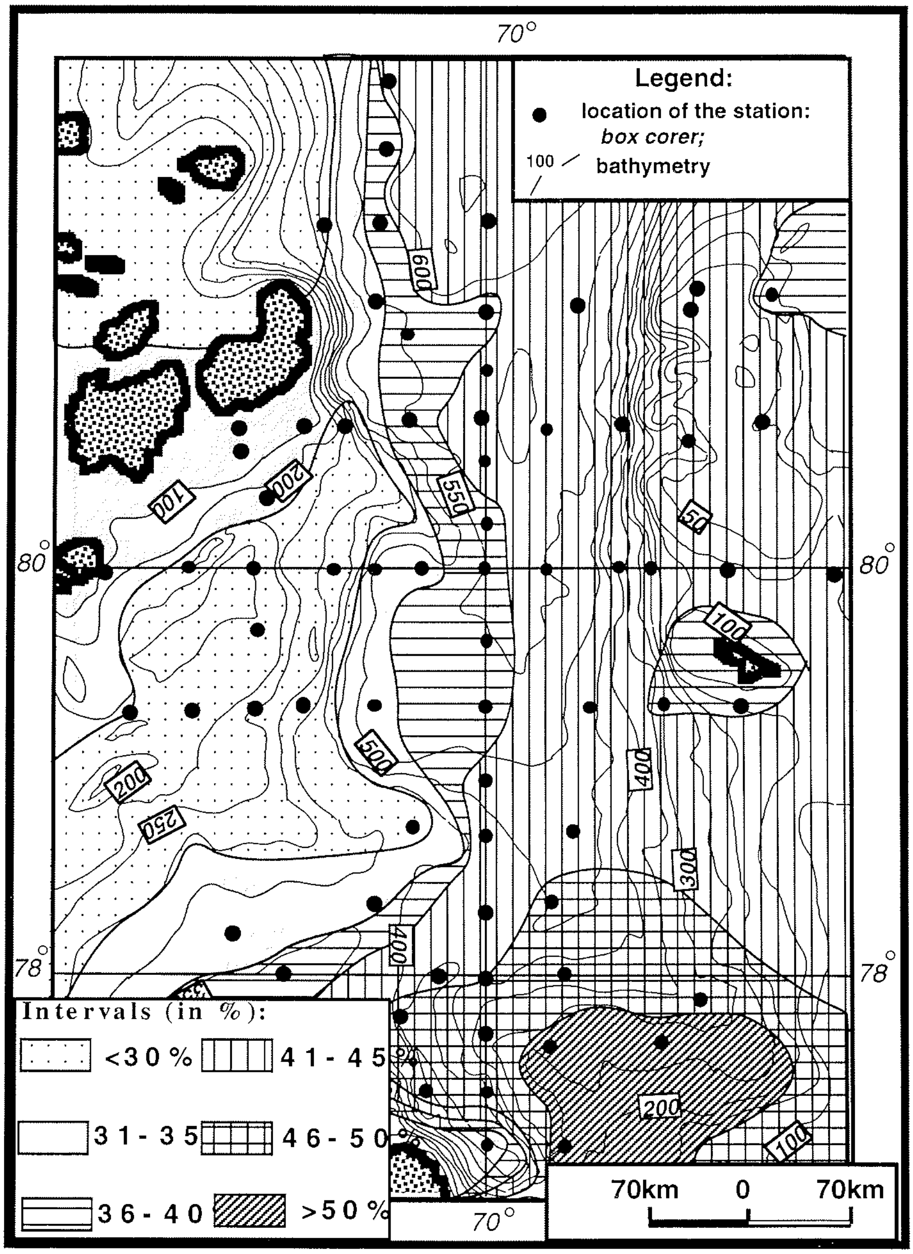

Fig. 3: Distribution of chlorite in surface sediments in the St. Anna Trough (Based on the data of Wahsner et al. (1996, 1999).

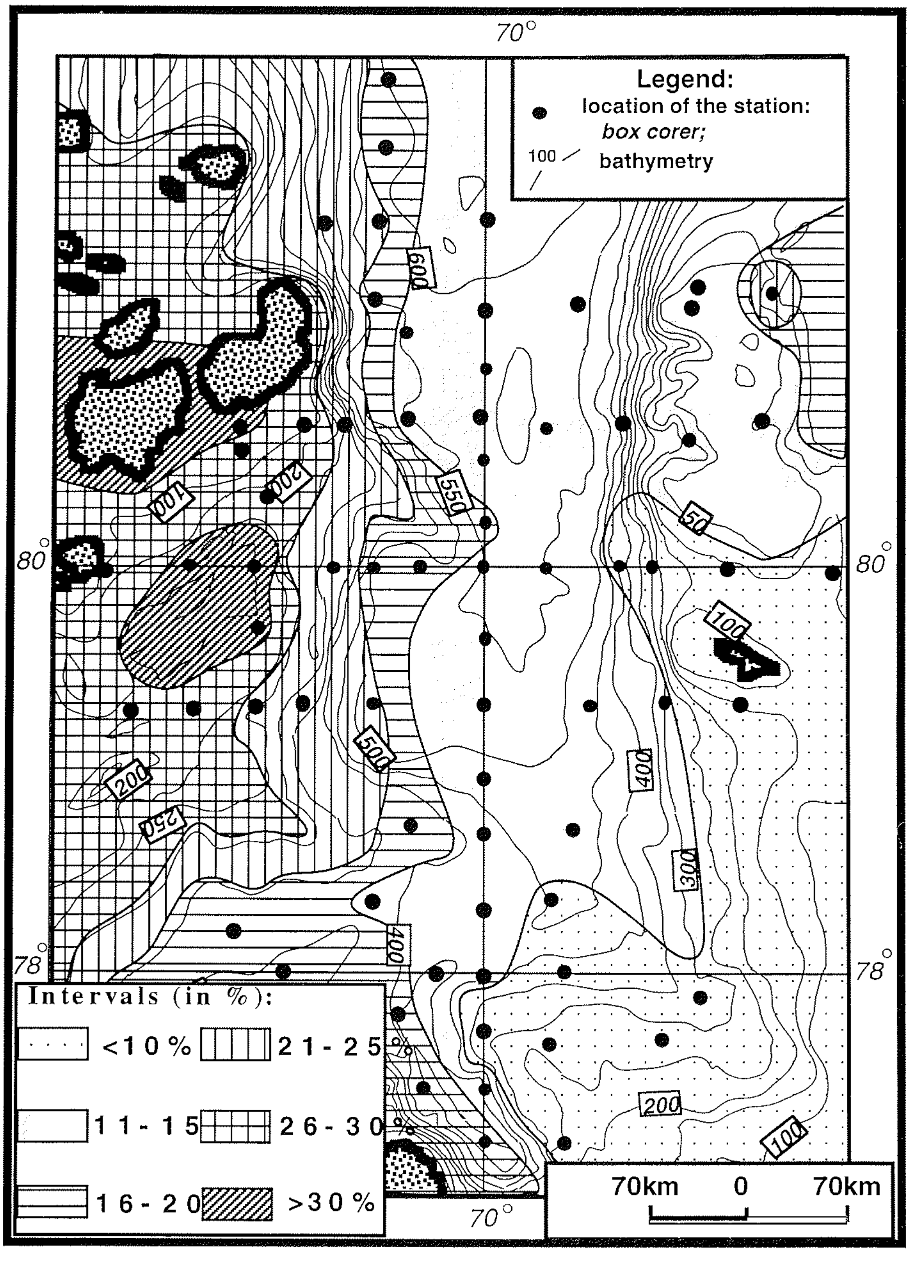

Fig. 4: Distribution of kaolinite in surface sediments in the St. Anna Trough (Based on the data of Wahsner et al. (1996, 1999).

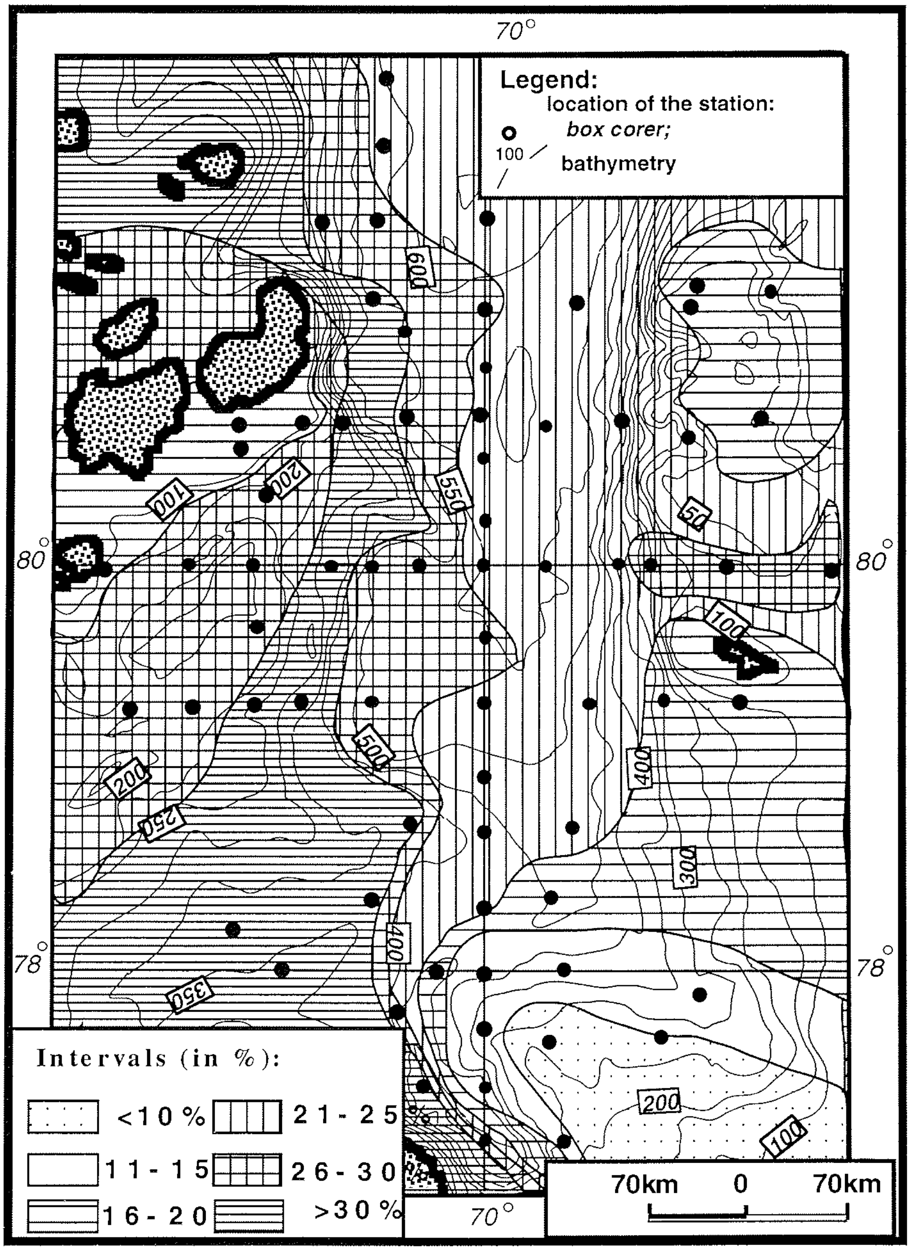

Fig. 5: Distribution of smectite in surface sediments in the St. Anna Trough (Based on the data of Wahsner et al. (1996, 1999).

Well-separated fields of data points are obvious in the smectite-chlorite-kaolinite ternary diagram (Fig. 6; Table 2, Appendix). Each field characterizes a certain geographic and morphostructural position of the stations. The most contrasting distinctions are typical for sediments of the south-eastern part and central deep-water part as well as the western, central and eastern areas (Fig. 6). These differences are explained by the different composition of the bedrocks of the islands surrounding the trough. For example, in the western part of the trough Cretaceous volcanogenic formations of basic composition occur (plateau basalt, after Dibner, 1970). Rocks composing the Ushakov and Vize islands are dominated by volcanogenic formations of acid and intermediate composition.

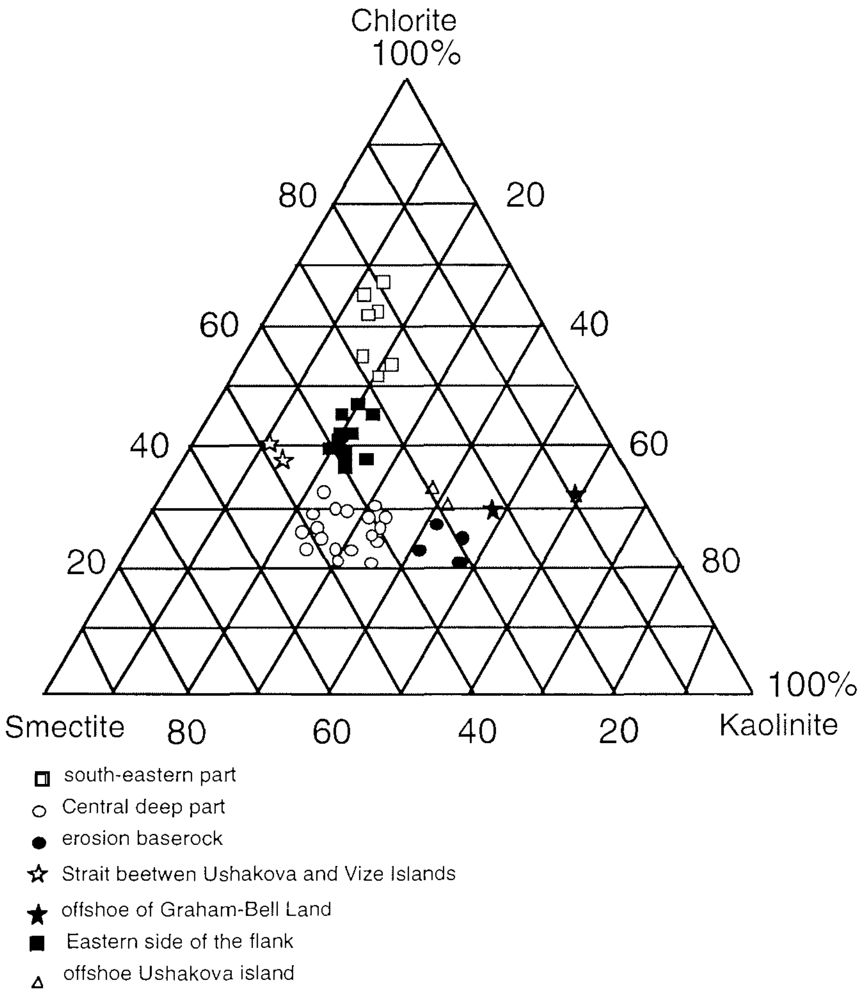

Fig. 6: Smectite-chlorite-kaolinite contents of surface sediments from the St. Anna Trough area, plotted in a ternary diagram and based on the data of Wahsner et al. (1996, 1999).

Conclusions

These data on clay mineral content in surface sediments and their lateral variability suggest that the major factors controlling the sediment accumulation in this region are different sources, distance from source area, water depth and water circulation. According to the lateral distribution patterns we can distinguish as main sources of the sediments in the St. Anna Trough: the Novaya Zemlya and Franz Josef Land (FJL) archipelagos, islands of Vize and Ushakov, and sediment flux from the southern Kara Sea.

Acknowledgments

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Table 1. Average contents of clay minerals in surface sediments in St. Anna Trough (in %); for original data see Wahsner et al. (1996, 1999).

	Smectite	Illite	Kaolinite	Chlorite	S/C	I/C	K/C	S/K	I/K	S/I	K/I
N OF CASES	55	55	55	55	55	55	54	55	53	54	55
MINIMUM	6	26	5	16	0.28	1.4	0.18	0.17	0.78	0.16	0.09
MAXIMUM	37	56	35	32	2.18	2.33	1.93	4.17	10.7	1.35	1.28
MEAN	**23**	**39**	**16**	**22**	**1.12**	**1.79**	**0.80**	**1.61**	**3.16**	**0.62**	**0.46**
STANDARD DEV.	6.8	7.1	7.3	4.2	0.487	0.195	0.453	0.638	2.095	0.271	0.28
C.V.	0.30	0.18	0.45	0.19	0.44	0.11	0.57	0.40	0.66	0.44	0.61

Table 2 Average contents of clay minerals in surface sediments in the differents parts of St. Anna Trough (in %); for original data see Wahsner et al. (1996, 1999).

	Smectite	Illite	Kaolinite	Chlorite	S/C	I/C	K/C	S/K	I/K	S/I	K/I
South-Eastern part	12	51	8	29	0.42	1.72	0.26	1.63	7.03	0.25	0.15
Offshore of Graham-Bell Land	11	37	32	21	0.55	1.78	1.56	0.36	1.15	0.31	0.88
Offshore of Ushakova Island	19	40	17	24	0.79	1.66	0.72	1.28	2.86	0.48	0.45
Offshore of Vize Island	19	40	13	28	0.67	1.42	0.45	1.47	3.11	0.47	0.32
Rise on the south-western part	23	28	31	19	1.26	1.54	1.68	0.76	0.93	0.82	1.10

PHYSICAL-MECHANICAL PROPERTIES OF SURFACE SEDIMENTS AND CLASSIFICATION OF SEDIMENTARY ENVIRONMENTS IN THE ST. ANNA TROUGH

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Introduction

Physical properties and the structure of the surface layer of bottom sediments are the result of interaction between sedimentation and lithodynamic processes. Despite of the urgency of studying the water-sediment boundary - the largest geochemical barrier of the Earth - its formation and structural features still remain not clear. It is caused not by facial diversity of the sea-floor surface but by technical difficulties. In particular, the majority of sampling equipment destroys the surface sediment layer, and error of geotechnical devices designated for measuring sediment strength is significantly higher than fluid and liquid-fluid sediments strength. In addition, minimum sampling intervals with standard devices are essentially larger than dimensions of sedimentary rocks mesostructures.

Therefore, it is not surprising that among all physical properties often only the water content is considered by the studies dealt with formation of the upper layer of the bottom sediments. In spite of this fact, when studying pelagic sediments of the Indian Ocean, Svalínov (1991) distinguished three structural layers at the mesoscale within first 20 cm and showed that they correspond to individual lithogenesis stages: protosyngenesis, syngenesis and protodiagenesis.

At the protosyngenesis stage the sedimentary substance is concentrated at the sea-floor surface as suspension characterized by Newton liquid properties. The possibility of the existence of a so unstable formation is explained by the availability of two lithodynamic barriers at the water - seafloor boundary, a low mobile viscous laminar sublayer of some cm in thickness and an immobile diffusive sublayer of some mm in thickness (Wimbush and Munk, 1971, Holister et al., 1984). The thickness of the suspension layer depends on the sea-floor morphology, near-bottom currents rate and intensity of sedimentary substance supply. It usually varies from 0.5 to 2 cm but can be significantly higher in natural "sedimentation traps" (local seafloor depressions). This ephemeral seasonal formation is not a geological body, it easily flows down the slopes as a heavy liquid, is transferred by near-bottom currents, is made turbid by wave actions and can be repeatedly redeposited. Suspension strengthens viscous properties of the laminar layer although it washes out the dynamic boundary between the seafloor and near-bottom waters.

Despite the fluid consistency, at the syngenesis stage the sediments have a structure and properties of the solid body run by rheologic laws. The thickness of these sediments lies within the first tens cm, their age is not more than 5 Kys. The syngenetic layer is not only permanently accreted owing to diffusive layer suspension but interacts with it through porous solutions.

There currently exist numerous methods of determination of near-bottom currents rate by grain-size characteristics of psammitic sediments or on the basis of visual analysis of sea-floor morphostructural features (Heezen and Hollister, 1971; Ichshenko et al., 1991). There also exists a series of empiric dependencies where scouring velocities for clayey and silty sediments of different water contents are shown (Gardner, 1978). But to solve a number of practical tasks one should determine not only the area of bottom erosion and hydrodynamic activity of the near-bottom layer but also the areas of intensive sediment accumulation. In addition to direct methods, such as installation of sedimentation traps and determination of the modern sediment thickness, one can use indirect methods based on studying physical properties of the surface (syngenetic) layer of the bottom sediments (Shpikov et al., 1987).

A joint Russian-German research program including detailed oceanographic measurements (Ivanov et al., 1998) and sedimentological investigations, i.e., determinations of bulk and clay minerals, heavy minerals, grain-size distributions as well as physical properties, was performed on sediments from the Kara Sea to characterize and quantify the terrigenous supply and to identify source areas and transport pathways of the terrigenous matter.

Attention to the St. Anna Trough with respect to sedimentogenesis processes are attributed to several factors. First, this area is a large important transit zone for the transport of contaminants between the Barents and Kara Seas and the Arctic Ocean. Studying the physico-mechanical and physico-chemical properties of the bottom sediments plays an important role in this context. Major attention was paid to key element of the geoecosystem, the water-sediment boundary. It was considered not only as the most powerful geochemical barrier which defines the character and intensity of interaction between hydrosphere and lithosphere but as a sensitive indicator of sedimentation conditions.

Main tasks of this investigation were as follows:

- to elucidate the regularities of formation of physico-mechanical properties and structures of the sedimentary layer at the initial lithogenesis stage;
- to define the character and location of migration barriers in the structure of the surface layer of the bottom sediments;
- to assess the hydrodynamic activity of the near-bottom waters and the intensity of sedimentation processes by physico-mechanical indicators of the syngenetic layer.

Data and methods

Physical properties of surface sediments were studied at 70 stations during of the multidisciplinary cruise onboard RV "Professor Logachev" in August-September 1997 in the St. Anna Trough, Kara Sea. The study area is located between the Franz Josef Land Archipelago, Ushakov Island and northern end of Novaya Zemlya (77-82°N and 55-80°E, Fig. 1). The average water depth within the polygon is about 400 m, ranging from 33 m to 638 m. (Ivanov et al., 1995).

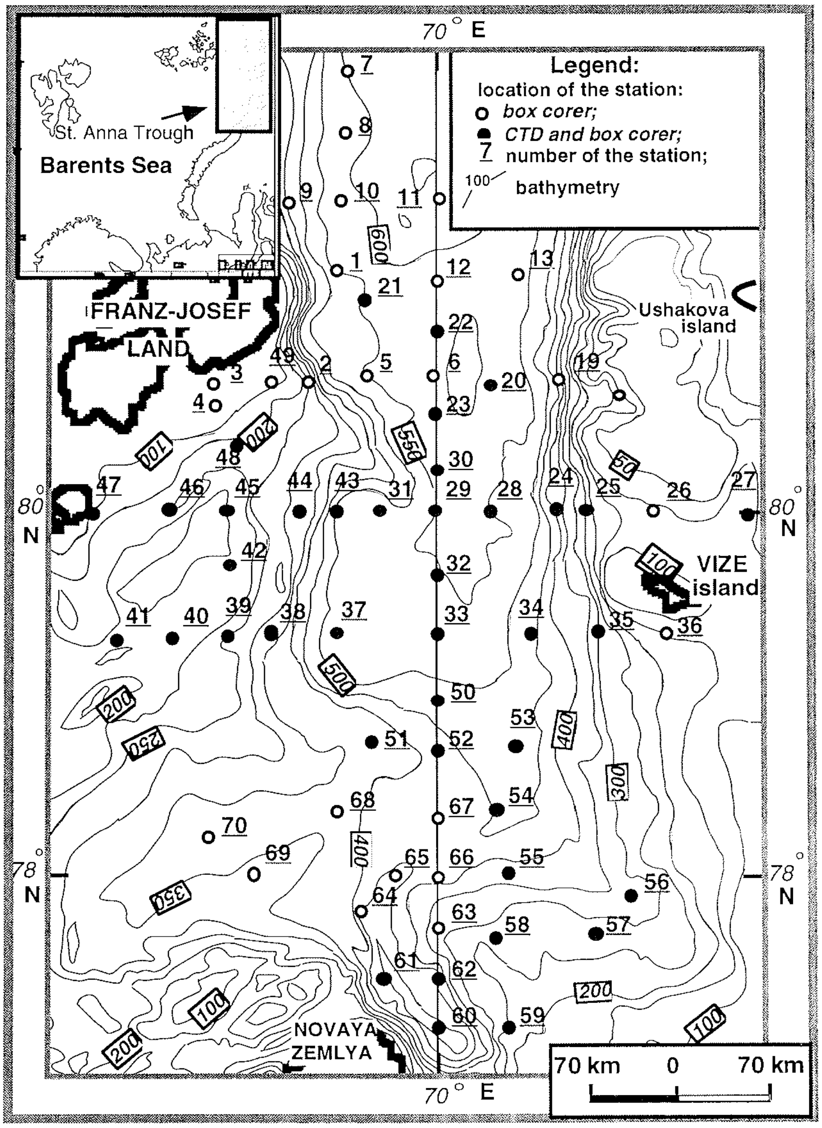


Fig. 1: Location of stations and profiles within the polygon in the St. Anna Trough.

In accordance with aims of the study of physical-mechanical properties, the first 15 cm from the surface were sampled. Samples were taken from box-corer in plastic tubes (subcores with a diameter of 145 mm and a length of 150 mm). Sampling intervals accounted for 0.5 cm within the upper 3 cm. These samples were studied by the complete set of methods including determination of water content, fluidity boundary, pH, strength, grain size and pore water composition. Downward to the depth of 10 cm, water content and strength of the deposits were determined in 1 cm intervals. The deeper intervals were studied with regard to lithological features of the core. The set of indicators of physico-mechanical properties determined onboard included water content, fluidity boundary, sediment contraction and specific penetration resistance. These indicators were used to calculate coefficients of dehydratation and condensation of muds, indicators of sedimentation intensity and coefficients of sediment contraction anisotropy. The pH value of sediments was measured in the box corer on the desk.

The relative water content (W=qw/qs) characterizes the ratio between liquid and solid phases in the sediment, where qw = the amount of evaporated water when the sample is dried up to constant weight at a temperature of 105°C, and qs = dry residue (GOST 5180-84, 1984). For water-saturated soils the relative water content is quasifunctionally related to density and porosity.

The water content at liquid limit (LL) or upper level of flowage is a generalized indicator of soil composition and its hydrophily. The fluidity boundary or upper limit of ductility (liquid limit LL) is determined as water content of sediment paste brought to standard strength (penetration resistance 76 KPa) at which it passes from ductile state to fluid one. LL is the most important integral indicator of the composition and hydrophily of the sediments (Shpikov, 1980). It is a constituent of the most classifications of fine-dispersed sediments (Somerville and Paul, 1983; Shpikov, 1986). The higher the water-retaining ability of the sediments, the higher is LL. It is proportional to the specific surface of the sediments and the thickness of hydrate shells of the clay minerals. Therefore, its value mostly depends on the dispersity and mineral composition of the sediments, content of organic matter and physico-chemical properties of the pore water. The water content of swelling, total water content capacity and maximum molecular water content capacity, consolidation rate, deformation and strength sediment properties are to one or another extent caused by hydrophily. In particular, the water content of the surface layer of silty and clayey terrigenous muds (initial water content - Wb) usually accounts for 2 LL.

The sedimentation intensity coefficient (Ks=Ws/2LL) characterizes the intensity of sediment accumulation processes for the surface sedimentary layer or erosion. It is calculated as ratio between surface layer water content (Ws) and double liquid limit (2LL). The method is based on the fact that the transition from a free-dispersed system (suspension) to aggregated sediment occurs as a result of interparticle coagulation interaction, i.e., approaching of the particles until their hydrate shells contact (distant coagulation links), and their transition from a fluid state to a ductile one (near coagulation links). As thickness and total volume of hydrate shells are proportional to hydrophily, the water content of the sediment at the transition from suspension to an aggregated state is proportional to the liquid limit. It was established that the water content of the surface layer of silty and clayey sediments is close to 2 LL (Shpikov, 1980). An exception is made by erosional seafloor zones and natural "sedimentation traps". A comparison of the real water content of surface sediments with the hypothetical initial water content which is equal to 2 LL, is an essence of the method. For terrigenous muds this ratio is a constant value and accounts for about 1 at stable sedimentation. The sedimentation coefficient correspondingly increases under avalanche sedimentation conditions and sharply decreases at sea-floor erosion (Shpikov et al., 1987). Ks is about 1.1 under normal conditions increasing at avalanche sedimentation and decreasing to less than 0.9 at erosion.

The coefficient of condensation and dehydratation (Kdg) characterizes the degree of mud condensation and is proportional to sediment consistency. To characterize sediment dehydratation degree under diagenesis processes Shpikov (1980) proposed to compare its natural water content (W) with the hypothetic initial water content (Wb) which is equal to 2 LL as mentioned above. Consequently, the coefficient of condensation and dehydratation can be expressed as W/2LL (Shpikov, 1980). The coefficient of condensation and dehydratation of muds at the surface of the syngenesis layer corresponds to the sedimentation coefficient, i.e. is close to 1, and at the transition from muds to clays always accounts for 0.5.

The coefficient of contraction anisotropy shows the orientation degree of structural elements of disperse sediments. A decrease in volume at drying (contraction) is characteristic for sediments with the coagulation type of sediments. Contraction occurs due to liquidation of hydrate shells of clay minerals, therefore the orientation of structural elements and porous space is reflected in the anisotropy of volume decrease of a cylindrical sediment sample at drying. The coefficient of contraction anisotropy is determined as ratio between large and small ellipse axes and its strength.

The sediment strength is the most general integral indicator of sediment diagenesis. Strength increase is a necessary and sufficient condition of sediment transformation to rocks. The sediment consistency reflects the type of contacts between particles and its strength. The sediment strength in the surface layer is studied at mesoscale using a portable penetrometer. To decrease the depth of indentor penetration a cone with an opening angle 60° and a sphere with a diameter of 2 cm was used. The time of conventional stabilization of indentor penetrating into the sediment, is accepted as 0.05 mm/min. Each interval is sampled in three points with three steps of loads: 30, 50, 100 g. The depth of indentor penetration into the sediment accounted for from 1 to 3 cm. In this case the measured penetration resistance is conventionally referred to the interval surface regardless of the depth of indentor penetration into the sediment.

Results and Discussion

The deposits in the St. Anna Trough down to the first 1.5 m are mainly represented by silt-pelitic and pelitic mud while at the depths < 100 cm by silt and psammitic sediments (Ivanov et al., 1997). Inclusions of clastic material are observed almost at all stations. Active bioturbation (Polychaeta tubes) is pronounced within the first 30 cm southward of 79°N (Stein et al., 1996, Wahsner et al., 1999).

The oxidized layer at the contact with near-bottom waters is represented by brown and dark-brown muds. Its thickness changes from the south to the north. Reduced gray and gray-green sediments occur downwards. The largest thickness of oxidized sediments is observed in the northern and central parts of the polygon (Figs. 2 and 3, Table 1).

Table 1: Indicators of environment sedimentation, composition and physical properties of surficial bottom sediments in the St. Anna Trough.

Landscape	Index on	St. par.	Depth (m)	Ks	W	LL	Thickness of oxygenous layer (cm)
Oxygenous, trans-aquiatic, hydrodynamically active waters: shoals (a) and submarine elevations (b)	1-a 1-b	x s n	160.5 61.5 8	0.97 0.01 8	0.79 0.05 8	0.40 0.05 8	7 2 8
Oxygenous trans-accumulative of low active waters of "shadow" slope and deep part of the trough	2-a	x s n	506.0 37.0 16	1.06 0.02 16	1.06 0.02 16	0.75 0.03 16	26.00 3.80 16
Oxygenous gley, trans-accumulative of low active waters of the platform shelf	2-b	x s n	429.00 24.90 10	1.11 0.02 10	1.81 0.08 10	0.81 0.04 10	2.50 0.30 10
Oxygenous hydrogen sulfate and weakly reduced accumulative, of passive waters of "shadow"	3-a	x s n	348 41.4 19	1.17 0.02 19	1.62 0.1 19	0.69 0.03 19	20 36 19
Oxygenous-gley, accumulative, of passive waters of the frontal zone 78?	3-b	x s n	298 64.5 11	1.22 0.03 11	1.74 0.07 11	0.72 0.03 11	23 7.9 11
Polygon, total		x s n	400.3 168.7 64	1.11 0.11 64	1.56 0.48 64	0.71 0.18 64	17.9 15.7 64

Comments: St.: Statistical; par.: parameters, x: mean, s: standard deviation, n: number of samples index- Index on the Fig.11; Ks: Sedimentation intensity coefficient (Ks=Ws/2LL), W: Relative moisture (W=qw/qs), LL: liquid limit

The direct dependence between the thickness of oxidized layer and seafloor depth (correlation coefficient rij =0.63) is observed northward of 80°N. At depths of > 400 m it reaches 70 cm, averaging 35 cm (Figs. 2 and 3).

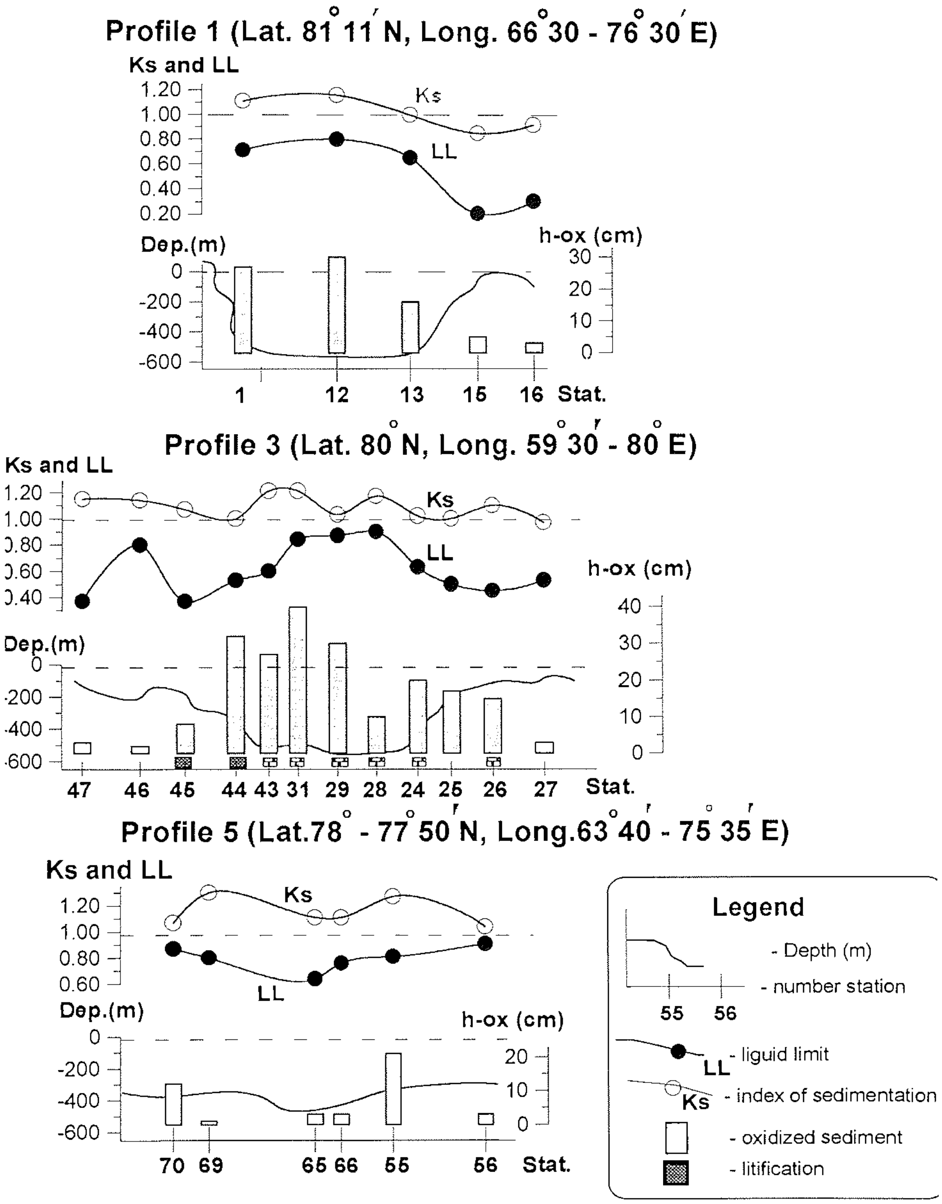
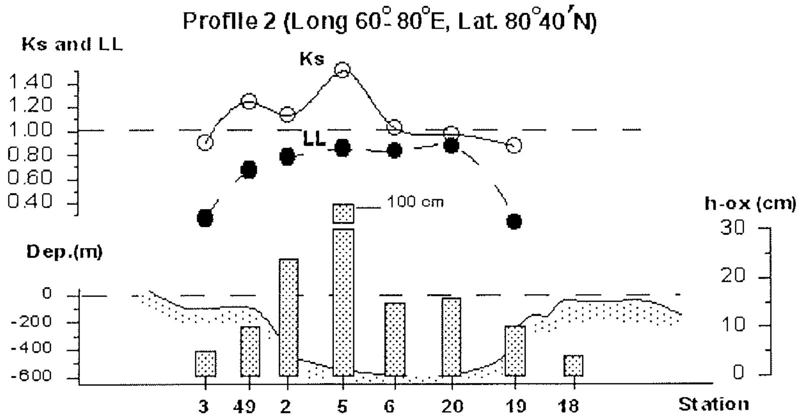


Fig. 2: Character of the thickness of oxidized layer (h-ox.), LL, Ks of the bottom sediments in the St. Anna Trough (sublatitudinal profiles- 1, 3, 5).



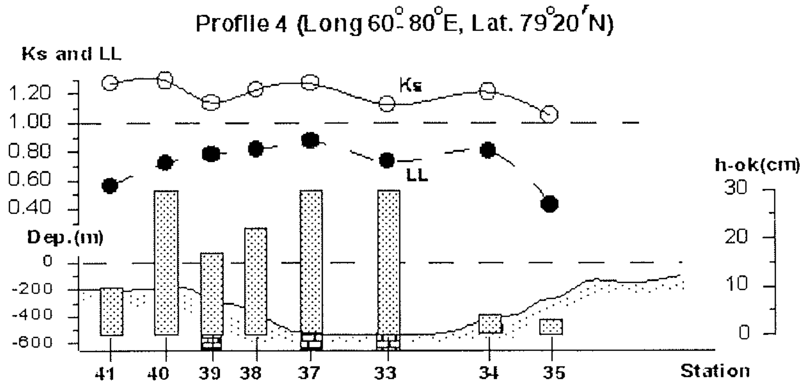


Fig. 3: Character of the thickness of oxidized layer (h-ox.), LL, Ks of the bottom sediments in the St. Anna Trough (sublatitudinal profiles- 2, 4).

The transition between oxidized and reduced sediments is gradual. The thickness of oxidized layer decreases to 20 cm in the central part (Figs. 2 and 3). The contact between oxidized and reduced sediments changes particularly sharply. 3-7 cm interlayers of dark-brown and ocherous lithificates appear at the base of the oxidized layer. Southward of 78°30′N the oxidized layer sharply degrades to 3-5 cm and sometimes is absent. The lithificated interlayer at the contacts between oxidized and gley sediments disappears (Figs. 2 and 3).

One should note the tendency of the decrease of the oxidized layer thickness with the southward decrease in sedimentation depth. It is possibly connected with an increase in near-bottom layer temperature, a decrease of dissolved oxygen in near-bottom water with depth, and with an increase of biogenic components in the sediments in the shoals and southern part of the polygon.

Variations of physical properties in the surface sediments.

Detailed studies of variations of water content and strength in the upper 10-cm layer of sediments revealed the complex picture of formation of structures and physical-mechanical properties at the initial stages of lithogenesis (Figs. 4-6). Its mesostructure bears the imprint of sedimentation conditions as well as regularities of structure formation of concentrated dispersed systems.

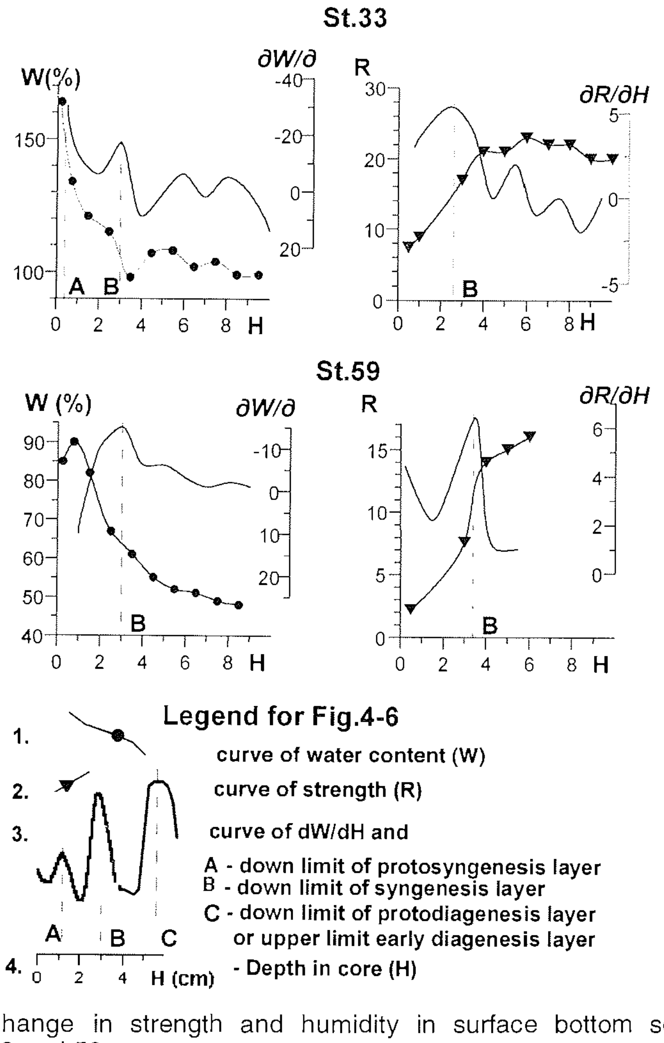


Fig. 4: Change in strength and humidity in surface bottom sediments at stations 33 and 59.

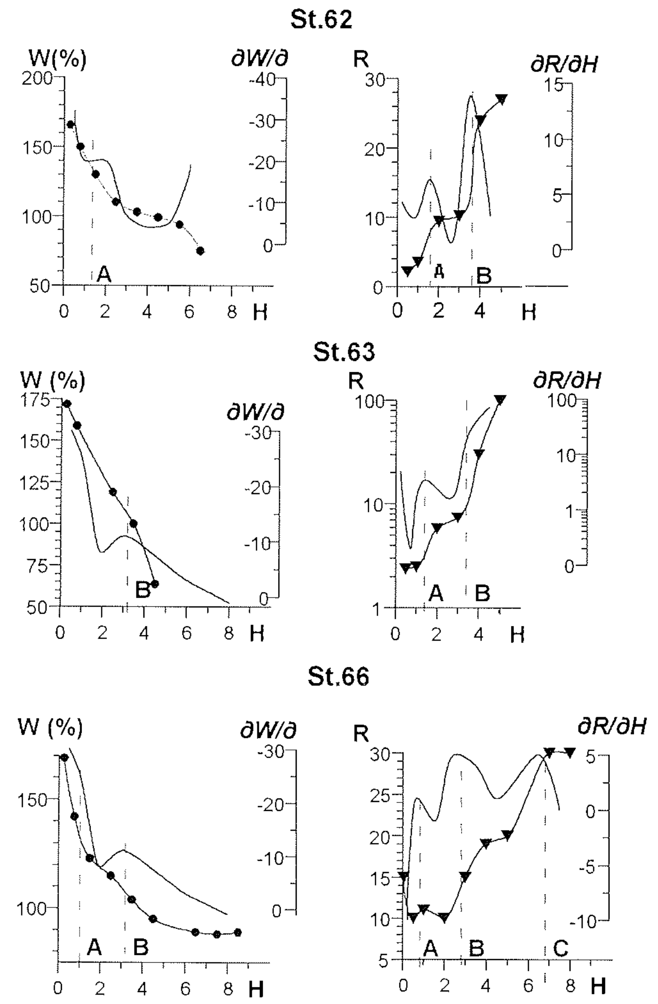


Fig. 5: Change in strength and humidity in surface bottom sediments at stations 62, 63, and 66. For legend see Figure 4.

In the hydrodynamically passive zones the suspension layer (the warp) is present at the sediment surface. The thickness of warp depends not only on sedimentation rate and thickness of viscous laminar layer of the near-bottom water but also from physical-chemical features of its diffusive sublayer. Maximum hydratation of the warp is noted in the center of the polygon, in the zone of lithification of the oxidized layer base and increased metal content in the pore water (st. 23, 28, 31, 38-43, 47-53).

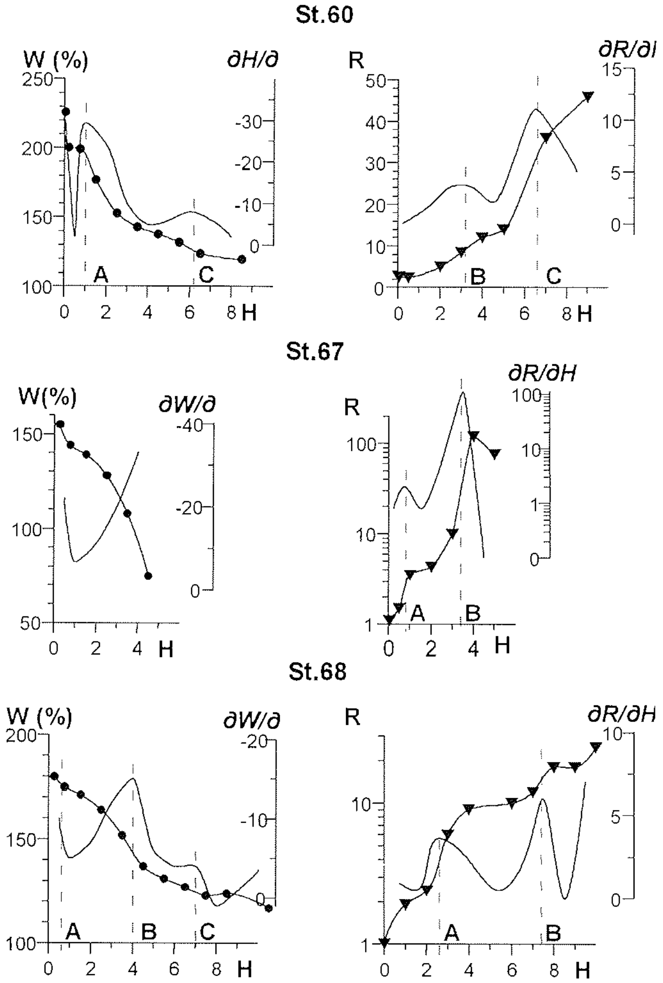


Fig. 6: Change in strength and humidity in surface bottom sediments at stations 60, 67, and 68. For legend see Figure 4.

Three layers of sediments with different consistency are distinguished within the upper 10 cm interval. These are the above-described warp with a thickness of 1-1.5 cm which corresponds to protosyngenesis stage, the liquid-fluid oxidized layer with a thickness of 2-5 cm corresponding to syngenesis stage, and fluid sediments at the protodiagenesis stage (Table 2).

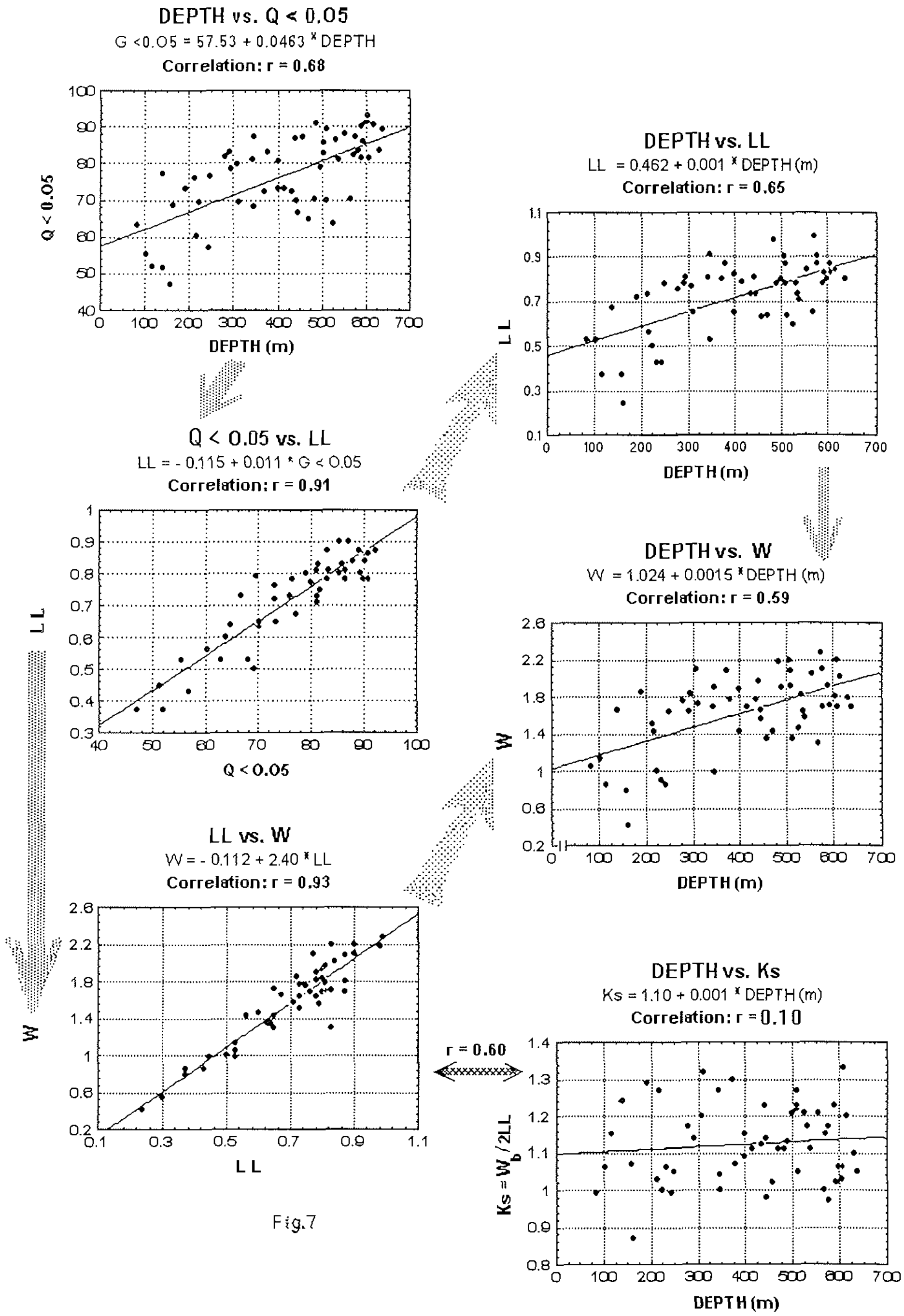


Fig. 7: Genetic and correlation links of sedimentation conditions and indicators of composition and physical properties of surface sediments in the St. Anna Trough.

The boundary between stages at the diagenesis stage are determined by the analysis of graphs of strength and water content variations along the core using the partial derivative method. Extremes of derivatives (positive ones for strength and negative ones for water content) are associated with sediment consistency variations. A significant increase in strength also occurs here. Changes of the physical state of the sediments (liquid -> liquid-fluid -> fluid -> fluid-ductile) reflect the change of lithogenesis stages, respectively protosyngenesis - syngenesis - protodiagenesis - early diagenesis (Svalínov, 1991). Each diagenesis stage corresponds to definite ranges of strength and coefficient of contraction and dehydration (Table 2). The lithological composition of sediments affects the thickness of syngenesis and protodiagenesis layers, it increases with dispersity growth. A jump-like increase of strength is caused by a discrete change of the coordination number Z (amount of contacting elements in structural point) with variations of micelles packing densities at porosity decrease, i.e. by a discrete change of the amount of individual contacts at condensation (Schukin, 1985).

Table 2: Structures and physical properties of surficial bottom sediments of the St. Anna Trough.

Medium	Consistency	Stages of lithogenesis	Physical properties of the medium		Thickness, cm	Barriers
			K_{dg}	R (KPa)		
Hydrospher	viscous laminar sublayer (suspension)	Protosyngenesis	1.5-1.1 1.3		0-5 2	1-th dynamic
	immobile diffusive sublayer	Protosyngenesis	---	1-5 3	0.1-0.2 0.1	2-th dynamic
Lithospher	liquid-fluid	Syngenesis	1.1-0.95 1.05	5-15 7	0-7 3	1-th diffusive
	fluid	proto-diagenesis	0.95-0.70 0.8	15-30 20	4-15 7	Gley 2-th diffusive
	fluid-plastic	early diagenesis	0.70-0.50 0.60	30-80 50	>30	Filtration

Comments: 1.5-1.1 / 1.3 (1.5-1.1: interval variations, 1.3: average)

When sediments pass from liquid-fluid state to fluid one the overlapping of free porous space by hydrate shells takes place. The first diffusion barrier appears and free water exchange between pore water and near-bottom waters is broken. Below the diffusion barrier the oxygen content in the pore water decreases which sharply changes the physical-chemical properties of the sediments, and the gley barrier emerges at the boundary between syngenesis and protodiagenesis layers. Therefore the boundary between them often coincides with the transition from oxidized to weakly reduced sediments.

Sediments of syngenesis and protodiagenesis layers have thixotropic properties. In case of mechanical disturbances of the boundary between them it is reconstructed during 2-3 days and, as a consequence, bioturbation almost has no effect on its location.

Sediments corresponding to an early diagenesis stage are studied down to 1.5 m in the central deep part of trough. They are represented by gray-green muds and clays. Further condensation of the sediments results in superimposing of hydrate shells of interacting particles and an increase in pore water viscosity. The second diffusion barrier appears at the contact between the sediments of fluid and fluid-ductile consistencies. The transition from a protodiagenesis stage to an early diagenesis stage in the center of the polygon is accompanied by the above-described sediment lithification. The thin interlayer (1-2 cm) of liquid-fluid sediments is underlain by lithificates. Below, the strength and the water content of the sediments vary from 30 to 80 KPa and 50 to 90%, respectively. The studied section is characterized by irregular alternation of liquid and fluid-liquid sediments. This massif contains small caverns and pockets filled in liquid-fluid muds. This type of condensation suggests that a low water-permeability of lithified interlayers precludes from gravity condensation of gray-green muds at an early diagenesis stage. Significant feature of the deposits at an early diagenesis stage consists of an almost complete isotropy of porous space which is determined by the character of dried cylindrical samples.

In accordance with the engineering-geological classification of muds (Shpikov, 1986) the surface layer of St. Anna Trough deposits can be attributed to deep-water, medium-hydrophilic, maximum hydrated, liquid-fluid and fluid muds, and deposits at an early diagenesis stage - to medium-hydrophilic, weakly condensed, fluid-ductile sediments.

Lateral variability of physical properties of the surface sediments

In addition to above-described regularities in variations of oxidized layer thickness and sediment lithification, a number of distinct regularities of sedimentogenesis and physical properties of surface sediments mainly caused by the depth of sediment accumulation, is noted in the St. Anna Trough. Genetic links between sedimentation conditions, lithological composition of sediment material and physical properties of the surface sediments are: - seafloor depth, - content of clay and silt fractions in the sediments, - hydrophily, - initial water content (porosity and density), and - sedimentation coefficient (Fig. 7). At a qualitative level this line can be extended at the expense of the influence of near-bottom currents, dip and exposition of the seafloor surface relative to the vector of current, bioproductivity of the water column etc.

Physical properties of the sediments depend primarily of their dispersity. Therefore the high degree of dependence (rij=0.68) between the < 0.05 mm fraction content and sediment accumulation depth (Fig.7) determines the link of the majority of physical property indicators with bathymetry. At the same time the trend of studied indicators is observed from the south to the north along the trough axis (Figs. 2, 3, 8 and 10) as well as the number of features connected with the sublatitudinal lithification zone in the center of the polygon. Current flowing along the eastern slope of the trough and in the north-west of the polygon have an essential effect on composition and properties of the sediments.

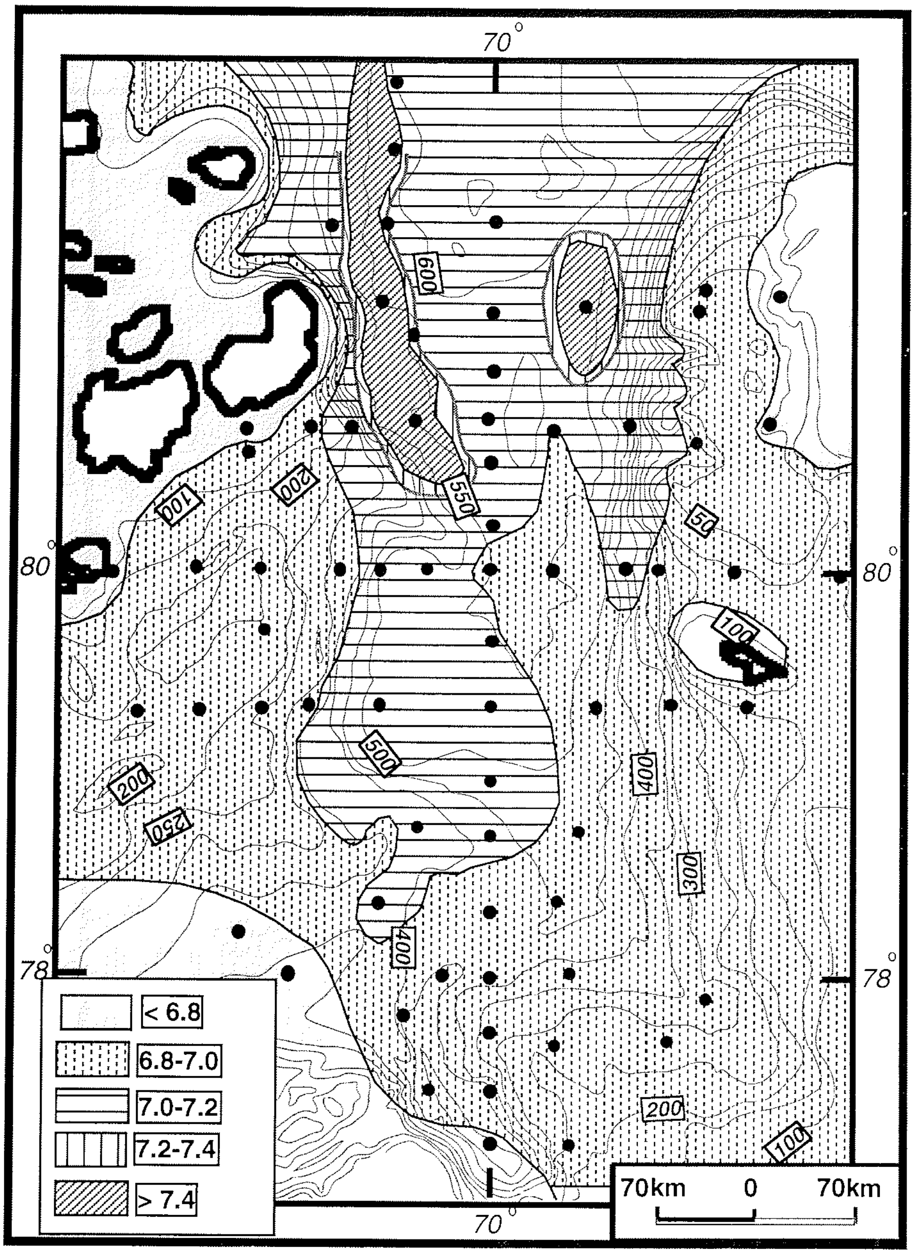


Fig. 8: Distribution of pH values in surface sediments of the St. Anna Trough.

The pH value in the surface layer increases northward from 6.8 to 7.4, with a density of isolines being significantly higher in the north of polygon than in the south. A sharp change of the pH gradient in meridianal direction passes along the sublatitudinal zone of syngenesis layer base lithification, approximately at 79°30´ N (Fig.8).

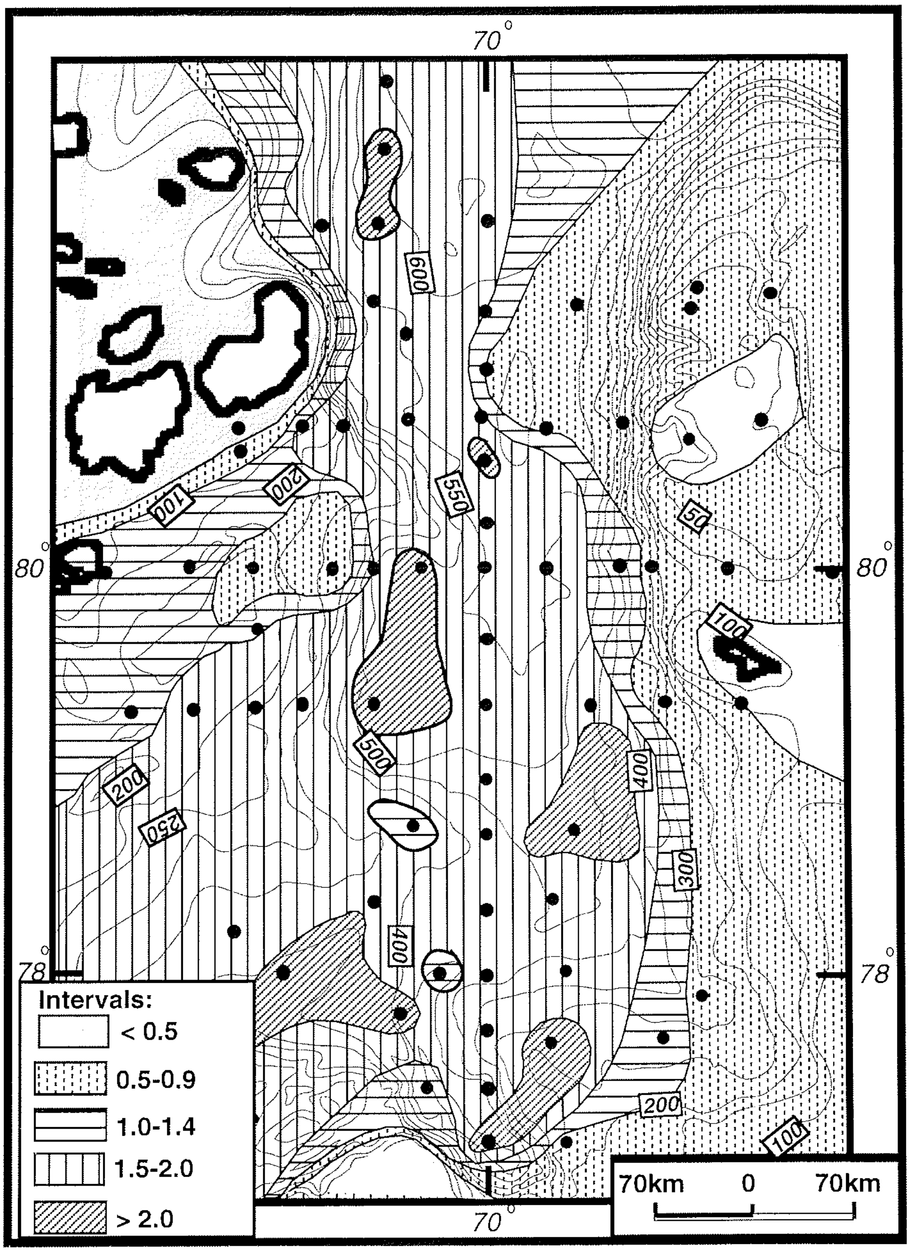


Fig. 9: Variations of humidity indicator in surface sediments of the St. Anna Trough.

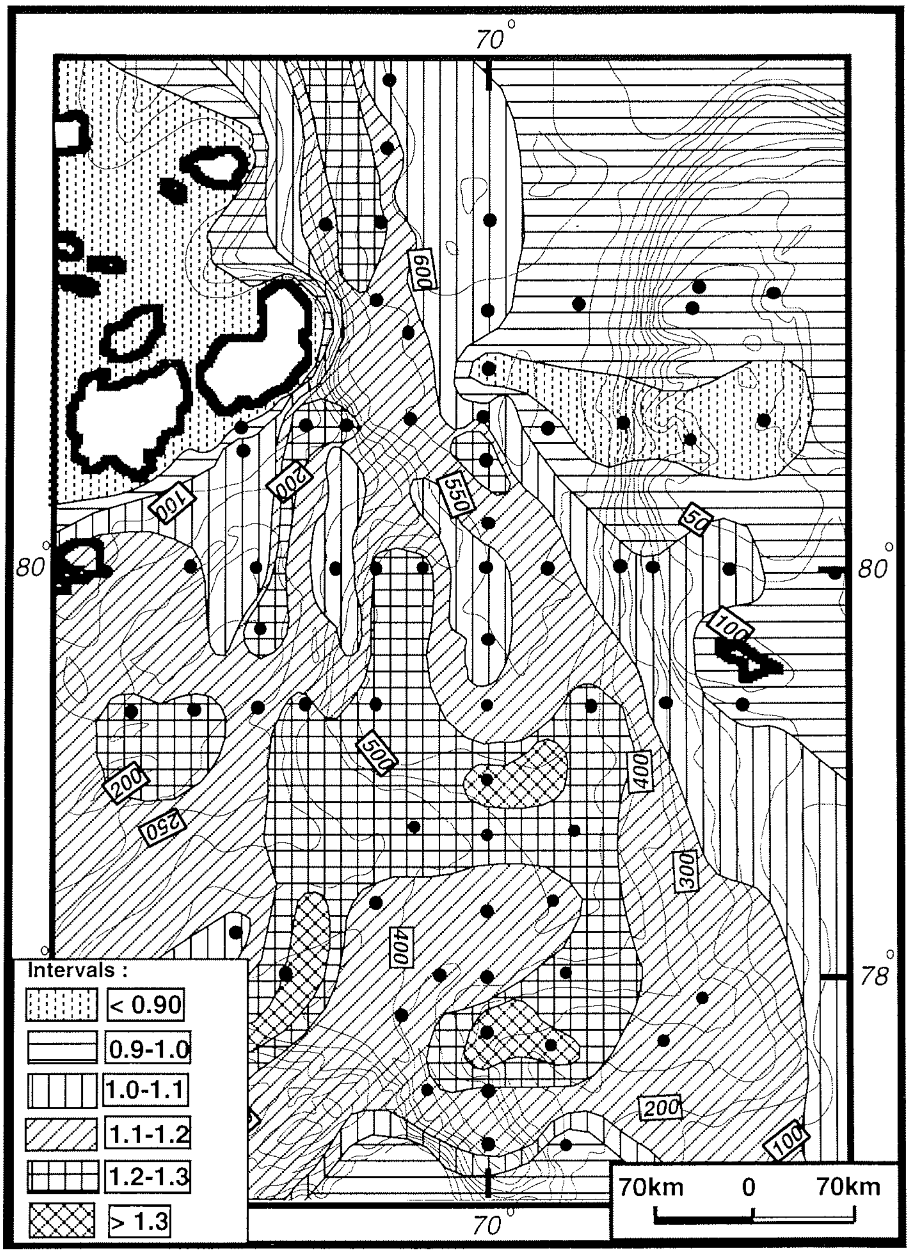


Fig. 10: Variations of sedimentation coefficient in the St. Anna Trough.

A comparison of LL with grain-size data of the sediments of the St. Anna Trough shows that it mostly depends on the content of the < 0.05 mm fraction. This is why the distribution of isolines of physical clay content and LL values generally coincide. The lateral LL variability is also caused by sea-floor bathymetry, but the impact of strong near-bottom current is observed on the eastern slope of the trough and in the north-west of the polygon.

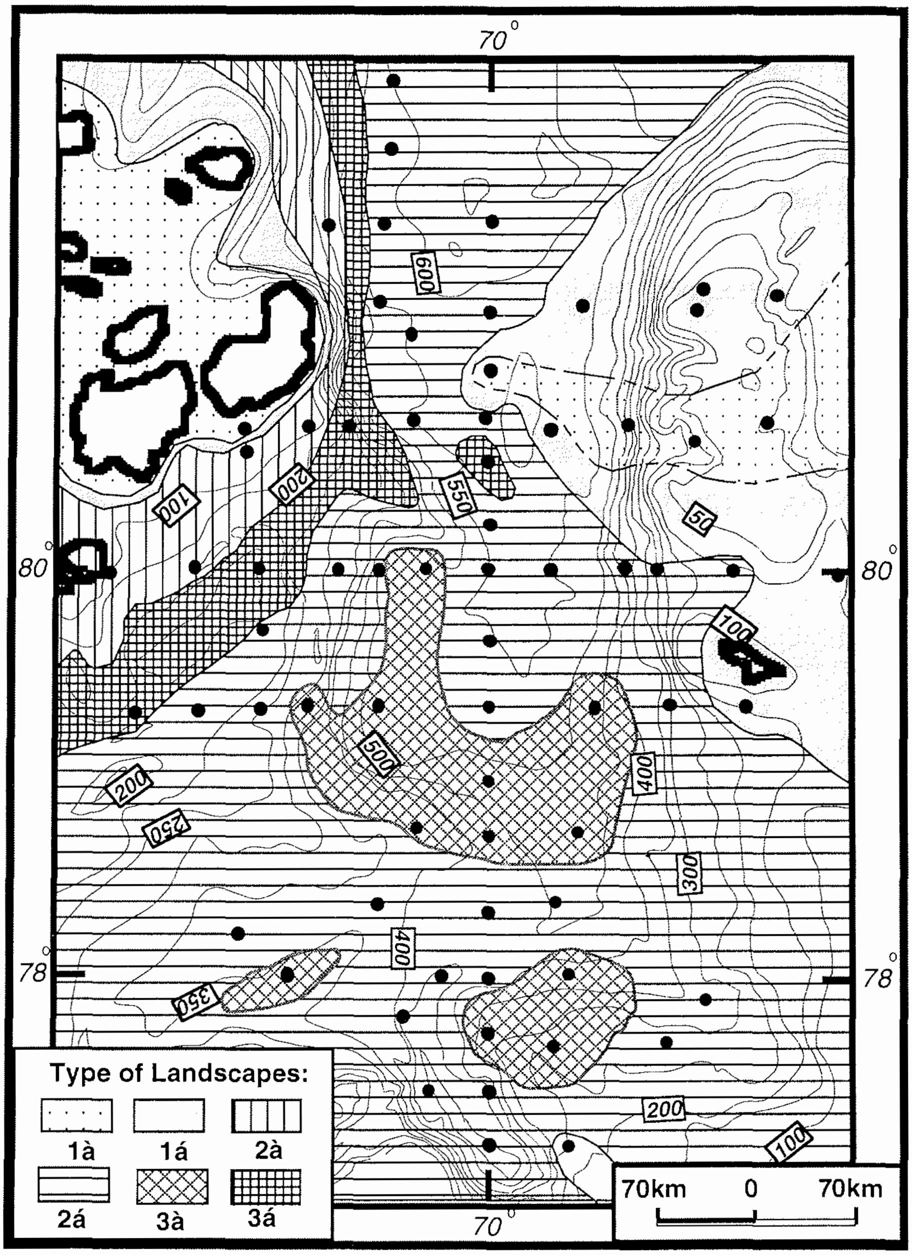


Fig. 11: Scheme of landscapes in the St. Anna Trough.

The water content of the surface layer is closely connected with sediment hydrophily (correlation coefficient rij = 0.93) and, respectively, with the < 0.05 mm fraction distribution in the surface layer and depth of sediment accumulation (Fig.9). Consequently, water content variations along the area generally reflect sea-floor bathymetry, but at the same time an increase of both mud field with water contents of surface sediments of > 150% southward of 79°30´N and mud band with water contents of about 200% at the bottom of north-western slope of the trough (Fig.9) is observed.

The sedimentation intensity coefficient (Ks) at the bottom and eastern slope of the trough accounts for 1.1 suggesting normal sedimentation conditions (Fig.10). The seafloor surface of the northeastern slope of the trough bears traces of strong near-bottom currents (Ks<0.7) while in the south the sedimentation intensity increases (Ks>1.2).

The sedimentation coefficient (Ks) is close to 1.1 in the trough bottom and accounts for about 1 at the slopes excluding its northeastern part (Fig. 10). This points to stable sediment accumulation conditions within its limits. An increase in sediment accumulation rate is noted in the southern part of the polygon, north-westward and north-eastward of the Novaya Zemlya termination. This is possibly connected with a bioproductivity increase in this part of the sea basin and variations of direction and speed of the currents. The sedimentation coefficient also increases in the lithification zone (central part of the polygon) and at the base of the western slope. The lowest Ks values (0.85) occur in the northeast of the polygon (southward of the Ushakov Island) and at the eastern slope of the trough. The bottom sediments of transaquatic areas are represented by dense sands and silts suggesting high hydrodynamic activity of the near-bottom layer along the eastern slope of the trough and also in the shoals of Vise and Ushakov islands.

Despite the decrease in sediment accumulation depth, the southern part of the polygon is characterized by a high hydrophily of the sediments and an increase in sediment accumulation rate. Seafloor areas with high sedimentation coefficients values occur at the western slope of the trough. The availability of the protosyngenesis layer of > 3 cm in thickness is typical for these areas. The decrease in pH, degradation of oxidized sediment layer, and growth of sediment hydrophily seem to increase in part of biogenic components in the sediments from the southern part of the polygon.

In general, the obtained data rather sufficiently reflect sedimentation and lithodynamic conditions within the St. Anna Trough. Indicators of the physical state of the surface sediments and sedimentaion rate coincide with independently obtained results of grain-size determinations and chemical composition of the pore water (Ivanov et al., 1997). The features of lateral distribution of physical and physical-chemical properties of surface sediments were generalized in the scheme of lithological-geochemical zonation (Fig. 11). The classification of bottom sediments by the sediment accumulation conditions is based on the geomorphological structure of the seafloor and values of sedimentation coefficient which reflects the hydrodynamic activity of the near-bottom unit. Moreover, the lithological and geochemical features of the surface layer are taken into account.

The sediment strength within first 1.5 m widely ranges from 0.0002 to 0.2 MPa. Maximum strength is characteristic of silty-psammitic deposits of the north-eastern flank of the trough and on the oxidized layer bottom between 78° and 80°N where they are strongly condensed, up to compacted sediments. Undercondensed muds occur below.

The upper 10 cm layer is heterogenous. Its structure depends on sedimentation conditions and regularities of structure formation of concentrated disperse systems. If washing-out currents are absent at the sediment surface then the suspension layer is present. This ephemeral formation does not constitute sedimentary cover being easily scoured by seasonal currents and run down the slopes. At the same time, sediments are formed at the protodiagenesis stage. The strength at the depths of 1.5-2 and 5-7 cm increases jump-wise parallel to an almost linear decrease of water content. This is evidence of an essential re-organization of the sediment structure within these intervals. Nevertheless, the correlation between specific resistance of penetration and water content remains very high (rij>-0.85).

The type of condensation and strength of sediments do not virtually depend on bioturbation. A jump-wise increase in strength and change of the physical state of sediments (liquid -> fluid -> fluid-plastic) corresponds to a change of lithogenesis stages, respectively (protosynthesis -> syngenesis -> protodiagenesis (scheme of V.N. Svalínov). At these stages the strength ranges from 0.0002 to 0.0005 MPa. Bioturbation does not mainly influence the general regularities of strength properties formation at initial stages of diagenesis.

The increase in strength of reduced deposits with depth within the study area is even more irregular. The deposits with strength of 0.13 MPa are often underlain by deposits with lower density having the strength of 0.5 MPa. In this case, as mentioned above, dense deposits or compacted interlayers usually underly liquid-fluid or fluid mud. The type of condensation of the deposits occurring down to 1.5 m shows that low water permeability of the contact between reduced and oxidized layers prevents from gravity condensation of gray-green mud. Despite the decrease in average seafloor depth in the south, the sediments of the upper layer are more hydrophilic, their sedimentation intensity coefficient is lower, and lateral variability of properties and composition is significantly lower than in the central and northern parts of the polygon (Table 1).

Conclusions

1. The water-sediment boundary has a complex lithological structure determined by sediment consistency variations. Three layers of sediments of various consistency are distinguished within upper 10-cm interval.
2. Variations in physical properties of the sediments from liquid to fluid-viscous correspond to the change of lithogenesis stages, from protosyngenesis to early diagenesis.
3. Variations of sediment consistency are noted by extremes of partial derivatives, of positive ones for strength and of negative ones for humidity. The strength of the sediment therewith sharply increase. A jump-like

increase in strength is caused by a discrete change of number of individual contacts at condensation.

4. Zones of water-sediment boundary contain several lithodynamic and geochemical barriers which most often correspond to the boundaries of the layers distinguished. The active surface of water-seafloor boundary occurs at the first diffusive barrier at the boundary of syngenesis and protodiagenesis layers. Modern sedimentation conditions most adequately reflect the composition and physical properties of the sediments at syngenesis stage.
5. Variations of composition and physical properties of the sediments at syngenesis stage show distinct differences under conditions of sediment accumulation and formation of the northern, central and southern parts of the polygon.
6. The north of the polygon is dominated by transaquatic and oxygen-accumulative sedimentation conditions. The south of the polygon is characterized by oxygen - hydrogen sulfate accumulative conditions, the central deep-sea part of the trough by accumulative oxygenous-gley ones.
7. The distribution of significant protosyngenesis layer, composition of pore waters, availability of thick gley and filtration barrier on the active surface of water-bottom boundary in the center of the polygon point to the existence of a strong endogenic factor in this part of the polygon. Its genesis is possibly associated with the sublatitudinal zone of the fault between Vise and Ushakov Islands.

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The Late Quaternary System

GRANULOMETRIC COMPOSITION OF THE UPPER QUATERNARY SEDIMENTS IN THE ST. ANNA TROUGH.

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Introduction

In order to investigate the composition of the Upper Quaternary sediments in the northern part of the Kara Sea more than 70 stations were carried out during the expedition of RV "Professor Logachev" and RV "Academician Golitsyn". Sediment cores of 20 to 380 cm in length were taken. The granulometric composition of the sediments was analyzed in detail in 12 of these cores. In the study area large morphostructures can be distinguished: elevations (Franz Josef Land, Central Kara and North-East Barents Sea), a trough (St. Anna Trough) and a depression (Severonovozemelskaya). For each of them the distribution of lithotypes and their granulometric composition depending on their morphostructural belonging, are presented and discussed in this paper.

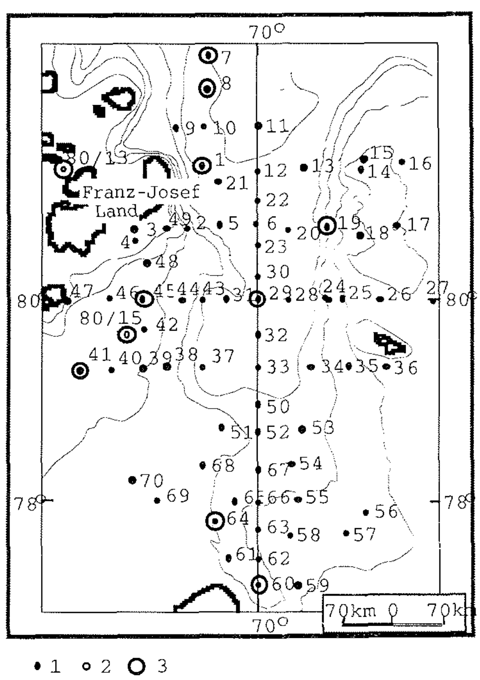

Fig.1: The study area: location of the stations. 1 — RV "Professor Logachev", 2 — RV "Academician Golitsyn", 3 — cores with detailed grain-size data.

Materials and methods

Investigations of the granulometric composition were carried out at VNIIOceangeologia, MMBI, and AWI. In the lithological-mineralogical laboratory of VNIIOceangeologia cores PL-94-01, PL-94-07, PL-94-17, PL-94-19, PL-94-29, PL-94-41, PL-94-45 and PL-94-64 were analyzed, whereas cores Gol-80/13 and Gol-80/15 and cores PL-94-08, PL-94-60, and PL-94-64 were studied in the MMBI and AWI laboratories, respectively. Sampling of the cores were performed every 10 cm. Additional samples were taken at lithological changes. Analyses were conducted by the aqua-sieve method principally similar in all three laboratories, but different in the classification of fraction used:

	VNIIOcean-geology, mm	MMBI *, mm	AWI, mm
gravel:	>1.0	>10	
sand:	1.0-0.63	1-0.5	>0.25
	0.63-0.40	0.5-0.2	0.25-0.125
	0.40-0.315	0.2-0.1	0.125-0.063
	0.315-0.20		
	0.20-0.16		
	0.16-0.10		
Aleurite	0.10-0.063	0.10-0.05	0.063-0.032
(silt)	0.063-0.05	0.05-0.025	0.032-0.002
	0.05-0.01	0.025-0.01	
Pelite	0.01-0.05	< 0.01	< 0.002
(clay)	0.05-0.001		
	< 0.001		

* classification and nomenclature by Lisitsyn and Bezrukov (1960) and Lisitsyn (1986) were used.

The selection of cores for detailed investigation of the granulometric composition of the Upper Quaternary sediments are based on the morphostructures they are from. Stations PL-94-07, PL-94-08, and PL-94-29 characterize the central part of the trough, station PL-94-01 the western flank and station PL-94-19 the eastern flank, stations PL-94-41, PL-94-45 and Gol-80/15 the north-eastern Barents Sea elevation, station PL-94-17 the Central Kara elevation, station Gol-80/13 the elevation of Franz Josef Land, and stations PL-94-60 and PL-94-64 the Severonovozemelskaya depression.

Results

1. Lithological characteristics of the sediments.

According to the lithological features four lithological units can be distinguished (Fig. 2) peculiar to the Upper Quaternary sediments of the West sector of the Arctic (Tarasov, 1996; Musatov, 1996):

<u>Unit I</u> (0-3 cm) formed by the modern sediments, is distributed all over the area. These sediments are represented by soft aleuritic-pelitic semi-slurry of red, greenish-yellow or brown colour. At the flanks of the trough (st. PL-94-19) and in the area of the elevations (PL-94-17, PL-94-36, PL-94-40, Gol-

80/15) and slopes of the Franz Josef Land archipelago (PL-94-47, Gol-80/13) the silty sediment also contains significant amounts of sand, gravel, and pebble. Water content is up to 60 %. The boundary to the underlying unit is even, well cut and clear.

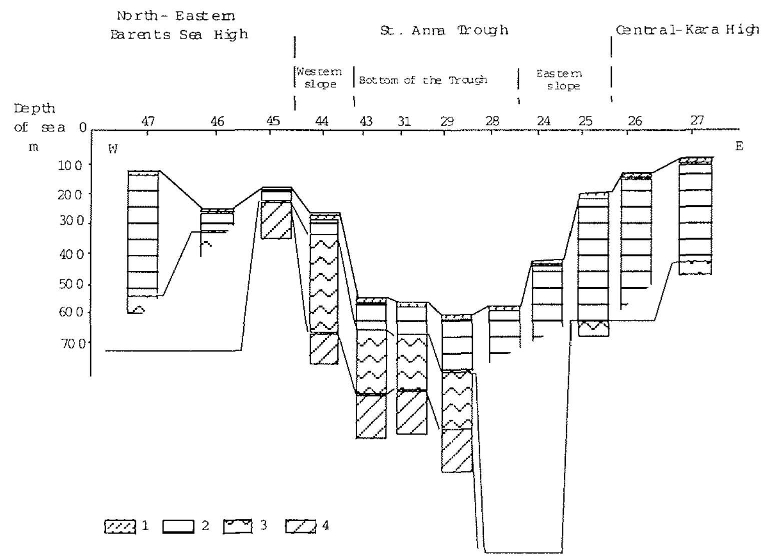

Fig.2: A transect of lithological sections across the St. Anna Trough at latitude 80°N; 1 Unit I, 2 — Unit II, 3 — Unit III, 4 — Unit IV.

The sediments of Unit II are generally represented by horizontally bedded, seldom by massive flow-plastic aleuro-pelites. The sediments are variable in their colour (greenish-red-gray), textures and enclosures. Lamination which is typical of the sediments, is indicated by changes in colour, thin layers of sand, distribution of enclosures, and horizons of hydrotroilite. For these sediments the presence of polychaete tubes, remnants of plants, and fauna is typical. Occasionally, separate rounded pebbles occur. The thickness of Unit II ranges from 20 to 80 cm on the elevation and on the western flank of the trough (PL-94-43, PL-94-45, PL-94-46), from 10 cm (PL-94-19) in the north of the eastern flank to 160 cm in its southern part (PL-94-34), > 290 cm in the eastern part of the trough (PL-94-28), and > 360 cm in the Severonovozemelskaya depression (PL-94-60). Relative density and water content of the sediments of Unit II are 1.30-1.50 g/cm^3 and 35-40 %, respectively. In the area of the Central Kara elevation sediments of Unit II are absent (PL-94-17, PL-94-36) and the surface sediments occur directly on the glacial- marine sediments (Unit III) and diamicton-like sediments (Unit IV).

The glacial-marine, bedded, turbidite-like sediments of Unit III are represented by gray less often beige-gray aleuro-pelites of flow-plastic consistence, often with gradational lamination. The admixture of sandy and sandy-gravel material and the presence of argillaceous rounded clasts, broken shells and plant remnants are typical. The density of sediments is in average 1.65 g/cm^3, the water content is 20-40%. The sediments of Unit III are best developed in the central part of the depression where their thickness ranges from 30 cm in the north of the area (PL-94-11) to 113 cm in the central part (PL-94-30), diminishes sharply to 20 cm in the area of station PL-94-20 and again increases in the southern part of the trough PL-94-50, >143 cm). Across the strike of the structure the thickness of Unit III changes from 13 cm in the area of the north-eastern Barents Sea elevation (PL-94-41) to 130 cm and more in the western flank (PL-94-02, PL-94-44), decreasing to 80-90 cm at the bottom of the trough (PL-94-13, PL-94-29). In the area of the Central Kara elevation (PL-94-15, 18) and in the trough to the north of Vise island (PL-94-25, PL-94-27) the upper part (about 20-30 cm) of Unit III is dissected.

The most distinct feature of the glacial-marine sediments of Unit III is the presence of a 2 - 12 cm thick "marker horizon" of dense almost dry ferruginizated clay of red or dark gray colour with patches of ferric hydrate. The marker horizon is present in all sedimentary columns from the central part of trough and in its western flank. In the sediments in the limits of the elevations and in the eastern flank of the trough the marker horizon is not present.

The glacial-marine (glacial?) diamicton-like sediments of Unit IV are represented by dense clays of dark-gray colour enriched in gravel-pebble material; sometimes lenses of sand and aggregates of broken shells occur. In the two sedimentary sequences from the central part of the trough a 10 cm thick layer of fine-grained sand of dark gray colour, probably of fluvial-glacial nature, is present in the upper part. In general, the sediments of Unit IV differ sharply from the overlying sediments by a greater density (up to 2,2 g/cm^3).Their water content does not exceed 20-25%. Diamicton-like sediments are dissected in the central part of the trough and in the western flank at the basis of the Late Quaternary section. In the north-eastern Barents Sea elevation (station PL-94-45) at a water depth of 173 m, the sediments of Unit IV occur below the 15 cm thick sediments of units I and II. An analogous situation is observed at station PL-94-19 in the northern part of the eastern flank of the trough (water depth of 302 m) and at station PL-94-17 (water depth of 32 m) in the area of the Central-Kara elevation.

2. Granulometric composition of the sediments

In general, the granulometric characteristics of the sediments are monotonous, aleuritic pelites predominate. Some changes in their composition are shown in Figure 3. The most monotonous granulometric composition of sediments is observed in the sections of the northern part of the trough (stations PL-94-07 and PL-94-08) and in the Severnaya Zemlya depression (stations PL-94-60 and PL-94-64) (Fig.4). Relative constant contents of sand (10-15%), aleurite (20-30%) and pelite (55-60%) occur in the sections from the northern part of the trough (PL-94-07) in all lithological units, reflecting the stable accumulation of well-sorted sediments.

The granulametric composition of the sediments in the central part of the trough (station PL-94-29) is more variable (Fig.5) and shows similar tendencies as deposits formed on its western flank in the northern part of the structure (station PL-94-01). There, fluctuations in both the ratio of sand, aleurite and pelite fractions and dispersion of pelites are observed. The predominance of large and dispersed clay fraction and sharp fluctuations in their ratios are typical of Unit IV. Unit III is characterized by the decrease of the large dispersed fraction up to its complete disappearance.

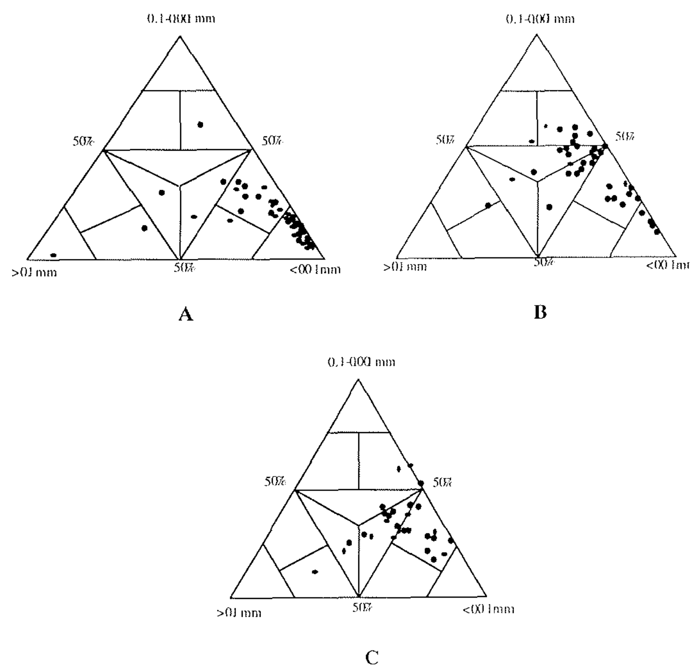

Fig.3: Grain-size diagrams for units: I (A), II (B), IV (C).

At the elevations the granulometric composition of sediments is more differentiated. In the area of the Central-Kara elevation an increase of coarse-grained components is observed: up to 45% of sand at station PL-94-19 and up to 50% of aleurites at station PL-94-17. In the area of the north-eastern Barents Sea elevation granulometric composition of sediments of Unit IV is characterized by fluctuations of the middle-fine dispersed fraction. The sediments of Unit II show a gradual increase of sand (station PL-94-45).

Discussion and conclusions

From the grain-size data it can be concluded that the four lithological units have different granulometric characteristics:

* Unit I: modern sediments with a substantially pelite composition and a predominance of the large-grained pelite fraction;

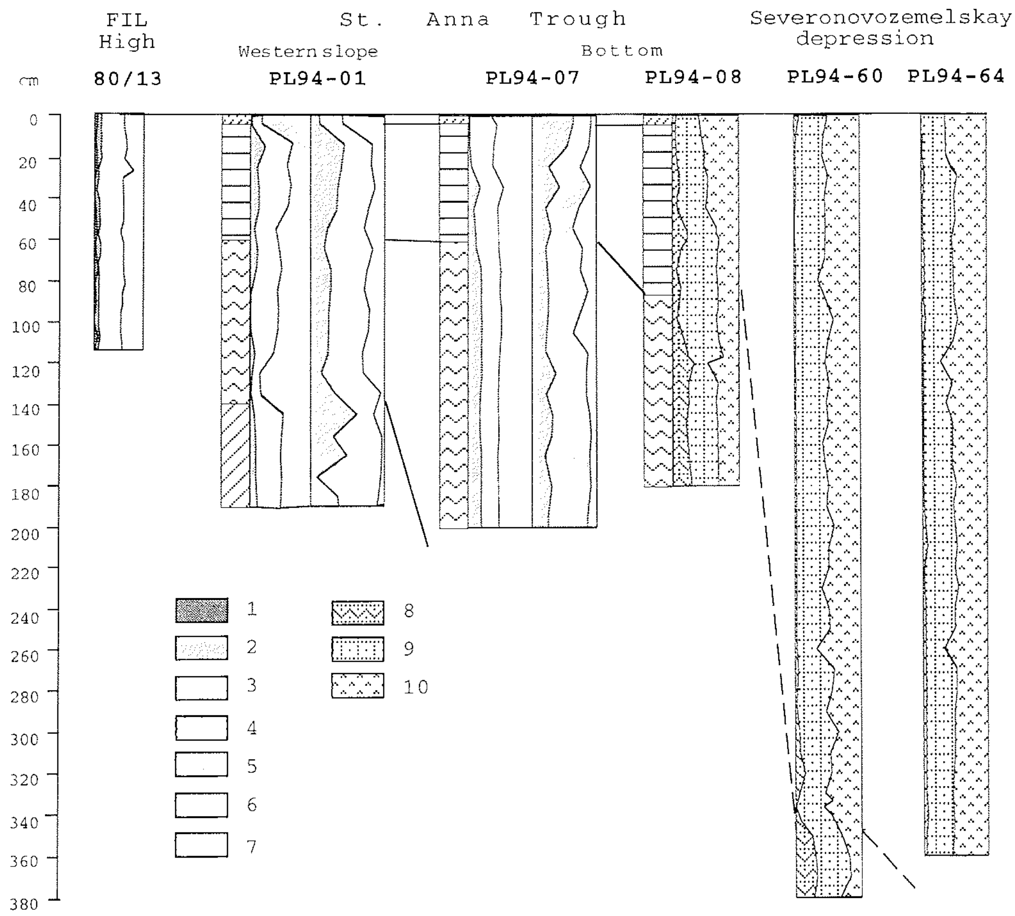

Fig.4: Grain-size of Upper Quaternary sediments from the north and south parts of the St. Anna Trough. 1 — gravel (> 1.0mm); 2 — sand (1.0-0.1 mm); 3 — aleurite (0.1-0.01mm); 4 — pelite (< 0.01mm); 5 — large dispersed pelite (0.01-0.005 mm); 6 — middle-fine dispersed pelite (0.005-0.001 mm); 7 — fine dispersed pelite (< 0.001 mm); 8 — sand (0.250-0.032 mm); 9 - aleurite (0.032-0.002 mm); 10 — pelite (< 0.002 mm).

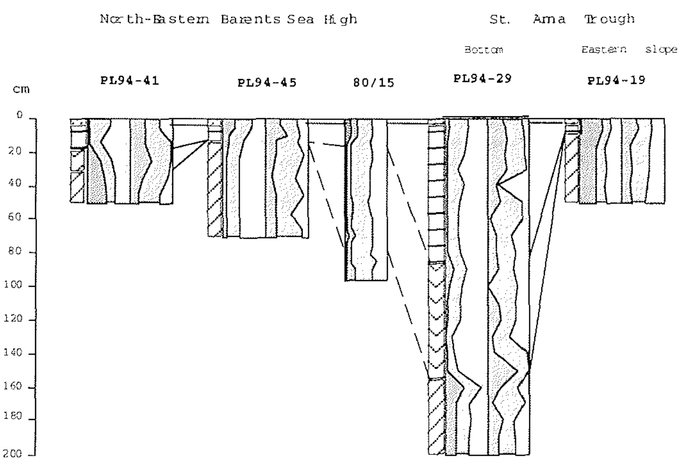

Fig.5: Grain-size of Upper Quaternary sediments from the central parts of the St. Anna Trough. 1 — gravel (> 1.0mm); 2 — sand (1.0-0.1 mm); 3 — aleurite (0.1-0.01mm); 4 — pelite (< 0.01mm); 5 — large dispersed pelite (0.01-0.005 mm); 6 — middle-fine dispersed pelite (0.005-0.001 mm); 7 — fine dispersed pelite (< 0.001 mm); 8 — sand (0.250-0.032 mm); 9 - aleurite (0.032-0.002 mm); 10 — pelite (< 0.002 mm).

* Unit II: typically marine sediments with a substantially pelite composition and periodic fluctuations in the content of sand fraction and in the dispersity, but with a predominance of aleurite (Fig. 6a);

* Unit III: glacial-marine turbidite-like deposits which are characterized by periodical increases in grain size with practically stable contents of the aleurite fraction and an almost equal ratio of the three pelite classes (Fig. 6b);

* Unit IV: glacial-marine (glacial ?) diamicton-like deposits with equal amounts of sand, aleurite and pelite and very variable contents of finest fractions (< 0.01 mm), well reflected in the histograms of Figure 6.

The glacial-marine (glacial?) deposits of Unit IV have the most sandy composition in the area of the depression axis where during the period of marine sediment accumulation (Unit II) most fine-grained sediments are formed (Fig. 7). But at the same time the most sandy sediments are typical at the eastern flank of the trough where they reach the greatest thickness. This suggests that the depot center of the main accumulation in the Late Pleistocene period was situated east of the modern depression axis. During the Holocene transgression its shifting took place due to the re-distribution of the terrigenous matter of paleo-deltas of the West-Siberian rivers.

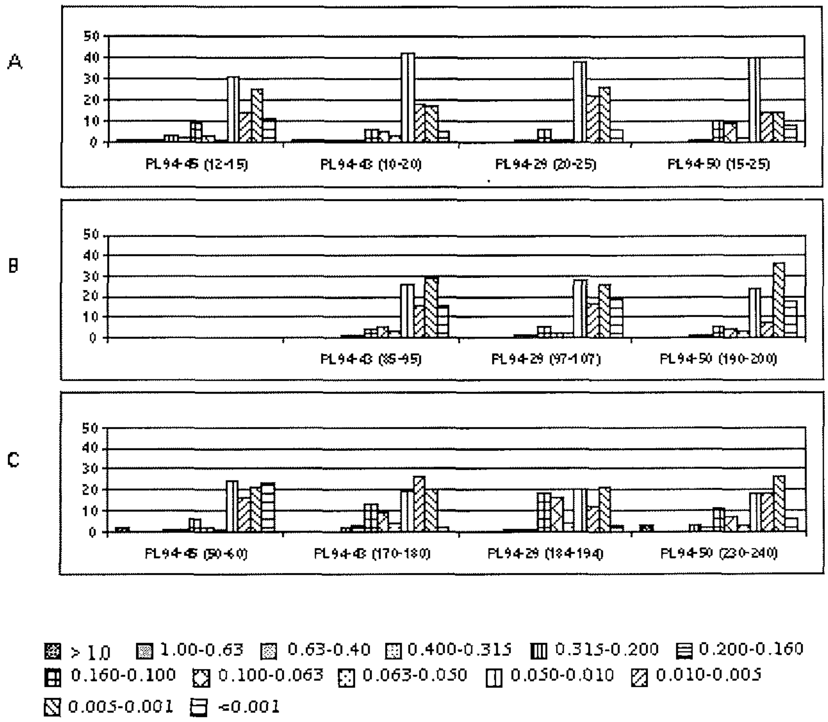

Fig.6: Grain-size spectra in Units II (A), III (B) and IV (C).

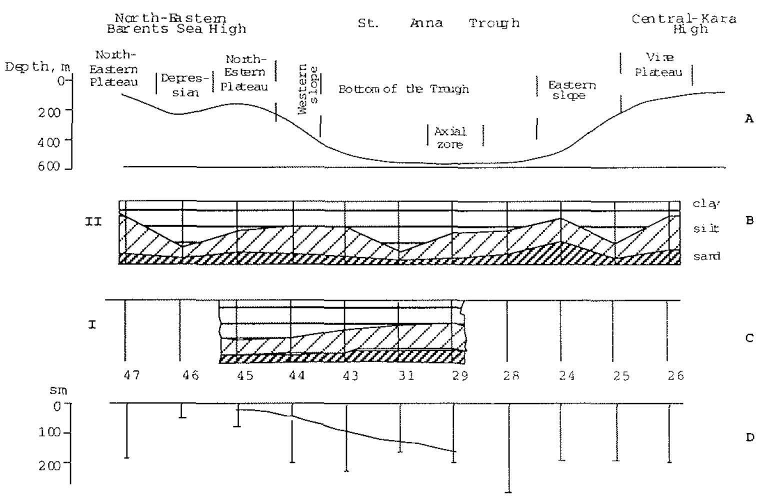

Fig.7: The relationship between seafloor relief (A) and grain size (B,C,) of deposits units IV and II. D - Core length in relation to the top of Unit IV.

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HEAVY MINERALS IN UPPER QUATERNARY SEDIMENTS OF THE NORTHERN AND EASTERN KARA SEA

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Introduction

The problems of Quaternary geology in the Kara Sea have a very disputable character. Number, volume, boundaries of the late Weichselian glacier centers in the region, its duration, the age of beginning and end of the glaciation as well as sediment sources are the main problems still under discussion. Their detailed study lies out of this paper´s framework. The only thing we would like to notice: the analysis of heavy minerals assemblages plays a quite definite role in this context.

According to most wide-spreaded views, we suppose that the eastern boundary of late Weichselian glaciation took place in the western Kara Sea (St. Anna Trough and not far eastward from the East Novaya Zemlya Trough) (L. Polyak, oral communication, 1998). At that time the eastern territory of the modern Kara Sea was represented by alluvial - lacustrine plain with permafrost. Thus, for this paper we chose sediment cores characterizing just these two parts of the region differing by their late Quaternary history.

Facts and methods

Studied sediment cores are mainly located in the St. Anna Trough area (geological stations of the 9-th cruise of R/V „Professor Logachev", 1994). Three sediment cores of R/V „Polarstern" cruise (1995) occur in the Voronin Trough (PS2792) and near the entrance in the Vilkitsky Strait (PS2718, PS2719). Position of R/V „Professor Logachev" and R/V „Polarstern" cores are given by Ivanov et al. (1998) and (Rachor, 1996).

Mineral composition of heavy fraction from R/V „Professor Logachev" sediment cores N 1, 29, 45 was studied by L.S. Smirnova in VNIIOkeangeologia using the method described in this issue (Levitan et al., this vol.). Heavy minerals of the fraction 63-125 µm from R/V „Professor Logachev" sediment cores N 8, 60, 64, and from R/V „Polarstern" sediment cores were studied by M.V. Bourtman in Shirshov Institute of Oceanology using the method described by Behrends et al., (1996). The separation of the fraction 63 -125 µm and the preparation of special samples for heavy mineral analysis was made at AWI. The lithological description of sediment cores was performed by I.A. Andreeva, G.I. Ivanov, L.V. Polyak, R. Stein and D. Nürnberg.

Results and discussion

As the studied sediment cores are located in three different areas, we consider them separately.

St. Anna Trough area

The recent environment and distribution of heavy minerals in surface sediments of the St. Anna Trough are described in detail by Ivanov et al. (this vol.) and Levitan et al. (this vol.). Thus, we concentrate our efforts on problems of lithostratigraphic correlation and mineral composition of source provinces as the base for mineralogical data interpretation.

In our investigated cores we also could identify the three units published for upper Quaternary sediments in the Barents Sea and St. Anna Trough by Vorren et al. (1988), Spiridonov et al. (1992), Polyak et al. (1995, 1997), and Kosheleva and Yashin (1996). These 3 units (downward) are considered as marine, glacio-marine and glacial sediments. In the St. Anna Trough the lower Unit III is represented by stiff diamicton with a number of rock fragments of gravel- and pebble-size. The middle Unit II is composed of laminated rather dense pelitic and aleuro-pelitic clays including locally sand layers (up to turbidites), dense „dry" silty clays („hardgrounds") and buried oxidized horizons. The upper Unit I is mainly represented by soft bioturbated aleuro-pelitic muds with rare buried oxidized horizons. Grain-size parameters of these units are given in Table 1 (Appendix).

It is clear from Table 1 (Appendix) that the background composition of Units I and II is quite similar (if we use the western classification), and diamicton is differed by its much higher sand contents. According to Russian classification, the amount of the fraction 0.01-0.1 mm varies unregularily.

According to L. Polyak's data (Polyak et al., 1997), the Unit II / III boundary is dated to 13.3 ka (or slightly older), and the Unit I / II boundary to 10 ka. Thickness and sedimentation rates for these units are given in Table 2.

The thickness of Unit I in sediment core DM 4397 which is located in the upper part of the right tributary of the St. Anna Trough, is 380 cm (Levitan et al., 1994). In general, thicknesses and sedimentation rates of Units I and II increase southward, indicating that the main flux of sediment matter during deglaciation and postglacial times was supplied from the south (from the Northern Island of Novaya Zemlya and southern parts of the Northern Kara Rise and Franz Josef Land Archipelago). Furthermore, sedimentation rates of glacial-marine sediments (Unit II) are 2-4 times higher than those of marine sediments (Unit I). According to AMS ^{14}C data for sediment core PL 94-67 (Polyak et al., 1997), sedimentation rates in the beginning of the Holocene (up to 8.5 ka) were 2-2.5 times higher than during the upper Holocene. Polyak et al. (1997) relate this either to enhanced erosion of banks, increased sediment supply by Siberian rivers, or enhanced coastal abrasion. Our data allow to suppose that just in this time Ob and Yenisey rivers supplied much more sediment matter (Levitan et al., 1996).

We can point out some peculiarities of heavy mineral assemblages in sedimentary sequences of potential source areas (Andreeva, 1979, 1984; Dibner, 1957a,b, 1965; Dibner and Sedova, 1959; Dibner et al., 1962; Samoilovich et al., 1981). Upper Cretaceous sediments of the eastern and south-eastern islands of Franz-Josef Land contain up to 50 % of tourmaline, zircon and rutile, and up to 20 % of pyrite; lower Cretaceous sediments and plateau basalts - pyroxenes (72-82 %), pyrite and Fe hydroxides (15-20 % in sum). Upper Jurassic sediments contain black ore minerals (30-50 %), pyroxenes (up to 20 %), pyrite - siderite - Fe hydroxides (up to 15 %), epidote (5-20 %), and zircon (5-10%). Lower Jurassic sediments are characterized by the abundance of black ores (60 %); there are also zircon (15 %), garnet (15 %), pyrite and Fe hydroxides (5 %). Upper Triassic sediments contain epidote (up to 45 %), black ores (10-20 %), zircon (5-20%), tourmaline (10 %), pyrite and siderite as concretions.

High amounts of epidote (40-45 %), garnet (up to 18 %), black ores (14 %), pyrite (20-26 %), and iron-carbonate aggregates (20 %) were described in Cretaceous sediments and Pleistocene sands of Vise Island. Upper Pleistocene sediments of Ushakov Island contain up to 60 % of black ore minerals and 13 % of garnet. There are also a lot of Fe hydroxides. Furthermore, one can observe zircon, epidote, pyroxenes and amphiboles in very limited amounts. Paleozoic sediments of Novaya Zemlya are characterized by high amount of stable minerals.

For upper Quaternary sediments of the St. Anna Trough we found the same minerals as described for recent sediments (Levitan et al., this vol.): clinopyroxenes, epidotes, amphiboles, black ore minerals, and different accessories. Authigenic minerals such as pyrite, siderite and iron - carbonate aggregates (usually their amount does not exceed 2 %), however, become dominant (up to 20-30 % and more) in Units II and III, indicating clastogenic nature of these minerals. In Figure 1 it is well shown that during the transition from Unit I to Unit II and - downward - to Unit III one can observe in general decreasing of amounts of black ore minerals, clinopyroxenes and amphiboles; and increasing amounts of pyrite, siderite, epidote/clinopyroxene (Ep/ClPx) ratio. A similar trend is reported for heavy minerals of sediment core PL 94-07 (Polyak et al., 1997).

Sediment core PL 94-08 is located not far from PL 94-07. Here the black ore - epidote - clinopyroxene assemblage of Unit I is changed downward to the same assemblage, however, with an increased Ep/ClPx ratio and a sharp increasing of pyrite and siderite in separate layers (Fig. 2). Unit III is different from the overlying sediments by its very high amount of pyrite, siderite and black ore minerals (50-60 % in sum). The amount of clinopyroxenes is strongly decreased.

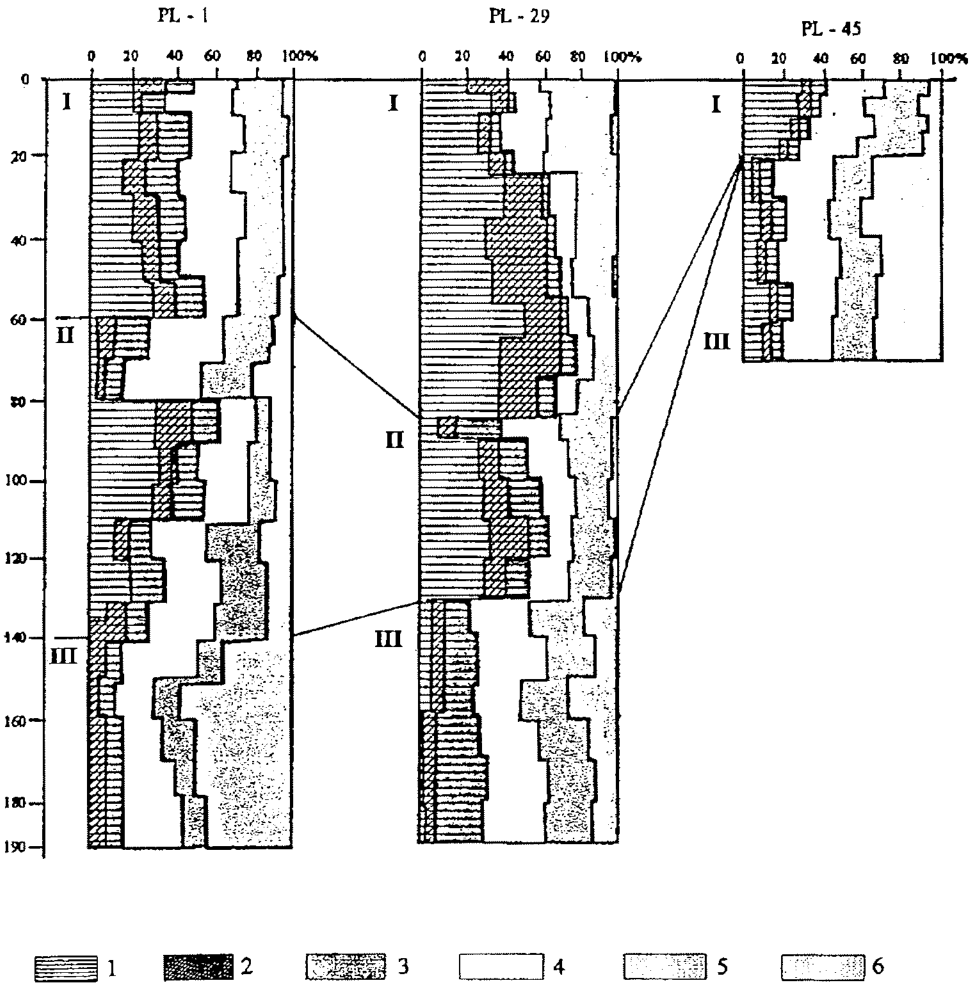

Fig.1: Heavy minerals (%) in sediment cores PL 94-01,29,45. 1 - clinopyroxenes; 2 - amphiboles; 3 - epidote; 4 - accessories; 5 - black ore minerals; 6 - pyrite and siderite; I, II, III - sedimentary units.

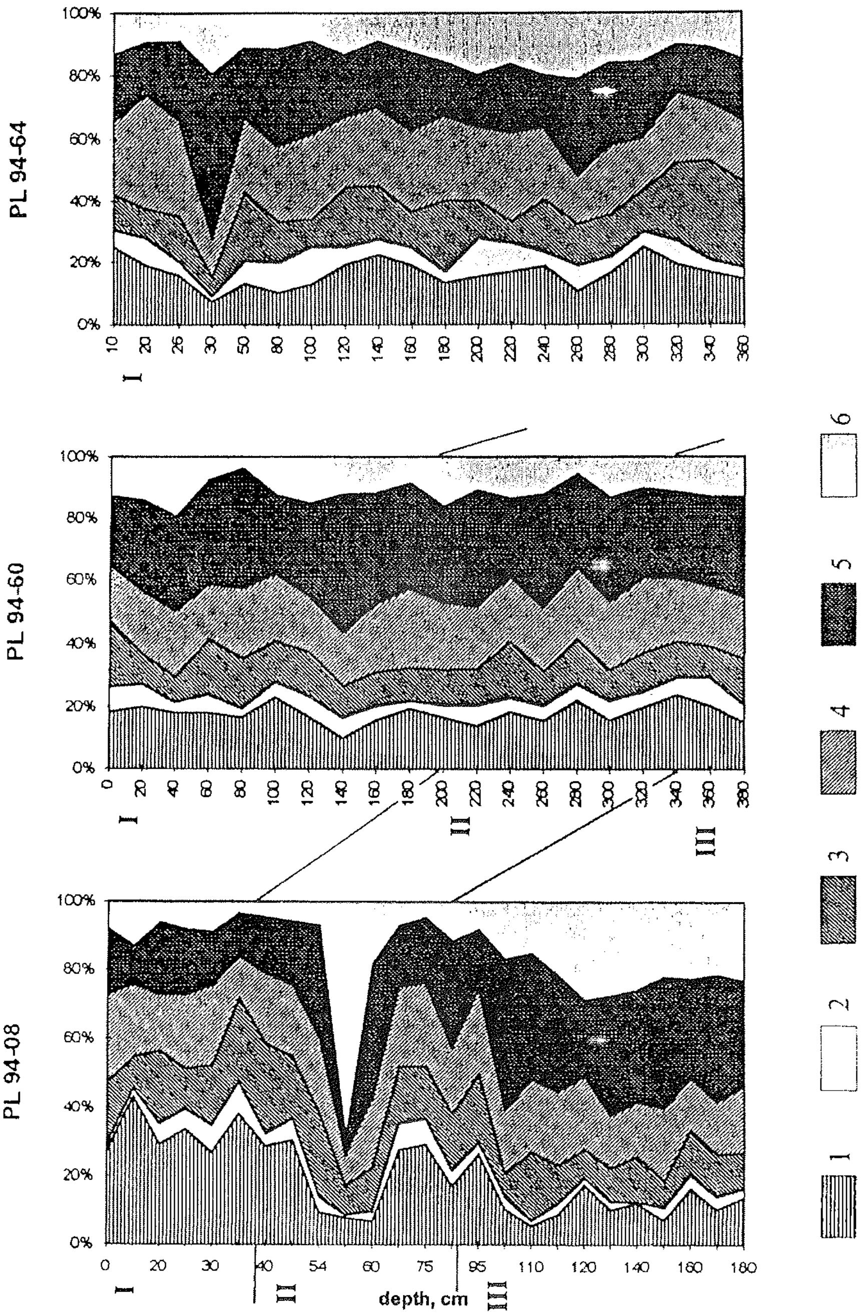

Fig.2: Heavy minerals (%) in sediment cores PL 94-08,60,64. For legend see Figure 1.

Interestingly, sediment core PL 94-60 contains practically a similar assemblage in all three units: epidote - clinopyroxene - black ores (Fig. 2), suggesting a stable ratio between sources of main minerals in the area during the last about 15 ka. A similar assemblage (Fig. 2) was accumulated, however, with much higher sedimentation rate (Table 2) in Unit I of sediment core PL 94-64. Here we observe the increasing of the Ep/ClPx ratio only in the lower part of the profile.

Table 2: Thicknesses (cm) and sedimentation rates (cm/ky) for main upper Quaternary sedimentary units in the St. Anna Trough.

sediment core	water depth, m	length of sediment core, cm	Thickness / sedimentation rate		
			Unit I	Unit II	Unit III
PL 94-07	633	161	40 / 4.0	52 / 15.8	> 70
PL 94-08	620	180	38 / 3.8	50 / 15.2	> 100
PL 94-11	632	151	60 / 6.0	70 / 21.2	> 21
PL 94-01	542	190	60 / 6.0	80 / 24.2	> 50
PL 94-45	173	70	> 15		> 55
PL 94-29	605	194	85 / 8.5	79 / 23.9	>30
PL 94-67	443	235	230 / 23.0	> 5	
PL 94-64	475	370	>370/>37.0		
PL 94-60	574	382	197 / 19.7	143 / 43.3	>42

In summary, 5 of the 6 sediment cores (PL 94-07, 08, 01, 45, 29) containing all 3 units generally display a similar sequence of heavy mineral assemblages. Unit I is characterized by an epidote - amphibole - clinopyroxene assemblage, Unit II - by an epidote - clinopyroxene assemblage locally enriched by accessories, black ore minerals, pyrite and siderite. There is a strong dominance of pyrite, epidote, siderite and - sometimes - black ore minerals in Unit III.

Hence, during last 15 (?) ka a change of source provinces took place in the studied region. It seems, that during diamicton formation the northern Kara Rise (Cretaceous and Pleistocene sediments of Vise Island, etc.) served as the main source of heavy minerals because it was not covered by an ice cap, and erosion processes were very active in this area. According to high Ep/ClPx ratios, the role of Siberian river discharge was less important than the role of local sources. During deglaciation, retreat of the ice from Franz-Josef Land and its glacioisostatic uplift resulting in increased erosion of its sequences, became more and more important. During the formation of Unit I also bottom erosion of edaphogenic sources between Franz-Josef Land and Novaya Zemlya was an important process. It was mentioned earlier (Levitan et al., 1998), that most part of the St. Anna Trough sea floor at the present receives its sediments from Franz-Josef Land.

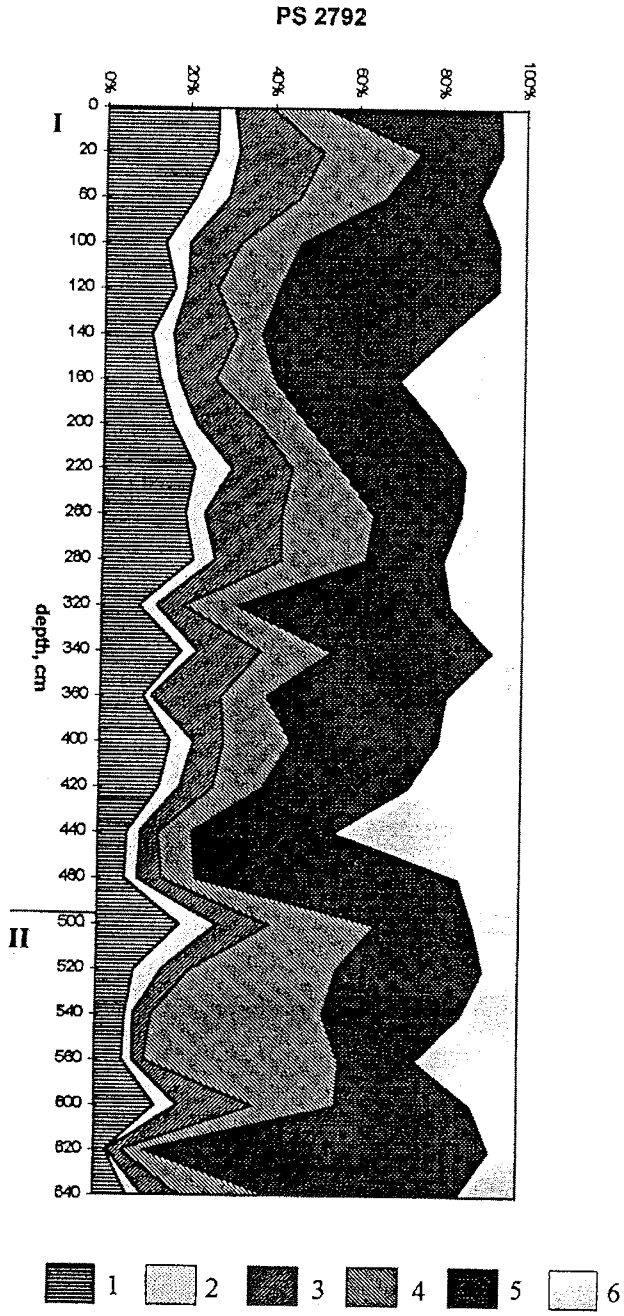

Fig.3: Heavy minerals (%) in sediment core PS 2792. For legend see Figure 1.

Voronin Trough

This trough is located between the Northern Kara Rise and the Severnaya Zemlya Archipelago. In its geomorphologic relation it belongs to the same type of structures as the Franz-Victoria and St. Anna Trough. That is why one supposes also the importance of the Voronin Trough for the supply of sediment matter from the Kara Sea shelf into the Nansen deep-sea basin, and for the advection of Atlantic Waters southward. Geologically the Voronin Trough is studied rather bad. „Parasound" data indicate the wide distribution of submarine slides off Severnaya Zemlya (Rachor, 1996).

Sediment core PS2792 was obtained just in the center of the Voronin Trough. The 690 cm long sedimentary sequence can be divided into 3 units. Downward it was reported: Unit I (0-490 cmbsf) consists of bioturbated silty clays of dark olive-gray colour. The interval between 280-490 cm is enriched in black lenses (diameter up to 7 mm) and mollusk shells. Unit II (490-682 cmbsf) is composed of dense clays of dark grey-brown colour including black lenses and mollusk shells in the interval 602-631 cm. Unit III (682-690 cmbsf) is located just beneath an erosional surface and is represented by lumped and laminated clays with lenses of weakly consolidated sands and nodules of grey, green and pink colors (diameter 0.2-5 mm). The density record (Rachor, 1996) demonstrates a very sharp boundary between Units I and II (density shift from 1.54 to 1.74 g/cm^3), and below 600 cm density is decreased to 1.62 g/cm^3.

Detailed study of heavy minerals revealed the dominance of 4 mineral groups: epidote, clinopyroxenes, black ores and iron oxides/hydroxides (Fig. 3). Minerals of the last two groups give in sum 20-85 %. Generally an epidote - clinopyroxene - black ore (with Fe hydroxides) assemblage prevails throughout the sediment core. It resembles modern sediments of the eastern St. Anna Trough adjacent to the Northern Kara Rise near Ushakov Island, which are slightly enriched in garnet too. Thus, we consider just the Northern Kara Rise as the main source of heavy minerals for PS2792.

Amount of individual minerals varies significantly in Unit I. Mean values are 15 % for ClPx, 10 % for epidotes, and 1.5 for the ClPx/Ep ratio. In general, concentrations of ClPx and Ep are higher in upper 280 cm than below.

In Unit II the amounts of ClPx, Ep and ClPx/Ep ratio are sharply increased downward (on the background of strong decreasing of black ores and Fe oxides/hydroxides sum), and then the amounts of Ep and ClPx decreased. Black ore minerals and Fe hydroxides are sharply enriched in individual layers and lenses, especially below 600 cm. Also we should notice the strong enrichment by accessories in the interval 490-600 cm, and rather high mean amounts of pyrite and siderite.

As we have no geochronological or biostratigraphic data we propose the following lithostratigraphic division (based on correlation with the St. Anna Trough data). The upper interval (0-280 cm) probably is of Holocene (0-8.5 ka) age with a rather low sedimentation rate (33 cm/ky). The interval 280-490 cm reflects the epoch of strong erosion in the Kara Sea region during the early Holocene (10-8.5 ka) resulting in high sedimentation rates of 147 cm/ky. The interval 490-680 cm we correlate with Unit II in the St. Anna Trough (geochronologically, and not genetically). In this interval we distinguish 3 layers. Layer 1 (interval 490-602 cm) and 3 (interval 631-680 cm) were accumulated with lower sedimentation rate and had different source provinces, and layer 2 (interval 602-631 cm) with higher sedimentation rate due to activization of slope processes.

The eastern Kara Sea (near the entrance in the Vilkitsky Strait)

Two sediment cores PS2718 and PS2719 were obtained in a small shelf deep with water depth of 130-150 m. Main source provinces for this region are the Bol'shevik Island from the Severnaya Zemlya Archipelago, the Taimyr Peninsula and the Northern Siberia region with Yenisey River and its tributaries.

Sediment core PS2718 consists of a quite monotonous cross-section of silty clays and clays with dark grey or black colour, diagenetic specks of Fe monosulfides and rare small shells of bivalvia in the interval 713-757 cm. Most part of the upper meter is lost. Physical property data confirm monotonous lithology of the core (Rachor, 1996).

An epidote - black ores - clinopyroxene assemblage dominates throughout the core. It is enriched in hornblende in the intervals 140-200 and 680-730 cm. Downward to 570 cm no strong changes in the composition of the assemblage occur, but below the amount of epidote significantly decreases and the ClPx/Ep ratio increases. We interpret these data of the lower part as a reflection of enhanced sedimentation rate due to supply of sediment matter by Yenisey and/or by erosion of the Taimyr Peninsula. Upward, sedimentation rates decreased. Intervals of hornblende enrichment are probably related to sediment supply from the Bol'shevik Island.

The length of sediment core PS2719 is 655 cm. Two lithological units can be distinguished. Unit I (0-538 cm) consists of dark grey silty clays with shells of bivalves and gastropods, specks of Fe monosulfides, rare fragments of sandstones and coal. Unit II contains interlayering of very dark grey silty clays and sands. These data are in good accordance with physical property data (Rachor, 1996). According to these results, Unit II is characterized by strong increasing of density and decreasing of magnetic susceptibility (MS) in comparison to Unit I.

Mineralogical data also confirm our lithostratigraphic division and - together with more detailed analysis of physical properties data - allow to divide Unit I into 3 Subunits. Subunit I A (0-75 cm) contains an accessories - epidote - black ore - clinopyroxene assemblage and is characterized by strongly variable values of MS and density. Remarkable is the coincidence of ClPx and MS maxima at the level 30-40 cm. This coincidence (in more broad geographical sense) was also reported by Niessen and Weiel (1996) who explained it by supply of ClPx and ferrimagnetics (magnetite and titano-magnetite, mainly) from the same source rocks - basalt sheets and dykes.

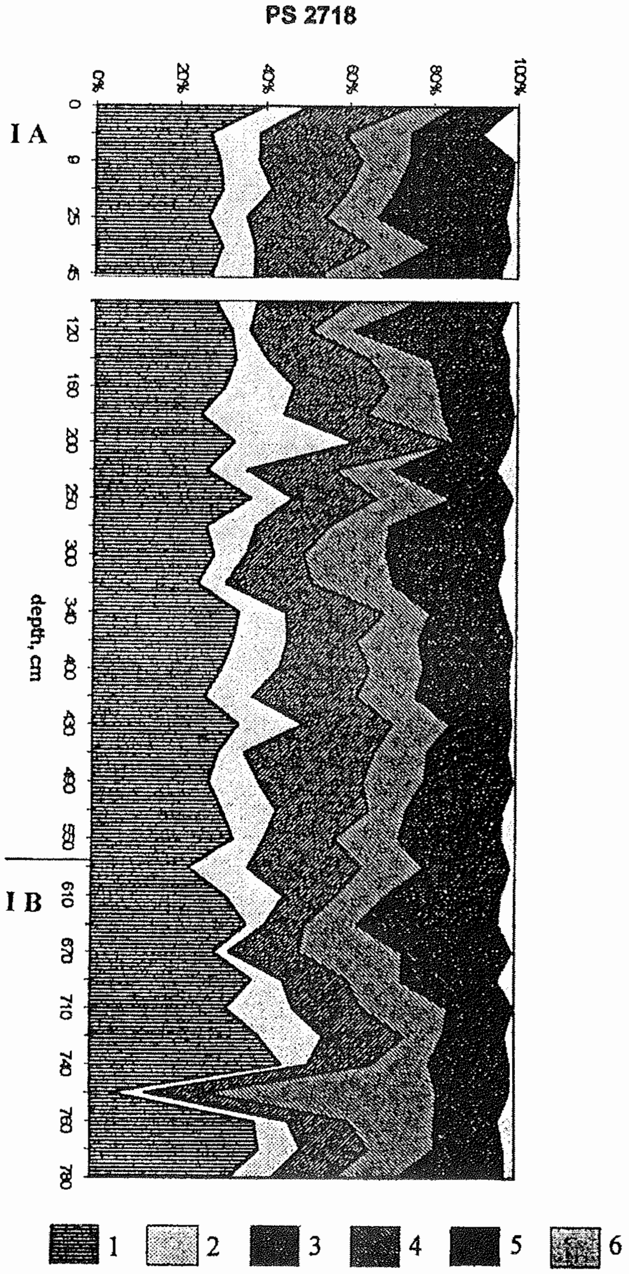

Fig.4: Heavy minerals (%) in sediment core PS 2718. For legend see Figure 1. IA, IB - sedimentary subunits.

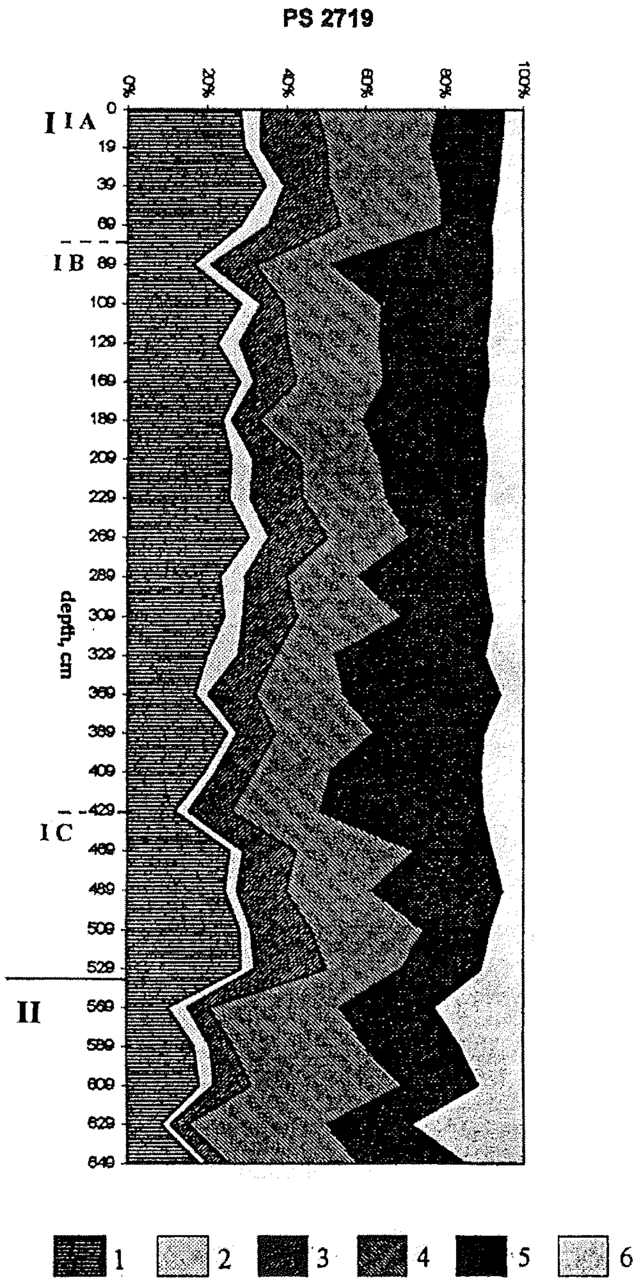

Fig.5: Heavy minerals (%) in sediment core PS 2719. For legend see Figure 1. IA, IB, IC - sedimentary subunits.

Subunit I B (75-430 cm) is characterized by its epidote - accessories - clinopyroxene - black ore assemblage and weak monotonous increasing of MS and bulk density down-core. Here the importance of black ores is increased, and the importance of accessories diminished.

The amount of clinopyroxenes is much higher in Subunit I C (430-538 cm), and the amount of black ore minerals is lower. MS is increased very sharply. This heavy mineral composition is classified as an epidote - black ore - accessories - clinopyroxene - assemblage.

Sediments of Unit II are characterized by one principle composition: an epidote - clinopyroxene - black ore - accessories assemblage dominates, ClPx/Ep ratio is strongly increased, amounts of pyrite and syderite are increased too.

Thus, a sharp change of environment took place at the Unit I/Unit II boundary. Supply of sands enriched in accessories from the Bol'shevik Island (?) and high sedimentation rates were changed to supply of finer sediments from other sources with several well expressed events of enhanced Yenisey River discharge(?). We suggest that sedimentation rates of Unit I were lower than those of Unit II.

Conclusion

In all three studied regions heavy mineral assemblages (together with lithology and physical properties) are a good indicator of changing environments and source provinces. Such changes are due to the history of last glaciation and deglaciation in the St. Anna Trough, changes in degree of erosion and the area of eroded regions related to neotectonics, climatic changes, sea level rise, and other reasons in the eastern Kara Sea.

It seems that, in spite of lack of glaciation in the eastern part of the modern Kara Sea, in general changes of sedimentation rates during the last 15 (?) ka had a more or less synchronous character, decreasing upward (especially near the Pleistocene/Holocene and Early/Middle Holocene boundaries). We need, however, many additional radiocarbon data to confirm (or to refute) these conclusions.

Acknowledgments

We wish to express our appreciation to R. Stein, D. Nürnberg and G.I. Ivanov for their lithological descriptions of several sediment cores. Physical property data of R/V „Polarstern" sediment cores were kindly given by F. Niessen. The discussion of paleogeographic problems with L. Polyak led to improvement of the paper. M.V. Bourtman is sincerely thankful to the AWI Direction for permission to participate in the cruise of R/V „Polarstern" and the possibility to fulfill part of the experimental study in the AWI laboratories.

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Appendix (Levitan et al.)

Table 1: Mean grain-size parameters (wt %) of upper Quaternary sedimentary units (Polyak et al., 1997; our data)

Sedimentary units	sediment cores PL 94 - 7, 11, 29, 67			sediment core PL 94-01			sediment core PL 94-29			sediment core PL 94-45		
	sand	silt	clay	fr. 0,01-0,1 mm	fr. 0,05-0,1 mm	heavy fraction	fr. 0,01-0,1 mm	fr. 0,05-0,1 mm	heavy fraction	fr. 0,01-0,1 mm	fr. 0,05-0,1 mm	heavy fraction
I	6 +/- 2 (n=51)	40 +/- 7 (n=51)	52 +/- 9 (n=51)	44,8 (n=6)	23,5 (n=6)	0,85 (n=6)	34,2 (n=9)	2,8 (n=9)	2,00 (n=9)	37,3 (n=3)	7,3 (n=3)	0,78 (n=3)
II (background, no sands)	6 +/- 4 (n=22)	38 +/- 2 (n=22)	52 +/- 7 (n=22)	32,1 (n=8)	7,1 (n=8)	0,73 (n=8)	24,8 (n=7)	3,2 (n=7)	1,37 (n=7)			
III	23 +/- 2 (n=35)	32 +/- 3 (n=35)	43 +/- 3 (n=35)	42,1 (n=5)	15,1 (n=5)	0,79 (n=5)	36,7 (n=4)	10,5 (n=4)	1,19 (n=4)	30,3 (n=5)	3,7 (n=5)	0,59 (n=5)

LATE QUATERNARY ORGANIC CARBON RECORDS IN THE ST. ANNA TROUGH (KARA SEA)

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Abstract

In order to understand processes controlling organic carbon deposition (i.e., primary productivity vs. terrigenous supply), surface sediments and sediment cores from the St. Anna Trough (northern Kara Sea) were investigated for their content and composition of organic carbon.

In the surface sediments, hydrogen indices of about 100 to 200 mgHC/gC suggest a dominance of terrigenous organic matter with, however, significant amount of marine organic matter. River-derived terrigenous organic material from the Siberian hinterland and local input from Franz-Josef-Land and Novaya Zemlya are probable source areas for terrigenous organic matter. In the central St. Anna Trough, a couple of samples with high TOC values and C/N ratios of about 6 also show relatively high biogenic opal values of 3 - 5 %, suggesting some increased surface-water productivity.

The organic carbon records from the three investigated sediment cores can be related to the glacial/postglacial history of the St. Anna Trough area. During the last glacial maximum, the St. Anna was covered by grounded ice resulting in a diamicton characterised by high terrigenous organic carbon content. During the following postglacial interval an increase in marine organic carbon content is related to first postglacial inflow of Atlantic water. Since about 10 ka, modern full marine conditions influenced by Atlantic-water inflow were established as indicated by the deposition of terrigenous organic matter with a significant proportion of marine organic matter being preserved in the sedimentary records of all three investigated cores.

Introduction

Within a joint Russian-German research project funded by the German Ministry for Education, Science, Research, and Technology (BMBF), detailed sedimentological, mineralogical, and geochemical investigations were performed on sediments from the St. Anna Trough area. Major objectives of these studies were (1) the quantification and characterisation of terrigenous sediment input, (2) the identification of source areas and transport pathways of the terrigenous matter, and (3) the reconstruction of the depositional environment and its change through late Quaternary times. In addition, some organic-geochemical investigations concentrating on the characterisation and quantification of the organic-carbon fractions of these sediments were included in the project.

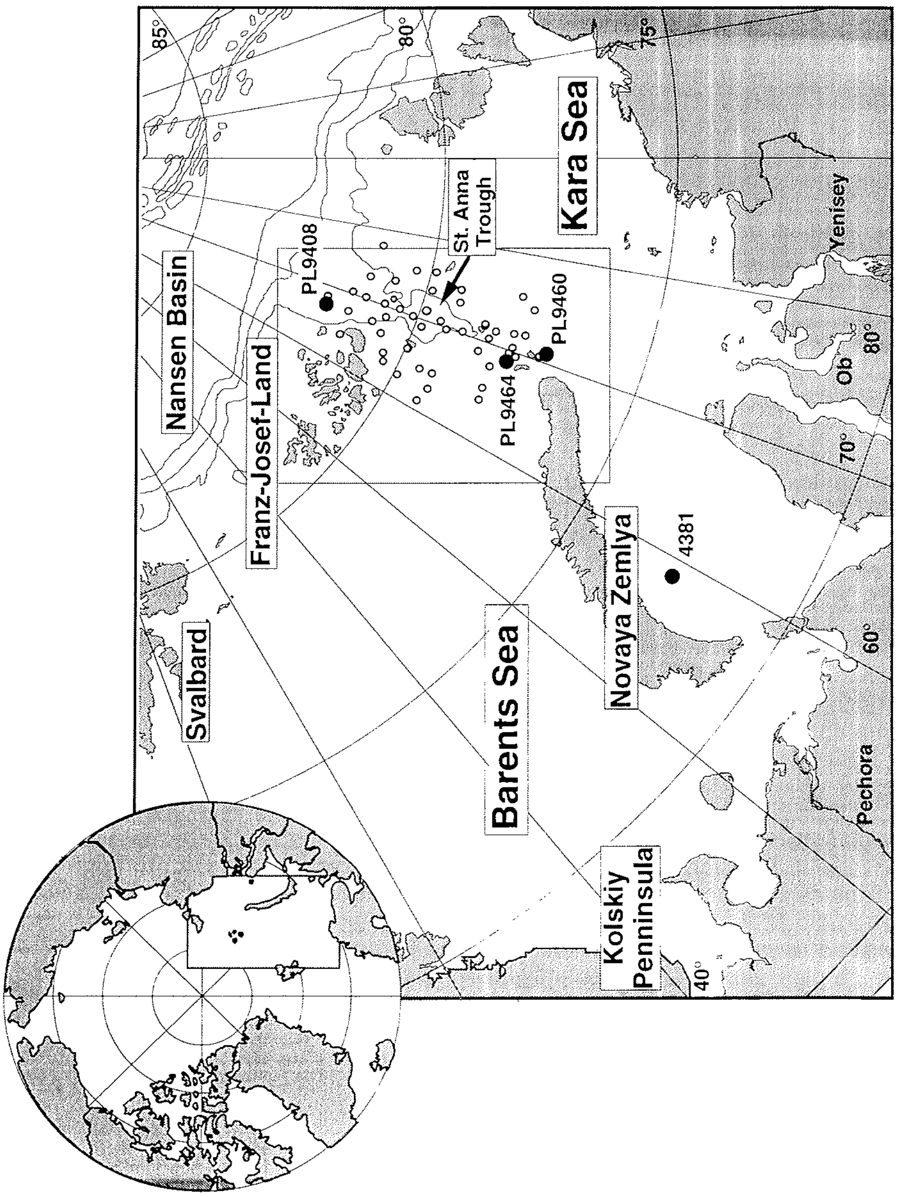

Fig. 1: Study area in the northern Kara Sea, St. Anna Trough, and location of surface sediment samples and investigated sediment cores.

In this report, we attempt (i) to determine the amount of organic carbon and (ii) to characterise the mechanisms controlling organic carbon deposition (i.e., surface-water productivity vs. terrigenous input). The investigations including determinations of total organic carbon contents, hydrogen index (HI) values, and carbon/nitrogen (C/N) ratios, were performed on surface-sediment samples and three selected sediment cores (Fig. 1). For more precise determinations of the marine and terrigenous proportions of the organic-carbon fraction, other more sophisticated methods such as kerogen/coal petrography and gas chromatography (GC) and gas chromatography/mass spectrometry (GC/MS) techniques are required (e.g., Prahl and Muehlhausen, 1989; for Arctic Ocean sediments see Schubert and Stein, 1997; Fahl and Stein, 1997, 1999; Boucsein et al., 1998; Knies and Stein, 1998; Knies et al., 1999; Stein et al., 1999) which are planned for future studies on Kara Sea material.

Material

During RV *Professor Logachev* Expedition 1994, surface sediments and long cores were recovered from the St. Anna Trough area in the northern Kara Sea. Within this study, all surface sediment samples taken during the expedition as well as three selected sediment cores were studied (Fig. 1).

Based on X-Ray radiographs, different lithological units can be distinguished in the investigated sediment cores. Core PL9408 consists of three lithological units: Unit III (bottom of core to about 120 cmbsf; massive diamicton with high amount of coarse-grained material), Unit II (120 - 32 cmbsf; alternation of homogeneous mud and laminated intervals; minor amounts of ice-rafted detritus; laminated intervals occur at 118-108, 55-59, and 42-32 cmbsf), and Unit I (32 cmbsf to top of core; bioturbated mud).

Core PL9460 also consists of the three lithological units: Unit III (bottom of core to 341 cmbsf; massive diamicton with high amounts of coarse-grained material), Unit II (341 - 318 cmbsf; laminated mud with ice-rafted detritus), and Unit I (318 cmbsf to top of core; bioturbated mud).

Core PL9464 only consists of one lithological (Unit I: bioturbated mud).

According to Polyak et al. (1997) who investigated and dated other nearby *Professor Logashev* sediment cores from the St. Anna Trough, an age of > 13.3 ka is inferred for the boundary between Unit III and II; the age of the UnitII/I boundary is approximately 10 ka.

Methods

Total carbon, nitrogen, and organic carbon were determined on ground bulk samples and carbonate-free sediment samples by means of a Heraeus CHN-analyser. The carbonate content was calculated as

$$CaCO_3 = (TC - TOC) * 8.333$$

where TC = total carbon and TOC = total organic carbon (both in wt% of the bulk sample). C/N ratios, as indicator for the composition of the organic carbon, were calculated as "total organic carbon / total nitrogen ratios". C/N ratios of marine organic matter (mainly phytoplankton and zooplankton) are around 6, whereas terrigenous organic matter (mainly from higher plants) has C/N ratios of > 15 (e.g., Bordowskiy, 1965; Scheffer and Schachtschabel, 1984).

In organic-carbon-rich (TOC > 0.5 %), immature sediments, Rock-Eval pyrolysis parameters (S2 peak, hydrogen and oxygen indices) are also useful indicators for the characterisation of the composition of the organic-carbon fraction (i.e., to estimate the amount of terrigenous and marine proportions) (e.g., Tissot and Welte, 1984; Stein, 1991). The pyrolysis was conducted out on bulk sediment samples to determine the amount of hydrocarbons already present in the sample (S1 peak in mg hydrocarbons per gram sediment), the amount of hydrocarbons generated by pyrolytic degradation of the kerogen during heating of up to 550°C (S2 peak in mg hydrocarbon per gram sediment), the amount of carbon dioxide generated during heating of up to 390 °C (S3 peak in mg carbon dioxide per gram sediment), and the temperature of maximum pyrolysis yield (Tmax value in °C) (Espitalié et al., 1977). The hydrogen index (HI) corresponds to the quantity of pyrolyzable hydrocarbons per gram TOC (mgHC/gC), the oxygen index (OI) corresponds to the quantity of carbon dioxide per gram TOC (mgCO_2/gC). In immature sediments, HI values of < 100 mgHC/gC are typical of terrigenous organic matter (kerogen type III), whereas HI values of 300 to 800 mgHC/gC are typical of marine organic matter (kerogen types I and II) (Tissot and Welte, 1984).

Results and Discussion

Modern organic carbon distribution

In the St. Anna Trough surface sediments, carbonate contents are very low (mostly < 2 % with a few exceptions of 2-8 %; Table 1). Total organic carbon (TOC) values vary between 0.6 and 2.2 % (Fig. 2, Table 1). The maximum values occur in the vicinity of Franz-Josef-Land, north of Novaya Zemlya, and in the central part of the trough. The minimum TOC values of < 0.75 % are obvious along the eastern margin of the St. Anna Trough. Hydrogen indices vary between about 60 and 190 mgHC/gC (Fig. 3; Table 1). The low hydrogen indices < 100 mgHC/gC were determined in samples from the northernmost part of the study area and north of Novaya Zemlya. The latter are corresponding to maximum TOC values. Most of the C/N ratios vary between 5 and 7 (Table 1). Southeast of Franz-Josef-Land, C/N ratios are higher reaching 8-12.

Table 1: Carbonate content, total organic carbon (TOC), Rock-Eval parameters (S1, S2, and S3 peaks, hydrogen and oxygen indices, Tmax values), and C/N ratios of St. Anna Trough surface sediments. For explanation of Rock-Eval parameters see text.

Sample		CaCO3	TOC%	S1	S2	S3	HI	OI	Tmax	C/N
PL 9401		0.8	1.01	0.33	1.23	1.11	122	110	534	5.9
PL 9402		0.0	1.40	0.39	1.9	1.27	136	91	535	6.6

Table 1 cont.

Sample		CaCO3	TOC%	S1	S2	S3	HI	OI	Tmax	C/N
PL 9403		0.0	1.35	0.08	1.02	1.59	76	118	433	12.1
PL 9404		0.3	1.51	0.2	2.39	0.76	158	50	509	8.8
PL 9405		1.0	1.02	0.33	1.24	4.14	122	406	549	5.6
PL 9407	D4	3.9	1.09	0.31	0.83	1.54	76	141	453	5.6
PL 9407		3.5	1.10	0.28	0.8	1.74	73	158	543	6.2
PL 9408		3.3	1.12	0.33	0.86	5.05	77	451	549	6.4
PL 9409	D4	0.0	1.61	0.4	2.15	1.66	134	103	536	6.7
PL 9409	KM	0.1	1.67	0.43	1.87	1.82	112	109	531	6.7
PL 9410		2.5	1.07	0.31	1.03	4.79	96	448	549	5.9
PL 9411	D4	1.1	1.15	0.4	1.6	1.38	139	120	540	6.2
PL 9412		1.4	1.15	0.45	1.66	4.2	144	365	548	5.8
PL 9413	KM	1.5	0.95	0.4	1.08	3.87	114	407	548	5.4
PL 9413	D4?	0.9	0.89	0.3	1.15	2.9	129	326	548	5.5
PL 9416	D4	1.1	0.92	0.11	0.61	1.73	66	188	428	5.8
PL 9416	KM	2.9	0.58	0.09	0.56	0.41	97	71	437	7
PL 9418	KM	2.2	1.17	0.41	1.83	4.72	156	403	546	6.1
PL 9419	KM	0.9	0.68	0.08	0.4	1.43	59	210	485	7.6
PL 9419	D4	0.0	0.76	0.1	0.21	1.75	28	230	445	7.7
PL 9420		1.5	1.44	0.55	1.55	5.7	108	396	547	6.2
PL 9422	KM	0.8	1.08	0.39	1.26	4.05	117	375	549	5.8
PL 9423		1.2	1.32	0.52	1.95	1.53	148	116	544	5.8
PL 9425	KM	1.9	0.63	0.24	0.9	3.25	143	516	548	4.5
PL 9426	D4	1.3	0.61	0.19	1.1	0.72	180	118	544	5
PL 9428		1.4	1.50	0.56	1.68	5.66	112	377	549	6.3
PL 9430		1.0	1.34	0.51	1.86	1.52	139	113	543	6.6
PL 9431	KM	0.8	1.12	0.36	1.42	4.44	127	396	548	5.9
PL 9432		8.0	1.48	0.59	1.55	5.56	105	376	546	2.6
PL 9433		0.0	0.64	0.26	1.05	3.19	164	498	549	6.6
PL 9435		1.4	0.66	0.2	1.05	2.45	159	371	547	5.4
PL 9437		0.4	1.19	0.34	1.66	4.24	139	356	547	6.3
PL 9438		0.0	1.29	0.4	1.7	4.12	132	319	548	6.6
PL 9439		1.0	1.23	0.36	2.24	1.22	182	99	530	5.7
PL 9440		1.0	1.02	0.31	1.93	1.19	189	117	517	6
PL 9441	KM	0.5	0.91	0.28	1.23	3.12	135	343	546	5.3
PL 9442	KM	0.4	1.41	0.5	1.95	4.23	138	300	546	6.5
PL 9444	KM	0.9	0.85	0.24	0.88	3.08	104	362	450	4.7
PL 9446		0.0	1.69	0.48	2.65	3.74	157	221	524	8.4
PL 9450		1.2	1.24	0.44	1.92	1.46	155	118	532	5.4
PL 9451		0.7	0.84	0.26	1.21	2.97	144	354	549	5.5
PL 9453		0.0	1.65	0.61	2.04	5.91	124	358	547	6.1
PL 9454		0.0	1.52	0.39	1.74	1.36	114	89	540	6.9
PL 9455		0.4	1.59	0.56	1.96	1.35	123	85	541	7.1
PL 9456		0.8	1.41	0.51	1.26	5.2	89	369	455	6.3
PL 9457		0.8	1.30	0.48	1.42	4.69	109	361	549	6.3
PL 9458		0.0	1.48	0.51	1.56	1.35	105	91	518	7.2
PL 9462		1.1	1.62	0.69	2.45	1.13	151	70	397	5.8
PL 9463		0.5	1.42	0.48	1.81	0.97	127	68	389	5.8
PL 9464		0.0	2.09	0.75	2.56	2.01	122	96	543	6.9
PL 9465		0.1	1.45	0.51	1.89	1.13	130	78	511	6.4
PL 9467		0.9	1.26	0.46	1.72	1.22	137	97	538	5.7
PL 9468		1.2	1.23	0.43	2.02	1.43	164	116	533	6.2
PL 9469		0.0	2.43	0.59	1.93	1.96	79	81	546	7.9

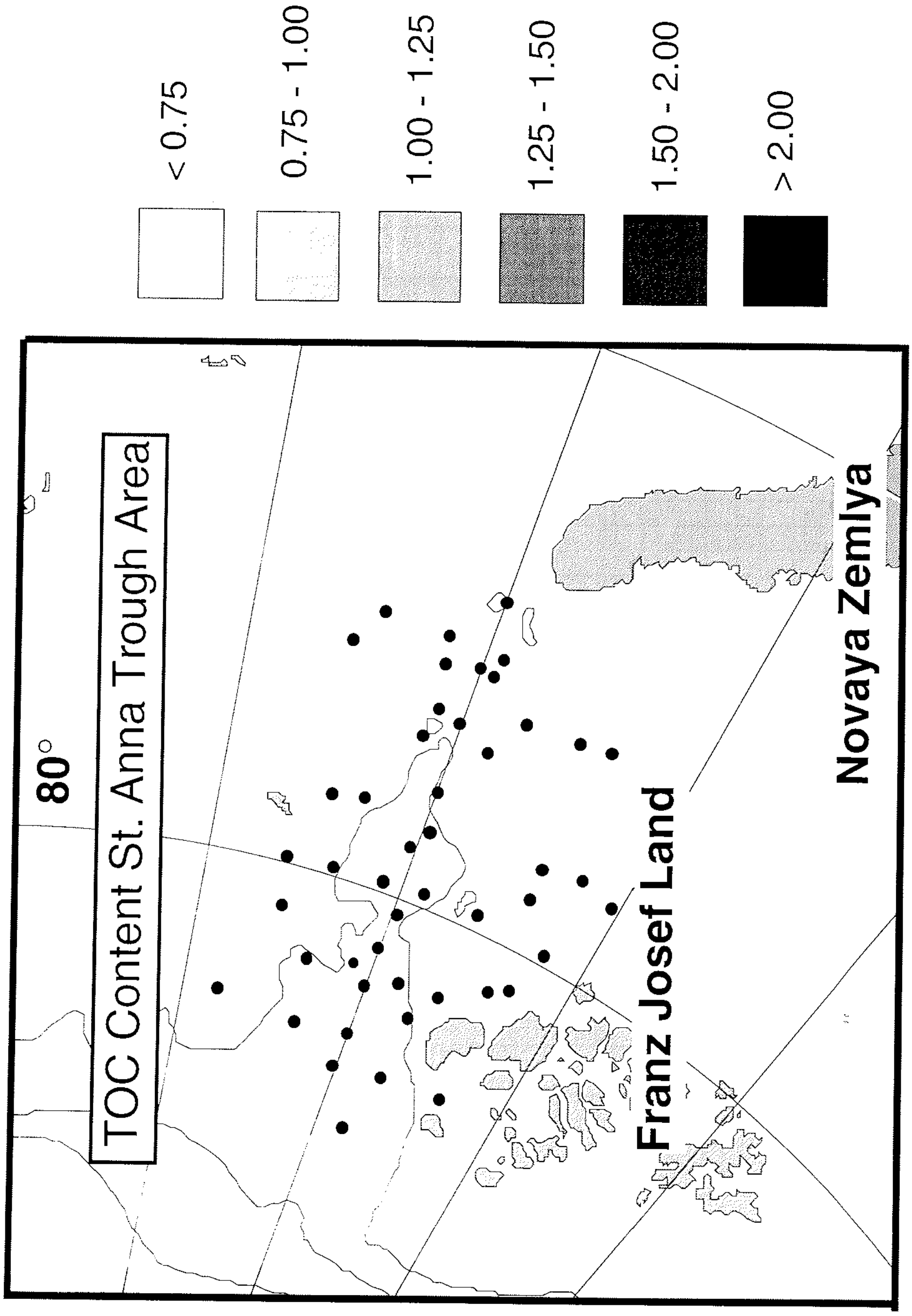

Fig. 2: Distribution of total organic carbon (TOC) in St. Anna Trough surface sediments.

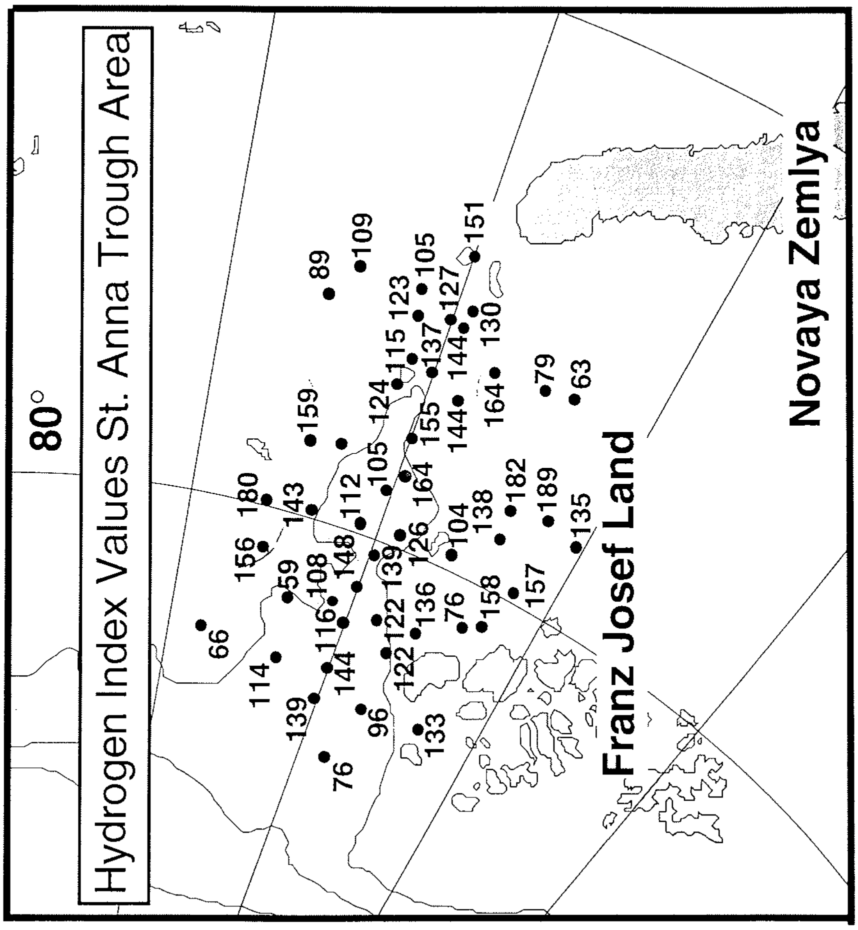

Fig. 3: Hydrogen index values (mgHC/gC) in St. Anna Trough surface sediments.

Hydrogen indices most of them varying between about 100 and 200 mgHC/gC, suggest a dominance of terrigenous organic matter (Figs. 3 and 4) with, however, significant amount of marine organic matter being preserved in the surface sediments. River-derived terrigenous organic material from the Siberian hinterland probably contribute in major proportions to the organic carbon content in the sediments of the Kara Sea/St. Anna Trough area. This is also supported by similar data from the inner Kara Sea and the Ob/Yenesei estuaries (Stein, 1996; Boucsein et al., 1998). In addition, Franz-Josef-Land and Novaya Zemlya are important source areas for terrigenous organic matter deposited west and southwest of the St.-Anna Trough area, as indicated by increased TOC values, some lower hydrogen indices, and higher C/N ratios (Figs. 2 and 3; Table 1). In the central St. Anna Trough, a couple of samples with high TOC values and C/N ratios of about 6 also show relatively high biogenic opal values of 3 - 5 % (Nürnberg, 1996) which may suggest some increased surface-water productivity. This first interpretation of the bulk organic carbon data has to be proved, however, by other techniques (kerogen microscopy, GC, and GC/MS data).

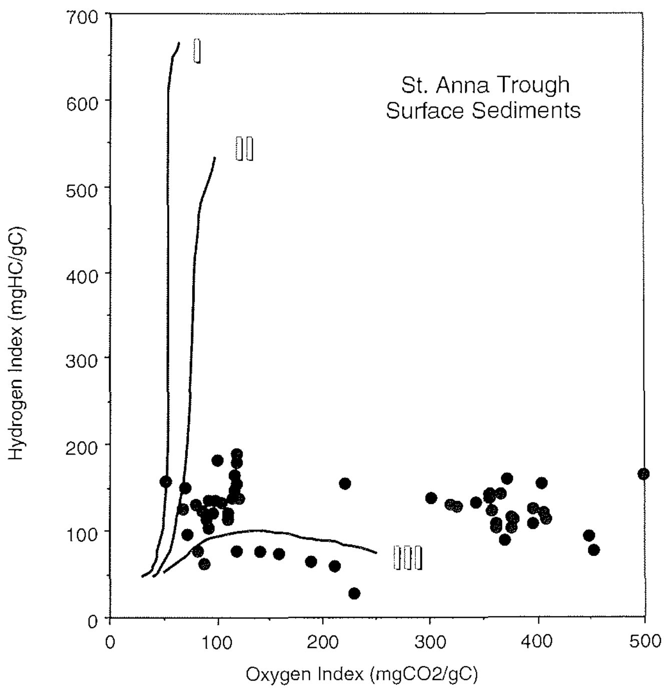

Fig. 4: Hydrogen index versus oxygen index ("van–Krevelen–type") diagram of St Anna Trough surface sediments. Roman numbers mark different kerogen types: I and II marine, III terrigenous organic matter (classification after Espitalié et al., 1977; Peters, 1986).

Late Quaternary organic carbon records

TOC, carbonate, C/N, as well as hydrogen index values determined in the sediments of cores PL9408, PL9460, and PL9464 are presented in Figures 5 to 7 as well as in Tables 2 to 4.

At Core PL9408, carbonate contents are generally very low (< 2.5 %); two single peaks with values of 4.2 % and 4.5 % occur at 160 and 85 cmbsf, respectively (Fig. 5). According to the organic carbon records, the sedimentary sequence of Core PL9408 can be divided into two intervals (Fig. 5). Below 120 cmbsf (Unit III), TOC values vary between 1.1 and 1.7 %, whereas the upper part (Units II and I) is characterised by TOC values between 0.4 and 0.9 %. The uppermost (surface) sediment sample display again a high value of 1.3 %. Furthermore, the lower interval shows minimum hydrogen index values of < 60 mgHC/gC and C/N ratios > 10. Increased hydrogen index reach values > 100 mgHC/gC occur between 85 and 65 cmbsf (middle part of Unit II) and in the uppermost Unit I. The absolute hydrogen maximum of 233 mgHC/gC occurs at 85 cmbsf, coinciding with the carbonate maximum of 4.5% (Fig. 5). In Unit II and Unit I, C/N ratios are mostly < 7.

Table 2: Carbonate content, total organic carbon (TOC), Rock-Eval parameters (S1, S2, and S3 peaks, hydrogen and oxygen indices, Tmax values), and C/N ratios of Core PL9408 sediments. For explanation of Rock-Eval parameters see text.

Depth cmbsf	CaCO3	TOC %	S1	S2	S3	HI	OI	Tmax	C/N
0	2.25	1.27	0.3	1.05	6.61	83	521	444	6.61
10	1.03	0.78	0.19	0.91	4.8	116	614	536	5.04
20	0.28	0.67	0.16	0.9	4.31	134	639	543	5.07
25	0.69	0.50	0.1	0.64	3.51	129	705	546	3.89
30	0.94	0.59	0.12	0.9	3.2	153	545	433	4.85
35	0.55	0.67	0.12	0.87	2.86	129	425	546	5.47
40	0.39	0.70	0.12	0.66	2.34	95	336	547	5.72
45	0.32	0.57	0.1	0.48	1.91	84	334	537	4.73
54	0.79	0.42	0.02	0.3	1.53	71	364	544	4.84
56	0.83	0.55	0.01	0.38	2.1	69	381	546	6.13
60	0.86	0.89	0.02	0.47	1.13	53	127	429	9.01
65	1.45	0.61	0.05	0.77	2.66	126	436	517	5.65
75	0.26	0.64	0.09	0.62	1.77	97	277	535	6.58
85	4.46	0.25	0.1	0.58	1.75	233	705	546	2.34
95	0.45	0.85	0.1	0.48	2.99	57	353	423	7.36
100	0.33	0.74	0.04	0.43	2.12	58	286	448	6.28
110	0.51	0.80	0.01	0.42	1.63	53	205		7.37
118	2.35	0.78	0	0.47	3.98	60	508	437	8.51
120	1.08	1.26	0.01	0.53	4.97	42	395	432	11.34
130	2.56	1.32	0.02	0.6	6.87	45	521	430	10.47
140	0.72	1.69	0.02	0.72	4.02	43	238	428	11.48
150	1.80	1.48	0.02	0.63	4.94	43	334	427	13.22
160	4.21	1.13	0.02	0.59	4.04	52	357	428	10.10
170	1.78	1.61	0.02	0.66	4.17	41	260	428	13.38
180	1.87	1.57	0.03	0.88	4.12	56	262	426	13.69

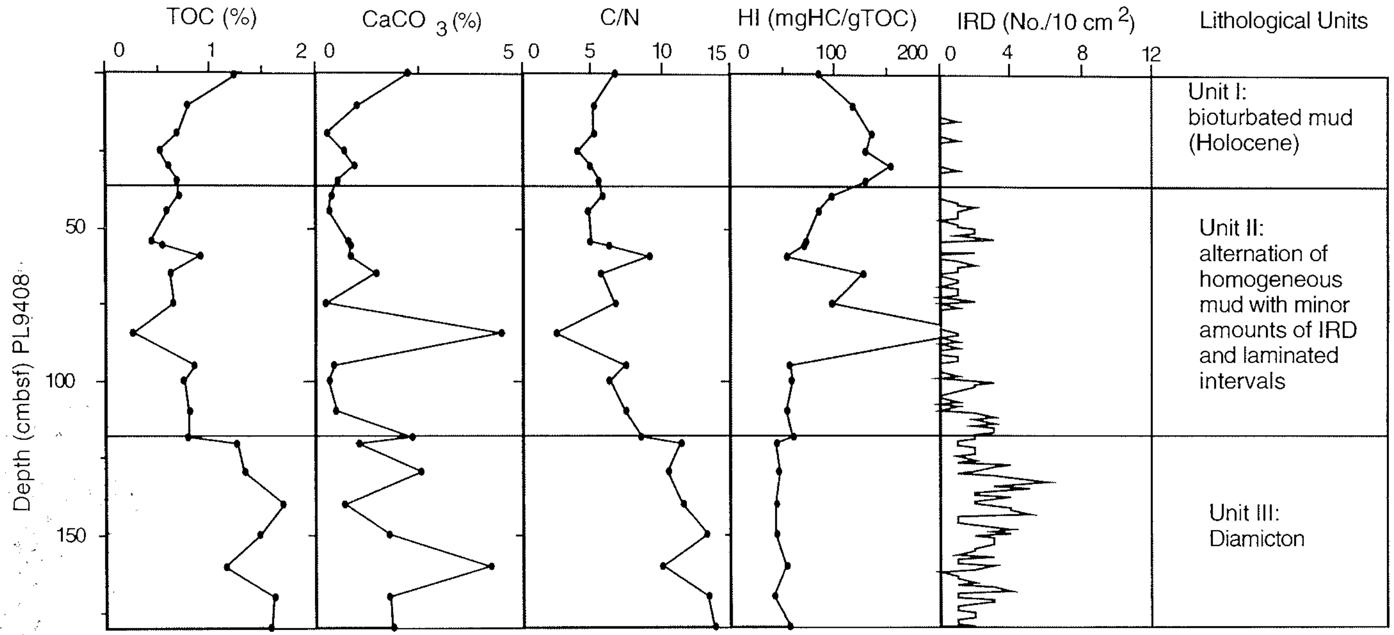

Fig. 5: Total organic carbon (TOC) content, carbonate content, total carbon/total nitrogen (C/N) ratios, hydrogen index values, amount of ice-rafted (IRD), and lithological units of the sedimentary sequence of Core PL9408.

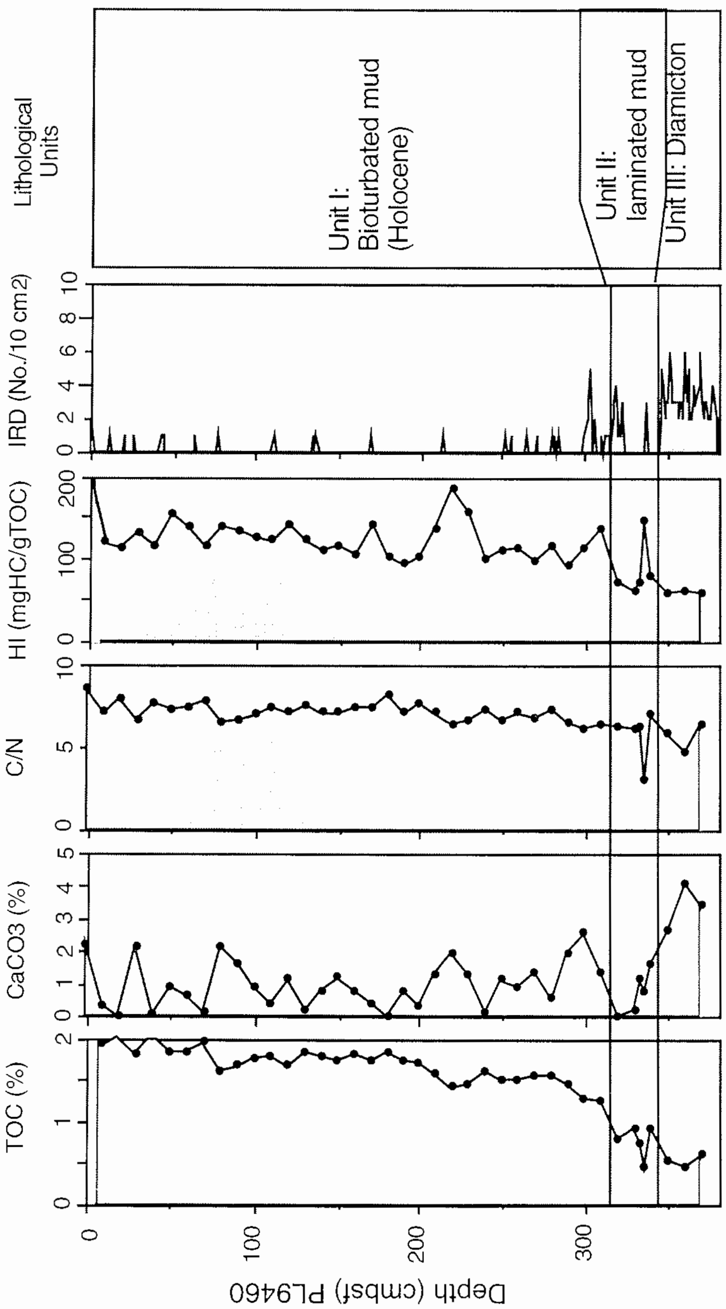

Fig. 6: Total organic carbon (TOC) content, carbonate content, total carbon/total nitrogen (C/N) ratios, hydrogen index values, amount of ice-rafted (IRD), and lithological units of the sedimentary sequence of Core PL9460.

Table 3: Carbonate content, total organic carbon (TOC), Rock-Eval parameters (S1, S2, and S3 peaks, hydrogen and oxygen indices, Tmax values), and C/N ratios of Core PL9460 sediments. For explanation of Rock-Eval parameters see text.

Depth (cmbsf)	CaCO3	TOC %	S1	S2	S3	HI	OI	Tmax	C/N
0	2.23	2.32	2.07	6.54	2.29	282	99	425	8.61
10	0.34	1.95	0.67	2.32	2.09	119	107	410	7.10
20	0.00	2.04	0.59	2.34	2.05	115	100	412	7.95
30	2.17	1.83	0.63	2.43	2.15	133	117	412	6.71
40	0.07	2.06	0.6	2.43	2.23	118	108	400	7.65
50	0.90	1.85	0.69	2.86	1.75	155	95	411	7.33
60	0.63	1.86	0.68	2.59	1.73	139	93	406	7.45
70	0.15	1.98	0.75	2.31	1.94	117	98	404	7.80
80	2.12	1.63	0.56	2.27	1.73	139	106	413	6.62
90	1.66	1.69	0.55	2.27	1.68	134	99	413	6.75
100	0.93	1.78	0.5	2.23	1.71	125	96	409	7.06
110	0.41	1.80	0.5	2.23	1.71	124	95	409	7.38
120	1.11	1.69	0.53	2.39	1.62	142	96	408	7.11
130	0.19	1.86	0.62	2.27	1.61	122	86	403	7.60
140	0.75	1.80	0.52	2.01	1.74	112	97	401	7.18
150	1.23	1.73	0.49	2	1.75	116	101	410	7.10
160	0.82	1.82	0.48	1.93	1.81	106	99	404	7.37
170	0.41	1.74	0.62	2.48	1.5	142	86	408	7.41
180	0.00	1.85	0.85	1.92	2.88	104	156	400	8.24
190	0.75	1.74	0.43	1.62	1.9	93	109	405	7.17
200	0.34	1.71	0.65	1.75	2.88	102	168	392	7.71
210	1.27	1.61	0.72	2.19	3.01	136	188	409	7.20
220	1.90	1.44	0.54	2.66	2.77	185	193	374	6.49
230	1.31	1.47	0.4	2.31	2.76	157	187	478	6.72
240	0.14	1.64	0.34	1.66	1.52	101	93	406	7.27
250	1.11	1.50	0.34	1.65	1.58	110	105	402	6.78
260	0.96	1.52	0.37	1.75	1.52	115	100	403	7.13
270	1.37	1.56	0.32	1.53	1.81	98	116	396	6.83
280	0.60	1.56	0.5	1.85	1.5	118	96	392	7.28
290	1.93	1.46	0.35	1.34	3.07	92	210	403	6.52
300	2.58	1.28	0.36	1.47	2.64	115	207	413	6.11
310	1.36	1.25	0.33	1.71	2.35	136	187	484	6.43
320	0.00	0.81	0.09	0.57	0.69	70	85	539	6.29
330	0.21	0.91	0.05	0.57	0.82	63	91	537	6.20
333	1.16	0.75	0.06	0.53	1.05	71	140	533	6.30
336	0.77	0.46	0.04	0.66	0.54	145	119	513	3.06
340	1.61	0.90	0.09	0.73	1.08	81	120	446	6.96
350	2.62	0.53	0.02	0.32	1.38	60	259	427	5.80
360	4.06	0.45	0.02	0.28	1.48	62	327	429	4.77
370	3.46	0.60	0.03	0.37	1.51	61	250	419	6.36

At Core PL9460, carbonate contents are also very low (< 2.5 %). Only in the lowermost part of the sedimentary sequence (Unit III) some higher values of about 4 % occur (Fig. 6). TOC values are lowest in Unit III (< 0.6 %), increasing up to 0.9 % in Unit II, and reaching maximum values of 1.3 to 2.3 % in Unit I (Fig. 6). In the two lower units, hydrogen index values are generally < 80 mgHC/gC, whereas in Unit I values of 100 to 150 mgHC/gC are typical (Fig. 6). Maximum hydrogen index values occur at 220 and 0 cmbsf (185 and 282 mgHC/gC, respectively). C/N ratios are relatively constant thoughout the entire sedimentary sequence (5 to 8).

At Core PL9464, carbonate values are < 2 %. TOC contents are high and relatively constant thoughout the entire section (1.3 - 2 %). Hydrogen index values and C/N ratios vary between 50 and 130 mgHC/gC and 6 and 10, respectively (Fig. 7).

The occurrence of a glacigenic diamicton in the St. Anna Trough (Unit III) provides evidence that grounded ice extended to the shelf edge in this area during the last glacial maximum (Polayak et al., 1997). In the northern St. Anna Trough (Core PL9408), the diamicton is composed of sediments rich in terrigenous organic carbon as indicated by high TOC values, low hydrogen indices, and high C/N ratios (Fig. 5). This composition is common for diamictons in the Barents Sea and related to redeposition of Mesozoic bedrocks and/or a Franz Josef Land source (Elverhoi et al., 1989; Polyak and Solheim, 1994; Polyak et al., 1997). The diamicton at the southern Core PL9460 has significantly lower TOC values suggesting a different (Novaya Zemlya?) source area. According to AMS ^{14}C datings from the overlying deglacial sediments of Unit II, Polyak et al (1997) postulate a minimum age for the retreat of grounded ice from the central deep St. Anna Trough of 13.3 ka. During this interval (i.e., middle part of Unit II), high hydrogen idex values and low C/N ratios in the record of Core PL9408 suggest increased amounts of marine organic carbon being deposited at the sea floor. This may be related to a first postglacial inflow of warm Atlantic water resulting in seasonally ice-free conditions and increased surface-water productivity (cf. Knies and Stein, 1998, and further references therein). Since about 10 ka, modern full marine conditions influenced by Atlantic-water inflow were established as indicated by the deposition of terrigenous organic matter with a significant proportion of marine organic matter being preserved in the sedimentary records of all three investigated cores (Unit I, Figs. 5 to 7).

Table 4: Carbonate content, total organic carbon (TOC), Rock-Eval parameters (S1, S2, and S3 peaks, hydrogen and oxygen indices, Tmax values), and C/N ratios of Core PL9464 sediments. For explanation of Rock-Eval parameters see text.

Depth (cmbsf)	CaCO3	TOC %	S1	S2	S3	HI	OI	Tmax	C/N
10	0.81	1.78	0.68	2.08	2.31	117	130	393	7.84
20	1.11	1.73	0.65	2.34	1.94	135	112	408	7.74
26	0.00	1.95	0.48	1.84	2.39	95	123	394	8.50
30	0.88	1.66	0.42	1.59	2.78	96	167	371	7.70
40	0.33	1.84	0.49	1.8	2.19	98	119	406	8.24
50	0.14	1.84	0.44	1.57	2.33	85	127	390	8.14
60	0.24	1.85	0.46	1.66	2.28	90	123	388	8.39

Table 4 cont.

Depth (cmbsf)	CaCO3	TOC %	S1	S2	S3	HI	OI	Tmax	C/N
70	0.00	2.00	0.44	1.47	2.16	74	108	398	9.69
80	0.57	1.73	0.57	1.5	4.34	86	250	391	8.42
90	0.57	1.64	0.56	1.37	3.86	83	235	397	8.42
100	1.88	1.86	0.48	2.46	4.95	132	266	440	8.99
110	0.33	1.74	0.54	1.37	4.18	79	241	403	8.72
120	0.16	1.81	0.56	1.48	4.23	82	234	406	8.83
130	0.00	1.80	0.49	1.17	4.59	65	255	393	8.73
140	0.00	2.02	0.6	1.63	4.08	81	202	416	10.02
150	0.96	1.61	0.59	2.01	3.48	125	217	413	8.63
160	1.64	1.58	0.44	1.47	4.01	93	254	401	8.20
170	0.55	1.69	0.45	1.36	4.18	80	247	401	9.05
180	0.02	1.75	0.48	1.42	3.95	81	226	417	9.94
190	0.00	1.64	0.37	1.02	4.3	62	263	394	7.31
200	1.11	1.44	0.36	0.94	4	65	277	396	8.24
210	1.54	1.28	0.39	1.36	3.87	106	302	524	7.91
220	1.12	1.43	0.28	1.16	4.01	81	279	501	5.93
230	0.62	1.44	0.27	1.02	3.83	71	265		6.50
240	0.00	1.52	0.29	0.99	3.92	65	259	500	7.77
250	0.53	1.50	0.3	1.24	4.41	83	293	460	6.65
260	0.04	1.61	0.31	1.2	4.62	75	288	542	7.14
270	0.36	1.45	0.27	1.06	4.22	73	291	547	6.37
280	0.01	1.33	0.25	0.78	4	58	300		6.91
290	2.34	1.32	0.26	0.85	4.1	64	311	471	6.31
300	0.16	1.34	0.23	0.71	4.14	53	308	396	6.93
310	0.00	1.44	0.27	0.73	3.89	51	271	403	6.65
320	0.62	1.48	0.27	0.89	4.03	60	271	402	6.43
330	0.00	1.49	0.23	0.72	4.25	48	285	403	8.24
340	1.24	1.39	0.25	0.74	4.55	53	326	408	6.31
350	0.00	1.49	0.23	0.71	4.54	48	305	401	7.88
360	0.10	1.43	0.23	0.8	4.25	56	298	485	7.03
370	0.00	1.37	0.2	0.63	4.09	46	298	440	7.72

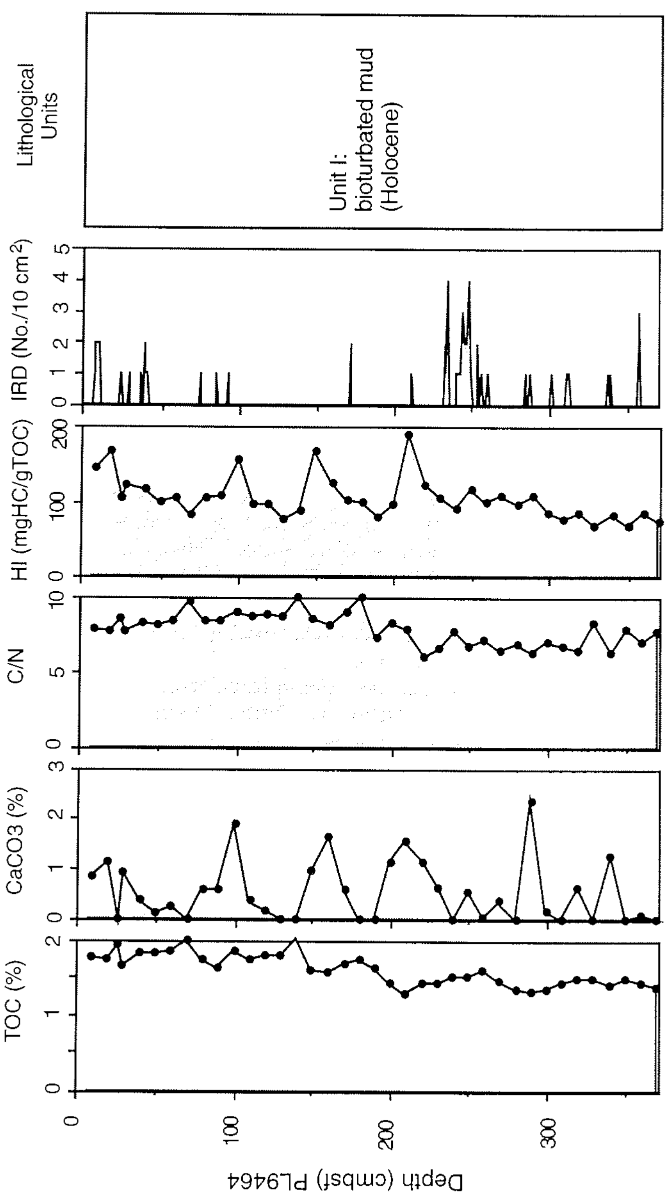

Fig. 7: Total organic carbon (TOC) content, carbonate content, total carbon/total nitrogen (C/N) ratios, hydrogen index values, amount of ice-rafted (IRD), and lithological units of the sedimentary sequence of Core PL9464.

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