Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Non-Steady Behaviour in the Cenozoic Polar North Atlantic System: The Onset and Variability of Northern Hemisphere Glaciations

J. Thiede and A. M. Myhre

Phil. Trans. R. Soc. Lond. A 1995 **352**, 373-385
doi: 10.1098/rsta.1995.0077

Email alerting service Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to:
http://rsta.royalsocietypublishing.org/subscriptions

This journal is © 1995 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Non-steady behaviour in the Cenozoic polar North Atlantic system: the onset and variability of Northern Hemisphere glaciations

BY J. THIEDE[1] AND A. M. MYHRE[2]

[1] *GEOMAR Research Center for Marine Geosciences, Kiel University, 24148 Kiel, Germany*

[2] *Department of Geology, University of Oslo, 0316 Oslo, Norway*

Changes of the extent of the Arctic Ocean sea-ice cover over the past century, the geological record of the Arctic Ocean seafloor of the youngest geological past, as well as the evidence of a pre-Glacial temperate to warm Arctic Ocean during Mesozoic and Palaeogene time are witnesses of dramatic revolutions of the Arctic oceanography. The climate over northwestern Europe on a regional scale as well as the global environment have responded to these revolutions instantly over geological time scales. Results of ocean drilling in the deep northern North Atlantic document an onset of Northern Hemisphere glaciation towards the end of the middle Miocene (10–14 Ma). While the available evidence points to early glaciations of modest extent and intensity centred around southern Greenland, the early to mid-Pliocene intervals record a sudden intensification of ice-rafting in the Labrador and Norwegian Greenland seas as well as in the Arctic Ocean proper. The Greenland ice cap seems to have remained rather stable whereas the northwest European ice shields have experienced rapid and dramatic changes leading to their frequent complete destruction. Many sediment properties seem to suggest that orbital parameters (Milankovitch-frequencies) and their temporal variability control important properties of the deep-sea floor depositional environment. Obliquity (with approximately 40 ka) seems to be dominant in pre-Glacial (middle Miocene) as well as Glacial (post late Miocene) scenarios whereas eccentricity (with approximately 100 ka) only dominated the past 600–800 ka. Plio-Pleistocene deposits of the Arctic Ocean proper, of the entire Norwegian Greenland and of the Labrador seas have recorded the almost continuous presence of sea-ice cover with only short 'interglacial' intervals when the eastern Norwegian Sea was ice-free. The documentation of long-term changes of the oceanographic and climatic properties of the Arctic environments recorded in the sediment cover of the deep-sea floors might also serve to explain scenarios which have no modern analog, but which might well develop in the future under the influence of the anthropogenic drift towards warmer global climates.

1. Introduction

The Arctic and sub-Arctic seas exert major influences on global climate and ocean systems. High northern latitude oceans directly influence the global environment through the formation of permanent and seasonal ice covers, transfer of sensible

Phil. Trans. R. Soc. Lond. A (1995) **352**, 373–385
Printed in Great Britain

© 1995 The Royal Society
TEX Paper

The Royal Society is collaborating with JSTOR to digitize, preserve, and extend access to *Philosophical Transactions: Physical Sciences and Engineering.* www.jstor.org

Downloaded from rsta.royalsocietypublishing.org

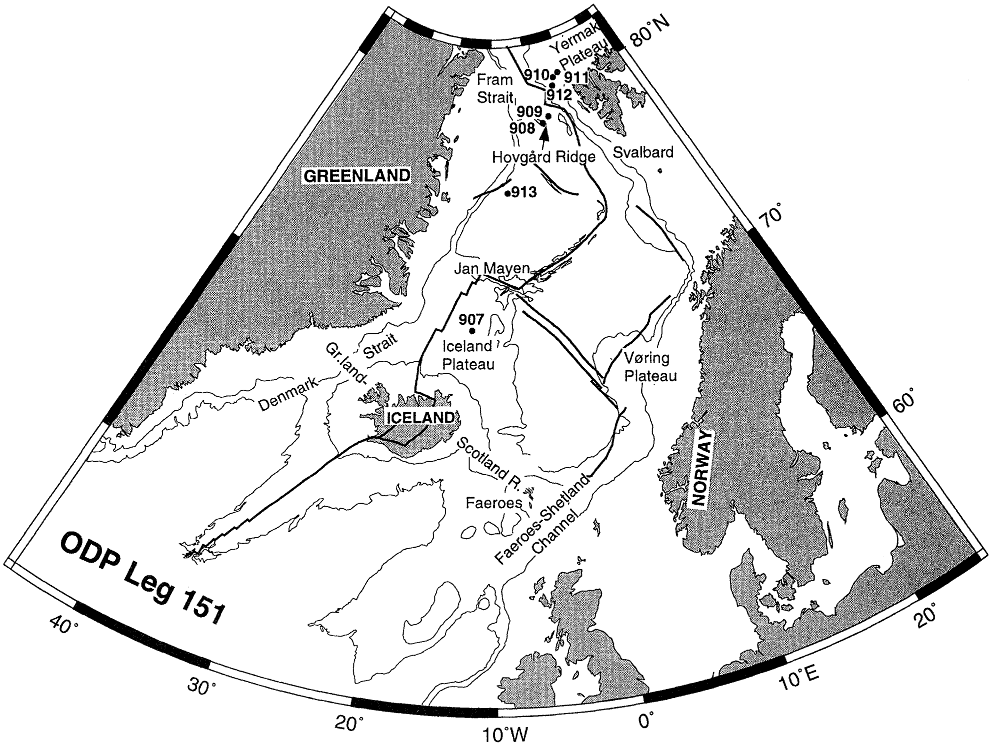

Figure 1. Bathymetric map of the Norwegian Greenland Sea, showing drill site locations for Leg 151. Contour interval is 2000 m.

and latent heat to the atmosphere, deep-water renewal and deep-ocean ventilation. Thus, any serious attempt to model and understand the Cenozoic variability of global climate must take into account the palaeoenvironmental changes in the Arctic and sub-Arctic deep-sea basins.

Due to the permanent sea-ice cover, the Arctic Ocean is the only major ocean basin that has not been drilled by DSDP or ODP. Of all the Arctic and sub-Arctic deep-sea basins the Norwegian Greenland Sea (figure 1) without doubt has the most important influence on evolution and change of the Northern Hemisphere palaeoenvironments; therefore the arguments presented in this paper will mainly be drawn from the ODP and DSDP legs devoted to this area.

2. Cenozoic climate evolution of high northern latitudes

It is still not known how and when climatic, tectonic, and oceanographic changes in the Arctic (Thiede *et al.* 1992) contributed to Cenozoic global ocean cooling and to increased thermal gradients. In order to understand the Cenozoic evolution of the global climate system, it is necessary to clarify when the Arctic Ocean became ice-covered and to document the variability of ice covers in the Arctic. It has been proposed that the Arctic Ocean has been permanently ice-covered since the beginning of the late Miocene (Clark 1982) or even earlier (Wolf & Thiede 1991). Other studies concluded that this event happened in the Matuyama or at the Brunhes/Matuyama boundary (Herman & Hopkins 1980; Carter *et al.* 1986; Repenning *et al.* 1987).

A major threshold of the climate system was passed with the inception of glaciers

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

and ice sheets in the Northern Hemisphere. Data from ODP Leg 104 document minor input of ice-rafted debris (IRD) into the Norwegian Sea in the late Miocene and through the Pliocene, pointing to the existence of periods when large glaciers were able to form and reach coastal areas in some of the regions surrounding the northernmost North Atlantic (Jansen & Sjøholm 1991; Wolf & Thiede 1991). IRD data from ODP Leg 105, Site 646, suggest the onset and discontinuous early existence of ice in the Labrador Sea to the south of Greenland since middle/late Miocene times (Wolf & Thiede 1991). The major shift to a mode of variation characterized by repeated large glacials in Scandinavia probably occurred at about 2.5 Ma† and was further amplified at about 1 Ma (Jansen *et al.* 1988; Jansen & Sjøholm 1991). Terrestrial data indicate significant cooling on Iceland at about 10 Ma (Mudie & Helgason 1983) and glaciation in elevated areas of Iceland in the latest Miocene and the Pliocene (Einarsson & Albertsson 1988). Terrestrial evidence also suggests forested areas in the Arctic fringes, which are far north of the present forest/tundra boundary, until about 2 Ma (Carter *et al.* 1986; Nelson & Carter 1985; Funder *et al.* 1985; Repenning *et al.* 1987). The chronology from these land sites is, however, poorly constrained, and there are no continuous records from land sites that document the climatic transition into a cold Arctic climate.

In addition to the above questions that address the magnitude of glaciations and the passing of certain climatic thresholds in the Earth's history, the frequency components of the climatic, oceanographic, and glacial evolution of the Arctic and sub-Arctic are of importance for assessing the climate system's response to external forcing. Results from DSDP Leg 94 sites in the North Atlantic have shown that sea-surface temperatures and ice volumes have a strong response to orbital forcing over the last 3 Ma. However, the amplitudes of climatic changes and the dominant frequencies have varied strongly, indicating variations in the way the climate system responds to external forcing (Ruddiman *et al.* 1986; Ruddiman & Raymo 1988; Raymo *et al.* 1990). Work is under way, based on Leg 104 material (Jansen & Sjøholm 1991; Henrich 1992) to study the cyclicity of IRD input into the sub-Arctic Norwegian Sea. This can aid in understanding the controlling factors for subpolar ice-sheet variations. However, available data do not permit extending this type of high-resolution study on orbital time scales to other parts of the Arctic Ocean and the Norwegian Greenland Sea.

3. Environmental frame of the Norwegian Greenland Sea

The Cenozoic history of the boundary between the North American and Eurasian plates (figure 1) has generated a series of interconnected deep-sea basins which exchange their water masses through the North Atlantic-Arctic gateways. The basins consist of the main North Atlantic in the south, and the Norwegian Greenland Sea and the eastern Arctic basin in the north. Water exchange between them is constricted by two gateways, namely in the south by the Greenland–Scotland Ridge with Denmark Strait in the west and the Faroe–Shetland Channel in the east, and in the North by Fram Strait between the continental margins of northeastern Greenland and Svalbard. The geologically young connection between the Atlantic and Arctic oceans has proven of great importance because they allowed climatically highly sensitive surface and bottom currents to develop. To study how the depositional environment in and around the two North Atlantic Arctic gateways responded to the

† 1 Ma = 1 million years, 1 ka = 1000 years

Downloaded from rsta.royalsocietypublishing.org

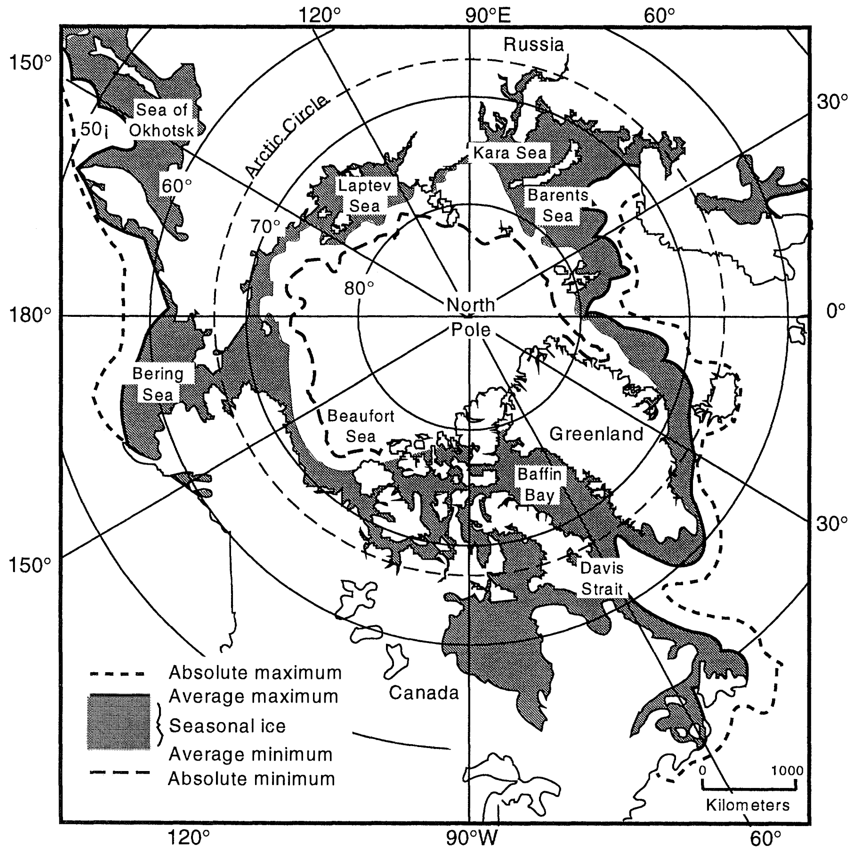

Figure 2. Average and extreme sea ice limits (greater than $\frac{1}{8}$), after CIA (1978) and Barry (1989).

Cenozoic tectonic and climatic changes in the area, was the main scientific objective of ODP Leg 151, the first of two drilling legs devoted to the North Atlantic–Arctic gateway problem.

The eastern segment of the Greenland–Scotland Ridge is crossed by the North Atlantic Drift (figure 2) which imports temperate surface water masses into the Norwegian Sea. After branching into the North Sea these waters, now called the Norwegian Current, follow the Norwegian continental margin bounded to the east by the Norwegian Coastal Current, to the west by the Arctic polar water masses of the central Norwegian Greenland Sea. Off northern Norway the Norwegian Current branches into the North Cape Current, turning to the east and the West Spitsbergen Current, trailing the Barents Sea continental margin to the north until it dips below the Arctic sea-ice cover in the northern part of Fram Strait. In the west these inflowing Atlantic waters are partly balanced by the East Greenland Current which carries cold, brackish, partly and seasonally highly variable ice-covered Arctic surface waters from the Arctic Ocean along the East Greenland continental margin into the northwestern Atlantic Ocean.

The deep waters of the Norwegian Greenland Sea are renewed by two principally different processes which both produce very cold, saline, dense and oxygenated bottom waters, namely the down-welling of surface waters between the Polar and

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

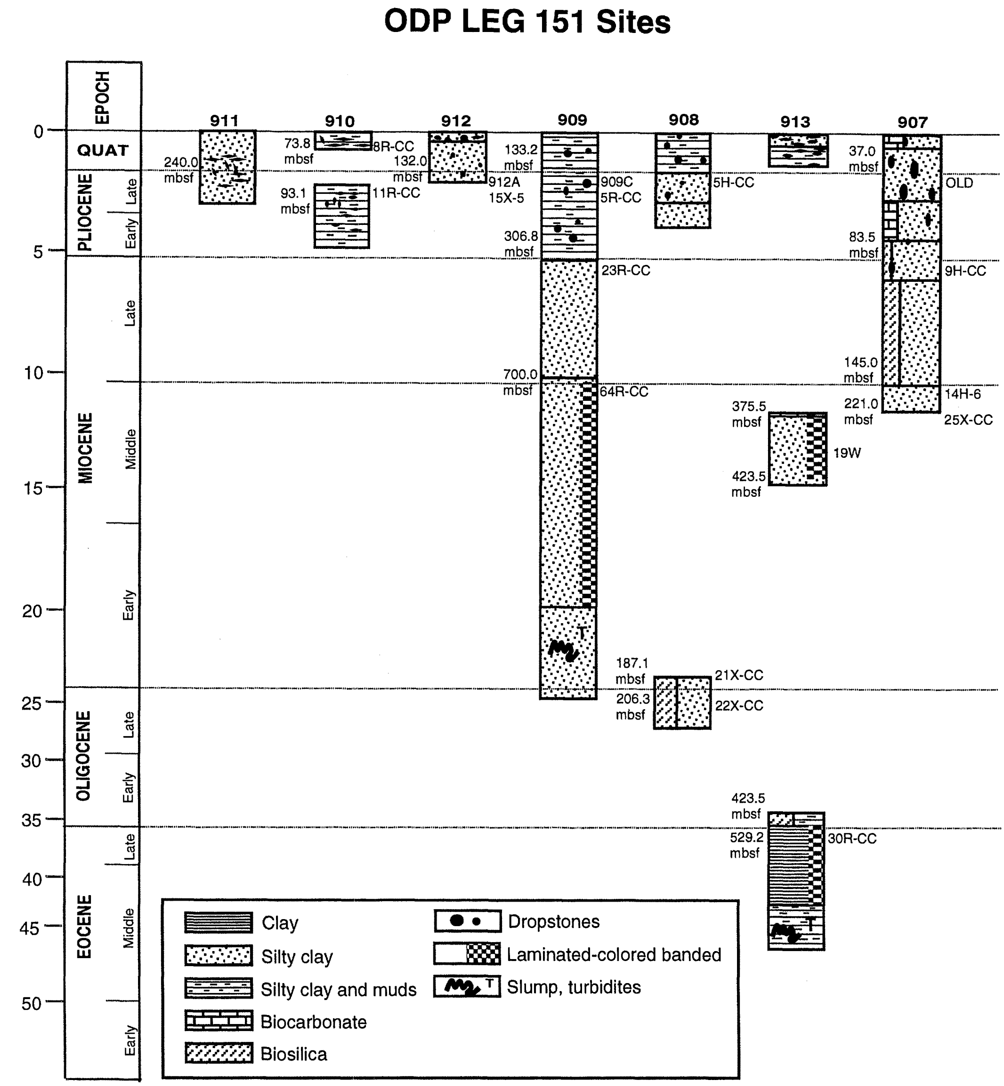

Figure 3. Lithologic summaries of Leg 151 drill sites, showing lithologic units and ages. (From Myhre *et al.* 1995.)

Arctic fronts in the open Greenland Sea (Koltermann 1987) and as a result of seasonally highly variable sea-ice formation by the production of dense brines on the shelves which then flow across the continental margins into the adjacent deep-sea basins (Quadfasel *et al.* 1987). The Norwegian Greenland Sea is filled beyond the sill depth of the southern gateway by these cold deep waters which spill through Denmark Strait, the Iceland Faroe Ridge and the Faroe–Shetland Channel into the deep North Atlantic. The North Atlantic deep water (NADW) is fed by these water masses as they flow across various segments of the Greenland–Scotland Ridge. The overflow of cold, saline and oxygenated deep waters from the Norwegian Greenland Sea into the North Atlantic Ocean (Meincke 1983) and its historic variability as documented in the ocean sediments is one of the most dynamic processes of the global

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

environment (Broecker 1991) and is expected to respond sensitively to any climatic change of the high northern latitudes.

4. Previous ocean drilling in Northern Hemisphere polar and subpolar deep-sea basins

A history of scientific drilling in the Northern Hemisphere polar and subpolar deep-sea basins for studying the palaeoenvironment and Cenozoic palaeoclimate would not be complete without a brief excursion to the North Pacific Ocean DSDP Leg 18 and 19 results (Kulm *et al.* 1973; Creager *et al.* 1973). Both legs are part of the very early DSDP activities, but they visited the northern rim of the Pacific and the Bering Sea, providing some important data on the imprint of the onset of Northern Hemisphere Cenozoic glaciations in an area geographically opposite to the Norwegian Greenland Sea drill sites. DSDP Leg 18 visited the northern Pacific and found glacio-marine deposits in Sites 178–182 (Alaska Abyssal Plain, Aleutian Trench and continental margin off southwest Alaska). The oldest record of ice-rafted erratics has been observed in the glacio-marine deposits of the Alaska Abyssal Plain, where upper Pliocene and Pleistocene deposits down to 258 mbsf (metres below sea-floor) with erratics can be subdivided into 3 lithologic units, each with variable amounts of erratics and henceforth documenting a certain pattern of temporal variability of ice-rafting. No attempt has been made to identify a potential North American source region.

DSDP Leg 19 continued the programme of Leg 18 towards the West, but it also crossed over the Aleutian island chain into the deep Bering Sea. Like Leg 18, it stayed in relatively low latitudes (south of 57° N) and therefore the drill sites are not well placed to address onset and evolution of Cenozoic Northern Hemisphere glaciations. The possibility of making pertinent observations was further reduced by the fact that these early legs only performed spot rotary-coring, obtaining an incomplete and intensely disturbed record of the youngest parts of the sedimentary sequences. However, evidence for ice-rafting with variable intensity has been found in sediments possibly as old as early Pliocene (Site 187), almost always in the Upper Pliocene to Quaternary deposits at most of the drill sites. No attempts have been made to quantify ice-rafting or to determine potential provenances of the erratics. Later, ODP Leg 145 also visited the North Pacific Ocean and continuously cored several deep sites which showed that the onset of the Northern Hemisphere glaciation occurred at 2.6 Ma, marked by abundant dropstones coming both from Siberian and Alaskan sources (Rea *et al.* 1993*b*).

DSDP visited the North Atlantic several times, but only once the Norwegian Greenland Sea (Talwani *et al.* 1976) during Leg 38. Spot- and rotary-coring and mostly geophysical and tectonic objectives did not allow the deciphering of much of the detail of the Late Cenozoic palaeoenvironmental history. Many of the Norwegian Greenland Sea drill sites contained ice-rafted detritus (both erratics and Cretaceous *Inoceramus* prisms are mentioned); their stratigraphic distribution confirmed that sea-ice covers and ice-rafting were not restricted to the Quaternary. Ice-rafting exhibiting considerable temporal variation extended clearly into the Tertiary, at that time Pliocene. Warnke & Hansen (1977) based on the Leg 38 material, later confirmed this and established a regional distribution of ice-rafting with maxima along the Greenland and Norwegian continental margin.

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

ODP Leg 104 was the next major contribution towards deciphering the history of Northern Hemisphere Cenozoic cooling and glaciation. The major scientific objective of the central drilling location on the Vøring Plateau off mid-Norway was oriented towards sampling a thick, dipping reflector sequence of volcanic origin (Eldholm *et al.* 1987) related to the initial opening of the Norwegian Greenland Sea (Hinz *et al.* 1993; Eldholm & Thomas 1993). However, together with additional drill sites on either side along a transect across the Vøring continental margin, this site also revealed important data about the history of the Norwegian Current and the onset of Northern Hemisphere Cenozoic glaciations.

5. New deep-ocean drilling in high northern latitudes: Leg 151

Following recommendations defined after Leg 104 (Thiede *et al.* 1989) and further specified by the NAAG DPG (Ruddiman *et al.* 1991), Leg 151 was scheduled to drill a series of sites (figure 1) in several remote geographic, partly ice-covered locations (the northern gateway region, i.e. Yermak Plateau and Fram Strait, the East Greenland Margin, and the Greenland-Norway Transect, the Iceland Plateau, the Greenland–Scotland Ridge) with the aim of reconstructing the temporal and spatial variability of the oceanic heat budget and the record of variability in the chemical composition of the ocean. Leg 151 was also to undertake a study of circulation patterns in a pre-glacial, relatively warm polar and subpolar ocean, and the mechanisms of climatic change in a predominantly ice-free climatic system. In addition, the proposed drilling included a collection of sequences containing records of biogenic fluxes ($CaCO_3$, opal and organic carbon) and stable-isotopic carbon and oxygen records which addressed aspects of facies evolution and depositional environments as well as the carbon cycle and productivity. The drilling approach focused on rapidly deposited sediment sequences to be used for high-resolution, Milankovitch-scale palaeoclimatic analysis and rapid sub-Milankovitch-scale climate changes.

The voyage of the Joides Resolution during Leg 151 to the Norwegian Greenland–Iceland Sea, Fram Strait and the marginal Arctic Ocean, brought a scientific drilling vessel into higher northern latitudes with waters more ice-infested than ever before. The drill ship was escorted by the Finnish icebreaker Fennica. ODP Leg 151 opened completely new scientific perspectives to Arctic geoscientific research, thus representing a historic step in the scientific exploration of the Arctic. The sedimentary sections penetrated at these sites were investigated to unravel the history of surface and bottom waters in the Norwegian Greenland Sea and in the Arctic Ocean. These are connected through the narrow northernmost gateway of the Atlantic Ocean, the Fram Strait, with a complicated history of water exchange between these two polar to subpolar Northern Hemisphere deep-sea basins. Yermak Plateau and Fram Strait are also relatively young geological features whose origin is not known in enough detail to resolve their impact on the changes in current patterns and whose basement age and nature as well as subsidence have to be established by means of deep-ocean drilling. Four areas of the North Atlantic–Arctic Gateway province have been drilled during ODP Leg 151 during July to September 1993 (figure 1):

(i) Site 907, located on the eastern-central Iceland Plateau, was drilled to obtain Quaternary and Neogene biogenic and terrigenous sediment sequences with a detailed palaeoenvironmental record;

(ii) Sites 908 and 909, in the southern Fram Strait, represent a depth transect with shallow (on Hovgård Ridge) and deep (on the Greenland Sea/Arctic Ocean sill

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Downloaded from rsta.royalsocietypublishing.org

depth) locations to study the history of the water exchange between the two adjacent polar deep-sea basins as well as the opening and tectonic history of Fram Strait;

(iii) a suite of sites (Sites 910, 911 and 912) was planned for the Yermak Plateau to study the origin of its basement as well as its history of subsidence, and to establish as far back as possible the history of the truly Arctic marine palaeoenvironment along a depth transect as well as its interaction with the Upper Cenozoic Arctic ice sheets; and

(iv) sites at the East Greenland Margin (Site 913) were aimed at studying the history of the East Greenland Current and of the Greenland Sea.

The main scientific objectives of ODP Leg 151 comprised the investigation of the short and long-term variability of the Late Cenozoic palaeoceanography of the Norwegian Greenland Sea and of the Arctic Ocean proper, which is controlled by or responds to tectonic evolution and Northern Hemisphere palaeoclimatic change. It was important to investigate properties and changes of the surface and bottom water masses, as well as the history of their main current systems. Special attention was paid to the history of the sea-ice cover as well as to glaciations and deglaciations on the adjacent continents. Following ODP Leg 104, which addressed the processes controlling the origin of the dipping reflector sequence on the Vøring Plateau and the history of the temperate Norwegian Current in the eastern Norwegian Greenland Sea, the cluster of drill sites at ODP Leg 151 combines shallow and deep locations in the western and northern Norwegian Greenland and in the Arctic Ocean proper (figure 1). Detailed descriptions of the stratigraphic sections penetrated at each of the drill sites have recently been published in the Initial Reports of ODP Leg 151 (Myhre *et al.* 1995). We therefore present here only a brief interpretation of the palaeoenvironmental evolution of the northern part of the North Atlantic Arctic gateway as it can be deduced from said drilling results.

6. Narrative of Cenozoic palaeoenvironmental evolution of high Northern Hemisphere deep-sea basins

(*a*) *Middle Eocene (Site 913)*

The lowermost sediments at Site 913, the oldest material recovered during Leg 151, contain multiple-fining upward-sediment gravity flows with coal and mud clasts, and laminations, with highest abundances of terrigenous organic matter recovered during Leg 151. This suggests a site close to a continental source, possibly in an active tectonic or high-sedimentation-rate area, such as an early post-rift basin.

Above the mass-wasted sediment are finer-grained, interbedded, laminated and massive deposits, with moderate bioturbation. These sediments show a general fining upward trend in the middle Eocene, suggesting a change in sediment source, depocentre, or possibly a tectonic barrier, preventing coarse sediment influx. The chemistry of the sediment shows little change, consisting of high silica continental sediments, derived from a granitic source. High terrigenous organic carbon values continue, although they also decrease through the middle Eocene. The abundance of fish teeth found in some samples from this interval suggests a slow sedimentation rate.

Palaeontological evidence from Site 913 suggests increasing productivity throughout the middle Eocene. Biogenic silica is preserved only in the upper middle Eocene. Decalcified *Bolboforma* and the absence of calcareous planktonic and benthic foraminifers and nannofossils place this site below the calcite compensation depth (CCD).

Downloaded from rsta.royalsocietypublishing.org

Similarities to the agglutinated benthic foraminifers in the Labrador Sea suggest that the bottom waters were in connection with the North Atlantic.

(*b*) *Late Eocene to early early Oligocene (Site 913)*

At Site 913 there is a renewed influx of terrigenous organic carbon in the late Eocene, at approximately the same level as the first appearance of biogenic silica. The sediments themselves show little change, being interbedded, massive and laminated silty clay and clay. Up-section, however, they become very colourful, with exciting shades of blue, purple and green. This coincides with an increase in the preservation and abundance of siliceous microfossils. Discrete siliceous ooze intervals were recovered and SiO_2 is also high in the pore waters. The siliceous intervals are formed during times of high productivity, resulting in high pelagic sedimentation rates and high values of organic carbon.

The high productivity is believed to have been caused by upwelling. Decay of organic matter would result in low oxygen conditions, decreased bottom-water pH and the dissolution of carbonate. As a result calcareous microfossils are absent during this interval. Similarities to the agglutinated benthic foraminifers in the Labrador Sea suggest that the bottom waters were exchanged with the North Atlantic.

(*c*) *Late Oligocene to early early Miocene (Sites 908, 909?)*

Evidence for this interval from Site 908 suggests moderately well-mixed oceanic conditions in the Norwegian Greenland Sea. The predominantly fine-grained and hemipelagic sediments record relatively high, but fluctuating, surface-water productivity. This is particularly well demonstrated by organic carbon concentrations showing the highest variability of any Leg 151 site, generally between 0.75% and 1.5%, although some layers were over 2%. The average values are also higher than at most other Leg 151 sites. High productivity is further supported by the abundance of siliceous microfossils, with a diverse assemblage of diatoms and a low diversity assemblage of radiolarians. Absence of planktonic foraminifers, rare nannofossils, and benthic foraminifers place this site below the calcite lysocline during this time. Intermediate bottom-water oxygen content is suggested by the benthic foraminiferal morphologies and the low diversity of the assemblage. Extensive bioturbation suggests at least intermediate oxygenated bottom waters, although thin, poorly bioturbated, laminated intervals suggest fluctuations to lower oxygen levels.

(*d*) *Middle Miocene*

A glimpse of the middle Miocene is observed in the laminated clay and sandy muds of Core 913-19W which contains a moderate abundance of siliceous microfossils with low-diversity radiolarians and moderate diversity diatoms. Ebridians are also common. This suggests moderately high pelagic productivity, although the organic carbon values are very low, less than 0.5%. Dissolution of all calcareous biota and the occurrence of a low diversity assemblage of siliceous agglutinated benthic foraminifers suggest that this site was below the CCD during this time.

(*e*) *Early to late Miocene and early Pliocene*

This interval is recovered in two dramatically different sections in Site 909 (Fram Strait) and 907 (Iceland Plateau). In the southern Norwegian Greenland Sea, Site 907 suggests high productivity of siliceous microfossils, although preserved organic carbon is low, less than 0.5%. Terrigenous input is also low, and volcanic glass forms

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

about 10% of the sediment. Diatoms suggest upwelling conditions and an Atlantic source of surface water. The resulting lowered pH causes the dissolution of all carbonate. These oceanographic conditions are interrupted during two brief intervals with enhanced preservation of carbonate, and deposition of the only nannofossil ooze recovered during Leg 151. Timing of these events is constrained by the calcareous microfossils and palaeomagnetics.

At Site 909, in the Fram Strait, the lower Miocene to Pliocene interval suggests restricted oceanic circulation. On average, total organic carbon is slightly higher than 1%. The sediments show a general fining upward trend. They alternate on a decimetre scale between massive, moderately to extensively bioturbated, and laminated, weakly to unbioturbated sediments, probably reflecting changing bottom water conditions. No biogenic silica or carbonate is preserved. Agglutinated benthic foraminifers record very low oxygen bottom water in the late Miocene to early Pliocene, supporting the interpretation of corrosive bottom water. The lowermost sediments at Site 909 contain a few Oligocene nannofossils.

The upper Oligocene to lower Miocene section at Site 909 differs considerably from Site 908, which presents a problem, since they are adjacent though at different depths. Possibly, at Site 908 there are undetected nonconformities which can be invoked to explain these differences. Likewise, the Miocene section at Site 913 is very different, but geographically further away. The laminations here, as with the laminated middle Eocene section at Site 913, may have been produced when the basin circulation was restricted.

The oldest dropstone recovered on Leg 151 is from the uppermost Miocene at Site 907. This is somewhat surprising because this site also has the lowest abundance of dropstones. The next oldest dropstone is also an isolated occurrence, this time in Site 909, however, its location at the edge of a drilling biscuit makes it suspect.

(*f*) *Pliocene to Quaternary*

Pliocene and Quaternary sediments were recovered from all sites, (Sites 910, 911, 912: Yermak Plateau, Sites 909 and 908: Fram Strait, Site 913: East Greenland Margin, and Site 907: Iceland Plateau), and are dominated by silty clay and muds. With the exception of Site 907, the first occurrence of dropstones at all sites, based on palaeomagnetic ages, is in the lower Pliocene. At several sites, e.g. Site 908, 909, 911, the onset of dropstones is preceded by an increase in potash (K_2O) concentration in the sediment, suggesting a change in the sediment source. The introduction of fresher, less weathered sediment appears to proceed the onset of glacial dropstones. The increasing potassium trend continues as the abundance of dropstones increases, and then levels off at the higher value.

At about 2.5 Ma most sites show a substantial increase in dropstone abundance. Above this the number of dropstones at each site (normalized for recovery) shows different absolute abundances and types of fluctuations. In most sites, there is a substantial decrease in dropstone abundance in the upper Quaternary. Unfortunately the age resolution, and the location of nonconformities are not well constrained at this time, and hence it is not possible to see if these changes reflect glacial/interglacial changes.

Microfossils are generally more common in this interval, more so in the youngest part than in the older sections. Pre-glacial fossiliferous Pliocene sediments were recovered only at Site 910. The well preserved carbonate microfossil groups record good circulation and carbonate preservation at this shallow site. Organic carbon values

Downloaded from rsta.royalsocietypublishing.org

average about one percent. High glacial, especially Quaternary, sedimentation rates (greater than 10 cm ka^{-1}) are recorded at the Yermak Plateau Sites 911 and 912, whereas Site 910, also on the Yermak Plateau, has a very high Pliocene sedimentation rate.

At least four sites (907, 909, 911 and 912) record a lower Quaternary to upper Pliocene calcium carbonate dissolution event. This event was also observed on the Vøring Plateau. Dissolution of carbonate is caused by increased CO_2 in the bottom water. This occurs during ageing, for instance when bottom-water formation decreases.

The presence of biogenic sediments, particularly in the upper section (less than 50 mbsf) at most sites, suggests more mild climatic conditions. These sediments are more colourful, with olive gray and very dark gray layers.

At Sites 908, 910 and 911, there is a steep increase in the bulk density and strength over the top 20 to 30 mbsf (upper Quaternary), followed by a gradual decrease with depth. These are three of the four shallowest sites (1273, 556, and 901 mbsf respectively). Data at the other shallow site, Site 912 (1037 mbsf), is not good enough to see any trend. Although no obvious compositional changes were observed, the anomalously high values may be related to overcompaction due to ice, or may possibly be a permafrost feature due to freezing. This problem will be investigated in considerably more detail when cores from the geotechnical hole, Hole 910D are studied. Physical properties such as bulk density of sections older than 600–700 ka show remarkably regular fluctuation with time, imaging the 40 ka-obliquity Milankovitch frequency.

7. Future Northern Hemisphere high latitude deep ocean drilling

After the successful North Atlantic legs of the Ocean Drilling Program (Legs 104, 105, 151, 152, and the upcoming second NAAG-leg (ODP Leg 163 in 1995) and the North Pacific Transect, which revisited (Rea *et al.* 1993*a*) areas that were drilled during DSDP Legs 18 and 19, the question remains if and how deep-sea drilling can contribute in the future to solving the mysteries of the geological, environmental and biological history of the Northern Hemisphere polar and subpolar deep-sea basins. Once the second NAAG-Leg with its important scientific targets in the southern Norwegian Greenland Sea and on both sides of the Greenland–Scotland Ridge is completed, many of the presently defined high priority drilling targets will have been exhausted.

Considering only the available and established drilling techniques the following future high priority areas can be suggested to further study the Northern Hemisphere palaeoenvironment.

(i) *Bering Sea.* Transition from a pre-glacial to a glacial palaeoenvironment, variability of the glacial palaeoceanography, back-arc-spreading phenomena.

(ii) *Sea of Okhotsk.* Late Cenozoic palaeoenvironments, areas of high fluid and gas exchange from the sea floor into the overlying water column (areas of highest methane emission, seeps and their geological setting and history), back-arc spreading phenomena, Kamtchatka volcanic and tectonic history.

(iii) *North Atlantic–Arctic.* Deep penetration on Yermak-Plateau to establish nature and age of basement as well as of the overlying sediment column. Transect across one of the trough-mouth fans with the aim of correlation to the glacial history of the continental hinterland.

Considering alternative drilling platforms the plans of the Nansen Arctic Drilling

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

(NAD) programme (Thiede & NAD Scientific Committee 1992) receive the highest priority. It is the aim of this programme to bring deep-sea drilling into the permanently ice-covered Arctic Ocean to resolve its tectonic and palaeoenvironmental history. Areas of high priority have been established as follows.

(i) *Alpha–Mendeleev Ridge.* Sampling of the Mesozoic and lower Cenozoic preglacial pelagic sedimentary sequence of the Arctic Ocean, establishment of the age and nature of the volcanic basement.

(ii) *Lomonosov Ridge.* Sampling of extended post-rift sedimentary sequence on top of the Lomonosov Ridge to establish timing of onset of the Arctic Ocean glaciation and of the variability of the depositional environments.

(iii) *Laptev Sea.* Intersection of the active mid-ocean Gakkel Ridge with the Laptev Sea continental margins, tectonic history of the area, nature of rifting, palaeoenvironment of high resolution terrigenous sections in front of a large Arctic delta.

In the preparation of this paper we have been able to draw on the latest version of the Leg 151 Initial Results (Myhre *et al.* 1995), the site proposals submitted by Scandinavian, Danish and German working groups as well as the written deliberations of the North Atlantic Arctic Gateway Detailed Planning Group (Ruddiman *et al.* 1991) and of the Joides advisory structure. Their contributions are gratefully acknowledged.

References

Barry, R. G. 1989 The present climate of the Arctic Ocean and possible past and future states. In *The Arctic seas: climatology, oceanography, geology and biology* (ed. Y. Herman), pp. 1–46. New York: van Nostrand Reinhold.

Broecker, W. S. 1991 The great ocean conveyor. *Oceanography* **4**, 79–89.

Carter, L. D., Brigham-Grette, J., Marinkovich, L., Pease, V. L. & Hillhouse, J. W. 1986 Late Cenozoic Arctic Ocean sea ice and terrestrial palaeoclimate. *Geology* **14**, 675–678.

CIA 1978 Polar regions – atlas. Central Intelligence Agency. (Reprinted 1981.)

Clark, D. L. 1982 Origin, nature, and world climate effect of Arctic Ocean ice-cover. *Nature, Lond.* **300**, 321–325.

Creager, J. S. *et al.* 1973 *Init. Reports* DSDP **19**. Washington, DC: US Government Printing Office.

Einarsson, T. & Albertsson, K. J. 1988 The glacial history of Iceland during the past three million years. In *The past three million years: evolution of climatic variability in the North Atlantic region* (ed. N. J. Shackleton, R. G. West & D. Q. Bowern), pp. 227–234. Cambridge University Press.

Eldholm, O. *et al.* 1987 *Proc.* ODP *Init. Rep.* **104**. College Station, TX: Ocean Drilling Program.

Eldholm, O. & Thomas, E. 1993 Environmental impact of volcanic margin formation. *Earth planet. Sci. Lett.* **117**, 319–329.

Funder, S., Abrahamsen, N., Bennike, O. & Feyling-Hanssen, R. W. 1985 Forested Arctic: evidence from North Greenland. *Geology* **13**, 542–546.

Henrich, R. 1992 Beckenanalyse des Europäischen Nordmeeres: Pelagische und glaziomarine Sedimentflüsse im Zeitraum 2.6 Ma bis rezent. *Habil.-Thesis, Fac. Nat. Sci.* Kiel University.

Herman, Y. & Hopkins, D. M. 1980 Arctic Ocean climate in late Cenozoic time. *Science, Wash.* **209**, 557–562.

Hinz, K., Eldholm, O., Block, M. & Skogseid, J. 1993 Evolution of North Atlantic volcanic continental margins. In *Petroleum Geology of Northwest Europe: Proc. 4th Conf.* (ed. J. R. Parker), pp. 901–913. London: Geological Society.

Jansen, E. & Sjøholm, J. 1991 Reconstruction of glaciation over the past 6 million years from ice-borne deposits in the Norwegian Sea. *Nature, Lond.* **349**, 600–604.

Downloaded from rsta.royalsocietypublishing.org

Jansen, E., Bleil, U., Henrich, R., Kringstad, L. & Slettemark, B. 1988 Palaeoenvironmental changes in the Norwegian Sea and Northeast Atlantic during the last 2.8 m.y.: Deep-Sea Drilling Project/Ocean Drilling Program Sites 610, 642, 643 and 644. *Palaeoceanography* **3**, 563–581.

Koltermann, K. P. 1987 Tiefenzirkulation der Grönland-See als Folge des thermohalinen Systems des Europäischen Nordmeeres. Ph.D. thesis. Faculty of Natural Sciences, Hamburg University.

Kulm, L. D., *et al.* 1973 *Init. Reports* DSDP **18**. Washington, DC: US Government Printing Office.

Meincke, J. 1983 The modern current regime across the Greenland–Scotland Ridge. In *Structure and development of the Greenland–Scotland Ridge: new methods and concepts* (ed. M. H. P. Bott, S. Saxov, M. Talwani & J. Thiede), pp. 673–650. New York: Plenum.

Mudie, P. J. & Helgason, J. 1983 Palynological evidence for Miocene climatic cooling in eastern Iceland about 9.8 Myr ago. *Nature, Lond.* **303**, 689–692.

Myhre, A. M. *et al.* 1995 *Proc.* ODP *Init. Rep.* **151**. College Station, TX: Ocean Drilling Program.

Nelson, R. E. & Carter, L. D. 1985 Pollen analysis of a late Pliocene and early Pleistocene section from the Gubik Formation of Arctic Alaska. *Quat. Res.* **24**, 295–306.

Quadfasel, D., Gascard, J.-C. & Koltermann, K.-P. 1987 Large-scale oceanography in Fram Strait during the 1984 Marginal Ice Zone Experiment. *J. Geophys. Res.* **92** (C 7), 6719–6728.

Raymo, M. E., Rind, D. E. & Ruddiman, W. F. 1990 Climatic effects of reduced Arctic sea ice limits in the GISS II General Circulation Model. *Palaeoceanography* **5**, 367–382.

Rea, D. K., Basov, L. A. & Janecek, T. R. 1993*a* North Pacific Transect. *JOIDES J.* **19**, 21–28.

Rea, D. K., *et al.* 1993*b* *Proc.* ODP *Init. Rep.* **145**. College Station, TX: Ocean Drilling Program.

Repenning, C. A., Brouwers, E. M., Carter, L. D., Marincovich, L. Jr & Ager, T. A. 1987 The Beringian anchestry of Phenacomys Criceridae) and the beginning of the modern Arctic Ocean borderland biota. *US Geol. Surv. Bull.* **1687**, 1–28.

Ruddiman, W. F. & JOIDES NAAG-DPG 1991 North Altantic–Arctic Gateways. *Joides J.* **17**, 38–50.

Ruddiman, W. F. & Raymo, M. E. 1988 Northern Hemisphere climatic régimes during the past 3 Ma: possible tectonic connections. *Phil. Trans. R. Soc. Lond.* B **318**, 411–430.

Ruddiman, W. F., Raymo, M. & McIntyre, A. 1986 Matuyama 41 000-year cycles: North Atlantic Ocean and Northern Hemisphere ice sheets. *Earth planet. Sci. Lett.* **80**, 117–129.

Talwani, M., *et al.* 1976 DSDP *Leg 38 Init. Rep.* **38**. Washington, DC: US Government Printing Office.

Thiede, J., Eldholm, O. & Taylor, E. 1989 Variability of Cenozoic Norwegian Greenland Sea palaeoceanography and Northern Hemisphere palaeoclimate. In *Proc.* ODP*, Sci. Res.* (ed. O. Eldholm *et al.*), **104**. College Station, TX: Ocean Drilling Program, pp. 1067–1118.

Thiede, J. & NAD Science Committee 1992 The Arctic Ocean record: key to global change (initial science plan). *Polarforschung* **61**, 1–102.

Warnke, D. A. & Hansen, M. E. 1977 Sediments of glacial origins in the area of DSDP leg 38 (Norwegian Greenland seas): Preliminary results from Sites 336 and 344. *Naturforsch. Ges. Freib. Breisgau Ber.* **67**, 371–392.

Wolf, T. C. W. & Thiede, J. 1991 History of terrigenous sedimentation during the past 10 m.y. in the North Atlantic (ODP Legs 104, 105, and DSDP 81). *Mar. Geol.* **101**, 83–102.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES