ARCTIC PALEOCEANOGRAPHY - QUO VADIS?

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Introduction: The new Arctic Challenge

Not counting the geographic exploration of the Arctic coast lines by fishermen, commercial traders and a few explorers it is only little more than 100 years ago that systematic investigations of the natural properties of the Arctic Ocean began. It was the German Carl Koldewey who sailed to Fram Strait in 1868 to study the nature of the ice margin, and he was followed by the famous Norwegian Fridtjof Nansen who drifted 1893-1895 (Nansen, 1904) along with the central eastern Arctic Transpolar Drift - on his newly built polar research vessel FRAM - in his attempt to reach the North Pole (Fig. 1). Both men and their crews were driven by the desire to understand the special oceanographic properties of the Arctic Oceans as well as the climatic variability and significance of the Arctic sea ice and its distribution. The motive of modern Arctic research is much the same as more than 100 years ago, but part of our tools and approaches have been improved over the past 100 years in such a way that we stand a much greater chance to succeed than these scientific pioneers.

One of the most important challenges for modern societies is a scientifically based and quantitative attempt to forecast the properties of the global environment in the foreseeable future, in particular since we have learned mainly from geological studies that frequent, fast and dramatic changes of global impact can occur (Bond et al., 1993). We have to assume that a "Greenhouse" effect will lead to a severe perturbation of the natural climate variability in the hundred years to come. One is therefore searching for tools for the early detection of such changes and the Arctic Ocean environment may well be a most suitable one, because
1) its sea ice cover is one of the most sensitive expressions of the modern climate regime, its extreme seasonal fluctuations being a good indicator of its potential instability,
2) through the fresh water influx and the wide permafrost regions it interacts with the wide continental hinterlands both in Eurasia and North America;
3) heat exchange between the Arctic and the North Atlantic oceans controls the NW European climate and on historic time scales is known to fluctuate intensively; and
4) changes in the Arctic may affect the "salt converyor belt" (Broecker, 1994) and thus have an impact on the properties of the entire world ocean.

Time is ripe for some major advances of our understanding of the oceanography of the Arctic Ocean and of its history. This fact is closely tied to some developments over the past years:
1.This book bears witness of the political changes in the countries of the former Soviet Union; relevant Russian institutions are getting increasingly involved in the international exploration of the Arctic. They have accumulated a tremendous experience in Arctic research (Gordijenko, 1967) and are

making their resources, in terms of manpower, technical facilities and data available to the international scientific community.

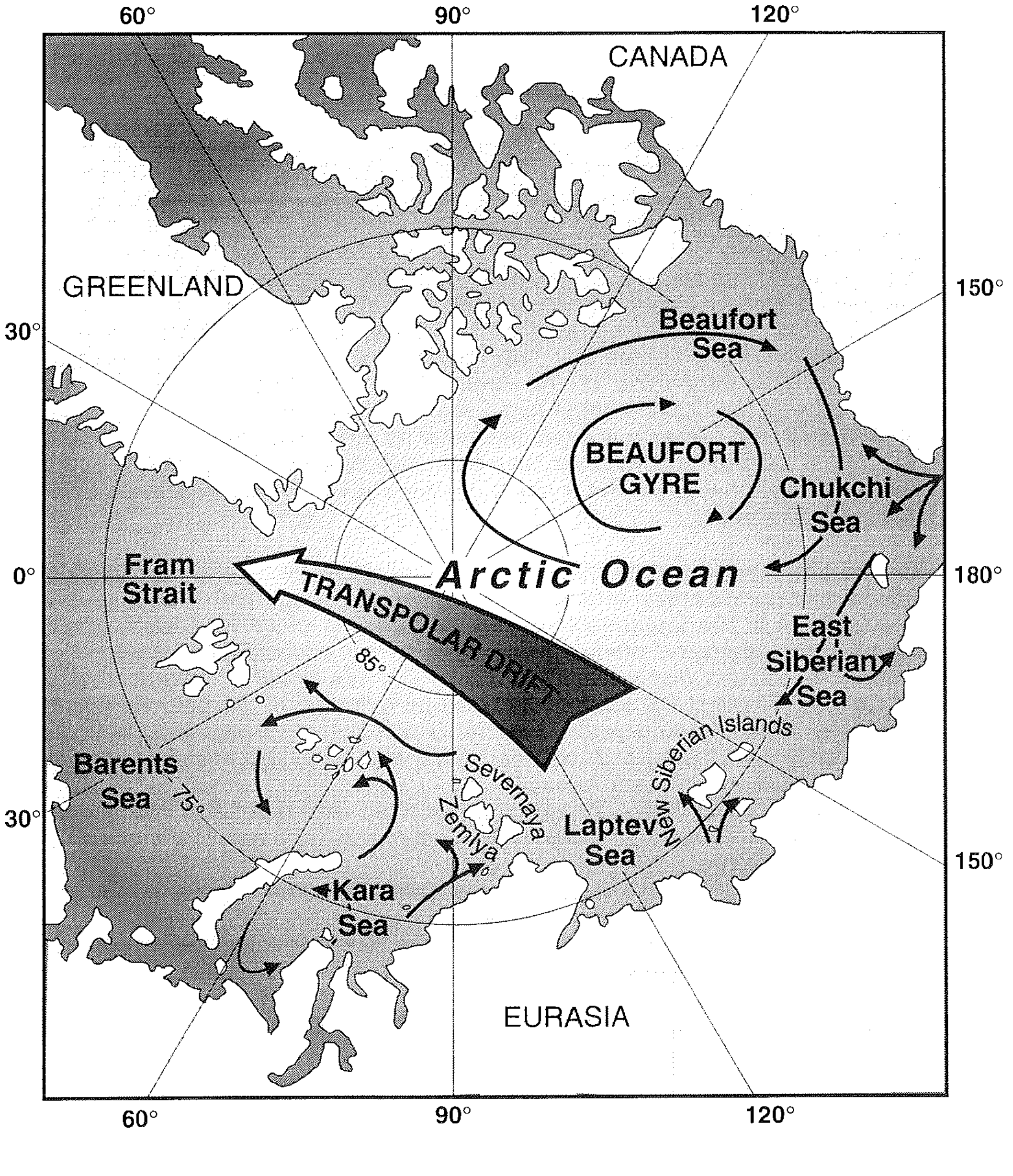

Fig. 1.: Schematic description of the major elements of the circulation patterns of the Arctic sea ice cover (from Kassens et al., 1995).

2. Russia controls a dominant segment of the Eurasian shelf seas which are the largest shelf seas on earth. After these areas were virtually closed to international exploration for a number of decades, they are now increasingly opening up for exploratory scientific work.
3. Shortly before the opening of the Eurasian shelf seas, renewed interest both in North America and in Europe have resulted in a number of major efforts to explore the interior of the Arctic Ocean based on state-of-the-art instrumentation and approach (Gudmandsen, 1980). After the preludes on the Swedish YMER 80-expedition (Schytt et al., 1981) and the German POLARSTERN's first deep penetration into the eastern Arctic (Thiede, 1988) the Swedish ODEN and POLARSTERN as the first conventionally driven research ice breakers jointly succeeded to reach the North Pole (Anderson et al., 1991; Fütterer, 1992); both ships entered the Arctic Ocean from the NW European Barents Sea. In 1994 the US American POLAR SEAS and the Canadian LOUIS ST. LAURENT crossed the Arctic via the North Pole along their transect from the Bering to the Fram Straits (Aagaard et al., 1996) collecting en route important geologic and oceanographic data and samples. Arctic sea floor sampling is still difficult, but close to be routine provided the availability of suited ships.

These new developments allow for the first time to consider the entire Arctic Ocean including its deep-sea basins and shallow rim areas, both as individual entities and as systems responding to each other. Even though Arctic research is and will be expensive, new avenues for understanding this important compartiment of the global environment which was lagging behind the other oceans in terms of basic and advanced oceanographic knowledge, are opening up, representing a real (grand) challenge for those countries who have a scientific interest in the area.

The Arctic per se also represents one of the most extreme environments on earth, with some very practical consequences. Its increasing use and exploitation require a deep understanding of some of its basic natural properties. Russia is presently developing the Northern Sea Route (Brigham, 1991) requiring long-term forecasts of the ice cover in the Eurasian shelf seas. The Arctic continental margins are known to host large quantities of fossil hydrocarbons, whose exploration and exploitation require special insight into permafrost phenomena and the processes controlling formation and stability of clathrates (Kvenvolden, 1995). If these problems are approached unprudently, enormous damage may arise reaching in its consequences far beyond the local or regional environment which is directly affected. In the next chapters an attempt will be made to define a number of scientific goals where Arctic paleoceanographic studies can make a contribution of particular significance.

The Arctic Ocean as a Monitor of Global Change

Modern society is using our globe at an ever increasing pace, mostly without being concerned about the consequences for future generations. A debate about the possible onset of a "greenhouse effect" has arisen only lately, but satellite based monitoring of changes of the extent and movement of the Arctic sea ice cover (Colony, in press), of its thickness (Wadhams, 1990, Johannessen et al., 1995), as well as of the stability of terrestrial ice sheets

(Andersen and Borns, 1994) has been used to address this problem. A Russian compilation of changes of the sea ice cover during this century (Abramov, 1994) suggests a close correspondence between the sea ice extent and the global mean temperature; this conclusion is supported by Wadhams (1990) data on Arctic sea ice thickness which have been collected from submarines and which suggest a considerable thinning over the past decades.

Sea ice distributions will be continuously monitored in the years to come, and particular emphasis will be paid to seasonally rapidly moving fringes of the sea ice margins. Lately, large sediment concentrations have been observed first in the segment of the Transpolar Drift crossed by the transects from Svalbard to the North Pole where relatively old sea ice is found (Wollenburg, 1993, Pfirman et al., 1990), later also in the area of sea ice formation in the Eurasian shelf seas. Sediment concentrations in sea ice are changing albedo and a long-term monitoring program in the Laptev Sea presently tries to establish the potential variability and climatic significance of the processes of sea ice formation with sediment entrainment (Kassens et al., 1995). The Eurasian marginal seas usually freeze during late September, early October, while during 1995 large tracts of the central Laptev Sea remained ice free with cold surface waters in 7-15 m water depth being underlain by a previously unobserved, +2-+4°C warm subsurface water layers of unknown origin (TRANSDRIFT III Shipboard Scientific Party, in prep.).

Contributions to scientifically based forecasts of the potential change of the global environment will remain for some time one of the major challenges for Arctic research, but we have now taken the first steps to reach one of the prerequisites by establishing a certain basic understanding of the synoptic state of the Arctic oceanography, of its short-term changes as expressed in hydrographic data and of its ability to leave a signal resulting from long-term trends preserved in sea-floor sediments.

The oceanography of the Arctic deep sea has recently - based on measurements from the above listed modern expeditions - been described in a series of papers (Schlosser et al., 1991, Bönisch and Schlosser, 1995). The distribution of the stable light oxygen isotopes in the Arctic surface waters (Bauch et al., 1995) reflect a particularly interesting pattern because they allow to trace the influx of Atlantic and Pacific waters into the Arctic and the interaction of the Arctic Ocean waters with the fresh water influx from the surrounding continents, and because they can be traced through plankton remains in ocean floor sediments. Distributions of the shell material of planktonic foraminifers living in a hitherto poorly defined interval of the upper water column (Carstens and Wefer, 1992), but surprisingly found throughout the Arctic Ocean even under thick sea ice, and their oxygen isotope ratios have recently been mapped (Fig. 2, from Spielhagen and Erlenkeuser, 1994), illustrating the close correspondence of the distributional patterns of the oxygen isotope ratios to surface-water salinities.

Parallel to the advance in oceanography, geoscientific investigations are establishing ocean wide distribution patterns of a number of paleoceanographic proxies (cf. Fig. 2). Beside biogenic remains, terrigenic sediment components such as various minerals allow to identify the long-term and average importance of source regions on the surrounding continents.

Most of the major river systems draining into the Arctic Ocean carry their individual signal in the mineralogy of suspended materials (Wahsner, 1995) which can then be mapped out in its distributional pattern providing a tool to trace the history of these rivers back in time. Sediment accumulations in the marginal seas are known to accumulate fast as compared to the central Arctic Ocean and will provide detailed records of changes.

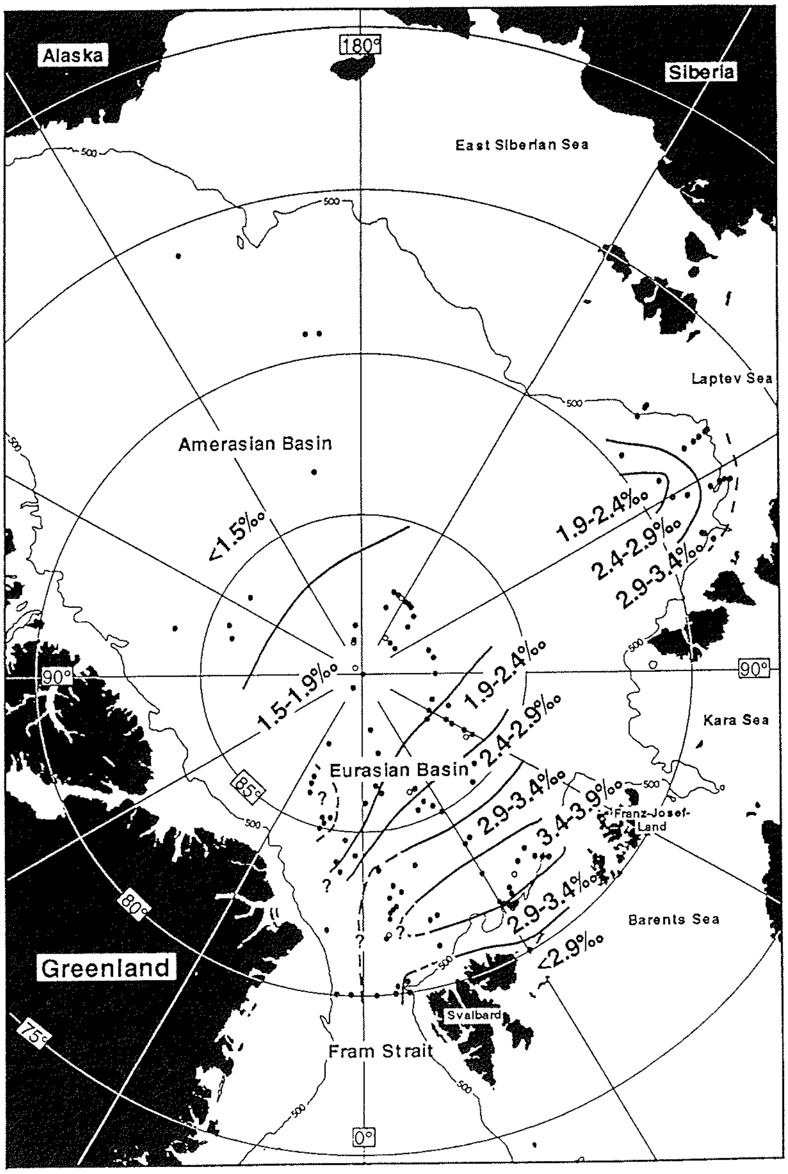

Fig. 2.: Distribution patterns of delta $\partial^{18}O$ isotope ratios in planktonic foraminiferal shell material from surface sediments of the Arctic Ocean (after Spielhagen and Erlenkeuser, 1994).

These ecclectic points selected to address the modern Arctic Ocean and its potential to monitor global change are by no means complete or even representative of the important advances to understand the modern Arctic and the processes controlling its major natural properties. However, they offer a hint that this extremely "Mediterranean" sea whose exploration has been lagging behind the other ocean basins, offers countless challenging new research possibilities in the years to come, and that modern society has the means to do so if the political climate in the circum-Arctic countries stays stable. In addition to much of the detail of the above described properties of the Arctic Ocean major open questions concern the nature and mode of sea ice formation, of the Atlantic influx and its overlying waters, of renewal of the Arctic deep water masses, of the ocean and sea-floor chemistry with respect to its organic carbon (Stein et al., this vol.) and carbonate budgets, of the distributional patterns and life strategies of the endemic plankton and nekton of a low productivity ocean (Nürnberg, this vol.; Stein et al., this vol.), to name a few.

The Chance of Arctic Paleoceanography

The renewed interest in the Arctic Ocean and the novel technical possibilities to visit and sample the areas under the permanent sea ice cover allow to advance in geoscientific problems, too. Even though important for Arctic paleoceanography, the plate tectonic origin of the Arctic deep-sea basins (Lawver et al., 1990) and the particular interesting phenomena of the modern boundary between the Eurasian and North American-Greenland plates will not be considered here. New stratigraphic methods (Eisenhauer et al., 1994), new facilities to obtain ultralong cores (IMAGES, 1994) and to drill the Arctic deep-sea floors (Myhre, Thiede, Firth et al., 1995) as well as to extend the regional core coverage over the entire Arctic permit a new Arctic paleoceanography. The shallow shelf seas around the Arctic rim, however, remain extraordinarily poorly studied at the present time. For the purpose of this book I have chosen to highlight 3 problems, namely the questions of onset of northern hemisphere glaciation, of long- and short-term variability of the ice covers, and the regional patterns of circulation during the last glacial maximum. It is also clear in this perspective that many of the questions which could be posed have to remain open at the present time.

Paleoceanography of the Pre-Glacial Arctic Ocean

The few available fragments of stratigraphic sections representing a pre-glacial depositional environment (Cretaceous to Paleogene in age) represent an Arctic Ocean which was fully marine, but whose gateways to the world ocean are poorly known. The microfossil evidence points to temperate, possibly relatively warm surface waters which were highly productive resulting in the deposition of siliceous oozes (Thiede and NAD Sci. Comm., 1992). The laminated nature of these sediments as well as the occasional occurrence of sapropels (Clark, 1988) points to poorly ventilated bottom waters and henceforth a stable stratification of the water column. As far as the plate tectonic evolution has been resolved (Lawver et al., 1990), prior to the Neogene the Arctic Ocean consisted probably of a series of deep-sea basins separated from each other by the Alpha-Mendeleev and Lomonosov ridges, but with no deep water connection to the adjacent Pacific and North Atlantic Ocean. It must also have had a relatively stable permanent stratification of the water column which did not permit the deep waters to be renewed. To establish and model patterns and modes of the pre-glacial Arctic oceanography (cf. Clark, 1988) is one of the exciting challenges of the future and requires intense sampling efforts of Mesozoic and Paleogene to lower Neogene sediments on the structural highs which are sufficiently old (mainly Lomonosov Ridge, Alpha-Mendeleev Ridge, Chukchi Plateau, Morris Jesup Rise, Yermak Plateau) and which can be expected to be covered by such deposits. Such sampling will be attempted from the Swedish icebreaker ODEN during summer 1996 (Kristoffersen and Backman, pers. comm.).

Onset of Cenozoic Northern Hemisphere Glaciation

The Cenozoic North Atlantic to Arctic records covering the onset of Cenozoic northern hemisphere glaciation are superior to the Pacific ones because of the stratigraphic details and the spatial resolution of the DSDP and ODP drilling in high latitudes. Since DSDP Leg 38 (Talwani, Udintsev, et al., 1976) it has been well known that 1) the Norwegian-Greenland Sea housed temperate to subtropical surface waters during the Paleogene, 2) indicators of early northern ice covers were not confined to the Quaternary, but also found in unspecified Mio- Pliocene sediments (Warnke and Hansen, 1977), and 3) the history of northern hemisphere glaciation during the latest part of the Cenozoic was much more variable than indicated by the available terrestrial records from Europe and North America, in essence that the deep-sea records were stratigraphically more complete and showed more numerous heavy glaciation events than the corresponding terrestrial ones. Locations drilled to the south of the Greenland-Scotland Ridge during the late phase of DSDP which used a coring technique with often close to 100 % recovery of undisturbed section (Shackleton et al., 1984) later confirmed these results and dated the onset of major northern hemisphere glaciation to 2.4 Ma.

A suite of later ODP legs visited the western North Atlantic with drill sites located to the south of the Greenland Scotland Ridge and in the Labrador Sea. They established the middle to late Miocene onset of glaciation on Greenland (Wolf and Thiede, 1991; Larsen et al., 1994) as well as of an intensification of northern hemisphere glaciation (probably inter alia also on Greenland) approximately 4 Ma. ODP Leg 104 (Eldholm, Thiede, Taylor et al., 1989) drilled a transect across the outer Vøring Plateau off central Norway which allowed a detailed description of the history of the northern extension of the Gulf Stream system, called here the Norwegian Current. As outlined by Jansen and Sjøholm (1991), modest ice-rafting as a sign of incipient glaciation was also observed in upper Miocene sediments on the Vøring Plateau, but the intensification and onset of the highly variable system of alternations of glacials and interglacials observed off S Greenland at 4 Ma, occurred only at 2.6 Ma in the eastern Norwegian-Greenland Sea. During the past 2.6 my the Vøring Plateau area which should react early to warming events was affected by 26 severe glaciations which left dark gray horizons very rich in ice-rafted material (Thiede et al., 1990) in the stratigraphic sequences which over and beyond these intervals mostly represented the products of cold depositional environments, whereas interglacial sediments representing the intrusion of temperate Atlantic waters are exceptional. After ODP Leg 104 it was clear that some kind of a glacial climate mode dominated the entire late Pliocene and Quaternary. Interglacials like the one we are experiencing today are truely exceptional.

The latest and most interesting information on the topic of this paper has been produced by ODP Leg 151 which visited the westernmost Norwegian-Greenland Sea and the approaches to the Arctic Ocean as part of the ODP "North Atlantic-Arctic Gateways" drilling program (Ruddiman et al., 1991). Beside sites on the Iceland Plateau and along the East Greenland continental margins it succeeded to drill the sill depth between the deep Norwegian-Greenland Sea and the Arctic Ocean (Fram Strait) as well to sink wells into the Yermak Plateau which represents an extension of probably volcanic origin of the continental margin of the Barents Sea towards the true Arctic Ocean. The records of the ODP Leg 151 sites (Myhre, Thiede, Firth et al., 1995) contain many examples of the variability of sediment properties in phase with the major orbital Milankovich-frequencies, but it is most astounding to note that the onset of glaciation of these ODP sites of the highest northern latitude ever drilled for scientific purposes seems to occur considerably later than further south (off Greenland), namely only during early Pliocene. Further investigations at key locations in the Arctic Ocean proper are urgently needed to solve this mystery (Thiede and NAD Sci. Comm., 1992).

To use the approach of scientific drilling in the Arctic is expensive and will limit efforts to very few well chosen localities. The problem of the history of the onset of northern hemisphere glaciation will therefore have to be dealt with by means of time series (Imbrie et al., 1992), whereas a set of adequately documented time slices will probably never be available.

<u>Long- and Short-term Variability of the Cenozoic Arctic Ice Cover</u>
Mounting evidence points to the existence of an Arctic sea ice cover for the past several millions years (Thiede and NAD Sci. Comm., 1992, Myhre, Thiede, Firth et al., 1995, Spielhagen et al., subm., cf. Fig. 3). The amount of ice-rafting, however, fluctuated wildly, being relatively monotonous and small prior to 6-700 ka, but revealing four phases of intense ice-rafting (corresponding to O-isotope stages 16, 12, 10 and 6, acc. to Spielhagen et al., subm.) since then (Fig. 3). Other glacial periods such as the last glacial maximum seem to have had a lesser impact on the central Arctic ice-rafting record. These phases of intense ice-rafting have to be related to dynamically changing ice-shields which at variable rates were shedding icebergs transporting these coarse materials probably both from North America/ Greenland as well as on the Eurasian side.

In the near future the facilities to take long sediment cores in the deep central Arctic Ocean will be available. In preparation of scientific drilling into the deep Arctic Ocean floors and with the opportunity of presently available ice breaker capabilities it will be important to plan for a systematic long and large volume sediment coring program with the aim to sample the major structural highs with undisturbed pelagic sediment sequences at locales with relatively high sedimentation rates. At the same time the coring program which could be a contribution to the international IGBP Core Project IMAGES (IMAGES, 1994) should be planned that all major distinct elements of the Arctic sea ice cover and of the surface, intermediate as well as bottom waters are covered.

This approach as well as newly developed stratigraphic techniques (Clark et al., 1986; Eisenhauer et al., 1994) would allow to establish time series for the various compartiments of the Arctic paleoenvironment as well to construct time slices for a number of crucial scenarios such as the pre-O-isotope stage 16 type of ice rafting, the 4 important ice rafting events, for a number of well developed interglacials as well for preglacial and deglacial transitional periods.

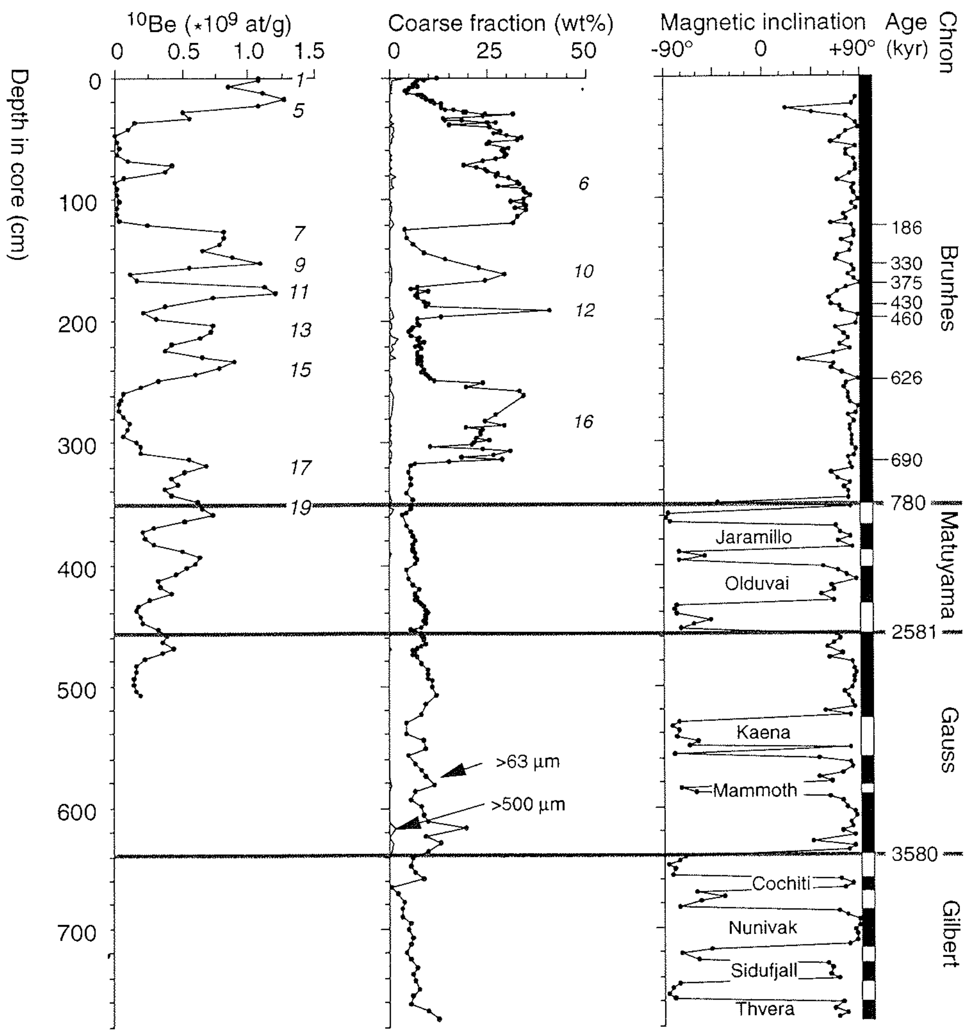

Fig. 3.: Stratigraphy of Core PS 2185 on the crest of the Lomonosov Ridge at 87°32´N 144° 56´E at 1052 m water depth (from Spielhagen et al., subm.). The newly established ^{10}Be stratigraphy together with AMS, ESR, and Amino Acid Dating and on the basis of magnetostratigraphic data have resulted in a temporal resolution comparable to the paleoceanographic records of the Norwegian-Greenland Sea. Henceforth a detailed picture of the paleoceanographic changes of the central Arctic can be deduced from these core materials (Fütterer, 1992).

The Arctic Ocean During the Last Glacial Maximum

In Figure 2 we have shown the distribution of the light stable oxygen isotope values in the shell material of planktonic foraminifers after they have settled down to the sea-floor surface corresponding to the modern or late Holocene situation. By virtue of the relationships between the oxygen isotope ratios and the salinity of the surface waters (under the assumption that these waters in the Arctic Ocean are pretty much isothermal) one can construct the distribution of salinities from these values assuming an average temperature of the surface waters (corresponding to the habitat of the planktonic foraminifers) being at -1.7°C (from Nørgaard-Pedersen, 1996 in prep.). The impact of the high salinities of the Atlantic waters in the south-eastern part of the eastern Arctic Ocean can clearly be shown by means of this approach. Now, by using the stratigraphies (cf. Fig. 3) of as many cores as possible where the last glacial maximum could be identified by a variety of stratigraphic methods one can attempt to construct a similar map for the last glacial maximum. This is shown in Fig. 4 of this report identifying the potential of this method. The oxygen isotope ratios of the planktonic foraminifers reveal isotopic values for the entire Fram Strait area and the area of the Yermak Plateau coinciding well with the values reconstructed for the Norwegian-Greenland Sea as shown by Sarnthein et al. (1995). The obvious difference to the modern or late Holocene is the disappearance of the relatively light values related to the influx of Atlantic waters. Any attempts to estimate salinities based on this method must then show the complete disappearance of the current pattern as could be shown for the modern circulation system we know from the northern Norwegian-Greenland Sea, from the Fram Strait and from the eastern Arctic Ocean adjacent to the Eurasian continental margin. However, the most astonishing aspect of this reconstruction is the emergence of lower salinities in the westernmost Fram Strait and, in particular, in the central and western part of the Arctic Ocean where a similar gradient of decreasing salinities towards a water mass which was much more brackish than the water mass adjacent to the Fram Strait could be identified. The geographic pattern of this gradient has not been identified and described properly because in the moment we do not have access to a sufficiently large number of cores from the entire Arctic Ocean but it is quite clear that a different system has to be assumed for the "glacial" circulation patterns and ice covers in the Arctic Ocean. One of the great challenges for the reconstruction of the Arctic paleoceanography is henceforth (as difficult as it may be) the establishment of as many time slices as possible which can be identified for a sufficiently large number of cores which will decrease in precision and number with increasing sediment age for the Arctic Ocean. It was a lucky coincidence of the first probing attempts to enter the eastern Arctic Ocean by European researchers to identify areas of sedimentation of relatively high temporal resolution and to be able to pin-point this pattern of paleoceanographic variability at all (Boström and Thiede, 1984).

Beside the establishment of time slices great efforts will be devoted to identify areas of ultra-high sedimentation in the eastern Arctic Ocean to be able to resolve its paleoceanographic variability in greater detail than has been hitherto. Particular promising areas can be found along the northern and deeper parts of the continental slope along the entire Eurasian continental margin. Here we find a zone where terrestrial signals mix with oceanic signals and where it will be possible not only to decipher the paleoceanographic history of the oceanic water masses, but also the geological and environmental history of the shelf areas adjacent to the continental slopes as well as that of the continental hinterlands in northern Europe and in Siberia. Both are areas of great paleoclimatic significance and promising scientific challenge (confer the recently established QUEEN Program of the European Science Foundation). The ultimate goal of these high resolution studies will comprise attempts to describe the history of the ice cover as well as of the oceanic water masses and the other environmental parameters in a temporal resolution of less than 100 years. Promising high sedimentation rate areas have recently been found off the Lena-Delta in the outer Laptev Sea (Spielhagen and Bauch, pers. comm., 1996).

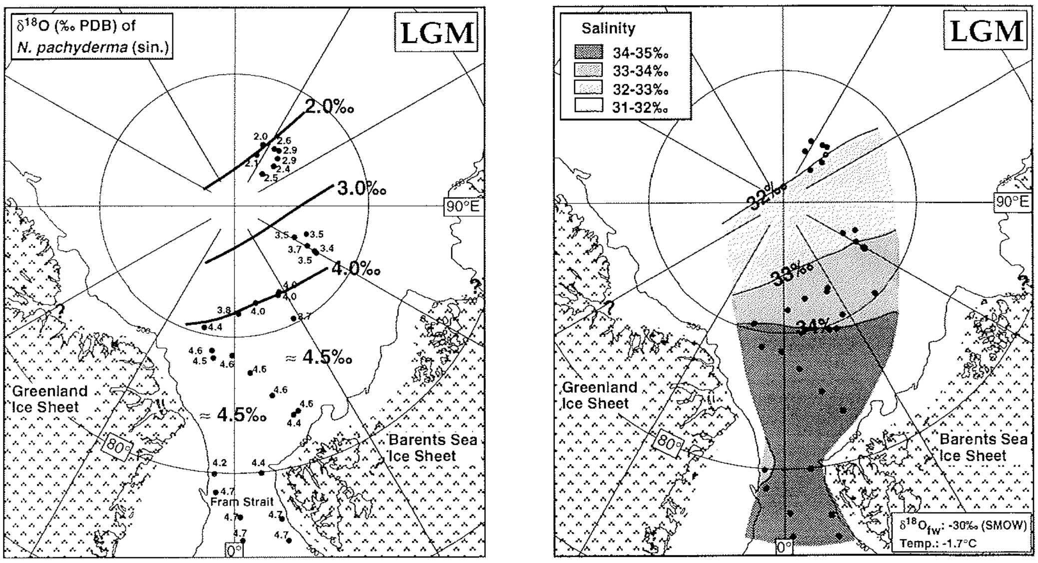

Fig.4.: Surface water salinities in the eastern and central Arctic Ocean (right) during the last glacial maximum (LGM) as reconstructed from oxygen isotope values (left) of planktic foraminifers Neogloboquadrina pachyderma (sin.) (from Nørgaard-Pedersen, in prep.).

The Problem of the Evolution of Polar Marine Biota

Marine biota have developed in the polar seas of both hemispheres. They are adapted to extreme environments and they exhibit in many aspects a great degree of similarity, although only very few bipolar species have been identified hitherto. On the other hand, they are also displaying considerable differences in their composition and nature. Their history is virtually incomparable because Antarctic marine biota adapted to cold extreme paleoenvironments over 30-40 m.y. ago, while the Arctic biota had only 10 - 12 m.y. for this adaptation.

It can be shown that both the southern Ocean as well as the Arctic Ocean were fully marine throughout their Cenozoic history, covering the entire time span of the cooling of surface- und bottom-water masses from the temperate regimes of the early Cenozoic to the extreme and very cold regimes during the latest part of the Cenozoic. All other parameters of the habitat of these biota remained fully marine; it can be assumed that a detailed record of the evolution of the polar biota may provide one of the simplest and most quantitative experiments in evolutionary studies in paleontology.

However, both in the polar waters of the southern hemispheres as well as in the Arctic Ocean the paleontologic record of the marine biota is changing very fast in its composition, because the preservation of the skeletal record of the marine biota in the oceanic sediments documents switches from one fossil group to the other and certain evolutional trends within these. No contiguous evolution of one fossil group covering the entire time span has been produced (maybe with the exception of palynomorphs such as dinoflagellates). A survey how to procede was published by the Nansen Arctic Drilling Science Committee (Thiede and NAD Sci. Comm., 1992) and it will require substantial drilling efforts to resolve this part of the polar life histories.

Modelling Different Arctic Oceans

The Arctic Ocean as a separate ocean basin has been isolated or virtually isolated for deep- as well as shallow-water exchange from the rest of the world ocean for most of the time of its existence. It had a polar position throughout the last 7-80 m.y. and comprised always (as far as can be documented by the available sample record) fully marine environments with highly different temperature regimes as well as a variety of types of ice covers during the latest geological past. It is a major challenge to the modelling community within oceanography to try to model (cf. Clark, 1988) the functioning of an Arctic Ocean in a polar position when surface water masses were temperate, fertile and highly productive while bottom water masses were oxygen deficient and probably stagnant (= ? euxinic). Up to now this stage is only documented by very few cores but it would be challenging to know how it could have functioned in terms of oceanography producing very fertile surface water masses resulting in a siliceous biogenic record.

Modelling efforts will be needed to understand when, where and how incipient ice covers began to develop in the Arctic Ocean and how a variety of types of ice covers as documented by the sediment cores could develop over the Arctic Ocean.

The latest effort which requires an integration of modelling of the terrestrial temperature regime of the ice-sheet record of the continents and shelf seas surrounding the Arctic Ocean as well as of the sea-ice covers will be needed to gain some understanding of the framework condition which led to the highly variable youngest part of the history of the Arctic Ocean.

Based on these modelling efforts one will have to make assumptions and efforts to come up with a scientifically based quantitative assessment of the potential of future environmental change in the Arctic Ocean which will have to be matched by the observation record collected during these years. The Arctic Ocean per se is representing, indeed, a grand challenge for European polar sciences.

A New Concerted Effort

The new political climate around the Arctic as well as the available technical facilities call for a new and concerted effort of parties who have a scientific and environmental interest in the natural properties of the Arctic seas. At present progress in Arctic paleoceanography is less a question of available techniques of scientific analyses, but rather a problem of organizing (scientifically, financially and politically) the necessary field operations. It is a strange observation that sufficient ship time on ice-breakers and on ice-reinforced drilling platforms is available if necessary financing can be found and that some of the many available tools are sitting idle because of the poor and disconcerted organisation of Arctic science. What should be done?

- There is no detailed geophysical data base from the Arctic which would allow to plan adequately (quality of site locations, safety considerations) for proper locations for scientific drilling or even for taking giant piston cores. A major effort to conduct site surveys in the Arctic deep and shallow areas should immediately be mounted. ODP requirements and procedures provide good examples how this could be achieved.
- The Nansen Arctic Drilling Program (NAD) has been formed at the IGC 1989 and is trying to provide a programmatic framework for scientific drilling in the permanently ice-covered central Arctic (Thiede and NAD Science Committee, 1992). Technical means are available though yet unproven in the Arctic deep sea. The first attempt to use a light drill rig from the Swedish ODEN will be carried out in 1996 (Kristoffersen and Backman, pers. comm., 1995).
- Under the frame of NAD scientific drilling will also be attempted in the shallow shelf, with the aim to sample continent-near sites with extraordinarily high sedimentation rates and henceforth temporal resolution. Selected target areas are the McKenzie Delta where commercial drilling has provided access to a long and very valuable stratigraphic section and new drilling in the Laptev Sea employing mainly Russian scientific institutions and drilling technology. Site survey and safety requirements as well as the political and financial preparation of such drilling will, however, result in considerable delays of the actual drilling.
- New giant piston coring systems can easily be adopted to a number of the available ice breakers and proposals are under preparation for an Arctic IMAGES-program (IMAGES, 1994). Sufficient shallow reflection seismic profiles are already available at present to select coring sites where complete undisturbed young sediments can be found and where outcropping older parts of the stratigraphic sequence can be cored. On the flanks of Lomonosov Ridge, for example, a probably complete Neogene section could be sampled using a stepwise approach, provided ice conditions allow a sufficiently precise positioning of the ice breaker.
- Visits of ice breakers to the North Pole have demonstrated that the Arctic sea ice cover presently is in a state being navigable for sufficiently powerful ships. Provided sufficient preparation and international coordination, synoptic studies of a wide range of oceanographic disciplines can be carried out in the Arctic, in this case a concerted effort to collect high sedimentation

rate young deposits to decipher the paleoceanographic variability of the Arctic and to adequately describe the geologically important properties of its recent depositional environment.

- Ice breakers are sometimes not the most efficient tools to carry out systematic surveys. For several years possibilities have been evaluated to involve (nuclear) submarines or large, long-range AOVs in Arctic sub-ice surveys (swath mapping, side scan sonar surveys, seismic reflection surveys, a wide variety of hydrographic, chemical and biological measurements) should be vigorously persued.

The availability of powerful ice breakers (Russia, Japan, US, Canada, Sweden, Germany, Finland) suitable to support research activities to a range of research communities, the political and financial situation as well as the establishment of relatively large and diversified groups of scientists in government, industrial and academic research institutions represent a golden opportunity to advance Arctic deep-sea research to a level equivalent with the other oceans which should be used by the international scientific community.

Acknowledgments

Many of the ideas described in this short report have been developed in close and intimate intellectual exchange with a small working group at GEOMAR, with colleagues at the Alfred-Wegener-Institute in Bremerhaven and with many international researchers with whom we cultivate an intense scientific exchange. The source of many of these ideas is resulting rather with this entire group than with one individual author and I would like to take the opportunity to acknowledge this free academic and scientific exchange of thoughts between the various communities.

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