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1. NORTH ATLANTIC–ARCTIC GATEWAYS[1]

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ABSTRACT

The Arctic and subarctic seas exert major influences on global climate and ocean systems. Understanding the causes and consequences of global climatic and environmental change is an important challenge for humanity. The high-northern-latitude oceans are of high relevance for this task, as they directly influence the global environment through the formation of permanent and seasonal ice covers, transfer of sensible and latent heat to the atmosphere, deep-water renewal, and deep-ocean ventilation, all of which control or influence both oceanic and atmospheric chemistry. Thus, any serious attempt to model and understand the Cenozoic variability of global climate must take into account the paleoenvironmental changes in the Arctic and subarctic deep-sea basins. Because of the permanent sea-ice cover, the Arctic Ocean is the only major ocean basin that so far had not been drilled by either the Deep Sea Drilling Project (DSDP) or the Ocean Drilling Program (ODP). The North Atlantic-Arctic Gateways (NAAG) effort of the Ocean Drilling Program is an important contribution to solving these problems.

Four areas of the North Atlantic-Arctic Gateways province were drilled during Leg 151 from July to September 1993. The sedimentary sections collected were investigated to unravel the history of surface and bottom waters in the Norwegian-Greenland Sea and in the Arctic Ocean. These water masses are connected through the narrow gateway between Svalbard and Greenland, the Fram Strait. The paleoceanographic history between these two polar to subpolar Northern Hemisphere deep-sea basins is one of the keys to understanding the Cenozoic climate evolution. Yermak Plateau and Fram Strait are also relatively young geological features whose origin is not known in the detail necessary for resolving their impact on the changes of current patterns, and whose basement age and nature as well as subsidence history have to be established by deep ocean drilling.

Site 907 is located on the eastern Iceland Plateau and was drilled to obtain Quaternary and Neogene biogenic and terrigenous sediment sequences with a detailed paleoenvironmental record.

Sites 908 and 909 are located in the southern Fram Strait and represent a depth transect with a shallow (on Hovgaard Ridge) and deep (on the Greenland Sea-Arctic Ocean sill depth) location to study the history of the water exchange between the two adjacent deep-sea basins as well as the opening and tectonic history of Fram Strait.

Sites 910, 911, and 912 were drilled on the Yermak Plateau to study the origin of its basement and its history of subsidence, and to establish the history of the truly Arctic marine paleoenvironment along a depth transect as well as its interaction with late Cenozoic Arctic ice sheets.

Site 913, located at the East Greenland Margin, was drilled to study the history of the East Greenland Current and the evolution of the Greenland Basin.

INTRODUCTION

During Leg 151 (July to September 1993), the *JOIDES Resolution* of the Ocean Drilling Program (ODP) voyaged to the Norwegian-Greenland-Iceland Sea, to Fram Strait, and to the marginal Arctic Ocean, higher into waters of the northern latitudes than ever before. The drill ship was escorted by the Finnish icebreaker *Fennica*. Leg 151 opened completely new scientific perspectives for the fourth dimension of Arctic geoscientific research and represents an important historic step in the scientific exploration of the Arctic.

True oceanographic study of the Arctic began with the exploratory voyages of the German Carl Coldewey, who investigated the nature of the ice margin along East Greenland and in the Fram Strait in 1868, and was followed by the Norwegian Fridtjof Nansen's famous expedition into the eastern Arctic ice in 1893–1896, on his newly built polar research vessel *Fram*. These expeditions were organized, respectively, 125 and 100 years before the epic voyage of the *JOIDES Resolution* into the northern polar oceans, during the 25th year of deep-sea drilling operations. Bøggild (1906) described the first bottom samples from the "North Polar Sea," which had been taken by Nansen's *Fram* expedition. Nansen also laid a base for the first bathymetric map of the Norwegian-Greenland Sea and Arctic Ocean, in a clear conceptual illustration of the North Atlantic-Arctic Gateways (see Frontispiece).

Below, we will (1) describe the basic physiography of the modern deep sea basins, and their plate tectonic and volcanic history, (2) outline the modern oceanography of water masses along pathways between the Arctic and North Atlantic oceans, (3) evaluate the present knowledge of paleoceanographic and paleoenvironmental changes of these water masses, and (4) outline the drilling objectives of Leg 151.

Physiography and Plate Tectonic Evolution

The physiography of the Norwegian-Greenland Sea and the southeastern part of the Arctic Ocean reflects the plate tectonic evolution of the area (Figs. 1, 2, and 3). The southern boundary of the Norwegian-Greenland Sea is defined by the shallow transverse aseismic ridge between Greenland, Iceland, and Scotland. North of this ridge the main features are the passive rifted and sheared margins surrounding the ocean basins, with three prominent marginal plateaus: the Vøring and Yermak plateaus and Morris Jesup Rise. The mid-ocean ridge system, offset by major transforms, defines the plate boundary between the American and Eurasian plates and has been described in detail by Eldholm et al. (1990). The plate boundary and deep basins divide naturally into three regions separated by first order fracture zone systems (Figs. 2 and 4). The southern region lies between the Greenland-Scotland-Ridge and the Jan Mayen Fracture Zone. The central part is bounded by the Jan Mayen and Greenland-

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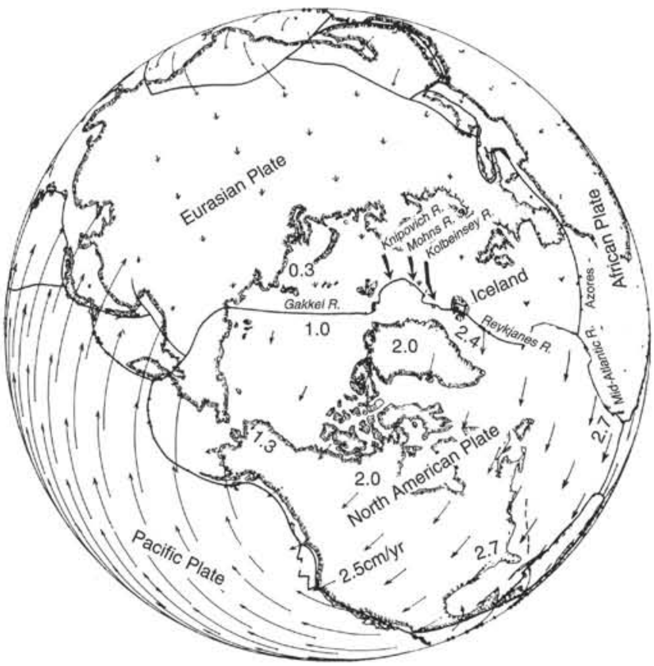

Figure 1. The northern perspective: Northern Hemisphere plate boundaries and movements relative to a fixed Eurasian Plate. Plate movements in cm/yr (Vogt, 1986b).

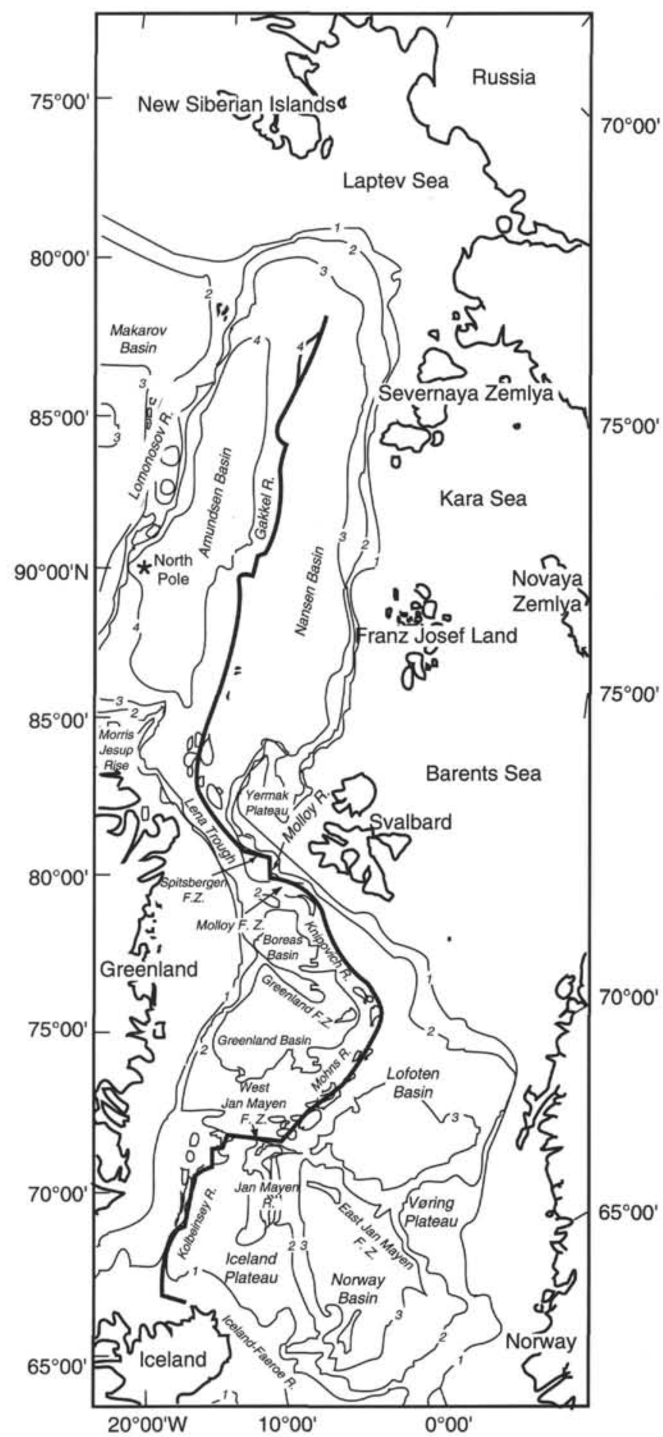

Figure 2. Main physiographic and structural elements in the Norwegian-Greenland Sea and eastern Arctic Ocean (Eldholm et al., 1990). Simplified bathymetry from Perry et al., 1985 (in km).

Senja fracture zones, whereas the northern region lies between the Greenland-Senja and Spitsbergen fracture zones. The transition zone between the Greenland Sea and Arctic Ocean is not known in detail but has an extremely complicated tectonic evolution, which is reflected in the rough bathymetry of the area (Figs. 5 and 6). Shallow features like the Jan Mayen and Hovgaard Ridge microcontinents (Figs. 2 and 6) have been created by jumps or readjustments in the spreading axis (Talwani and Eldholm, 1977; Myhre et al., 1982).

Ridges and Transforms

In the Norwegian-Greenland Sea, the present-day mid-ocean-ridge spreading axis consists of three active segments from South to North (Fig. 2). The Kolbeinsey Ridge continues from Iceland to the Western Jan Mayen Fracture Zone and transects the Iceland Plateau. The Mohns Ridge is centrally located in the ocean basin and divides the Norwegian Sea into the Greenland and Lofoten basins. It continues into the Knipovich Ridge, which is situated in the eastern part of the Greenland Sea and abuts the lower slope of the Svalbard Margin West of Spitsbergen. The present-day plate boundary between the Knipovich Ridge in the Greenland Sea and the Gakkel Ridge in the Eurasia Basin is probably a complicated system of short spreading axis elements and transform faults (Fig. 5), but is still not completely understood (Vogt et al., 1979; Perry et al., 1986; Eldholm et al., 1990; Eldholm, 1990; Thiede et al., 1990b). The spreading axis is transformed by the Spitsbergen Transform, which consists of the Molloy and Spitsbergen fracture zones and the Molloy Ridge, into the Gakkel Ridge centrally situated in the Eurasia Basin, the easternmost part of the Arctic Ocean. Detailed bathymetric maps have been produced and described by Perry et al. (1985; 1986) and Perry (1986) (see Fig. 3).

To the South, the shallow Greenland-Scotland Ridge is an anomalous, partly emerged, volcanic aseismic ridge that transects the North Atlantic Ocean from the East Greenland shelf to the northern Scottish shelf. The Greenland-Scotland Ridge (Bott et al., 1983) defines the boundary between the main North Atlantic Ocean and the Norwegian-Greenland Sea, and is part of the large volcanic province extending from Baffin Island across Greenland, the Faeroes, and to the British Isles. The Denmark Strait between the East Greenland and Iceland shelves has a sill depth of about 600 m where the two margins almost merge. The East Greenland continental margin broadens to about 250 km over the ridge with water depths between 200 and 400 m, and with no well-defined shelf break (Larsen, 1983). The Iceland

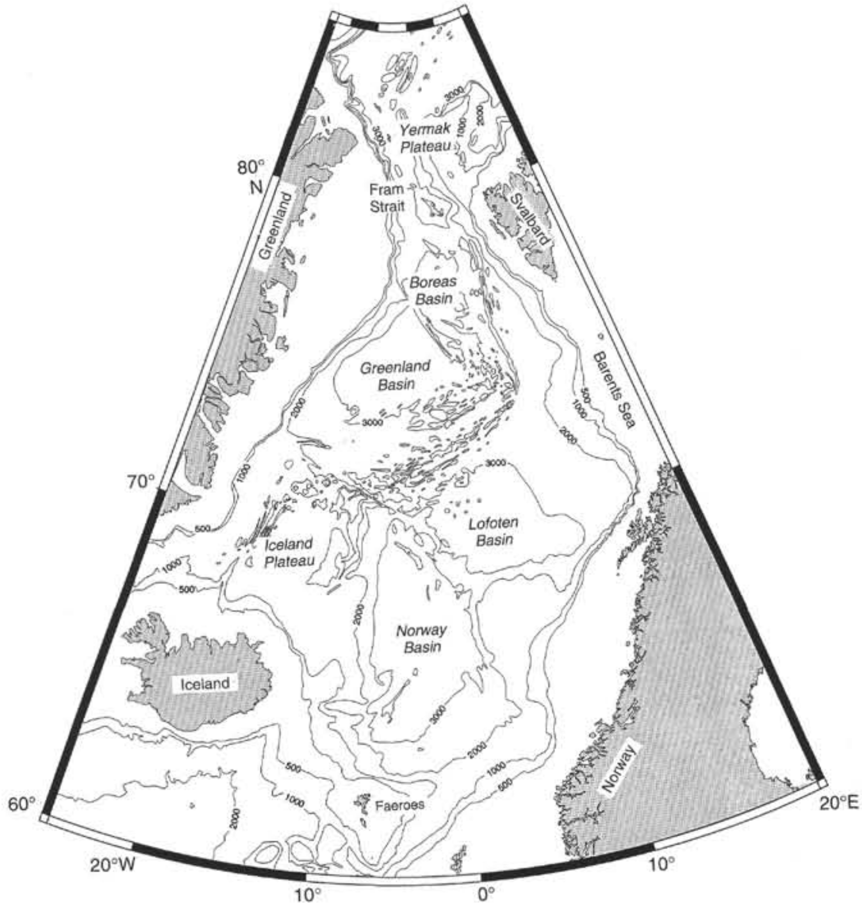

Figure 3. Bathymetry of the Nordic Seas (Perry et al., 1980).

Shelf toward the Denmark Strait, however, is marked by a clear shelf break with depths to 200 m. The two shelves are divided by the 20- to 30-km-wide Denmark Strait Channel. The ridge between Iceland and the Faeroes is nearly 300 km long and about 200 km wide. The ridge forms a plateau-like, 400- to 600-m-deep area having a smooth crest and separated from the Icelandic and Faeroe shelves by short bathymetric scarps (Bott, 1983). Between the Faeroe and Scottish shelves lies the 900- to 1000-m-deep Faeroe-Shetland Channel system.

The southernmost part of the Kolbeinsey Ridge is a continuation of the Iceland shelf and slope and has no distinct rift valley. The middle part, however, roughly between 69° and 70°45′N, is characterized by parallel ridges ranging in depth from 370 to 1400 m. An axial rift valley also is developed and varies in depth from 1000 to 1400 m. Between 70°50′ and 71°40′N the ridge consists of shallow banks, and no rift valley is observed (Perry, 1986). The Kolbeinsey Ridge ends at the Western Jan Mayen Fracture Zone. The fracture zone is a linear transverse depression of the ocean floor and has been mapped for over 500 km with an average depth of 2200 m. It cuts across the northern slope of the volcanic Jan Mayen Island. The offset between the Kolbeinsey Ridge and the Mohns Ridge along the Jan Mayen Fracture Zone is more than 185 km (Fig. 2).

The Mohns Ridge (Frontispiece), situated between the Lofoten and Greenland basins, consists of a series of linear, symmetric flank ridges in water depths of 1000–2000 m and exhibits a well-developed rift valley between 2600 and 3400 m (Perry, 1986). Continuity from the Mohns Ridge rift valley into the rift valley of the Knipovich Ridge (Talwani and Eldholm, 1977) has been observed. The latter has a prominent central rift, 3200–3400 m deep, somewhat deeper than the Mohns Ridge, and crestal mountains between 900 and 1600 m that stand higher on the western side of the ridge. The bathymetry is characterized by groups of seamounts arranged in an en-echelon pattern, which is not typical for mid-ocean ridges (Perry, 1986). The location of the Knipovich Ridge is strongly asymmetrical in the Greenland Sea (Figs. 2 and 3), and the continental slope off Svalbard extends to the axial mountains of the ridge with sediments overflowing into the rift valley. Bathymetrically, the rift ends at 78.5°N, but continues as a buried feature turning North-Northwest (Eldholm and Windisch, 1974).

The plate movement is taken up by the Molloy Fracture Zone, which appears as a depression. Seismic data show that it is part of a buried fault trough striking 300°. The deepest part of this depression, the Molloy Deep, is 5607 m (Figs. 5 and 6) (Perry, 1986; Thiede et al., 1990b), which is the greatest depth recorded in the Norwegian-Greenland Sea and Arctic Ocean. The Molloy Deep appears to be a nodal basin between the Molloy Fracture Zone and the Molloy Ridge. Perry (1986) suggested the Molloy Ridge spreading axis is located in a 70-km North-trending trough with water depths of 3800 m, whereas Eldholm et al. (1990) placed it West of the trough at the crest of the flanking seamounts. Vogt et al. (1981), however, defined it even farther West in a ridge-and-trough topography province. This has been supported by detailed SeaBeam and high-resolution seismic studies by Thiede et al. (1990b). The Molloy Ridge (Figs. 5 and 6) continues into the Spitsbergen Fracture Zone, which has a strike of 308° and a maximum water depth of 4532 m. There appears to be a continuous depression, the Lena Trough, between the Spitsbergen Fracture Zone and the Gakkel Ridge. The continuity between the Lena Trough-Gakkel Ridge is geometrically similar to the Mohns-Knipovich Ridge transition (Eldholm et al., 1990).

The Gakkel Ridge extends across the Eurasia Basin almost to the North Asian continental margin where, at 79°N, it ceases to be reflected in the bathymetry (Grachev and Naryshkin, 1978). The floor

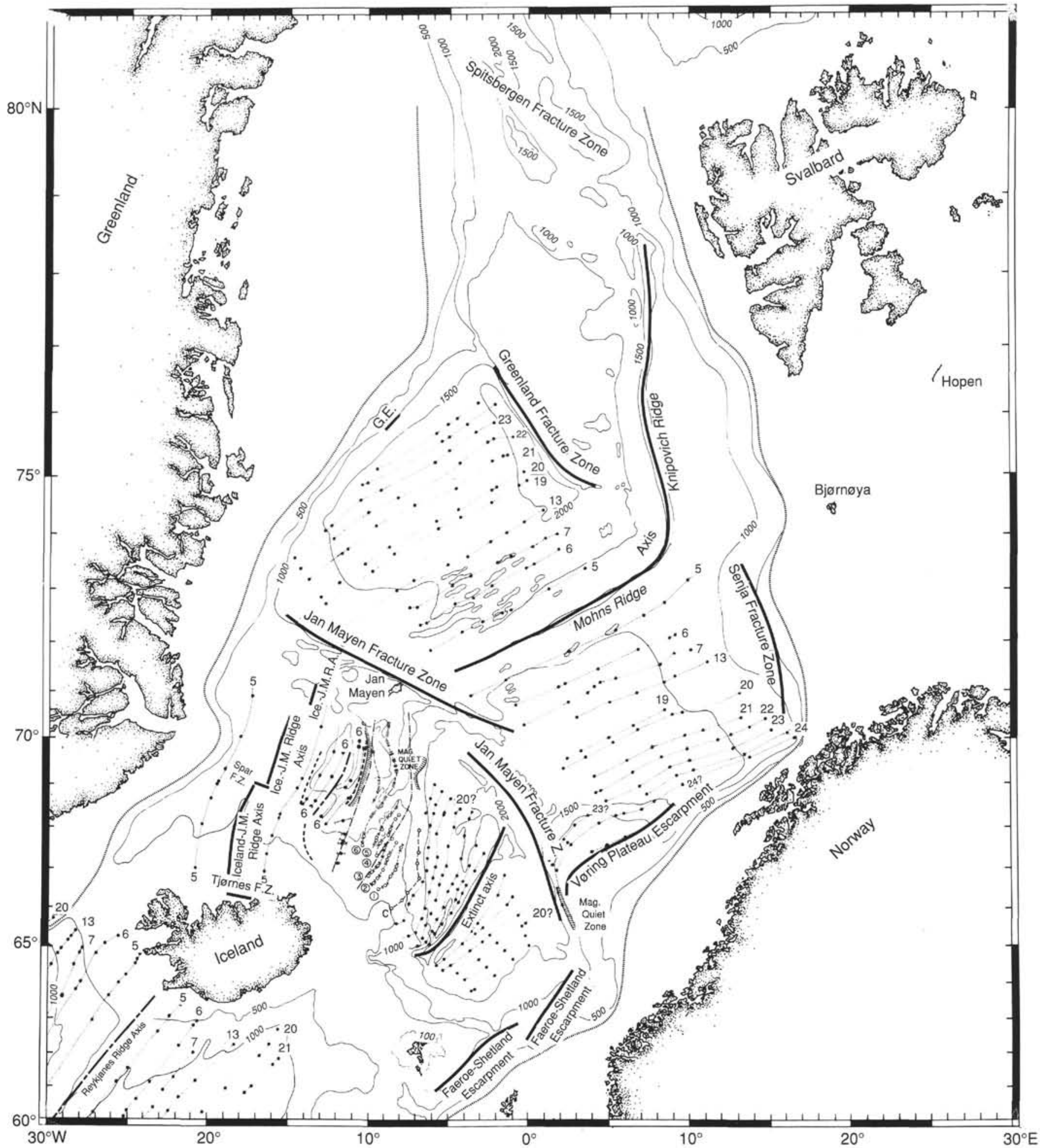

Figure 4. Identified magnetic lineations in the Norwegian Sea (Talwani and Eldholm, 1977). G.E. = Greenland Escarpment.

of the rift valley generally lies at depths between 3500 and 5500 m, with axial mountains rising between 2000 and 2500 m above the rift valley floor (Feden et al., 1979; Vogt et al., 1979; Perry et al., 1986). The Gakkel Ridge rift valley is the deepest and slowest active spreading axis in the world ocean.

Only the western part of the Jan Mayen Fracture Zone is an active transform today and strikes 110°; the eastern part is inactive and is striking at 130°–150° toward the base of the Vøring Plateau (Fig. 4). It has a Southwest-facing escarpment that reflects the difference in basement elevation between the Lofoten and Norway basins.

Both the Greenland and Senja fracture zones are inactive today. The Senja Fracture Zone has no bathymetric expression, being buried under a thick sequence of sediments derived from the Barents Sea. Originally, it was defined by Talwani and Eldholm (1977) by means

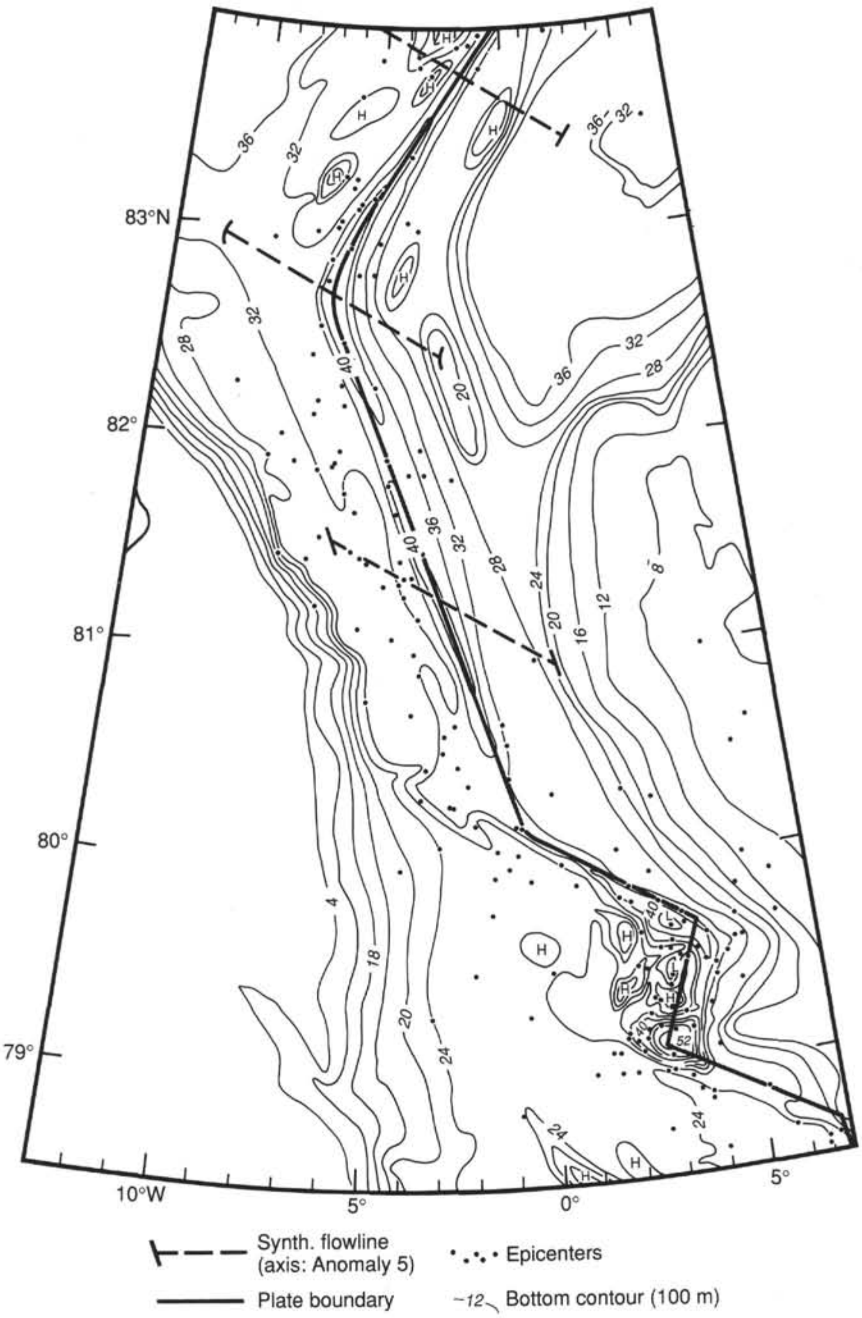

Figure 5. The plate boundary region between Knipovich Ridge and Gakkel Ridge, the Spitsbergen Transform. Bathymetry contour interval 400 m, from Perry et al. (1980; 1985). Earthquake epicenters and flowlines from Talwani and Eldholm (1977).

of the associated major gravity anomaly. The Greenland Fracture Zone (Frontispiece), however, has a distinct bathymetric expression. It is an elongated ridge extending southeastward from the Greenland continental slope, becoming more easterly at the southeastern end. The southern flank of the ridge appears as a steep escarpment in contrast to the northern, more gentle slope. The crest of the ridge lies mainly within the 2000-m isobath with the shallowest part at 1475 m. Perry (1986) suggested that the detailed morphology could be interpreted as if the ridge segments are arranged in an en-echelon pattern.

Continental Margins

The continental margins surrounding the Norwegian-Greenland Sea and in the adjacent Arctic Ocean display characteristics typical of formerly glaciated shelves. They are characterized by deep shelves with shelf edges between 200 and 500 mbsl, in addition to longitudinal and transverse channels, numerous banks, and depressions reflecting the glacial influence (Holtedahl, 1993). The detailed bathymetry and morphology of the East Greenland continental margin is not known in great detail, especially in the northern part, owing to the permanent ice cover. A broad shelf is developed to the North that narrows southward toward the aseismic Greenland-Scotland Ridge and the Denmark Strait (Fig. 3). The East Greenland shelf has typical water depths in the range of 250–350 m, sometimes with shallow banks situated at the outer shelf. Transverse channels originate from the major fjords with water depths in the range of 400–600 m, with some as deep as 1000 m (Larsen, 1990).

The northern Greenland continental margin, however, is one of the least known in the entire Arctic Ocean. The southeasternmost part

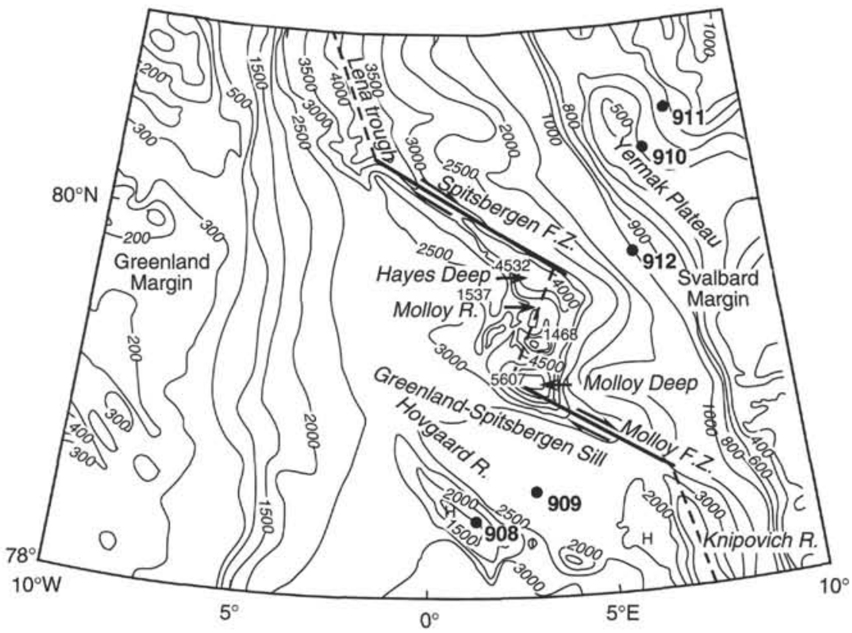

Figure 6. Bathymetric map of the Fram Strait showing drilled sites in the Fram Strait and on the Yermak Plateau (from Perry et al., 1980; 1986; modified by Thiede et al., 1990b). F.Z. = Fracture zone.

of this margin, the Wandel Sea, is characterized by an extremely narrow margin where the continental shelf is only 30–60 km wide, and the shelf edge lies in water depths of about 400 m. The continental slope has a steep gradient and continues directly into the Amundsen Basin and Lena Trough with water depths of more than 4000 m (Dawes, 1990). Farther North, outside Peary Land, the Morris Jesup Rise trends northeastward into the Amundsen Basin, extending the width of the margin to about 300 km. The rise is a broad structure about 200 km wide and is defined by the 2000-m isobath. According to Dawes (1990) the rise is characterized by steep, rugged sides. The eastern part has a linear edge, is flat-topped, and has a scarp of about 3 km into the Amundsen Basin.

The Barents Sea and Svalbard shelves, 70°–80°N, are transected by wide depressions extending to the 250- to 400-m-deep shelf edge. Two prominent transverse features, South and North of Bear Island, attain depths of 500–600 and 350 m, respectively, appearing as major drainage systems into the Lofoten Basin and Greenland Sea. The Spitsbergen Margin narrows to the North, and the shelf is only about 30 km wide at 79°N. Transverse channels West of Spitsbergen appear to be extensions of the fjord systems.

Physiographically the northern Svalbard Margin is divided into two different regions, the Yermak Margin including the Yermak Plateau to the Northwest, and the Hinlopen Margin between the plateau and 20°E (Fig. 7). The Yermak Margin has a narrow shelf with a wide slope characterized by an irregular slope gradient. The Yermak Plateau is a prominent arcuate marginal plateau extending for almost 400 km in a North-northwestward direction from the continental shelf of Svalbard. The plateau, defined by the 1000-m contour, is elevated more than 2000 m above the Arctic Basin to the North and East. The southern part of the plateau extends to approximately 82°N and is enclosed by the 700-m isobath with a series of shallow banks along the crest having water depths of about 500 m (Sundvor et al., 1978). To the Southwest the plateau dips gently toward the Spitsbergen Transform. The topography of the eastern part is more blocky and rough, reflecting the outcrop of the opaque basement reflectors and major faulting down toward the East into the deep basin, together with canyons cutting into the eastern flank of the plateau. The northernmost part of the plateau strikes Northeast with minimum depths of 700 m and is parallel to the Gakkel spreading axis.

The Iceland Plateau

The Iceland Plateau is a shallow, flat-floored platform East of the Kolbeinsey Ridge, defined by the 1800-m contour, gently increasing in depth away from the ridge. To the North the plateau is bounded by the western segment of the Jan Mayen Fracture Zone separating the plateau from the deep Greenland Basin; to the South it becomes shallower up toward the Iceland shelf. The eastern part of the plateau drops off into the Norway Basin along an almost 620-km-long North-South line. The slope begins at the 1800-m isobath and terminates at the 3400-m isobath with an average gradient of 1:50. Although Perry (1986) included the shallow linear Jan Mayen Ridge as morphologically a part of the Iceland Plateau, Talwani and Eldholm (1977) did not. There is a fundamental difference in origin of the major part of the Iceland Plateau, underlain by Neogene oceanic crust, and the continental origin of the Jan Mayen Ridge. The flat-topped Jan Mayen Ridge is 275 km long and up to 110 km wide just South of Jan Mayen island. The ridge plunges and decreases in width southward where it is defined by the 1000-m isobath. The western slope of the Jan Mayen Ridge is steep and narrow. The eastern part of the ridge runs parallel to the slope of the plateau while the eastern part of the ridge runs parallel to the slope of the Iceland plateau. The island of Jan Mayen, with its young (~500 ka; Fitch et al., 1965) volcanic origin, is not regarded as a part of the Jan Mayen Ridge.

The Basins

The Norway Basin (Fig. 3 and Frontispiece), one of the major basins in the Norwegian-Greenland Sea and the deepest, is bounded by the Greenland-Scotland Ridge, Iceland Plateau, the Eastern Jan Mayen Fracture Zone, and the lower slope of the Norwegian Margin. The floor of the basin lies between 3200 and 3600 m and is transected by a set of parallel seamounts approximately 28 km apart dividing the Norway Basin into two parts. The central trough of the seamount chain is more than 3800 m deep and represents the extinct Ægir spreading axis active from Anomaly 24 to Anomaly 7 time (Fig. 4).

Farther North, the Greenland and Lofoten basins are situated symmetrically about the Mohns Ridge, both with developed abyssal plains (Frontispiece). The Lofoten Basin has an average water depth

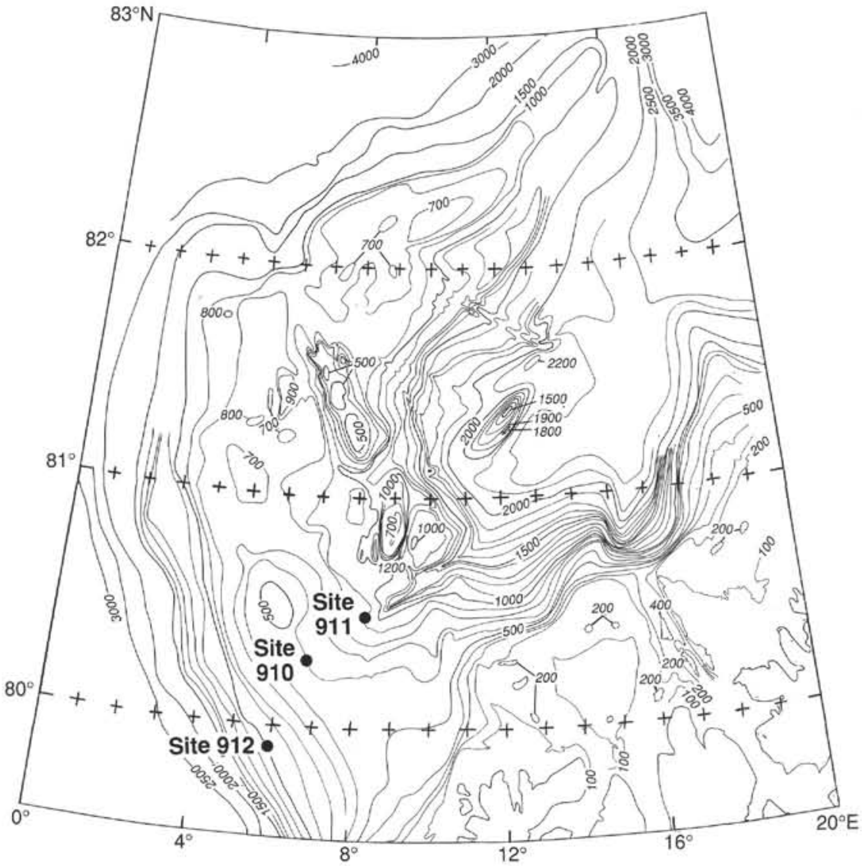

Figure 7. Bathymetric map of the Yermak Plateau showing drilled sites on the plateau. Contours in uncorrected meters, assuming a water velocity of 1463 m/s (Sundvor et al., 1982a).

of 3200 m, and the basin floor dips gently from the Barents Sea Margin toward the Southwest. The Greenland Basin, however, dips from Southwest to Northeast, and the basin floor lies between the 3600- and 3700-m isobath (Perry, 1986). The 400-m difference in water depth is probably due to differences in the influx of sediments. An isolated seamount in the southeastern part of the Greenland Basin, the Vesteris Bank, rises to 133 m below sea level with a vertical relief of more than 2800 m, its age younger than 100 ka (J. Thiede, pers. comm., 1993).

The Boreas Basin is separated to the South from the Greenland Basin by the Greenland Fracture Zone. The smooth abyssal plain lies at approximately 3000–3200 m, about 600 m shallower than the Greenland Basin. The difference in water depth has been ascribed to a younger crustal age of the Boreas Basin (Eldholm and Windisch, 1974). The small abyssal plain terminates abruptly against the steep southern side of the Hovgaard Ridge.

Hovgaard Ridge

The Hovgaard Ridge was originally defined by Johnson and Eckhoff (1966) and named the Hovgaard Fracture Zone. The Southeast-trending ridge is situated just North of 78°N, and consists of two morphologically different segments offset and separated by a trough (Figs. 6 and 8). The bathymetric map (Eldholm and Myhre, 1977) shows the northern element with a minimum water depth of 1171 m and the southern with a minimum of 1307 m. Furthermore, the northern element appears as an elongated, flat-topped, ridge-like feature with a steep southward-facing escarpment, whereas the southern part is more like a peak. The Hovgaard Ridge separates the Boreas Basin from a small basin or terrace to the North having an average depth of about 2500 m, the Greenland-Spitsbergen Sill (Fig. 6). It appears as a Northwest-Southeast trending dam-like bathymetric structure. The sill dips to the Northwest, where it reaches its maximum depth of 2650 m at 79°N, 1°W (Perry, 1986).

Plate Tectonic Evolution and Volcanic History

The major parts of the passive margins surrounding the Norwegian-Greenland Sea lie within the North Atlantic Volcanic Province (NAVP) extending from the Charlie Gibbs Fracture Zone at about 55°N to the Svalbard Margin at 75°N. The margins can be classified as volcanic rifted or sheared, created in early Tertiary times (Hinz et al., 1993). These volcanic margins are some of the best studied in the world, both by geophysical data and by scientific drilling (DSDP Leg 38, ODP Legs 104 and 152). The Norwegian and East Greenland margins have undergone several post-Caledonian extensional episodes in the late Paleozoic and Mesozoic before complete continental separation in the earliest Eocene. The various phases have been documented from East Greenland's onshore geology, from seismic data and from commercial wells drilled on the Norwegian margin. These data show that there has been a depositional area between Norway and Greenland since the Carboniferous and at least four distinct rift phases can be observed (Brekke and Riis, 1987; Larsen, 1987; Ziegler, 1988; Dore, 1991; Faleide et al., 1992). Off Norway, it appears that the subsequent rift pulses and basin development migrated westward through time (Skogseid et al., 1992). This is also the case further North where the late Paleozoic rifting extended into the Barents Sea proper, whereas the Mesozoic rifting gradually moved West to a

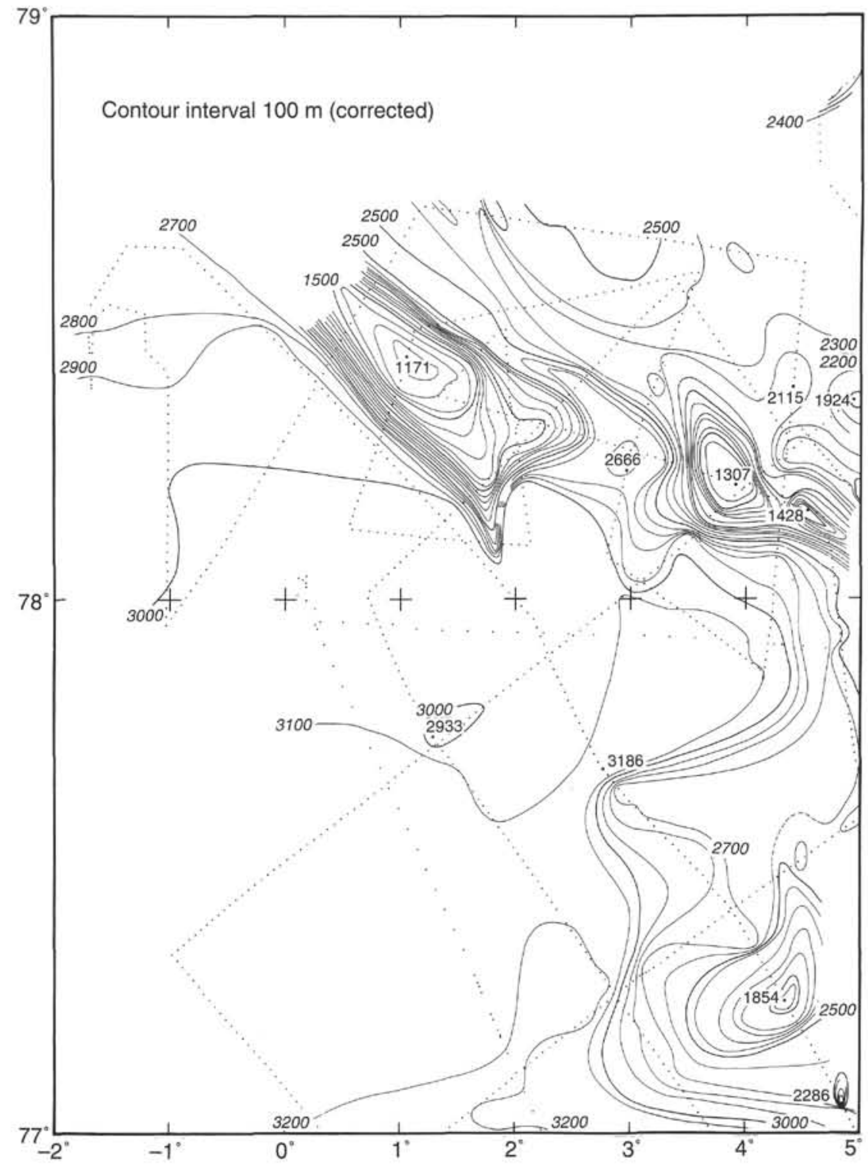

Figure 8. Bathymetric map over the Hovgaard Ridge. Sounding control shown by dotted lines (Eldholm and Myhre, 1977).

position between Svalbard and Greenland (Faleide et al., 1992). The deep basins in the southwestern part of the Barents Sea imply that the underlying crystalline continental crust is extremely thin, suggesting that the crustal extension almost reached the seafloor spreading stage (Jackson et al., 1990).

The most important extensional phase before the final rifting and breakup in Late Cretaceous–Paleocene times is the Late Jurassic–Early Cretaceous rift event. Deep basins were formed off the mid-Norwegian margin and in the western Barents Sea, with a maximum Cretaceous sediment thickness ranging between 6 and 8 km in the Vøring and Møre basins outside mid-Norway, and probably more than 10 km in some of the basins in the western Barents Sea. According to Skogseid (1994), East Greenland was marginal to the central rift zone during the Late Jurassic–Early Cretaceous episode, which caused only minor basin formation there. In East Greenland the Cretaceous sediment thickness is less than 1.5 km (Birkelund and Perch-Nielsen, 1976; Marcussen et al., 1987). The Late Cretaceous rifting episode has been observed over large areas associated with the North Atlantic Volcanic Province, the Rockall Trough, the Norwegian and Northeast Greenland continental margins (Hinz et al., 1993), western Barents Sea, and in addition, the Labrador-West Greenland continental margins.

The last extensional episode was initiated in the latest Cretaceous at about the Campanian–Maastrichtian time leading to the final breakup and continental separation at the Paleocene/Eocene boundary. There is evidence for a late syn-rift extensive uplift of the central rift before the igneous activity. The uplift created a land area that acted as a source for Paleocene sediments deposited into the bordering epicontinental seas. In the Vøring Basin the Paleocene sediment, which is mainly from a western source region, exceeds a thickness of 1500 m.

The rift episode lasted about 18 m.y. (Skogseid et al., 1992), and the final breakup was accompanied by the emplacement of both the onshore flood basalts and massive extrusive complexes along the continent-ocean transition on the rifted continental margins (Fig. 9). The volcanic activity along the more than 2600-km-long plate boundary was extremely short lived, lasting for about 3 m.y. The igneous activity affected a more than 300-km-wide rift (Skogseid, 1994), and had a profound influence on the North Atlantic region, with respect to both structural and paleoenvironmental evolution (Eldholm and Thomas, 1993). The volcanic activity can be divided into a short-lived or transient longitudinal part called the Reykjanes-Mohn Line, and a more persistent transverse part, active for the last 60 m.y., referred to as the Iceland Hotspot, which created the Greenland-Scotland Ridge.

The synrift uplift, extensive volcanism, and segmentation of the plate boundary created large positive areas and shallow basins. The volcanic surge, however, abated shortly after seafloor spreading

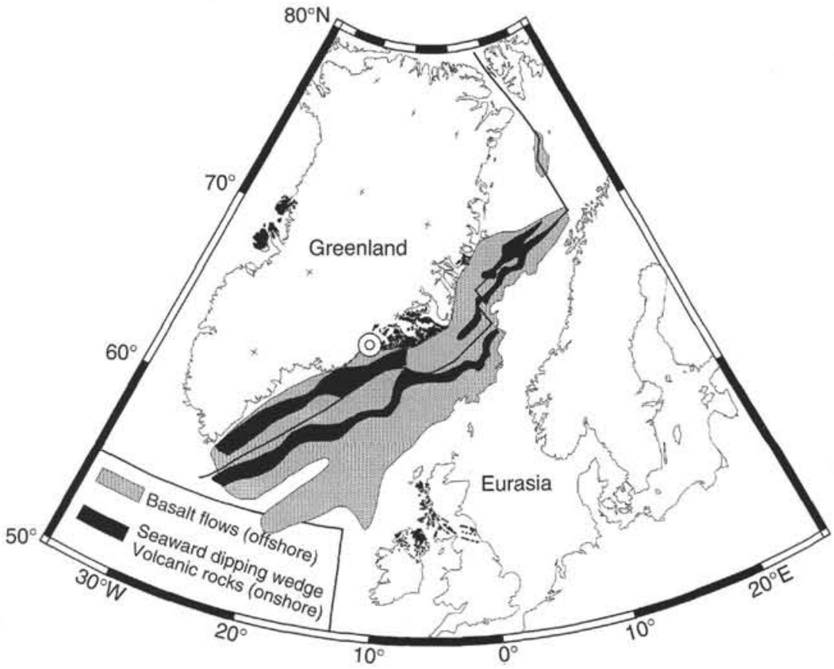

Figure 9. Extent of North Atlantic Volcanic Province (NAVP) at magnetic Anomaly 23 time (Eldholm and Thomas, 1993). Hot-spot location (double circle) from White and McKenzie (1989).

started; the spreading axis subsided below sea level, and normal seafloor spreading was created in early Eocene. The positive areas were rapidly eroded and subsided below sea level. Separate deep basins formed in the middle Eocene but were probably isolated to a large extent throughout the Paleogene (Eldholm, 1990).

The incipient plate boundary between Eurasia and Greenland comprises two structural mega-lineaments: (1) The North Atlantic rift zone, or the Reykjanes-Mohn Line, between the Charlie Gibbs and Greenland Senja fracture zones; and (2) a regional shear zone, the De Geer Zone (Harland, 1969), between Svalbard and Greenland, continuing into the Arctic Ocean along the northern Greenland and Canadian continental margins. The two lineaments intersect near the oldest part of the Senja Fracture Zone. Hence, the Norwegian and Greenland Sea margins are structurally composed of predominantly Northeast-trending rifted segments in the southern region, and an approximately North-Northwest-trending complicated pattern of sheared, rifted, and shear/rifted margin segments in the northern region.

Both the segmentation of the ocean basins and the structural margin framework are governed by the plate tectonic evolution of the Norwegian-Greenland Sea, which comprises two main stages (Fig. 10) (Talwani and Eldholm, 1977). From breakup (Anomaly 24R) and throughout the Eocene, Greenland moved as a separate plate in a northwesterly direction with respect to Eurasia, as indicated by the azimuth of the Jan Mayen, Greenland, and Senja fracture zones. The Norway, Lofoten, and Greenland basins developed bordered by volcanic passive margins together with the southernmost part of the Greenland Sea. The northern Greenland Sea, however, had not started to open yet, and plate motion was achieved by continent-continent translation along a regional transform.

Deformation along the transform resulted in pull-apart basins to the South, while transpressional movements to the North resulted in the Spitsbergen Orogeny (Eldholm et al., 1987a), which produced the Spitsbergen Fold and Thrust Belt along the western coast of Svalbard. Today only the easternmost part of the deformed region is exposed on land, the remainder being downfaulted and buried beneath the continental margin.

The oldest seafloor magnetic spreading anomaly that has been identified in the Eurasian Basin is Anomaly 24, but according to Vogt et al. (1979), there is room for Anomalies 25–29 between Anomaly

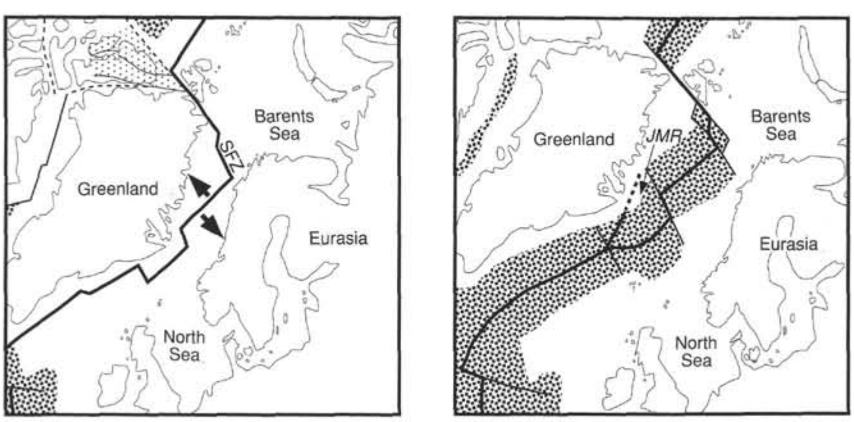

Figure 10. Schematic Norwegian-Greenland Sea plate tectonic reconstructions to the time of breakup (left), and to the time of change in relative plate motion near the Eocene-Oligocene transition, Anomaly 13 time (right) (Eldholm et al., in press). SFZ = Spitsbergen Fracture Zone; JMR = Jan Mayen Ridge.

24 and the lower part of the northern Barents Sea slope. This region is underlain by a broad shallow magnetic low that can be explained by either a suppression of the anomalies by sediment fill or some other process associated with initial rifting. The area also may be underlain with thinned, subsided continental crust. The Gakkel Ridge extends across the Eurasia Basin, passing into the Laptev Sea continental margin (Fig. 2). The ridge appears to have been a stable plate boundary throughout the Cenozoic, and the spreading rate has been very slow, varying between 1.03 and 0.33 cm/yr half rate (Vogt et al., 1981). The spreading rate in the Amundsen Basin between the Gakkel and Lomonosov ridges is 5%–10% slower than in the Nansen Basin South of the Gakkel Ridge (Fig. 2).

With respect to plate tectonic evolution, the Norwegian-Greenland Sea can be divided into three major provinces. The area between the Greenland-Scotland Ridge and the Jan Mayen Fracture Zone shows a complicated evolution with a westward migration of the spreading axis from the Norway Basin at about Anomaly 7 time, splitting off the Jan Mayen microcontinent from the East Greenland Margin (Fig. 4). An asymmetry in spreading in the Norway Basin has been suggested by Nunns and Peacock (1983) and Vogt (1986a), implying that the eastern flank of the Ægir Ridge spread faster than the western flank did. Fan-shaped magnetic anomalies between Anomaly 20 and the extinct axis also confirm the complicated evolution of the Norway Basin (Fig. 4). A possible short-lived spreading axis existed on the Iceland Plateau from about Anomaly 6B–5D (Talwani and Eldholm, 1977) before the present-day Kolbeinsey axis came into existence in the early/middle Miocene. According to Vogt et al. (1980) this intermediate axis does not exist and the new post-Anomaly 7 axis evolved into the present-day Kolbeinsey spreading axis.

The almost symmetrical position of the Mohns Ridge in the basins between the Jan Mayen and the Greenland-Senja fracture zones shows that only minor adjustments of the plate boundary have taken place in the southernmost part before Anomaly 23 in the early Eocene (Fig. 4). The spreading rate at the Mohns Ridge has varied between 1.29 and 0.64 cm/yr half rate. A difference in spreading rate between the Lofoten and Greenland basins also has been demonstrated by Vogt et al. (1982). They showed that the spreading in the Greenland Basin was 10%–15% faster than in the Lofoten Basin between opening and Anomaly 13 time (late Eocene–early Oligocene). Since Anomaly 13, the asymmetry has not been so significant and shows more local variations along the spreading axis.

The Greenland Sea appears to have a complicated evolution. The present-day spreading axis is situated close to the Svalbard Margin abutting the lower slope with sediments overflowing into the rift valley. Sundvor and Eldholm (1979) suggested a jump in the spreading axis to its present-day position at about 5–6 Ma. The present-day plate boundary between the Knipovich Ridge in the Greenland Sea and the Gakkel Ridge in the Eurasia Basin is known to be a complex system of short spreading axis elements and transform faults (Figs. 5 and 6)(Perry et al., 1985; Eldholm et al., 1990; Thiede et al., 1990b). Well-developed seafloor magnetic anomalies occur both in the Norwegian Sea and the Eurasian part of the Arctic Ocean, whereas in the Greenland Sea, a distinct seafloor spreading anomaly pattern is not observed (Fig. 11). A few weak anomalies have been observed and tentatively identified by Phillips et al. (unpubl. data) in the southern Greenland Sea; the northern part is almost without any magnetic signature. In addition to the lack of identifiable magnetic anomalies, the ice conditions make it difficult to acquire other geophysical data. Although the present-day plate boundary is known to some extent, the evolution of the Greenland Sea and the earlier transformation of the plate boundary into the Arctic Ocean is not well documented.

With the cessation of spreading in the Labrador Sea in the early Oligocene, Greenland became a part of the American plate, and the relative plate movements between the American/Greenland and Eurasian plates changed to a more West-Northwest direction. The opening of the Greenland Sea resulted in a complicated evolution of its eastern margin, consisting of two large shear-margin segments, the Senja Fracture Zone and the Hornsund Fault Zone, connected with a Northeast-trending volcanic rifted segment. The Hornsund Fault Zone, extending along the Svalbard Margin, acted as a shear zone during the Eocene. However, Myhre et al. (1982) and Myhre and Eldholm (1988) proposed that when this area came under extension in the early Oligocene, the western block of the Hovgaard Ridge, a continental sliver, was split off from the Svalbard continental margin. With the change in the plate movement at Anomaly 13 time (late Eocene–early Oligocene), the northern Greenland Sea started to open, but, according to Lawver et al. (1990) and Eldholm (1990), complete continental separation was not achieved before the middle or late Miocene.

Johnson and Heezen (1967) suggested that the two shallow Southeast-trending segments in the northern Greenland Sea were a fracture zone and named them the Hovgaard Fracture Zone (Fig. 8). Both the gravity and magnetic data shown by Eldholm and Myhre (1977) could indicate that the western and eastern segments have different crustal compositions. Gravity modelling of the western segment by Grønlie and Talwani (1982) showed that it does not resemble a typical oceanic fracture zone.

On top of the western ridge segment, small infilled sedimentary basins are cut by a major unconformity with a horizontally stratified sequence above (Myhre and Eldholm, 1988). Partly because of the strong seafloor multiple, only a few short reflector segments can be identified in the deeper part of the rift basins or beneath them. On the northeastern flank major sediment-filled rotated fault blocks are observed, in addition to some folding in the sediments that could have a Mesozoic age. This led Hinz et al. (1993) to suggest transpression in the area. Seismic lines across the Greenland-Spitsbergen Sill, Northeast of the Hovgaard Ridge, show that this terrace is underlain by a complicated system of basement blocks. Some of the blocks closest to the ridge could consist of stretched and thinned continental crust, making it difficult to define the continent/ocean transition between the Hovgaard Ridge microcontinent and the oceanic crust to the North.

Plate tectonic reconstructions indicate that the two segments of the Hovgaard Ridge may be part of a former plate boundary, as the Knipovich spreading axis appears to be a recent feature, perhaps only 5–6 m.y. old (Sundvor and Eldholm, 1979). The complicated pattern of the present-day plate boundary, the Spitsbergen Transform, may have extended farther South. The Hovgaard Ridge could have been part of the southern boundary of a complex region that offset the spreading ridge between the southern Greenland Sea and the Arctic Ocean in Oligocene to early Miocene times. Various models have been suggested for the timing of opening and seafloor spreading resulting in a deep-water connection of this gateway (Crane et al., 1982; Eldholm et al., 1987a; Lawver et al., 1990; Eldholm, 1990; and Kristoffersen, 1990). These models assign age ranges of early Oligocene to late Miocene.

Not only the opening of the Fram Strait, but also the timing of the evolution and subsidence of the Morris Jesup Rise and Yermak Plateau may have had a profound influence on the northern gateway between the Arctic and the Atlantic oceans. The formation of the two aseismic structures is closely linked to the complicated plate boundary, a possible triple-junction between the northern Greenland Sea and the Eurasian Basin under influence of an active hot spot. The evolution and subsidence of these structures have been controlled by the different plate tectonic adjustments among the Greenland, Eurasian, and American plates from the onset of rifting in the Eurasia Basin, seafloor spreading, and the extensive transform rift and adjustment in the northern Greenland Sea.

The northern passive margin of the Barents Sea and Svalbard archipelago developed in the early Tertiary, when seafloor spreading started in the Eurasia Basin, and the Lomonosov Ridge microcontinent was rifted off from the northern Eurasian continental margin

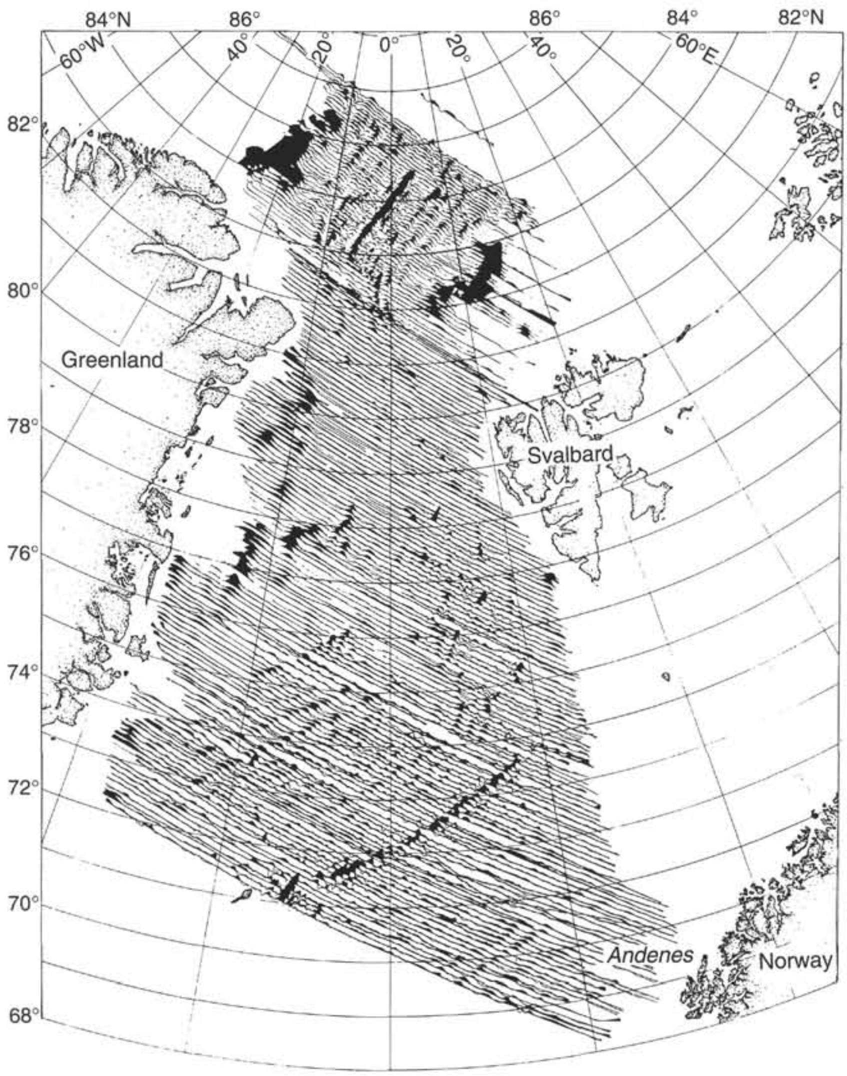

Figure 11. Aeromagnetic anomalies in the northernmost part of the Greenland and Lofoten basins, Greenland Sea, and southern Eurasia Basin. (Perry et al., 1980).

(Jokat et al., 1993). A flank uplift has been suggested on the basis of observed clinoforms in the northern Barents Sea, with outbuilding from a northern source, possibly the Lomonosov Ridge. Plate tectonic reconstructions of the Eurasia Basin before Anomaly 13 time do not leave enough space for large parts of the Morris Jesup Rise and the Yermak Plateau. Therefore, a volcanic origin has been suggested for these structures to allow the closing of the Eurasia Basin without any significant overlap.

Due to sea-ice cover, little geophysical information except aeromagnetic and bathymetric data exists about the Morris Jesup Rise; however, in addition to aeromagnetic data, a fairly extensive grid of multichannel-seismic data has been collected from the Yermak Plateau. The morphological division of the Yermak Plateau into two parts is also reflected in the magnetic field, which is extremely subdued over the southern part, whereas the northernmost part (North of 82°N) is characterized by high-amplitude magnetic anomalies, 700–900 nT, parallel to the seafloor magnetic spreading anomalies in the Eurasia Basin. Similar strong magnetic anomalies exist over the Morris Jesup Rise. (Fig. 11). Depth estimates to magnetic basement over the northern part by Kovacs and Vogt (1982) suggest magnetic source depths of less than 2 km.

Various institutions have collected a regional grid of multichannel reflection seismic data and refraction measurements over the southern part of the Yermak Plateau (Austegard et al., in press). Little seismic information from the northern part exists except for one multichannel seismic line (Kristoffersen and Husebye, 1985) and some refraction measurements (Jackson et al., 1984). The seismic data show that the extension of the onshore metamorphic basement of northern Svalbard can be traced as far as 25 km under the shelf (Sundvor et al., 1982b). One of the most prominent reflectors observed on the southern plateau is the strong, smooth, opaque acoustic basement reflector (O), associated with velocities of 5+ km/s. In some places along the crest of the plateau, reflector O crops out at the seafloor, with sediment coverage increasing to more than 2.5 s two-way traveltime (TWT) both toward the East and West. Refraction velocities of less than 2.5 km/s are observed in the upper part of the sedimentary sequence; velocities between 2.6 and 4.4 km/s are found in the deeper parts of the basins. The seismic character of reflector O is similar to other strong reflectors observed along the Norwegian-western Barents Sea Margin. These reflectors have been interpreted to have a volcanic origin, either as sills, low-angled dikes, or volcanic flows.

The nature and age of the crust underlying the Yermak Plateau have been discussed extensively. Sundvor et al. (1982a) suggested the southern part to be of continental origin based on the magnetic quiet field and dredged samples from the outcrop of reflector O. These samples consisted of Precambrian gneisses similar to the bedrock on northern Svalbard, although these authors pointed out that no fresh samples had been dredged. Based on the same data used by Sundvor et al. (1982a), together with heat-flow, gravity, and crustal

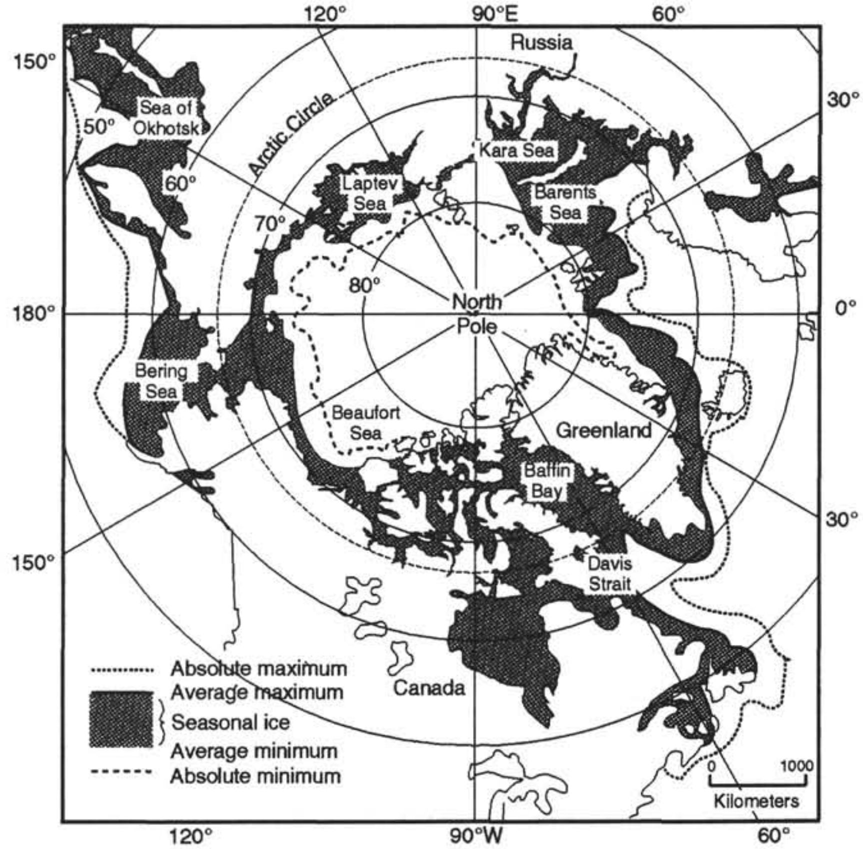

Figure 12. Average and extreme sea-ice limits (>1/8), after CIA (1978) and Barry (1989).

refraction velocities, which indicated different crustal properties beneath the northern and southern part, Jackson et al. (1984) also argued for a thinned downfaulted block of continental crust at the southern plateau, with the northern part being created by a hot spot situated at a triple junction. Feden et al. (1979), however, had problems accommodating a continental or partly continental Yermak Plateau in their plate tectonic reconstructions, and suggested that the Yermak Plateau and Morris Jesup Rise were created by hot-spot activity between Anomaly 18 and 13 time (middle Eocene to earliest Oligocene). The high heat-flow values observed by Crane et al. (1982) also contradict a partly continental origin of the southwestern plateau, and they argued for oceanic crust not older than 13 Ma underlying the westernmost part of the Yermak Plateau. They also implied that a thermal boundary exists between the warm western segment and the cold margin off the Nordaustlandet. New seismic data discussed by Sundvor and Austegard (1990) show a continuous basement reflector dipping under the Svalbard shelf below a sedimentary basin with a maximum thickness of 4.5 km. This reflector is also associated with velocities of 5.0–5.7 km/s. They also suggest a tentative continent/ocean boundary with a triangular piece of thinned continental crust underlying the plateau where the opaque reflector is observed.

To understand the paleoceanographic evolution of this area, both the evolution of the plate boundary and the evolution and subsidence of the volcanic Yermak Plateau and Morris Jesup Rise have to be unraveled. The timing of the subsidence of the Yermak and the Morris Jesup volcanic features has had a profound influence on the exchange of the shallow and deep water masses between the Arctic Ocean and the Norwegian-Greenland Sea, in addition to the oblique opening of the deep water passage in the Fram Strait.

The western part of the Fennoscandian landmass, the Barents Sea and Svalbard, was uplifted between 1000 and 2000 m in late Tertiary and Quaternary with deposition of extensive wedges of Pliocene and Quaternary sediments along the continental margins. It has not yet been determined if a coeval uplift took place along the East Greenland Margin.

Environmental Variability and Global Change

Here we will describe some of the features of the modern atmospheric and oceanic circulation and water mass distributions of the northern polar and subpolar deep-sea basins. Water masses leave their geological imprint on the seafloor; any changes in this imprint record events of great environmental importance and, therefore, of interest for the societies living on the Northern Hemisphere, especially in northwestern Europe. This can be illustrated easily and convincingly by the the latitudinal climatic zonation, which is greatly distorted under the influence of the heat advection and extension of the Gulf Stream system into the polar and subpolar northern deep-sea basins (Helland-Hansen and Nansen, 1909). The oceanic current regime in this area is highly unstable and variable over short and long intervals as suggested by modern real time monitoring and time series on ice distributions in the western Norwegian-Greenland Sea (Fig. 12), and by historic reconstructions based on proxy data (Fig. 13). These data carry ample evidence for the sensitive response of the Norwegian-Greenland Sea current systems to even minor Holocene climatic fluctuations. For example, toward the end of the Middle Ages (in the early "Little Ice Age"), the ice cover of the East Greenland Current extended far into the eastern Norwegian-Greenland Sea, probably under the influence of intensified large gyres over the Iceland Plateau and Jan Mayen (Lamb, 1972). This resulted in disrupted early traffic to Greenland and perturbed the commercial base for the then important, multinational European "Hanse" trade organization.

Except for the modern investigations of the MIZEX (Marginal Ice Zone Experiments) program in the Fram Strait (Johannessen, J.A., et al., 1987) and of the Overflow expeditions in the region of the Green-

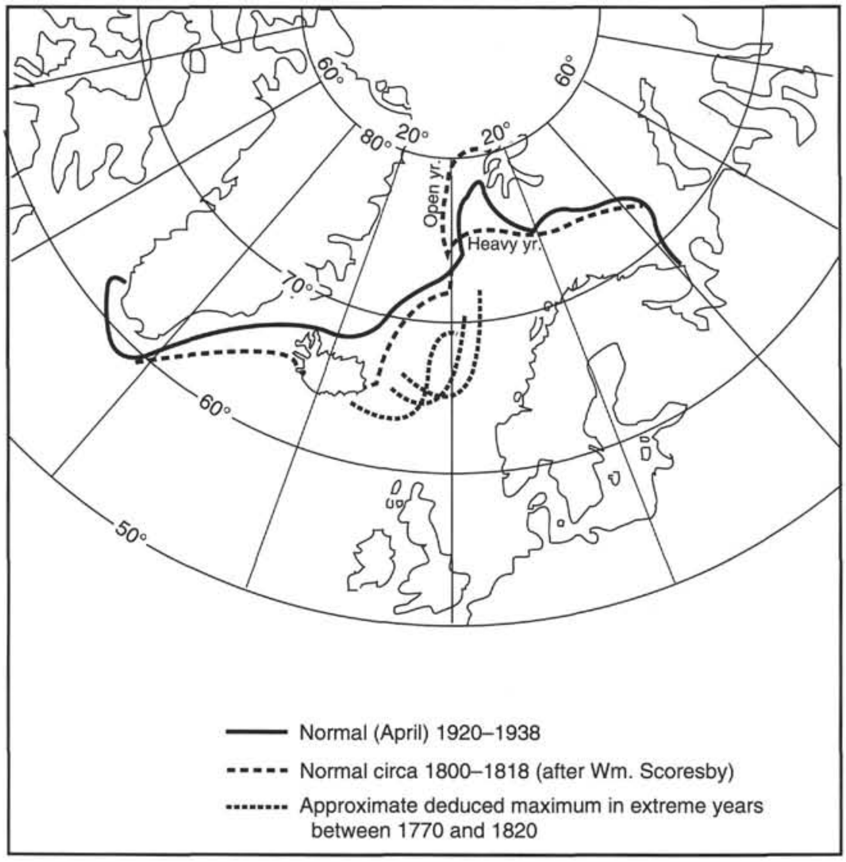

Figure 13. Variability of the historic Norwegian-Greenland Sea ice cover (Lamb, 1972).

land-Scotland Ridge (Meincke, 1983), little is known about the short-term modern temporal variations of the deep currents (Schlosser et al., 1992) through the northern and southern gateways.

Oceanographic Setting and the Global Context

The series of interconnected basins (Norwegian-Greenland Sea, Arctic Ocean) making up the northern polar and subpolar deep seas contains a total volume of approximately 10×10^6 km^3 or about 0.7% of the volume of the world ocean, if the Amerasian Basin (Canadian and Makarov basins) of the Arctic Ocean is excluded. The Eurasian Basin of the Arctic Ocean makes up nearly 60% of this volume. The North Atlantic-Arctic Gateways, crossing the Greenland-Scotland Ridge in the South and the narrow deep-water passage between the continental margins of East Greenland and Svalbard in the North, the Fram Strait, are channelling the flow of surface and deep waters and represent the most recent stage in the plate tectonic development of the Atlantic Ocean from a zonal (much like the modern Pacific and Indian oceans) to a meridional ocean basin allowing the deep-water exchange from both polar hydrospheres. The North Atlantic-Arctic Gateways have a global impact by maintaining and modulating the "salinity conveyor belt" (Broecker, 1991).

Surface Currents

The chief components of the surface water current systems of the Norwegian-Greenland Sea include the influx of warm and relatively high-salinity waters via the North Atlantic Drift (Fig. 14), which continues its northward flow as the Norwegian Current, and the outflow of cold and low-salinity waters via the East Greenland Current. The Norwegian Current is sufficiently cooled to allow deep water formation within the cyclonic gyre of the Greenland Sea. Another branch of this current continues along the western margin of Svalbard as the West Spitsbergen Current before entering the Arctic Ocean and dipping under the Arctic sea-ice cover. Within the Arctic, this relatively warm water mass mixes with low-salinity surface waters, sinks, and flows as an intermediate water mass counterclockwise before being exported out of the Arctic Ocean via the Fram Strait along the Greenland Margin. The surface outflow from the Arctic Ocean sweeps the East margin of Greenland before entering the Irminger Sea of the North Atlantic via the Denmark Strait.

Most of the marginal Yermak Plateau Northwest of the Svalbard archipelago is under waters permanently covered with ice; however, in good ice years the ice retreats to North of 81°N when the West Spitsbergen Current advances, and in late summer/early autumn, parts of the Yermak Plateau can be accessible. Because of its specific morphologic and tectonic setting, the Yermak Plateau is particularly well suited to study the impact of the influx of Atlantic waters, the response of the modern system to the glacial/interglacial fluctuations (oceanography, sea-ice cover, Barents Sea ice shield), the paleoceanographic transition of the temperate to the ice-covered Arctic Ocean, and the properties of the pre-glacial Neogene and Paleogene Arctic Ocean, which were all part of the scientific objectives of Leg 151.

The modern oceanography over the Yermak Plateau and its surroundings has been studied in considerable detail since the days of Nansen (1928), and more recently as a result of the efforts of the MIZEX program (Gascard et al., 1988; Johannessen, J.A., et al. 1987; Quadfasel et al., 1987). It was recognized early that the current system in the Fram Strait and its surroundings comprise some of the dynamically most unstable hydrographic elements in the gateways between the Arctic and North Atlantic oceans. Here the West Spitsbergen Current, as a continuation of the Norwegian Current, transports temperate Atlantic Ocean waters through the Fram Strait to the edge of the Arctic sea-ice cover. In the northern Fram Strait these waters are either recirculated into the East Greenland Current or they continue on their path into the Arctic Ocean under the sea-ice cover

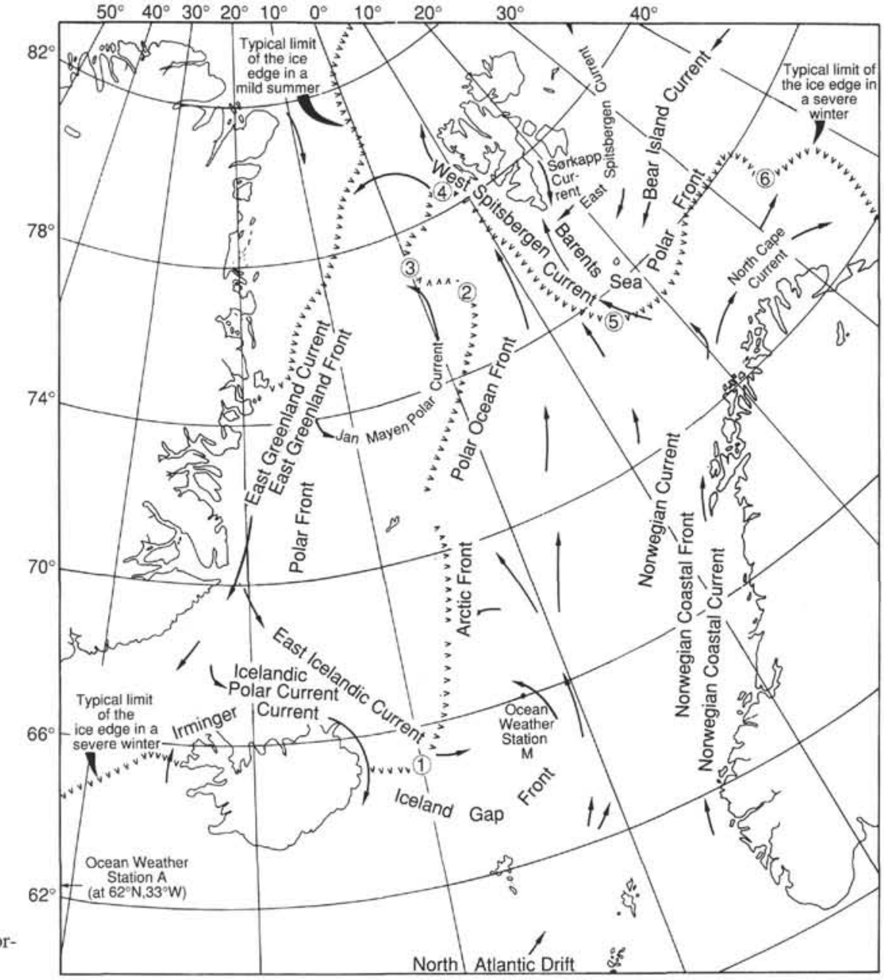

Figure 14. Major currents and sea-ice features in the Norwegian-Greenland Sea (Hurdle, 1986).

and a relatively thin layer of cold Arctic surface waters. Bourke et al. (1988) and Manley et al. (1992) described in great detail how a branch of the Atlantic waters turns East immediately North of Svalbard (Svalbard branch), whereas another branch continues along the outer Yermak Plateau (Yermak Branch) to return into the Litke Trough East of the Yermak Plateau. The marginal ice zone at the same time experiences extensive mesoscale (10–30 km in diameter) eddy formation. The East Greenland Polar Front (Manley et al., 1992), which is marked by the sea surface outcrop of the 0°C isotherm and which usually coincides with the ice edge, also follows the highly turbulent water mass boundary between the Arctic waters of the East Greenland Current and the relatively warm West Spitsbergen Current with geostrophic velocities of 30–80 cm/s.

Bottom Waters

Aagaard et al. (1985) concluded that nearly 50% of the water volume in the polar and subpolar northern deep seas, including the Amerasian Basin, is potentially in communication with the world ocean (Fig. 15). These basins might hence be characterized as belonging to the "lungs" of the present world ocean, implying that it is of fundamental importance to acquire a detailed understanding of the timing and history of deep and shallow water exchange between the Arctic Ocean and Norwegian-Greenland Sea and the remainder of the world ocean. The unique topographic constraints provided by a single deep, narrow passageway to the North (Fram Strait) and a major submarine ridge system to the South (Greenland-Scotland Ridge) make it pertinent to address this question of the Cenozoic paleoceanography of the world ocean as a gateway problem (see Frontispiece).

Cenozoic Paleoenvironments

The modern oceanography of the Norwegian-Greenland Sea and the Arctic Ocean can be assumed to represent an interglacial scenario, but reconstructions of the glacial situation of the sea-ice cover, as well as of the northern extension of the Barents Sea Ice Sheet, are much more difficult to find. Most of the presently available reconstructions are not supported by sufficient data from the Yermak Plateau, Fram Strait, and Arctic Ocean proper, although a large body of data is available from the Norwegian-Greenland Sea (Sarnthein et al., 1992; Jansen and Veum, 1990; Henrich, 1992). Data-supported reconstructions of the time of transition from the pre-glacial to the glacial Neogene Arctic and of the temperate late Mesozoic/Paleogene Arctic Ocean are virtually not available (Thiede and NAD Science Committee, 1992).

To understand the geological history of the Cenozoic climates, one has to discern some long-term trends, short-term catastrophic changes overprinted on the long-term trends, and a cyclic variability that has modulated the change from late Mesozoic and Paleogene equable climates of our globe to the modern extremes with steep temperature gradients between poles and equator (Frakes, 1979). Because of plate tectonic evolution, today two climatically and oceanographically isolated but otherwise widely different physiographic provinces have been positioned over the North and South

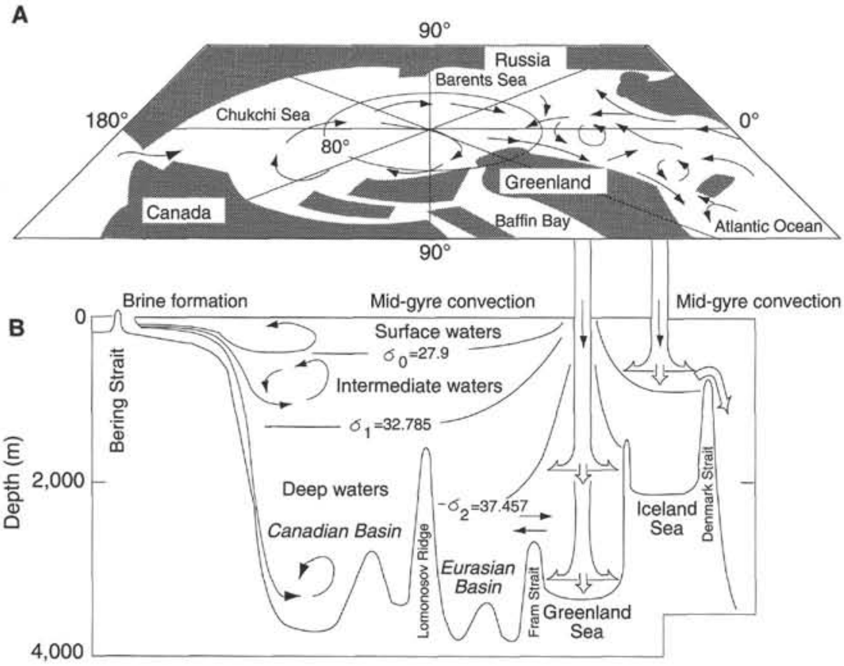

Figure 15. Schematic illustration of the ocean circulation in the Arctic Ocean and the Nordic Seas (Aagaard et al., 1985). The upper map shows the major elements of Arctic Ocean and Norwegian-Greenland Sea surface circulation. The lower panel describes water budget of northern polar deep-sea basin intermediate and deep-water movements.

poles. This process, and probably other unknown reasons, led to a bipolar glaciation during the late Cenozoic unlike during geologically much older phases of cold polar climates (Frakes, 1979). Bipolar glaciation has led to the development of modern climates, and the biogeography as well as nature of habitats of modern plants and animals. The plate tectonic isolation of Antarctica over the South Pole and of the Arctic Ocean over the North Pole shows astounding differences, but also similarities. A most interesting synchroneity can be seen in the separation of the Australian continental margin including Tasmania from the Antarctic continental margin during Anomaly 13 time (Kennett, 1977) coinciding with a major reorientation of the pole of rotation between the Eurasian and the North American plates, leading to the initial opening of the Fram Strait at approximately the same time (Vogt, 1986a). This plate tectonic evolution was accompanied by a general, sometimes slow, sometimes drastic cooling of the polar and subpolar seas, finally reaching the extremes of the modern climate. As documented in ice cores from Greenland (Johnsen et al., 1992) and deep-sea sediment cores from the Atlantic Ocean to the North of the Greenland-Scotland Ridge, fast and drastic changes have affected the global climate. Leg 151 was planned to study the record of these changes in the polar and subpolar deep-sea basins that make up the northern extension of the Atlantic Ocean. From South to North, these areas consist of the Norwegian and Iceland seas, the Greenland Sea, and the Arctic Ocean, which together commonly are referred to as the Arctic Mediterranean (Sverdrup et al., 1942) or the Nordic Seas (Hurdle, 1986).

During the last decade it has been realized that much of the natural variance in the Earth's environment on time scales of less than 1 m.y. originates from changes in the geometry of the Earth-Sun orbital system. The sensitivity of the Earth system to orbital forcing has been especially high over the last 1 m.y. It is necessary to obtain records that document how the climatically sensitive, high-latitude regions have developed to gain an understanding of how this high sensitivity to external forcing has evolved from periods of less sensitivity and lower amplitude variation, and for understanding the way environmental change is forced by this and other mechanisms that operate on longer time scales (such as plate reorganizations, orogeny, carbon cycle variations). The Arctic and subarctic deep-sea basins are known to have reacted faster and with a more extreme range of temperature fluctuations than any other part of the world ocean during the late Cenozoic climate change (CLIMAP, 1976; Sarnthein et al. 1992). It follows that this focus on high northern latitude paleoenvironmental questions requires deep-sea drilling in the areas North of the Greenland-Scotland Ridge.

Climate Evolution of High Northern Latitudes

A major element in the evolution of Cenozoic environments has been the transformation from warm Eocene oceans with low latitudinal and bathymetric thermal gradients into the type of oceans characterized by strong thermal gradients, oceanic fronts, cold deep oceans, and cold high-latitude surface-water masses (Shackleton and Boersma, 1981). This transformation is linked with the climatic transition into cold high-latitude climates and with the connection of both surface and deep-ocean circulation between high-latitude regions and the lower latitude oceans. It is still not known what role the Arctic and subarctic regions played in this transformation, or how and when climatic, tectonic, and oceanographic changes in the Arctic contributed to the global ocean cooling and increased thermal gradients (Thiede et al., 1990a; Thiede and NAD Science Committee, 1992).

At present, it is uncertain when cold climates evolved in the Arctic and surrounding regions. To understand the 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 and Thiede, 1991). Other studies conclude that this event happened during the Matuyama or at the Brunhes/Matuyama boundary (Herman and Hopkins, 1980; Carter et al., 1986; Repenning et al., 1987). This discrepancy in timing cannot be settled by the available sediment cores.

A major threshold of the climate system was passed with the inception of glaciers and ice sheets in the Northern Hemisphere. Data from Leg 104 document frequent but separate events of 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 and

Sjøholm, 1991; Wolf and Thiede, 1991). IRD data from Leg 105, Site 646, suggest the onset and discontinuous existence of sea-ice cover in the Labrador Sea to the South of Greenland since middle/late Miocene times (Wolf and 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 and Sjøholm, 1991). With the presently available sediment cores, it is impossible to document clearly when glaciers started to evolve in the Arctic and high subarctic, and it is impossible to describe the glaciation history of the different individual areas. For example, when was Greenland glaciated? What distinguished the climatic responses in the Arctic parts of this area (Greenland, Svalbard, and Arctic Ocean fringes) from those of the subarctic North European areas? Did the cooling and glacial inception of the high Arctic and Greenland take place at an earlier stage than in the subarctic? Terrestrial data indicate significant cooling on Iceland at about 10 Ma (Mudie and Helgason, 1983) and glaciation in elevated areas of Iceland in the latest Miocene and the Pliocene (Einarsson and Albertsson, 1988). Terrestrial evidence also indicates forested areas in the Arctic fringes, far North of the present forest/tundra boundary, until about 2 Ma (Carter et al., 1986; Nelson and Carter, 1985; Funder et al., 1985; Repenning et al., 1987). The chronology from these land sites is, however, poorly constrained, and because this is only scattered evidence, no continuous records from land sites document the climatic transition into a cold Arctic climate. Clear documentation and proper timing of the climatic evolution, therefore, will depend on the availability of new, continuous, deep-sea sediment cores.

Because the glacial and climatic history of the high northern latitudes is so poorly known, the ability to model and understand the linkages between low- and high-latitude climates and between Southern and Northern Hemisphere climates is limited. The Norwegian-Greenland Sea and the Arctic Ocean are surrounded by land masses that acted as loci for the late Cenozoic Northern Hemisphere ice sheets. Therefore, these are key areas where Northern Hemisphere glacials can be documented in the form of input of IRD into the ocean. The history of large glaciations in the high northern latitudes has been firmly documented only back to approximately 2.5 Ma (Shackleton et al., 1984; Ruddiman and Raymo, 1988; Jansen et al., 1988), although glaciation in some areas must have started earlier in the Neogene. This contrasts with the history of glaciation in the Antarctic, which probably dates back at least to the early Oligocene, about 36 Ma (Barron et al., 1988). The apparent interhemispheric asynchroneity in the climatic evolution of high-latitude regions in the Southern and Northern hemispheres is a major unresolved question for understanding Cenozoic paleoenvironments.

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 subarctic 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 m.y. However, the amplitudes of climatic changes and the dominant frequencies have varied strongly, indicating variations in the way the climate system responded to external forcing (Ruddiman et al., 1986; Ruddiman and Raymo, 1988; Raymo et al., 1990). Work is under way, based on Leg 104 material (Jansen and Sjøholm, 1991; Henrich 1992), to study the cyclicity of IRD input into the subarctic 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.

Some models constructed to investigate and explain the evolution and operation of the global climate system include variations in the magnitude and mode of thermohaline ocean circulation (e.g., Barron and Washington, 1984; Broecker et al., 1985; Mix and Pisias, 1988; Boyle, 1988). Further improvements of such models will depend on records that can assess the actual climatic and oceanographic evolution of the high northern latitudes.

North Atlantic-Arctic Gateways and Paleoceanography

The tectonic development and the opening of the Fram Strait have determined the history of water-mass exchange between the Arctic Ocean and the Greenland-Norwegian-Iceland seas. Submergence below sea level of the southern gateway (Greenland-Scotland Ridge), or parts of it (Thiede and Eldholm, 1983; Wold, 1992), has controlled the water-mass exchange between the Norwegian-Greenland Sea and the Atlantic Ocean, and thus the world ocean.

The Fram Strait, with a present critical sill depth of 2600 m (immediately to the North of Hovgaard Ridge), represents the only deep connection between the Arctic Ocean and the global ocean. This connection may have been initiated as early as Anomaly 13 time, close to the Eocene/Oligocene boundary (Crane et al., 1982; Kutzbach et al., 1993; see also reviews by Vogt, 1986a, b). The tectonic history of the Fram Strait area, however, is characterized by complex and, at present, only vaguely understood processes, which include stretching of the Svalbard continental crust and hot-spot activity. When taking into account the strongly oblique opening of the Fram Strait and the proximity to surrounding land areas (Greenland and Svalbard), it seems possible that a truly deep Arctic Ocean/Greenland-Norwegian Sea connection became established considerably later than Anomaly 13 time, perhaps as late as Anomaly 6 time (Kristoffersen, 1990; Eldholm, 1990). The history of water-mass exchange between the Arctic Ocean and the world ocean via the Greenland-Norwegian-Iceland seas is a key element in any large-scale model of post-Eocene paleoceanography. However, the documentation of this history will depend on new drilling efforts to make available material from within and from both sides of the gateway.

Few oceanic gateways can compete with the Greenland-Scotland Ridge in having such a profound influence on the present world hydrography (Fig. 16) (Bott et al., 1983). Overflow from northern sources occurs in the Faeroe-Shetland Channel, across the Iceland-Faeroe Ridge, and in the Denmark Strait. Tracer studies indicate that the overflow waters originate from waters shallower than 1000–1200 m, probably to a large extent formed by deep convection in the Iceland Sea (Peterson and Rooth, 1976; Warren, 1981; Aagaard et al., 1985). Reconstructions of the subsidence history of the ridge system suggest that its eastern parts sank beneath sea level probably during middle Eocene times, and during early to middle Miocene times in the Denmark Strait area. This view has been disputed lately by Wold (1992), who suggested the earliest drowning occurred in the Denmark Strait area. The distribution of shallow-water benthic foraminifers, however, indicates that the Norwegian-Greenland Sea was effectively isolated from any "deep" Atlantic influence until middle Miocene times (Berggren and Schnitker, 1983; Thiede, 1983; Thiede and Eldholm, 1983). The overflows have influenced both the Atlantic and global deep-water masses through their contribution to North Atlantic Deep Water (NADW) production and to the formation of North Atlantic sedimentary records. Basic questions as to why and when NADW production was initiated, and how and why the chemical and physical signature of this major water mass has varied, remain to a large degree unanswered. Obviously, the physical and chemical characterization of surface and deep waters through time directly in the main source regions (i.e., North of the Greenland-Scotland Ridge) will greatly improve the understanding of world ocean hydrography, global energy budgets, and North Atlantic patterns of sedimentation and erosion.

Sediment Budgets

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 mat-

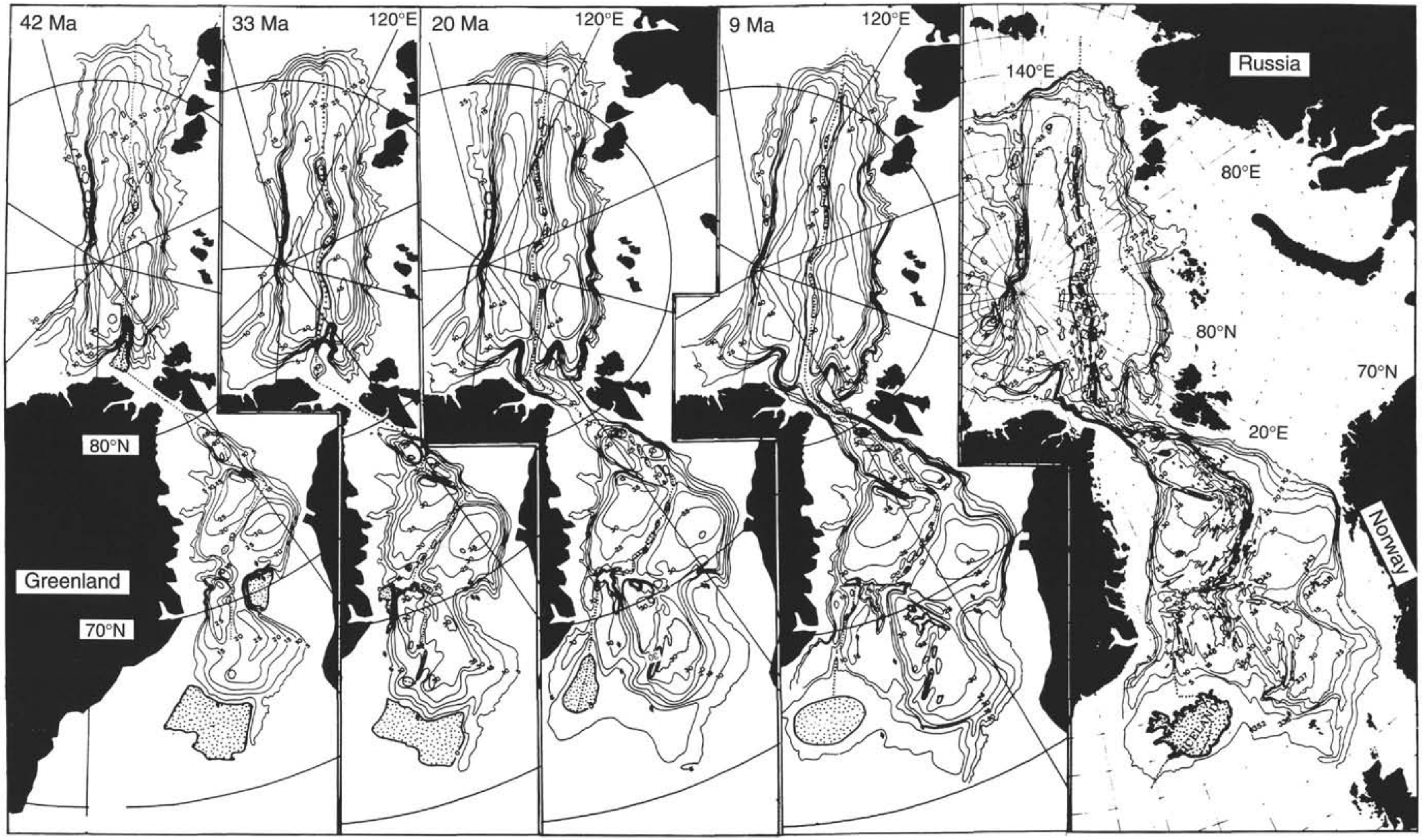

Figure 16. Paleophysiography of the Norwegian-Greenland Sea and of the eastern Arctic Ocean during four Paleogene and Neogene time slices (Vogt, 1986b). Bathymetry in hundreds of meters. Stippling signifies ocean crust above sea level. Based on Bernero (1982) from Vogt et al. (1981).

ter, and nonbiogenic sediment components determine the internal cycling of matter in the oceans and, therefore, are linked to the chemical state of both the oceans and the atmosphere (Broecker and 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 the modern deep-sea sediments, accumulate at rates 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, are also 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 to balance the total carbonate budget. The ocean circulation and the underlying causes for its development and change are thus key factors among the dissolution-related parameters.

Leg 104 documented a major deepening of the calcite lysocline at about 10 Ma in the Norwegian Sea. This was followed by a series of low-frequency variations in carbonate deposition/dissolution and opaline silica preservation. This 10-Ma event presumably reflects the cumulative effect of a large set of changes occurring in the global sediment budgets and paleoenvironments at around the middle/late Miocene transition, such as an increase from 5% to 10% in the recycling rate of the total sediment mass on Earth (Hay, 1985), the beginning of a remarkable decrease in the global organic carbon reservoir (Shackleton, 1987), or the substantial increase in latitudinal temperature gradients (Shackleton and Kennett, 1975; Thierstein and Berger, 1978). Concomitant changes induced by tectonic forcing also belong in this picture, where the activation of new ocean-circulation patterns through newly formed gateways must be an important factor contributing to the large-scale changes in the global climate-ocean-sediment system. It follows that many possible cause and effect relationships can be inferred to explain, for example, the deepening of the Norwegian Sea lysocline at 10 Ma. Yet, this shows that global patterns are preserved in the sediments of the Norwegian-Greenland and adjacent seas.

Biological Evolution

The North Atlantic-Arctic Gateway drilling program will recover high-quality APC/XCB (advanced piston corer/extended core barrel) sediment material reflecting a variety of paleoenvironmental conditions for Northern Hemisphere marine biota. It is anticipated that the material also will be used to address an array of significant scientific questions that have not been specifically mentioned in the three main themes.

Studying biological evolution is one additional but important scientific problem. Such studies will allow the assessment of the response of oceanic biota to changes in climate, ocean circulation, and chemistry. Cores from high northern latitudes, and particularly the Arctic Ocean, will provide the Northern Hemisphere end-member for examining topics such as patterns and modes of speciation, bipolar evolution, Arctic faunas/floras and their adaptation to extreme habitats, and Arctic/subarctic environmental influence on intra- and interspecific morphological variation.

Previous Ocean Drilling in Northern Hemisphere Polar and Subpolar Deep-sea Basins

North Pacific Ocean and Bering Sea

Leg 18 visited the North Pacific Ocean (Kulm, von Huene, et al., 1973) and drilled glacial-marine deposits at Sites 178–182 (Alaska Abyssal Plain, Aleutian Trench, and the continental margin off Southwest Alaska). The oldest record of ice-rafted erratics occurs in the glacial-marine deposits of the Alaska Abyssal Plain, where upper Pliocene and Quaternary deposits with erratics down to 258 mbsf document a pattern of temporal variability of ice-rafting. No attempt has been made to identify a potential North American source region.

Leg 19 continued the program of Leg 18 toward the West, but it also crossed over the Aleutian island chain into the deep Bering Sea (Creager, Scholl, et al., 1973). Like Leg 18, it stayed in relatively low latitudes (South of 57°N), and the drill sites were not well placed to address onset and evolution of Cenozoic Northern Hemisphere glaciations. However, evidence for ice-rafting with variable intensity has been found in sediments possibly as old as early Pliocene (Site 187), and 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. Although drilling results were also hampered by spot rotary coring, obtaining an incomplete and highly disturbed record of the youngest parts of the sedimentary sequences, Legs 18 and 19 still provide important high northern latitude paleoclimatic and paleoceanographic data in an area geographically opposite the North Pole from the Leg 151 drill sites.

Leg 145 also visited the North Pacific Ocean and continuously cored several deep sites, which showed that the onset of the Northern Hemisphere glaciation started at 2.6 Ma, marked by abundant dropstones coming from both Siberian and Alaskan sources. The input of continentally derived, fine-grained clastics into the deep sea increased several fold at the same time, and in the northwestern Pacific Ocean, abyssal reworking of bottom sediments also began at about 2.6 Ma and continues to the present (Rea, Basov, Janecek, Palmer-Julson, et al., 1993).

Norwegian-Greenland Sea: Legs 38 and 104

Although DSDP visited the North Atlantic Ocean several times, it only drilled the Norwegian-Greenland Sea once, during Leg 38 (Talwani, Udintsev, et al., 1976). Spot and rotary coring and mostly structural and plate tectonic objectives do not allow us to decipher much of the detail of the late Cenozoic paleoenvironmental history that later has been established with respect to onset and variability of the Northern Hemisphere glaciations in the North Atlantic (Shackleton et al., 1984) by means of drill sites South of the Greenland-Scotland Ridge. Many of the Norwegian-Greenland Sea drill sites contained ice-rafted detritus (various lithologies of both erratics and Cretaceous *Inoceramus* prisms are mentioned); their stratigraphic distribution confirmed that sea-ice cover and ice-rafting were not restricted to the Quaternary period, but exhibited considerable temporal variation extending clearly back into the Tertiary (Pliocene). Based on the Leg 38 material, Warnke and Hansen (1977) later confirmed this and also established a regional distribution of ice-rafting with maxima along the Greenland and Norwegian continental margins.

ODP Leg 104 was the next major contribution toward deciphering the history of Northern Hemisphere Cenozoic cooling and glaciation. The major scientific objective was sampling a thick, dipping reflector sequence of volcanic origin on the outer Vøring Plateau off mid-Norway (Eldholm, Thiede, Taylor, et al., 1987b). The reflector sequence is related to the initial opening of the Norwegian-Greenland Sea (Hinz et al., 1993; Eldholm and Thomas, 1993). Together with additional drill sites on either side along a transect across the Vøring continental margin, this site revealed important data about the history of the Norwegian Current and the onset of Northern Hemisphere Cenozoic glaciations. The most important observations (Eldholm, Thiede, Taylor, et al., 1989b) on paleoenvironmental evolution were the following:

1. Even though the stratigraphy of Sites 642 and 643 is incomplete owing to several poorly defined hiatuses, both sites have sampled intervals documenting the arrival of the first eastern

Norwegian-Greenland Sea ice cover. Pre-glacial conditions provided favorable habitats for rich siliceous and calcareous plankton communities with excellent sediment records preserved from the Miocene and Pliocene.
2. A major revolution of the deep-water habitats and hydrographies in the eastern Norwegian Sea is suggested by the invasion of calcareous benthic foraminifers at approximately 13.5 Ma, when the first probable ice-rafted sediment components occurred at DSDP Site 341.
3. Calcareous pelagic microfossils occur sporadically in upper Miocene to Quaternary sediments. In many instances, in particular in the Quaternary, their occurrence is controlled by dissolution. Only during the last 1 m.y. has their frequency followed an increasing trend.
4. Unlike the area South of the Greenland-Scotland Ridge where indicators for glaciation are observed only as late as 2.4 Ma (Shackleton et al., 1984), IRD appeared over the Vøring Plateau at least intermittently, and first in relatively small quantities, during late Miocene times. In the Labrador Sea, small amounts of ice-rafted terrigenous debris have been found as deep as in upper middle Miocene sediments (Wolf and Thiede, 1991).
5. At 2.8–2.5 Ma, the abundance of ice-rafted terrigenous debris suddenly increases, suggesting a dramatic intensification of glaciation. South of Greenland (ODP Site 646; Wolf and Thiede, 1991) a similar development can be observed, but the intensification occurred at approximately 4 Ma.
6. Since 2.8–2.5 Ma, more than 26 severe glacial events have affected the eastern Norwegian Sea, supporting the notion that the Northern Hemisphere ice covers are unstable and react to a highly dynamic climate system.
7. At the same time, evidence for interglacials is an exception in the Leg 104 sediments, suggesting the interglacials were short and that the dominant mode of the depositional environment of the eastern Norwegian Sea has been glacial.
8. Dropstones sometimes can be related to their source regions in Scandinavia, Greenland, and the North Sea area. Their distributions vary considerably with time, indicating major changes in the spatial distribution and dynamics of the large circum-Arctic continental ice sheets.
9. Glacial-interglacial changes exhibit cyclical variations related to the Milankovitch frequencies, which are documented by a variety of sediment properties, thereby providing a medium for dating the historic climate record as a basis for climate prediction.

New Deep-ocean Drilling: Approach and Priorities of Leg 151

The Norwegian-Greenland Sea and adjacent deep-sea basins are characterized by strong latitudinal gradients in the sea-surface environment and also by unusually steep meridional gradients as a result of the warm Atlantic influence in the East and the cold polar influence in the West (Figs. 14 and 15). Intense seasonal variability is also a prominent feature of the surface environments, resulting in strong and rapidly migrating ocean fronts. The onset and subsequent variability of these fronts are almost totally unknown. Apart from the data obtained from the Norwegian Margin during Leg 104, no high-quality samples exist that are older than a few hundred thousand years. Thus, to derive a comprehensive understanding of the whole ocean-climate system of this area including its modus operandi with respect to a global-perspective critical system, it is necessary to obtain continuous sediment cores at a range of locations that can document changes of the sea-surface environments and the underlying causes for these changes through late Paleogene and Neogene through Quaternary times.

No scientific drilling has been performed in the Arctic Ocean so far, and, because of the area's inaccessibility, limited material is available from conventional coring (Thiede and NAD Science Committee, 1992). Sediment cores from the areas North of 76°N, where DSDP Site 344 is located, represent less than 10% of the last 70 m.y., so that essentially no knowledge exists of the paleoceanography of the Arctic Ocean (Thiede et al., 1990a). This stands in distinct contrast to the fundamental oceanographic and climatic influence of this ocean. Although the ice cover prevents entry of the *JOIDES Resolution* to most parts of the Arctic Ocean (Fig. 12), areas on the Yermak Plateau North of Svalbard and hence North of the gateway (Fram Strait) between the Norwegian-Greenland Sea and the Arctic Ocean are ice-free and accessible in late summer during normal ice years and can potentially be drilled using normal ODP methods.

Most of the proposed sites were arrayed as either broad North-South or East-West transects to monitor spatial paleoclimatic variability or closely spaced suites of cores across a range of depths to monitor vertical variability. Other approaches included sites chosen for deep drilling that would better constrain the time of opening of Fram Strait and sites placed to monitor downstream sedimentological effects of deep flow through narrow gateway constrictions.

In addition to the paleoenvironmental objectives, a couple of sites on the Iceland and Yermak plateaus addressed the age and nature of basement rocks. The sites to the North of Svalbard also constituted the first scientific drilling to be conducted in the Arctic Ocean proper, thereby representing one of the first steps of the Nansen Arctic Drilling (NAD) Program.

Following the recommendations of the NAAG Detailed Planning Group (DPG), the scientific objectives of Leg 151 can be summarized as follows (from Ruddiman et al., 1991):

Cenozoic Paleoceanography of the Norwegian-Greenland Sea and Arctic Ocean

1. To study the timing and history of deep and shallow water exchange between the Arctic Ocean and the Norwegian-Greenland Sea via the Fram Strait (northern gateway), and between the Norwegian-Greenland Sea and the North Atlantic Ocean across the Greenland-Scotland Ridge (southern gateway).
2. To investigate the initiation and variability of East-West and North-South oceanic fronts in surface waters, and the history of vertical, physical, and chemical gradients.

Cenozoic Evolution of Climate in High Northern Latitudes

1. To investigate the timing and development of polar cooling and the evolution of low- to high-latitude thermal gradients in the Northern Hemisphere.
2. To establish the temporal and spatial variation of sea-ice distribution, the glacial history of the circumarctic, Greenland, and northern Europe, and the history of IRD sedimentation in the Arctic.
3. To investigate variations in climatic zonality and meridionality through time as response to tectonic forcing.
4. To establish the history of the higher frequency components of the climatic and glacial evolution of the Arctic and subarctic areas.
5. To identify ocean-atmosphere interactions associated with Northern Hemisphere deep-water formation and the inter-hemispheric couplings and contrasts in climatic evolution.

Sediment Budgets

1. To investigate fluxes of biogenic carbonate, opaline silica, organic matter, and nonbiogenic sediment components through time.

2. To study bathymetric variability through time of the carbonate compensation depth (CCD) and lysocline.
3. To establish the spatial and temporal history of silica preservation.
4. To investigate Arctic and subarctic oceanic influence on global biogeochemical cycles.

These objectives are thought to be achievable through the following studies:

Surface Water-Mass Evolution

The Norwegian-Greenland Sea is characterized by strong oceanographic gradients, not just latitudinally but also meridionally, caused by the northward flow of relatively warm Atlantic water in the East and southward flow of cold polar water and ice in the West. Strong seasonal variability also results in rapid migrations of sharply defined fronts. Apart from material obtained from the Norwegian Margin during Leg 104 and in the Labrador Sea during Leg 105, the history of these surface-ocean gradients prior to the last few hundred thousand years is almost unknown. Leg 151 drilling will provide material from the colder western regions for tracing the spatial evolution of surface-water environments and thus enhance the understanding of climatic change.

Temporal and Spatial Variation of Sea-ice Distribution

The present Arctic climate is strongly influenced by its sea-ice cover, which greatly increases the regional albedo and reduces heat and gas exchange with the atmosphere. Little is known about how this ice cover first developed and subsequently varied. Although *JOIDES Resolution* is prevented from drilling within the permanent pack ice in the central Arctic, drilling along the present ice margins will provide better constraints on the history of sea-ice extent just North of a key Arctic gateway and southward into the Norwegian-Greenland Seas.

The Gateway Problem

The gateways in the North (Fram Strait) and South (Greenland-Scotland Ridge) are among the most important submarine topographic constrictions to global oceanic circulation. Opening of Fram Strait and subsidence of the Greenland-Scotland Ridge below critical levels are necessary conditions for deep-water exchange between the Arctic and Atlantic oceans via the Norwegian-Greenland Sea, although other tectonic changes also may play a role in determining the subsequent long-term evolution of meridional exchanges across these former barriers (Fig. 16). The history of these gateways is thus a key component in understanding the long-term evolution of both Northern Hemisphere and global climate.

Leg 151 focuses on two key objectives not addressed in previous drilling: (1) constraining the tectonic history of opening of these barriers, primarily by drilling to obtain basement ages; and (2) defining the subsequent history of surface and deep-water exchange across these barriers, based both on proxy water-mass indicators and on current-sculpted features on the seafloor.

Deep Water-Mass Evolution

ODP drilling in the Norwegian-Greenland Sea will improve the understanding of deep-water evolution by providing regional and vertical transects that constrain the development of physical-chemical gradients in deep waters, sites located in regions where vigorous deep-water outflow has altered normal pelagic sedimentation, and evidence of surface ocean climate changes in regions of deep-water formation.

History of Mountain Glaciers and Ice Sheets

Both the location and kind of terrestrial ice covers remain uncertain. Were there mountain glaciers that reached the sea, or small ice sheets? Were they located on Greenland, on Svalbard, over the Barents Sea, or elsewhere? Thus, a primary drilling objective is to obtain sediments from sites adjoining these regions to assess their glacial histories individually.

Sediment Budgets

To derive a broad understanding of global sediment budgets, it is necessary to integrate biogenic (and lithogenic) flux data from all ocean basins. The present coverage of high-quality material from the Norwegian-Greenland Sea is insufficient both regionally (no sites in the central, western, or northern parts) and vertically (lack of deeper sites). The proposed drill sites cover the major water masses and depth gradients and will permit calculation of burial fluxes of opal, $CaCO_3$, and organic carbon, as well as deductions about the intensity of $CaCO_3$ dissolution through time.

Drilling Strategy

Most of Leg 151's objectives require drilling long sequences of rapidly deposited (>20 m/m.y.) sediments. This approach permits retrieval of continuous sections for high-resolution analysis of the higher frequency (orbital-scale or higher) variations of the climate system. At the same time, it provides sequences spanning millions of years, during which the long-term baseline climatic state may evolve toward generally colder conditions, as may the spectral character of orbital-scale variations. In the following discussion of objectives, references to the history, evolution, or development of key components of the Arctic and subarctic climate system should thus be understood to include both orbital-scale and tectonic-scale changes.

As part of the NAAG program Leg 151 was to drill a series of proposed sites along a North-South transect, an East-West transect (linked to the Leg 104 sites in the East), and a bathymetric transect (Fig. 17). The sites should be double, or even triple, APC/XCB cored to achieve 100% recoveries. The North-South transect extends from the Arctic Ocean (the Yermak Plateau) via the Fram Strait, the Greenland and Iceland seas, into the northwestern North Atlantic Ocean. It can thereby tie into existing North Atlantic (DSDP Legs 81 and 94) and Labrador Sea (ODP Leg 105) high-resolution stratigraphies and address the evolution of North-South environmental gradients from the Arctic to the North Atlantic oceans.

The second transect (Fig. 17) uses Leg 104 sites on the Vøring Plateau as its eastern tie-point and extends across to the areas immediately off East Greenland. The main intention of this transect is to sample the strong environmental gradient between the polar regions off East Greenland and the temperate Atlantic waters off Norway to study the inception and evolution of the strong middle- to high-latitude East-West gradients and oceanic fronts, and to investigate differences in the oceanic and glacial evolution between Greenland and northern Europe. In addition, it is necessary to include a central sample point along this transect to obtain clean pelagic records from the central parts of the basin.

Two bathymetric transects (Fig. 17) were also proposed to study sediment budgets, lysocline/CCD- variability, and bathymetric gradients in ocean chemistry: one on the Yermak Plateau in the Arctic Ocean and the other on the slope between the Iceland Plateau and the Ægir Ridge (extinct axis) in Norway Basin. This second area is located centrally in the Norwegian-Greenland Sea and is not influenced by various continental margin effects.

The overall drilling strategy is controlled by (1) the priority of the proposed drill sites, (2) the availability of ice-breaker coverage, and (3) ice conditions. The following specific aspects apply to areas and sites chosen for Leg 151.

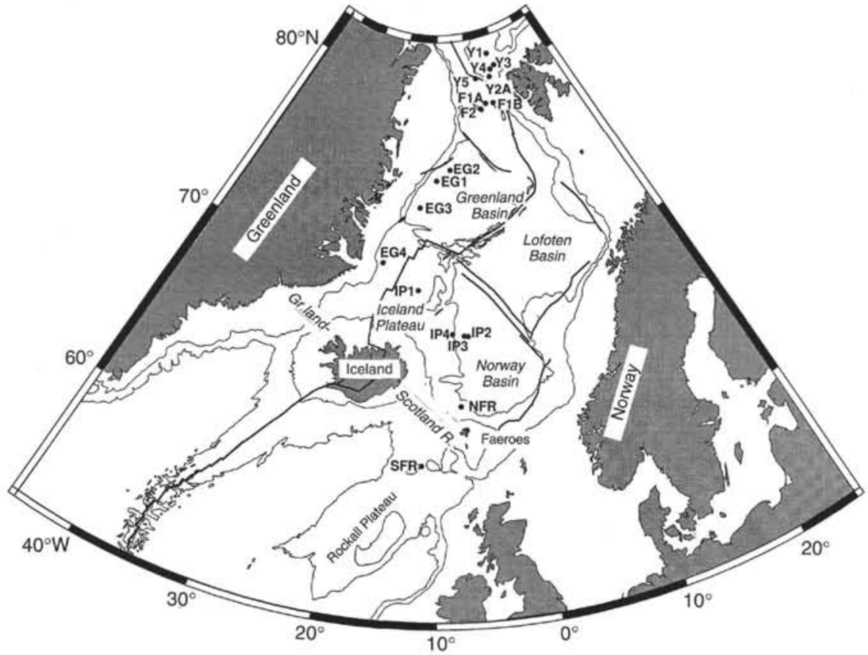

Figure 17. Simplified bathymetric map of the Yermak Plateau and the Greenland-Iceland-Norwegian seas, showing the location of proposed drill sites. Bathymetry in km.

Yermak Plateau

Drilling in this area enables a study of environmental responses pre- and postdating the opening of the deep gateway into the Arctic Ocean. Drilling documents the timing of this event, the physical and chemical nature of the water masses associated with the gateway opening, and its influence on ocean circulation and climate. It furthermore provides a check for the theory that links this event with changes in the relative plate motion starting at about Anomaly 13 time and the possible global impacts of the establishment of a deep connection between the Arctic and the world ocean. The other main achievement from drilling this area is that it should provide a continuous upper Neogene-Quaternary record from the Arctic Ocean of the same quality as is available from lower latitude areas. This will make possible the identification of the onset of permanent ice cover in the Arctic Ocean, test models of the pre-glacial ice-free Arctic, and the magnitude of glaciation and ice sheets in the Arctic areas by identifying the onset and variation of IRD input into the Arctic Ocean. It should further enable studies of Milankovitch cyclicity in Arctic Ocean climates and circulation and how this cyclicity has evolved with time.

The area forms the northernmost end-member of a North-South transect of drill sites that ties into the other oceans. This would be the first scientific drilling in any part of the Arctic. It will be the northernmost control point for stratigraphic studies, a reference area for Arctic studies, and a northern tie point for studies of the evolution of global thermal gradients. A series of sites in this region has been proposed for three reasons: (1) the necessity for drilling more than one site to recover a complete stratigraphic section covering the time period of interest; (2) the area lies in the marginal ice zone, and the northern and western sites especially are accessible only during favorable ice years, and for this reason it is necessary to have a series of proposed sites to choose from, should one of them not be accessible; and (3) it is desirable to obtain a bathymetric transect of sites in the Arctic Ocean to monitor depth gradients in sediment-accumulation and water-mass properties.

Proposed site YERM 1 is located on the eastern flank of the Yermak Plateau and is designed as a relatively deep target site (Figs. 7 and 17). This site has been proposed to document the subsidence history of the Yermak Plateau and its control on the water-mass exchange through the Arctic gateway, and to determine the age and nature of basement. Furthermore, it will provide records of surface and deep-water communication between the Arctic Ocean and the Norwegian Sea and the IRD-sedimentation history of the Arctic.

Proposed site YERM 2A serves as an alternate site for YERM 1 (Figs. 6, 7, and 17). YERM 2A is located deeper than proposed site YERM 1 on the Southwest slope of the plateau. Besides being an alternate site for YERM 1, this site is designed to study the Neogene-Quaternary glacial history of the Arctic and the history of North Atlantic surface water influx to the Arctic, and to serve as an intermediate member of a bathymetric transect.

Proposed site YERM 3 is located on a thick sequence of draping sediment cover on the eastern flank of the plateau (Figs. 6, 7, and 17). The site is planned to study Neogene variations in climate and oceanography, and will specifically address the Neogene Arctic glacial history and the variations in Atlantic water influx to the Arctic. The site is also the shallow-water member of the bathymetric transect.

Proposed site YERM 4 is located on the thick draping sediment sequence on the western flank of the plateau (Figs. 6, 7, and 17). The objectives are the same as for proposed site YERM 3.

Proposed site YERM 5 is located in 2850 m of water on the lower western slope of the plateau. It will serve as a deep-water end member of the bathymetric transect. The objectives are the same as for other YERM sites, with the addition of studies of deep bottom water history.

Fram Strait (FRAM)

Proposed site FRAM 1 is located in the Fram Strait on a gentle elevated area Northeast of the Hovgaard Ridge (Figs. 6 and 17). Two alternate sites, FRAM 1A and 1B, are proposed as backup sites in case of problematic ice conditions. Proposed site FRAM 1A is the highest priority, but both sites are located in the same area, and the multichannel seismic (MCS) records provide an easy tie between these alternate sites and show the same features on both of them. The site is designed to document the timing of the opening of a deep passageway through the Fram Strait and the history of deep- and shallow-water exchange between the Arctic and the world ocean. It also will provide records of the onset and evolution of Arctic glacial history and climatic variability. The sites are located West of the spreading axis, on post-Anomaly 13 crust. MCS and 3.5-kHz lines document a gently draping sediment cover. The area is elevated with respect to the surrounding regions and should be protected against turbidites and slumps originating from the continental margins. A number of piston cores from this area document normal pelagic sedimentation rates and pelagic sediments with good isotopic and biostratigraphic age control for the late Quaternary.

Proposed site FRAM 2 is situated on the crest of the Hovgaard Ridge (Fig. 6). It is proposed to (1) determine the age and lithology of the sedimentary processes immediately postdating the opening of the Fram Strait, and (2) investigate the shallow water-mass exchange in and out of the Arctic Ocean.

East Greenland Margin (EGM)

The proposed sites on the East Greenland Margin (Fig. 17) are located on a North-South transect paralleling the path of the East Greenland Current (EGC). The objectives are to date the onset of the EGC, monitor deep-water formation and surface-water paleoenvironments in the Greenland Sea, determine their influence on the variability of the polar front and on the Northern Hemisphere paleoclimate, decipher the evolution of the Greenland Ice Sheet, monitor contour current activity and sediment drift deposition in the Greenland Basin, and study Paleogene paleoceanography. Because of time constraints none of the EGM locations except proposed site EGM 2 (Site 913) was drilled.

Iceland Plateau (ICEP)

The sites proposed for this area make up a bathymetric transect of three sites, as well as a site in the central Iceland Sea designated to be a part of the East-West transect (Fig. 17).

Proposed site ICEP-1 represents the midpoint in the East-West transect in the southern Norwegian-Greenland Sea, and is proposed to (1) monitor the history of oceanic and climatic fronts moving East and West across the Iceland Plateau, (2) derive an open-ocean record of IRD and carbonate, and (3) determine the history of the formation of northern-source deep waters. As mentioned previously, the Leg 104 sites, being located close to the Norwegian continental margin, suggest local influence on the IRD records and possible increased dissolution and dilution of carbonate. It is thus of crucial importance to drill a good, open-ocean site isolated from such influence and where subarctic IRD and environmental changes can be properly assessed.

The Iceland Sea is the final station for deep-water production and modification of deep waters formed in the Greenland Sea and in the Arctic Ocean, before the deep waters are exported into the North Atlantic. Results from this drill site are considered necessary to determine the timing, evolution, and variations of these water masses.

The proposed site is located on middle Miocene crust and is overlain by about 300 m of sediment, allowing high-resolution studies of the past 10–12 m.y. Piston cores document Quaternary pelagic carbonate sequences having pronounced glacial-interglacial cycles and ash layers.

Iceland-Faeroe Ridge (NIFR and SIFR)

The proposed areas for drilling North and South of the Iceland-Faeroe Ridge (Fig. 17) were to hold key information on the early spreading stages of the southern Norwegian Sea, the subsidence history of the Iceland-Faeroe Ridge, and the history of one of the major gateways responsible for Northern Hemisphere climate development. Because of time constraints none of the proposed sites was drilled.

Additional Considerations

Sea Ice

The proposed YERM sites, and to a large extent the proposed FRAM sites, are located near a region with close to year-round sea-ice cover (Fig. 12). Sea ice is the potentially largest operational concern for drilling the proposed sites. From studies of the average August and September sea-ice conditions (Vinje, 1976; 1985; Wadhams, 1991) on expected sea-ice hazards, it appears that, in the worst ice years, all proposed sites from the FRAM and YERM areas might be affected by ice. However, the likelihood for ice problems in the August to mid-September window was low and close to negligible for the FRAM 1 and the YERM 2A proposed sites. In normal ice years, the FRAM 2 and the YERM 3 and 4 proposed sites also should be accessible to *JOIDES Resolution*. The YERM 1 and 5 proposed sites would be accessible only during favorable ice years.

Hence it was concluded that the major portions of the drilling program could be accomplished in normal years, including some of the Arctic sites, and all sites could be drilled in good ice years. Thus the chances of success were deemed to be good, and the importance of drilling these frontier regions for the first time certainly made it worthwhile. To drill under optimal sea-ice conditions, an ice forecast/ice surveillance program was implemented, and an ice picket boat employed. The Finnish icebreaker *Fennica* was selected and chartered for this purpose.

Weather

Although the proposed sites are located in high latitude areas, weather conditions in the summer weather window (July–September) are not particularly adverse, and do not pose any threat to the success of the drilling program. Legs 38, 104, and 105 were conducted without weather problems. Recent drilling in the Southern Ocean has proven the capabilities of *JOIDES Resolution* to provide excellent results under much harsher weather conditions than those expected for the summer season in the Norwegian-Greenland Sea and Arctic Ocean.

Heat Flow

An extensive survey of heat-flow measurements on the Svalbard Margin (Crane et al., 1982; Sundvor, 1986) has shown a zone of anomalously high heat flow along a Northwest trend off Svalbard. Only proposed sites YERM 3 and 4 lie within the zone of highest heat flow. Both of these are shallow target sites. The proposed deep target sites, YERM 1 and 2A, are both located in areas with less heat flow.

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