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The Arctic Ocean Record: Key to Global Change (Initial Science Plan)

By Nansen Arctic Drilling Program NAD Science Committee*

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

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

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

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

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

Prioritized program objectives* and applications # are:

* Complete paleoenvironmental record	#Prediction of climates and faunal adaptation
* Paleoceanography	#Past and future climate
* Structure of major Arctic features and margins	#Hydrocarbon potential
* Nature and age of Arctic basement	#Paleogeography
* Former productivity levels	#Biosphere and climate interaction
* Former extent and composition of sea ice and icebergs	#Atmosphere and ice feedbacks
* Paleo-windflux	#Atmosphere feedback

The final product is to provide data to global models that will now have realistic inputs from the Arctic for predicting ocean-atmosphere-cryosphere systems and interactions and to determine the structural fabric and geologic evolution of the northern high latitude regions.

Zusammenfassung: Der große Einfluß des Nordpolarmeeres auf die globale Umwelt, die schnelle Veränderlichkeit der arktischen Eisdecke und die daraus folgenden Konsequenzen für „Global Change", ebenso wie die ungelösten Probleme der tektonischen Entwicklung der nördlichen Hemisphäre machen es unbedingt notwendig, Tiefseebohrungen in den ständig eisbedeckten Teilen des Nordpolarmeeres abzuteufen. Die Tiefseeablagerungen der Arktis haben die Geschichte der mittel- und langfristigen Abkühlungsgeschichte der nördlichen Hemisphäre, der daraus folgenden Mechanismen der Erneuerung der ozeanischen Bodenwassermassen, und der Anpasung von Floren und Faunen an extreme Lebensbedingungen gespeichert. Gesteine des tieferen Untergrundes spiegeln in ihrer Zusammensetzung und ihrem Alter die Entstehung und die Tektonik der arktischen Becken und Schwellen wider; bisher konnten sie nicht beprobt werden und ihr Aufbau ist daher unbekannt.

Eine der wichtigsten ungelösten Fragen der Erdwissenschaften betrifft die paläo-ozeanologische und paläoklimatische Entwicklung der arktischen Tiefseebecken. Um die Auswirkungen des Treibhauseffektes in ihrer geschichtlichen Entwicklung zu erfassen, muß man die Größenordnungen, Häufigkeiten und Raten der natürlichen Klimaänderungen kennen. Von vielen hundert Sedimentkernen aus der Arktis enthalten nur sieben Ablagerungen, die eine Zeit vor dem Einsetzen der kalten känozoischen Klimate belegen. Es gibt bisher keine arktischen Tiefseeproben, die die Zeitspanne von 5-40 Ma umfassen, als das Klima beträchtlicher Abkühlung unterlag. Es gibt daher aus diesem Gebiet keine Aussagen, die es ermöglichen würden, den Zeitpunkt des Einsetzens der glazialen Klimate oder die die Abkühlung verursachenden Kräfte zu bestimmen. Heutzutage sinkt kaltes, dichtes und sauerstoffreiches arktisches Oberflächenwasser auf die Tiefseeböden und fließt von dort nach Süden, wo es die Tiefseebecken des Atlantischen und Pazifischen Ozeans füllt. Die Hydrographie der arktischen Wassermassen beeinflußt damit große Teile des gesamten Weltmeeres.

Die geologische Entstehung des Nordpolarmeeres muß in engem Zusammenhang mit dem Ursprung der unmittelbar benachbarten Kontinente und Ozeanbecken gesehen werden. Die historischen und rezenten Plattenbewegungen der Arktis müssen erkannt werden, bevor ein vollständiges Verständnis der Plattentektonik und der Paläogeographie der nördlichen Hemisphäre gewonnen werden kann.

Die känozoische Geschichte des Eurasischen Beckens ist einigermaßen bekannt, weil die eurasische und die nordamerikanische Platte ausführlich weiter südlich untersucht worden sind. Dieses Becken enthält auch eine gut untersuchte und leicht entzifferbare Geschichte der Bildung magnetischer Anomalien. Über die übrigen Teile des Nordpolarmeeres ist nur wenig bekannt, wobei die Entwicklung des Amerasischen Beckens das größte Problem darstellt.

Die wichtigsten wissenschaftlichen Ziele des „Nansen Arctic Drilling Program" umfassen die folgende Fragestellungen:

* Wie verlief die klimatische und paläozeanologische Entwicklung der Arktis und was war ihre Auswirkung auf das globale Klima, die Biosphäre und die Dynamik des Weltmeeres und der Atmosphäre?
* Wie setzen sich die wichtigsten tektonischen Einheiten des Nordpolarmeeres und seiner Kontinentalränder zusammen und wie verlief ihre geologische Entwicklung?

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Reihung der Zielsetzungen* und Anwendungen# im Rahmen eines NAD sind:

* Vollständige Geschichte der arktischen Umwelt	#Vorhersage von Klima und Reaktion der Biosphäre
* Paläo-Ozeanologie	#Klimarekonstruktion und Klimavorhersage
* Tektonik der Arktis und ihrer Kontinentalränder	#Höffigkeit für fossile Kohlenwasserstoffe
* Zusammensetzung und Alter des tieferen Untergrundes der Arktis	#Paläogeographie
* Geschichte der Produktivität	#Wechselwirkung Atmosphäre und Biosphäre
* Verbreitung, Aufbau und Herkunft von Meereis und Eisbergen	#Wechselwirkung von Eis und Atmosphäre
* Paläo-Windssysteme	#Reaktion der Atmosphäre

Das Endziel von NAD wird es sein, Daten für globale Modelle zu Verfügung zu stellen, die erstmals auf Messungen in der Arktis beruhen, um die Wechselwirkung des Systems Ozean-Atmosphäre-Kryosphäre zu bestimmen. Außerdem müssen die tektonischen Strukturen und die geologische Geschichte der Gebiete in hohen nördlichen Breiten beschrieben werden.

1. INTRODUCTION

1.1 *Prologue*

Statement of Dr. Nicholas Shackleton (Cambridge University), chairman of the Ocean Drilling Program panel on Ocean History and member of the Nansen Arctic Drilling (NAD) Science Committee.

I cannot overemphasize how important this project is seen to be by the ocean history and paleoclimate community in general, as well as by the JOIDES Ocean History Panel (OHP) in particular. As you probably know, in our last prioritization round at OHP we ranked Norwegian Sea drilling with a strong component at the most Arctic end a clear first. You may not know that there was a strong feeling in the meeting that drilling at the limit with the *JOIDES Resolution* was an important step towards attaining true Arctic deep sea objectives by other means. I think that if at any stage Arctic drilling were on the table at our panel it would instantly rise to top priority. Recall how much support the Jurassic Pacific Ocean obtained from the broader community despite the low statistical chance of real scientific success, and you will appreciate how heavily the community would support Arctic drilling. I would also like to emphasize the fact that, important as geophysical survey data are in evaluating some aspects of Arctic history, there is absolutely no doubt that physical sampling is essential if we are going to answer any of the key questions regarding the climatic history of far northern latitudes or the role of the Arctic waters in paleoceanographic history.

1.2 *Rationale and Name of the Program*

New and major scientific enterprises should carry an easily identifiable symbol. Why should we not devote this drilling program to the memory of F. Nansen, the great Norwegian Polar Explorer, who prepared, organized and executed the well-known *Fram* expedition to the Arctic Ocean during 1893-1896? He was truly interdisciplinary, as a biologist he also brought with him the first sediment samples from the Arctic deep-sea floors, and made important scientific contributions to meteorology, geography, geology, oceanography and biology. He was daring and courageous, and truly international. The centennial of the first *Fram* expedition will come during 1993-1996, which would allow for a few years for preparations, barely enough for a scientific effort of the complexity and magnitude of deep-sea drilling in the permanently ice-covered Arctic.

The principal purpose of this document is to provide interested readers with an overview of the scientific perspectives and priorities of drilling in the ice-covered Arctic Ocean. Many of the technical aspects of site surveying and deep-sea drilling in ice-covered waters will be dealt with in a report of the Nansen Arctic Drilling (NAD) Technology Committee. Objectives were defined at the first NAD meeting in Washington, D. C. during the International Geological Congress in 1989. Further discussions were held at a NAD meeting in October 1990 in Stockholm, Sweden after the preparation of the cruise plans for the international multidisciplinary expedition ARCTIC'91. The discussions in Stockholm also led to the formation of a Site Survey Subcommittee under the leadership of Yngve Kristoffersen, Bergen. Options to establish an Arctic Data Bank are presently being evaluated by Garret Brass, Miami. This document was finished and approved by NAD during a meeting on July 31, 1991, immediately prior to the departure for the ARCTIC'91 expedition.

This science plan addresses deep-sea drilling in the central Arctic. The program is interdisciplinary and international in scope and participation as only by a cooperative effort can Arctic deep-sea drilling be achieved. Arctic continental margin drilling is now under active planning and a separate science plan will be constructed. The North Atlantic-Arctic Gateways Detailed Planning Group (NAAG-DPG) of ODP has developed a drilling prospectus for the Norwegian-Greenland Sea and if ice conditions permit the Yermak Plateau in the Arctic Ocean.

1.3 *Guidance from the Scientific Community*

The objectives of NAD were derived from several workshops, national and international funding agencies, agencies of all Arctic rim nations and a number of other interested countries. The scientific background for NAD has been prepared by the SCOR (Scientific Committee in Ocean Research) Working Group 82 „Polar Deep-Sea Paleoenvironments" and several workshops and meetings of the IUGS (International Union of Geological Sciences) CMG (Commission for Marine Geology) as well as the ICL (International Commission on the Lithosphere) Subcommittee on the Arctic. Arctic deep-sea drilling has been emphasized during the COSOD (JOIDES sponsored Conference on Scientific Ocean Drilling) conferences; it achieved a high priority in the working group on „Changes in the Global Environment" of COSOD II. Further comments and active participation from the scientific community are solicited. NAD has established formal linkages with ODP and the IGBP paleoclimate core program PAGES.

1.4 *Progress and Plans*

The reader is directed to the appendix (Chapter 15) which lists in priority order the sites which have been proposed as initial targets.

During the summer of 1991 the RV *Polarstern* and USCC *Polar Star* have collected sediment from the deep Arctic. A modified „super corer" capable of > 20 meter samples has been loaned to the RV *Polarstern* by Bedford Institute of Oceanography; box cores, piston and gravity cores have been collected by the two vessels in a cooperative program.

In 1992 continental margin sites will be identified on the basis of scientific objectives and logistic feasibility. A standard ODP type scientific prospectus will be written up and cost estimates obtained for using existing commercial shallow drilling vessels. It is anticipated that support can be found so that a 1993 start date is possible. It is also assumed that the newly established detailed planning group of ODP (Ruddiman et al., 1991) will lead to renewed efforts in northern high latitude deep-sea drilling efforts outside of heavy ice areas. Tentative plans call for a first field season in the Greenland Sea in 1993, with a possible second one in summer 1994. It is planned that deep Arctic drilling as outlined in Chapter 15 will commence in the middle to late 1990´s.

Preparation for Arctic drilling will necessitate extensive operations for site surveying in major parts of the Arctic Ocean, whereas drill sites will be confined to a few well chosen localities over prominent basement structures in the central Arctic. For both operations extensive logistic support will be established, which could also be used by other scientific programs and therefore lead to a general increase in Arctic research involving not only geosciences but other disciplines as well.

1.5 *Technology*

The question of how deep-sea drilling could be accomplished in ice-covered waters has lingered on for some time until late 1986 when the international scientific organizations (IUGG-ICL, IUGS-CMG, SCOR WG 82) called for a workshop to assess the technical feasibility of Arctic deep-sea drilling. It was apparent that such drilling would be very costly, very complicated, but was technically feasible. Regardless which platform is finally chosen, it will have to cope with the usually slow, but variable movements of the Arctic ice. The water depths to be drilled will range from 1,000-4,000 m, allowing for some limited lateral drift of the drilling platform. In terms of coring techniques the workshop participants agreed that continuous coring, using riserless techniques developed by ODP, should be adapted to any drilling platforms considered. The holes would not require reentering capability, but would be single bit holes penetrating the entire sedimentary section up to 50 m into the underlying basement. Drilling platforms must have the ability to target specific scientific objectives. This rules out a passive drifting platform as an appropriate vehicle.

1.6 *The Future*

The future holds great promise for unraveling the secrets of the Arctic and relating the climate dynamics both of the past and present of the world´s ocean. Some of the most promising efforts are:

1991 Long sediment cores obtained from the central Arctic during the international expedition ARCTIC´91.
1993 Long sediment cores to be obtained on the international "Over the Top" US-Canadian-expedition.
1993-94 Ocean Drilling Program drilling of Arctic gateways.
1994 Soviet scientific drilling ship with ice capability to be completed.
1995-96 International effort for long sediment cores.
1997 First Arctic deep-sea drilling.

2. RATIONALE FOR NEW GEOSCIENTIFIC RESEARCH IN THE ARCTIC

Deep-sea drilling has developed since the late sixties and is presently sampling all the world's oceans with the exception of the Arctic. This is a result of two factors, namely, existing scientific drilling platforms are not capable of working in an ice-covered ocean and present site survey techniques utilized for preparation of deep ocean drill sites are not adapted to Arctic operations.

However, the profound influence of the Arctic Ocean on the global environment, the rapid variability of the Arctic ice cover and its consequences for global change as well as the unresolved geology of the basement under the Arctic Ocean and its rims have resulted in a growing interest in drilling the deep-sea floors of the ice-covered Arctic Ocean. This science plan will address, however, only deep-sea drilling which cannot be done by *JOIDES Resolution*, the drill ship of the Ocean Drilling Program (ODP). The Nansen Arctic Drilling Program (NAD) is linked, but does not duplicate efforts promoted through ODP-proposals for renewed Bering and Norwegian-Greenland seas drilling which are presently under evaluation, as well as to programs to drill circum-Arctic shelf seas and continental margins.

During the International Geological Congress in Washington, D.C., summer 1989, a group of scientists and representatives of government and funding agencies of the Arctic rim countries and a number of additional nations met in Washington to found committees to further Arctic deep-sea drilling. In commemoration of Fridtjof Nansen's famous transpolar Arctic drift expedition on the then modern oceanographic polar research vessel *Fram* the effort has been called Nansen Arctic Drilling Program (NAD). It consists of an executive committee assisted by science and technology committees with representatives from interested nations.

2.1 *Global Change*

General circulation models predict that a global warming of about 1° to 5° C may occur during the next century as a result of projected increases in the atmospheric content of greenhouse gases. The models further suggest that the amount of warming may be significantly greater in high latitude regions than in lower latitudes, but they do not agree well on the relative amount of warming to be expected at high latitudes. High latitudes may experience the earliest unambiguous signs of the onset of global warming from the "greenhouse effect."

"The main effects will likely be evidenced in shifting wind systems, including the jet stream, rainfall, snow, and the increased frequency of damaging extreme weather events such as heat waves, droughts, hurricanes, and storm surges. Thus, it is probable that regional changes will vary dramatically from the global average, causing impacts such as crop destruction and coastal flooding, with potentially profound effects on human society" (UCAR 1988).

One of the challenges of global change research is to improve upon what is known of past changes in temperature of the earth as a function of space and time. The most important objective of this science plan is a quantitative assessment of geological history and variability of the Arctic cryosphere.

A compilation representative of what is known today is shown in Figure 1, which portrays a sample of estimated surface temperatures through the first 180 million years of earth history. These data have been compiled without evidence gathered from the Arctic.

2.2 *Fossil Hydrocarbons and Other Resources*

The Arctic is known to harbour great riches in non-living resources. Their origin and distribution cannot be evaluated without a decided knowledge of the plate tectonic history of the Arctic and of the paleoclimatic evolution. At the present time approximately 10 % of the world's hydrocarbon reserves and 20 % of natural gas reserves are located in the Arctic. Gas hydrate reserves are suspected to be immense and pose a potential threat to the global environment by release of methane.

Numerous regions in the Arctic Ocean Basin possess favourable geologic structures for placer deposits. At least

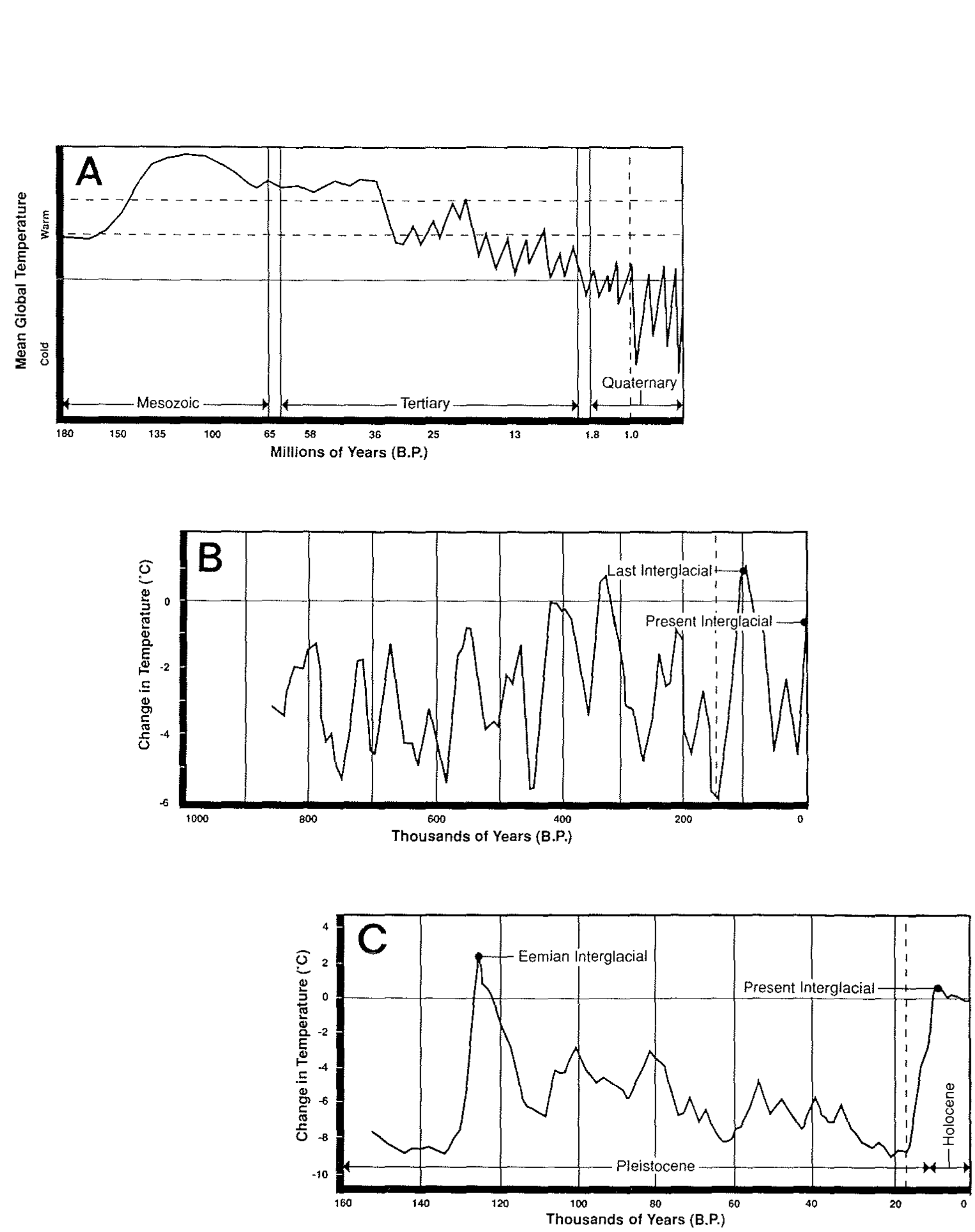


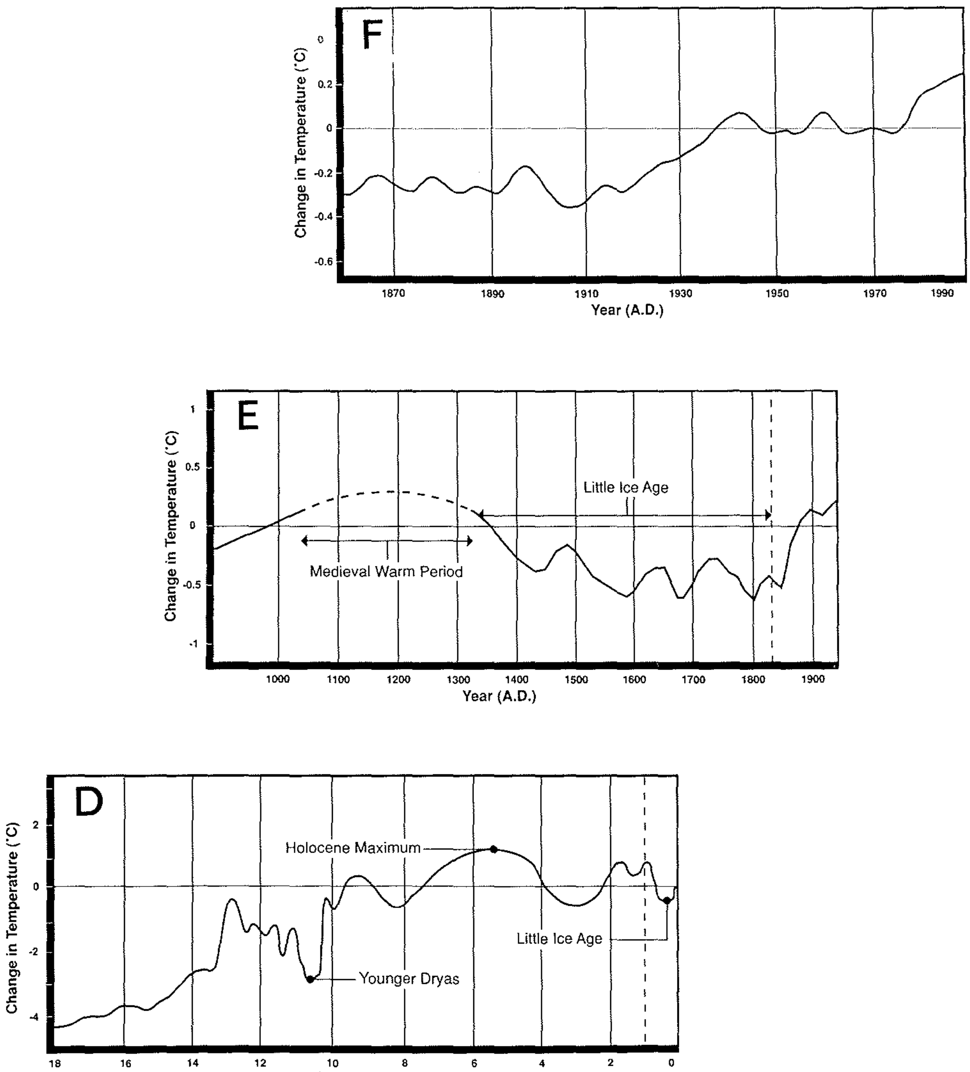
Fig. 1: Changes in time in the temperature of the earth (WEBB 1991). The graphs are arranged from (1) to (6) in ever more recent eras and with greater and greater expansion of the time scale. Temperatures shown are in degrees Celsius in most cases as a departure from the mean value at the turn of the present century of about 15° C. The vertical scale varies.

(A) Mean global temperature through the last 180 million years derived from oxygen isotope analyses of various marine and terrestrial deposits (FRAKES 1980). The present (ca. 1,900) condition, for reference, is shown as a horizontal line. Of note are (i) a global cooling trend since the time of the Cretaceous, and (ii) the onset of a continuing series of deeper, periodic glacial/interglacial oscillations in the Quaternary period. Also shown (dark band) is the range of modeled surface temperatures based on a doubling of atmospheric CO_2, projecting an increase from present values of about 2-5° C (CROWLEY 1990).

(B) Surface temperatures through the last 850,000 years, derived from measurements of the ratio of ^{16}O to ^{18}O in fossil plankton in a deep-sea core from the equatorial Pacific Ocean (SHACKLETON & OPDYKE 1973). The changes mainly reflect variations in global ice volume; the scale used here was added to show schematically the probable associated changes in global average surface temperature, based on a model-derived difference of 4-6° C between full glacial and full interglacial conditions (CLARK 1982). The reference line at 15° C corresponds to surface temperatures of the modern era. The glacial/interglacial oscillations, characteristic of the Pleistocene epoch, are now thought to be induced by periodic variations in the orbit of the earth and in its axis of inclination, which act together to bring about systematic changes in the seasonal distribution of sunlight over the surface of the planet.

(C) Air temperature over Antarctica, expressed as a difference from the modern surface temperature value. These estimates are derived from hydrogen/deuterium ratios measured in an ice core from the Vostok station in Antarctica (JOUZEL et al. 1987). Of note are the present (Holocene) and the preceding, somewhat warmer „Eemian“ interglacial periods, each characterized by a rapid onset to an early interglacial maximum temperature, and a subsequent, slower decline. The glacial period between is itself characterized by significant variations in temperature that fall systematically to a cold extreme (maximum glaciation) about 20,000 years before the present (B.P.).

(D) Variations in surface temperature, estimated from a variety of sources, principally isotope ratios from Greenland ice cores for the last 18,000 years. The onset and subsequent character of the present interglacial or Holocene epoch are depicted. Of note are century-scale oscillations in temperature,



identified in the Greenland record and in certain European lakes, during the period of deglaciation between about 15 and 10 ka, and a broad Holocene maximum about 5-6 ka, when summer temperatures may have been 1-2° C warmer than at present. At these expanded scales, the temperature excursions depicted in this and the subsequent graph are the most conjectural of the set (modified from HOUGHTON & JENKINS 1990).

(E) Variations in surface air temperature estimated from a variety of sources, including temperature-sensitive tree growth indices and written records and accounts of various kinds, largely from western Europe and eastern North America. Of note is a possible protracted global warming through the Medieval period, when surface temperatures may have averaged about 0.3° C warmer than the A.D. 1.900 reference. It was followed by a longer period of much colder conditions, loosely termed the „Little Ice Age", when the estimated global mean temperature may have fallen about 0.6° C below the reference norm, reflecting global temperatures almost 1° C lower than the values attained during the middle of the current century (modified from HOUGHTON & JENKINS 1990).

(F) Globally averaged, direct measurements of the combined sea surface temperature and air temperature over the land, showing this case relative to 1951-1980. A stepped warming of about 0.6° C is evident (HOUGHTON & JENKINS 1990).

Abb. 1: Zeitliche Veränderlichkeit der Durchschnittstemperatur des Erdklimas (WEBB 1991). Die Kurven folgen von (A) bis (F) aufeinander, indem jeweils jüngere Zeitabschnitte und eine zunehmend gedehnte Zeitskala aufgetragen werden. Die Temperaturen sind in Grad Celsius aufgetragen worden, in den meisten Fällen jedoch als Abweichung vom Durchschnittswert von ca. 15° C zu Beginn dieses Jahrhunderts. Die vertikalen Skalen sind veränderlich.

(A) Globale Durchschnittstemperaturen während der letzten 180 Millionen Jahre, abgeleitet aus den Sauerstoffisotopenanalysen verschiedenster mariner und terrestrischer Ablagerungen (FRAKES 1980). Die gegenwärtige Situation (ca. 1900) wird als Bezugsebene gezeigt (horizontale Linie). Bemerkenswert sind a) die globale Abkühlung seit der Kreidezeit, und b) der Einsatz einer fortgesetzten Reihe von tiefen, periodischen glazial-interglazialen Klimaschwankungen im Quartär. Ebenso wird die Schwankungsbreite (dunkles Band) der modell-berechneten Oberflächentemperaturen gezeigt, unter der Annahme einer Verdopplung des atmosphärischen CO_2, die einen Temperaturanstieg von ca. 2-5° C ankündigt (CROWLEY 1990).

(B) Oberflächentemperaturen während der letzten 850.000 Jahre, abgeleitet aus den Verhältnissen der stabilen Sauerstoffisotope ^{16}O zu ^{18}O in fossione offshore tin placer has been brought into production in the Soviet Union. Gold placers are now commercially mined near Nome, Alaska. Dredging activities for sand and gravel on the Arctic Ocean shelves are frequently related to nearby offshore hydrocarbon development and other large coastal and offshore construction projects.

2.3 *Benefits for Science and Society*

* Improved models and data for predicting global change and its effects.

* Assessment of potential release of new greenhouse gases (methane), of the „dissolution" of clathrate horizons and of the reduction of the circum-Arctic permafrost province.

* Knowledge of past climates and their forcing functions so the future may only be understood in a historical perspective and may be predicted.

* Improved knowledge of evolutionary patterns of marine biota under precisely known ecological conditions.

* Reconstruction of the poorly known Arctic and circum-Arctic paleogeography and -bathymetry.

* Improved estimates of occurrence and knowledge to exploit oil and gas.

3. LINKAGES TO OTHER PROGRAMS AND ORGANIZATIONS

The perspectives of NAD have been discussed intensively in national and international funding organizations, agencies of all Arctic rim countries and a number of other interested nations. The scientific background for NAD has been prepared by the Scientific Committee for Ocean Research (SCOR) Working Group 82 "Polar Deep-Sea Paleoenvironments" and several workshops and meetings of the International Union of Geological Sciences (IUGS) Commission for Marine Geology (CMG) as well as the International Commission on the Lithosphere (ICL) Subcommittee on the Arctic (BLASCO et al. 1987).

Arctic deep-sea drilling has been emphasized during the Conferences on Scientific Ocean Drilling (COSOD); it achieved a high priority rating in the Working Group on "Changes in the Global Environment" of COSOD II, in Strasbourg, July 1987 (COSOD 1987). As a consequence of these discussions and of the applicability of many techniques developed by the Ocean Drilling Program (ODP) NAD has also established a formal liaison to JOIDES.

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lem Plankton aus einem Tiefseesedimentkern im äquatorialen Pazifik (SHACKLETON & OPDYKE 1973). Die Veränderungen spiegeln zumeist Schwankungen des globalen Eisvolumens wider; die hier benutzte Skala wurde angewandt, um schematisch vermutlich damit verknüpfte Veränderungen der globalen Oberflächentemperaturen (Druchschnittswerte) zu beschreiben, die auf einen modell-berechneten Unterschied von 4-6° C zwischen Hochglazial und -interglazial zurückgehen (CLARK 1982). Die Bezugslinie bei 15° C entspricht den heutigen Oberflächentemperaturen. Die glazial-interglazialen Schwankungen, die so typisch für das Quartär sind, wurden vermutlich durch periodische Veränderungen der Erdbahnparameter und der Neigung der Erdachse hervorgerufen, die dann zusammenwirken und systematische Änderungen der saisonalen Verteilung der Sonneneinstrahlung auf die Erdoberfläche hervorrufen.

(C) Lufttemperatur über der Antarktis, als Abweichung von der heutigen Oberflächentemperatur aufgetragen. Die Abschätzungen sind aus den Wasserstoff/Deuterium Verhältnissen in Eiskernen der Vostok-Station in der Antarktis abgeleitet worden (JOUZEL et al. 1987). Bemerkenswert sind das gegenwärtige (holozäne) und das letzte, im Vergleich etwas wärmere „Eem" Interglazial, die jeweils durch einen schnellen und extremen Temperaturanstieg zu einem frühen interglazialen Maximum, aber einen darauffolgenden, im Vergleich langsameren, Abfall gekennzeichnet sind. Das dazwischen liegende Glazial wird selber durch bedeutende Temperaturschwankungen geprägt, die systematisch zu einem Kältemaximum (Hochglazial) vor etwa 20.000 Jahren vor heute hinführten.

(D) Zeitliche Veränderlichkeit der Oberflächentemperaturen, die von einer Reihe von Messungen, hauptsächlich aber von den grönländischen Eiskernen abgeleitet wurden während der letzten 18.000 Jahre. Auf das Einsetzen und die darauf folgende Entwicklung des gegenwärtigen Interglazials (oder Holozäns) wird besonders hingewiesen. Bemerkenswert sind die hundert Jahre dauernden Schwankungen, die in den Temperaturkurven von Grönland und von ausgewählten europäischen Seen gefunden worden sind, besonders im Zeitraum der Deglaziation im Zeitraum 15-10.000 Jahre vor heute, sowie eine breites holzänes Temperaturoptimum vor etwas 5-6.000 Jahren, als die Durchschnittstemperaturen während des Sommers vermutlich 1-2° C wärmer als heute waren. In den gestreckten Zeitskalen, die hier betrachtet werden, sind die Schwankungen, die in diesem und in den folgenden Diagrammen gezeigt werden, von besonderem Interesse (verändert nach HOUGHTON & JENKINS 1990).

(E) Veränderlichkeit der Lufttemperaturen an der Oberfläche, die aus einer Vielzahl von Quellen abgeleitet worden sind, darunter vor allem temperaturempfindliche Baumringindices und ausgewählte historische, u. a. auch schriftliche Überlieferungen, die hauptsächlich in Nordamerika und Europa gesammelt worden sind. Besonders auffallend ist eine länger andauernde globale Erwärmung während des Mittelalters, als die Durchschnittstemperaturen etwa 0,3° C höher als etwa um 1900 lagen. Ihr folgte ein längerer Zeitraum mit beträchtlich kühleren Temperaturen, der als „Kleine Eiszeit" bezeichnet werden kann, als die globalen Oberflächentemperaturen um etwa 0,6° C unter den Referenzwert fielen. Sie spiegeln globale Oberflächentemperaturen wider, die beinahe 1° C niedriger waren als die Werte, die um die Mitte des jetzigen Jahrhunderts erreicht wurden (verändert nach HOUGHTON & JENKINS 1990).

(F) Global gemittelte, wirklich gemessene Oberflächentemperaturen von Land- und Meeresoberflächen, relativ zum Zeitraum 1951-1980. Deutlich erkennbar ist ein stufenweiser Temperaturanstieg von 0,6° C (HOUGHTON & JENKINS 1990).

3.1 *Ocean Drilling Program*

Some of the paleoenvironmental perspectives of this science plan can be and have been pursued in subarctic deep sea basins and during DSDP Leg 10 in the Bering Sea, DSDP Leg 38 as well as ODP Leg 104 in the Norwegian-Greenland Sea and ODP Leg 105 in the Labrador Sea to Baffin Bay area. New proposals which are presently being discussed in a newly established Detailed Planning Group (DPG) of ODP (RUDDIMAN et al. 1991) will hopefully lead to renewed efforts in northern high latitude deep sea drilling efforts (though clearly outside the permanently ice covered Arctic regions), with the following scientific aims.

A comparison of the available data from the northern and the southern hemisphere reveals that the history of the circum-antarctic deep-sea regions has been studied in considerably more detail and with more success than the records of the northern hemisphere. Presently it appears that the glacial history of the southern hemisphere began at 20 to 30 Ma, well before that of the northern hemisphere. However, we believe that at least part of this asymmetry is due to an artefact of available samples and regional coverage of drill points, because we have been unable to sample the Arctic Ocean proper and the western parts of the Norwegian-Greenland Sea. In addition, sediments in the northern Labrador Sea, particularly in Baffin Bay, have produced enormous stratigraphic difficulties. New proposals focus on the Norwegian-Greenland Sea to complete the information on the northern hemisphere which was collected during ODP Leg 104 and Leg 105. The Norwegian-Greenland Sea is a particularly interesting area to study, because the East Greenland Current is carrying the history of the glacial ice cover of the Arctic Ocean.

To date, the Norwegian-Greenland Sea has been visited by DSDP Leg 38 and ODP Leg 104. The drilling campaigns covered the eastern and southern parts of this deep-sea basin including the Greenland-Scotland Ridge. Due to the poor recovery on DSDP Leg 38 high resolution stratigraphic records are lacking, and thus important knowledge on paleoenvironmental changes in the southern part of the Norwegian-Greenland Sea basins. In contrast, the results of ODP Leg 104 (ELDHOLM, THIEDE et al. 1989) provide us with detailed information about the eastern part of the basin, in particular: 1) the development of paleoenvironments in the Norwegian Sea, especially of the (relatively warm) Norwegian Current system, and 2) the variability of Cenozoic paleoclimate in the northern hemisphere.

The results open important prospects for future deep-sea drilling activities in the northern, western, and southern areas of the Nordic Seas that have not yet been drilled in detail. The new drilling program proposed to JOIDES addresses: 1) the paleoceanographic evolution of the Norwegian-Greenland Sea (cold East Greenland Current versus warm Norwegian Current); and 2) the opening of Nordic Sea gateways and the development of northern hemisphere Cenozoic paleoclimate.

The target areas proposed for renewed ODP drilling are arranged in terms of two transects. One transect extends from the Fram Strait along the East Greenland continental margin to the Denmark Strait following the eastern boundary of the East Greenland Current. The other transect reaches from the northern Iceland Plateau to the south of the Iceland-Faroe Ridge, an important barrier for water masses between the Norwegian-Greenland Sea and the North Atlantic.

3.2 *Continental Margin and Shelf Drilling*

The environmental history of the Canada Basin is being addressed by a cooperative effort between the Geological Survey of Canada (GSC) and the US Geological Survey (USGS). The GSC/USGS effort has two main components. The first component involves field documentation and land-based drilling of the upper Cenozoic terrestrial sequence of the Yukon Basin and the adjacent Old Crow Basin. Outcrop and geophysical evidence suggest several kilometers of sediments are preserved in these basins. Outcrop samples show that the Yukon and Old Crow Basin sections extend well back into the Miocene and contain various types of microfossils and tephra beds that will be useful for dating. Thus, these sequences are likely to contain a good record of the late Cenozoic evolution of terrestrial environments adjacent to the Arctic Ocean.

The second component of the GSC/USGS effort involves marine geophysical studies and piston coring on the

Beaufort Shelf and the Northwind Ridge. Multichannel seismic data and reconnaissance coring indicate a relatively thick Mesozoic to Holocene record is preserved in the Northwind Ridge section. Only the upper and basal units of the Northwind Ridge section have been sampled. Preliminary analysis of cores indicates that upper Quaternary interglacial intervals are represented by foraminifer-rich beds and all interglacials of the Brunhes Epoch appear to be present. In addition, Cretaceous sediments recovered from the base of the section contain foraminifers. Thus, the unsampled section between the Upper Quaternary and Cretaceous has high potential for yielding useful information for understanding the open marine paleoenvironmental evolution of the Canada Basin. Multichannel seismic records from the Beaufort Shelf have revealed structures that bring deep units near the surface. Reconnaissance coring sampled a few of these structures and sediments in the base of these cores which appear to represent preglacial conditions. Although very preliminary, the results from the Beaufort Shelf suggest additional coring in this area can obtain a marginal marine to shelfal upper Cenozoic record that will form an important tie between the mainly terrestrial record from the Yukon and Old Crow basins and the more open marine Northwind Ridge sequence. Similar efforts, organized by Norwegian institutions, are underway in the Barents Sea, led by the Institute for Continental Shelf Studies (IKU) in Trondheim. Comparable programs are carried out or prepared by Soviet institutions in the east European and Siberian shelf seas.

3.3 *Other National and International Efforts*

The perspectives of NAD have been presented to the Arctic Ocean Sciences Board (AOSB) and will be presented to the International Arctic Science Committee (IASC), which is entertaining the foundation of a marine geology and geophysics working group. Program objectives of NAD are closely related to and will be part of the Nansen Centennial Arctic Research Program (NCAP) proposed by the Norwegian Academy of Sciences and the Norwegian Research Council for Science and the Humanities (NAVF). The Arctic System Science Workshop (US-NSF) also recommended an intensified program of research in Arctic Ocean paleoceanography to determine paleoclimatic conditions (MORITZ 1990).

The Past Global Changes (PAGES) core program initiated by the International Geosphere Biosphere Program (IGBP) has a formal liaison with NAD and joint coordinated efforts are in the planning stage. NAD activities must also be considered in relation to PONAM, ECOPS, ARCTIC'91 and NEREIS, all of these projects or activities are being carried out or promoted by international organizations, European Science Foundation (ESF) or national agencies.

NAD will also extend the temporal and regional scope of the ice coring presently carried out on the Greenland ice shield. NAD will benefit from scientific success of the ice drilling because of the different nature of the sample material, the different time scales being addressed and the supporting information drawn from the ocean basin adjacent to the Greenland ice shield.

4. INTRODUCTION TO THE ARCTIC PALEOENVIRONMENTS

4.1 *History of the Arctic*

Global Change

Sea-ice covers and their margins (Fig. 2) have responded rapidly to the extreme climate changes during the most recent geological past (Fig. 1). Oceanic surface water masses close to the sea ice margins cool to below 0° C; as a result, oxygen-rich and dense surface waters sink to the seafloor to contribute to the renewal of the bottom water masses of the global ocean. Through this oceanographic process, the polar and subpolar seas have a global impact on the entire marine environment.

Geological data suggested some time ago (KELLOGG 1976) that the marine ice-covers and their impact on the climate could change quickly and drastically. The most illustrative example is the North Atlantic Ocean and Norwegian-Greenland Sea (Fig. 2) which because of its peculiar oceanography is subject to rapid changes between glacial and interglacial situations. The temperate water masses of the Norwegian Current as a continuation of

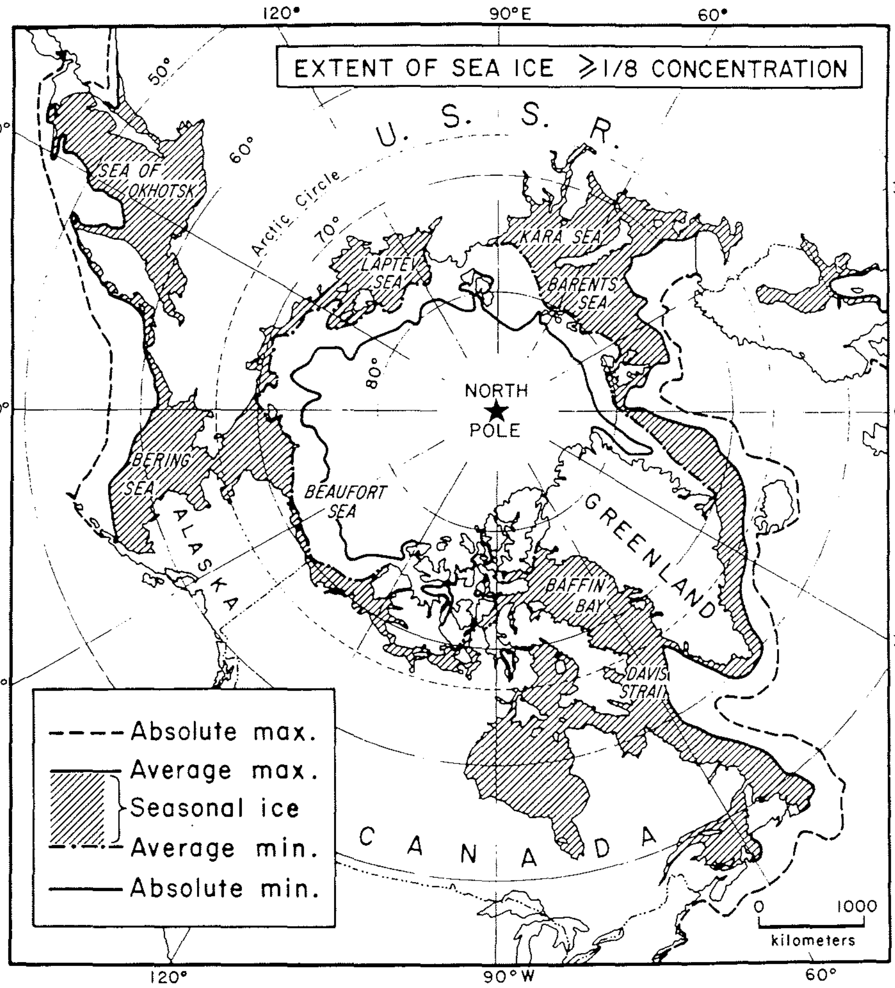

Fig. 2: The average and extreme seasonal limits of Arctic sea ice extent for ice concentrations > 1/8: after Atlas of the Polar Regions CIA, 1978; BARRY 1989.

Abb. 2: Durchschnittliche und extreme Eisrandlagen des arktischen Meereises (für Konzentrationen > 1/8), nach einem Atlas der CIA 1978 und BARRY 1989).

the Gulf Stream, generate a large climatic zonal anomaly leading to comfortable living conditions in northwestern Europe. From historic data (LAMB 1972) and from recent observations of ice-core data in Greenland (DANSGAARD et al. 1989) it is now clear that the nature of the ice cover in the Norwegian-Greenland Sea and probably also in the Arctic Ocean can change rapidly, probably over the time span of decades rather than centuries or millennia.

Determining the spatial and temporal scale of variability of the northern hemisphere sea-ice coverage will therefore be essential for predicting future climatic change due to the "greenhouse" effect. These data are also needed to provide important boundary conditions for climate models, both for the future as well as the past. The data obtained from Arctic deep-sea drill sites will offer important insight into nature, frequency and rate of change. They will be critical for the Global Change Program.

Paleoclimate

The Arctic ice cover is an expression of an extreme climatic scenario which only developed during the Cenozoic cooling of both poles (Fig. 3). Glaciation of the poles has been observed several times during the earth's history and can be documented for a few relatively short intervals which are separated by long time spans with apparently little or no polar ice (FRAKES 1980). The Cenozoic evolution of polar ice caps is only the most recent example of the development of glacial climates with extreme temperature gradients between tropical and polar regions.

As far as documented in the geological record all "glacial" climates older than the Cenozoic one led to uni-polar glaciation because only one of the polar regions was covered by a large continent, while the other one was in open marine deep water. It is only during the Cenozoic that plate tectonic processes generated a climatically isolated land area over the south pole and an oceanographically isolated ocean basin over the north pole which were both repeatedly, but in very different ways affected by glaciations (Fig. 3).

The climatic change leading from the temperate late Mesozoic and early Cenozoic climates on earth to the modern extremes is one of the most exciting and least understood chapters of the earth's history. The efforts of ODP have provided many new and exciting insights to Antarctic paleoceanographic change during the past 60 my (Fig. 3b). In the northern hemisphere, however, deep-sea drilling has only reached the subpolar basins of the north Atlantic (ODP Leg 104, 105, DSDP Leg 38) and of the North Pacific (DSDP Leg 19). A key for understanding Mesozoic and Cenozoic northern hemisphere climates is still hidden in the sedimentary sequences of the Arctic Ocean itself. Therefore, understanding the processes of oceanographic and climatic change during the past 80-100 my has the highest priority of this proposal.

Plate Tectonics

When considering the present understanding of the tectonic and paleogeographic evolution of the northern hemisphere including the Arctic Ocean, there is no question that many regional basement structures are unknown or little understood. Figures 3a and 4 illustrate well the present plate configuration whereas Figure 5 depicts the first map showing the Arctic Ocean as a deep-sea basin published by F. NANSEN (1897, 1904) after return from

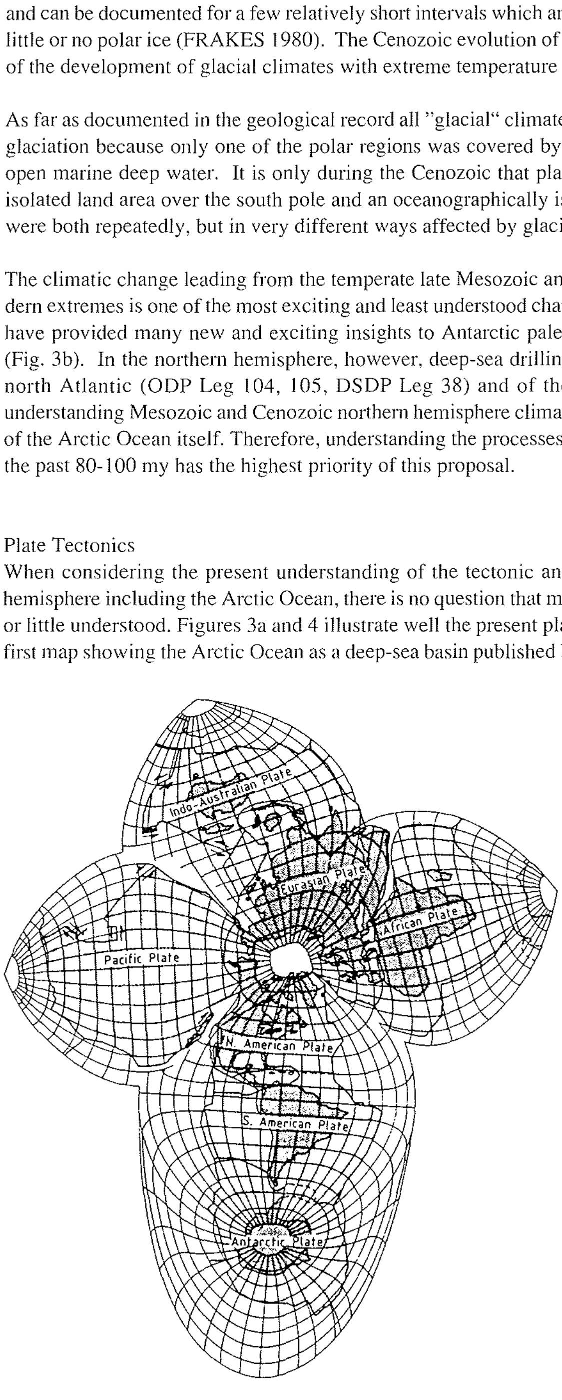

Fig. 3a: Distribution of land and sea on the modern Earth, with Antarctica and the Arctic Ocean as climatically and oceanographically isolated regions. After an equal area map of the world prepared by SPIELHAUS (1983), from BLEIL & THIEDE 1990.

Abb. 3a: Heutige Verteilung von Land und Meer auf der Erde mit der Antarktis und dem Nordpolarmeer in einer klimatisch und ozeanographisch isolierten Position. Nach einer flächentreuen Karte der Erde von SPIELHAUS 1983, aus BLEIL & THIEDE 1990.

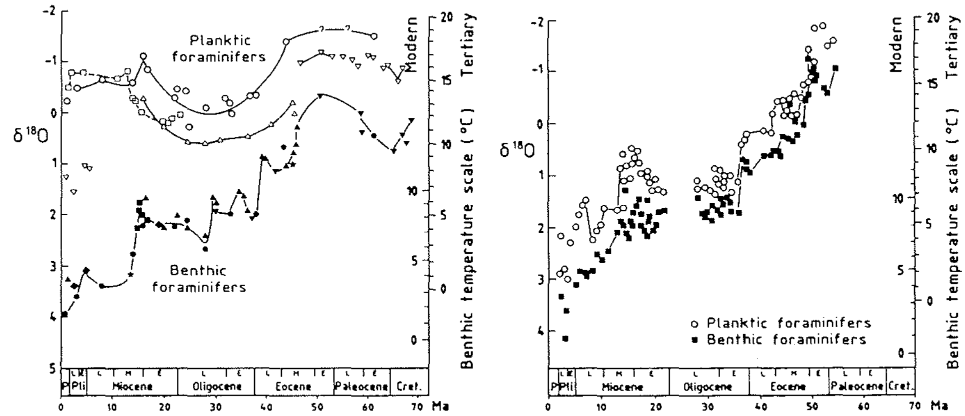

Fig. 3b: Paleotemperature variations of ocean surface and bottom waters in the North Pacific (left: after SAVIN 1977) and in the sub-Antarctic Pacific (right: after SHACKLETON & KENNETT 1975) as deduced from oxygen isotope ratios in the skeletal parts of calcareous benthic and planktic foraminifers (after KENNETT 1982).

Abb. 3b: Paläotemperaturschwankungen der ozeanischen Oberflächen-und Bodenwassermassen im Nordpazifik (links : nach SAVIN 1977) und im sub-Antarktischen Pazifik (rechts: nach SHACKLETON & KENNETT 1975), abgeleitet aus den Sauerstoffisotopenverhältnissen in den Gehäusen von kalkschaligen benthischen und planktischen Foraminiferen (nach KENNETT 1982).

his epic expedition. Past movements of the North American/Greenland and Eurasian plates over the northern hemisphere have controlled the paleogeographic and paleobathymetric Cenozoic evolution of the Arctic and its gateways to the world ocean.

Whereas the Cenozoic history of seafloor spreading in the Labrador Sea/Baffin Bay and Norwegian-Greenland Sea systems are well understood and the course of the mid-ocean ridge is well defined, the complicated plate boundaries of Fram Strait and of the slow spreading, very deep Gakkel Ridge are poorly known and little investigated (Fig. 4). The form of crustal accommodation of the Gakkel Ridge entering the Laptev Sea shelf represents one of the few examples of an intersection of an active spreading center with a passive continental margin. While Cenozoic spreading explains the opening of the eastern Arctic and the shapes of the continental margins between the Eurasian continental margin and Lomonosov Ridge, the nature of the basement units (Lomonosov Ridge, Alpha-Mendeleev Ridge) and the age of the generation of interspersed deep-sea basins (Makarov Basin, Canada Basin) are virtually unknown. Reconstructions of the paleogeography prior to Cenozoic times of the older Arctic Ocean subbasins is therefore hypothetical at best (see below), but are clearly needed for future hydrocarbon exploration.

Many of the problems of Arctic structural geology can only be solved by means of drilling so we can determine the age and identify the basement rocks. Without such data no satisfying plate tectonic reconstructions of this important deep-sea basin, which apparently existed since mid-Mesozoic time, can be achieved. A detailed knowledge of the age and nature of all major Arctic Ocean basement units is indeed a prerequisite to solving its paleogeographic and paleoenvironmental history. However, because of the regional extent of many of the structural units drilling of these basement targets has the second priority.

4.2 *Specific Stratigraphic Problems*

Aside from the technical challenges of deep-sea drilling and site surveying, one specific scientific problem has prevented much progress in our understanding of Arctic Ocean history. Despite the numerous sediment cores which have been taken from ice-islands and icebreakers in the Arctic since the mid-sixties (CLARK et al. 1980) little progress has been achieved in establishing a quantitative chronostratigraphic framework. Great uncertainties exist in the interpretation of bio-, magnetic-, aminoacid- and isotope-stratigraphic data which have been published about many of these cores by North American and European authors.

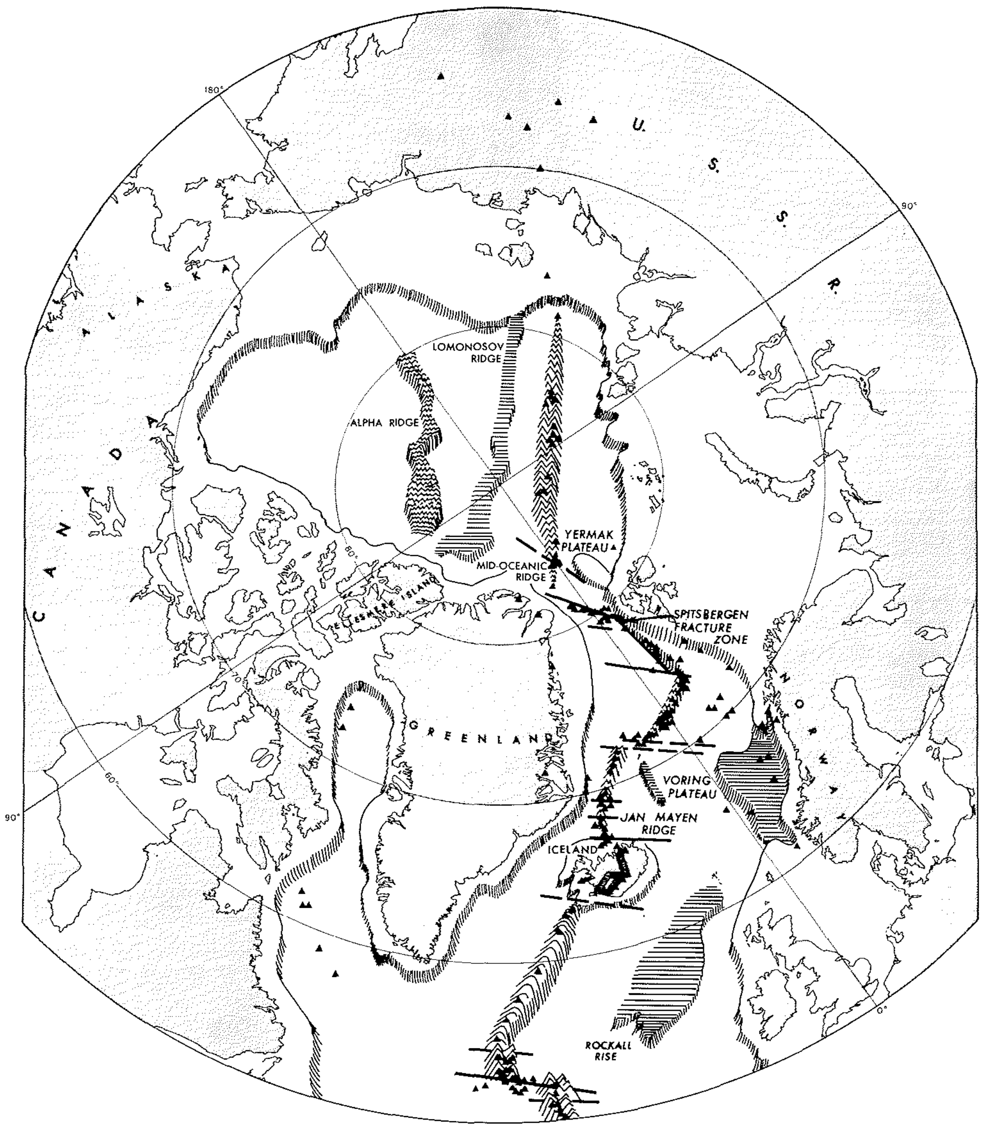

Fig. 4a: Physiographic chart of the Arctic schematically showing major structural elements of the Arctic (JOHNSON et al. 1979).

Abb. 4a: Physiographisches Diagramm des Nordpolarmeeres und der angrenzenden Tiefseebecken, in dem schematisch die wichtigsten tektonischen Einheiten gezeigt sind (JOHNSON et al. 1979).

Biostratigraphic interpretations have been used to date the few Mesozoic and Paleogene cores which are available from the Arctic. However, the endemic nature of many of the floras and faunas used for these interpretations makes any detailed correlation to temperate or tropical areas tentative. The presently available age assignments for these older cores have to be considered tentative at best (Fig. 6).

The suite of cores documenting Neogene and Quaternary intervals of the Arctic Ocean history has been correlated by means of biostratigraphic and lithostratigraphic methods. Their correlation is convincing and suggests that the sequence of lithostratigraphic units reflects a variety of depositional, basin-wide environments which developed in the entire Arctic during the youngest geological past. However, the detailed correlation of the Arctic

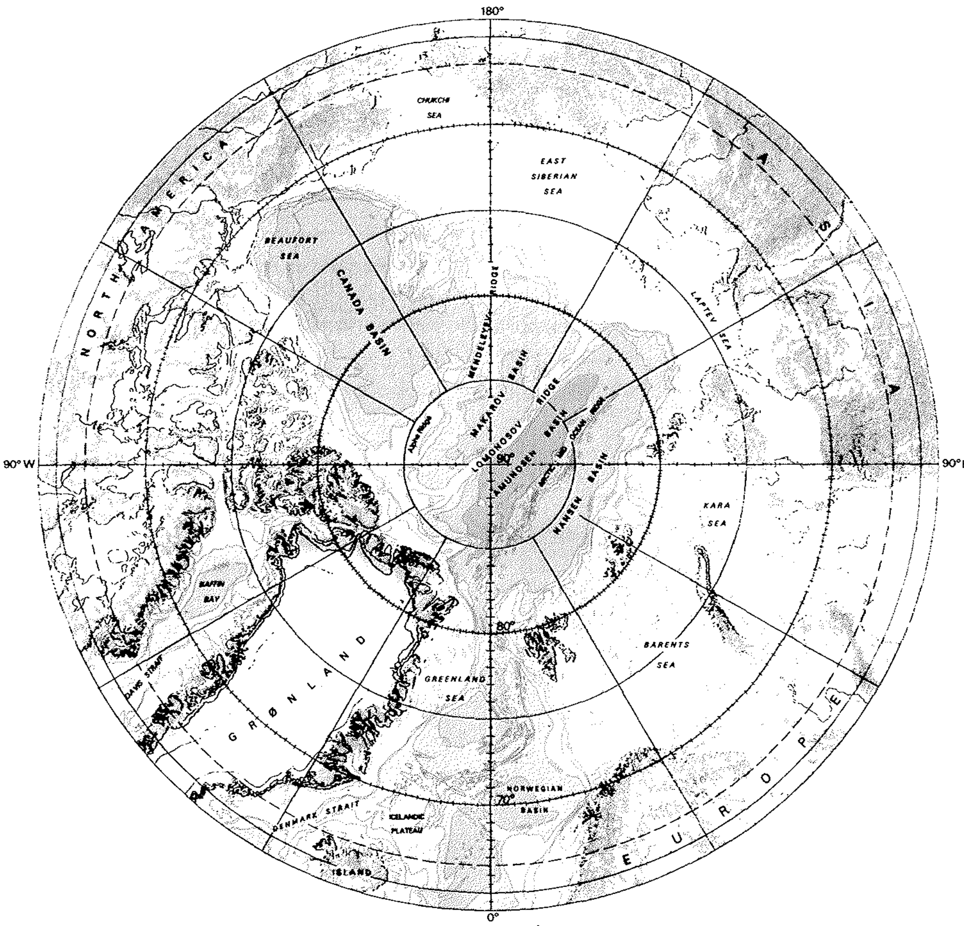

Fig. 4b: General Bathymetric Chart of the Arctic Ocean (GEBCO, Sheet 5.17) and adjacent deep-sea basins (JOHNSON et al. 1983).

Abb. 4b: GEBCO-Karte (Blatt 5.17) des Nordpolarmeeres und der angrenzenden Tiefseebecken (JOHNSON et al. 1983).

paleoceanographic record to temperate subtropical deep-sea basins and the terrestrial record requires further study and data.

Only the surface sediments of some of the Arctic Ocean cores have been dated in detail by radiocarbon methods. The results suggest that we are dealing with sediments of very low sedimentation rates in the central Arctic (CLARK et al. 1986) whereas sedimentation rates are higher in the eastern Arctic (ZAHN et al. 1985).

Even though a number of stable oxygen and carbon isotope curves have been established on sediment cores from the central Arctic Ocean it has been very difficult to interpret them. The range of the oxygen isotope ratios (planktic foraminifers) in Pleistocene sediments is somewhere between $\partial^{18}O$ 4.0-4.5 ‰ in the central Arctic Ocean which is approximately 2 ‰ higher than the value of the global ice-volume signal in isotope curves of some tropical latitudes (IMBRIE et al. 1984). An explanation in terms of a temperature difference suggests unreasonably warm surface waters which is contrary to the belief that the Arctic has been ice covered both during glacial and interglacial periods. The drastic changes of the oxygen isotope ratios therefore seem to be much more easily explained by salinity fluctuations in the course of the deglaciation processes affecting the Arctic Ocean.

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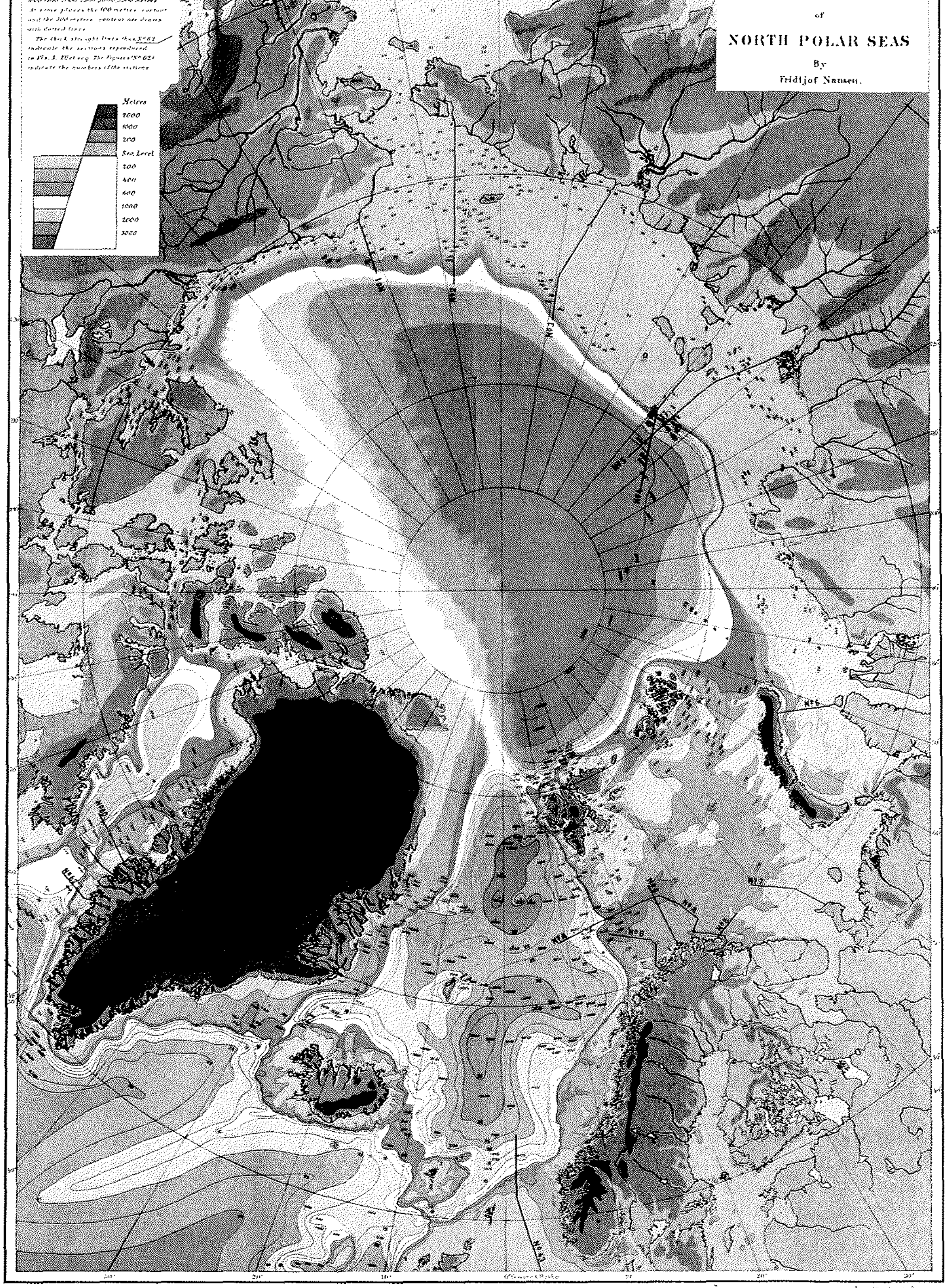

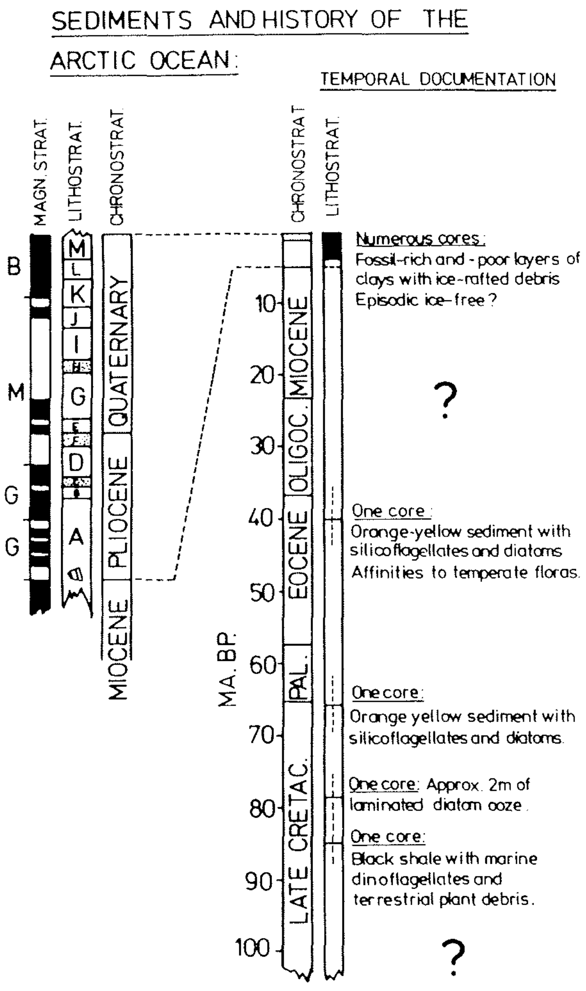

Fig. 6: Available records of sediments and history of the Arctic Ocean. Recent coring by the USGS on Northwind Ridge has added to the Cretaceous record (PHILLIPS et al. 1990).

Abb. 6: Verfügbare Dokumentation der Sedimentationsgeschichte der arktischen Tiefsee. Neue Sedimentkerne, die vom USGS auf dem Northwind-Rücken gesammelt worden sind, haben die Informationen über die Kreidezeit erweitert (PHILLIPS et al. 1990).

4.3 *Arctic Paleogeography*

To support the high priority given to determination of the evolution of the Arctic paleoenvironment, some major aspects of Mesozoic and Cenozoic paleoceanography need to be briefly described.

There have been numerous attempts to reconstruct the paleogeography as well as the paleobathymetry of the Arctic basin (GREEN et al. 1982). However, none has solved some of the major paleophysiographic constraints of the paleoceanographic evolution of the Arctic Ocean. Many of the deep-sea basins of the Arctic have been reconstructed based on a compilation and interpretation of seafloor spreading type magnetic anomalies (Fig. 7 and see also TAYLOR et al. 1981). This compilation may be supplemented by Russian data in the eastern Arctic (cf. VOGT 1986); it offers a good impression of the data coverage available from the entire Arctic basin as well as the sub-Arctic Norwegian-Greenland Sea and Labrador Sea/Baffin Bay areas. The maps of VOGT (1986) and

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Fig. 5: First bathymetric chart depicting the Arctic Ocean and the Norwegian-Greenland Sea as contiguous deep-sea basins, compiled after F. Nansen's epic expedition on the *Fram* 1893-1896 (NANSEN 1897, 1904).

Abb. 5: Erste bathymetrische Darstellung, die das Nordpolarmeer und das Europäische Nordmeer als zusammenhängende Tiefseebecken zeigt und die nach F. Nansen's berühmter Expedition auf der *Fram* 1893-1896 zusammenstellt wurde (NANSEN 1897, 1904).

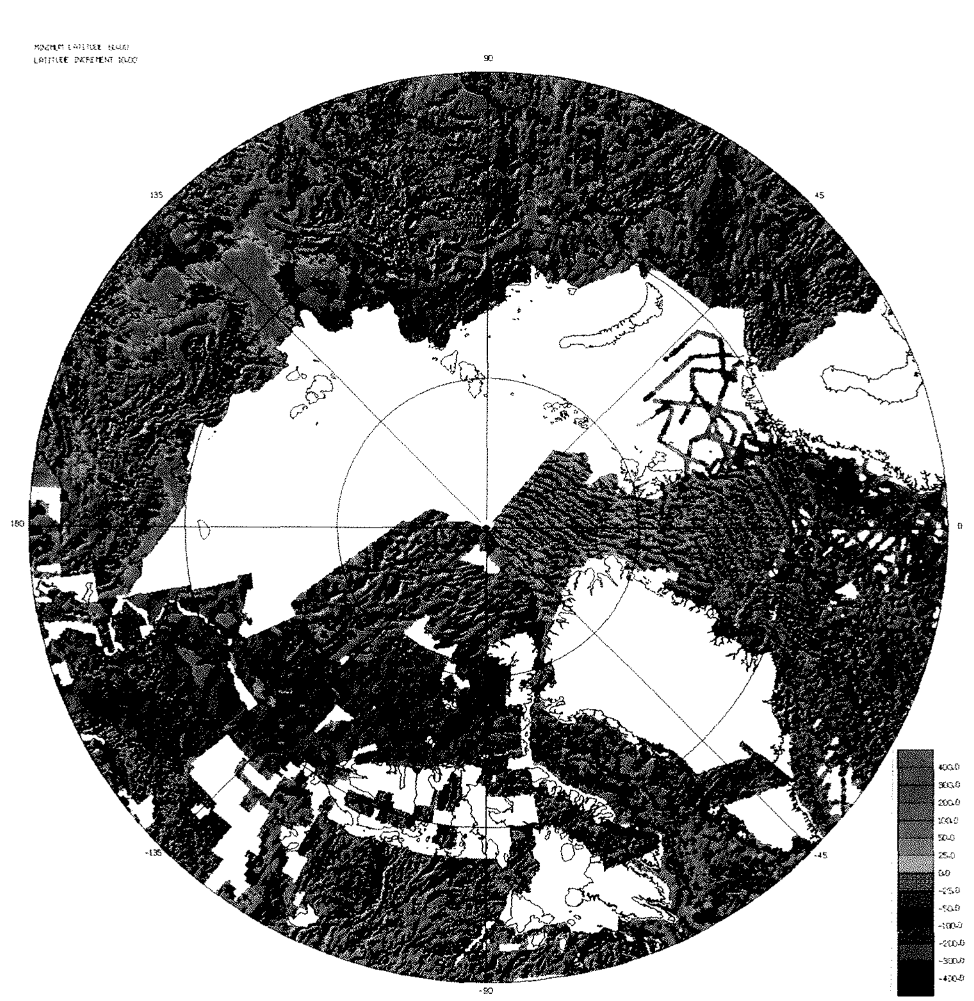


Fig. 7: This preliminary shaded relief map of the magnetic anomaly of the Arctic was produced from a data base assembled at the Atlantic Geoscience Center (AGC) of the Geological Survey of Canada; additional data sets are being acquired from international sources to fill as much of the map area as possible. Some *ad hoc* levelling has been applied to the merged data for plotting purposes; final adjustment and levelling will be done after all available data sets have been incorporated in the data base. The final map is expected to be ready for distribution at the end of 1992.
Illumination is from the upper left hand corner. The plot was produced by G. Oakey, J. Verhoef, R. Macnab and members of the AGC Project Team compiling magnetic data from the Arctic and North Atlantic Oceans.

Abb. 7: Vorläufige, schattierte Reliefkarte der arktischen magnetischen Anomalien, die nach am Atlantic Geoscience Center (AGC) des Geological Survey of Canada gesammelten Daten zusammengestellt worden ist. Die Karte wird fortlaufend um neue Datensätze aus in- und ausländischen Quellen erweitert, um einen möglichst großen Teil der Karte zu dokumentieren. Einige Glättungsverfahren wurden bereits angewandt, um die Daten darstellen zu können. Die abschließende Abgleichung und Glättung der Daten werden erst vorgenommen, wenn alle verfügbaren Datensätze erfaßt sind. Die ausgearbeitete Karte wird Ende 1992 verfügbar sein.
Das Relief ist von links oben beleuchtet. Die vorliegende Karte wurde gefertigt von G. Oakey, J. Verhoef, R. Macnab und den Mitgliedern der AGC Projektgruppe, die die magnetischen Daten aus dem Arktischen und Nordatlantischen Ozean zusammenstellen.

other authors compare well with data published and interpreted by SRIVASTAVA (1985).

The convincing and successful deciphering of the Cenozoic magnetic anomalies in the Norwegian-Greenland Sea and in the eastern Arctic easily allows a detailed reconstruction of the Cenozoic paleobathymetric and paleogeographic evolution of these deep-sea basins, as shown by VOGT (1986), in Figure 8. The available data illustrate how the eastern Arctic basin and the adjacent Norwegian-Greenland Sea were generated from late Paleocene/early Eocene times until present. At first they consisted of isolated deep-sea basins which were only later connected through the deep water channel of Fram Strait (THIEDE et al. 1990). The major question arises as to when Fram Strait actually allowed deep water exchange. New seismic reflection data collected by Norwegian

Fig. 8: Reconstruction of the Cenozoic paleogeography and paleobathymetry in the European Nordic Seas (VOGT 1986).

Abb. 8: Rekonstruktion der känozoischen, paläogeographischen und bathymetrischen Verhältnisse im Europäischen Nordmeer und im östlichen Nordpolarmeer (VOGT 1986).

researchers in the areas of the Svalbard and north-east Greenland continental margins (JACKSON et al. 1990; FALEIDE 1990) suggest a complicated evolution of this transform margin which was subdivided into many small subbasins with a very complicated seafloor spreading structure between Greenland and Svalbard. Originally, it was thought that Fram Strait opened at magnetic Anomaly 13 time (approximately 30-35 Ma). These new data and the assumed histories of Yermak Plateau and Morris Jesup Rise in terms of build-up due to volcanic events and of their paleogeography and paleobathymetry make a much later opening of Fram Strait for deep water circulation more plausible. An effective deep water channel might not have existed before late Miocene and even Pliocene times (KRISTOFFERSEN 1990).

The older Arctic deep-sea basins between Lomonosov Ridge and Alpha-Mendeleev-Ridge and the Amerasian continental margins can for simplicity's sake be considered "frozen" during Cenozoic times even though the history of Bering Strait and of the Amerasian continental margin adjacent to it suggest considerable changes during Cenozoic times.

The opening of the Makarov and Canada basins is an unsolved riddle. None of the available reconstructions have solved the problem of paleogeographic and paleobathymetric evolution of the older Arctic deep-sea basins to our satisfaction. Much depends on the point of view of the various authors since the interpretation of the magnetic anomalies for example presented by TAYLOR et al. (1981) is not acceptable to all of them. Some authors prefer different base data leading to alternative paleogeographic scenarios. However, there seems to be little doubt that

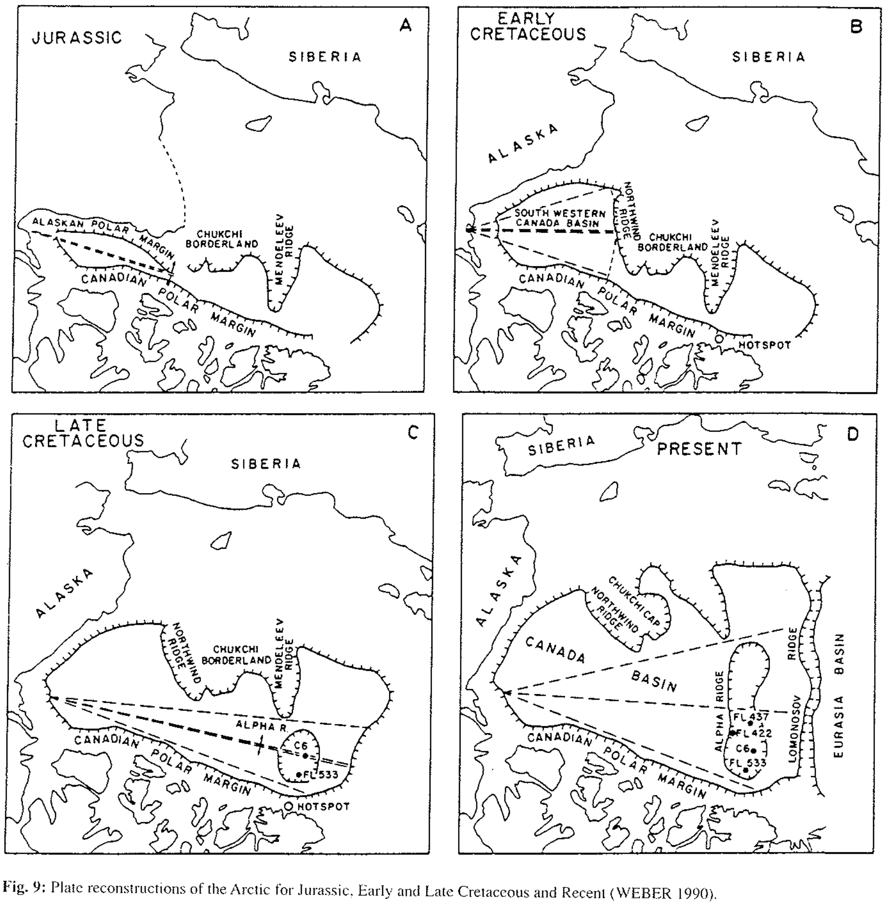


Fig. 9: Plate reconstructions of the Arctic for Jurassic, Early and Late Cretaceous and Recent (WEBER 1990).

Abb. 9: Platttentektonische Rekonstruktion der Arktis für Jura, Unter- und Oberkreide und heute (WEBER 1990).

the earliest Arctic deep-sea basin evolved in Jurassic times, that seafloor spreading opened the Canada Basin mainly in the course of the Cretaceous and that the Arctic Ocean for most of the Mesozoic consisted of an isolated deep-sea area with no major deep-water connection to the world ocean (Fig. 9). Since the volcanic history of Alpha Ridge, its potential connection to the Mendeleev Ridge, and the opening of Makarov Basin are not known, no further progress can presently be achieved on the tectonic history during late Cretaceous/early Tertiary times which preceded the re-adjustment of the northern hemisphere plate boundaries.

5. THE MODERN ARCTIC OCEAN AND ITS DEPOSITIONAL ENVIRONMENTS

Arctic sea-ice cover (Fig. 2) has existed for several million years affecting global heat budgets and therefore the global climate system. However, knowledge about the modern environmental setting of the Arctic Ocean is

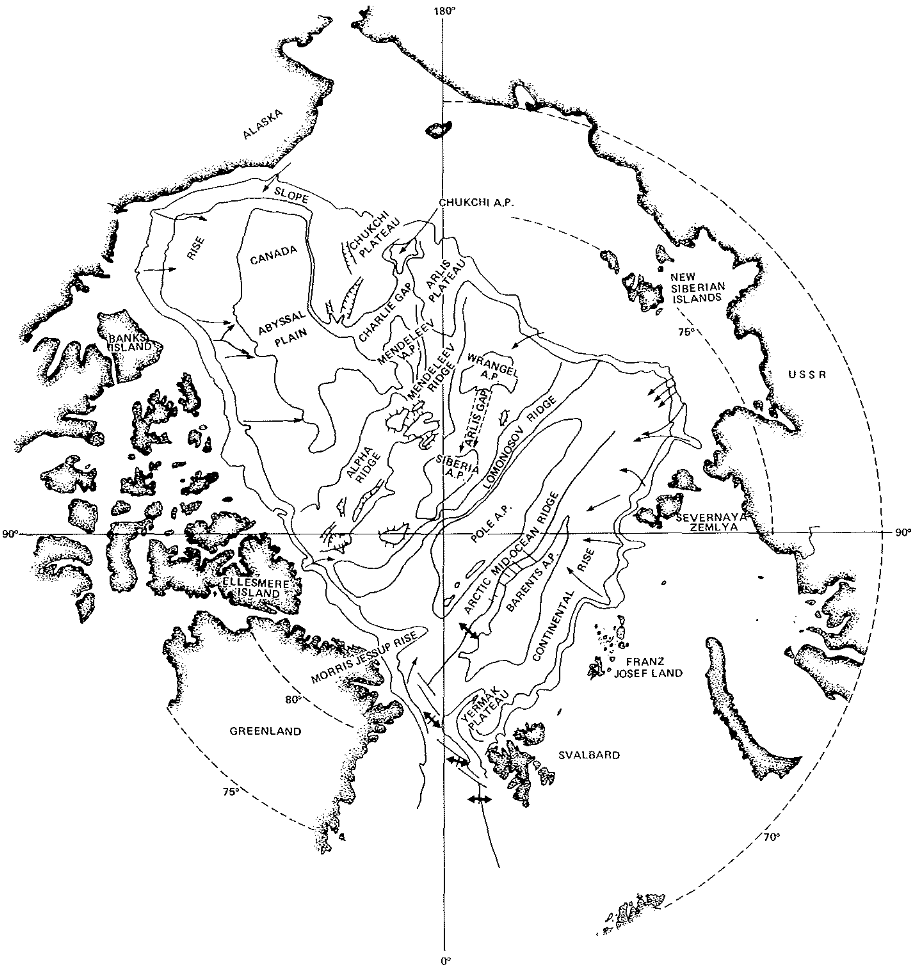


Fig. 10: Physiographic provinces of the Arctic. Heavy arrows denote plate motion away from spreading center; thinner arrows are major submarine canyon systems; compare with Figure 4a (JOHNSON et al. 1979).

Abb. 10: Physiographische Einheiten der Arktis. Dicke Pfeile markieren die Richtungen der Plattenbewegungen relativ zum mittelozeanischen Rükken; dünne Pfeile kennzeichnen submarine Canyon-Systeme, vergl. auch Abbildung 4a (JOHNSON et al. 1979).

extremely poor. For example, the origin and the sedimentary budget of sea ice transport is not known. Despite 100 years of studies on ice motion and ice budget in the Arctic Ocean, many details of the variations in seasonal and annual ice drift (min./max. sea ice extent) and sea ice character (first versus multiyear ice) as well as their relation to climatic changes are poorly known.

For the purposes of NAD research, the processes and characteristics of the Arctic ice pack, especially distribution and concentration of multiyear ice, and motion and drift patterns of the sea ice, are the most important features of the modern Arctic environment. A general description of the sedimentary environment and the hydrography of the modern Arctic Ocean is a very important prelude to NAD; it represents a base for any paleoenvironmental reconstruction, and is needed for planning and operational purposes.

5.1 *Physical Setting and Hydrography*

Many of the distinctive biogenic and sedimentological features, as well as the ice distribution and drift in the Eastern Arctic, are related to the presence of relatively warm water advected northward from the Atlantic into the Arctic Ocean through Fram Strait and the Barents Sea. Hydrography of the Arctic water is strongly influenced by river runoff, sea ice formation and decay and the incoming Atlantic water through Fram Strait.

The physical setting of the Arctic Ocean includes several major features (Fig. 10): the submarine Lomonosov Ridge subdivides the Arctic Ocean into the Canadian and the smaller Eurasian Basin (subtle differences in the deep-water properties of both basins provided the first clue to the existence of Lomonosov Ridge). The Eurasian Basin is subdivided by an active midocean ridge, the Gakkel Ridge, into the Nansen and Fram basins. About 36% of the Arctic Ocean is occupied by the shelf areas, especially the broad and shallow Siberian shelves (East Siberian, Laptev and Kara seas) with a maximum width of 800 km. The shelf areas are generally low energy environments. Weak currents and deposition of suspended sediments from rivers characterize major parts of the Arctic shelves.

The riverine freshwater supply results in a density stratification in the uppermost 100-200 m of the water column (Fig. 11). The low salinity layer has a strong stratification in summer caused by the melting of sea ice decreasing vertical mixing and heat exchange between ocean and atmosphere. The residence time of the surface waters is about 10 years (BARRY 1989). Sea ice formation occurs mainly on the shallow shelves. The extensive ice formation on the shelves causes the rejection of high saline, low temperature solutions (brines), which sink and flow from the shelves across the slopes into the deep ocean. The supply of fresh, oxygen-rich winter water by this process and convective chimneys in the Norwegian-Greenland Sea are the most important processes for formation of North Atlantic Deep Water (NADW) and thus for ventilation of the world deep ocean.

AAGAARD et al. (1985) suggested that the large-scale circulation of the Arctic Ocean occurs in a cyclonic flow of narrow boundary currents along the periphery of the major basins (Fig. 12). The main driving force of the thermohaline circulation in the Arctic Ocean is the formation of sea ice mainly in the marginal shelf regions. In addition to the importance of the exchange with the world ocean through primarily Fram Strait, Barents Sea, Labrador Sea and Bering Strait the Arctic oceanography seems to be mainly forced and influenced by its marginal areas (AAGAARD 1989). Oceanographic data as well as sedimentological data demonstrate that the Arctic Ocean is not a single uniform ocean basin. At least one has to distinguish between the two major basins, the Eurasian and the Amerasian Basin, with a weaker deep circulation in the Amerasian Basin and therefore a much longer time scale for deep water renewal (AAGAARD 1989).

The $\partial^{18}O$-distribution in the central Arctic Ocean indicates that during the winter season the only freshwater source is runoff with an addition of brine by forming sea ice (ANDERSON & DYRSSEN 1989). ^{18}O-data also allow the calculation of the fractions of Atlantic water, river runoff to and sea ice in the central Arctic Ocean. Investigations of the $\partial^{18}O$ in planktic foraminiferal tests in Recent seafloor sediments of the Eastern Arctic Ocean indicate the sensitivity of planktic organisms to water temperature and salinity (KÖHLER 1991). The record of the foraminiferal tests strongly reflects the recent oceanography of more saline Atlantic water and less saline polar waters.

The only previous study of freons in the Nansen Basin indicated the presence of significant levels of freon. More recently however, a surprising finding of the ARK IV/3 expedition was the measurement of a large pool of water in the center of Nansen Basin below 3000 m with no detectable freon. This strongly indicates that the deep water is at least several decades old (THIEDE et al. 1988, WALLACE et al. in press).

5.2 *The Ice Cover of the Arctic Ocean*

Composition and interactions of Arctic sea ice

The Arctic Ocean and its surrounding seas occupy an area of 14 million km^2, which is totally ice covered in wintertime (Fig. 2). Sea ice is the most important feature of the Arctic environment and the main reason for the lack of scientific data from the central Arctic Ocean. The Arctic environment is characterized by a strong seasonality, caused by the change in solar radiation. In August and September at the end of the melting season

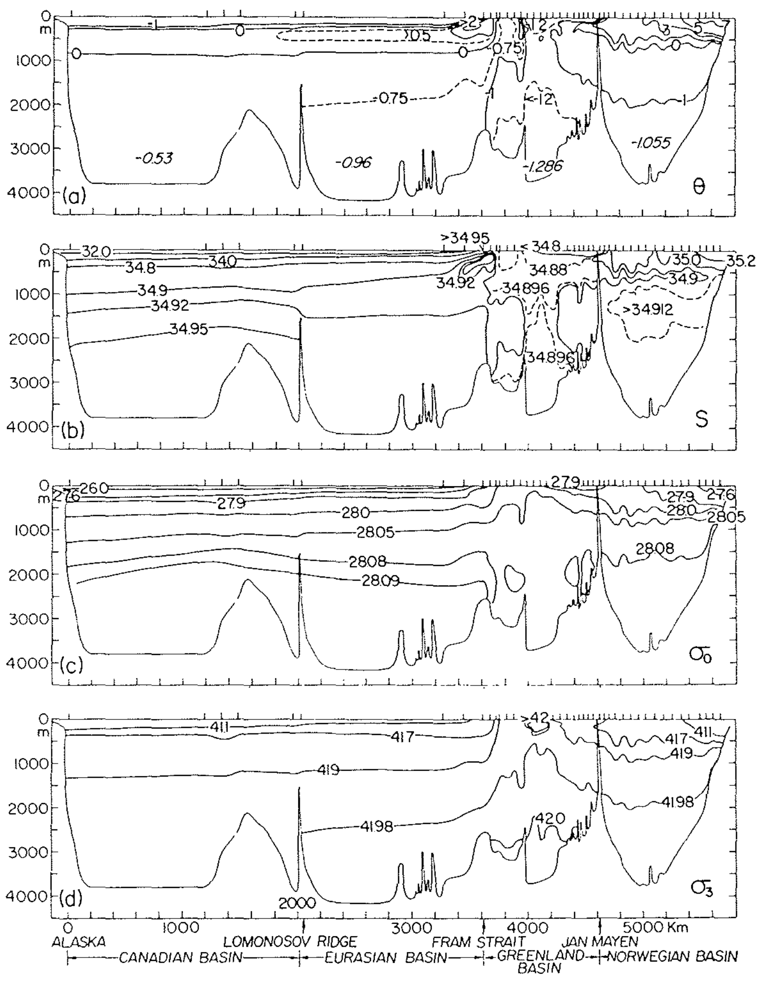


Fig. 11: Distribution of potential temperature, salinity, and density across the Arctic Ocean and the Greenland and Norwegian seas (AAGAARD et al. 1985).

Abb. 11: Verteilung von potentieller Temperatur, Salzgehalt und Dichte entlang eines Schnittes durch das Nordpolarmeer und das Europäische Nordmeer (AAGAARD et al. 1985).

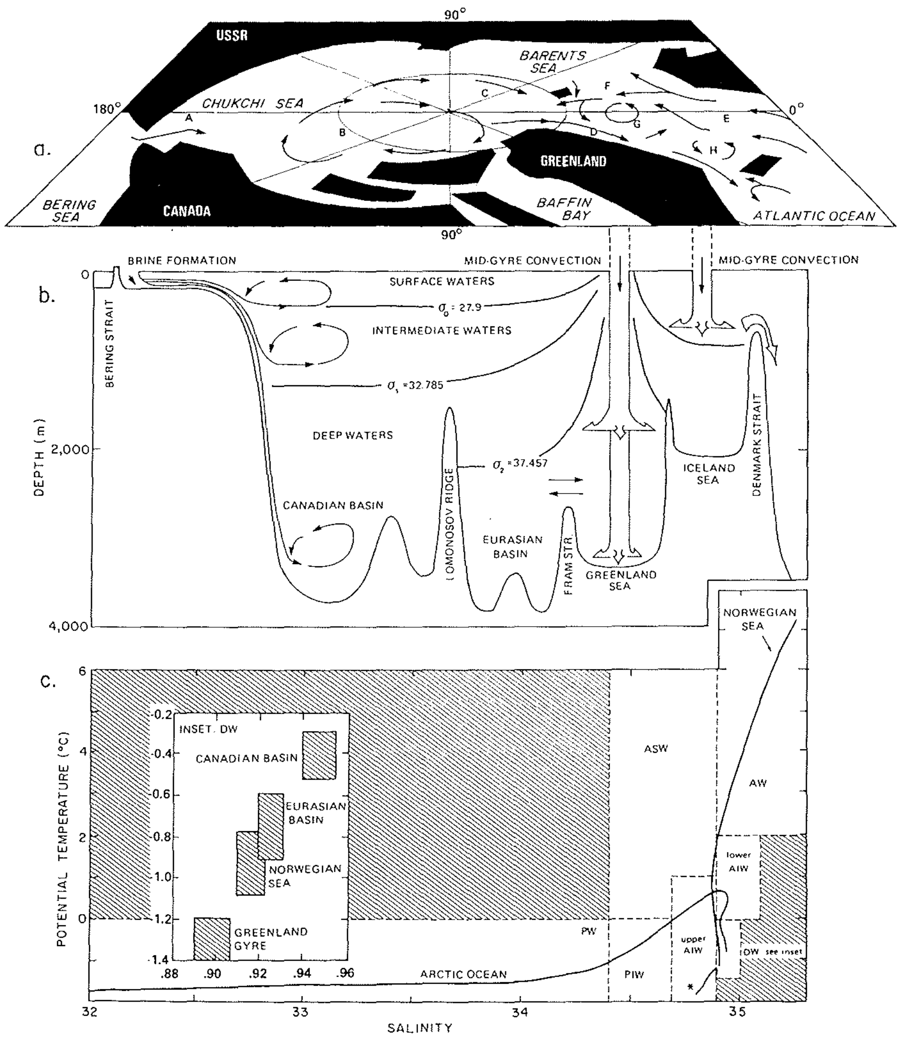


Fig. 12: Schematic circulation and water mass structure in the Arctic Ocean and the Greenland and Iceland Seas. The upper panel represents near-surface circulation only (AAGAARD et al. 1985).

Abb. 12: Schematische Darstellung von Strömungen, Struktur der wichtigsten Wassermassen des Nordpolarmeeres, der Grönland- und der Islandsee. Das obere Diagramm gibt nur die Zirkulation der oberflächennahen Wassermassen wieder (AAGAARD et al. 1985).

the minimum ice extent is only approximately 8 million km^2 (Fig. 2) in comparison to the 14 million km^2 in winter. As a result about 50 % of sea ice survives the melting season and becomes second- or (after more than one summer) multi-year ice in the Arctic ice pack. Thus, the Arctic pack ice is a mixture of young (i.e., first-year), second- and multiyear sea ice with a highly variable thickness. Only relatively small amounts of glacier ice (icebergs, etc.) are present in the central Arctic Ocean. Source areas for icebergs are the Canadian Arctic (e.g. Ellesmere and Devon Island), Svalbard, Novaya Zemlya and the New Siberian Islands. Today, therefore, iceberg rafting affects mainly marginal areas, such as the Barents Sea and the areas west of Greenland (Baffin Bay, Labrador Sea). Accordingly, sedimentation of coarse-grained sediments (> 0.2 mm) is expected to be very low under today's "interglacial" conditions in the central Arctic.

One of the most important parameters in global climate models is the extent and albedo of sea ice. The thin sea ice cover separates two media with usually steep temperature-gradients, the ocean and the atmosphere. Sea ice has a dramatic influence on marine biota and oceanography. The interactions of sea ice cover and hydrography are shown in Figure 13. The most important area for geological and biological investigations of the modern Arctic environment is the marginal ice zone (SAKSHAUG & SKJOLDAL 1989). This area is characterized by freshwater supply, brine release and ice edge upwelling. The release of nutrients and particulate material caused by the formation and decay of ice results in phytoplankton blooms, increased density of populations of Arctic life (seals, polar bears, whales) and increased sedimentation of biogenic and lithogenic material.

Albedo of the Arctic ice pack is thought to be one of the major controls on climatic changes. Sediments connected with biogenic material decrease the albedo of sea ice. Nearshore sea ice has an albedo reduction of 20 % during the melting season (LANGLEBEN 1966). Similar values were measured on wet and dirty snow (WARREN & WISCOMBE 1980). Measurements of light transmission show a reduction of algal growth under sea ice due to fine-grained particles and experiments with kelp indicate an increased growth of 35 % under clean sea ice (DUNTON & SCHONBERG 1980).

The extent of the marginal ice zone is largely controlled by ocean, wave and ice interaction caused by prevailing wind characteristics. North of the oceanic Polar Front in the Barents Sea VINJE (1985) noted that ice disintegration in summer is influenced by meteorological factors, i.e., radiative warming of surface water and direct radiative melting of the ice. Wave and tide effects (NANSEN 1897; EINARSSON 1972; WADHAMS et al. 1979) and turbulent heat transfer from the air and wind drift also cause rapid disintegration of ice fields (VINJE 1985).

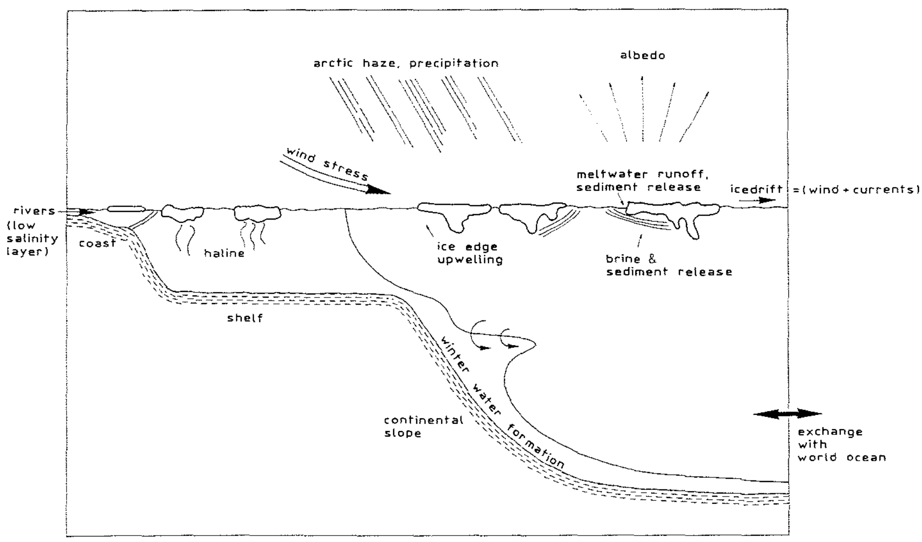


Fig. 13: Arctic sea ice interactions (WOLLENBURG 1991).

Abb. 13: Einflüsse auf Bildung und Eigenschaften des arktischen Meereises (WOLLENBURG 1991).

Ice motion in the Arctic Ocean

The mean ice drift in the Arctic is in general well known (Fig. 14), but some irregularities and annual variations complicate this pattern. The ice drift is only a vague indicator of the origin of a particular floe and the distribution pattern and budget of old multiyear ice are an unsolved problem of the dynamics of the ice cover. Sea ice drift is a very complex balance of wind and water movements, Coriolis force, tides, air pressure gradients, internal pressure and strength of the ice. But primarily the daily motion is generated by synoptic wind; minor forces for ice drift are surface currents and the horizontal stress component within the ice (COLONY & THORNDIKE 1984).

Two major circulation patterns characterize Arctic sea ice drift. In the Amerasian Basin, long periodic ice drift is characterized by an anticyclonic movement (i.e., the Beaufort Gyre, Fig. 14). The position of the Beaufort Gyre is defined by the axis of the atmospheric pressure system. The ice in the Beaufort Gyre system is the oldest in the Arctic Ocean with an average age of about 10 years (GIERLOFF-EMDEN 1982) and a maximum age of about 16 years (KOERNER 1973). Drift data suggest an average time of 8 years for one rotation.

The main ice drift in the eastern Arctic is characterized by the Transpolar Drift. The Beaufort Sea is an important source for sea ice in the Beaufort Gyre region (COLONY & THORNDIKE 1985) which carries sea ice westward across the Arctic Ocean (e.g. NANSEN 1897; KOCH 1945; COLONY & THORNDIKE 1985). Much of this ice exits through Fram Strait (COLONY & THORNDIKE 1985) after undergoing several years of melting, refreezing, and deformation. The drift in the Transpolar Drift Stream is calculated in average 2-3 years with a maximum of 5 years (KOCH 1945; COLONY & THORNDIKE 1985; WEEKS 1986; KOERNER 1973).

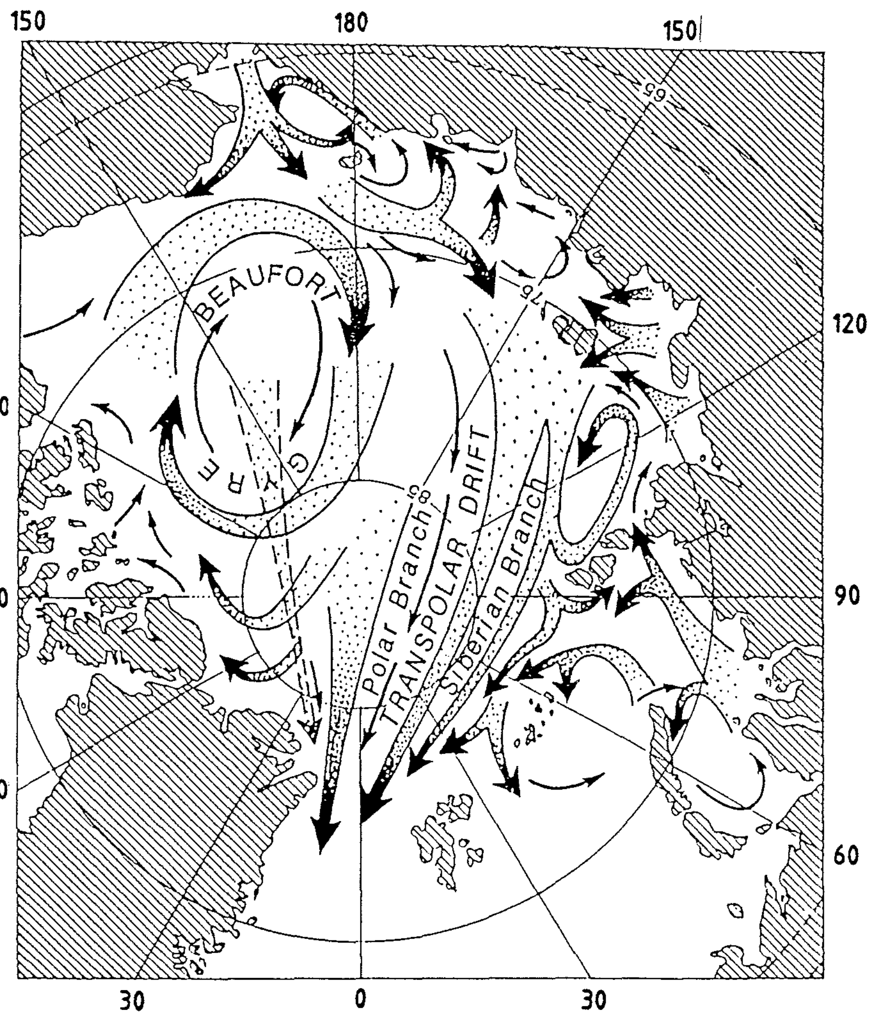


Fig. 14: Main surface drift pattern in the Arctic Ocean (after GORDIENKO & LAKTIONOV 1969).

Abb. 14: Die wichtigsten Driftsysteme des arktischen Meereises (nach GORDIENKO & LAKTIONOV 1969).

Station			Rates in nm/day actual	real	Coefficient of meandering
A) TRANSPOLAR DRIFT Including W leg of Pacific Gyral					
Chukchi Sea side					
NP 2	1950-51	(23)	3.7	0.9	4.1
NP 4	1954-55	(18)	3.7	0.8	4.3
NP 6	1956-57	(7)	3.8	0.5	7.2
NP 6	1957-58	(8)	3.9	1.1	3.4
Centre					
NP 4	1955-56	(19)	3.7	1.1	3.2
NP 5	1955-56	(11)	3.7	1.2	3.1
NP 7	1957-58	(29)	2.9	0.6	4.3
ALPHA	1957-58	(27)	3.2	0.6	5.3
ALPHA	1958-59*	(28)	2.7	1.5	1.8
NP 6	1958-59*	(9)	3.7	1.8	2.1
Greenland Sea side					
NP 3	1954-55	(22)	2.6	1.2	2.3
NP 4	1956-57	(20)	2.8	1.1	2.6
NP 7	1958-59	(30)	2.4	1.2	2.0
B) PACIFIC GYRAL					
West leg					
NP 2	1950-51	(23)	3.7	0.9	4.1
NP 4	1954-55	(18)	3.7	0.8	4.3
NP 4	1955-56	(19)	3.7	1.1	3.2
NP 7	1957-58	(29)	2.9	0.6	4.3
ALPHA	1957-58	(27)	3.2	0.6	5.3
ALPHA	1958-59*	(28)	2.7	1.5	1.8
North leg					
T-3	1952-53	(13)	2.6	0.6	4.2
T-3	1953-54	(–)	1.5	0.2	6.8
East leg					
T-3	1957-58	(14)	1.2	0.6	2.0
T-3	1958-59	(15)	1.9	1.1	1.7
South leg					
T-3	1959-60	(16)	2.7	1.3	2.0
ARLIS I	1960-61*	(17)	4.0	2.6	1.5
CHARLIE	1959-60*	(–)	5.1	0.5	10.0

Table 1: Drift rates by areas (DUNBAR & WITTMAN 1963). * = not a full year's drift; (-) = extended well into the Greenland Sea side.

Tabelle 1: Driftraten des arktischen Meereises nach Regionen gegliedert (DUNBAR & WITTMAN 1963). * = Driftdauer weniger als ein Jahr, (-) = reichte deutlich in Richtung Grönlandsee.

In addition, there is a small average export of ice from the Arctic Basin to the Barents Sea during the summer (VINJE 1987). Ice exchange between the Beaufort Gyre and the Transpolar Drift is not well known but is likely to occur in a transition zone. The data of a number of manned drift stations, ships and drift buoys distinguish very clearly the two major ice drift patterns (DUNBAR & WITTMAN 1963). After many years of Soviet and American drift stations a lot of data is available to calculate the speed of the drift (Table 1). The mean annual drift, which is the net rate measured over the general path, varies from 0.2 -2.6 nm/day (0.3 - 4.2 km/day). The actual drift including all the circular motions and zig-zags is much higher. On average the actual drift rate is between 1.2 - 4.0 nm/day (1.9 - 6.4 km/day) and a maximum of 5.1 nm/day (8.2 km/day). Over short periods of time there are considerable variations in the drift rates (DUNBAR & WITTMAN 1963).

The highest and lowest velocities in the central Arctic occur in the Beaufort Gyre, with a minimum of 0.2 nm/day (ice island T-3) and a maximum of 3.8 nm/day (ice island Karluk). The highest drift rates have been recorded in the Marginal Ice Zone (DUNBAR & WITTMAN 1963). In the East Greenland Current and the outflow through the Canadian Arctic, drift rates vary from 4 nm/day to 9.9 nm/day. Data from drifting buoys throughout the central Arctic Ocean allow, for the first time, the simultaneous analysis of Arctic ice drift (LOSEV et al. 1987). Figure 15 shows the measured velocities in the Transpolar and East Greenland Drift Streams.

A very important consideration for planned investigations in the Arctic Basin is the thickness distribution of the sea ice and its interannual and annual variations. Data from upward-looking sonars on submarines (WADHAMS 1989) and modelling of the dynamics of the sea ice cover (HIBLER 1980) are useful to calculate the sea ice conditions (Fig. 16). Sonar measurements of the under-ice topography in the central Arctic allow the classification of special provinces (MCLAREN 1989). The Amerasian Basin seems to have more severe ice conditions than the Eurasian area. The Amerasian Basin is characterized by more moderate under-ice topography and more areas of open-water, refrozen polynyas and leads in comparison to the most severe topography of the Arctic sea ice in the area of the Makarov and Nansen basins and the Gakkel Ridge (MCLAREN 1989). This pattern is the result of the dynamic system of the moderate Beaufort Gyre and the Transpolar Drift with higher stress components and may be a permanent feature of the Arctic Basin (MCLAREN 1989).

5.3 *Sedimentation in the Modern Arctic Ocean*

Sediment distribution and sedimentation processes

The modern Arctic Ocean sedimentary environment is strongly influenced by the extent and concentration of sea ice cover (Fig. 2). During the 1893-1896 *Fram* expedition in the eastern Eurasian Basin, NANSEN (1897, p. 436) noted that the "upper surface of the floes is nearly everywhere of a dirty brown colour, or at least, this sort of ice preponderates, while pure white floes, without any traces of a dirty brown on their surface, are rare"

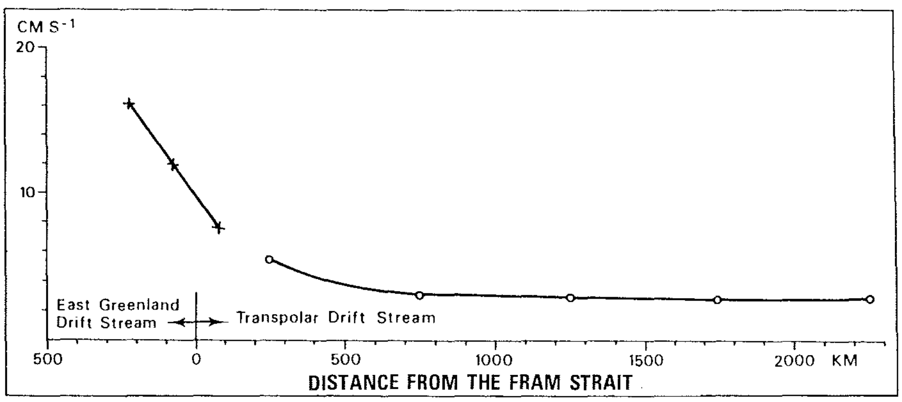


Fig. 15: Drift rates in the East Greenland Current and Transporlar Drift System (VINJE 1982).

Abb. 15: Driftgeschwindigkeiten der Eisbedeckung des Ostgrönlandstromes und des transpolaren Driftsystems (VINJE 1982).

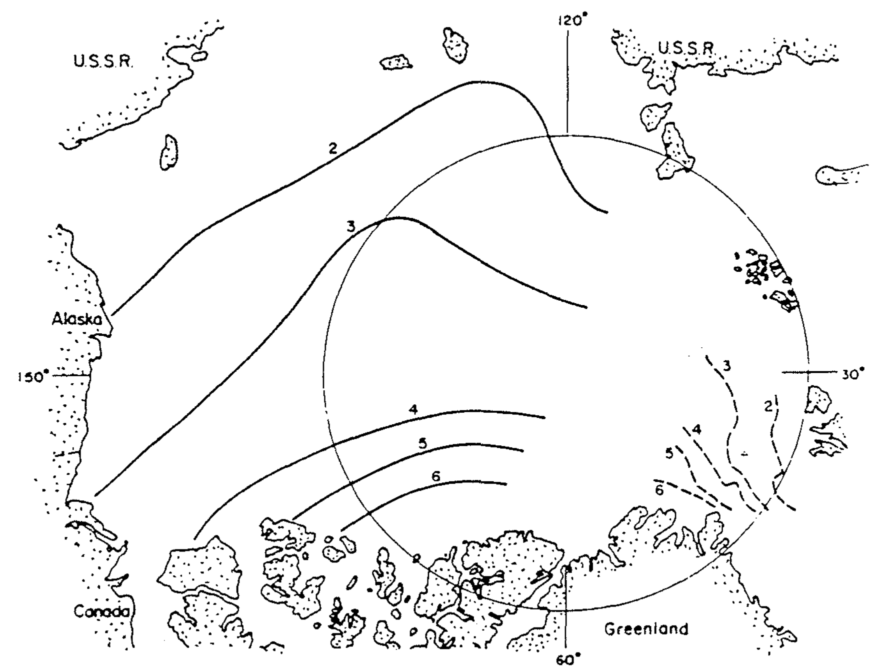


Fig. 16: Approximate contours of mean ice thickness (in meters) over the Arctic Ocean, based on a mix of summer and winter submarine profiles (HIBLER 1980).

Abb. 16: Durchschnittskontouren der Mächtigkeit des Meereises (in Metern) im Nordpolarmeer, gezeichnet nach einer Reihe von Sommer- und Winterprofilen der Untereismorphologie (HIBLER 1980).

(July 18, 1894, approximately 81° 30' N, 125°E). Following the observations of widely distributed dirty sea ice with very high sediment concentrations during the ARK IV/3-expedition, sediment transport by sea ice is receiving more attention as mainly responsible for today's sedimentation in ice-covered areas (PFIRMAN et al. 1989 a, b; WOLLENBURG et al. 1990; WOLLENBURG 1991).

Ice transport

Seafloor sediments from shallow continental shelves can be incorporated into sea ice by several mechanisms (Fig. 17; e.g. BARNES et al. 1982; CLARK & HANSON 1983; REIMNITZ et al. 1987; WOLLENBURG 1991). The major process of sediment entrainment occurs during initial ice formation on the shelves by frazil and anchor ice on the shelves. Storms during freeze-up in the autumn result in resuspension of sediments in shallow seas and supercooling of the water column. Under these turbulent conditions, seafloor sediments are resuspended and ice crystals form within the water column ("frazil"). Rising frazil filter suspended sediments from the water column and add them into the forming ice cover. Anchor ice forms when supercooled water encounters the sea bed, forming ice which can raft bottom sediment and benthic shallow water organisms into the ice column. Sediments were recently observed by VINJE (1987) to accumulate on the underside of the ice during March on Spitsbergenbanken when the water column contained large quantities of suspended sediment. Ice gouging of the seafloor by pressure ridges can also result in accumulation of fine-grained material on the underside of ice.

The concentration and the observed areal distribution of sediments indicate that sea ice rafting has the potential to contribute a major portion of today's sediment flux and probably to be the most important process of transporting fine grained terrigenous material and benthic shallow water organisms into the deep ocean. Preliminary calculations show that sea ice rafted material can account for the total flux rate necessary for the observed sedimentation rate in the potential regions of melt such as Fram Strait (WOLLENBURG 1991).

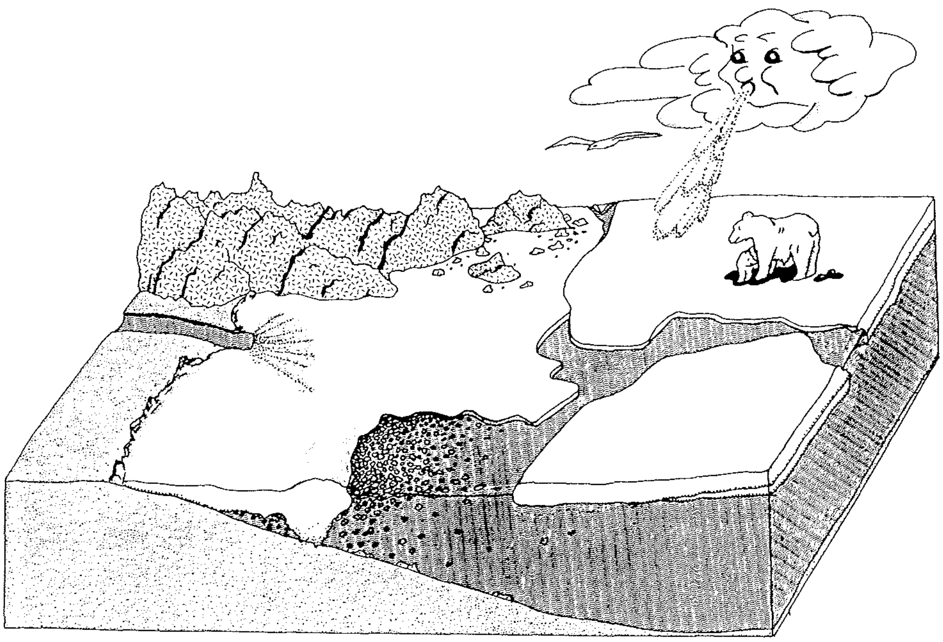


Fig. 17: Mechanisms of sediment transport to the Arctic Ocean (WOLLENBURG 1991).

Abb. 17: Mechanismen des Sedimenttransportes in das Nordpolarmeer (WOLLENBURG 1991).

The amount of sediment released by sea ice during transport is not well understood (Fig. 18). Because incorporated material is concentrated mostly at the ice surface, it appears likely that deposition on the sea floor will occur primarily along the drift path of the ice flow as it finally disintegrates, although some deposition should also occur during rafting events and seasonal melting. In addition, wave and water action along the periphery of the ice floes (Fig. 18) will result in release of particles along the edges of the floes.

All of these effects are strongest near regions of open water adjacent to the ice pack. Thus, greatest ice flow disintegration, and therefore potential for sediment deposition from the ice, is expected to occur during summer (June - October; VINJE 1985) in the marginal ice zone, near polynyas and large leads. Data from sediment traps deployed across Fram Strait support the assumption that during ice drift very little material is released. But, in areas of extensive melting and disintegration of sea ice, there are much higher fluxes of fine grained lithogenic material (HEBBELN & WEFER 1991).

Aeolian sediment input

Sea ice can trap aeolian material transported over long distances into the ocean interior. Annual deposition rates from long-range aeolian transport on the central Arctic ice pack appear orders of magnitude too low to account for the high particulate loads observed in the Eurasian Basin (LARSSEN et al. 1987; PFIRMAN et al. 1989b. For the western part of the Arctic Ocean, with sedimentation rates on the order of mm/ky (CLARK et al. 1986; THIEDE et al. 1988), atmospheric dust could conceivably form an important contribution to the sedimentary budget (MULLEN et al. 1972; DARBY et al. 1974). Nearshore aeolian transport of sediments from snow and ice free terrain may lead to the accumulation of significant amounts of particulate material on shorefast ice (e.g., KINDLE 1924). Winds along the north coast of Siberia blow from the continent to the Arctic Basin in winter (BORISOV 1965). Wind velocities can reach locally 40-50 m/sec. WINDOM (1969) estimated the contribution of dust derived from the Arctic tundra to the pelagic sedimentation at about 10 %.

These processes, which increase particle concentration in the upper section of sea ice columns, are important

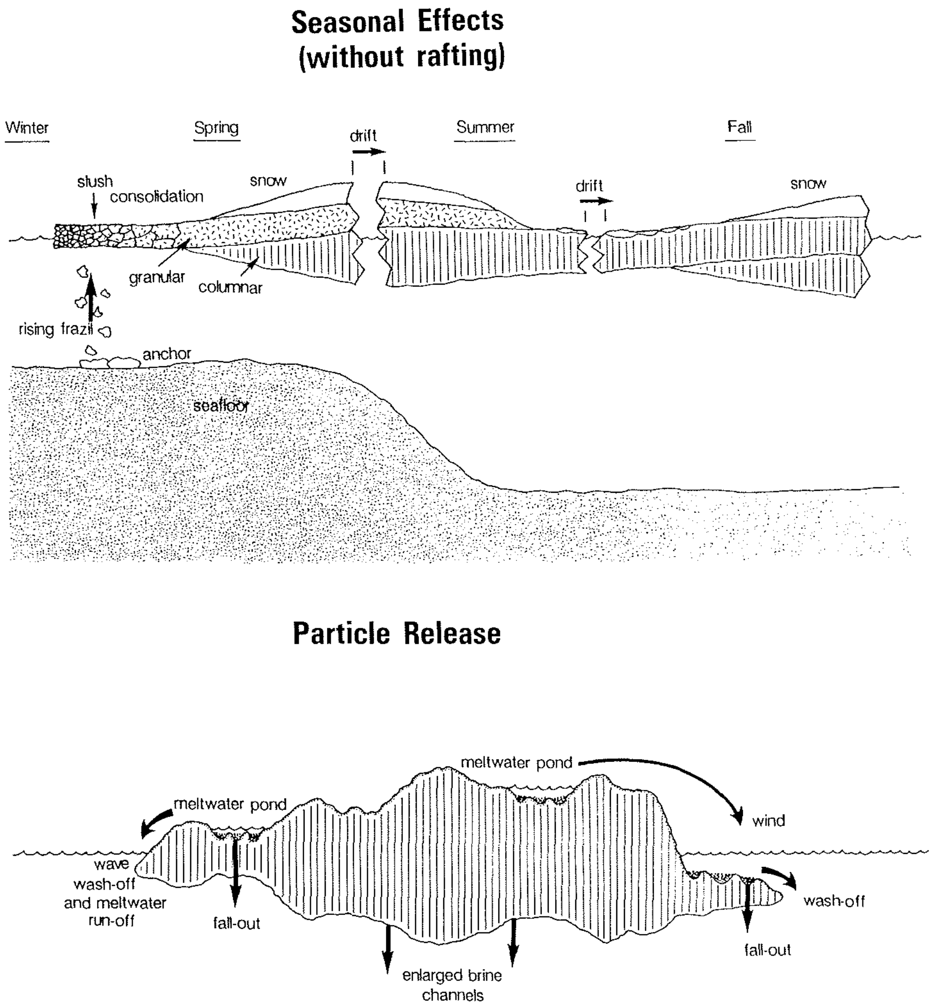


Fig. 18: Mechanisms of particle concentration and release from modern Arctic sea ice (WOLLENBURG 1991).

Abb. 18: Mechanismen der Partikelkonzentration im und des Ausschmelzens von Sediment aus dem Meereis (WOLLENBURG 1991).

because particle content has an effect on the ice albedo and therefore on Arctic heat balances, interpretations of satellite microwave observations, and on melting of the floes and therefore contributions of meltwater and particles to the water column.

MULLEN et al. (1972) and DARBY et al. (1974) estimated that airborne dust (based on observations of snow samples obtained approximately 500 km north of the Alaskan north coast during the drift of ice island T-3) may contribute 0.02 mm to 0.09 mm/ky (respectively) of sediment in the Amerasian Basin. Deposition rates of atmospheric dust might be expected to be higher in the Eurasian Basin because it is closer to the proposed Eurasian and local source regions. This assumption fits well with the higher sedimentation rates of the eastern Arctic Ocean (1.06 cm/ky MIENERT et al. 1990; 1.74 cm/ky ZAHN et al. 1985) in comparison to the proposed sedimentation rates of the western Arctic of 1-2 mm/ky.

River discharge

Some of the biggest rivers in the world discharge into the Arctic Ocean (e.g., Lena, Ob, Yenisei, Kolyma), which is the largest drainage basin in the world (MILLIMAN & MEADE 1983). The rivers discharge a large amount of suspended sediments to the Arctic Ocean. Most of the material is deposited on the shelves but some material is likely carried in suspension into the deep ocean and contributes to pelagic sedimentation (mainly clay-sized particles). The Yenisei, Ob and Lena rivers for example drain an area of 2.5 million km^2 and carry a total sediment load of 41 million tons/year (MILLIMAN & MEADE 1983).

Sediment type

The youngest sediments of the Arctic seafloor consist mainly of fine-grained, clastic material derived from sea ice, wind and river discharge from surrounding continents, as well as particles of biogenic origin (benthic and planktic organisms). Sediment samples show a redistribution of sediments in the deep basins by movements of bottom waters. Knowledge of oceanography and interactions of these water masses with the seafloor sediments is poor, as patterns of deep circulation are basically unknown. DARBY et al. (1989) described the surface sediments of the central Arctic Ocean as silty to sandy lutites with various amounts of sand. The clay minerals consist of 10-30 % kaolinite and chlorite and of 30-60 % illite. Montmorillonite is only a minor part of the clay minerals. Surface sediments of eastern Arctic Basin obtained during the *Ymer-80-* and *Polarstern* ARK IV/3-expeditions are also fine-grained muds with only small amounts of sand and very little ice-rafted detritus (MARKUSSEN 1986, SPIELHAGEN et al. 1988).

Recent surface sediments of the eastern Arctic Ocean show well preserved *Neogloboquadrina pachyderma* and indicate only weak dissolution (MARKUSSEN 1986; PAGELS 1991). The relatively high amounts of planktic foraminifers found in an area of low productivity are a result of dilution by variable terrigenous inputs. Plankton net data (CARSTENS 1988) indicate a decrease of standing stocks of planktic foraminifers towards the central Arctic Basin (Fig. 19).

The distribution and preservation of carbonate in sediments is a good indicator of water masses (Fig. 20). The Yermak Plateau and the Fram Basin are regions with relatively high carbonate contents (> 7.5 % $CaCO_3$). The higher carbonate values in the Fram Basin (Eurasian Basin) are similar to the carbonate contents in the Canada Basin (Amerasian Basin), with 11-29 % $CaCO_3$ (CLARK 1969, DARBY et al. 1989). The differences in sediment characteristics, sedimentation rate and carbonate content between the Amerasian and Eurasian Basin are probably an effect of different water masses (PAGELS 1991). The inflow of warm Atlantic water of the West Spitsbergen Current into the Arctic Ocean correlates with the high carbonate values on the Yermak Plateau. High carbonate contents in the area of the East Greenland Current are due to ice rafted terrigenous carbonate rocks (SPIELHAGEN 1990).

The comparison between the carbonate contents in surface sediments and the amount of planktic foraminifers per gram dry sediment to determine the biogenous productivity is tenuous (Fig. 20). In general, the carbonate content and the amount of planktic foraminifers are in good agreement with the exception of the NE-Greenland slope and the Yermak Plateau. There the input of ice-rafted terrigenous carbonate rock fragments and the dilution effect of high terrigenous input into the shelf and continental slope is controlling the above described pattern.

5.4 *Sedimentation Related to the Arctic Marine Biota*

Strong changes in insolation cause extreme seasonality in the Arctic environment. Variations in ice cover, as the obvious result of this seasonality, interact with the bloom of single-celled algae which are the base of the Arctic food chain and which grow only during the short summer season. Changes in algae and faunal patterns from Svalbard slope into the deep eastern Arctic Ocean under perennial ice cover were surprising. The water masses (Fig. 19) seem to have more effect on the planktic and benthic community than available light (*POLARSTERN* SHIPBOARD SCIENTIFIC PARTY 1988).

Biogenic particle production is not only important because of its resultant sedimentation but also because there is a positive correlation between biogenic production and sedimentation of fine lithogenic particles (HEBBELN

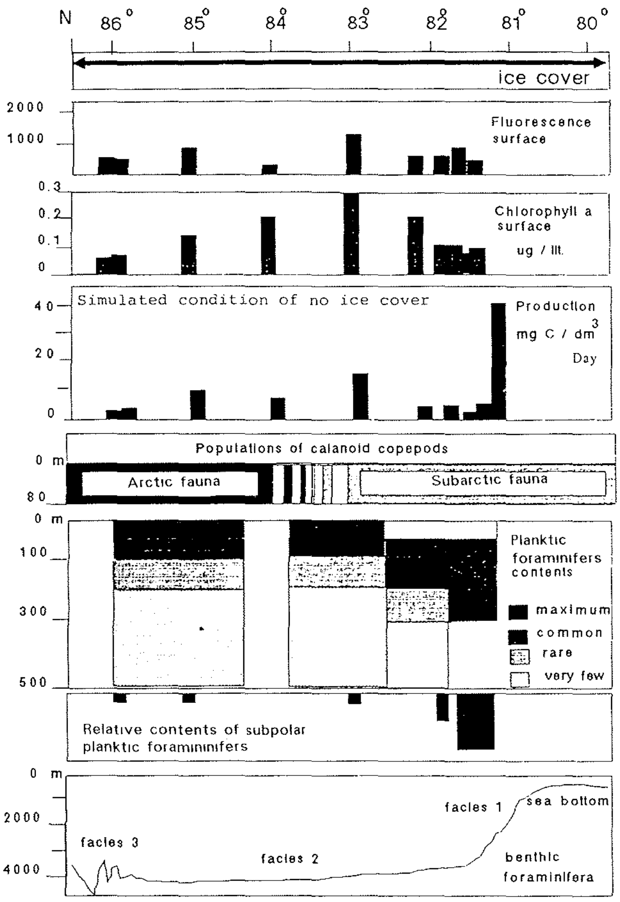


Fig. 19: Selected parameters of the biological transect from the Barents Shelf to the Gakkel Ridge (THIEDE et al. 1988).

Abb. 19: Zusammenstellung ausgewählter Beobachtungen eines biologischen Schnittes vom Barentsschelf zum Gakkel-Rücken (THIEDE et al. 1988).

& WEFER 1991). The fine grained material with high organic content transported by sea ice is a supply of food for under-ice communities or organisms living in the water column. Thus formation of fecal pellets may be the major sedimentation process for this material, whereas the amount of sediment release during ice drift is still unknown. Water column particle flux dominated by coccoliths indicate that the entire Norwegian-Greenland Sea and probably the Arctic Ocean are "carbonate seas". Coccoliths are photosynthetic and tolerate a temperature as low as a few degrees Celsius. Therefore the finding of coccolithophorids in water samples taken under the ice in the eastern Arctic Ocean (PFIRMAN & HONJO unpubl., BAUMANN 1990) was very surprising. Surface sediment samples obtained by the *Ymer-80*-expedition (BOSTRÖM & THIEDE 1984) and during the ARK IV/3-expedition (*POLARSTERN* SHIPBOARD SCIENTIFIC PARTY 1988) show relatively high occurrences of coccoliths (*Coccolithus pelagicus* and *Emiliania huxleyi*) in surface sediments. This strongly suggests the influence of Atlantic water on the interior basin which flows as boundary current along the slope of the Barents Shelf.

The implied large capacity of the Arctic Seas for fixing carbon dioxide and storing it in the seabed may be an important component of the global carbon budget. The high correlation between biogenic carbon and fine-grained sediment supports the hypothesis that accelerated settling of aggregated fine particles is the major mechanism of Arctic sedimentation.

The metabolism of deep-water organisms is thought to be fueled both by food particles falling from the surface layer and by organic matter included within the water masses during their formation. Results of *FRAM II* ice island show that although surface productivity in the ice pack is generally low, the rain of organic material from the surface is still the major source of energy for deep-water organisms.

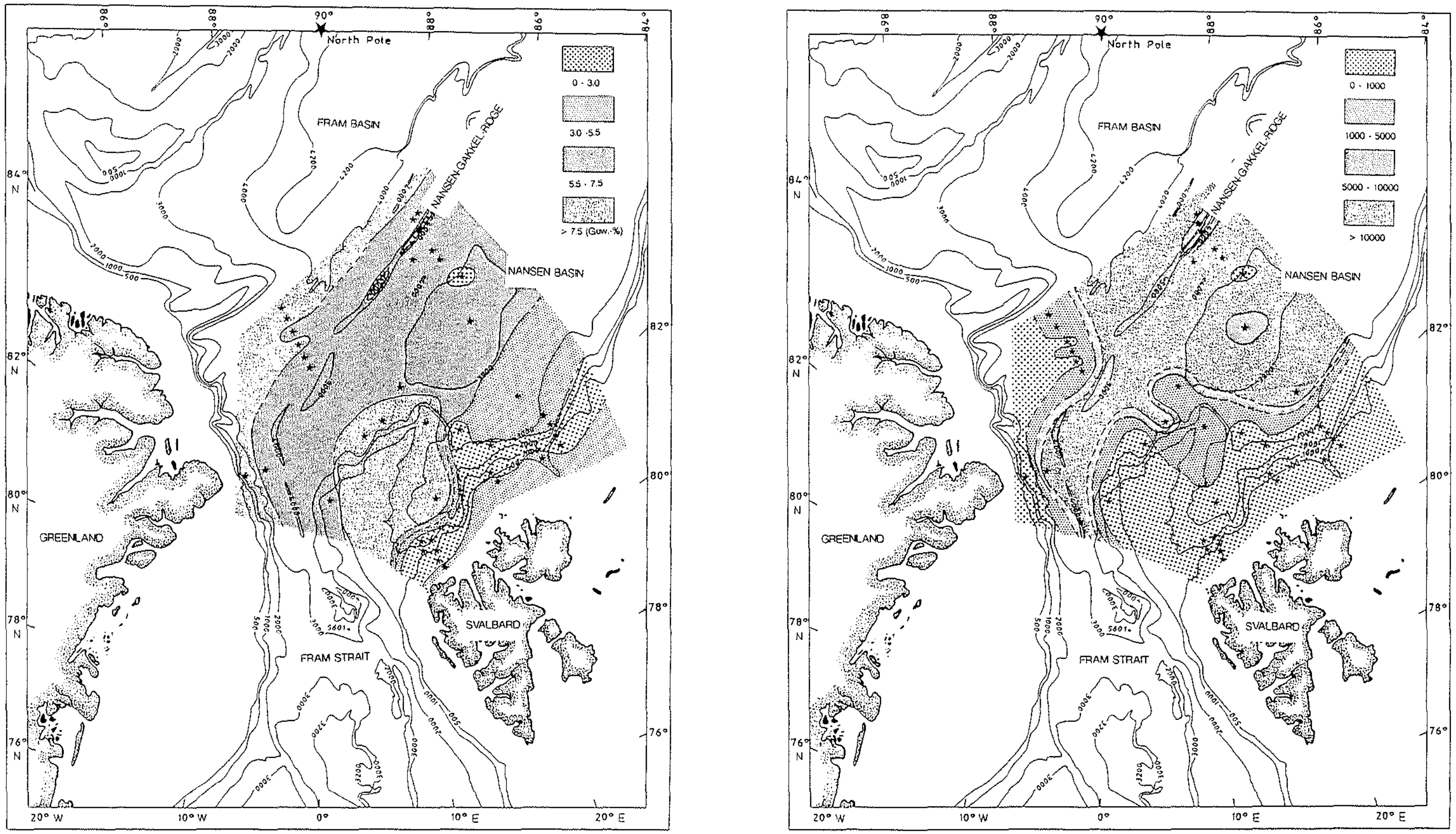


Fig. 20: Surface sediments: **a** = Recent distribution pattern of $CaCO_3$ (wt. %) in surface sediments of the eastern Arctic Ocean.
b = Recent distribution pattern of planktic foraminifers (nos/g dry sample) in surface sediments of the eastern Arctic Ocean. Analyses based on 39 core tops (locations indicated by asterisk) by PAGELS (1991), MARKUSSEN (1986), SNAARE (1985).

Abb. 20: Oberflächensedimente: **a** = Verteilung des Kalziumkarbonatgehaltes (Gew. %) im Oberflächensediment des östlichen arktischen Ozeans.
b = Verteilung von planktischen Foraminiferengehäusen (Anzahl pro g Trockensediment) in den Oberflächensedimenten des östlichen arktischen Ozeans. Als Datenbasis standen 39 Proben zur Verfügung (Positionen als Sternchen). PAGELS 1991, MARKUSSEN 1986 und SNAARE 1985.

6. CENOZOIC PALEOCEANOGRAPHY

The Arctic Ocean Cenozoic paleoceanography can be subdivided into three widely different phases of which only the last one can be documented to some degree in the Arctic Ocean proper: 1) the Paleogene and Early Neogene "preglacial" time spans; 2) the onset of a "glacial" type oceanography in the Arctic and sub-Arctic deep-sea basins; and 3) the development of fully glacial/interglacial conditions in the Arctic Ocean.

As outlined before and discussed by THIEDE et al. (1990) and many other authors, the detailed correlation of the lithostratigraphy to the Late Cenozoic chronostratigraphic framework is very weak when sediments beyond the range of the radiocarbon dating technique are analyzed. Any interpretation of the Cenozoic paleoceanographic history of the Arctic Ocean is therefore tentative at best. The stratigraphic problems encountered make the recovery of undisturbed, large volume sediment cores mandatory (Fig. 21).

6.1 *Paleogene and Early Neogene Paleoceanography*

One sediment core from ice island T-3 and a recently recovered core during ARK-VU/3 of *Polarstern* (FÜTTERER 1992) comprise the only records of the Paleogene from the central Arctic Ocean. The T-3 core contained displaced sediments and consisted of obviously laminated siliceous oozes with Eocene phytoplankton (BUKRY 1984, see also discussion in MUDIE et al. 1986). Thus the Paleogene oceanographic scenario is similar to that during the Late Mesozoic.

Except for the presence of glendonites and the possible occurrence of ice rafted clastics (DALLAND 1976) in the Paleogene sequence of Svalbard, there is no evidence of glaciation in the Paleogene and lower Neogene record of the Arctic, which is obviously quite different from the Antarctic record. ODP Leg 119 which successfully cored sediments on the Antarctic continental shelf in Prydz Bay has documented a late Eocene to early Oligocene onset of Antarctic glaciation (BARRON, LARSEN et al. 1988). The flora of the Eocene Arctic Ocean core, evidence from the surrounding land areas, and vertebrate faunas (HICKEY et al. 1983) support the idea of a moderate Arctic climate with perhaps a shorter and much warmer winter than that of the present.

6.2 *Onset of "Glacial" Environments*

No sediment record from the Arctic Ocean proper covering the span of Miocene and Early Pliocene time has been recovered to date (see also MUDIE et al. 1986). One has, therefore, to turn to the sub-Arctic basins of the extensions of the North Pacific and Atlantic oceans to recover records documenting the transition from preglacial to glacial environments. There is a wealth of data available from DSDP Leg 19 (CREAGER, SCHOLL et al. 1973) which drilled sites in the Bering Sea and the northern-most North Pacific Ocean. ODP Leg 104 (ELDHOLM, THIEDE et al. 1989) in the Norwegian-Greenland Sea, and ODP Leg 105 (SRIVASTAVA, ARTHUR et al. 1989) in the Labrador Sea and Baffin Bay documented a Miocene onset of glacial conditions in the North Atlantic Ocean.

Figure 22 describes one of the best records of the transition from preglacial to glacial conditions in the North Atlantic. Site 646 (ODP Leg 105) to the south of Greenland documents a complete Miocene, Pliocene and Quaternary section; occurrences of ice rafted rock fragments suggest a modest ice cover existed already during Late Miocene times (WOLF & THIEDE 1991), as early as 10 Ma or even before. A modest influx of ice rafted material probably continued into the Early Pliocene. At approximately 4 Ma an intensification of ice rafting can be observed. Since then the history of the sub-Arctic deep sea basin has been dominated by a "glacial" oceanography with frequent occurrences of intensive ice rafting events. One has to conclude that the Arctic Ocean has experienced a similar climatic history even though only its youngest part can presently be documented in the Arctic Ocean proper.

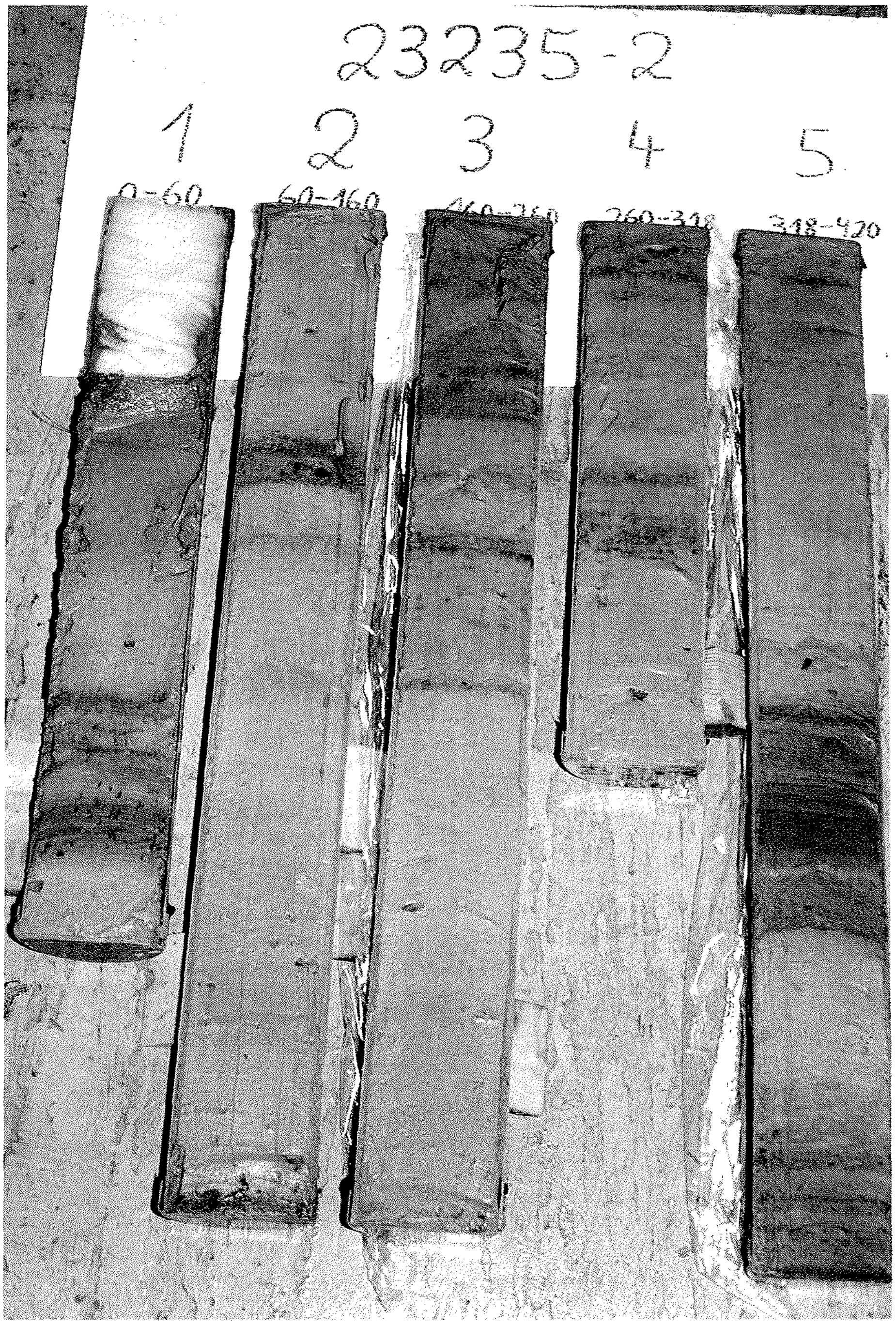


Fig. 21: The colorful and highly variable upper Quaternary sediment sequence of an eastern Arctic deep-sea sediment core. Core PS23235, 78° 51´N / 01° 18.6´ E, for detailed data on the sediment description see SPIELHAGEN et al. 1988.

Abb. 21: Farbenreiche und außerordentlich variabel zusammengesetzte Abfolge eines quartären Sedimentkernes aus dem östlichen arktischen Ozean. Kern PS 23235, 78° 51´N / 01° 18,6´ E; detaillierte Kernbeschreibung siehe in SPIELHAGEN et al. 1988.

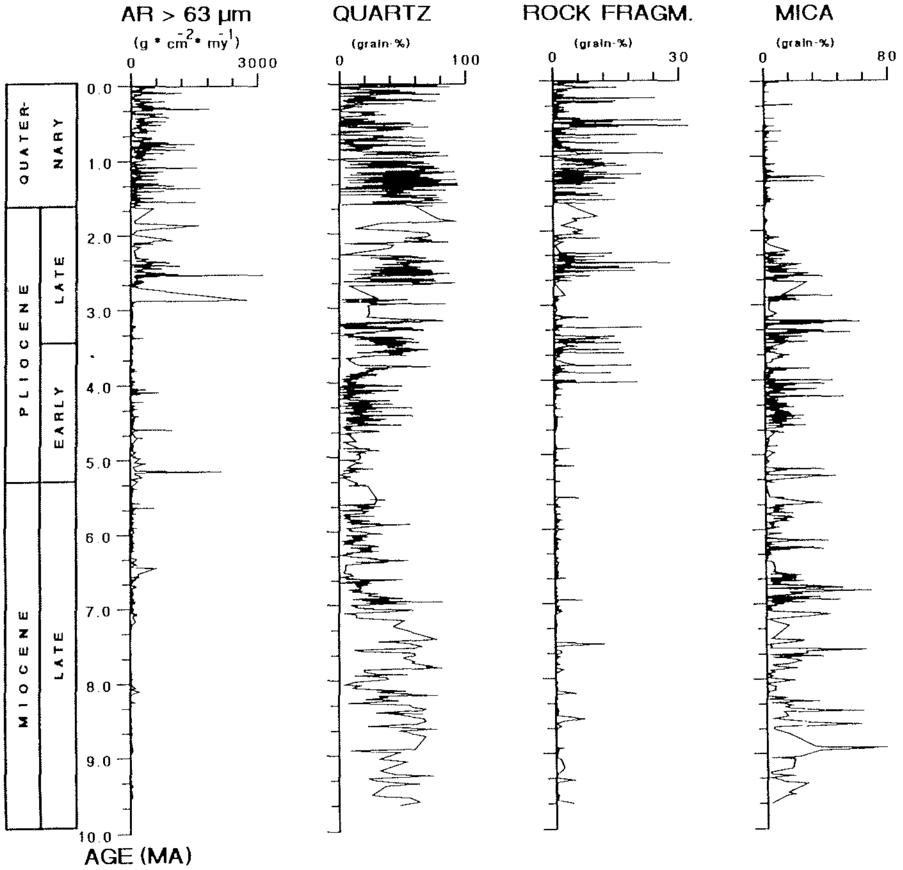


Fig. 22: Coarse fraction data of terrigenous particle input at ODP Leg 105, Site 646 during the past 10 my; AR = Accumulation Rates; (WOLF & THIEDE 1991).

Abb. 22: Grobfraktionsdaten der terrigenen Sedimentkomponenten im neogenen und quartären Teil der Bohrung 646 (ODP Leg 105). AR = Akkumulationsrate (WOLF & THIEDE 1991).

6.3 *Glacial Paleoceanography*

The Pliocene and Quaternary history of the Arctic Ocean is dominated by the history of its ice cover (CLARK 1990). The ice controlled sedimentary processes which resulted in a highly variable depositional environment in the central Arctic, responded to Pleistocene earth orbital variations (BOYD et al. 1984). This trend can be documented by numerous cores which consist of alternating layers rich in terrigenous material and in biogenic components as illustrated in Figures 23 and 24. However, many aspects of the interpretation are hampered by the fact that no clear-cut correlation to a chronostratigraphic framework exists.

In Figure 23 the lithostratigraphic framework established by CLARK et al. (1980) is given to document some of the main results of lithologic observations from the UT-3 ice island cores. The uppermost few meters of the sedimentary column can be subdivided into a sequence of lithostratigraphic units of quite different properties. In part B (Fig. 23) the correlation of the Alpha Ridge stratigraphy by CLARK et al. (1980) has been compared to the eastern Alpha Ridge cores as described by MINICUCCI & CLARK (1983). It is obvious that most of these cores taken from the flanks and the upper parts of structural highs can be correlated easily with each other, hence documenting the basin-wide response of the depositional environments to differences in the sediment input. This result is also confirmed by the correlation of sediment cores from the western Norwegian-Greenland Sea to the

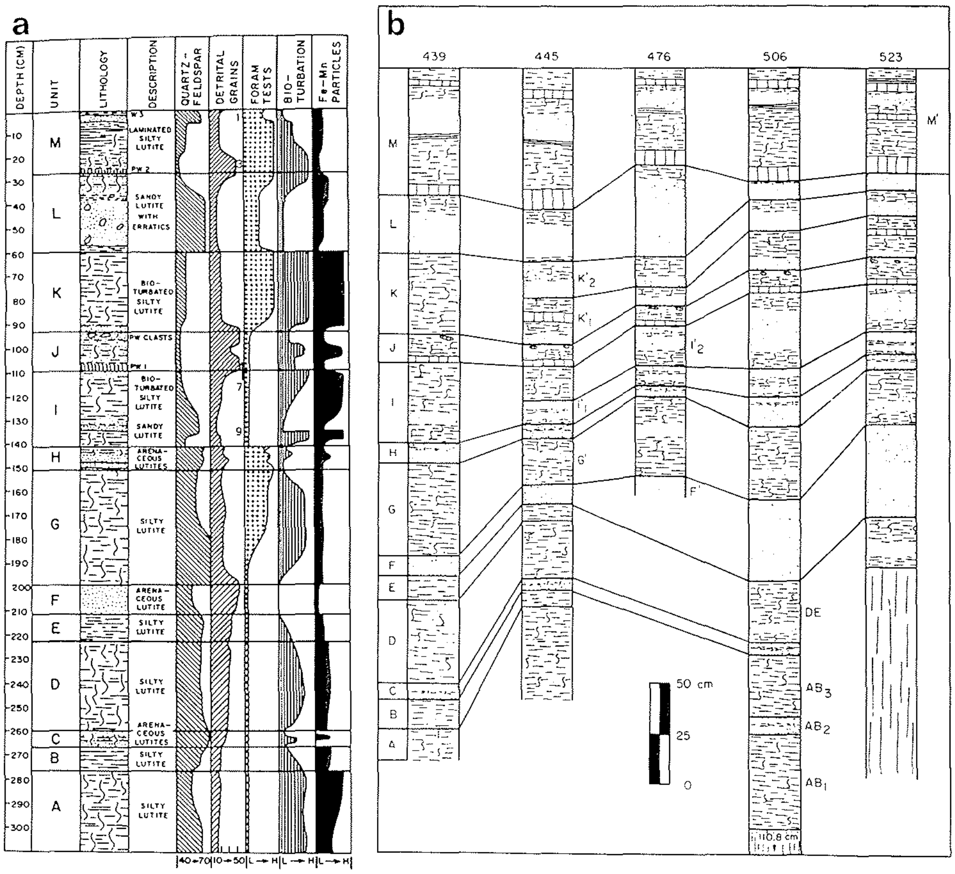


Fig. 23: a Lithostratigraphic units A to M in the central Arctic Ocean. Sedimentary parameters include percentages of quartz-feldspar and total detrital grains. L to H indicate low to high abundance. Numbers in „detrital grains" column refer to carbonate maxima peaks (after CLARK et al. 1980).
b Correlation of Alpha Rise stratigraphy (CLARK et al. 1980) with the „eastern" Alpha Ridge area described by MINICUCCI & CLARK (1983).

Abb. 23: a Lithostratigraphische Einheiten A-M im zentralen Nordpolarmeer. Die Sedimentbeobachtungen umfassen u. a. Quarz-Feldspatverhältnisse und die Anteile detritischer Körner. L bis H zeigen niedrige bis hohe Konzentrationen an. Die Zahlen in der Säule „detrital grains" beziehen sich auf Karbonatmaxima (nach CLARK et al. 1980).
b Korrelation von Sedimentkernen vom Alpha-Rücken (CLARK et al. 1980) mit solchen vom östlichen Alpha-Rücken, die von MINICUCCI & CLARK 1983 beschrieben worden sind.

Fram Strait and into the Arctic Ocean based on the occurrences of coccoliths (GARD 1986) as shown in Figure 24. Based on a wide variety of dating techniques and lithostratigraphic correlations such as shown by GARD (1986), it is today relatively easy to document that the Arctic Ocean has been ice covered permanently for the past few hundred thousand years, although the properties of the ice cover and the intensity of ice rafting has obviously changed considerably with time. This interval is documented by hundreds of sediment cores which have penetrated the upper few meters of the sediment cover of the central and marginal Arctic Ocean. Age assignments are relatively firm as far the correlation to the chronostratigraphy of the youngest Quaternary is concerned (cf. numerous publications of CLARK, HERMAN and co-workers; THIEDE et al. 1990).

Any interpretation of the older depositional environments, however, is highly tentative because of the lack of high quality chronostratigraphies. CLARK et al. (1990) for example used some of the sediment evidence to suggest a significant change of the depositional environment at 2-1.5 Ma. They believe that Neogene Arctic sediment older than this is glacial marine but their faunas (mainly arenaceous foraminifers and very little calcareous material) document a specific non-calcareous depositional environment. They further suggest that planktic and calcareous benthic foraminifers first entered the Arctic at that time. Whether or not this is correlated to vertical

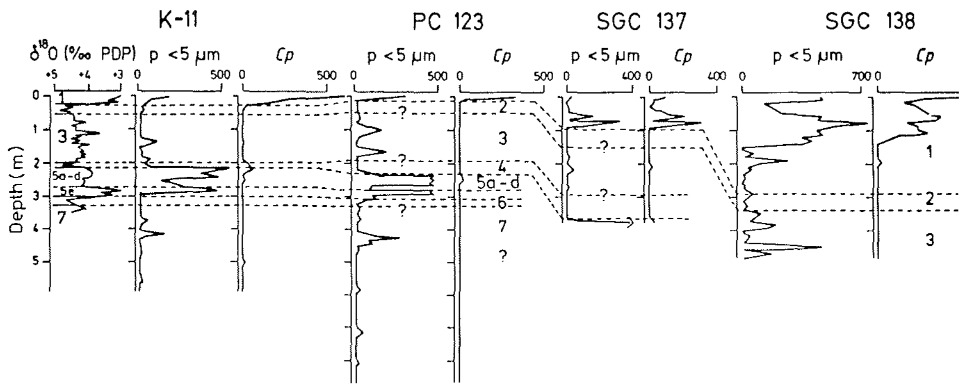


Fig. 24: Correlations between K-11 (Norwegian-Greenland Sea) and *YMER-80* PC 123, SGC 137, and SGC 138 cores with suggested oxygen-isotope stage boundaries. Coccolith occurrences: p = placoliths; Cp = *Coccolithus pelagicus* (GARD 1986).

Abb. 24: Korrelationen zwischen den Sedimentkernen K-11 (Europäisches Nordmeer) und den *Ymer*-80-Kernen PC 123, SGC 137 und SGC 138, mit Angabe von vermuteten Sauerstoffisotopenstadien. Coccolithenvorkommen: p = Placolithen, Cp = *Coccolithus pelagicus* (nach GARD 1986).

fluctuations of the lysocline and CCD is unknown; the correlation suggested by CLARK et al. (1990) is highly tentative. A problem like this can only be solved by examining sediment cores with excellent stratigraphic properties and in areas with relatively high sedimentation rates. Obviously such cores cannot be expected in the central Arctic Ocean but they should be obtainable close to the continental margins.

6.4 *Spectral Properties of the Arctic Marine Sedimentary Record*

An important objective of paleoceanographic research is to provide an observational record of oceanographic and climatic change. While this task produces records that are extremely useful in establishing the chronology of these changes (to the limits of our stratigraphic resolution), the fundamental goal of paleoceanographic research is the interpretation of these records in terms of the processes that control the ocean-climate system. The downcore variations in paleoceanographic parameters that are measured in cores represent the response of the ocean climate system to internal and external forcing. If these forcing functions can be identified, then "systems theory" provides that through the analysis of the response function (the geologic record) the mechanisms of the ocean climate system can be defined and thus the fundamental objective of understanding the processes controlling oceanic and climatic change can be achieved.

Over the years, numerous climatic forcing mechanisms have been proposed, but one, the Milankovitch theory of astronomical forcing has stood the test of observational data; its application to the paleoceanographic record has provided revolutionary insight into the nature of ocean-climate interactions. Originally proposed to explain the cause of Pleistocene ice ages, this theory asserts that changes in the annual cycle of incoming radiation, combined with albedo effects, time delays, and other ice-related feedbacks, are the cause of the cyclic and asymmetric growth and decay of ice in the Northern Hemisphere over the last 2.5 my (MILANKOVITCH 1941). More recent evidence has indicated that some of the same factors have influenced geologic processes over many parts of the geologic record (e.g. ARTHUR & GARRISON 1986). The "incoming radiation" (the amount of solar radiation striking the top of the atmosphere at any given latitude and season) is controlled by three components of the earth's orbit: obliquity or tilt of the earth's axis, precession, and eccentricity of the earth's orbit. The geometry of these orbital parameters has been calculated (BERGER 1978); all vary cyclically with dominant periodicities of 41 ky for the tilt, 19 and 23 ky for precession, and roughly 100 ky for eccentricity. Of particular relevance to Arctic Ocean paleoceanography is that aspect of Milankovitch's theory which provides that it is the intensity of solar radiation received during the summer at high latitudes that is the critical factor controlling the growth and decay of ice.

Deep-sea sediment cores provided the first unambiguous test of the Milankovitch theory. In their pioneering work, HAYS et al. (1976) performed spectral analyses on downcore measurements of several paleoclimatic parameters including $\partial^{18}O$, sea surface temperature (SST) and demonstrated that a considerable amount of climatic variance can be directly linked to orbital forcing at the frequencies of obliquity (41 ky) and precession (19 and 23 ky). More importantly, even these early studies demonstrated a clear phase relationship between orbital forcing and climatic response (i.e., a 9,000 year lag between ice volume change and the 41 ky obliquity record) that provided direct information on the climate ocean system.

One of the most surprising results of these early spectral analysis studies was the overwhelming dominance of 100 ky periodicity in almost all paleoceanographic parameters over the last 600 ky. This was surprising because Milankovitch's theory predicts that the 100 ky eccentricity cycle has only a very minor ($\approx$ 0.1 %) effect on the insolation. Thus, it cannot be the direct (linear) response to orbital forcing (IMBRIE & IMBRIE 1980). The critical need to understand the origin of the 100 ky cyclicity that has so dominated our climate for the last 600 ky, has led to the development of a number of non-linear models for the climate system, each model producing 100 ky cyclicity by making different assumptions about the workings of the climate ocean system (see IMBRIE & IMBRIE 1980 and IMBRIE et al. 1989, for a summary).

Despite the inherent differences in these non-linear models, each calls upon variations in northern hemisphere ice sheet dynamics, ocean circulation, or both, to play a key role in the system's response. The ultimate test of these models will be the collection of long paleoceanographic records in critical locations; the Arctic Ocean, with its important contribution to deep-water formation and its clear association with ice sheet history will be of prime importance in deciphering the behavior of the global ocean-climate system.

Given the critical importance of the high northern latitudes in terms of both the linear response of climate to solar radiance and possible non-linear effects of ice sheet and ocean circulation interactions, much effort has been put into the few piston and deep-sea drilling cores available in the region. Through the spectral analysis of a number of paleoceanographic proxies representing different components of the ocean-climate system ($\partial^{18}O$ = ice volume, IRD = size and location of ice sheets, micro-fossil species abundances = SST and watermass history, content of $CaCO_3$ = ice volume through dilution in the North Atlantic and bottom water chemistry in Pacific, aeolian components = atmospheric circulation and aridity), the behavior of the ocean-climate system is beginning to be elucidated and climate models becoming more refined (IMBRIE et al. 1989).

Applications of these techniques to North Atlantic cores have shown that a mass of cold, ice-laden polar water filled the subpolar North Atlantic to about 45° N during glaciations. These fluctuations were dominated by 100 ky and 41 ky SST signals directly in phase with the $\partial^{18}O$ (ice volume) record. They imply that the high latitude ocean follows (with no lag) the growth and decay of the high latitude ice sheets which by albedo effects guide the circum-Arctic into and out of glaciations (RUDDIMAN 1985).

South of 45° N, the SST record is more influenced by the 23 ky precessional forcing. Here, however, the SST lags 2-3 ky behind the ice volume signal. This lag has been attributed to the input of icebergs from mid-latitude glaciers and the effect of warm water flowing north - each of these fluctuating with a 23 ky period (RUDDIMAN & MCINTYRE 1984).

Superimposed on this spatial variability is temporal change. Spectral analyses of $\partial^{18}O$ records from the high eastern North Atlantic reveal that with the onset of significant glaciation (= 2.6 Ma) a sequence of about 40 climatic cycles with a 41 ky obliquity rhythm began. During the mid-Pleistocene, the obliquity rhythm was replaced by an increased response at 100 ky, with the 100 ky cyclicity growing in strength throughout the Brunhes chron (RUDDIMAN & RAYMO 1988).

RUDDIMAN et al. (1986) and RUDDIMAN & RAYMO (1988) have examined the synchronous response of the high North Atlantic SST and the ice volume record and have concluded that northern hemisphere ice sheet growth directly controls the high North Atlantic's surface ocean response through cold winds that are generated on ice sheet flanks and blow across ocean waters. They attribute the temporal change in climate response to the rapid growth of both the Himalayan and western North American mountains during the last 3 my and the effect that these mountains have on atmospheric circulation in the northern hemisphere. Supported by GCM model results, they offer the increased meridionality in northern hemisphere atmospheric circulation caused by rapid mountain growth as a means to trigger the growth of large northern hemisphere ice sheets and thus initiate a strongly non-linear (ice sheet dominated) climatic mode (RUDDIMAN & RAYMO 1988).

The application of time-series analyses to the deep-sea paleoclimatic record has had a profound effect on the understanding of the functioning of the ocean-climate system. Milankovitch's theory provides a known and identifiable external forcing; deviations from a linear response to this forcing are measurable in the sedimentary record and thus provide observational data sets against which to test more complex models of ocean climate response. The high north, with its dominant role in determining ice sheet growth and ocean circulation patterns, is a critical component of all global climate models yet, the collection of long paleoceanographic records in this region has been limited to relatively ice free waters south of about 70° N. With the evolution of more sophisticated climate models, the need for long, paleoceanographic time series in this area becomes more critical.

Specific questions that need to be addressed include:

* What is the periodicity of fluctuations in SST (microfossil assemblages), ice volume ($\partial^{18}O$), ice margins (IRD) and warm water incursions (microfossils) in the Arctic Ocean? Have these periodicities changed through time, especially before and during the onset of major northern hemisphere glaciations?

* What is the distribution of climatic response at high latitude between simple linear response to solar radiance and the non-linear (100 ky) signal?

* What is the magnitude of 100 ky variance in the Arctic Ocean where glacial-interglacial ice volume changes are diminished and can gradients in the 100 ky variance between the Arctic and sub-Arctic provide insight into non-linear mechanisms?

* Can paleowind indicators be isolated in the deep-sea Arctic Ocean record? DARBY et al. (1989) indicate that aeolian dust could account for 1-10 % of the Arctic sedimentary record in some areas. Will cores collected from deep-basin highs contain an aeolian record that will help test the hypothesis of RUDDIMAN & RAYMO (1988) regarding the onset of large ice sheet growth? What is the periodicity of the aeolian record (i.e., what forcing is it responding to)?

* Are the phase relationships between orbital forcing, ice volume, ice margin, surface- and deep-water, and paleowind indicators (if possible) in the Arctic Ocean? Are these all in phase or is there a sequence of events? How have these relationships changed through time, especially before the onset of major northern hemisphere glaciations?

6.5 *Interaction Between the Arctic Ocean and Ice Shields on Surrounding Continents*

Arctic ice caps

The Arctic Ocean and the Norwegian-Greenland seas are surrounded by landmasses that acted as loci for the upper Cenozoic northern hemisphere ice sheets. Therefore these seas are key areas where northern hemisphere glacials can be documented in the form of input of ice rafted glacial debris (IRD) into the ocean. Glaciations in some northern areas, must have started in Miocene as terrestrial data indicate significant cooling in Iceland at about 10 Ma (MUDIE & HELGASON 1983), glaciation in the elevated areas of Iceland in the latest Miocene and Pliocene (EINARSSON & ALBERTSSON 1988) and glaciation in Alaska 6 Ma ago (EYLES 1990). The lack of glacial ice-sheets over western Alaska (except in mountainous regions) and eastern Siberia is noteworthy (HOPKINS 1967). However, evidence from the continental margins adjacent to the Arctic Ocean is sparse.

Queen Elizabeth Island

Distribution of erratics suggests that continental ice at one time extended onto Prince Patrick Island and at least as far north as Ellef Ringnes Island, and that Greenland ice overran the northeast margin of Ellesmere Island. During these and other times, ice was possibly generated within the northern archipelago either from an ice complex over the eastern islands, or as ice caps on individual islands.

The extent of the last glaciation is much disputed. The demonstrated extent is restricted to an extension of up to 60 km of existing ice caps (referred to as the Franklin Ice Complex). A greater (hypothesized) expansion which provided contiguous ice caps and shelves in eastern and southern islands has been named, the Queen Elizabeth Islands Glacier Complex. An even more extensive (pan-archipelago) Innuitian Ice Sheet has been hypothesized, partly on the basis of the Holocene emergence record; however, this emergence has also been explained as an isostatic depression resulting from the composite load of a small local ice complex, and adjacent Laurentide and Greenland ice (HODGSON 1989).

Greenland

Evidence from the Greenland continental shelves indicates that an early glaciation of Greenland, which was more extensive than any succeeding one, occurred near the end of the Pliocene (about 2.4 Ma). A more recent phase of glaciation (about 1.8 Ma) is recorded near the base of the Kap Koebenhavn Formation on eastern Peary Land and in the Lodin Elv Formation found on Jameson Land. Sediments above deposits related to this glaciation were deposited under cool temperate conditions. Tree remnants included in these sediments suggest a climate incompatible with existence of a continental ice sheet in the immediate vicinity (FUNDER 1989).

The ice-free areas of Greenland record only one main ice advance of the last ice age. This ice advance occurred after 40 ka and is referred to as the Sisimiut, Flakkerhuk, and Independence Fjord glaciations in West, East, and North Greenland, respectively. This ice was grounded as far as 30-50 km offshore West Greenland; and locally off East Greenland it extended as far as 200 km. The culmination of this glaciation apparently occurred about 14 ka and large scale oscillations apparently were in phase in all parts of the ice sheet (FUNDER1989).

Barents Sea and other East Arctic shelves

Recent work indicates that the Barents Sea has been glaciated several times during the late Cenozoic. VORREN et al. (1988) speculate that these glaciations have occurred since 0.8 Ma. However, on the Svalbard archipelago glaciation may have started earlier, in late Miocene/Pliocene (VORREN et al. 1991). Views on the Cenozoic glaciation of the continental margin of the Arctic Russia vary from non-glaciation to almost a full cover. A recent reconstruction by GROSSWALD (1983) indicates that a continuous ice sheet covered the Arctic shelves from the Norwegian-Greenland Sea in the west to the Bering Strait in the east. Most of the Barents Sea was glaciated during the maximum of the last glaciation (19-16 ka). A two-stepped deglaciation, 16 to 13 ka and 13 to 10 ka, occurred (VORREN et al. 1988).

Interaction between the Arctic Ocean and adjoining ice caps

The interaction between the peripheral ice caps and the central Arctic Ocean may have taken place in several ways, e.g., sea ice and ocean surface currents, deep water renewal, and sedimentary regime.

Sea ice - surface currents

The characteristics of the modern (interglacial) situation are the permanent ice cover, the inflow of Pacific waters through the Bering Strait and the large continental run-off which generates a low-salinity surface layer, and the inflow of Atlantic waters resulting in relatively warm intermediate waters. The present conditions depend primarily on the water structure. The surface water has a salinity of about 30 ‰. Below a depth of about 50 m, the salinity increases and, below some 300 m, oceanic salinity is reached. In the surface layer, the temperature varies seasonally from - 1.4° C (end of summer) to - 1.7° C (end of winter). At 100-150 m, water temperature rises and at a depth of about 300-500 m, there is water of Atlantic origin with a temperature well above 0° C and occasionally as high as + 1° C. The halocline prevents mixing between the water masses, allowing the formation of a surficial sea-ice, some 3 m thick (WADHAMS 1989). Beneath the Atlantic water lies cold, nearly uniform deep water. The water is well oxidized down to the bottom.

Contrasting types of sea surface environments have been suggested to exist during glacials, namely that

1) the halocline was more or less absent during glacials due to decreased fresh water supply. This could lead to more open water conditions and intense deep water formation;

2) the Arctic Ocean was occupied by a 1000 m or more thick ice cap during all or most of the Pleistocene (HUGHES et al. 1977, WILLIAMS et al. 1981, KEIGWIN 1982, FILLON 1984);
3) based on deep-sea sediments, a permanent ice cover developed at approximately 0.7 Ma. Before this time, the Arctic fluctuated between highly productive and unproductive cold water and this produced different kinds of organisms and sediment than accumulated during the past 700 ky (HERMAN & HOPKINS 1980);
4) the ice-cover has been more or less continually present since its formation at some unknown time during the late Cenozoic (CLARK et al. 1980; CLARK & HANSON 1983).

Several factors must have caused changes in the surface current system. During the larger glacials, the Bering Strait was above sea level. The straits between Svalbard and Novaya Zemlya were covered by glaciers. Continental run off was probably considerably reduced, particularly if an ice cap existed on the East Arctic shelves damming the large Siberian northward flowing rivers. More data are needed before reliable models for the glacial mode circulation pattern and sea-ice extent can be produced.

Deep water renewal

Presently, fifty percent of the deep water in the Arctic Ocean is potentially in communication with the world ocean through the Greenland-Norwegian Sea (AAGAARD et al. 1985). Thus, Arctic Ocean deep water may play a critical role in the formation of North Atlantic Deep Water (NADW), a water mass which is very important to the global climate system. Contributing to the formation of Arctic Ocean deep water are dense brines formed on the surrounding shelves by the freezing of sea-ice, and deep water entering from the Greenland Sea.

Variations in the cover of Arctic sea-ice also influence ocean/atmosphere heat transfer and albedo, each of which has important feedback to the regional and global climate system. The nature and formation of the sea-ice cover in the Arctic depend on the extent of marine ice sheets on the Arctic shelves, contribution of fresh water by rivers, inflow and outflow of surface waters and of low salinity waters from the Bering Sea. At the moment, our understanding of the history of these surface waters as well as deep waters is extremely limited.

Sedimentary regime

The rates at which the various deep-sea sediment types accumulate are essential to the global geochemical balances, because mass accumulation rates of biogenic carbonate, opaline silica, organic matter and the non-biogenic sediment components determine the internal cycling of matter in the oceans. They are, therefore, linked to the chemical state of both the oceans and the atmosphere (BROECKER & PENG 1982). Accumulation of biogenic matter and carbonate are, for example, closely linked with atmospheric CO_2-levels. Biogenic sediment components, which account for more than 50 % of all deep-sea sediments, accumulate at rates which are determined by the productivity rates in the surface waters and the dissolution of these components at depth.

The availability of nutrients determines the productivity rates which, therefore also are dependent on the ocean circulation (e.g., vertical mixing, upwelling), and on climate as a driving force for the circulation. Dissolution of biogenic carbonate is basically a function of the degree of calcite saturation in seawater at the sediment-water interface. Averaged globally, the degree of calcite saturation varies in order to balance the total carbonate budget. The ocean circulation, and the underlying causes for its development and change, is thus a key factor among the dissolution related parameters.

In the Arctic Ocean the availability of nutrients, changing environmental parameters and variations in clastic sediment influx, must have been influenced by the waxing and waning of the adjoining ice sheets. Studies of the western Barents Sea margin (VORREN et al. 1988) indicate that profound changes occurred at the glaciated part of the Arctic Ocean margin. On the upper slope, sedimentation from meltwater plumes and calving icebergs was important during glacials. Additionally, flow tills are probably present. Redeposition by submarine mass movement most likely occurred both during glacial and interglacial periods. Most of the transport, however, occurred during glacial phases when destabilizing processes such as high sediment input and eustatic and isostatic changes were most pronounced. Besides the small and large slides, the most marked features on this margin are debris lobes. These lobes probably consist of glacigenic sediments which have been moved further downslope by debris flows, turbidity currents or other gravity-controlled bottom flows. When the glacier grounding line was situated near the shelf break, there was a very high sediment input along the shelf break. This situation caused oversteepened slopes or/and excess pore fluid pressures in the accumulated sediments, creating instability and mass movement. In periods when the glacier margin had a more landward position on the shelf, the continental slope and basin were mainly fed by icebergs and pelagic sediments.

The modern Arctic clastic influx is dominated by sea-ice transported, relatively fine-grained detritus. During glacial times a large part of IRD (= ice rafted debris) must have been derived from icebergs originating from the surrounding ice caps. If one is able to discriminate between the various types of IRD, a valuable archive of the late Cenozoic glacier and climatic change is filed in the Arctic Ocean deep-sea sediments.

6.6 *The Global Context*

Much of the deep water of the world's oceans originates in the Arctic and sub-Arctic regions of the North Atlantic. These cold, oxygen-rich waters ventilate the world's oceans (BROECKER 1987) and provide an important mechanism for global heat transfer and the cycling of nutrients and carbon. Variations in the nature and flux of these deep waters have a profound impact on the global temperature distribution as well as on ocean and atmospheric chemistry. Thus, the history of NADW formation plays a fundamental role in the development and maintenance of the global climate.

At present, the deep waters of the subarctic North Atlantic form partly from dense saline surface waters cooled in the Greenland and Iceland seas, and partly from deep waters flowing out of the Arctic Ocean (AAGAARD et al. 1985, SMETHIE et al. 1988; cf. Figs. 11 and 12). Because of their rapid formation and short residence time, these deep waters are rich in O_2 and poor in CO_2 and nutrients. The deep water in combination with Norwegian Sea intermediate water, spills over the Greenland-Scotland Ridge and mixes with the warmer waters of the North Atlantic to form southward flowing North Atlantic Deep Water (NADW). The NADW oxygenates the deep ocean. Shifts in the manner and magnitude of formation of the Norwegian-Greenland Sea water are thus intimately linked to the global temperature and CO_2, the stability of the present climate system, and the rates of climatic change (BROECKER et al. 1985, BOYLE 1988, DUPLESSY et al. 1988, MIX & PISIAS 1988). The rate and mode of deep water formation and of oceanic heat transfer to high latitude continental areas are a function of glaciations, sea-ice cover and water circulation. Unravelling the variation in the extent of glaciations and permanent sea-ice cover of the Arctic Ocean is essential to understanding global climate change. Given the paucity of existing Arctic data, the implementation of research programmes that will try to fill this gap is of great importance.

6.7 *Where to Drill for Complete Cenozoic Sequences*

The selection of sites to address these questions will be difficult. Arctic Ocean sedimentation rates are relatively low, thus limiting the availibility of temporal resolution. On the other hand, low sedimentation rates permit us to look at long time series with relatively short cores. Depending on the capability of the sampling system used, it may be necessary to mix sites with high and low sedimentation rates. Ideally, with the ability to recover relatively long cores, we would restrict sampling to areas of high sedimentation rates and thus maximize temporal resolution. We also seek areas where the sedimentation has been as continuous as possible and where the sediment has a large biogenous component (so that there is enough material for isotopic and SST studies). The strong paleomagnetic signal (BLEIL & THIEDE 1990) in Arctic Ocean sediments will be extremely helpful in providing the detailed and consistent stratigraphies that are essential to spectral analysis. To be relatively removed from the influence of turbidites and to help isolate aeolian components, some sites will be sought in the deep basins on local highs. The identification of such sites will have to await site survey results.

The Arctic Ocean basins contain thick sections of predominantly turbidites. Submarine ridges, however, are covered by a biogenic and hemipelagic section with interspersed ice-rafted debris. A high resolution seismic record across the Lomonosov Ridge in the vicinity of the North Pole shows the ridge to be covered by more than 200 m of acoustically well stratified and conformable sediments which may span at least the Neogene, considering the low sedimentation rates in the Arctic Ocean. The actual completeness of a Cenozoic section will be related to the history of bottom currents in the area.

Other potential areas for Cenozoic sequences may be local highs in the basins as shown in Figure 25. One suitably located site is north of the Yermak Plateau at the entrance to the Fram Strait gateway on upper Eocene to lower Oligocene oceanic crust. Areas in this type of setting would be only partially accessible to turbidites from the adjacent continental margins.

Yermak Plateau and Morris Jesup Rise

Based on geomorphological considerations, the Yermak Plateau and the Morris Jesup Rise are thought to be paired plateaus composed of excess oceanic crust. These plateaus are located in the vicinity of Fram Strait presently the only deep water connection between the Arctic and the rest of the world ocean. Drilling these features is expected to provide data on Atlantic versus Arctic water inflow and outflow; onset of ice rafting; variations in glacial and interglacial sediment input; and extent of glaciations.

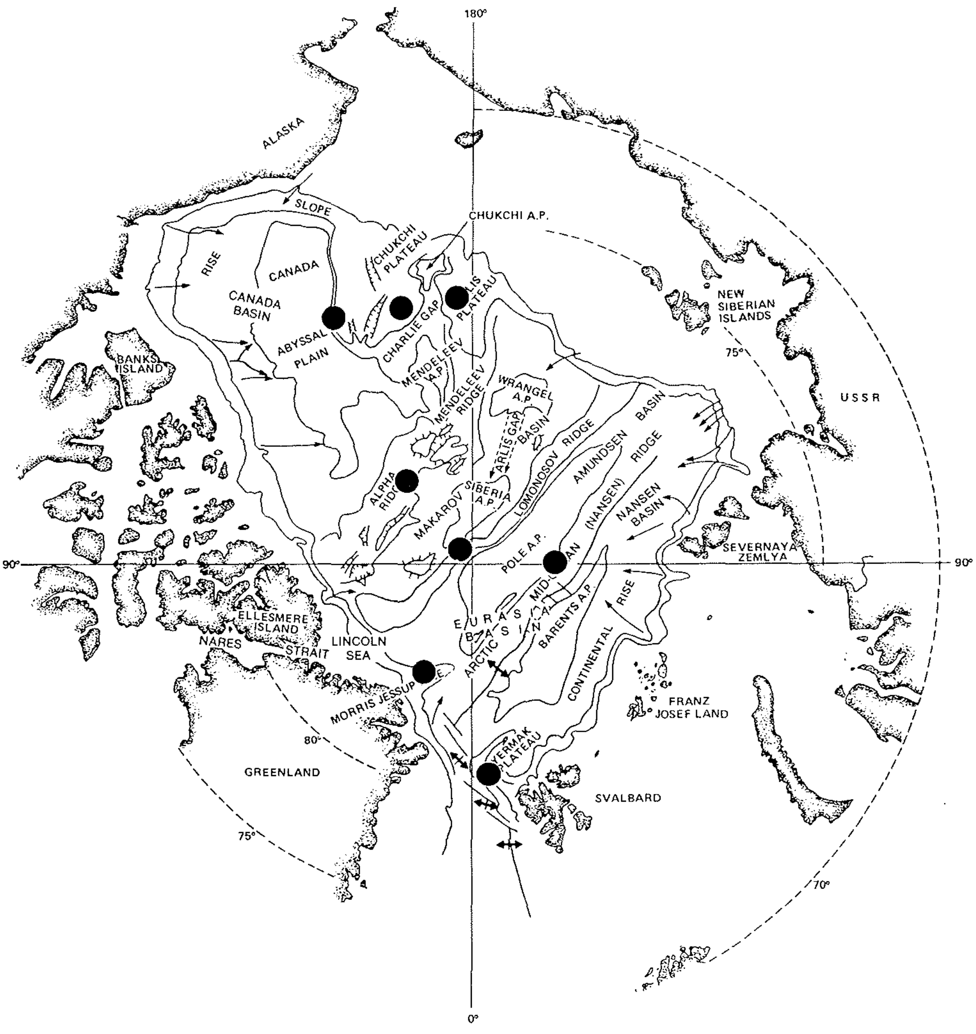


Fig. 25: Proposed locations for Cenozoic Arctic deep-sea drill sites; see appendix for details.

Abb. 25: Vorschläge zur Erbohrung känozoischer Sedimentabfolgen in der arktischen Tiefsee. Siehe Anhang wegen weiterer Details.

The Yermak Plateau is periodically free of sea ice and in a light ice year could be drilled with the *JOIDES Resolution*. One site is proposed for summer 1993, with drilling locations in < 1000 m water depth. The Morris Jesup Rise is located in a region with perennial, generally thick ice which would be difficult to penetrate even with icebreaker support. Sea ice in this region moves at relatively low velocity and therefore the best drilling approach might be a rig deployed on the ice, especially in view of the logistic support available nearby in Greenland. Water depths are about 1000 m.

Lomonosov Ridge

Based on geomorphologic considerations and magnetic lineations in the Eurasian Basin, the Lomonosov Ridge is believed to be a sliver of crust split off by seafloor spreading from the Barents-Siberian Shelf. Although superficially similar, the ice cover, circulation and sedimentation patterns of the Amerasian and Eurasian Basins, separated by the Lomonosov Ridge, show marked differences. The objectives for drilling the sediment cover along the ridge are to determine: 1) initiation and history of Arctic sea ice cover and northern hemisphere glaciation; 2) distribution of water masses and circulation patterns, particularly with respect to the history of Atlantic water inflow; and 3) changes in biologic productivity associated with these paleoclimatic and paleoceanologic variations.

Sites of interest along the Lomonosov Ridge crest vary in depth from 500-2000 m and sediment thickness is unknown. Except for locations just north of Greenland, ice drift can be expected to be fairly rapid. The site north of Greenland could be drilled in the same manner as the nearby Morris Jesup Rise, and perhaps with the same logistical support. Sites on the central and Siberian sides of the ridge would most likely require icebreaker support for attaining and maintaining locations.

Alpha-Mendeleev Ridge

Water depth of locations of interest range from 1000 m to nearly 2000 m. Ice thickness is 3 meters or more and drift rates are relatively low along the southern margin of the Alpha Ridge. Drilling in this region could be associated with the logistical support for the Lomonosov Ridge and Morris Jesup Rise sites. The northerly Alpha-Mendeleev Ridge sites are in regions with more active ice movement, and the ice is thinner with more open regions. Drilling would most likely require icebreakers to maintain position. The Mendeleev Ridge sites close to the Siberian continental margin may be approached from the seasonally ice-free shelf and could possibly be drilled by the *JOIDES Resolution* with icebreaker support.

Nansen Basin

Nansen Basin adjacent to the east Arctic shelves has the potential of serving as the most detailed monitor of Arctic marine ice sheets. High sediment accumulation rates may give high resolution sections. However, several hiatuses or erosional unconformities are to be expected on the continental rise and slope, with less occurring in the basin.

During the larger glaciations the margins of the marine Arctic ice-sheets expanded to the shelf break. The shelf break and upper slope then acted as depocenters. Frequent sediment gravity flows probably accumulated on the lower continental slope and in the basin. During interglacials this area received comparatively much less sediment. Thus, such lower slope areas are excellent monitors of the waxing and waning of the ice sheets. As mentioned, a continuous stratigraphy is not expected in these sedimentologically unstable areas. It is recommended that the Nansen Basin be investigated by several holes from the shelf break to the basin plain.

Makarov and Amundsen Basins

The Makarov and Amundsen basins contain records of the sedimentary development of the interior Arctic Basin. Analysis of sediment cores obtained in the Amundsen and Nansen Basin (MARKUSSEN 1986, THIEDE et al. 1988) appear to show markedly different sedimentation rates and sediment sources during Pleistocene to Recent times than central Arctic cores (CLARK et al. 1980, AKSU & MUDIE 1985, CLARK et al. 1986). It is not known if these characteristics gradually shift toward the basin interior, or if sea ice and water circulation patterns, together with varying sediment sources, create distinct sedimentological provinces.

Drilling in the central Arctic regions with rapid ice movement, relatively thin ice and seasonally open leads would require icebreaker support for maintaining position. Penetration as far north as the Makarov Basin was successfully realized during the ARCTIC'91 expedition. This expedition provided new data on possible drilling locations (e.g. Lomonosov Ridge) as well as information on logistical requirements (FÜTTERER 1992).

7. MESOZOIC PALEOCEANOGRAPHY

The modern Arctic Ocean is surrounded by the widest shelf seas of the world ocean. In Figure 26 it is shown that many of the shelf seas are underlain by Mesozoic and Cenozoic sedimentary basins which are known to

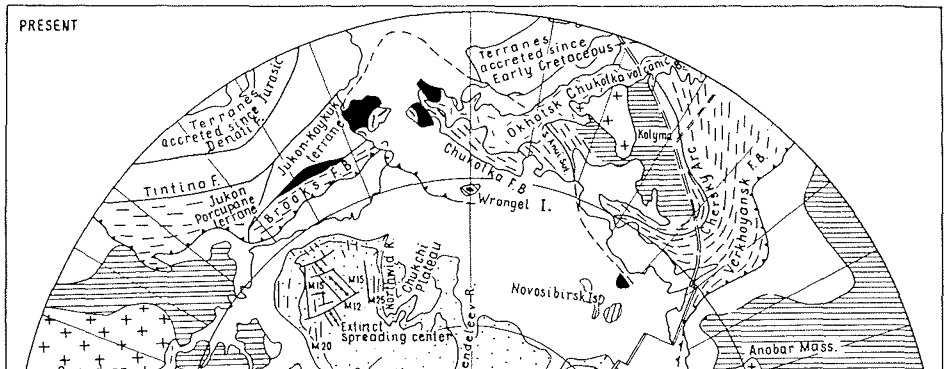


Fig. 26: Main geological structures of the Arctic. Dotted lines are oceanic basins deeper than 2.000 m; 2.000 m and 3.000 m isobaths are shown. The active spreading center is drawn as a double line, dashed where diffuse or uncertain. On the continents, shields (crosses), platforms (horizontally hatched), and orogenic belts (dashed lines) are shown. Ancient massifs, remnants of the Arctica continent, are black. Mesozoic and Cenozoic sedimentary basins are blank. Toothed lines indicate fronts of thrusting. Thick lines correspond to main sutures (ZONENSHAIN & NATAPOV 1989).

Abb. 26: Die wichtigsten geologischen Strukturen der Arktis. Gepunktete Linien markieren Ozeanbecken tiefer als 2.000 m; die 2.000-und 3.000 m Isobathen sind eingezeichnet. Der aktive mittelozeanische Rücken ist als Doppellinie eingezeichnet, gestrichelt, wo unsicher oder undeutlich. Auf den Kontinenten werden Schildgebiete (Kreuzchen), Plattformen (horizontal gestreift) und orogene Gürtel (gestrichelt) gezeigt. Alte Massive, Reste eines Arktis-Kontinents, sind schwarz gehalten. Mesozoische und känozoische Sedimentbecken sind ohne Signatur (weiß). Gezahnte Grenzen kennzeichnen Überschiebungen. Dicke Linien entsprechen den wichtigsten geologischen Suturen (ZONENSHAIN & NATAPOV 1989).

harbour important natural resources. They are also locations of wide spread gas hydrate accumulations and contain submarine permafrost provinces. They have therefore been investigated to a considerable degree by means of seismic reflection profiling and by exploration drilling. A large volume of exciting data covering the Mesozoic and early Cenozoic are available from this area. However, much of this information is not in the public domain (see NAIRN et al. 1981).

When trying to consider the Mesozoic and early Cenozoic history of the deep Arctic Ocean, however, the data base is more than scant. There are only seven Mesozoic rock and sediment cores from the Arctic deep-sea floor available (Fig. 6). There are no interpreted high quality seismic reflection lines available. The age and nature of the magnetic anomalies which have been used to reconstruct the paleogeography of the Arctic Mesozoic basins

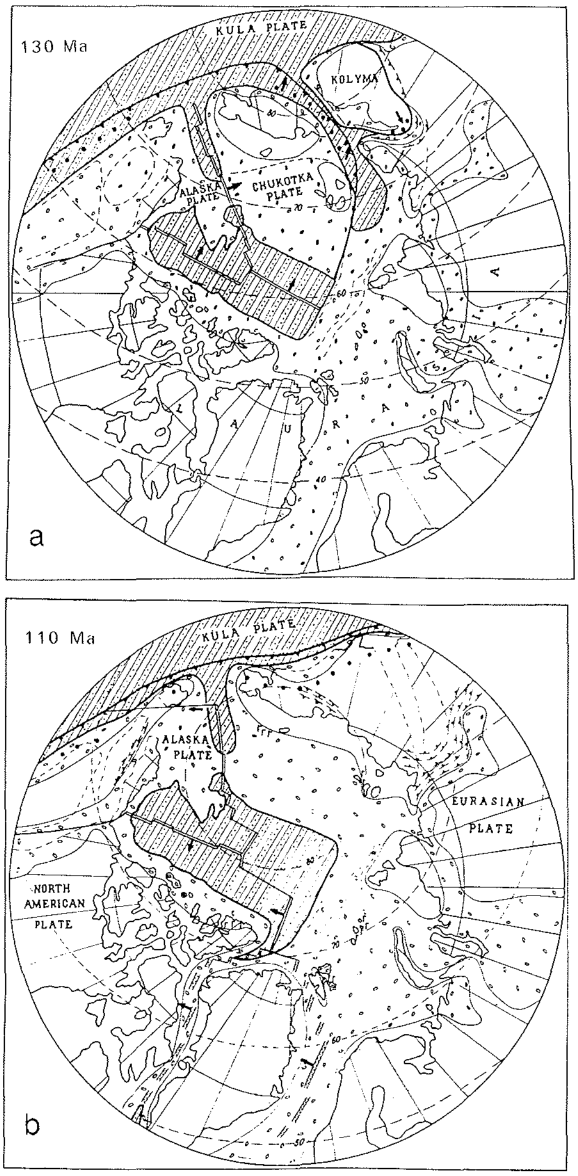
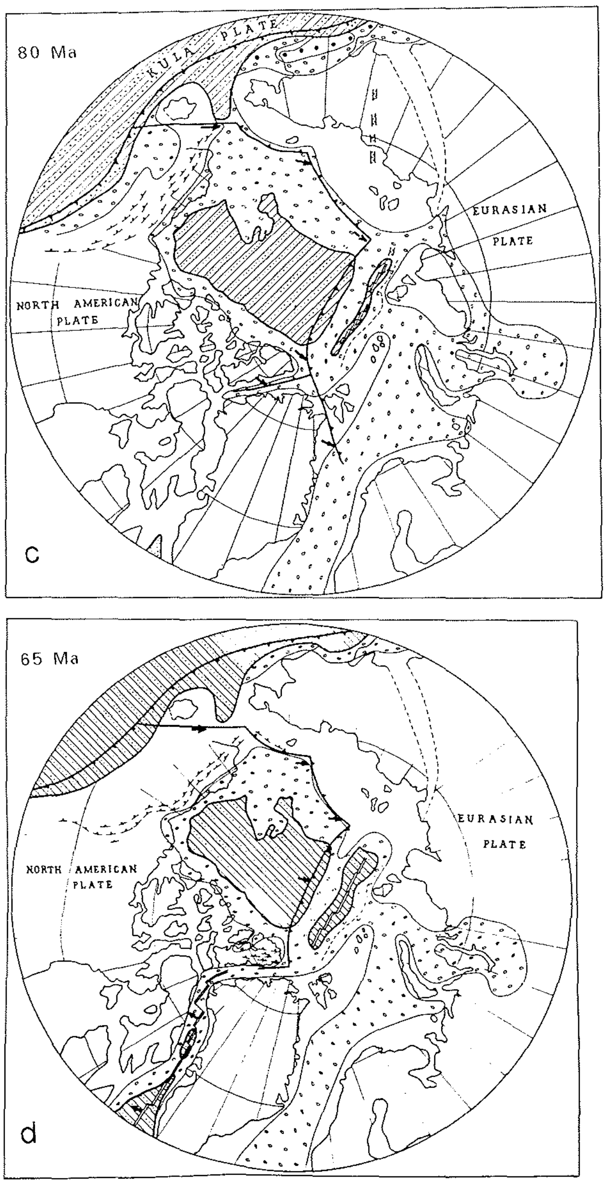


Fig. 27: Arctic paleogeography. **a** The 130 Ma reconstruction; **b** The 110 Ma reconstruction; **c** The 80 Ma reconstruction; **d** The 65 Ma reconstruction (ZONENSHAIN & NATAPOV 1989).

Abb. 27: Arktische Paläogeographie, Rekonstruktionen für die Zeiträume **a** = 130 Ma, **b** = 110 Ma, **c** = 80 Ma, **d** = 65 Ma (ZONENSHAIN & NATAPOV 1989).

(TAYLOR et al. 1981) are questionable. In Figure 27 the reconstructions of ZONENSHAIN & NATAPOV (1989) are shown to document the common opinion that the Arctic was an isolated deep-sea basin which developed in Jurassic and Cretaceous time (see Fig. 9). For the entire Mesozoic it remained restricted from deep-water exchange with the world ocean. ZONENSHAIN & NATAPOV (1989) interpret the Arctic Ocean to have grown from a mid-ocean ridge system which opened the Canada Basin first and which connected in a very complicated way the Pacific plate margins with those of the central Arctic.

Based mostly on circumstantial evidence, ZONENSHAIN & NATAPOV (1989) document the two major properties which are of importance for the depositional environment, namely a) that the Arctic remained one or two isolated basins during the entire Mesozoic, and b) that the major marginal basins as well the ridge systems



of the western Arctic underwent considerable change and subsidence throughout this time span. These properties are important for the understanding of the depositional environments sampled by the few available sediment cores as has recently been discussed in considerable detail by WEBER (1990).

7.1 *Mesozoic Sequences*

To date, only seven rock samples and/or sediment cores document the Mesozoic Arctic deep-sea basins.

A bed-rock sample has been recovered from the flanks of Alpha Ridge by the CESAR expedition (VAN WAGONER & ROBINSON 1985). It consists of tholeiitic basalt, is weathered and documents the volcanic origin of Alpha Ridge. Any age assignment remains questionable.

An upper Cretaceous black shale of probably Campanian age has been recovered from the flanks of the Alpha Ridge (CLARK & BYERS 1984). The black shale contains 15 % organic carbon, and the major proportion of the organic material apparently is of terrestrial origin. The sediments appear laminated and have been dated by means of palynomorphs. The plant debris could have its origin from the vegetative cover of islands when Alpha Ridge was emergent (WEBER 1990). Whether the black shales document anoxic conditions in isolated local basins or the depositional environment under an oxygen minimum in oceanic water masses remains an open question.

Upper Cretaceous sediments consisting of almost pure siliceous oozes (primarily excellently preserved diatoms and silicoflagellates, more typical of environments of temperate latitudes) have been found in two cores at a distance of about 150 km from Alpha Ridge. The sediments in both cores contain very little terrigenous material, are laminated, and lack any sign of benthic life. In one of the cores (Core 6 of the CESAR expedition, MUDIE & BLASCO 1985) a very clearly-expressed lamination can be observed which consists of a darker and lighter siliceous ooze. Siliceous phytoplankton differs in diversity, size and absolute frequency between the different layers.

Provided that age indicating fossils are not reworked the laminated silt stones collected in 3 cores on the east flank of Northwind Ridge are believed to be of Cretaceous age (PHILLIPS et al. 1990).

7.2 *The Mesozoic Arctic Ocean*

The depositional environment of the upper Cretaceous black shale collected from Alpha Ridge has been addressed above, suggesting that it is a marine sediment representing oxygen-deficient or oxygen free conditions along the flanks of a chain of islands (WEBER 1990).

The depositional environment of the laminated siltstones and the complex lithology of the Northwind Ridge deposits (PHILLIPS et al. 1990) cannot be interpreted in more detail at the present time. In contrast to other Cretaceous sediment cores, they contain benthic foraminifers. However, further interpretations await the availability of additional data on the laminated siltstones and the other complex lithologies.

The depositional environments of the laminated siliceous oozes have been extensively discussed. They are preserved in an oxidized state, even though paleontological and sedimentological evidence points to an oxygen free depositional bottom environment. It has been proposed that the lamination has been caused by fluctuations of a complicated Arctic Ocean upwelling system (KITCHELL & CLARK 1982) or by the activity of volcanic events or a hydrothermal vent system in the Arctic Ocean (this could be indicated by the presence of large amounts of micronodules as suggested by STOFFYN-EGLI 1987). Since the latter cores have been taken from sediments displaced from further upslope, no intact stratigraphic section or sediment sequence has been sampled. It remains to be determined how and where the sediments were originally deposited. At the present time, no further deductions regarding the paleoceanographic history of the Cretaceous Arctic Ocean can be made.

Since no samples have been obtained from the Jurassic deep Arctic Ocean, any ideas on the paleoceanographic scenario of that time have to remain hypothetical.

7.3 *Where to Drill for Mesozoic Sequences*

In Figure 28 we have marked several areas of potential drilling for Mesozoic pelagic sequences documenting the ice-free polar Arctic Ocean. The choice of the localities has been guided by the idea that marginal plateaus and some of the structural highs might contain condensed sequences of younger sediments which would then allow the drill to reach Mesozoic sequences with relatively little effort. The lack of seismic profiles has prevented any further precise definition of these localities.

I. Chukchi Plateau and Northwind Ridge;
II. Arlis Plateau;

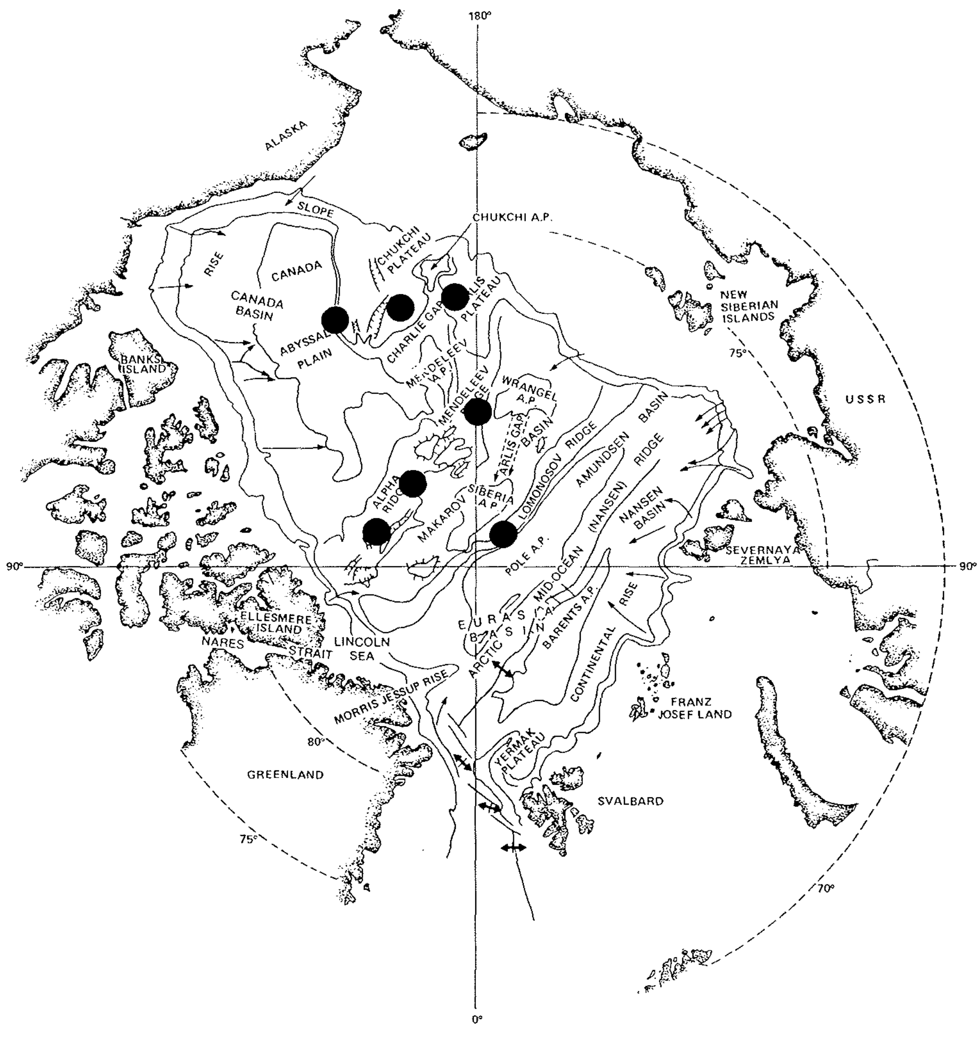


Fig. 28: Proposed drill site locations for Mesozoic sequences on the Chukchi and Arlis plateaus, Mendeleev, Lomonosov and Alpha ridges.

Abb. 28: Vorschläge für arktische Tiefseebohrungen auf mesozoische Sedimentabfolgen auf dem Chukchi- und Arlis-Plateau sowie am Mendeleev-, Alpha- und Lomonosov-Rücken.

III. The unknown sediment sequence of Mendeleev Ridge;
IV. Locations close to the site localities of previously sampled Cretaceous sediments. It should be attempted to establish a transect of cores from the deeper, possibly, older parts of Alpha Ridge towards the shallower part.
V. Seismic profiling carried out during ARCTIC'91 on Lomonosov Ridge gives evidence that Mesozoic sequences can be obtained there.

8. EVOLUTION OF MARINE POLAR BIOTA

In paleoceanography, biological and geochemical tracers are commonly used to test models of past ocean circulation. Microfossil assemblages, when studied quantitatively, can be used to detect the direction and magnitude of changes in sea surface temperature and paleoproductivity, or aid in reconstructing the general circulation of the ocean. Fluctuations between "polar" and low latitude microfossil assemblages in Cenozoic marine sediments have been demonstrated to occur in conjunction with the general cooling of the earth's climate since the Eocene (e.g. CLIMAP 1976, HAQ 1981). But just what is a "polar" assemblage?

A total of 58 sites have now been drilled in the Antarctic and sub-Antarctic region by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP). This wealth of cored material has allowed us to assemble a detailed record of the evolution of the Antarctic faunal and floral province since the Cretaceous (e.g., KENNETT 1978), and use the information derived from Antarctic microfossils for paleoceanographic reconstructions (e.g., MOORE et al. 1985).

Unfortunately, we do not have this luxury in the case of northern hemisphere marine faunas. There is a significant bias in our knowledge of Arctic marine biota. Micropaleontologic investigations of pre-Pleistocene strata are limited to few areas, such as the Beaufort Sea, Alpha Ridge, and Spitsbergen.

Moreover, what little we know about the history of the Arctic faunal province is either proprietary, or is necessarily based on shallow piston cores. Prior activity by the Ocean Drilling Program has recovered pre-Quaternary "sub-Arctic" microfossils in the Norwegian Sea and in Baffin Bay, and in areas influenced by the Greenland Current in the Labrador Sea. However, the Arctic Ocean is the only ocean that has not been cored by deep-sea drilling, and true Arctic pre-Quaternary faunas remain virtually uninvestigated. This science plan focuses on the precise definition of Arctic biota, their evolution, and using this information for achieving a better understanding of Arctic and northern Atlantic paleoceanography.

8.1 *Properties of Modern Polar Biota*

Marine faunas of the polar regions display less species diversity than tropical faunas, and many polar species typically have long geologic records. Planktic marine organisms found in polar regions are characterized by life histories which make them uniquely adapted to their environment. Organisms living at the poles must be adapted to subfreezing temperatures, the dark polar winter, and the strong seasonality of food supply.

These conditions favor life histories which include a seasonal resting stage, and an opportunistic vegetative stage which is active during summer. For example, polar planktic foraminifers can live encased in sea ice, and polar diatoms have a benthic resting stage. Marine benthos must also be adapted to a strongly seasonal food supply from a single summer plankton bloom.

The survival strategy of polar biota enables them to play an important role in the evolution of the world's biota. For example, following the mass extinctions of low latitude calcareous plankton associated with the Cretaceous/Tertiary boundary event, which may have included an extended period of darkness (ALVAREZ et al. 1980), the world ocean was recolonised by *Coccolithus pelagicus*, a species which is still the dominant coccolithophore in the Arctic Ocean today.

During the expedition of the HMS *Challenger*, biologists noted the general similarity between benthic organisms living on the continental shelf of Antarctica and those found living in the deep sea. This led Sir WYVILLE THOMSON in 1877 to speculate a polar origin for deep-sea benthos. However, HESSLER et al. (1979) have elegantly argued that the converse may also be true in the case of metazoans, since the deep sea contains the higher diversity. In the case of the foraminifers, neither idea has been adequately tested.

8.2 *Mesozoic Pelagic Biota*

Neritic Mesozoic sediments from the north slope of Alaska and from the Mackenzie Delta region consist of lithologies which are unfavorable for the preservation of biogenic carbonate and silica, and the micropaleontologic studies carried out in this region have centered on agglutinated benthic foraminifers (TAPPAN 1957, CHAMNEY 1975). According to CHAMNEY (1975), Cretaceous planktic foraminifers have not been found in the Beaufort Sea.

The entire known record of Mesozoic planktic microfossils in the central Arctic consists of three piston cores from the Alpha Ridge (CLARK 1988) and some recently recovered cores from the Naturalist Ridge (PHILLIPS et al. 1990). Some of the oldest recovered central Arctic Ocean sediment is from Core FL-533, and consists of a black, organic carbon-rich homogeneous mud of probable late Campanian age (CLARK et al. 1986). This sediment contains abundant plant material deposited in a marine environment. Microfossils recovered from this sediment include dinoflagellate species which are known from other oceanic areas. The late Campanian location of the Core FL-533 site would have been close to Spitsbergen (CLARK 1988), which was probably the source of the plant material. Marine connections with the world ocean are postulated to have passed through the Barents Sea (ZIEGLER 1988).

Sediments of probable Maastrichtian age have been recovered in Cores FL-437 and CESAR-6 on Alpha Ridge. Sediment in both cores consists of biogenic silica with abundant diatoms, silicoflagellates and ebridians. The sediment is finely laminated, with distinct light yellow and darker, yellow-gray bands. Microsampling of the laminations revealed that darker layers consist almost exclusively of diatom resting spores, whereas lighter layers consist of diatom vegetative cells with few or no spores. BARRON (1985) suggested that these laminations represent seasonal fluctuations in diatom populations in an area of high organic productivity. CLARK (1988) concluded that the late Cretaceous Arctic Ocean had free connections to the world ocean and supported strong upwelling with an abundant growth of marine phytoplankton.

8.3 *Cenozoic Pelagic Biota*

The early Cenozoic microfossil record of the Arctic Ocean is based upon numerous exploratory holes in the Mackenzie Delta and Beaufort Sea, and upon sparse data from the Alpha Ridge in the central Arctic. Detailed microfossil studies are restricted to the Plio-Pleistocene. A preliminary compilation of major paleoceanographic and faunal events in the Arctic, based on these data, is presented in Table 2.

In the clastic sediments of the Beaufort Sea, the only microfossils preserved are agglutinated benthic foraminifers and palynomorphs. Although a relatively complete record of Cenozoic benthic foraminifers has been compiled for the Beaufort Sea (McNEIL 1989), variable preservation of palynomorphs limits their utility to the lower to middle Eocene and Miocene portions of the succession.

McNEIL (1989) recognized a twelve-fold zonation of the Cenozoic in the Beaufort-Mackenzie Basin, based on the last occurrences of benthic foraminifers. No planktic foraminifers were observed in pre-Pleistocene sediments. The Paleocene to Eocene benthic zones are comprised mainly of endemic agglutinated species, which were interpreted as reflecting the relative isolation of the Arctic Ocean from the world ocean. In the central Arctic Ocean, Paleocene or Eocene sediment recovered in Core FL-422 on the Alpha Ridge is present in a similar biosiliceous facies as the Upper Cretaceous. CLARK (1988), however, interpreted the paleoenvironment of Core FL-422 as representing oceanic upwelling conditions, and challenged the idea that the Arctic Ocean was isolated from the rest of the world ocean. Calcareous benthic assemblages in the Sverdrup Basin may be interpreted as

Age	Events
0.4 Ma	Increase in calcareous sedimentation in the Central Arctic, greater influence of "Norwegian Sea" calcareous benthic foraminifers at the Alpha Ridge (SCOTT et al. 1989).
1.7 Ma	Permanent shift of benthic foraminiferal assemblages from agglutinated to calcareous benthics at the Alpha Ridge (AKSU et al. 1988).
2.5-2.2 Ma	Brief period of calcareous sedimentation at the Alpha Ridge. Presence of mixed calcareous benthic and agglutinated faunas, but no planktics (AKSU et al. 1988).
Pliocene	Similar sequence of dinocyst first and last occurrences in Central Arctic, North Atlantic and North Pacific implies open marine connections with the world ocean (AKSU et al. 1988).
Late Miocene	Turnover in the taxonomic composition of benthic foraminiferal faunas in the Beaufort Sea. Establishment of an essentially modern fauna. Interpreted as climatic cooling (McNEIL 1989).
7.5 Ma	Cooling of the East Greenland Current, and the onset of deposition by contour currents south of Greenland (KAMINSKI et al. 1989).
Early Oligocene	Influx of cosmopolitan calcareous benthic foraminifers in the Beaufort Sea, correlative to the Rupelian faunas of northwest Europe. Interpreted as the first influx of neritic benthic faunas into the Arctic (McNEIL 1989).
E/M Eocene	First influx of cosmopolitan benthic faunas into the deep Norwegian Sea. Interpreted as the branching of the Greenland-Scotland Ridge (KAMINSKI et al. 1990).
Paleocene to Eocene	Strong differences observed between the bathyal benthic faunas of the Beaufort Sea and the western Barents Sea region (McNEIL 1989)
Campanian to Paleocene	Biosiliceous facies observed in the Central Arctic interpreted as oceanic upwelling and open marine connections with oceanic areas farther organic south (CLARK 1988).

Table 2: Important Cenozoic paleoceanographic and floral/faunal events in the Arctic region (compiled by M. KAMINSKI 1990).

Tabelle 2: Übersicht über die wichtigsten „biologischen" (Floren und Faunen) und paläozeanographischen Ereignisse im Känozoikum der Arktis (zusammengestellt von M. KAMINSKI 1990).

evidence for at least some shallow water connections to the Atlantic. Preliminary investigations of the 7120/7-3 well in the western Barents Sea indicate that the outer neritic to upper bathyal benthic fauna of the area displays more affinity to the faunas from the Norwegian Sea and North Sea than to the Beaufort Sea Paleogene assemblage described by McNEIL (1989).

The Oligocene to Miocene foraminiferal zones in the Beaufort- Mackenzie Basin consist of a mixture of cosmopolitan calcareous and agglutinated species. McNEIL (1989) attributed the benthic faunal change in the Beaufort Sea to the establishment of open circulation between the Arctic and Atlantic, citing the paper of BERGGREN & OLSSON (1986), who accepted an Anomaly 13 age for the opening of the Fram Strait. This estimate for the establishment of deep marine connections between the Norwegian Sea and Arctic Ocean contrasts with the recent study of SCOTT et al. (1989) who basing their interpretations on analysis of piston cores from the Alpha Ridge, speculated that marine connections through the Fram Strait may have been established as late as the Pleistocene. In any case, dinocyst biostratigraphy in the Pliocene of CESAR Core 14 in the Central Arctic (AKSU et al. 1988) reveals a similar timing and sequence of first and last occurrences as observed at DSDP/ODP sites in the North Atlantic and North Pacific. This suggests open marine connections during the Pliocene. Exactly how deep the sill was between the Arctic and Norwegian Sea is not known. Based on geophysical reconstructions, LAWVER et al. (1990) have argued that the corridor of ocean crust between Spitsbergen and Greenland was not wide enough to allow deep water circulation until 7.5 to 5 Ma.

The last major event in the Cenozoic evolution of Arctic biota was the "Messinian event" of McNEIL (1989), which may correlate with the terminal Pliocene faunal turnover observed by AKSU et al. (1988). In both the Beaufort Sea and in the central Arctic, Miocene or lower Pliocene benthic foraminiferal assemblages were replaced

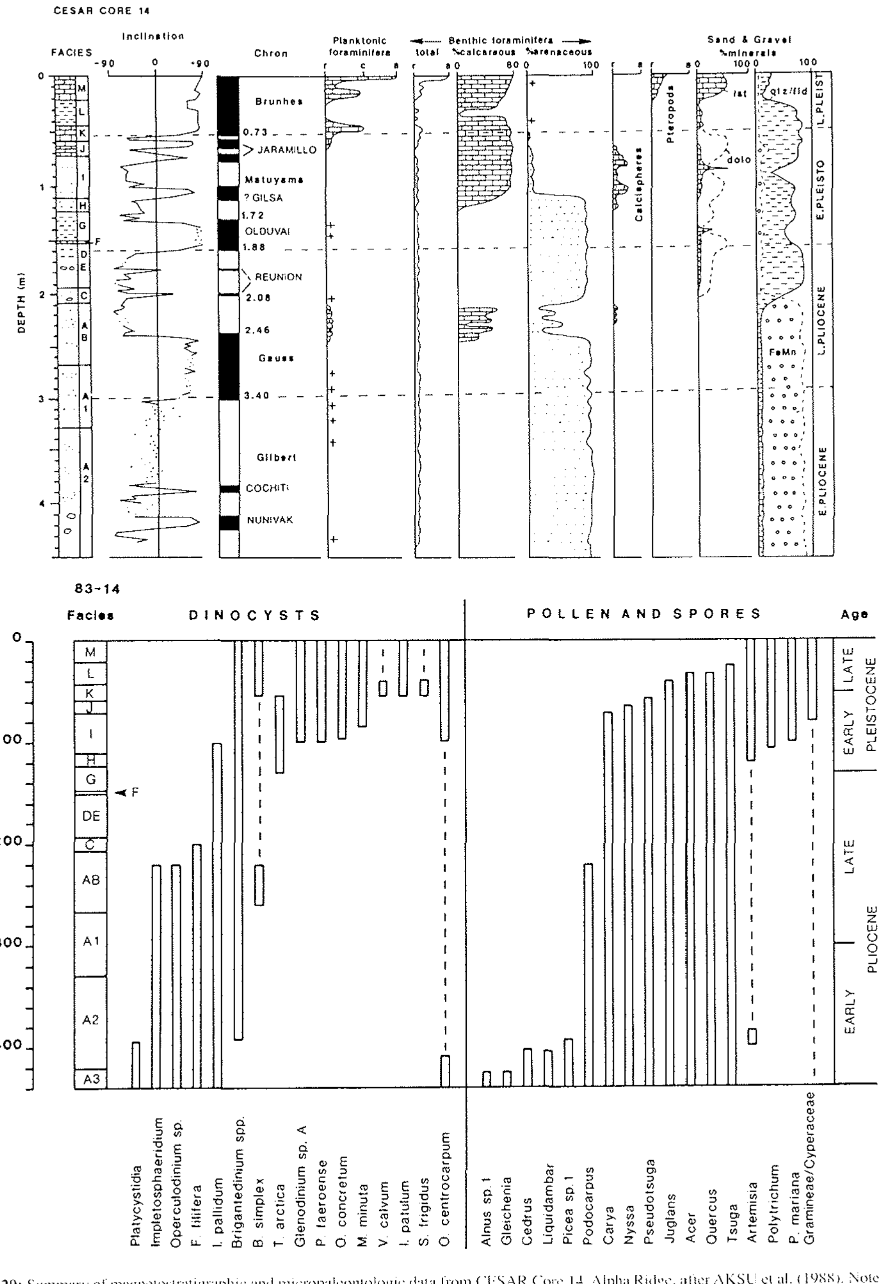


Fig. 29: Summary of magnetostratigraphic and micropaleontologic data from CESAR Core 14, Alpha Ridge, after AKSU et al. (1988). Note change from agglutinated to calcareous benthic assemblages in the upper Pliocene.

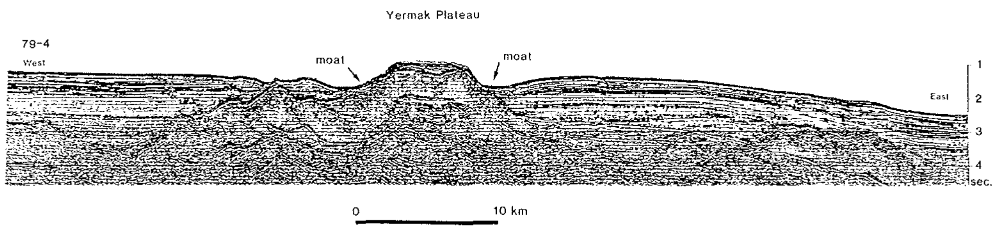
Abb. 29: Zusammenfassende Darstellung der magnetostratigraphischen und mikropaläontologischen Daten von CESAR-Kern 14 vom Alpha-Rükken, nach AKSU et al. 1988. Der Wechsel von Sandschalern zu kalkschaligen benthischen Foraminiferen im oberen Pliozän ist auffällig.

by an essentially modern calcareous benthic assemblage which contains some planktic foraminifers. In CESAR Core 14, this change just preceeded the first appearance of ice rafted detritus (Fig. 29). Although AKSU et al. (1988) offered no explanation for this faunal change, it probably reflects a significant change in the ventilation of the deep Arctic water masses in response to cooling and deep-water formation. The exact nature of this event remains to be studied in detail.

8.4 *Where to Drill?*

Studies of Arctic piston cores have provided an overview of Pliocene-Pleistocene paleoceanography of the Arctic but have given us a mere glimpse of its early history. The crucial gap in our knowledge is the Eocene to Miocene history of the Arctic and its associated biota. This is the time when tectonic events in the Norwegian Sea and Fram Strait areas shaped the present configuration of ocean basins and gateways, and set in motion the current circulation patterns in the northern Atlantic. However, information from the deep Arctic Ocean proper is completely lacking. Only a drilling program to collect reference sections in the Arctic Ocean will provide data on these and other topics, such as: a) the paleoceanography of the Arctic Ocean, b) the nature and evolution of polar biota, and c) the timing and magnitude of marine connections with the Atlantic.

To address these problems properly, a drilling plan should include sites on both sides of the Fram Strait. Highest priority should be placed on obtaining records from the southern part of the Yermak Plateau and Barents Abyssal Plain. The main paleoceanographic objectives at this locality are to study the effect and onset of the West Spitsbergen Current, which brings water of Atlantic origin into the Arctic. The southern Yermak Plateau has a cover of sediments which exceeds 1,000 m in places (KRISTOFFERSEN 1990). Moats around basement highs are evidence of current activity in the area (Fig. 30). A minimum of two sites (one on the Yermak Plateau, another on the Barents Abyssal Plain) will be neccessary to provide information on intermediate and deep water masses and a biota in the Arctic, and detect the influence of the West Spitsbergen Current.



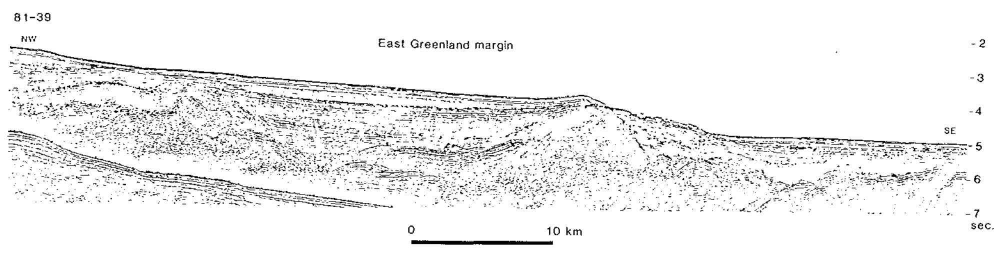


Fig. 30: Seismic sections across the Yermak Plateau and East Greenland margin (KRISTOFFERSEN 1990).

Abb. 30: Reflektionsseismisches Profil über das Yermak-Plateau und den Kontinentalrand von Ostgrönland (KRISTOFFERSEN 1990).

Sites drilled on the Greenland side of the Fram Strait should only record the influence of Arctic water masses (the East Greenland Current) and serve as a control. Two sites on the Morris Jesup Rise would provide an ideal reference section for a record of Arctic biota. An alternative location would be the East Greenland continental slope south of the Fram Strait. A seismic section collected in this area shows lenticular sediment packages which have been interpreted as contourites (KRISTOFFERSEN 1990). A site drilled in this area would detect the onset of contour currents originating in the Arctic Ocean, and would provide a test of the paleoceanographic record obtained at Site 646, drilled off the southern trip of Greenland during ODP Leg 105.

Recovery of cored material from these areas is essential for developing any reasonable understanding of the evolution of the Arctic environment (Tab. 2).

9. AGE AND NATURE OF MAJOR STRUCTURAL UNITS

The Arctic Ocean has, during its evolution since the Jurassic (GREEN et al. 1982) been divided into several ocean basins by major transpolar submarine ridges: the Alpha-Mendeleev Ridge, the Lomonosov Ridge and the presently active Gakkel Ridge.

During the last 60 my, the ocean has undergone a steady extension on the Eurasian side as a result of seafloor spreading. Except for the modern spreading center (Gakkel Ridge), the origin of the basement highs and the age and nature of basement rocks are unknown and can only be resolved by drilling.

9.1 *Lomonosov Ridge*

The 50-70 km wide Lomonosov Ridge is about 1,700 km long and extends from the Canadian continental margin to the margin of Siberia. Water depths are about 500-1500 m along the crest of the ridge. In terms of a linear feature on the ocean floor it compares with the Ninetyeast Ridge in dimensions, but is likely to have an entirely different origin. The seismic data (Figs. 31, 32 and 33) from the Canadian LOREX expedition near the North Pole show the ridge to consist of a series of tilted fault blocks with an upper 6 km thick layer having a seismic velocity of 4.7 km/s (SWEENEY et al. 1982). The underlying 6.6 km/s layer extends to 27 km depth. The gravity data require a low average crustal density (2.5 g/cm) for the ridge. The sediments on the seafloor on top of the ridge are armored by a gravelly lag deposit (BLASCO et al. 1979). The geological and geophysical data indicate that the investigated parts of the Lomonosov Ridge are composed of continental type crustal rocks rather than more magnetic, predominantly volcanic material. During the early Cenozoic, the ridge was adjacent to the continental margin between Svalbard and Severnaya Zemlya and may have originated as a crustal sliver severed off the margin concurrent with rifting between Norway and Greenland (VOGT et al. 1979). Rifting of a continental fragment of such a narrow width compared to its length (1:30) would require some unique properties of the rifting process as well as crustal rheology. Caledonian structures and their associated zones of crustal weakness are perpendicular to the margin north of Svalbard. However, the margin may have been preconditioned with parallel fractures from shear motion.

Volcanic rocks most likely contribute to the basement structure along some sections of the Lomonosov Ridge (GAKKEL 1958, WEBER & SWEENEY 1990 a & b).

9.2 *Makarov Basin*

Details about the Makarov Basin is basically unknown. On the Canadian side seismic refraction results (Figs. 31 and 32) reveal a crustal structure similar to the Alpha Ridge but thinner (FORSYTH et al. 1986). Crustal velocities range from 4.3 km/s to an upper mantle velocity of 8.3 km/s similar to that recorded on the Alpha Ridge. Mantle arrivals occur at a depth of 23 km in contrast to 38 km for Alpha Ridge. This structure which is similar to the Alpha Ridge but thinner suggests the Makarov Basin origin is closely tied to the Alpha Ridge and is not truly oceanic (WEBER & SWEENEY 1990). Soviet data from the Eurasian side of the basin yield similar

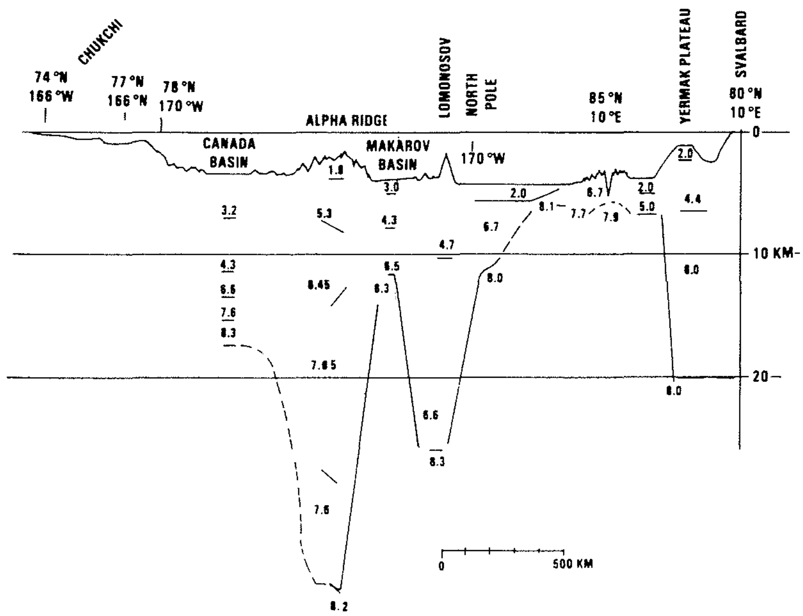


Fig. 31: Crustal structure columns from selected Arctic locales (adapted from FORSYTH & MAIR 1984, MAIR & FORSYTH 1982, JACKSON & JOHNSON 1986).

Abb. 31: Diagramm über den Aufbau der Kruste an ausgewählten arktischen Lokalitäten (übernommen von FORSYTH & MAIR 1984, MAIR & FORSYTH, 1982 und JACKSON & JOHNSON 19869).

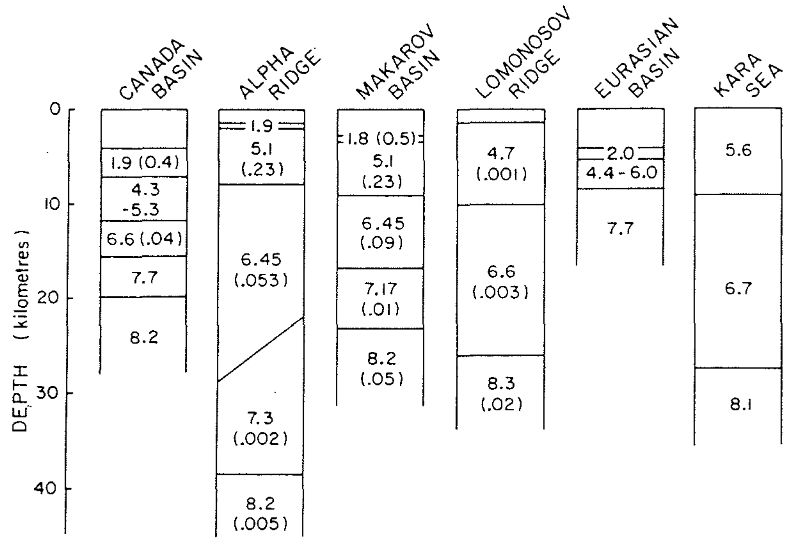


Fig. 32: Column diagram summarizing refraction measurements from basin and ridges in the Arctic Ocean velocities in km/s followed by velocity gradients in brackets, where they are available, are shown (JACKSON & JOHNSON 1986).

Abb. 32: Zusammenfassende Säulendiagramme von refraktionsseismischen Messungen von Becken- und Rückenpositionen im Nordpolarmeer. Geschwindigkeiten werden in km/s gezeigt und durch Geschwindigkeitsgradienten, wo verfügbar, in Klammern ergänzt (JACKSON & JOHNSON 1986).

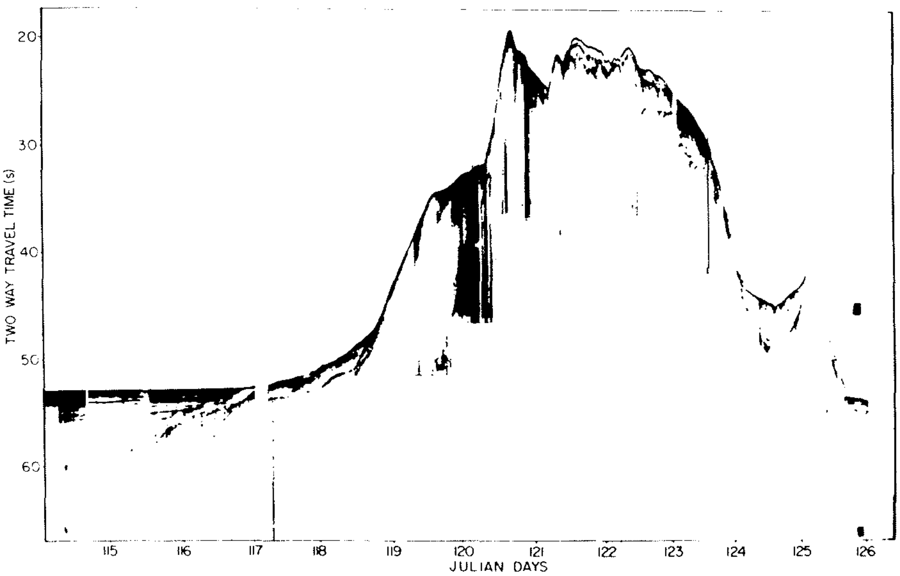


Fig. 33: Seismic reflection line across Lomonosov Ridge. Courtesy S. Blasco.

Abb. 33: Reflektionsseismisches Profil über den Lomonosov-Rücken. Von S. Blasco (Dartmouth) zur Verfügung gestellt.

results, suggesting that the entire basin may consist of stretched or transitional continental/ocean crust (VERBA et al. 1987). Little is known about the age of Makarov Basin. TAYLOR et al. (1981) suggested from aeromagnetic anomalies that seafloor spreading was present from 84 to 49 Ma; however, anomaly patterns are tenuous and may be related to structural relief. WEBER & SWEENEY (1990) suggest this basin was formed in the interval bracketed by seafloor formation in the Canadian Basin and the initiation of sea floor spreading in the Eurasian Basin, between 120 and 56 Ma.

9.3 *Alpha-Mendeleev Ridge*

The Alpha-Mendeleev Ridge is a 450 km wide, irregular transpolar bathymetric feature which rises over 2,700 m above the adjacent abyssal plain to known water depths of about 1,000 m (HALL 1973). The ridge section north of Canada was named after US ice station *Alpha* which made the first crossing in 1957-58. The complementary ridge north of the East Siberian margin was named after the Soviet chemist Mendeleev. The complex horst and graben ridge topography of volcanic rocks is covered by 0.5-2 km of sediments (HALL 1979; Fig. 34). The magnetic anomaly pattern over the ridge is partly irregular and generally correlated with ridge topography (TAYLOR et al. 1981). A single sample of weathered tholeiitic basalt represents the only fragment of basement of the Alpha Ridge available to date (VAN WAGONER & ROBINSON 1985). The oldest sediment samples recovered from the ridge are slump deposits of Upper Cretaceous, black, organic-rich mud and biosiliceous ooze (MUDIE et al. 1986).

A number of hypotheses has been forwarded to explain the origin of the Alpha-Mendeleev Ridge. It may be:
- a continental fragment (KING et al. 1966);
- an extinct axis of seafloor spreading (VOGT et al. 1970);
- a compressional feature representing an incipient island arc or subduction complex (HERRON et al. 1974);
- an inactive transform fault (YORATH & NORRIS 1975);
- an aseismic volcanic ridge (VOGT et al. 1979);
- a hot spot trace (WEBER 1990).

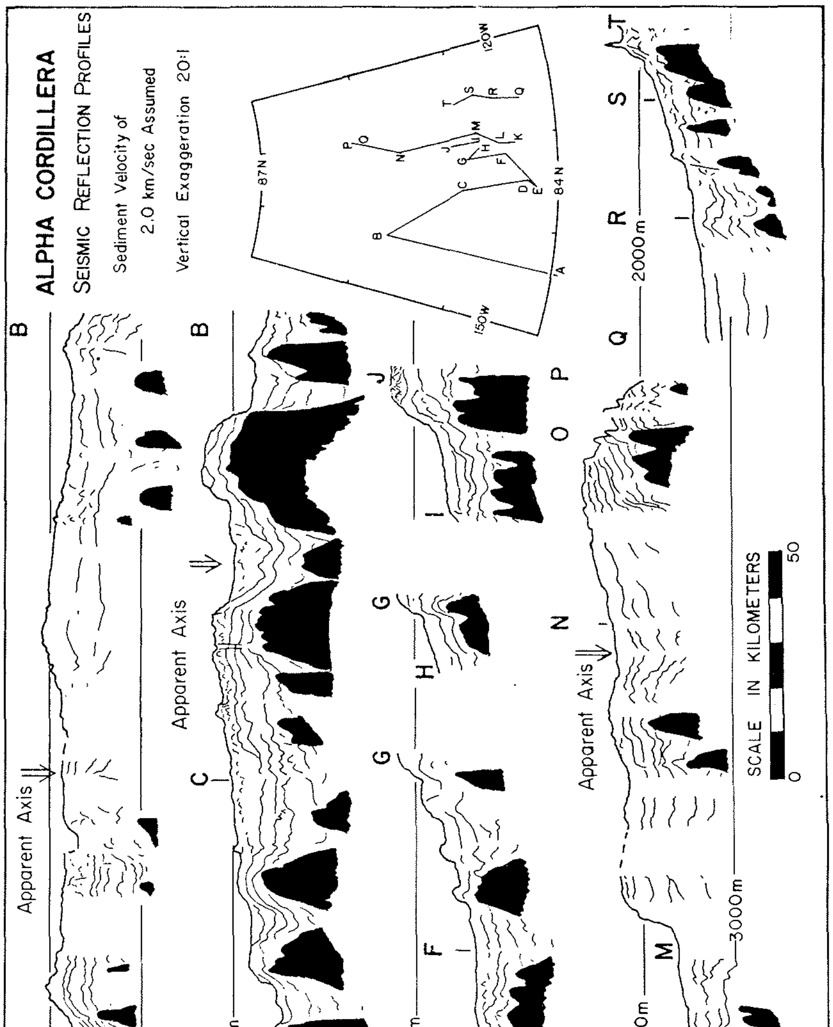


Fig. 34: Seismic reflection records from T-3 across the Alpha Ridge (HALL 1970).

Abb. 34: Reflektionsseismisches Profil über den Alpha-Rücken, aufgenommen von der Eisinsel T-3 (HALL 1970).

9.4 *Canada Basin*

The Canada Basin is probably underlain by Mesozoic ocean crust (TAYLOR et al. 1981). A thick cover of turbidites, however, and the lack of evidence for elevated areas at least partly shielded from turbidite deposition preclude any reasonable drill site proposal.

9.5 *Marginal Highs: Chukchi and Yermak Plateaus and Morris Jesup Rise*

Chukchi Borderland

The Chukchi Borderland occupies a rectangular area about 600 by 700 km protruding north of the Chukchi Sea, between eastern Siberia and western Alaska. This area consists of three north-south (N 20° E) trending segmented ridges; the Northwind Ridge, the Chukchi Cap and Rise, and the Arlis Plateau (HALL 1990). Basic geophysical data are largely lacking from the borderland. First order questions, such as whether the structural units are oceanic or continental in nature, are unanswered. Two cores from the base of the Northwind Escarpment yielded Cretaceous sediments of Cenomanian age (90 Ma). These are the oldest sediments yet recovered from the Arctic (PHILLIPS et al. 1990). A single refraction line suggests the plateau is composed of 7.4 km/sec material (HUNKINS 1966) with 2-4 km of overlying deformed sediments of possible Cretaceous age. This is supported by recent cores (GRANTZ et al. 1990).

The Chukchi Borderland is a key to the evolution of the Canada Basin. It is generally assumed that the large blocks are continental in nature; however, there is little agreement as to their source. Most reconstructions ignore them as they overlap continental crust in the Sverdrup Basin when the Arctic was closed up in early Cretaceous times. The horst and graben appearance of the borderland suggests that a tensional regime played a major role in its development. This simple evaluation does not consider the larger question of how the adjacent seafloor formed. GRANTZ & MAY (1983) suggested that the high-standing, flat-topped blocks that form the Chukchi Borderland are fragments of the continental Arctic platform that moved northward and outward from the present shelf by a minor spreading axis. If the Chukchi Plateau and Mendeleev Ridge did not originate from the Chukchi Shelf, they might have been shifted by an abortive center seaward from the proto-Lomonosov Ridge and hence moved laterally across the Amerasian Basin by a spreading axis.

A more rigorous treatment of the proposed evolutionary models must await new information from the Chukchi Borderland and also a better understanding of the origin of the Amerasia Basin (HALL 1990).

Yermak Plateau

Yermak Plateau and Morris Jesup Rise are conjugate bathymetric features with respect to the Gakkel Ridge. Based on morphology and aeromagnetic data, the Yermak Plateau can be divided into a northern part (north of 82° N) and a southern part. The northern part is associated with high amplitude (>1000 nT) magnetic anomalies which are parallel to the magnetic anomaly pattern in the adjacent ocean basin to the north. A single seismic refraction line on top of the plateau shows a basement velocity of 5.0 km/s, deeper refractors in the range 6.0-7.2 km/s and a minimum crustal thickness of 18 km (JACKSON 1987). This velocity-depth structure is marginally different from that of the southern part of the plateau. The amount of sediment present on top of the plateau is unknown, but a multichannel seismic line collected from an ice drift station on the northern slope shows thick sedimentary sections heavily dissected by slide scars.

The southern part of Yermak Plateau is covered by 0-1 km of sediments and the structure is separated from the north Svalbard margin by a ~4 ENE-SWS trending basement depression.

Compressional velocities within the sediments are 1.7-4.4 km/s and 5.1-5.8 km/s at the basement interface (AUSTEGARD 1982). A seismic refraction line show refracting horizons of 6.0 km/s at 5 km depth and 8.0 km/s at 20 km depth. The observed velocity structure shows gross similarity to refraction results from central Spitsbergen (CHAN & MITCHELL 1982, GUTRECHT et al. 1982). This and a smooth magnetic field over this part of the plateau argue in favour of crustal material of continental affinity. Gneiss boulders have been dredged from the vicinity of a basement outcrop, but their true provenance is uncertain (JACKSON et al. 1984).

The geophysical data support the concept of the northern part of Yermak Plateau as a volcanic constructional feature. The volcanism must, in part, have been subaerial as present water depths are less than 1,000 m. When the lava pile is properly imaged by multichannel seismic measurements, it will probably exhibit a stack of northward dipping reflective horizons similar to what is observed for the Vöring Plateau. Basement is likely to be accessible to the drill with a minimum of sediment cover on the crest of the plateau. Basement on the southern part of the plateau outcrops at the seafloor 80°35' N (see Fig. 30).

Morris Jesup Rise

The structure of Morris Jesup Rise can be inferred from a single channel seismic reflection profile collected by US ice station *Arlis II* in 1964 (OSTENSO & WOLD 1977) and aeromagnetic data (FEDEN et al. 1979, KOVACS & VOGT 1982). The rise has a flat top, bounded to the east by a steep scarp and to the west by a series of progressively deepening sediment-covered fault blocks. It is associated with long wavelength, high amplitude magnetic anomalies (700-800 nT, locally 2,000 nT) which show broken and only partly lineated trends over the main part of the rise. The geophysical characteristics and conjugate position, with respect to the northern part of the Yermak Plateau, argue that Morris Jesup Rise is a volcanic constructional feature although a component of continental crust cannot be ruled out (DAWES 1990, FEDEN et al. 1979; Figs. 7, 8 and 9). Basement is accessible below a thin overburden on the rise.

The excessive volcanism at the end of the Arctic mid-ocean ridge that formed the northern part of Yermak Plateau and Morris Jesup Rise occurred between magnetic isochrons 21 and 13. FEDEN et al. (1979) have related this event to a Yermak hot spot. We note, however, that the timing of this volcanic activity corresponds closely to changes in the motion of Greenland in the waning stages of seafloor spreading in the Labrador Sea (KRISTOFFERSEN & TALWANI 1977). Furthermore, there are several examples of excessive volcanism at ridge segments adjacent to large fracture zones during changes in plate motion: 1) the J-anomaly ridge abutting the Newfoundland Fracture Zone and its timing with the opening between Spain and Newfoundland (TUCHOLKE & LUDWIG 1982); 2) the West and East Thulean basement ridges (VOGT & AVERY 1974) adjacent to the Charlie-Gibbs Fracture Zone and its timing with the opening of the Norwegian-Greenland Sea. Thus, an alternative explanation is that changes in plate motion may induce excessive deviatoric stresses at the ridge fracture zone intersection and lead to anomalous volcanism which may have been the case for Yermak Plateau and Morris Jesup Rise.

The main objectives for drilling Yermak Plateau and Morris Jesup Rise will be:
1) to investigate the nature and age of basement and changes in petrology of the volcanics through time to understand the origin of excessive volcanism and 2) to investigate the subsidence history of the structures and their role as barriers in the incipient Neogene Fram Strait gateway.

9.6 *Gakkel Ridge and Sadko Trough*

The Gakkel Ridge with a total opening rate of 0.85-1.5 cm/y represents one of the slowest spreading ridge segments in the world (Fig. 35). The depth of the axial valley and the crestal mountains are about 1 km shallower in the area west of 25° E than farther east where axial depths exceed 5 km. Towards the Siberian margin, the rift valley becomes progressively infilled with sediments except for a distinct depression: the Sadko Trough. High input of turbidites from the Siberian and Svalbard margin make the abyssal plain encroach upon the ridge flanks and bury the ridge completely in the eastern part.

Soviet and US aeromagnetic surveys (track spacing 7-20 km) have mapped the magnetic lineation pattern in the Eurasian Basin to the extent that it represents one of the best surveyed areas of the world ocean. The magnetic lineation pattern shows minor irregularities and only small fracture zones with offsets < 15 km may be present (VOGT et al. 1979). A bend in the ridge at 60° E may have been inherited from the time of the initial opening. Magnetic anomaly amplitudes are generally +50 to +100 nT. Quite conspicuously, the central anomaly reaches amplitudes of 2,000 nT within an over 200 km long section at the western end of the ridge, but has low amplitude elsewhere (FEDEN et al. 1979). The amplitudes of the adjacent magnetic anomalies also tend to be higher. Elevated ridge topography correlates with the zone of high magnetic intensity, but this is not sufficient to explain the anomaly amplitude differences, which also require higher magnetization of the oceanic crust. High magnetization has been related to presence of high Fe-Ti basalts.

Nearly two dozen seismic refraction measurements have been made in the Eurasian Basin mostly at the northern flank of the ridge. Many of the measurements show a normal thickness of the oceanic crust with some notable exceptions where the crust is observed to be 2-3 km thick on the northern flank. There are no observations available from the conjugate position on the southern flank to investigate possible symmetry in the occurrence of thin crust. Viewed as a whole there seems to be crustal thickness variations in the range of 2-3 km both along isochrons and flow lines.

The limited data from the Gakkel Ridge demonstrate that the rift valley seems to retain its morphological characteristics over the range of spreading half rates from 0.4-3 cm/yr. The Gakkel Ridge has a slightly wider rift valley for a given spreading rate than the width predicted by comparing to observations from other slow spreading ridges. Also when we include the data points from the Gakkel Ridge, the distance from the axis to the

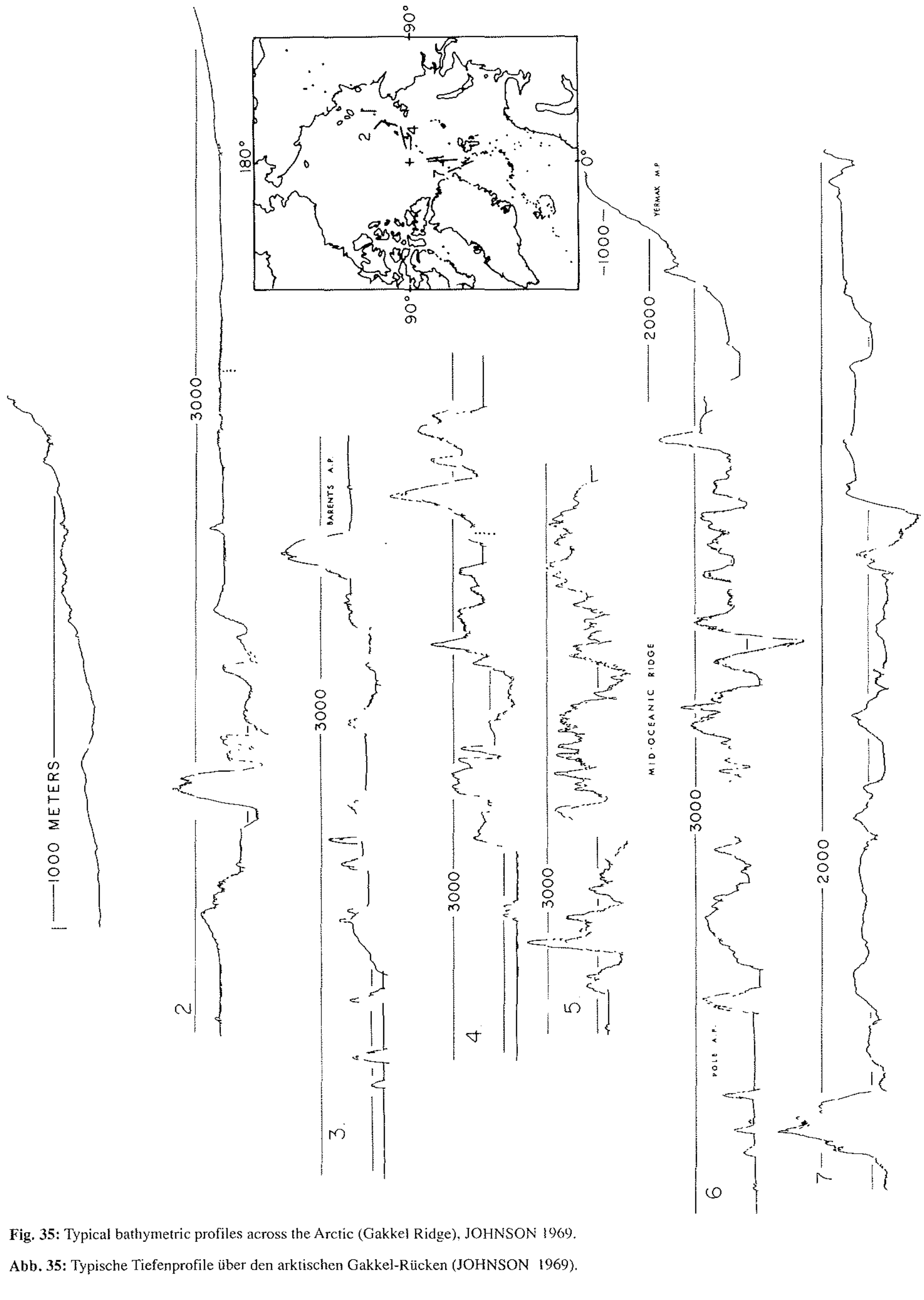


Fig. 35: Typical bathymetric profiles across the Arctic (Gakkel Ridge), JOHNSON 1969.

Abb. 35: Typische Tiefenprofile über den arktischen Gakkel-Rücken (JOHNSON 1969).

outer walls as well as the inner edge of the crestal mountains seems to decrease towards some minimum value for decreasing spreading rates at slow spreading ridges.

At slow spreading rates, volumes of magma can only exist temporarily in the crust due to heat loss (SLEEP 1975). The meager seismic refraction results available do indeed suggest that the depth to a 7.3 km/s refractor within the Gakkel Rift Valley (3 km) is greater than in other parts of the rift valley (2 km in the FAMOUS area; FOWLER 1976). Also, a seismic velocity of 4.6 km/s at the seafloor within the Gakkel Rift Valley could suggest that fractures and voids have largely been sealed by hydrothermal circulation in the vicinity of the outer wall.

Spreading rates may have a large effect on the composition of erupted basalt; the slower the ridge the lower the extent of melting. KLEIN & LANGMUIR (1987) have pointed out that it is the range of composition that is associated with spreading rate. All fast ridges have a limited range in depth and chemistry whereas slow spreading ridges exhibit the entire range in depth and chemistry (variability in MgO content).

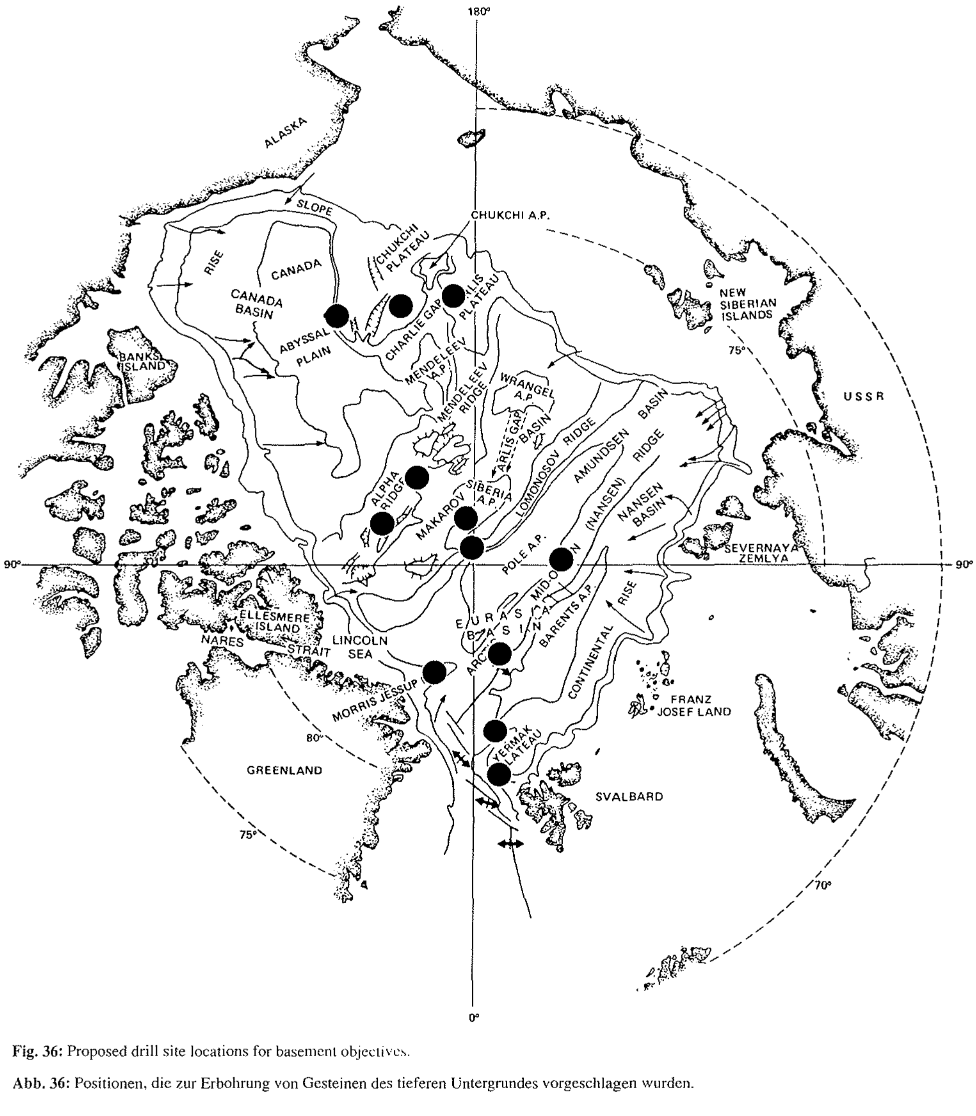


Fig. 36: Proposed drill site locations for basement objectives.

Abb. 36: Positionen, die zur Erbohrung von Gesteinen des tieferen Untergrundes vorgeschlagen wurden.

9.7 *Where to Drill for Basement Objectives?*

Locations where basement objectives can be drilled are spread over the entire Arctic Ocean (Fig. 36). However, in most cases they will be combined with drilling for paleoenvironmental objectives.

10. STRATEGY FOR ARCTIC DEEP-SEA DRILLING FROM THE SCIENTIFIC POINT OF VIEW

Preparation for Arctic deep-sea drilling will necessitate extensive operations for site surveying in major parts of the Arctic Ocean, whereas drill sites will be confined to a few well chosen localities over some of the most prominent basement structures in the central Arctic. For both operations extensive logistic support will be established, which could also be used by many other polar science disciplines. This science plan for Arctic deep-sea drilling should therefore lead to a general increase in the Arctic research effort involving not only geosciences but other polar research disciplines as well which can profit from the expanded logistic effort. This proposal will serve as the scientific basis for Arctic deep-sea drilling and thus move forward realisation of the goal in the mid-nineties.

10.1 *Finance and Funding*

Before final selection of a drilling platform, it will be impossible to accurately assess the financial requirements of the planned operations, which will have to include the scientific evaluation of the collected samples and data. It is clear that Arctic deep-sea drilling will be very costly, on the order of the funds needed for the Ocean Drilling Program (ODP), approximately 30-50 million dollars per year (excluding capital investment). Presently, NAD does not expect to find one single country which would be willing to cover these costs, but it is interested in forming a consortium of circum-Arctic and sub-Arctic countries (possibly including industry and international organizations).

10.2 *Technical Drilling Requirements*

The desirability of Arctic deep-sea drilling has been discussed for more than a decade, first under the auspices of the Deep Sea Drilling Project (DSDP) and more recently of the Ocean Drilling Program (ODP). Both drillships employed by these projects, first the *Glomar Challenger*, more recently the *JOIDES Resolution*, have drilled successfully in ice-infested waters. However, during these attempts it also became quite clear that these vessels, which are not sufficiently ice-strengthened, would not be permitted to enter permanently ice-covered waters.

JOIDES Resolution will probably return to the North Atlantic Ocean during 1993. Drilling proposals are presently evaluated within the JOIDES advisory structure. It is expected that she will drill for paleoenvironmental and tectonic targets in the area east of Greenland, maybe as far north as Svalbard and the Yermak Plateau (RUDDIMAN et al. 1991).

The question of how deep-sea drilling could be carried out in ice-covered waters has lingered on for some time until late 1986 when international scientific organisations (IUGG-ICL, IUGS-CMG, SCOR WG 82) called for a workshop in Halifax to assess the technical feasibility of Arctic deep-sea drilling.

With the help of industry personnel with many years experience with high Arctic hydrocarbon exploration, it could quickly be shown that such drilling would be very costly, very complicated, but technically feasible. A summary of potential drilling platforms is given in Table 3.

Regardless of the platform finally chosen, it will have to cope with the usually slow, but variable movements of the Arctic ice cover (Figs. 12, 14), which are reasonably well understood after several decades of monitoring ice station movements and which had been predicted and proven early by F. NANSEN. The water depths to be drilled in will range from 1,000-4,000 m, allowing for some (limited) lateral drift of the drilling platform. The relatively thin sediment sequences (estimated 500-1,000m) above the Arctic basement can be penetrated within a few days,

Platform	Capability Coring	Other	Cost Approx. 1989 (in KS $)	Limitations
A. Bottom Coupled	Continuous if ODP technology used	deep holes possible limited to one hole	1 mio per day	very high cost 60 m maximum depth of water
B. Ice (thickened)	continuous if ODP technology is used in existing rigs	deep holes possible	21–23 mio per core	limited mobility via air high logistic and support cost summer operations might be difficult
C. Drill ship	continuous if ODP technology is used in existing ships	most reasonable in both cost and in reaching science objectives limited mobility	30–60 mio per year with ice breaker	require ice breaker support rounded hull to minimize ice pressures
D. Shallow drilling	continuous	ship ice or land mounted	8,500 a day	depth limited (60 m) 120 m core length
E. Frozen-in barge	continuous if ODP technology is used	deep holes possible	40 mio per year without ice breaker	lack of mobility unless round hull is used subject to ice crushing, ice breaker escort required
F. Ocean Drilling Program (ODP)	continuous with well logging		32.5 mio per year	cannot work in even loose ice
G. Canadian Class 8	continuous	maximum depth of about 150 m	?	will be capable of steaming to any part of the Arctic
H. Ice breaker	continuous	drilling mounted semipermanently	50–60 k per day	station keeping capability

Table 3: Characteristics of drilling platforms which can be used for Arctic deep drilling (from Halifax workshop on Arctic Drilling Technology, Dec. 1986).

Tabelle 3: Zusammenstellung einiger wichtiger Eigenschaften von Arbeitsplattformen, die im Rahmen von arktischen Tiefseebohrungen eingesetzt werden können (zusammengestellt auf einem Arbeitstreffen über arktische Bohrtechnologie, Halifax, Dezember 1986.

if the efficacy of the platform is close to that of the *JOIDES Resolution*. If the ice moves too fast, drilling would have to be suspended or stratigraphic sections would have to be pieced together from stratigraphically overlapping sections obtained along the drift path by stepwise penetration.

In terms of coring techniques the workshop participants agreed that continuous coring using the riserless techniques developed by ODP, should be adopted to any of the drilling platforms considered. They would not require reentry capability, but would be single-bit holes penetrating the entire sedimentary section up to 50 m into the underlying basement.

Logistic requirements would be complicated and difficult to fulfill. Operations would have to be subdivided into legs of some 2-3 months in duration. In between these periods, the personnel would have to be exchanged (probably by aircraft) and supplies and spares would have to be replenished.

The complexity of the drilling operations will require the establishment of an extensive, capable, and dependable logistic network to manage operations.

Since most of the time the drilling platform would be located in regions which are only accessible with difficulty, it is evident that the platform should also offer space to experiments from many other polar research disciplines such as marine biology, physical oceanography, meteorology, geophysics, geochemistry, etc. It is presently considered that the entire effort should be interdisciplinary in nature, even though the geoscientific investigations will receive the highest priority.

10.3 *Existing Data and Needs for Site Surveys*

Existing seismic reflection data in the central Arctic Ocean presently do not fulfill the requirements of site surveys for deep-sea drilling (JACKSON et al. 1990). Site surveying of the proposed drill sites poses therefore a major problem, both for surveys before and after the drilling. If areas without adequate data are selected, new seismic lines have to be collected, which can be done in a number of ways:

1) A 900 m long snow streamer with gimballed geophones (25 m spacing) can be towed over the ice by a skidoo. At each shot point a hole is drilled through the ice and a 250 gram charge fired in the water. A single shot will give reflection points in the subsurface for every 12.5 m and yield single channel data coverage over a distance equal to half the streamer length (500 m). Estimated production is 150 km of good quality single channel seismic data per week by a three men crew supplied by aircraft.

2) Source and hydrophone array could be towed from a ship. Good quality single channel seismic data were obtained by US icebreaker *Polar Star* in 7/10 of ice over Northwind Ridge in 1988. About 1,500 km of multi-channel data were obtained by the international ARCTIC'91 expedition on board *Polarstern*. Submarines would be most practical for geophysical surveys, but their availability in the Arctic Ocean is uncertain. Preliminary studies suggest that submarine drones are promising, and preliminary engineering studies are under way.

3) Arrays of hydrophones or sonobuoys could be deployed symmetrically around the drilling platform, which would support the sound source.

4) Marginal regions such as the Yermak Plateau might be accessible for conventional research vessels during years of optimal ice conditions.

The NAD Science Committee has recently established a subcommittee for reviewing and planning site surveying activity as well as the establishment of an Arctic geoscientific data bank.

10.4 *Environmental Protection*

The planned operations (here only considered for the Arctic deep-sea basins and not the shallow gas-hydrate infested peri-Arctic shelf seas) will have to satisfy several aspects of environmental concern.

First, the entire suite of activities will have to be carried out with minimal disturbance of the natural environment; that this can be done to a certain degree has been successfully demonstrated by the ice-island stations, which have been occupied for many consecutive years by researchers from both eastern and western countries. However, extensive seismic reflection surveys have not been carried out in the central Arctic; their environmental impact has to be considered. This applies to the planned drilling operations as well.

Second, the selected site must satisfy the scrutiny of safety reviews, involving the best scientific and technical knowledge such as is presently represented in JOIDES and ODP safety panels, as well as any national safety regulations, before approval for drilling can be granted. The type of drilling will be riserless, as is usually employed for sampling deep-sea sections of pelagic sediments.

10.5 *Political Feasibility*

The political situation of the countries bordering the Arctic Ocean itself, and differences in opinion about the validity of their claims to the economic zones adjacent to the shelf regions is complex (Fig. 37). Different, and possibly unresolved, regional claims might exist in other parts of the Arctic Ocean.

The scientific exploration of the central Arctic with operations as complex and dangerous as deep-sea drilling in permantly ice-covered waters cannot be achieved without the active participation and assistance of all major potential partners.

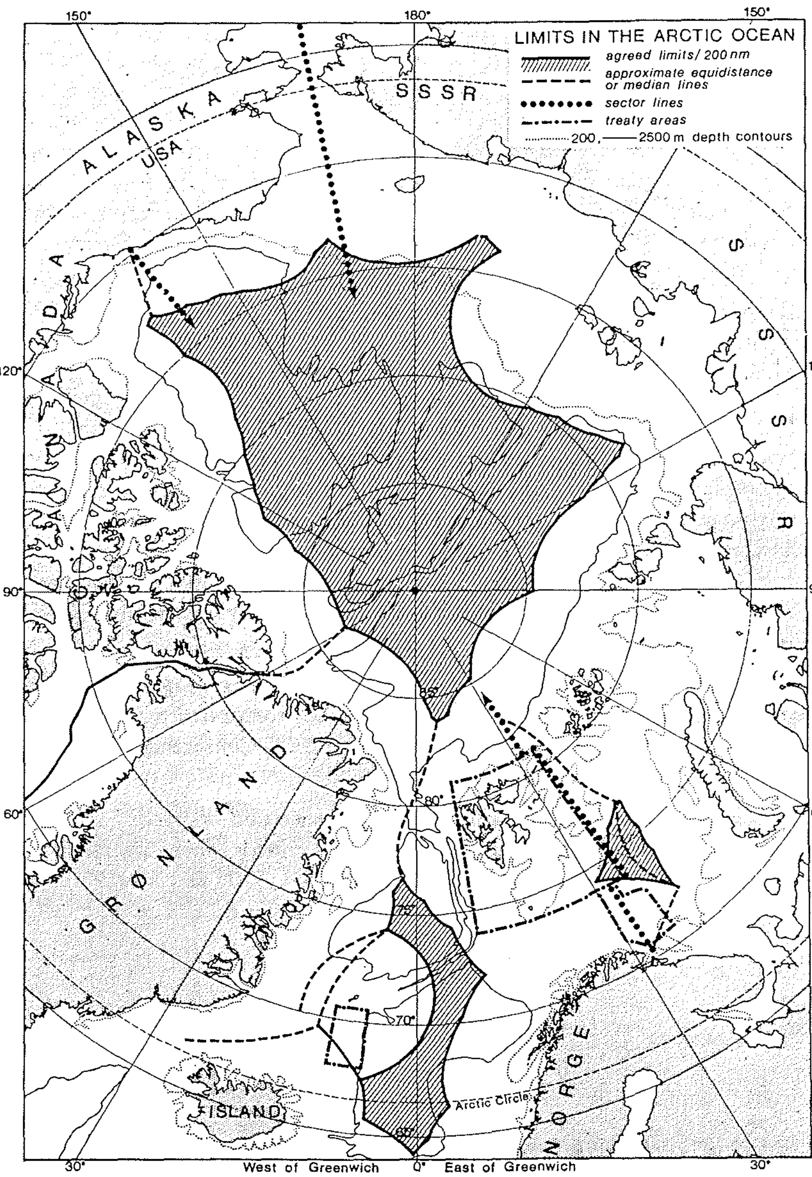


Fig. 37: Examples of political considerations for research licenses from Arctic deep-sea drilling close to the continental margins (JENISCH 1985).

Abb. 37: Darstellung der für die Erteilung von Forschungslizenzen im Nordpolarmeer zu berücksichtigenden politischen Grenzen (JENISCH 1985)

11. POSSIBLE APPROACHES TOWARDS THE ULTIMATE GOAL UNDER THE FRAMEWORK OF NAD

The unique scientific opportunities of exploring the natural properties of the sea floor under the permanent ice cover of the Arctic are presently under intensive discussion. Plans for Arctic deep-sea drilling are being pursued by a number of different groups with different scientific objectives; they were presented as a concerted effort for the first time during COSOD II (Conference on Scientific Ocean Drilling, Strasbourg July 1987).

There is also no question that the planning of Arctic deep-sea drilling will have to rely heavily on the expertise of the Ocean Drilling Program (ODP) and its advisory structure JOIDES. NAD will also have to seek close cooperation with the oil companies having experience in Arctic exploration.

However, for a variety of reasons, none of the existing organizations will in all likelihood promote these plans strongly enough so that Arctic deep-sea drilling can become a reality. Plans are therefore underway to organize a new effort aiming at the organization of a large international, interdisciplinary expedition to explore the nature of the deep Arctic. It will have to fulfill the following requirements:

1) The most exciting, complex and costly element of this effort will consist of the exploration of the geological structure of the Arctic deep-sea floors. The possibility of Arctic deep-sea drilling as the operational and scientific centerpiece of this effort is a *conditio sine qua non*.

2) The long duration of the drilling effort, the powerful logistic apparatus which will have to be organized and financed, as well as the remoteness of the areas will result in unique research opportunities for other polar science disciplines as well. The effort should be interdisciplinary.

3) The nature and shape of the Arctic Ocean and its continental margins, the location of the scientific targets with the highest priorities, as well as the complex and dangerous operations in an environment hostile to man will require the active participation of all circum-Arctic and several sub-Arctic countries.

4) The global impact of the geological evolution and of many natural properties of the modern Arctic will hopefully make it attractive to a number of powerful non-Arctic countries and major, world-wide operating oil companies to contribute to this effort, on the scientific, organisational, technical and financial level. It might also be of interest to a number of international organizations because the Arctic harbors keys to the problems of global change.

It is our proposal that the international scientific community joins forces to start preparations for expeditions to the Arctic with the aim to explore the natural properties and history of some of the least known, most hostile ocean basins of our planet through deep-sea drilling techniques.

12. CONCLUSIONS

1) The Nansen Arctic Drilling Program (NAD) prepares for investigations in the ice-covered Arctic Ocean to resolve the Late Mesozoic and Cenozoic paleoceanographic, paleoclimatic and tectonic Arctic history. It is time for the international scientific community to join forces in expeditions to the Arctic. It is NAD´s ultimate objective, to explore the natural properties and history of some of the least known, most hostile ocean basins of our planet through deep-sea drilling techniques.

2) The Arctic ice cover is an expression of the extreme climatic scenario which has only developed during the Late Cenozoic cooling of both poles. Sea ice covered areas and their marginal zones have experienced the most extreme and rapid climatic changes during the recent geological past. It is here that the ocean surface waters cool to below 0° C and where cold oxygen-rich and dense surface waters sink to the seafloor to contribute to the renewal of the bottom water masses of the global ocean. It is therefore critical to understand the short- and long-term changes of the Arctic Ocean to resolve the mystery of global change. The Arctic Ocean with its important contribution to deep water formation and its clear association with ice sheet history will play an important role in predicting the future behavior of the global ocean climate system.

3) Continental margins and sedimentary basins of polar and subpolar areas contain large quantities of natural resources. The geological history of the northern hemisphere and the framework for the formation of such resources cannot be reconstructed properly if the nature and evolution of the Arctic Ocean basement is not determined by means of obtaining undisturbed samples from basement rocks. Little is known about the large tectonic units such as Lomonosov Ridge, the Alpha-Mendeleev Ridge, Makarov Basin, the Canadian Basin and a number of continental margin features. Reconstructions of the paleogeography of the northern hemisphere prior to Cenozoic times are hypothetical at best and can only be solved by deciphering the plate tectonic puzzle of the Mesozoic Arctic.

4) The scientific goals of this science plan are to understand the climatic and paleoceanographic evolution of the Arctic region and its effects on global climate, the biosphere and the dynamics of the world ocean and atmosphere; and the nature and evolution of the major structural features of the Arctic Ocean Basin and circum-Arctic continental margins.This knowledge will allow realistic inputs from the Arctic for predicting the ocean-atmosphere-cryosphere coupled system so vital for global change prediction. In addition, it will be possible, for the first time, to develop models of the structural fabric and geologic evolution of the northern latitude regions.

5) Drill sites have been proposed to sample most major basement units of the Arctic Ocean and to describe the Late Mesozoic and Cenozoic depositional environment selecting both high and low sedimentation rate areas.

We are on the brink of technical feasibility of Arctic deep-sea drilling. NAD proposes a stepwise approach over several years to combine heavy coring with light and heavy drilling to obtain an undisturbed record of basement rocks and of the history of the Arctic Ocean depositional environment. It is envisioned that initial efforts will be on obtaining long piston cores, site surveys for deep water locations and shallow continental margin drilling. Figure 38 and Table 4 contain a prioritized list of proposed NAD drill sites.

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15. APPENDIX

This appendix ammends the Initial Science Plan of the Nansen Arctic Drilling Program (NAD), mainly by providing details on the individual sites which have been selected as preliminary drilling target. The sites selected have been subdivided into three categories of priority, (1) being the highest, as indicated in Table 4. It is clear, however, that the choice of sites will change when additional site survey data become available.

The Executive Summary of this plan defines the scientific goals of the Arctic deep-sea drill sites which have been proposed by NAD and which are documented with the available data in this Appendix. Scientific priorities are explained and argued for in the NAD initial science plan.

In addition to the specific site proposals this Appendix provides information on the NAD organization and membership. A list of abbreviations and acronyms used in the science plan and in its appendix is found at the end.

Specific drill site proposals were prepared by A. Dettmer, U. Grützmacher, C. Stolte, J. Thiede, G. Uenzelmann-Neben and T.C.W. Wolf with reference to the ODP-proposals by MUDIE, P.J., JACKSON, H.R. & BLASCO, S.M. (1988) and HEAD, M., KACZMARSKA-EHRMANN, J., MUDIE, P.J. & SWEENEY, J.F. (1990)

Site no.	Proposed General Area	Position		Priority (1-3)*
ARC-1	Yermak Plateau	80° 53' N	7° 19' E	1
ARC-2	Yermak Plateau	82° 42' N	9° 33' E	1
ARC-3	Lomonosov Ridge	89° 03' N	172° W	2
ARC-4	Lomonosov Ridge	89° 06' N	168° W	1
ARC-5	Mendeleev Ridge	79° 50' N	174° 20' W	1
ARC-6	Chukchi Plateau	76° 20' N	166° 30' W	1
ARC-7	Northwind Ridge	75° 45' N	156° 20' W	1
ARC-8	Alpha Ridge	85° 50' N	109° W	2
ARC-9	Alpha Ridge	85° 53' N	108° W	2
ARC-10	Alpha Ridge	85° 55' N	130° 30' W	2
ARC-11	Makarov Basin	88° 25' N	169° 20' W	3
ARC-12	Amundsen Basin	85 - 87° N	90 - 100° E	3
ARC-13	Gakkel Ridge	85 - 86° N	15 - 20° E	3
ARC-14	Arlis Plateau	78 - 80° N	176 - 178° W	1
ARC-15	Barents Abyssal Plain	83° 05' N	11° 50' E	3
ARC-16	Morris Jesup Rise	85° 29' N	25° 11' W	3
ARC-17	Lomonosov Ridge	87° 55' N	145° 38' E	1
ARC-18	Lomonosov Ridge	87° 36' N	147° 00' E	1
ARC-19	Lomonosov Ridge	87° 36' N	151° 59' E	1

Table 4: Listing of proposed NAD Arctic drill sites; * 1 has highest priority.

Tabelle 4: Übersicht über die bislang als Beispiele vorgeschlagenen Lokationen für arktische Tiefseebohrungen. * 1 steht für die erste Priorität

15.1 *Executive Summary*

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

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

The origin of the Arctic Basin is linked to the evolution of the adjacent ocean basins and continents. Understanding past and present plate movements in the Arctic is necessary before a complete model of plate motions and paleogeography in the northern hemisphere can be constructed. The Cenozoic tectonic history of the Eurasian Basin is relatively well known, since the Eurasian and North American plates have been studied extensively to

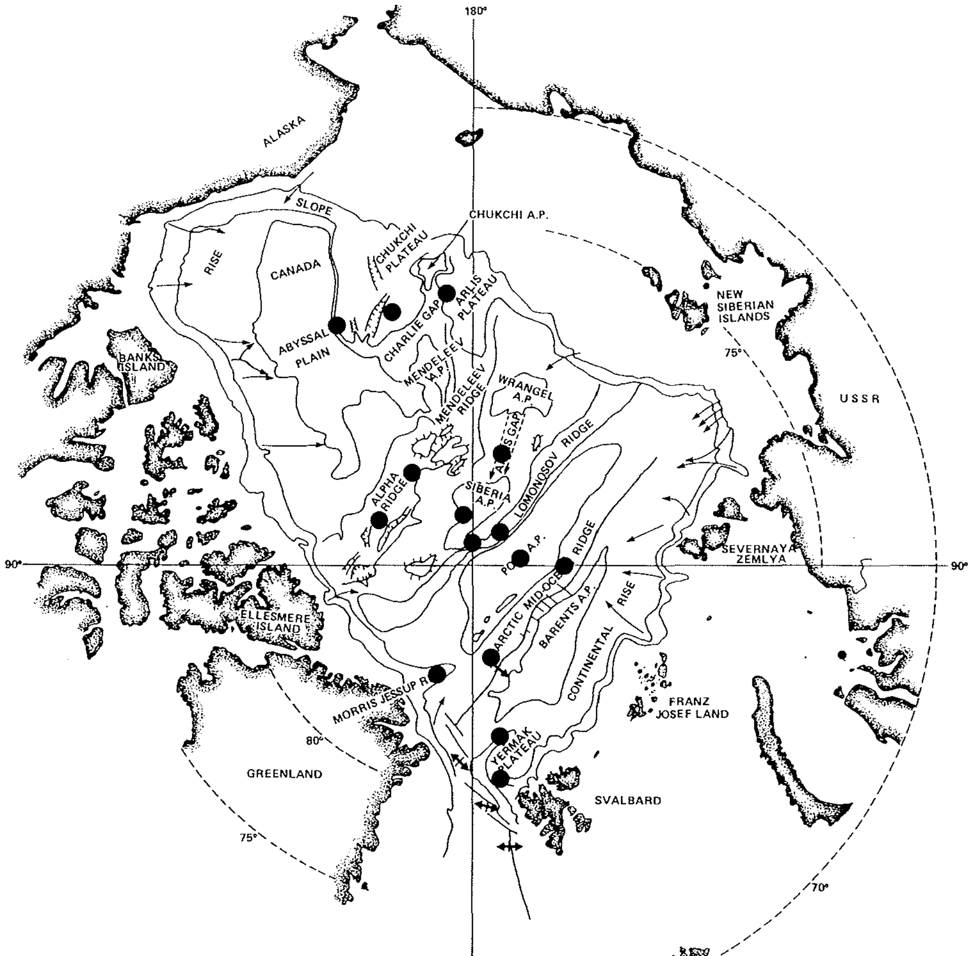


Fig. 38: Map of the Arctic Ocean with proposed drill sites ARC-1 through ARC-19 as listed in Table 4.

Abb. 38: Karte des Nordpolarmeeres mit den Lokationen der vorschlagenen Tiefseebohrungen ARC-1 bis ARC-19. Genaue Positionen siehe in Tabelle 4.

the south. The basin also contains a well documented and decipherable magnetic lineation history. Little is known about much of the rest of the Arctic Ocean with the evolution of the Amerasia Basin a major unresolved problem.

Based on the information in the NAD initial science plan the drill sites listed in Table 4 have been selected and prioritized (Fig. 38); they will have to be considered preliminary until a larger data base from new site surveys is available.

15.2 *Specific NAD Drill Site Proposals*

ARC-1, 80° 53' N / 07° 19' E, Yermak Plateau, Figures 39 and 40.

G e n e r a l o b j e c t i v e : Cenozoic Arctic paleoceanography; nature of basement.
S p e c i f i c o b j e c t i v e s : Development of exchange of water masses; initiation of ice-rafting; glacial-interglacial variations; development of marine Arctic biota; petrology changes of basement; subsidence history

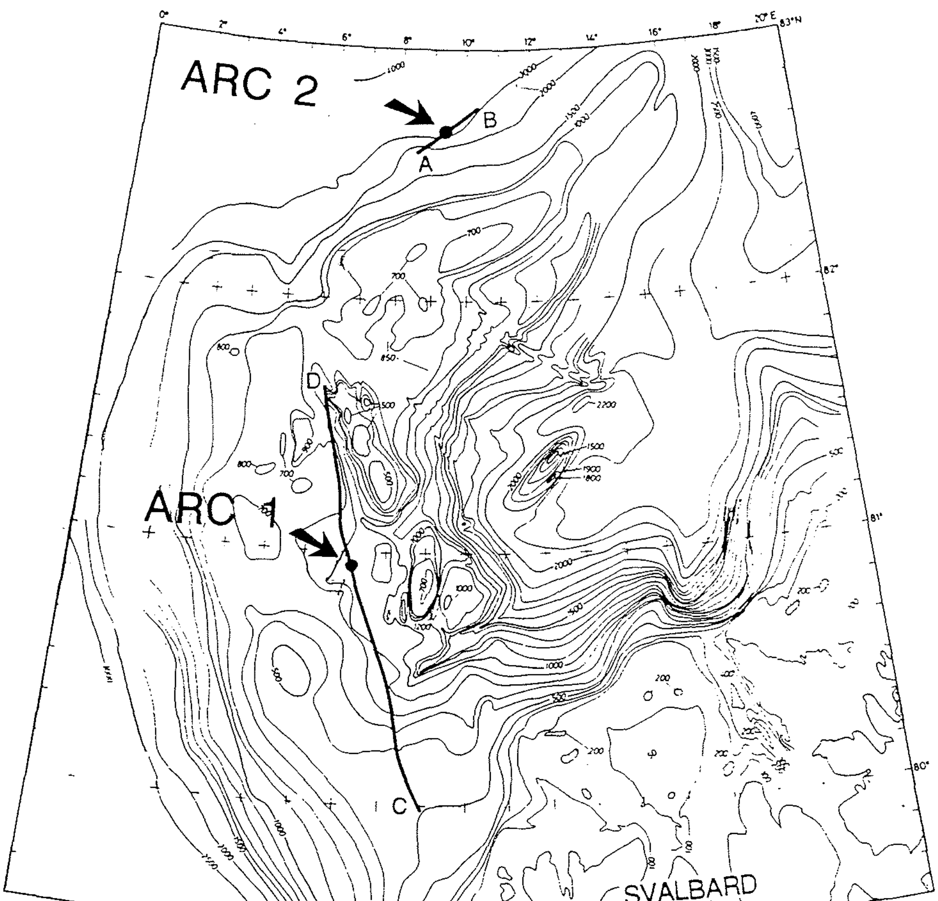


Fig. 39: Bathymetric map of Yermak Plateau Region (MUDIE et al. 1988), showing location of proposed drill sites ARC-1 and ARC-2 and tracks of seismic lines shown in Figs. 40 and 41.

Abb. 39: Bathymetrische Detailkarte des Yermak-Plateaus mit der Position der Bohrlochvorschläge ARC-1 und ARC-2, zusammen mit seismischen Profilen der Abb. 40 und 41.

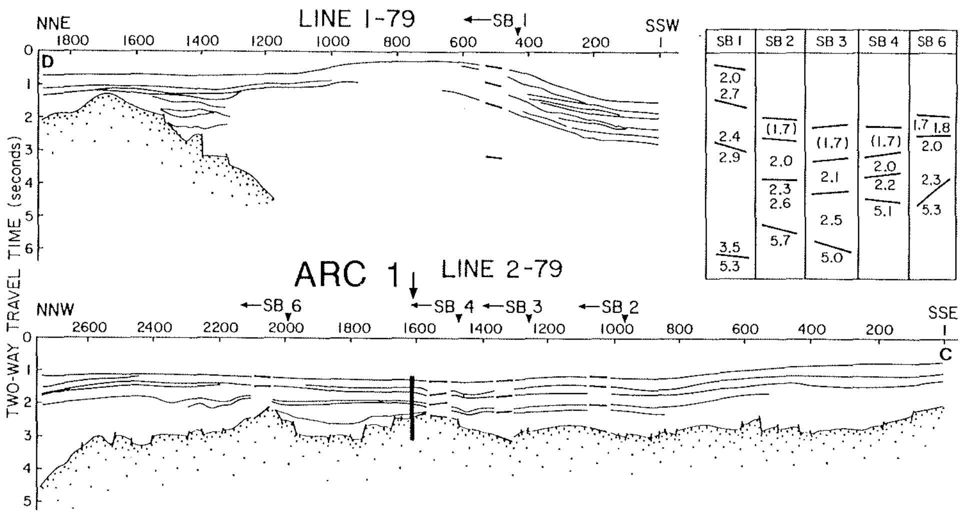


Fig. 40: Line drawing of seismic profiles (position C-D in Fig. 39, (MUDIE et al. 1988), showing location of proposed drill site ARC-1.

Abb. 40: Interpretationen des seismischen Profiles C-D in Abb. 39 (MUDIE et al. 1988), mit der Lokation des Bohrlvorschlages ARC-1.

and role as barrier.
Seismic profiles: Norwegian Petroleum Directorate (SUNDVOR et al. 1982, AUSTEGARD 1982).
Water depth: 800 m.
Sediment thickness: 800 m.
Total penetration: 1200 m. HPC and rotary drilling. Single bit. Logging for seismic stratigraphy and geochemistry.
Nature of sediments: Glacial-marine, hemipelagic muds, clastic deposits.
Rocks anticipated: Red sandstone/gneis, metamorphics.
Weather and ice conditions: Usually open water in summer. July through mid-September.
Requirements: Icebreaker support needed for safety; standard staffing, petrology.
Territorial jurisdiction: Norway.
Proponents: MUDIE et al.1988; see also RUDDIMAN et al. 1991.

ARC-2, 82° 42' N / 09° 33' E, Yermak Plateau, Figures 39 and 41.

General objective: Cenozoic Arctic paleoceanography; nature of basement. Alternate sites: 82° 10' N / 06° 45' E and 82° 05' N / 04° E.
Specific objectives: Development of exchange of water masses; initiation of ice-rafting; glacial-interglacial variations; changes of basement petrology; subsidence history and role as border; verify oceanic origin of the outer plateau.
Seismic profiles: Multichannel 120 cu inch airgun (KRISTOFFERSEN 1982; SUNDVOR et al. 1982).
Other data: 3.5 kHz profile, Sofia Basin (THIEDE 1988).
Water depth: 1400 m.
Sediment thickness: 600 m.
Total penetration: 1000 m. HPC and rotary drilling. Single bit. Standard logging.
Nature of sediments: Glacial marine muds, pelagic marine interbeds, pelagic sediments.
Rocks anticipated: Tholeiitic flows and interlayered clastics.
Weather and ice conditions: Usually open water in summer. July through mid-September.
Territorial jurisdiction: Norway.
Requirements: Standard staffing, petrology, icebreaker support.
Proponents: MUDIE et al. 1988; see also RUDDIMAN et al. 1991.

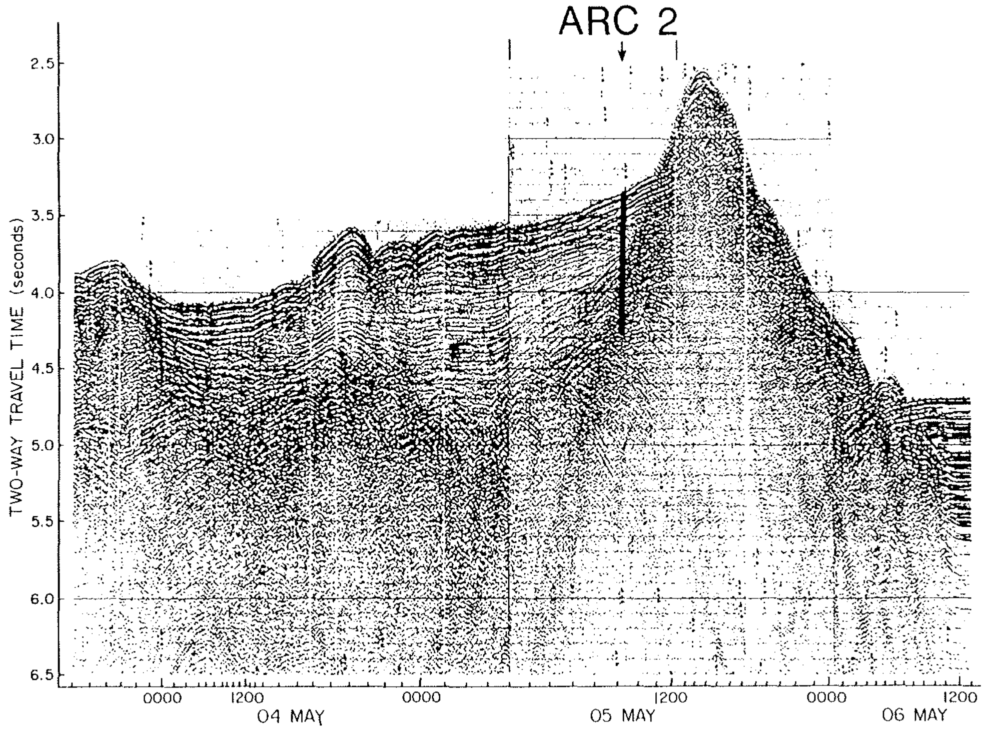


Fig. 41: Seismic profile of line A-B in Fig. 39 (MUDIE et al. 1988) showing location of ARC-2.

Abb. 41: Seismisches Profil (Position A-B in Abb. 39) mit der Lage des Bohrvorschlages ARC-2 (MUDIE et al. 1988).

ARC-3, 89° 03' N / 172° E, Lomonosov Ridge, Figures 42 and 43.

General objective: Cenozoic paleoclimate and paleoceanography; nature of continental and/or volcanic basement.
Specific objectives: History of deep water circulation; preglacial paleoceanography, onset of glacial environment; Mesozoic sequences, origin of basement; continental rather than oceanic.
Seismic profiles: *LOREX* (SWEENEY et al. 1982).
Other data: Gravity, seismic refraction, magnetic models (WEBER & SWEENEY 1990).
Water depth: 1500 m.
Sediment thickness: 300 m.
Total penetration: 500 m. HPC and rotary drilling. Single bit. Possibly reentry. Standard logging.
Nature of sediments: Glacial-marine muds, pelagic muds, biosiliceous deposits.
Rocks anticipated: Red sandstone, gneiss and other metamorphics.
Weather and ice conditions: Ice covered, strong ice drift.
Territorial jurisdiction: International.
Proponents: THIEDE et al. 1991.

ARC-4, 89° 06' N / 168° W, Lomonosov Ridge, Figures 42 and 43.

General objective: Cenozoic paleoclimate and paleoceanography; nature of basement: continental *versus* volcanic.
Specific objectives: History of deep water circulation; preglacial paleoceanography, onset of glacial environment; Mesozoic sequences, origin of basement, continental rather than oceanic.

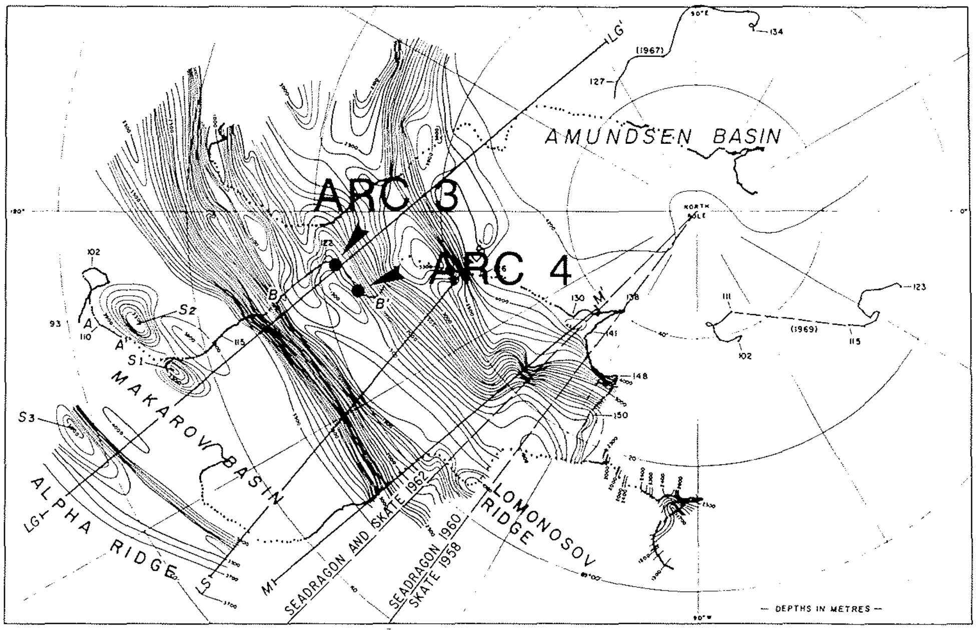


Fig. 42: Bathymetric map of Lomonosov Ridge and Makarov Basin (WEBER & SWEENEY 1990) showing trackline B-B' and locations of proposed drill sites ARC-3 and ARC-4.

Abb. 42. Bathymetrische Karte von Lomonosov-Rücken und Makarov-Becken (WEBER & SWEENEY 1990) mit dem Profil B-B' und Positionen der vorgeschlagenen Bohrungen ARC-3 und ARC-4.

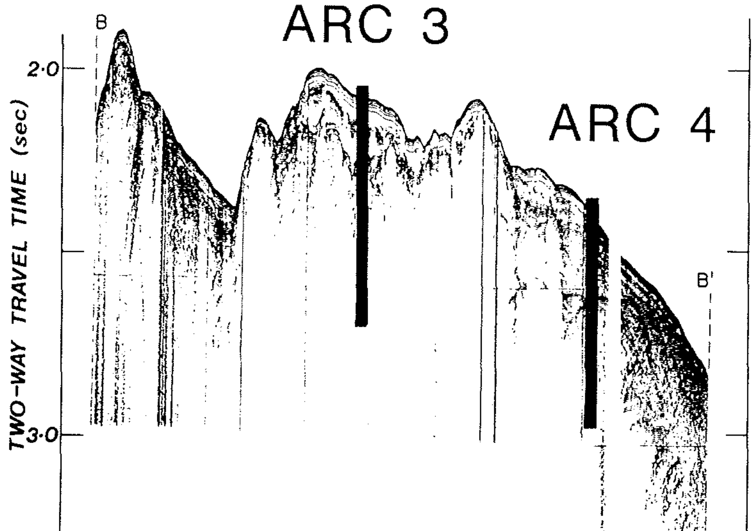


Fig. 43: Seismic profile of Lomonsov Ridge (position B-B' of Fig. 42, WEBER & SWEENEY 1990), showing locations of proposed drill sites ARC-3 and ARC-4.

Abb. 43: Seismisches Profil vom Lomonosov-Rücken (zwischen den Punkten B-B' in Abb. 42 nach WEBER & SWEENEY 1990) mit den vorgeschlagenen Bohrlochlokationen ARC-3 und ARC-4.

Other data: Gravity, seismic refraction, magnetic models WEBER & SWEENEY 1990.
Water depth: 1800 m.
Sediment thickness: 300 m.
Total penetration: 500 m. HPC and rotary drilling. Standard logging.
Nature of sediments: Glacial-marine muds, pelagic muds, biosiliceous deposits.
Rocks anticipated: Red sandstone, gneiss and other metamorphics.
Territorial jurisdiction: International.
Proponents: THIEDE et al. 1991.

ARC-5, 79° 50' N / 174° 20' W, Mendeleev Ridge, Figures 44 and 45.

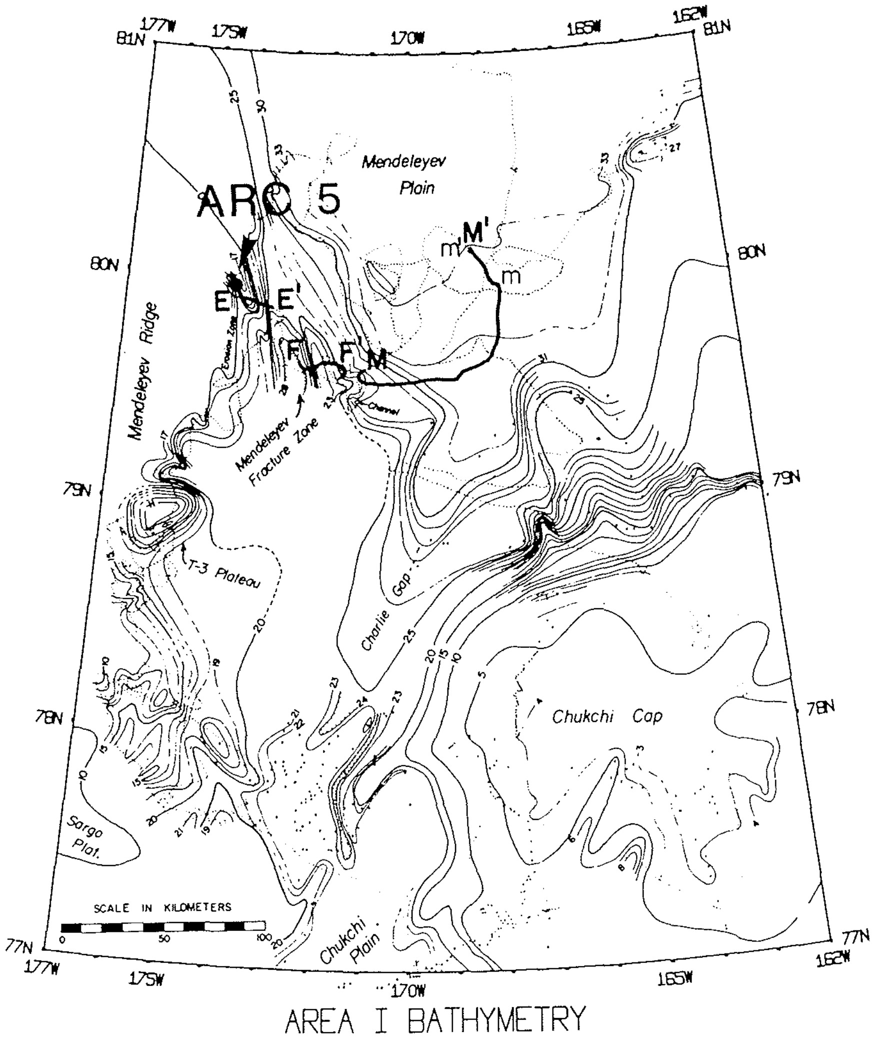


Figure 44: Bathymetric chart showing location of proposed drill site ARC-5 and trackline of the seismic profile in Fig. 45 (HALL 1979).

Abb. 44: Tiefenkarte mit der Lokation der vorgeschlagenen Bohrung ARC-5 und der Position der in Abb. 45 dargestellten seismischen Profillinie (HALL 1979).

G e n e r a l o b j e c t i v e : Cenozoic and Mesozoic paleoceanography; nature of basement.
S p e c i f i c o b j e c t i v e s : Coring of Mesozoic and Cenozoic sediments; evolution of marine polar biota; test hypothesis of origin: Continental fragment *versus* extinct axis of seafloor spreading *versus* compressional feature *versus* inactive transform fault *versus* aseismic volcanic ridge.
R e g i o n a l g e o p h y s i c a l d a t a : Stations *Alpha*, *Charlie* and *ARLIS II* (HALL 1979).
W a t e r d e p t h : 1800 m.
S e d i m e n t t h i c k n e s s : 200 m.
T o t a l p e n e t r a t i o n : 500 m. HPC and rotary drilling. Single bit. Standard logging.
N a t u r e o f s e d i m e n t s : Glacial-marine muds, pelagic muds, biosiliceous oozes; Mesozoic black shales.
R o c k s a n t i c i p a t e d : Basaltic or metamorphic basement.
T e r r i t o r i a l j u r i s d i c t i o n : International
P r o p o n e n t s : THIEDE et al. 1991.

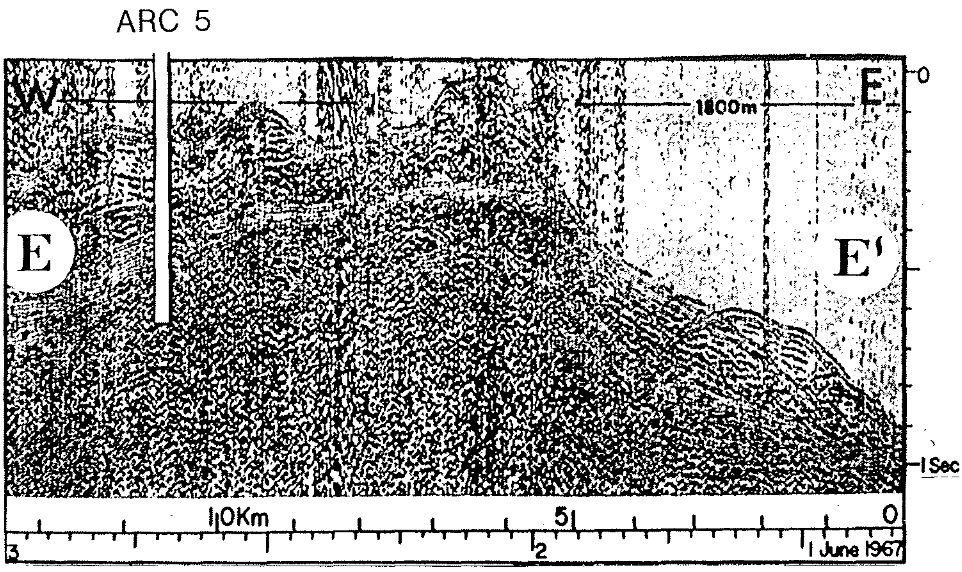


Fig. 45: Seismic profile with location of proposed drill site ARC-5 as shown in the bathymetric chart in Fig. 44 (HALL 1979).

Abb. 45: Seismisches Profil mit der Lokation der vorgeschlagenen Bohrung ARC-5, Position siehe Abb. 44 (HALL 1979).

ARC-6, 76° 20' N / 166° 30' W, Chukchi Plateau, Figure 46.

G e n e r a l o b j e c t i v e : Mesozoic history of the Arctic Ocean, nature of basement, continental *versus* oceanic.
S p e c i f i c o b j e c t i v e s : Key to the evolution of the Canada Basin. Role of Bering Sea / Pacific gateway; comparison of the synchroneity of climate changes of both hemispheres.
R e g i o n a l g e o p h y s i c a l d a t a : Ice station *T-3* (HALL & HUNKINS 1968).
O t h e r d a t a : WEBER & SWEENEY (1990).
W a t e r d e p t h : 400 m.
S e d i m e n t t h i c k n e s s : 400 m.
T o t a l p e n e t r a t i o n : 700 m. HPC and rotary drilling. Single bit. Standard logging.
N a t u r e o f s e d i m e n t s : Hemipelagic glacigenic mud, deltaic mud, shale.
R o c k s a n t i c i p a t e d : Continental crust.
W e a t h e r a n d i c e c o n d i t i o n s : Probably ice free in summer.
T e r r i t o r i a l j u r i s d i c t i o n : International / U.S.
P r o p o n e n t s : THIEDE et al. 1991.

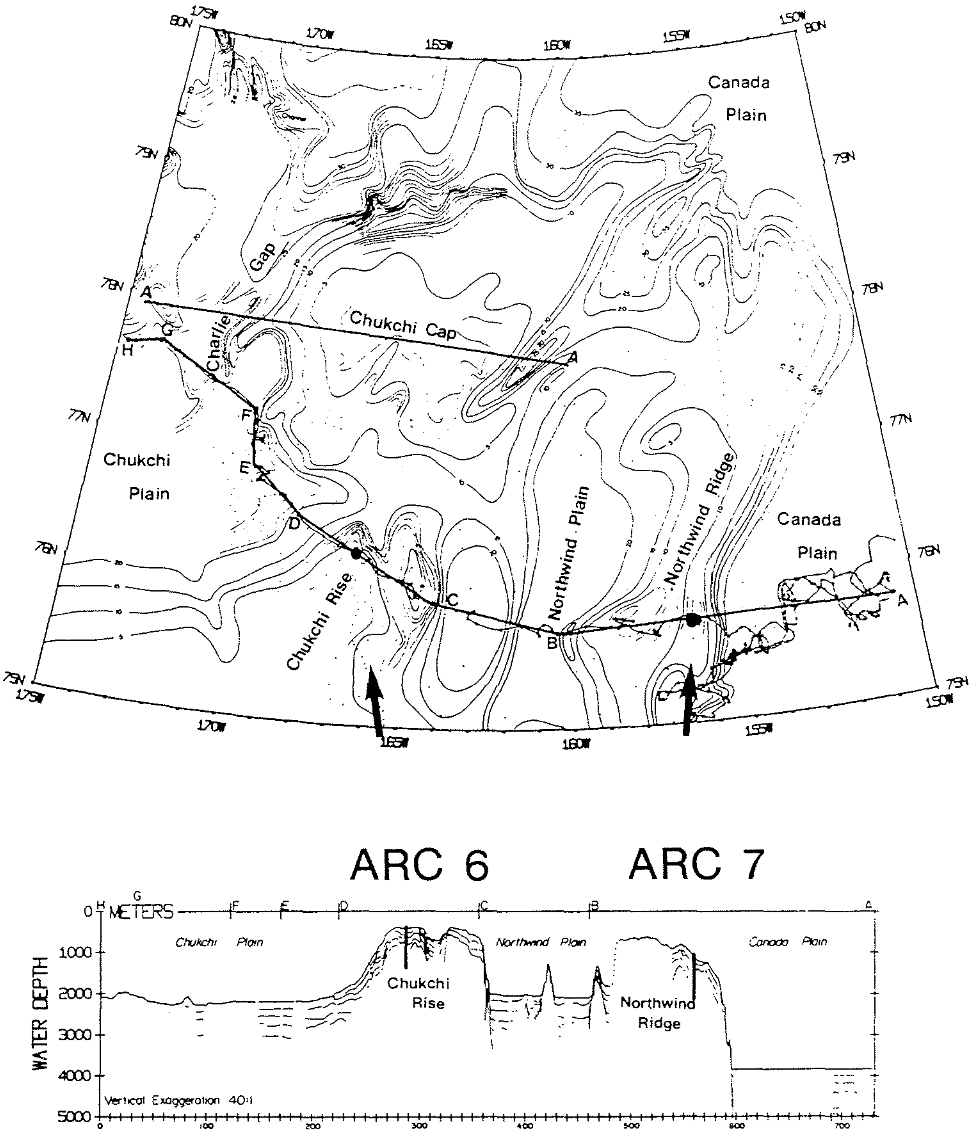


Fig. 46: Bathymetric chart of and seismic profile across the Chukchi Borderland (HALL 1970, HALL & HUNKINS 1968) showing locations of proposed drill sites ARC-6 and ARC-7.

Abb. 46: Bathymetrische Karte und seismisches Profil über das Chukchi „Borderland" (HALL 1970, HALL & HUNKINS 1968) mit den vorgeschlagenen Bohrlokationen ARC-6 und ARC-7.

ARC-7, 75° 45' N / 56° 20' W, Northwind Ridge, Figure 46.

General objective: Cenozoic and Mesozoic history of the Arctic Ocean. Coring of pre-Cretaceous basement.
Specific objectives: Evolutionary patterns of marine biota, especially of diatoms, investigate explosive speciation at the C/T boundary; paleomagnetic analysis, determine subsequent rotation relative to North American craton. Cenozoic record with high accumulation rates.

Regional geophysical data: Ice station *T-3* (HALL & HUNKINS 1968).
Other data: WEBER & SWEENEY 1990, PHILLIPS et al. 1990.
Water depth: 1000 m.
Sediment thickness: 400 m.
Total penetration: 700 m. HPC and rotary drilling. Single bit. Standard logging.
Nature of sediments: Hemipelagic sediments, laminated siltstones.
Rocks anticipated: Volcanics.
Weather and ice conditions: Probably open ice conditions during summer.
Territorial jurisdiction: International / U.S.
Proponents: HEAD et al. 1990

ARC-8, 85° 50' N / 109° W, Alpha Ridge, Figures 47 and 48.

General objective: Continuous Cretaceous through Tertiary sediment sequence; nature of the ridge.
Specific objectives: To drill complete Cenozoic litho- and biostratigraphic section; paleoenvironmental, geochemical and petrological events at the C/T boundary; hypotheses of origin of basement (see ARC-5).
Regional geophysical data: Airgun reflection seismics (JACKSON 1985).
Other data: WEBER & SWEENEY 1990, PHILLIPS et al. 1990.
Water depth: 1200 m.
Sediment thickness: 400 m.
Total penetration: 500 m. HPC and rotary drilling. Single bit. Standard logging.
Nature of sediments: Hemipelagic mud and sand, biosiliceous ooze, black mud.
Rocks anticipated: Volcanics.
Weather and ice conditions: Ice covered.
Territorial jurisdiction: International / Canada.
Proponents: MUDIE et al. 1988.

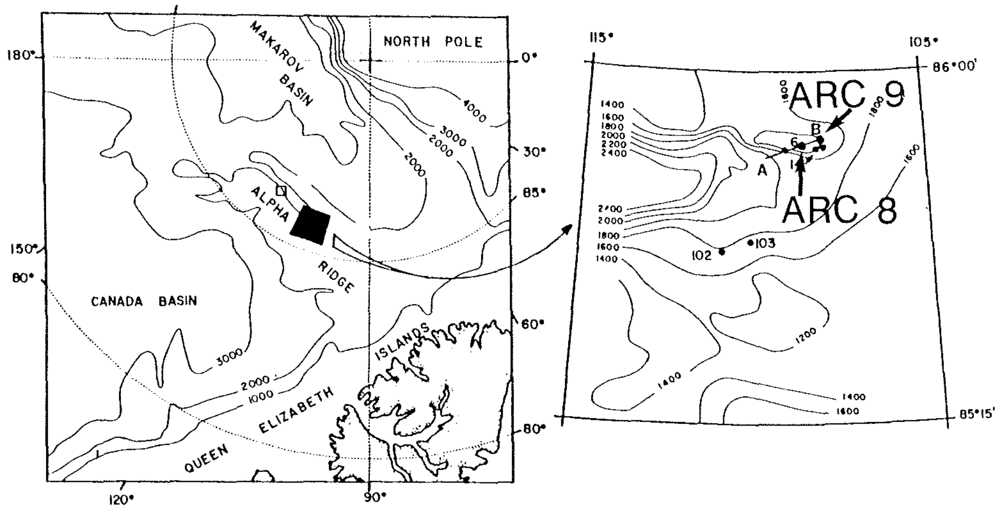


Fig. 47: Bathymetric chart of the Alpha Ridge showing locations of proposed drill sites ARC-8 and ARC-9 and trackline of seismic profile in Fig. 48 (JACKSON 1985).

Abb. 47: Bathymetrische Karte des Alpha-Rückens mit den Positionen der vorgeschlagenen Bohrlokationen ARC-8 und ARC-9 sowie der seismischen Profillinie in Abbildung 48 (JACKSON 1985).

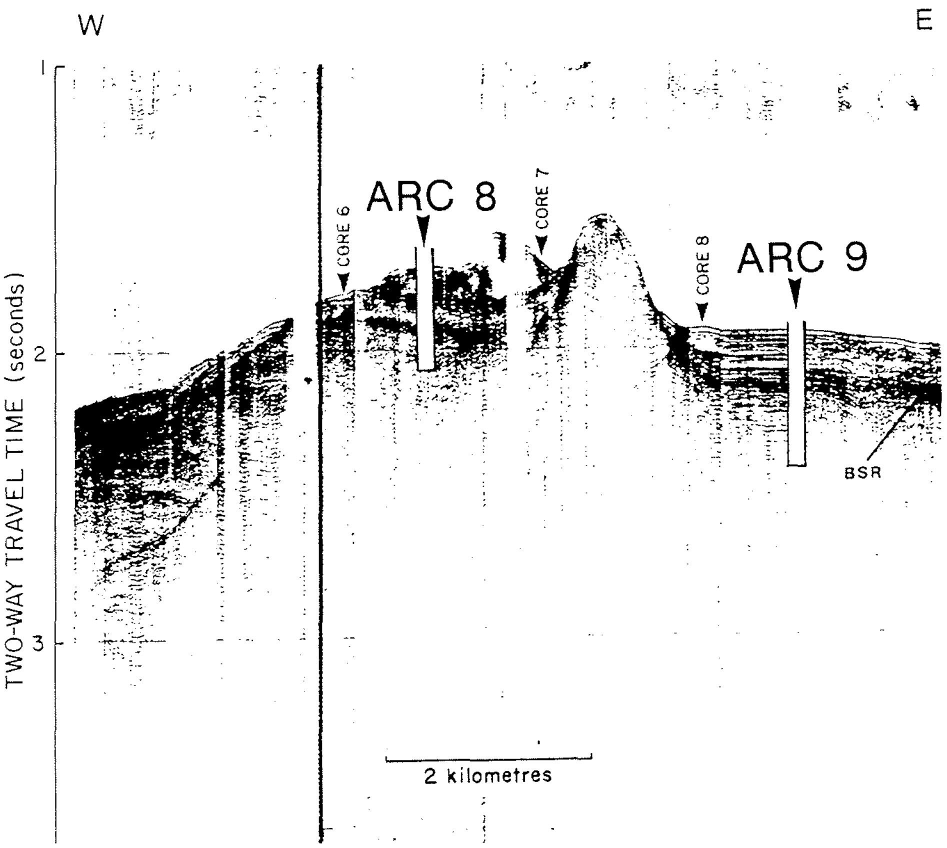


Fig. 48: Seismic profile with locations of proposed drill sites ARC-8 and ARC-9 as shown in the bathymetric chart in Fig. 47 (JACKSON 1985).

Abb. 48: Seismische Profillinie mit Lokationen der vorgeschlagenen Bohrungen ARC-8 und ARC-9. Positionen siehe Abb. 47 (JACKSON 1985).

ARC-9, 85° 53' N / 108° W, Alpha Ridge, Figures 47 and 48.

General objective: Continuous Cretaceous through Tertiary sediment sequence; nature of the ridge.
Specific objectives: To drill complete Cenozoic litho- and biostratigraphic section; paleoenvironmental, geochemical and petrological events at the C/T boundary; hypotheses of origin of basement (see ARC-5).
Regional geophysical data: Airgun reflection seismics (JACKSON 1985).
Water depth: 1500 m.
Sediment thickness: 500 m.
Total penetration: 600 m. HPC and rotary drilling. Single bit. Standard logging.
Nature of sediments: Hemipelagic mud and sand, biosiliceous ooze, black mud.
Rocks anticipated: Volcanics.
Weather and ice conditions: Ice covered.
Territorial jurisdiction: International / Canada.
Proponents: MUDIE et al. 1988.

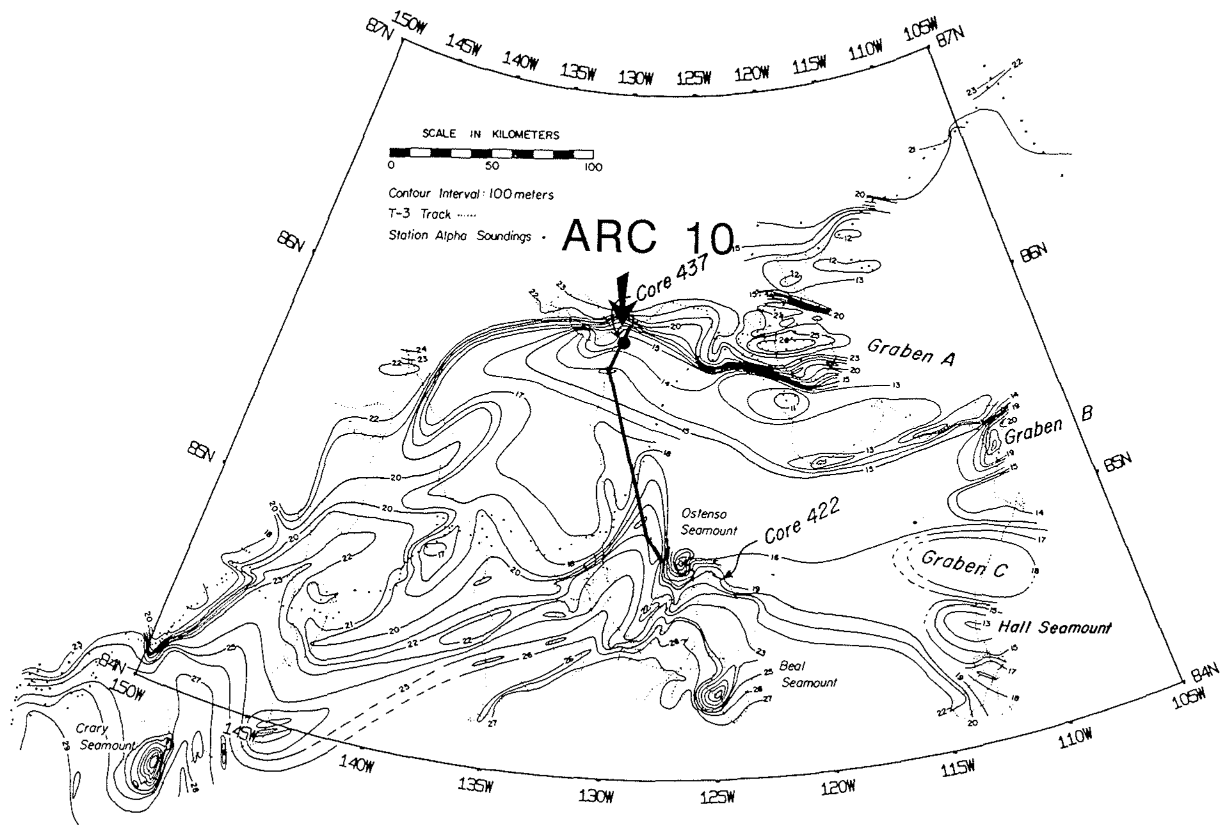


Fig. 49: Bathymetric chart showing location of proposed drill site ARC-10 and trackline of seismic profile from Fig. 50 (HALL 1979).

Abb. 49: Bathymetrische Karte mit den Lokationen der vorgeschlagenen Bohrung ARC-10 sowie des Verlaufes des seismischen Profils in Abb. 50 (HALL 1979).

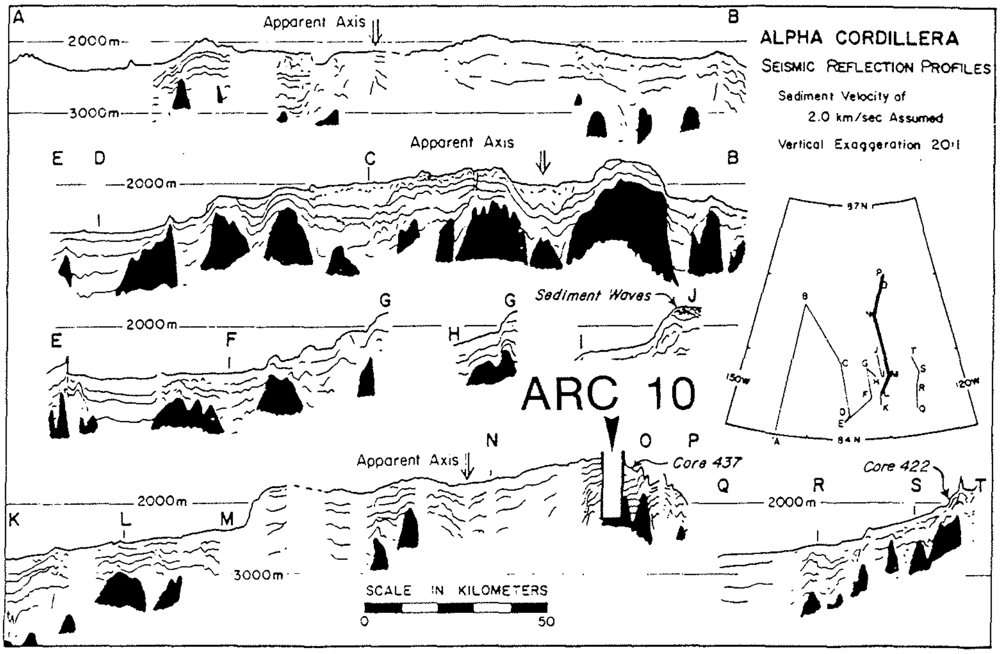


Fig. 50: Line drawing from seismic reflection profile with location of proposed drill site ARC-10 as shown in the bathymetric chart in Fig. 49 (HALL 1979).

Abb. 50: Interpretiertes reflektionsseismisches Profil mit der vorgeschlagenen Bohrlokation ARC-10; zur Position siehe Abb. 49 (HALL 1979).

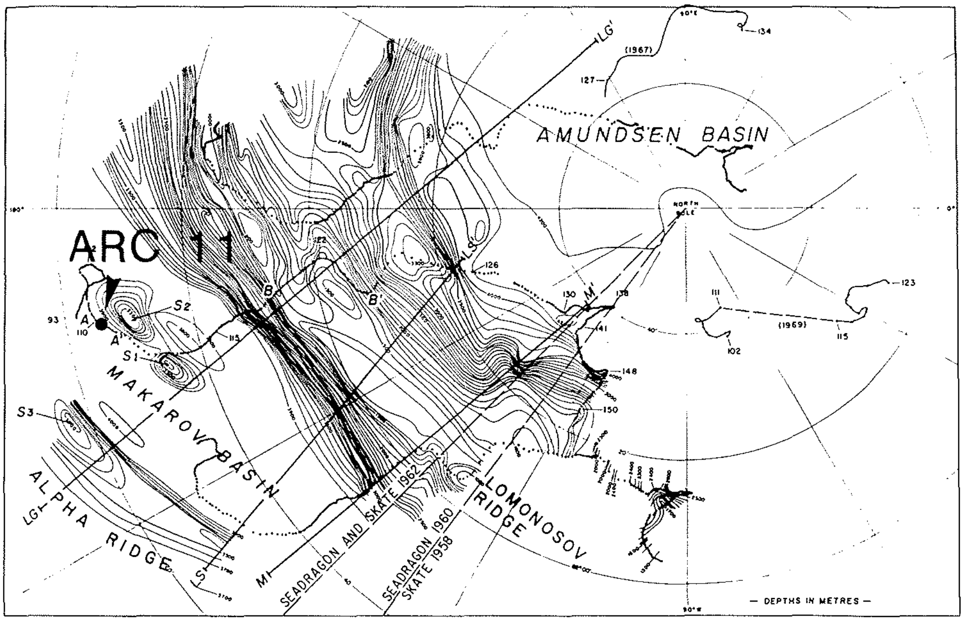
ARC-10, 85° 55' N / 130° 30' W, Alpha Ridge, Figures 49 and 50.

General objective: Continuous Cretaceous through Tertiary sediment sequence; nature of the ridge.
Specific objectives: To drill complete Cenozoic litho- and biostratigraphic section; possibly older part of ridge; events at the K/T boundary; origin of basement (see ARC-5)
Seismic profiles: Reflection seismic (ice station *T-3*, HALL 1979).
Water depth: 1800 m.
Sediment thickness: 700 m.
Total penetration: 1000 m. HPC and rotary drilling. Single bit. Standard logging.
Nature of sediments: Hemipelagic mud and sand, biosiliceous ooze, black mud.
Rocks anticipated: Volcanics.
Weather and ice conditions: Ice covered.
Territorial jurisdiction: International / Canada.
Proponents: MUDIE et al. 1988.

ARC-11, 88° 25' N / 169° 20' W, Makarov Basin, Figure 51.

General objective: Cenozoic high resolution sediment sequence, nature of the basement.
Specific objectives: Examine contribution of different sediment sources and sediment provinces, comparison with Amundsen Basin. Continental *versus* volcanic basement.
Regional geophysical data: Seismic reflection data, *ARLIS II, LOREX*.
Water depth: 4000 m.
Sediment thickness: 400 m.
Total penetration: 600 m. HPC and rotary drilling. Single bit. Standard logging.
Nature of sediments: Pelagic mud, biogenic oozes.

R o c k s a n t i c i p a t e d : Volcanics.
T e r r i t o r i a l j u r i s d i c t i o n : International.
P r o p o n e n t s : THIEDE et al. 1991.



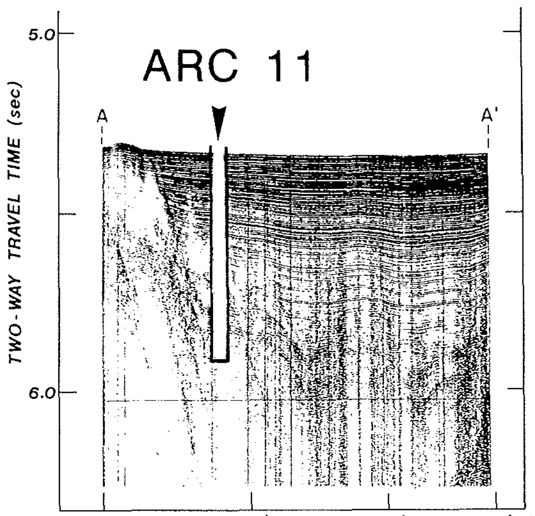


Fig. 51: Bathymetric chart and seismic profile showing location of proposed drill site ARC-11 in the Makaraov Basin (WEBER & SWEENEY 1990).

Abb. 51: Bathymetrische Karte und Lage der seismischen Profillinie mit der vorgeschlagenen Bohrlokation ARC-11 im Makarov-Becken (WEBER & SWEENEY 1990).

ARC-12, 85° to 87°N / 90° to 100° E, Amundsen Basin, Figure 52.

General objective: Cenozoic high resolution sediment sequences.
Specific objectives: Examine contribution of different sediment sources and sediment provinces.
Water depth: 3500-4000 m.
Sediment thickness: 1000-2000.m.
Total penetration: 1000 m. HPC and rotary drilling. Single bit. Standard logging.
Nature of sediments: Pelagic mud, biogenic oozes.
Rocks anticipated: Volcanics.
Territorial jurisdiction: International.
Proponents: THIEDE et al. 1991.

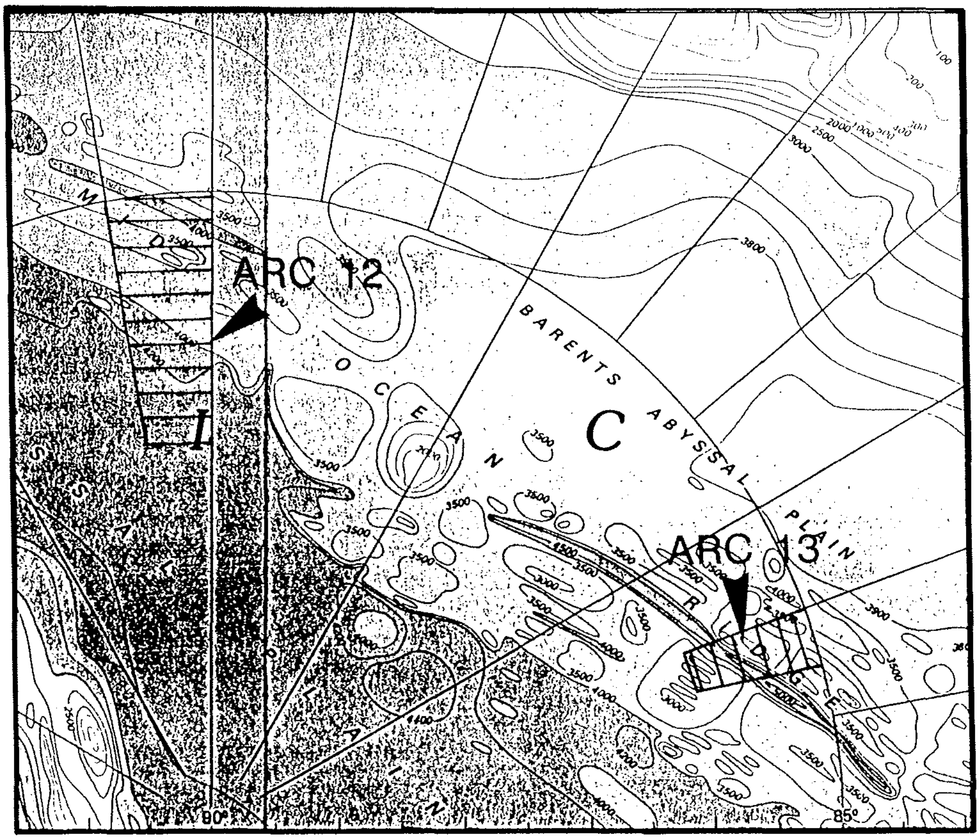


Fig. 52: Bathymetric chart of the Central Arctic Ocean showing areas for proposed drill sites ARC-12 and ARC-13 (GRANTZ et al. 1990).

Abb. 52: Bathymetrische Karte des zentralen Nordpolarmeeres mit den vorgeschlagenen Bohrlokationen ARC-12 und ARC-13 (GRANTZ et al. 1990).

ARC-13, 85° to 86° N / 15° to 20° E, Gakkel Ridge, Figure 52.

General objective: Nature of basement.
Specific objectives: Test of hypothesis whether the range of composition is related to spreading rate; Cenozoic volcanic clastics.
Water depth: 3500-4000 m.
Sediment thickness: 0-50 m.

Total penetration: 200 m. HPC and rotary drilling. Single bit. Standard logging.
Nature of sediments: Glacigenic muds.
Rocks anticipated: Basalts.
Weather and ice conditions: Permanently ice-covered.
Territorial jurisdiction: International.
Proponents: THIEDE et al. 1991.

ARC-14, 78° to 80° N / 176° to 178° W, Arlis Plateau, Figures 53 and 54.

General objective: Mesosozoic paleoceanography; origin of basement.
Specific objectives: Mesozoic development of Arlis Plateau compared to Chukchi Plateau.
Seismic profiles: Ice station *T-3* reflection seismic (GRANTZ et al. 1990).
Water depth: 1000 m.
Sediment thickness: 300 m.
Total penetration: 500 m. HPC and rotary drilling. Standard logging.
Nature of sediments: Hemipelagic muds, biosiliceous ooze, shales.
Rocks anticipated: Volcanics.
Weather and ice conditions: Ice covered.
Territorial jurisdiction: Russia
Proponents: THIEDE et al. 1991.

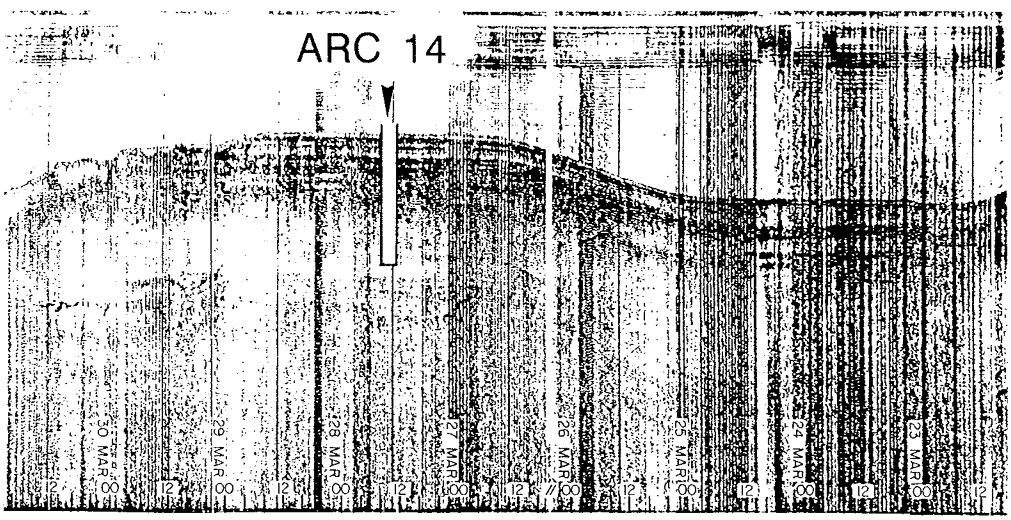


Figure 53: Bathymetric chart of the Arlis Plateau showing location of proposed drill sites ARC-14 and trackline of seismic profile in Fig. 54 (GRANTZ et al. 1990).

Abb. 53: Bathymetrische Karte des Arlis-Plateaus mit der vorgeschlagenen Bohrlokation ARC-14 und dem Verlauf des seimischen Profils aus Abb. 54 (GRANTZ et al. 1990).

Figure 55: Bathymetric chart showing location of proposed drill site ARC-15 and trackline of seismic profiles in Fig. 56 (KRISTOFFERSEN & HUSEBYE 1985).

Abb. 55: Bathymetrische Karte mit der vorgeschlagenen Bohrlokation ARC-15 und Verlauf der seismischen Profillinie in Abb. 56 (KRISTOFFERSEN & HUSEBYE 1985).

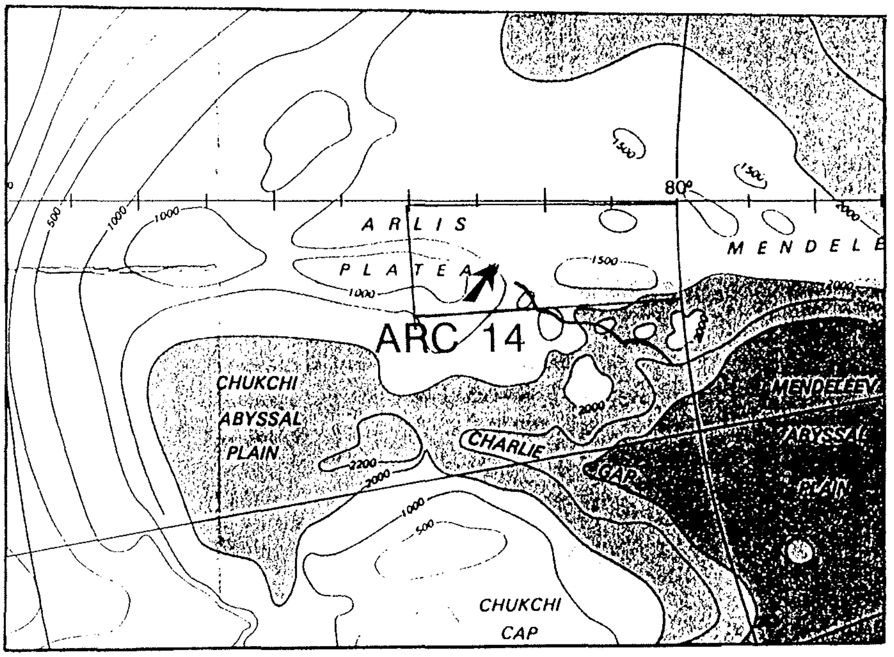
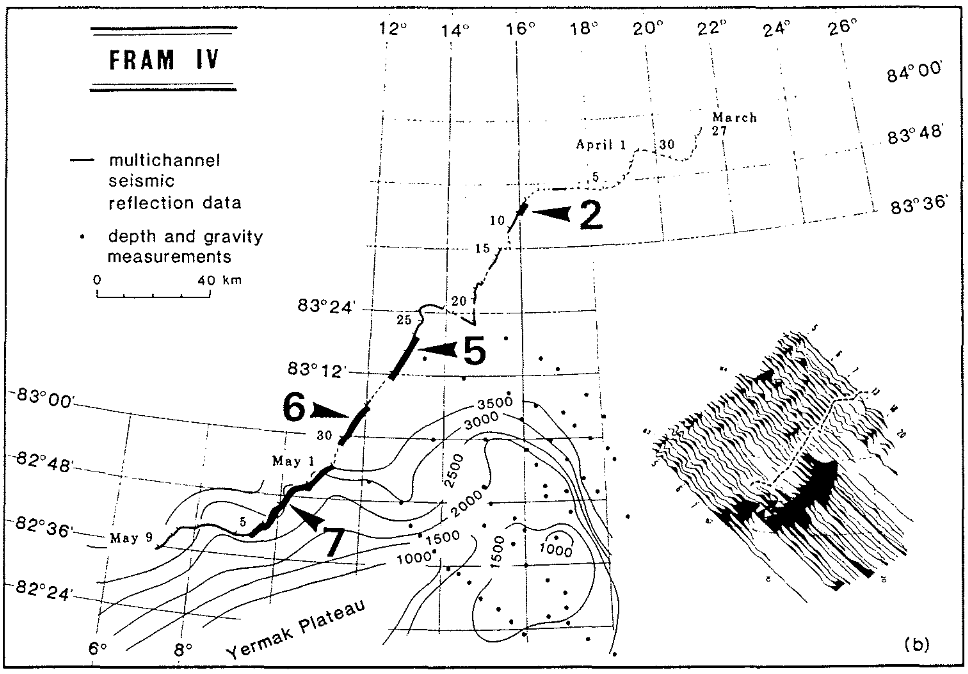


Fig. 54: Seismic profile with location of proposed drill site ARC-14 as shown in the bathymetric chart in Fig. 53 (GRANTZ et al. 1990).

Abb. 54: Reflektionsseismisches Profil mit der vorgeschlagenen Bohrlokation ARC-14, Position siehe Abb. 53 (GRANTZ et al. 1990).



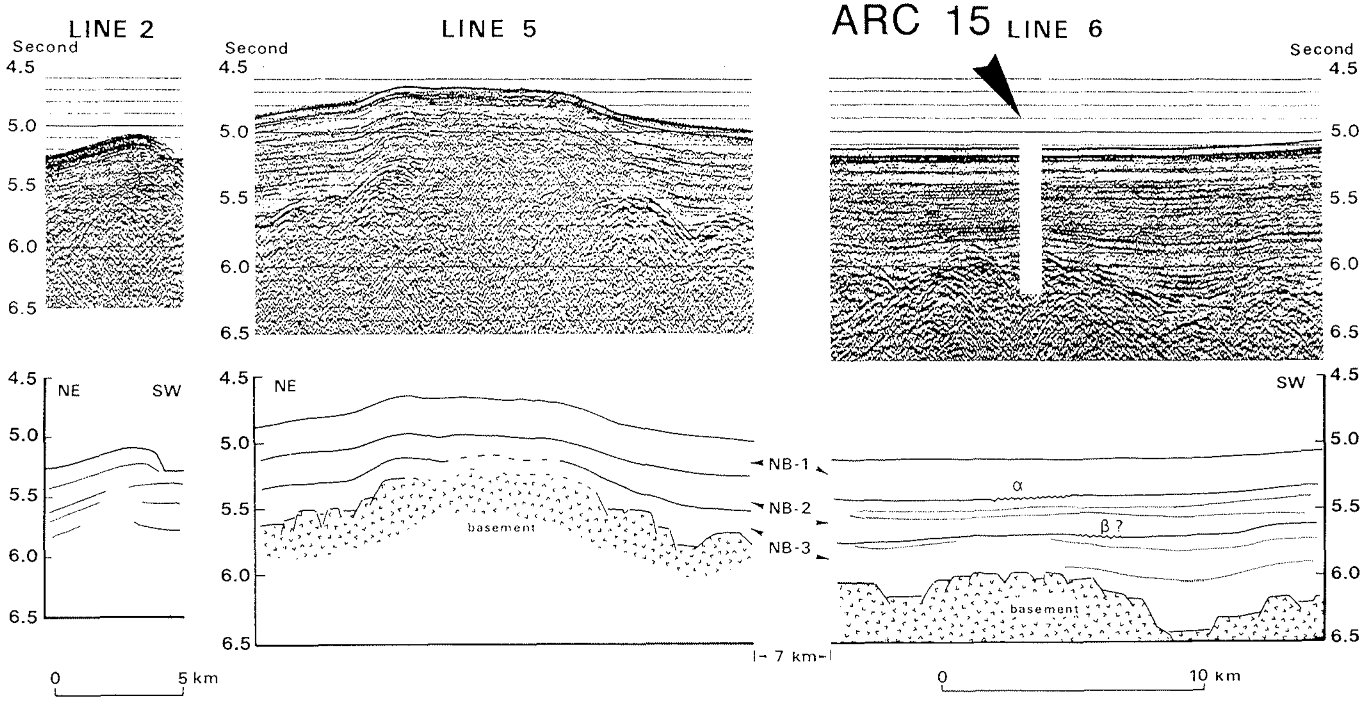


Figure 56: Seismic profile with location of proposed drill site ARC-15 as shown in the bathymetric chart in Fig. 55 (KRISTOFFERSEN & HUSEBYE 1985).

Abb. 56: Seismische Profillinie mit der vorgeschlagenen Bohrlokation ARC-15. Position siehe in Abb. 55 (KRISTOFFERSEN & HUSEBYE 1985).

ARC-15, 83° 05' N / 11° 50' E, Barents Abyssal Plain, Figures 55 and 56.

General objective: Evolutionary trends in the Cenozoic.
Specific objectives: High resolution record of high latitude marine biota, monitoring Arctic marine ice sheets, glacial and intra-glacial variation.
Seismic profiles: *Fram IV* Line 6 (KRISTOFFERSEN & HUSEBYE 1985).
Water depth: 4000 m.
Sediment thickness: 500 m.
Total penetration: 700 m. HPC and rotary drilling. Standard logging.
Nature of sediments: Pelagic to hemipelagic muds; glacial-marine deposits, biosililiceous oozes.
Rocks anticipated: Volcanics.
Weather and ice conditions: Ice covered.
Territorial jurisdiction: Norway.
Proponent: THIEDE et al. 1991.

ARC-16, 85° 29' N / 25° 11' E, Morris Jesup Rise, Figures 57 and 58.

General objective: Cenozoic Arctic paleoceanography; basement compared to Yermak Plateau.
Specific objectives: Examine exchange of water masses; history of ice rafting; origin of excessive volcanism, subsidence history and role as a barrier in Neogene Fram Strait.

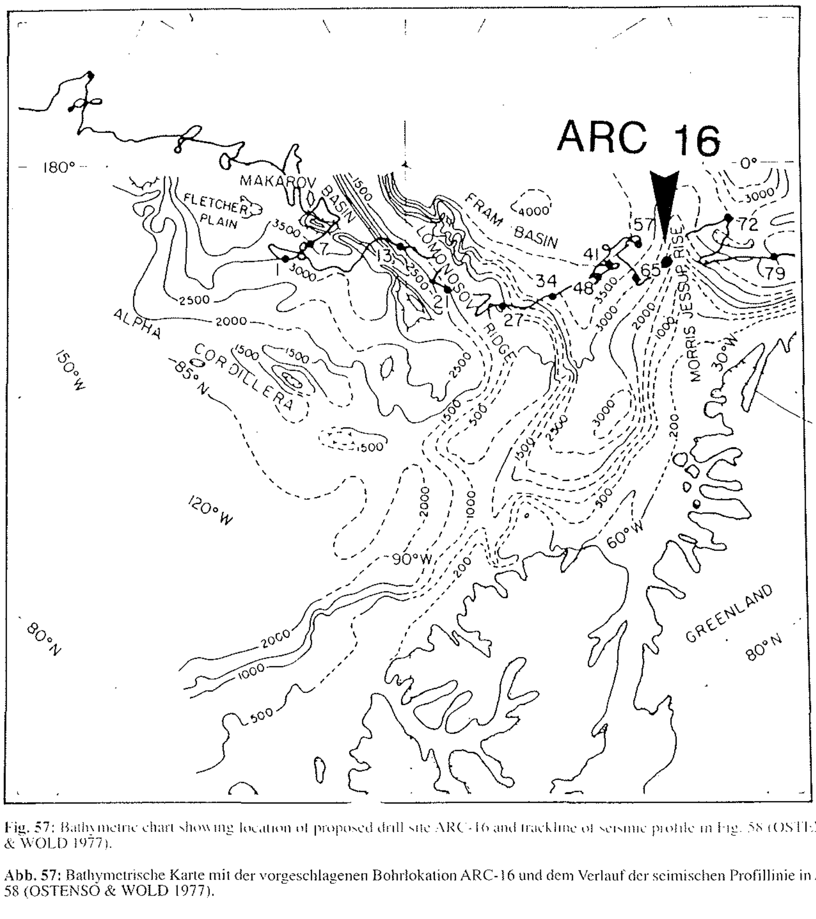


Fig. 57: Bathymetric chart showing location of proposed drill site ARC-16 and trackline of seismic profile in Fig. 58 (OSTENSO & WOLD 1977).

Abb. 57: Bathymetrische Karte mit der vorgeschlagenen Bohrlokation ARC-16 und dem Verlauf der seimischen Profillinie in Abb. 58 (OSTENSO & WOLD 1977).

Regional geophysical data: Seismic and gravity profiles *ARLIS II* (OSTENSO & WOLD 1977).
Water depth: >400 m.
Sediment thickness: >250 m.
Total penetration: 350 m. HPC and rotary drilling. Standard logging.
Nature of sediments: Hemipelagic and deltaic muds.
Rocks anticipated: Probably tholeiitic basalts
Weather and ice conditions: Permanently ice covered.
Territorial jurisdiction: Greenland /Denmark.
Proponents: THIEDE et al. 1991.

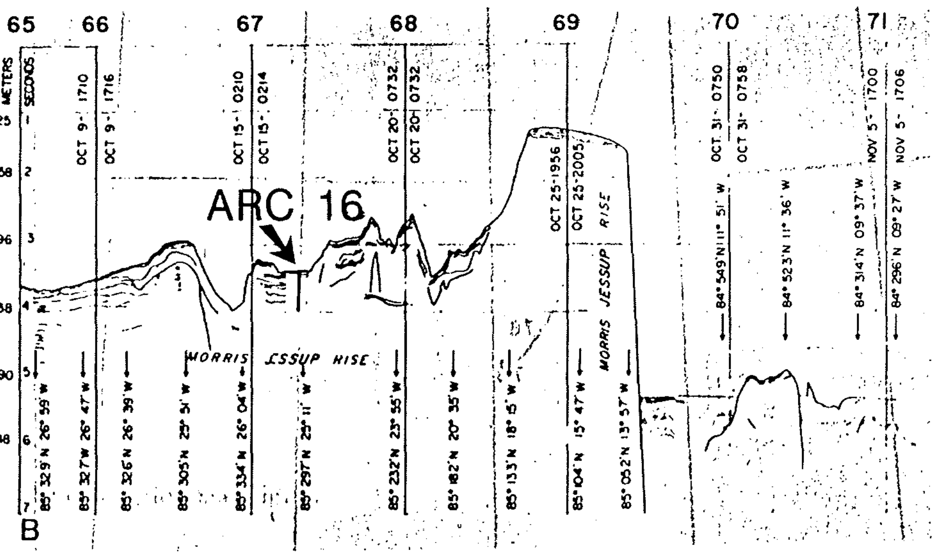


Fig. 58: Seismic profile with location of proposed drill site ARC-16 as shown in the bathymetric chart in Fig. 57 (OSTENSO & WOLD 1977).

Abb. 58: Seismisches Profil mit der vorgeschlagenen Bohrlokation ARC-16, Position siehe in Abb. 57 (OSTENSO & WOLD 1977).

ARC-17, 87° 55' N / 145° 38' E, Lomonosov Ridge, Figure 59.

General objective: Nature of the ridge; nature and stratigraphy of the sedimentary sequences.
Speciftic objectives: To determine the age of different sediment units and the prominent discontinuity; reconstruction of the subsidence history since proposed separation from the Eurasian shelf.
Seismic profiles: Multichannel reflection seismic data
Other data: COLES & TAYLOR 1991, JACKSON et al. 1991, SOBCZACK et al. 1991
Water depth: 1300 m
Sediment thickness: > 700 m.
Total penetration: 800 m. HPC and rotary drill. Single bit. Standard logging.
Nature of sediments: Gravelly lag deposits, hemipelagic mud.
Rocks anticipated: Continental crust.
Weather and ice conditions: Ice covered.
Territorial jurisdiction: International.
Proponents: JOKAT et al. 1992.

ARC-18, 87° 36' N / 147° 00' E, Lomonosov Ridge, Figure 60.

General objective: Nature of the ridge, nature and stratigraphy of the sedimentary sequences
Specific objectives: To determine the age of the different sediment units and the prominent discontinuity; reconstruction of the subsidence history since proposed separation from the Eurasian shelf.
Seismic profiles: Multichannel reflection seismic data.
Other data: COLES & TAYLOR 1991, JACKSON et al. 1991, SOBCZACK et al. 1991.
Water depth: 2150 m.
Sediment thickness: At least 700 m.
Total penetration: 800 m. HPC and rotary drill. Single bit. Standard logging.
Nature of sediments: Gravelly lag deposits, hemipelagic mud.
Rocks anticipated: Continental crust.
Weather and ice conditions: Ice covered.
Territorial jurisdiction: International.
Proponents: JOKAT et al. 1992.

ARC-19, 87° 36' N / 151° 59' E, Lomonosov Ridge, Figure 60.

General objective: Nature of the ridge, nature and stratigraphy of the sedimentary sequences
Specific objectives: To determine the age of the different sediment units and the prominent discontinuity; reconstruction of the subsidence history since proposed separation from the Eurasian shelf.
Seismic profiles: Multichannel reflection seismic data
Other data: COLES & TAYLOR 1991, JACKSON et al. 1991, SOBCZACK et al. 1991.
Water depth: 2900 m.
Sediment thickness: At least 650 m.
Total penetration: 750 m. HPC and rotary drill. Single bit. Standard logging.
Nature of sediments: Gravelly lag deposits, hemipelagic mud.
Rocks anticipated: Continental crust.
Weather and ice conditions: Ice covered.
Territorial jurisdiction: International.
Proponents: JOKAT et al. 1992.

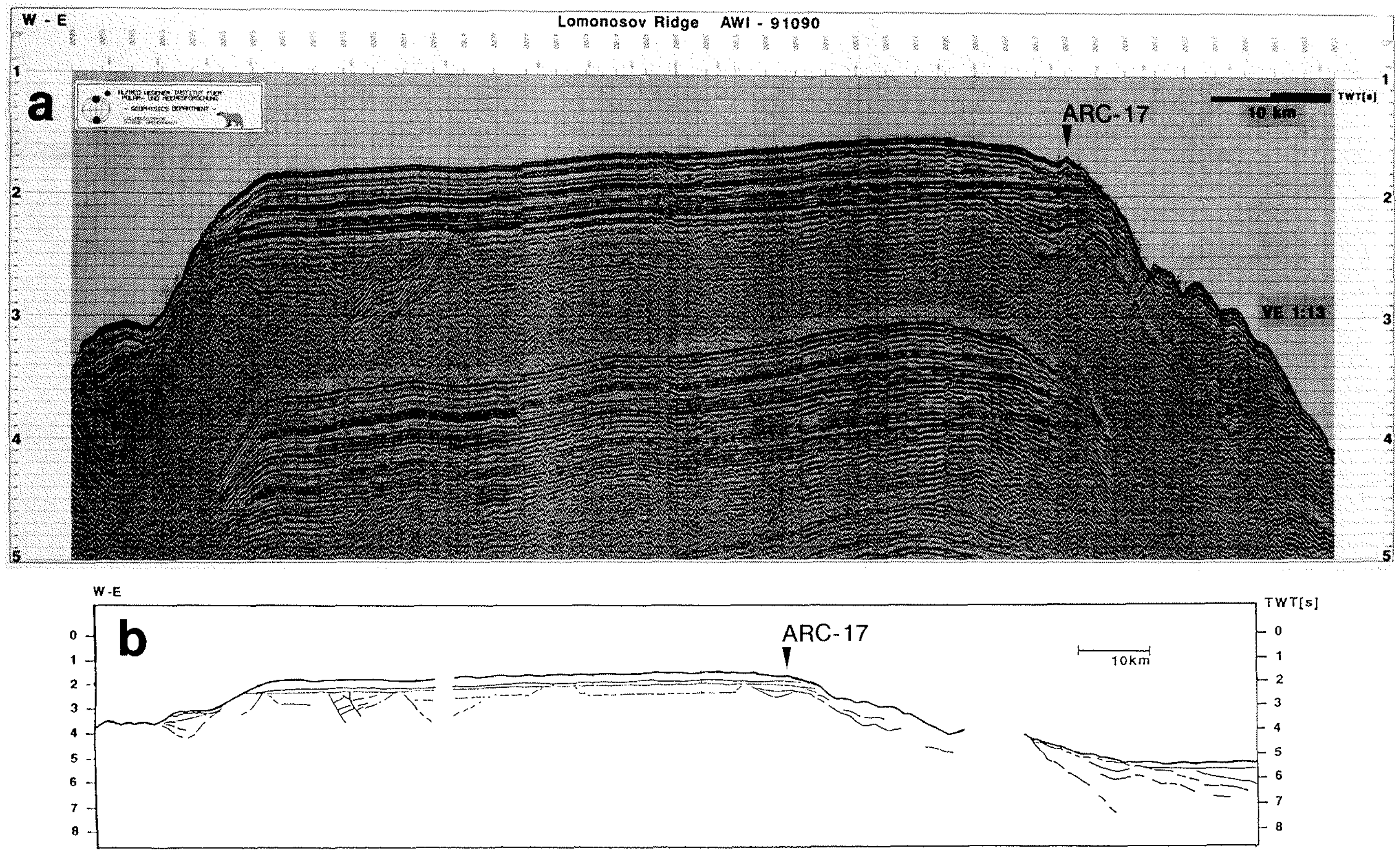
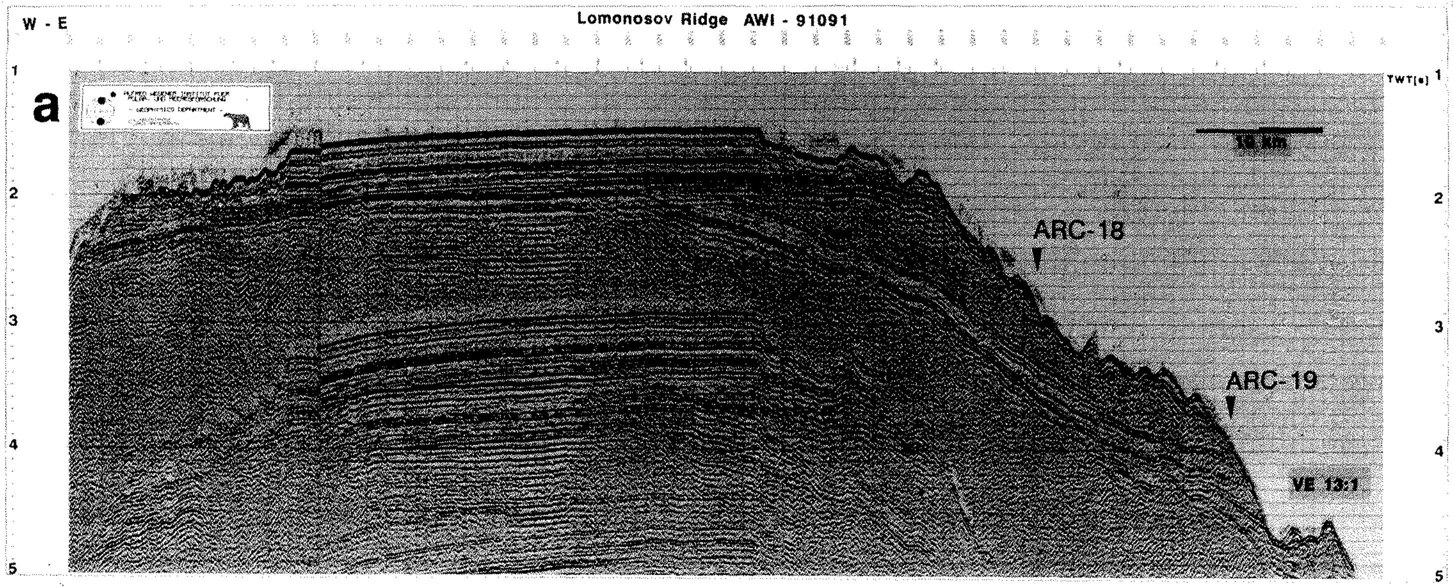


Fig. 59: Seismic profile AWI-91090 across the Lomonosov Ridge showing location of drill site ARC 17: a = brute stack; b = line drawing and interpretation.

Abb. 59: Seismisches Profil AWI-91090 über den Lomonosov Rücken mit Lage der vorgeschlagenen Bohrposition ARC 17. a = Grobe Stapelung. b = Strichzeichnung der Interpretation.



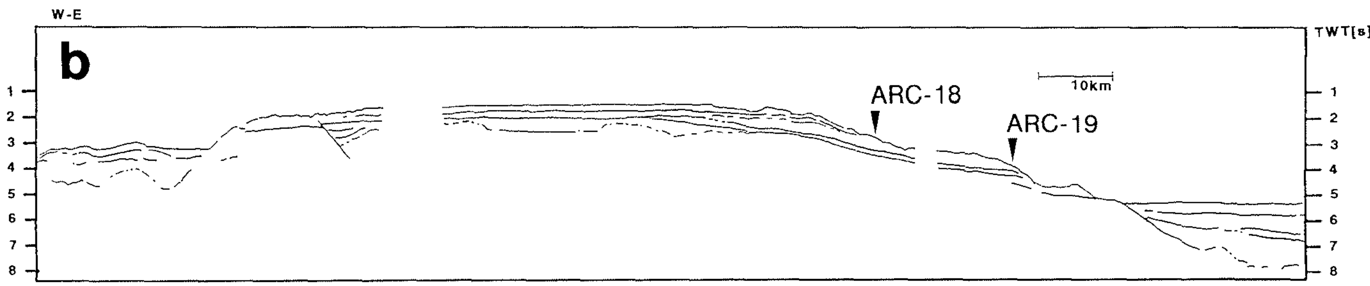


Fig. 60: Seismic profile AWI-91091 across the Lomonosov Ridge showing locations of proposed drill sites ARC 18 and ARC 19; a = brute stack; b = line drawing and interpretation.

Abb. 60: Seismisches Profil AWI-91091 über den Lomonosov Rücken mit Lage der vorgeschlagenen Bohrpositionen ARC 18 und ARC 19. a = Grobe Stapelung; b = Strichzeichnung der Interpretation.

15.4 *Nansen Arctic Drilling Project (NAD) Organization and Membership*

The Nansen Arctic Drilling project was founded on the occasion of the International Geological Congress in Washington, 1989. It presently consists of an Executive Committee with Science and Technology committees. Membership is from interested countries. NAD maintains a formal liaison office (funded by participating countries) with JOI, Inc. (Joint Oceanographic Institutions, Washington, D.C.).

The Science Committee has established subcommittees on "site surveying" and an "Arctic Data Bank".

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15.5 *List of Abbreviations and Acronyms*

AOSB	Arctic Ocean Sciences Board
ARCTIC'91	1991 Expedition of RVs *Polar Star*, *Oden*, *Polarstern* (ARK-VIII/3) to the eastern Arctic
ARK IV/3	3rd Leg of 1987 *Polarstern* Expedition into the Eastern Arctic (ARK IV)
CCD	Calcite Compensation Depth
CESAR	Canadian Expedition to Study Alpha Ridge
CLIMAP	Climate Long-Range Investigations; Mapping and Predictions
CMG	IUGS Commission for Marine Geology
COSOD	Conference on Scientific Ocean Drilling
C/T	Cretaceous/Tertiary boundary
DSDP	Deep-Sea Drilling Project
ECOPS	European Consortium on Ocean and Polar Sciences
ESF	European Science Foundation
FAMOUS	French-American Mid-Ocean Undersea Study
FRAM I-IV	Ice stations occupied by scientific parties in the 80's north of Svalbard
GCM	General Circulation Model
GSC	Geological Survey of Canada
HPC	Hydrolic Piston Core
IASC	International Arctic Science Committee
ICL	International Commission on the Lithosphere
IGBP	International Geosphere-Biosphere Project
IKU	Institutt for kontinentalsokkelundersøkelser, Trondheim (Norway)
IRD	Ice Rafted Debris
IUGG	International Union of Geodesy and Geophysical
IUGS	International Union of Geological Sciences
JOIDES	Joint Oceanographic Institutions for Deep Earth Sampling
JOI Inc.	Joint Oceanographic Institutions, Inc., Washington, D.C.
ka	Age in thousands of years B.P.(= before present)
ky	Time span in thousands of years
LOREX	Lomonosov Ridge Experiment
Ma	Age in millions of years B.P.(= before present)
my	Time span in millions of years
NAD	Nansen Arctic Drilling Program
NADW	North Atlantic Deep Water
NCAP	Nansen Centennial Arctic Program (Norwegian Academy of Sciences
NEREIS	Novel European Research Ship
NSF	National Science Foundation (USA)
ODP	Ocean Drilling Program
PAGES	Past Global Changes (IGBP Core Project)
PONAM	Polar North Atlantic Margins (ESF Network)
SCOR	Scientific Committee on Ocean Research
SST	Sea Surface Temperature
UCAR	University Corporation for Atmospheric Record
USGS	US Geological Survey
WG	Working Group