OCEAN DRILLING PROGRAM

LEG 151 SCIENTIFIC PROSPECTUS

NORTH ATLANTIC ARCTIC GATEWAYS 1

Dr. Annik M. Myhre
Co-Chief Scientist, Leg 151
Institutt for Geologi
Universitetet i Oslo
PostBoks 1047
N-0316, Oslo 3
Norway

Dr. Jörn Thiede
Co-Chief Scientist, Leg 151
Forschungszentrum für marine
Geowissenschaften
GEOMAR
Wischhofstrasse 1-3, Gebäude 4
D-2300 Kiel 14
Federal Republic of Germany

Dr. John Firth
Staff Scientist, Leg 151
Ocean Drilling Program
Texas A&M University Research Park
College Station, Texas 77845-9547

Philip D. Rabinowitz
Director
ODP/TAMU

Jack Baldauf
Manager
Science Operations
ODP/TAMU

Timothy J.G. Francis
Deputy Director
ODP/TAMU

April 1993

Scientific Prospectus No. 51
First Printing 1993

Distribution

Copies of this publication may be obtained from the Director, Ocean Drilling Program, Texas A&M University Research Park, 1000 Discovery Drive, College Station, Texas 77845-9547. Orders for copies may require payment for postage and handling.

DISCLAIMER

This publication was prepared by the Ocean Drilling Program, Texas A&M University, as an account of work performed under the international Ocean Drilling Program, which is managed by Joint Oceanographic Institutions, Inc., under contract with the National Science Foundation. Funding for the program is provided by the following agencies:

Academy of Sciences (Russia) - Inactive
Canada/Australia Consortium for the Ocean Drilling Program
Deutsche Forschungsgemeinschaft (Federal Republic of Germany)
Institut Français de Recherche pour l'Exploitation de la Mer (France)
Ocean Research Institute of the University of Tokyo (Japan)
National Science Foundation (United States)
Natural Environment Research Council (United Kingdom)
European Science Foundation Consortium for the Ocean Drilling Program (Belgium, Denmark, Finland, Iceland, Italy, Greece, The Netherlands, Norway, Spain, Sweden, Switzerland, and Turkey)

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation, the participating agencies, Joint Oceanographic Institutions, Inc., Texas A&M University, or Texas A&M Research Foundation.

This Scientific Prospectus is based on pre-cruise JOIDES panel discussions. The operational plans within reflect JOIDES Planning Committee and thematic panel priorities. During the course of the cruise, actual site operations may indicate to the Co-Chief Scientists and the Operations Superintendent that it would be scientifically or operationally advantageous to amend the plan detailed in this prospectus. It should be understood that any proposed changes to the plan presented here are contingent upon approval of the Director of the Ocean Drilling Program in consultation with the Planning Committee and the Pollution Prevention and Safety Panel.

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, since 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, 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 these paleoenvironmental changes in the Arctic and subarctic deep-sea basins.

Leg 151 is scheduled to drill a series of sites in four remote geographic, partly ice-covered locations (the northern gateway region, i.e., Yermak Plateau and Fram Strait, the East Greenland Margin, and the Greenland-Norway Transect, i.e., the Iceland Plateau) with the aim of reconstructing the temporal and spatial variability of the oceanic heat budget and the record of variability in the chemical composition of the ocean. Leg 151 will also undertake a study of circulation patterns in a pre-glacial, relatively warm polar and subpolar ocean, and the mechanisms of climatic change in a predominantly ice-free climatic system. In addition, the proposed drilling includes a collection of sequences containing records of biogenic fluxes ($CaCO_3$, opal, and organic carbon) and stable-isotopic carbon and oxygen records which will address aspects of facies evolution and depositional environments as well as the carbon cycle and productivity. The drilling approach focuses on rapidly deposited sediment sequences to be used for high-resolution, Milankovitch-scale paleoclimatic analysis and rapid sub-Milankovitch-scale climate changes. Most of the proposed sites are arrayed as either broad north-south and 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 include sites chosen for deep drilling that will 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, in particular in the Fram Strait and Yermak Plateau area, will address the age and nature of basement rocks. The sites to the north of Svalbard also constitute the first drilling to be conducted in the Arctic Ocean proper.

INTRODUCTION

During the last decade it has been realized that much of the natural variance in the Earth's environment on time scales less than 1 million years (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. Both for understanding 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 both by this and other forcing mechanisms which operate on longer time scales (such as plate reorganizations, orogeny, carbon cycle variations), it is necessary to obtain records that document how the climatically sensitive, high-latitude regions have developed. The Arctic and subarctic deep-sea basins are known to have reacted faster and with a more extreme range of temperature fluctuations during the late Cenozoic climate change than any other part of the world ocean (CLIMAP, 1976): it follows that this focus on high northern latitude paleoenvironmental questions requires deep-sea drilling in the areas (Fig. 1) north of the Greenland-Scotland Ridge. From south to north these seas 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).

The deep-water areas of the Nordic Seas were previously drilled during DSDP Leg 38 which occupied 17 sites spread out over some of the major basins (Talwani, Udintsev et al.,1976), and ODP Leg 104, which occupied three sites on a transect across the Vøring Plateau in the eastern Norwegian Sea (Eldholm, Thiede, Taylor, et al., 1987). The sites from Leg 38 were almost exclusively chosen to meet structural and geophysical objectives. The holes were rotary drilled and mostly spot cored. The quality and continuity of the Leg 38 material is therefore so poor that it is impossible to establish a chronologic resolution and precision which meet the requirements of modern paleoceanography. The Leg 104 sites were drilled with the advanced piston corer (APC) with high recovery and very good sample quality. The sequences from Leg 104 document parts of the Neogene fairly well despite a number of hiatuses (Goll, 1989). The Paleogene intervals of these sites are either missing or seriously altered by diagenesis. Thus, no sequences are available to document the whole Cenozoic history of these oceans, and major parts of the Cenozoic are still unavailable for investigation by modern methods. Although the upper Neogene especially is rather complete on the Vøring Plateau, the location of the sites basically implies that they must be considered as a single sample point along the meridional and latitudinal transects needed to study the paleoenvironmental evolution of the high latitude regions. The Leg 104 sites cannot on their own resolve the development of major regional differences and the evolution of environmental gradients and fronts.

No scientific drilling has so far been performed in the Arctic, and, due to its inaccessibility, very 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., implying that virtually no knowledge exists of the paleoceanography of the Arctic Ocean. 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. 2), areas on the Yermak Plateau north of Svalbard and hence north of the gateway (Fram Strait) between the Norwegian-Greenland seas and the Arctic Ocean are ice-free and accessible in late summer during normal ice years and can potentially be drilled by normal ODP methodology.

We conclude consequently that the presently available material is far from sufficient for solving the scientific objectives outlined above, and that a whole new program of APC/XCB drilling in various areas of the Nordic Seas is required for this purpose.

STUDY AREA

Oceanographic Setting

The series of interconnected basins making up the Nordic Seas contains a total volume of roughly 10×10^6 km^3, if the Amerasian Basin (Canadian and Makarov basins) of the Arctic Ocean is excluded, or about 0.7% of the volume of the world ocean. The Eurasian Basin of the Arctic Ocean makes up nearly 60% of this volume. The idea that deep waters are formed in the Norwegian-Greenland seas (Helland-Hansen and Nansen, 1909), and that some of this newly formed water flows into the deep Atlantic across saddles on the Greenland-Scotland Ridge (see Warren, 1981; Mantyla and Reid, 1983, for reviews), was suggested a long time ago. Previous notions about the Arctic Ocean indicated that it has been a passive recipient of ventilated water from the south. In recent years, however, it has been demonstrated that the Arctic Ocean itself is an important contributor of deep waters which flow southward through the Fram Strait and, after mixing with deep waters formed in the Greenland-Iceland seas, pass farther on into the world ocean (Aagaard, 1981; Aagaard et al., 1985). The processes leading to the formation of dense deep waters in the

Arctic Ocean are thought to involve either intense cooling of Atlantic waters on the Barents Sea Shelf (Swift et al., 1983) or an increase in salinity through salt release during sea-ice formation on the large Arctic shelves (Aagaard et al., 1985). Smethie et al.(1988) suggest that both processes are operating.

The chief components of the surface water systems of the Nordic Seas involve the influx of warm and relatively high-salinity waters via the North Atlantic Current (Fig. 3a), which continues its northward flow as the Norwegian Current and outflow via the cold and low-salinity 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. 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 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.

Aagaard et al. (1985) concluded that nearly 50% of the water volume in the Nordic Seas, including the Amerasian Basin, is potentially in communication with the world ocean (Fig. 3b). The Nordic Seas might hence be characterized as the "lungs" of the present world ocean, implying that it is of fundamental importance to derive a detailed understanding of the timing and history of deep and shallow water exchange between the Nordic Seas and the remainder of the world ocean. The unique topographic constraints provided by a single deep, narrow passageway to the North (the Fram Strait), and a major submarine ridge system to the south (Greenland-Scotland Ridge), make it pertinent to address the question of the Cenozoic paleoceanography of the Nordic Seas as a gateway problem (Fig. 4).

The 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, has determined the possibilities for water-mass exchange between the Nordic Seas and the Atlantic Ocean, and thus the world ocean.

The Fram Strait, with a present critical sill depth of 2600 m, represents the only deep connection between the Arctic Ocean and the global ocean. The initiation of this connection may have taken place as early as Anomaly 13 time, close to the Eocene/Oligocene boundary (Crane et al., 1982; Eldholm et al., 1987; 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 at best, which might include stretching of the Svalbard continental crust and hotspot activity. When taking into account the strongly oblique opening of the Fram Strait and the nearness 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). 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.

There are few oceanic gateways that can compete with the Greenland-Scotland Ridge in having such a profound influence on the present world hydrography (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 lately been disputed 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 Nordic Seas were effectively isolated from any "deep" Atlantic influence until middle Miocene times (Berggren and Schnitker, 1983; Thiede, 1983; Thiede and Eldholm, 1983). The overflows have both influenced 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.

The Nordic Seas are characterized by strong latitudinal gradients in the sea-surface environment and also by unusually strong meridional gradients due to the warm Atlantic influence in the east and the cold polar influence in the west (Fig. 3a). Strong 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 by ODP Leg 104, no high-quality samples exist which are older than a few hundred thousand years. Thus, to derive a comprehensive understanding of the whole ocean-climate system of the Nordic Seas, and the *modus operandi* of this, in a global-perspective critical system, it is necessary to obtain continuous sediment cores that can document how sea-surface environments have changed and the underlying causes for these changes through late Paleogene and Neogene through Quaternary times.

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 later 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 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.

At present it is uncertain when cold climates evolved in the Arctic and surrounding regions. In order 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 late Miocene (Clark 1982) or even earlier (Wolf and Thiede, 1991). Other studies conclude that this event happened in 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 verified 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 ODP Leg 104 document minor input of ice-rafted debris (IRD) into the Nordic Seas 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 Nordic Seas (Jansen and Sjøholm, 1991; Wolf and Thiede, 1991). IRD data from ODP Leg 105, Site 646, suggest the onset and discontinuous existence of sea-ice covers in the Labrador Sea to the south of Greenland since middle/late Pliocene 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, i.e., 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, which are 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; Wolf and Thiede, 1991). The chronology from these land sites is, however, poorly constrained, and since this is only scattered evidence, there are no continuous records from land sites that document the climatic transition into a cold Arctic climate. Both a clear documentation and a proper timing of the climatic evolution will therefore depend on the availability of new, continuous deep-sea sediment cores.

Since the glacial and climatic history of the high northern latitudes is so poorly known, the ability to model and understand linkages between low and high latitude climates and between southern and northern hemisphere climates is limited. The Norwegian-Greenland Seas 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, some 36 m.y. ago (Barron, Larsen, Baldauf, and Leg 119 Scientific Party, 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 responds to external forcing (Ruddiman et al., 1986; Ruddiman and Raymo, 1988; Raymo et al., 1990). Work is under way, based on Leg 104 material, 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 Nordic Seas.

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 thereby partly depend on records that can assess the actual climatic and oceanographic evolution of this particular region.

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 matter, and nonbiogenic sediment components determine the internal cycling of matter in the oceans and are therefore 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 deep-sea sediments, accumulate at rates which are determined by the productivity rates in the surface waters and the dissolution of these components at depth.

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

ODP 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 paleoenvironment 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 Nordic Seas.

Biological Evolution

The coring program envisaged herein will recover high-quality APC/XCB sediment material reflecting a wide variety of paleoenvironmental conditions in the Nordic Seas, and it is anticipated that the material also will be used to address a wide array of significant scientific questions which have not been specifically mentioned in the three main themes.

Studying biological evolution is one such additional but very important scientific problem. Such studies will allow the assessment of the response of oceanic biota to changes in climate, ocean circulation, and ocean 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 and floras, and Arctic/subarctic environmental influence on intra- and inter-specific morphological variation.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

Cenozoic Paleoceanography of the Nordic Seas

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).

2) To study the timing and history of deep and shallow water inflow and outflow between the Norwegian-Greenland Sea and the North Atlantic across the Greenland-Scotland Ridge.

3) To investigate water mass evolution, particularly addressing the initiation and variability of east-west and north-south oceanic fronts in surface waters, the initiation and variability of northern-source deep-water formation, 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 interhemispheric 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 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.

Specific Objectives and Methodology

Surface Water-Mass Evolution

The Norwegian-Greenland Sea links the cold Arctic Ocean with the warm-temperate North Atlantic Ocean via northern and southern "gateways" (Fig. 1). Fram Strait in the north is the single passage to the Arctic Ocean through which surface and deep waters are exchanged. Similar exchanges occur farther south at both the Denmark Strait, Faeroe-Shetland Channel, and Iceland-Faeroe Ridge.

The Nordic Seas are characterized by strong oceanographic gradients, not just latitudinally but also meridionally, due to 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 by ODP Leg 104 and in the Labrador Sea by ODP Leg 105, the history of these surface-ocean gradients is almost totally unknown prior to that of the last few hundred thousand years. ODP 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. Very little is known about how this ice cover first developed and subsequently varied. Although prevented from drilling within the permanent pack ice in the Central Arctic, *JOIDES Resolution* 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 Nordic 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 Nordic Seas and Atlantic Ocean, although other tectonic changes may also play a role in determining the subsequent long-term evolution of meridional exchanges across these former barriers (Fig. 4). 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

At present, deep waters of the subarctic North Atlantic form partly from dense saline waters cooled in the Greenland and Iceland seas, and partly from deep waters flowing out of the Arctic Ocean. Because of their rapid formation and short residence times, these deep waters are rich in O_2 but poor in CO_2 and nutrients. The deep water spills over the Greenland-Scotland Ridge and mixes with warmer North Atlantic waters to form southward-flowing North Atlantic Deep Water (NADW). NADW helps to oxygenate the deep ocean and transfers heat and salt to the Antarctic. Glacial/interglacial changes in deep-water formation in the Nordic Seas are implicated in conceptual models of atmospheric CO_2 variations.

ODP drilling in the Nordic Seas will improve the understanding of deep-water evolution by providing spatial/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 around the Nordic Seas

Results from ODP Leg 104 trace the glacial history of the Fennoscandian Ice Sheet back to 2.57 Ma. Sporadic earlier occurrences of minor quantities of ice-rafted debris in various North Atlantic drill sites indicate a still earlier onset of limited glaciation around the Nordic Seas. Both the location and kind of 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 somewhere else? It is thus a primary drilling objective to obtain sediments from sites adjoining these regions to assess their glacial histories individually.

Sediment Budgets

In order 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 Nordic Seas 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 PLAN/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 also 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/Nordic climate system should thus be understood to include both orbital-scale and tectonic-scale changes.

Leg 151 comprises a series of proposed sites drilled to form a north-south transect, an east-west transect (linked to the ODP Leg 104 sites in the east), and a bathymetric transect. The sites should be double, or even triple, APC/XCB cored in order 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. It can thereby tie into existing North Atlantic

(DSDP Legs 81, 94) and Labrador Sea (ODP Leg 105) high-resolution stratigraphies. This transect will cover the major ocean basins of the region and provide sites on both sides of the Fram Strait to the north of the Greenland-Scotland Ridge, and it will address the evolution of north-south environmental gradients from the Arctic to the North Atlantic. A second Arctic gateways leg is planned in order to drill those sites that were not drilled by Leg 151 due either to sea-ice limitations or time limitations.

The east-west transect will use the Leg 104 sites on the Vøring Plateau as its eastern tie-point and will extend 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 mid to high latitude east-west gradients and oceanic fronts, and to investigate differences in the oceanic and glacial evolution between Greenland and Northern Europe. Additionally it is necessary to include a central sample point along this transect in order to obtain clean pelagic records from the central parts of the basin.

Two bathymetric transects are also proposed to study sediment budgets, lysocline/ CCD-variability, and bathymetric gradients in ocean chemistry: one on the Yermak Plateau in the Arctic and the other on the slope between the Iceland Plateau and the Aegir Ridge (extinct axis) in the Norwegian Basin. This area is located centrally in the Norwegian Sea and will not be influenced by continental margin effects.

The overall drilling strategy will be affected by (1) the priority of the proposed drill sites, (2) the availability of ice-breaker coverage, and (3) ice conditions.

JOIDES Resolution will leave St. John's, Newfoundland, no later than 30 July 1993 and will rendezvous with the ice breaker MSV *Fennica* in Fram Strait on 16 August 1993, which allows roughly 18 days for transit and drilling operations before the ice breaker arrives. The *Fennica* will leave the *Resolution* on 13 September 1993, leaving us with 11 more days of operations and transit time before arriving in Reykjavik on 24 September 1993. The northernmost sites are the most important for meeting the leg objectives outlined above and are also the most likely to need support from the ice breaker. Therefore, the first part of the leg is designed to drill relatively ice-free sites en route to meeting the *Fennica*. Transit from St. John's to Fram Strait is estimated to take approximately 9 days, which leaves approximately 9 days for drilling. The first site to be drilled en route to Fram Strait is ICEP 1. Either FRAM 1A or FRAM 1B then will be drilled with the time remaining before rendezvous. FRAM 1B has a higher possibility of ice-free conditions than FRAM 1A. In order to maximize the use of the *Fennica,* we will attempt to drill first the Yermak Plateau sites (in order of priority: YERM 1, YERM 3, and YERM 5, with YERM 2A and YERM 4 as alternates), followed by the remaining sites in Fram Strait, then on the East Greenland Margin, the Iceland Plateau, and the Iceland-Faeroe Ridge. Throughout the leg, changing ice conditions will determine when and if any particular site is drilled, and how much of the drilling objectives are reached at any one site. Because of this, total estimated values for drilling time and penetration, logging time, and transit time are not calculated (Tables 1 and 2).

PROPOSED SITES

Yermak Plateau (YERM)

The Yermak Plateau is a topographic marginal high due north of Svalbard. The Morris Jesup and northeastern Yermak rises are a pair of plateaus rising to crestal depths of 0.5 to 1 km, which apparently were formed in Paleocene-Oligocene time by excess Iceland-like volcanism along the southwestern Gakkel Ridge. The southern part of the Yermak Plateau may be thinned continental crust (Jackson et al., 1984). Thick sediment drapes both the western and eastern flanks. Gravity and piston cores show that the present sediment cover contains some biogenic calcareous components and document normal pelagic sedimentation rates.

Drilling in this area will enable a study of environmental responses pre- and postdating the opening of the deep gateway into the Arctic. It will document 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 will furthermore provide a check for the theory linking 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 Ocean and the world ocean (cf. Fig. 4). The other main achievement from drilling this area is that it should provide a continuous upper Neogene 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, 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/chronostratigraphic 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 to monitor depth gradients in sediment-accumulation and water-mass properties.

Proposed site YERM 1 is located on the eastern flank of the Plateau and is designed as a deep target site (Fig. 5; Tables 1 and 2). 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 and the Norwegian Sea and the IRD-sedimentation history of the Arctic.

Proposed site YERM 2A might, in part, serve as an alternate site for YERM 1 (Fig. 5; Tables 1 and 2). YERM 2A is located deeper than proposed site YERM 1 on the southwest slope of the plateau. It will, however, not be drilled to basement. Besides being an alternate site for YERM 1, this site is designed to study the Neogene glacial history of the Arctic, the history of North Atlantic surface water influx to the Arctic, and to be an intermediate member of a bathymetric transect. Basement is considered to be oceanic crust.

Proposed site YERM 3 is located on a thick sequence of draping sediment cover on the eastern flank of the plateau (Fig. 5; Tables 1 and 2). It is planned as a site to study Neogene variations in climate and oceanography, and will specifically address the Neogene Arctic glacial history and the Neogene variations in Atlantic water influx to the Arctic. It 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 (Fig. 5; Tables 1 and 2). The objectives are the same as for proposed site YERM 3.

Proposed site YERM 5 is located at 2850 m on a conformable draping sediment sequence on the lower western slope of the plateau (Fig. 5; Tables 1 and 2). The site will be used to document the glacial history of the Arctic Ocean for the Neogene, the history of sea-ice cover, the history of Atlantic water influx, and deep water variations; it will serve as the deep end-member of the bathymetric gradient.

Fram Strait (FRAM)

Proposed site FRAM 1 is located in the Fram Strait on a gentle elevated area northeast of the Hovgaard Ridge (Fig. 5; Tables 1 and 2). Two alternate proposed sites, FRAM 1A and 1B, are proposed in order to have a backup site 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 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 will also provide records of the onset and evolution of Arctic glacial history and the climatic variability of the Arctic region. The sites are located west of the complex spreading center, on post-Anomaly 13 crust. MCS and 3.5-kHz lines document a gently draped 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 Quaternary.

Proposed site FRAM 2 is situated on the crest of the Hovgaard Ridge (Fig. 5; Tables 1 and 2). It is proposed in order to (1) determine the age and lithology of the sedimentary processes immediately postdating the opening of the Fram Strait, and (2) investigate the water-mass exchange in and out of the Arctic Ocean. The Hovgaard Ridge is a topographic high which is thought to be a continental fragment severed off Svalbard during the early rifting phase (Eldholm and Myhre, 1977; Myhre and Eldholm, 1988). A few small sediment basins are located on the ridge, which potentially contain sediments documenting the early history of sedimentation after the ridge subsided below sea level. Drilling at this site potentially should be able to document the earliest post-opening events, whereas proposed site FRAM 1 is better suited to document the Neogene sections.

East Greenland Margin (EGM)

The proposed sites on the East Greenland Margin (Fig. 5; Tables 1 and 2) 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.

Proposed site EGM 2 is located on the lower slope of the east Greenland continental margin and is the northern end of a north-south transect along the margin. It is proposed in order to document the history of the EGC and of deep-water flow out of the Arctic downstream from Fram Strait. Proposed sites EGM 1 and EGM 3 are alternate sites.

Proposed site EGM 4 is situated on the lower slope of the Trough Mouth Fan at Scoresby Sund. It is intended for high-resolution studies of the late Neogene history of IRD input and evolution of the Greenland Ice Sheet. It is also located where intermediate and deep waters from the Greenland Sea flow toward Denmark Strait. The Trough Mouth Fan of Scoresby Sund was surveyed by the Greenland Geological Survey (GGU), the Bundesanstalt für Geowissenschaften (BGR), and *Polarstern* (ARK/V).

Iceland Plateau (ICEP)

The sites proposed for this area comprise 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. 5; Tables 1 and 2).

Proposed site ICEP 1 represents the mid-point in the east-west transect in the southern Nordic Seas, 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 above, 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 in order 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 throughout the past 10-12 m.y. Piston cores document Pleistocene pelagic carbonate sequences with pronounced glacial-interglacial cycles and ash layers.

Proposed sites ICEP 2, 3, and 4 form a bathymetric transect from the Iceland Plateau down toward the Norway Basin along University of Bergen line ICEP-2 Segment D. As a southern end-member of the north-south transect, these sites will enable a study of the oceanic response to different stages in the opening of the Greenland-Scotland gateway north of the ridge. They will also provide a continuous high-resolution pelagic upper Neogene record. The bathymetric transect enables documentation of CCD and carbonate preservation as well as biogenic silica budgets and their response to changing oceanic and climatic conditions. As a key location for the east-west transect, they will enable a study of variations in surface currents and oceanic fronts. They will also provide a record of pelagic IRD input well away from the ice sheets, thereby avoiding strong continental influence. This will ensure a more complete biogenic record than is available from locations closer to the coasts.

The area is well suited for studies of the chemical characterization of intermediate and deep waters through time. In turn this will have a profound influence on the understanding of the initiation and variation in NADW and global ocean circulation.

The basement is of Anomaly 23-24 age and is overlain by 700-800 m of acoustically transparent sediment on an evenly draped gentle slope. The proposed sites are located to the south on the flanks of the Jan Mayen Ridge. This location makes it possible to avoid disturbances caused by the large vertical movements of the Jan Mayen microcontinent during the Paleogene.

Northern Iceland-Faeroe Ridge (NIFR)

The proposed area for drilling north of the Iceland-Faeroe Ridge (Fig. 5; Tables 1 and 2) holds key information on the early spreading stages of the southern Norwegian Sea and the subsidence history of the Iceland-Faeroe Ridge. Compared with selected sites south of the Iceland-Faeroe Ridge, lithological and biological facies changes may indicate the development of the complex current systems that have crossed the ridge since its initiation in Early to Middle Neogene times. This area provides the unique opportunity of describing the developments of Paleogene environments and determining exactly the early phases of warm surface-water inflow from the North Atlantic, as a key parameter for Northern Hemisphere climate.

Southern Iceland-Faeroe Ridge (SIFR)

The area south of the Iceland-Faeroe Ridge covers the key position for data on the origin and early subsidence history of the Iceland-Faeroe Ridge as the major gateway responsible for Northern Hemisphere climate development. Since the warm North Atlantic Current advected this area also during Early to Middle Neogene times, lithological and biological facies changes from the ridge into the southern Norwegian Sea may help to clarify the onset of surface- and bottom-water exchanges over the ridge. The location of the proposed area (Fig. 5; Tables 1 and 2) provides the opportunity of determining the age and nature of the Iceland-Faeroe Ridge and of the overlying sediments, which will provide crucial information about the early history of the ridge. Drilling in this area can also determine if a stepwise or more sudden exchange of surface and bottom water occurred across the Iceland-Faeroe Ridge during the Early Neogene.

ADDITIONAL CONSIDERATIONS

Sea Ice

The proposed YERM sites, and to a large extent the proposed FRAM sites also, are located near a region with close to year-around sea-ice cover. 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, 1985) of the Norwegian Polar Research Institute on expected sea-ice hazards, it appears that, in the worst ice years, all proposed sites from the FRAM and YERM areas might potentially be affected by ice. However, the likelihood for ice concerns in the August to mid-September window is low and close to being 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 will be accessible only during favorable ice years.

From this it is concluded that the major portions of the drilling program can be accomplished in normal years, including some of the Arctic sites, and all sites can be drilled in good ice years. Thus the chances of success are good, and the importance of drilling these frontier regions for the first time certainly makes it worthwhile. In order to drill under the most optimal sea-ice conditions, an ice forecast/ice surveillance program will be implemented, and an ice picket boat employed.

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. Both DSDP Leg 38 and ODP Leg 104 were carried out without weather problems. Recent drilling in the Southern Ocean has proven the capabilities of *JOIDES Resolution* to provide excellent results under much harder weather conditions than those expected for the summer season in the Nordic Seas.

Heat Flow

An extensive survey of heat-flow measurements on the Svalbard Margin (Crane et al., 1982; Sundvor et al., 1988) 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.

REFERENCES

Aagaard, K., 1981. On the deep circulation in the Arctic ocean. *Deep-Sea Res.* 15:281-296.

Aagaard, K., Swift, J.H., and Carmack, E.C., 1985. Thermohaline circulation in the Arctic Mediterranean Seas. *J. Geophys. Res.* C3, 90:4833-4846.

Barron, J., Larsen B., Baldauf, J., and Leg 119 Shipboard Party, 1988. Early glaciation of Antarctica. *Nature*, 333:303-304.

Barron, A.J., and Washington, W.M., 1984. The role of geographical variables in explaining paleoclimates: results from Cretaceous climate model sensitivity studies. *J. Geophys. Res.*, 89:1267-1279.

Barry, R.G., 1989. The present climate of the Arctic Ocean and possible past and future states. *In* Herman, Y. (Ed.), *The Arctic Seas - Climatology, Oceanography, Geology, and Biology.* New York, 1-46.

Berggren W.A., and Schnitker, D., 1983. Cenozoic marine environments in the North Atlantic and Norwegian-Greenland Sea. *In* Bott, M.H.P., et al. (Eds.), *Structure and Development of the Greenland-Scotland Ridge.* NATO Conf. Ser. IV, Plenum Press, New York, 495-548.

Bernero, C., 1982. *Tertiary Paleobathmetry of the Norwegian/Greenland Sea and Eurasia Basin of the Arctic Ocean.* Unpubl. B.S. Thesis, Univ. Oklahoma, Tulsa, Oklahoma.

Bohrmann, G., 1988. Zur Sedimentationsgeschichte von biogenem Opal im nördlichen Nordatlantik und dem Europäischen Nordmeer (DSDP/ODP-Bohrungen 408, 642, 643, 644, 646 und 647). *Berichte SFB 313, 9*, Univ. Kiel, 221 pp.

Bott, M.H.P., Saxov, S., Talwani, M., and Thiede, J. (Eds.), 1983. *Structure and Development of the Greenland-Scotland Ridge.* NATO Conf. Ser. IV, Plenum Press, New York, 1-685.

Boyle, E.A., 1988. Late Quaternary atmospheric carbon dioxide: Control by ocean circulation and vertical chemical fractionation. *J. Geophys. Res.*, C12, 93:15701-15714.

Broecker, W.S., and Peng, T-H., 1982. *Tracers in the Sea.* Eldigio Press, Palisades, N.Y., 690 pp.

Broecker, W.S., Peteet, D.M., and Rind, D., 1985. Does the ocean-atmosphere system have more than one stable mode of operation? *Nature*, 315:21-26.

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

CIA (Central Intelligence Agency), 1978. *Polar Regions Atlas*. Washington, 66 pp.

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

CLIMAP, 1976. The surface of the ice-age earth. *Science,* 191:1131-1137.

Crane, K., Eldholm, O., Myhre, A.M., and Sundvor, E., 1982. Thermal implications for the evolution of the Spitsbergen transform fault. *Tectonophys*., 89:1-32.

Einarsson, T., and Albertsson, K.J., 1988. The glacial history of Iceland during the past three million years. *Phil. Trans. R. Soc. Lond.*, B 318:637-644.

Eldholm, O., Faleide, J.I., and Myhre, A.M., 1987. Continent-ocean transition at the western Barents Sea/Svalbard continental margin. *Geology*, 15:1118-1122.

Eldholm, O., and Myhre, A.M., 1977. Hovgaard Fracture Zone. *Norsk Polarinst. Årbok , 1979*: 195-208.

Eldholm, O., Thiede, J., Taylor, E., et al., 1987. *Proc. ODP Init. Repts*., 104: College Station, TX (Ocean Drilling Program).

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

Goll, R.M., 1989. A synthesis of Norwegian Sea biostratigraphies: ODP Leg 104 on the Vøring Plateau. *In* Eldholm, O., Thiede, J., Taylor, E., et al., *Proc. ODP Sci. Results*, 104: College Station, TX (Ocean Drilling Program), 777-826.

Hay, W.W., 1985. *Impact of Ocean Drilling on the Earth Sciences*. JOI pamphlet.

Helland-Hansen, B., and Nansen, F., 1909. The Norwegian Sea: Its physical oceanography based upon the Norwegian researches 1900-1904. *Rep. Norw. Fish. Mar. Invest.*, 2:1-390.

Herman, Y., and Hopkins, D.M., 1980. Arctic Ocean climate in late Cenozoic times. *Science*, 209:557-562.

Hurdle, B.G. (Ed.), 1986. *The Nordic Seas:* Springer-Verlag, New York, 777 pp.

Jackson, H.R., Johnson, G.L., Sundvor, E., and Myhre, A.M., 1984. The Yermak Plateau; formed at a triple junction. J. *Geophys. Res.* B5, 89:3223-3232.

Jansen, E., Bleil, U., Henrich, R., Kringstad, L., and Slettemark, B., 1988. Paleoenvironmental changes in the Norwegian Sea and the Northeast Atlantic during the last 2.8 Ma.: DSDP/ODP Sites 610, 642, 643 and 644. *Paleoceanography,* 3:563-581.

Jansen, E., and Sjøholm, J., 1991. Reconstruction of glaciation over the past 6 Myr from ice-borne deposits in the Norwegian Sea. *Nature*, 349:600-603.

Kidd, R.B., and Hill, P.R., 1987. Sedimentation on Feni and Gardar sediment drifts. *In* Ruddiman, W.F., Kidd, R.B., et al., *Init. Repts. DSDP*, 94, Pt. 2: Washington (U.S. Govt. Print. Office), 1217-1244.

Kristoffersen, Y., 1990. On the tectonic evolution and paleoceanographic significance of the Fram Strait gateway. *In* Bleil, U., and Thiede, J. (Eds.), *Geological History of the Polar Oceans: Arctic versus Antarctic*. NATO ASI Ser., C308:63-76.

Mantyla, A.W., and Reid, J.L., 1983. On the abyssal circulation of the world ocean. *Deep-Sea Res.*, 30:805-833.

Miller, K.G., and Tucholke, B.E., 1983. Development of Cenozoic abyssal circulation south of the Greenland-Scotland Ridge. *In* Bott, M.H.P., et al., (Eds.), *Structure and Development of the Greenland-Scotland Ridge*. NATO Conf. Ser. IV, Plenum Press, New York, 549-590.

Mix, A.C., and Pisias, N.G., 1988. Oxygen isotope analyses and deep sea temperature changes: implications for rates of oceanic mixing. *Nature*, 331:249-251.

Mudie, P.J., and Helgason, J., 1983. Palynological evidence for Miocene climatic cooling in eastern Iceland about 9,8 Myr ago. *Nature*, 303:689-692.

Myhre, A., and Eldholm, O., 1988. The western Svalbard margin. *Marine Petrol. Geol.*, 5:134-156.

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

Peterson, W.H., and Rooth, C.G.H., 1976. Formation and exchange of deep water in the Greenland and Norwegian seas. *Deep-Sea Res.*, 23:273-283.

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

Raymo, M.E., Ruddiman, W.F., Backman, J., Clement, B.M., and Martinson, D.G., 1989. Late Pliocene variation in Northern Hemisphere ice sheets and North Atlantic Deep Water circulation. *Paleoceanography,* 4:413-446.

Repenning, C.A., Brouwers, E.M., Carter, L.D., Marincovitch, L., Jr., and Ager, T.A., 1987. The Beringian ancestry of *Phenacomys* (Rodentia: Cricetidae) and the beginning of the modern Arctic Ocean borderland biota. *U.S. Geol. Survey Bull.*, 1687:1-28.

Ruddiman, W.F., and Raymo, M.E., 1988. Northern hemisphere climate regimes during the last 3 Ma: Possible tectonic connections. *Phil. Trans. R. Soc. Lond.*, B 318:411-430.

Ruddiman, W.F., Raymo, M., and McIntyre, A., 1986. Matuyama 41,000-year cycles: North Atlantic Ocean and northern hemisphere ice sheets. *Earth Planet. Sci. Lett.*, 80:17-129.

Shackleton, N.J., 1987. The carbon isotope record of the Cenozoic: History of carbon burial and of oxygen in the ocean and atmosphere. *In* Brooks, J., and Fleet, A.J., (Eds.), Marine Petroleum Source Rocks. *Geol. Soc. London Spec. Publ.*, 26:423-434.

Shackleton, N.J., Backman, J., Zimmerman, H., Kent, D.V., Hall, M.A., Roberts, D.G., et al., 1984. Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region. *Nature*, 307:620-623.

Shackleton, N.J., and Boersma, A., 1981. The climate of the Eocene Ocean. *J. Geol. Soc. London*, 138:153-157.

Shackleton, N.J., and Kennett, J.P., 1975. Late Cenozoic oxygen and carbon isotopic changes at DSDP Site 284: Implications for glacial history of the Northern Hemisphere and Antarctic. *In* Kennett, J.P., Houtz, R.E., et al., *Init. Repts. DSDP*, 29: Washington (U.S. Govt. Print. Office), 801-807.

Smethie, W.M., Chipman, D.W., Swift, J.H., and Koltermann, K.P., 1988. Chlorofluoromethanes in the Arctic Mediterranean Sea: Evidence for formation of bottom water in the Eurasian Basin and deep-water exchange through Fram Strait. *Deep Sea Res.*, 35:347-370.

Sundvor, E., Myhre, A.M., and Eldholm, O., 1988. Heat Flow Measurements on the Norwegian Continental Margin. *Seismo-Series*, 27, University of Bergen.

Sverdrup, H.U., Johnson, M.W., and Fleming, R.H., 1942. *The Oceans: Their Physics, Chemistry, and General Biology*: Prentice-Hall, New Jersey, 1-1087.

Swift, J.H., Takahashi, T., and Livingston, H.D., 1983. The contribution of the Greenland and Barents Seas to the deep water of the Arctic Ocean. *J. Geophys. Res.*, 88:5981-5986.

Talwani, M., Udintsev, G., et al., 1976. *Init. Repts. DSDP*, 38: Washington (U.S. Govt. Print. Office).

Thiede, J., 1983. Outstanding geological problems of the Greenland-Scotland Ridge: An introduction. *In* Bott, M.H.P., et al. (Eds.), *Structure and Development of the Greenland-Scotland Ridge*. NATO Conf. Ser. IV, Plenum Press, New York, 313-318.

Thiede, J., and Eldholm, O., 1983. Speculations about the paleo-depth of the Greenland-Scotland Ridge during Late Mesozoic and Cenozoic times. *In* Bott, M.H.P., et al. (Eds.), *Structure and Development of the Greenland-Scotland Ridge*. NATO Conf. Ser. IV, Plenum Press, New York, 445-456.

Thiede, J., and NAD Science Committee, 1992. *The Arctic Ocean Record: Key to Global Change* (Initial Science Plan). *Polarforschung,* 61/1:1-102, 1991.

Thierstein, H.R., and Berger, W.H., 1978. Injection events in ocean history. *Nature,* 5687:461-466.

Vinje, T., 1985. Drift, composition, morphology and distribution of the sea ice fields in the Barents Sea. *Norsk Polarinst. Skrifter,* 179C:1-26.

Vogt, P.R., 1986a. Seafloor topography, sediments, and paleoenvironments. *In* Hurdle, B.G. (Ed.), *The Nordic Seas:*Springer-Verlag, New York, 237-412.

Vogt, P.R., 1986b. Geophysical and geochemical signatures and plate tectonics. *In* Hurdle, B.G. (Ed.), *The Nordic Seas:*Springer-Verlag, New York, 413-662.

Vogt. P.R., Bernero, C., Kovacs, L.C., and Taylor, P., 1981. Structure and plate tectonic evolution of the marine Arctic as revealed by aeromagnetics. *Oceanologica Acta SP:* 25-40.

Warren, B.A., 1981. Deep circulation of the world ocean. *In* Warren, B.A., and Wunsch, C. (Eds.), *Evolution of Physical Oceanography:* MIT Press, Cambridge, Mass., 6-41.

Wold, C.N., 1992. *Paleobathymetry and Sediment Accumulation in the Northern North Atlantic and Southern Greenland-Iceland-Norwegian Sea.* PhD Thesis, Kiel University, 255 pp.

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

TABLE 1
LEG 151 TIME ESTIMATES

Site	Location Latitude	Location Longitude	Water Depth (m)	Penetration (m)	Drill[1] (days)	Log[2] (days)	Total (days)	Transit (nmi)	Transit[3] (days)
St. John's	47°42'N	52°42'W						1680	7
ICEP 1	69°15'N	12°42'W	1950	370	4.4	1	5.4	600	2.5
FRAM 1B	78°33'N	5°E	2500	810	9	1.4	10.4		
or									
FRAM 1A	78°36'N	3°E	2590	875	8	1.3	9.3	120	-
Rendezvous with ice breaker MSV *Fennica* on 16 August 1993									
Priority of sites with ice breaker are as follows:									
YERM 1	81°05.5'N	7°E	900	750	6.3	1.2	7.5	50	-
YERM 3	80°25.5'N	8°13'E	975	500	4.4	1.1	5.5	70	-
YERM 5	79°58.5'N	1°42'E	2850	600	7.7	1.3	9	50	-
YERM 2A	79°54'N	5°50'E	1185	600	9.5	1.5	11	50	-
YERM 4	80°16'N	6°38'E	600	500	4	1	5	120	-
FRAM 1A or 1B: See above								25	-
FRAM 2	78°22'N	1°25'E	1290	360	3.9	1	4.9	240	-
EGM 2	75°25'N	7°20'W	3400	750	9.9	1.5	11.4	310	-
EGM 4	70°30'N	18°20'W	1670	800	7.7	1.3	9	280	-
EGM 1	74°52'N	10°06.5'W	3250	900	12	1.6	13.6	100	-
EGM 3	73°28.5'N	13°9'W	2650	900	10.7	1.5	12.2	430	-
ICEP 3	66°56'N	6°27'W	2807	500	4.7	1.1	5.8	25	-
ICEP 2	66°54'N	5°56'W	3250	700	8.7	1.4	10.1	25	-
ICEP 4	67°2'N	7°56'W	1800	300	6.5	1.1	7.6	240	-
NIFR 1	63°26.55'N	7°14.51'W	1240	1000	10.3	1.5	11.8	100	-
SIFR 1	60°33.30'N	11°29.0'W	1215	500	5	1.1	6.1	460	-
Reykjavik	64°N	22°W							

[1] Drilling time estimates based on APC penetration to 200 m, and either XCB or RCB penetration to full depth.

[2] Logging times based on logging to full depth, plus high-resolution logging of APC section (200 m), plus hole conditioning time, without use of the side entry sub (SES).

[3] Transit times are based on ship's speed of 10 kt.

TABLE 2
LEG 151 LOGGING ESTIMATES

Site	Water Depth (m)	Sediment Depth (m)	Standard[1] (hr)	FMS (hr)	Total Log (hr)	Total Log (days)
ICEP 1	1950	300	20.2	3.2	23.4	0.97
FRAM 1B	2500	810	29.4	5.1	34.5	1.44
or						
FRAM 1A	2590	875	27.3	4.7	32	1.33
YERM 1	900	750[2]	24.9	3.5	28.4	1.18
YERM 3	975	500	22.1	3.1	25.2	1.05
YERM 5	2850	600	26.4	4.7	31.1	1.29
YERM 2A	1185	600	31.5	5.2	36.7	1.53
YERM 4	600	500	21.5	2.8	24.3	1.01
FRAM 2	1290	360	20.3	2.9	23.1	0.96
EGM 2	3400	750	29.7	5.6	35.3	1.47
EGM 4	1670	800	27.7	4.3	32	1.33
EGM 1	3250	900	31.9	5.9	38	1.58
EGM 3	2650	900	31	5.4	36.4	1.52
ICEP 3	2807	500	21.5	3.8	25.3	1.05
ICEP 2	3250	700	27.8	5.2	33	1.37
ICEP 4	1800	520	23.6	3.7	27.3	1.13
NIFR 1	1240	300	31.7	5.3	37	1.54
SIFR 1	1215	500	22.8	3.4	26.2	1.09

[1] Includes geophysical tool, geochemical tool, hole preparation, rig-up and rig-down times, and 2 hr extra for high-resolution logging of 200 m of APC hole.

[2] Includes basement penetration of 50 m.

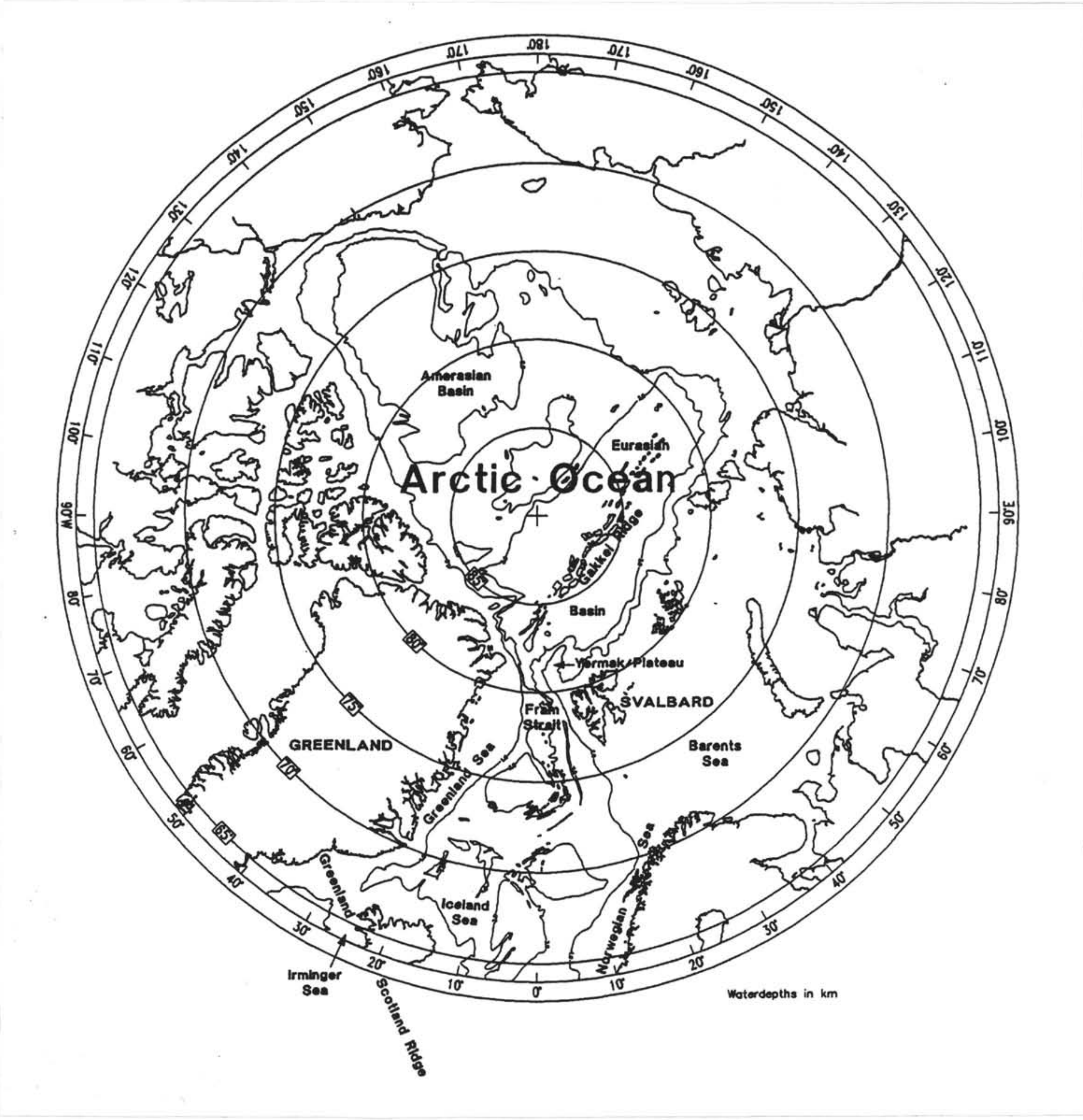


Figure 1. Bathymetric map of the Arctic. Water depths in kilometers.

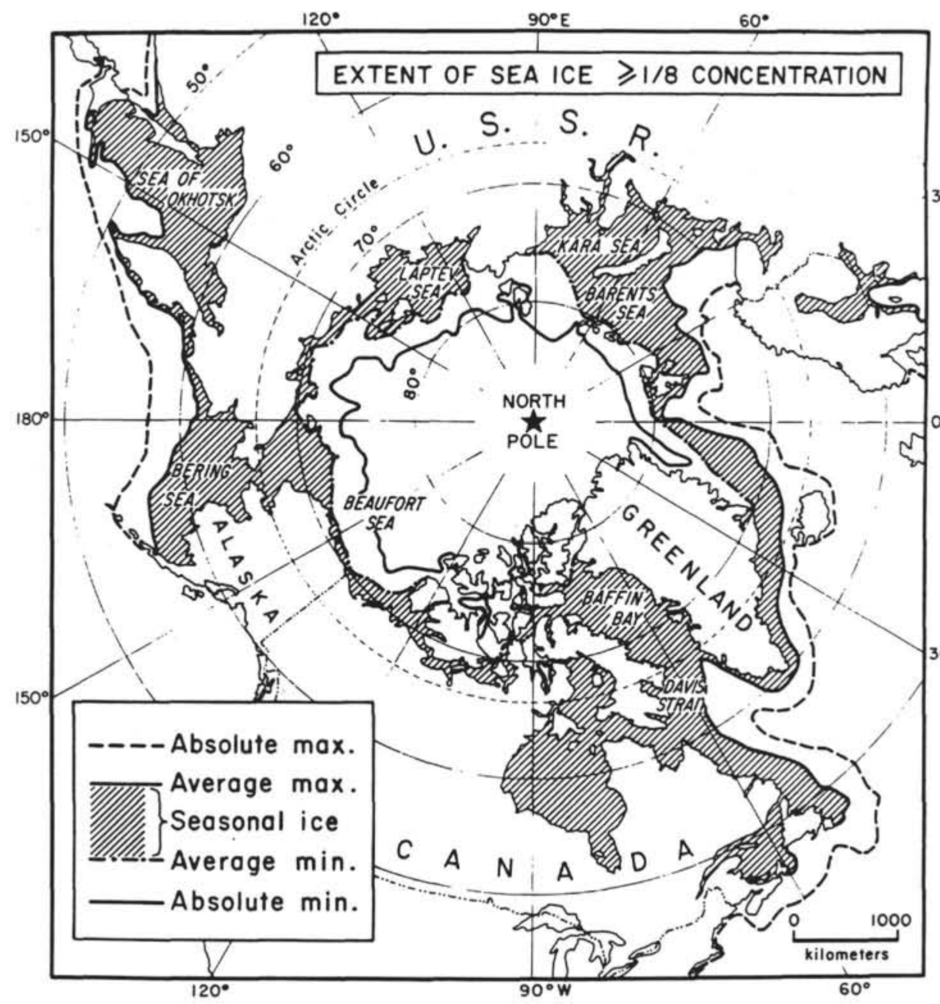


Figure 2. Average and extreme seasonal limits of Arctic sea ice extent for ice concentrations >1/8; after CIA (1978) and Barry (1989).

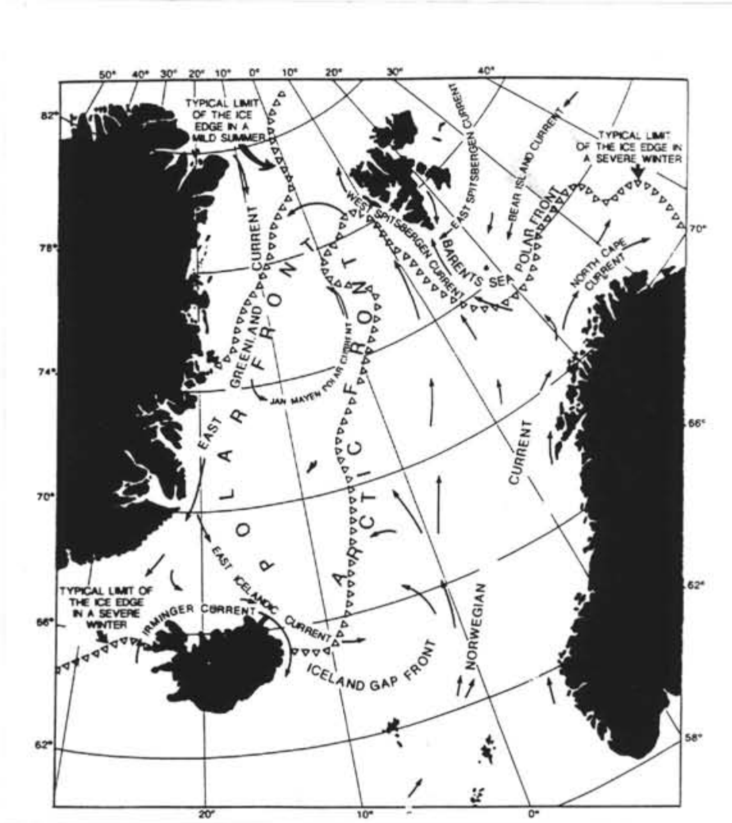


Figure 3a. Major currents and sea-ice features in the Nordic Seas (from Hurdle, 1986).

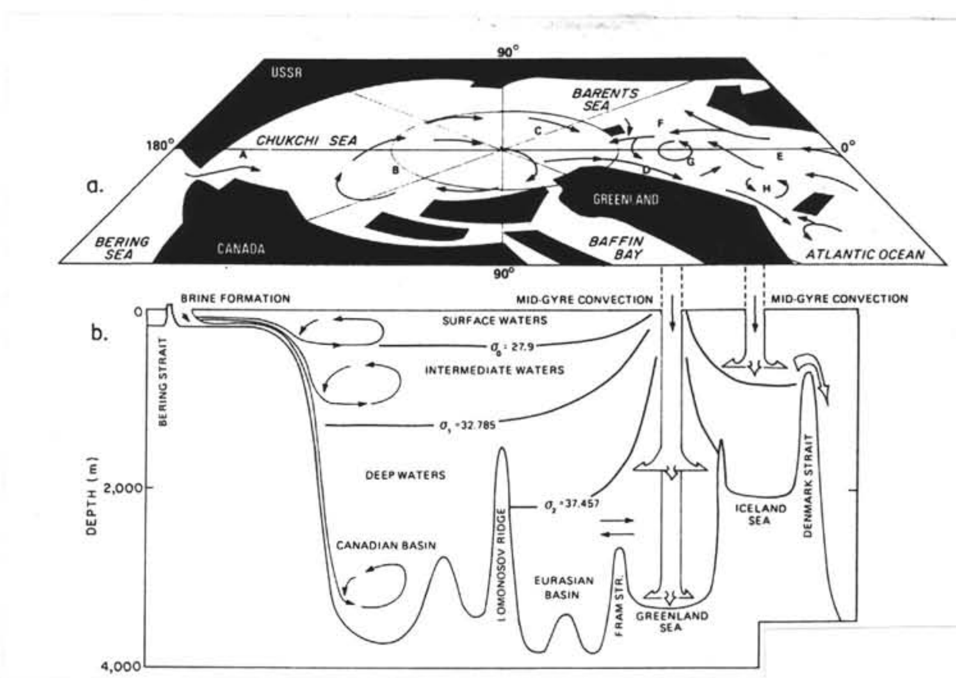


Figure 3b. Schematic illustration of the ocean circulation in the Arctic Ocean and the Nordic Seas (from Aagaard et al., 1985).

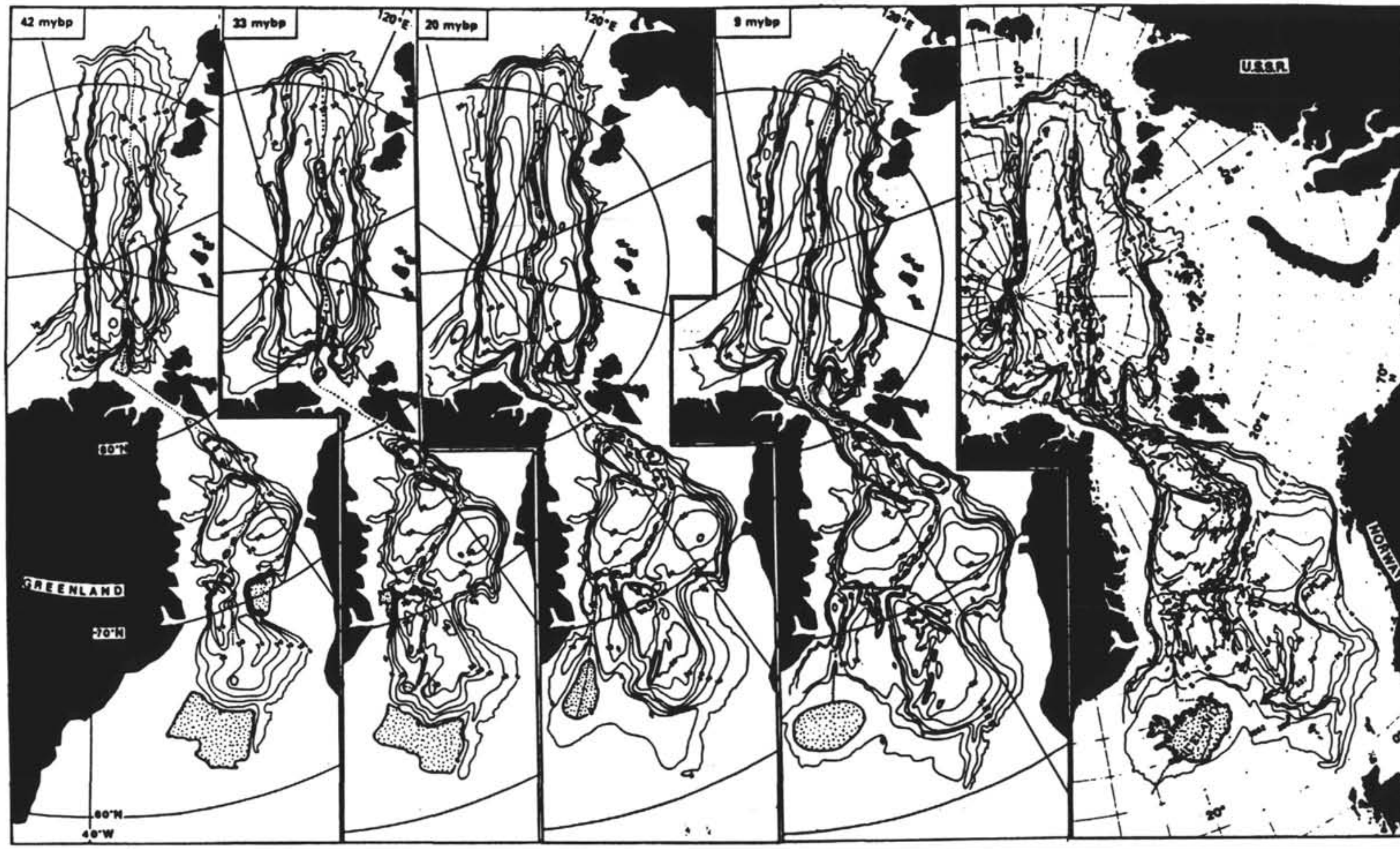


Figure 4. Paleobathymetry of the Nordic and Eurasia basins at 42, 33, 20, and 9 Ma and the present (in hundreds of meters). Stippling denotes oceanic crust above sea level. This figure is based on Bernero (1982) and Vogt, Bernero, et al. (1981).

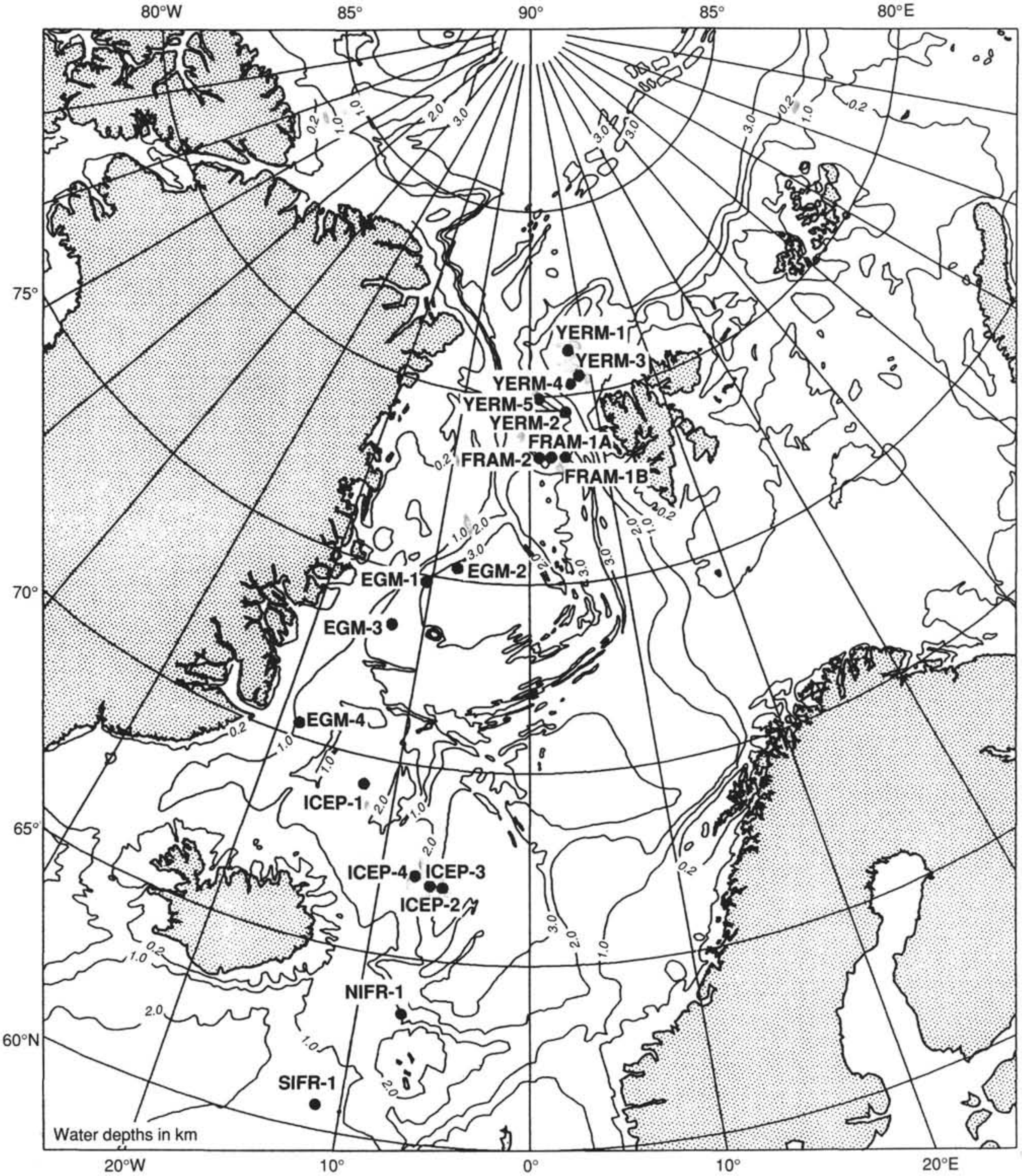


Figure 5. Bathymetric map of the Arctic Ocean and the Greenland-Iceland-Norwegian seas, showing the locations of proposed drill sites. Bathymetry in kilometers.

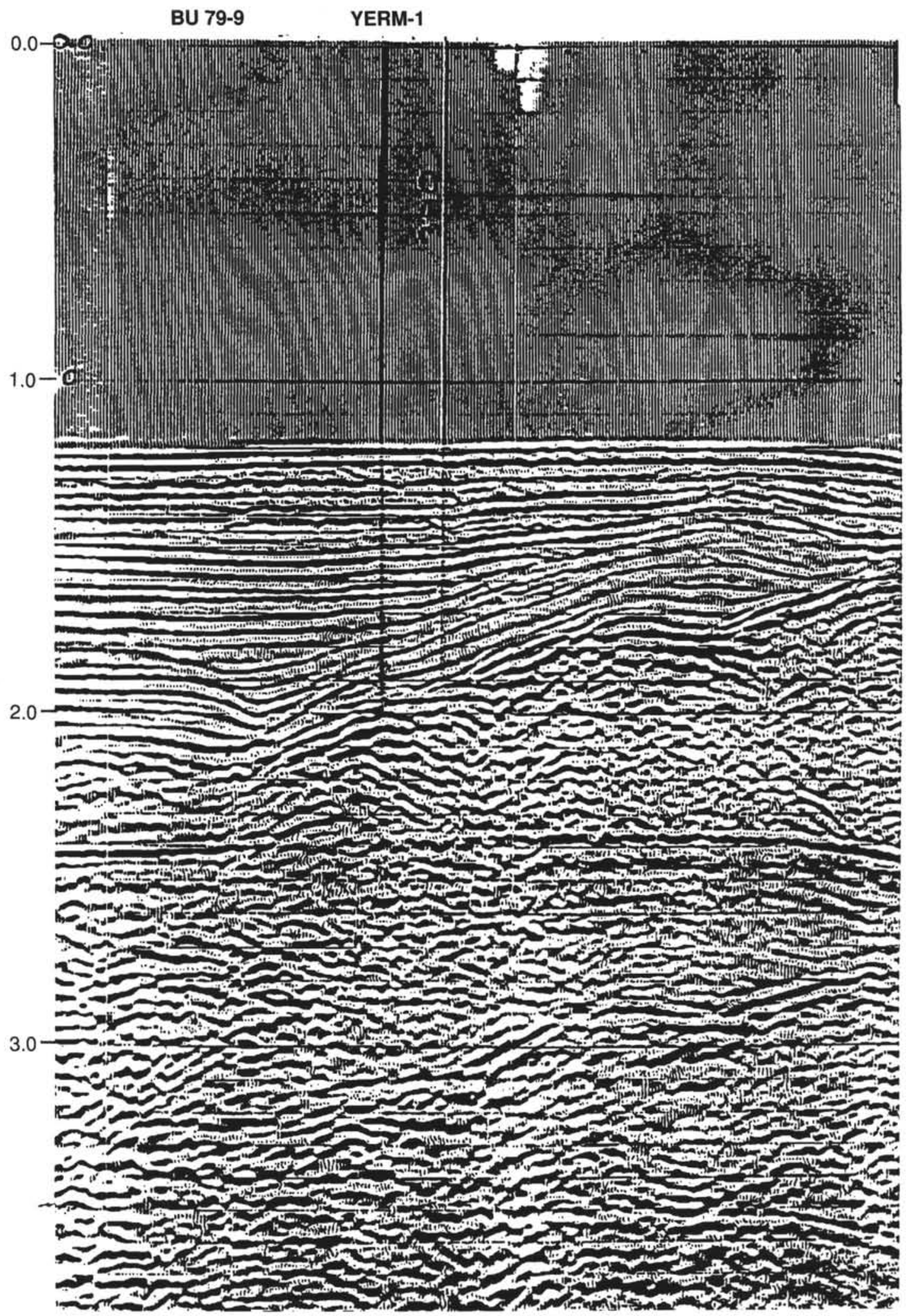
Site: YERM 1
Priority: 1
Position: 81°05.5'N, 7°E
Water Depth: 900 m
Sediment Thickness: 680 m
Seismic Coverage: BU 79-9 SP 400; BU 79-2 (x-ing).

Objectives: To study the subsidence history of the Yermak Plateau and its control on water-mass exchange through the Arctic gateway. To identify the nature and age of basement. To study the history of surface and deep-water communication between the Arctic and the Norwegian-Greenland Sea. To study the history of IRD sedimentation in the Arctic.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine muds, mudstones, sands, and basalts.



Seismic line BU 79-9 showing the location of proposed site YERM 1.

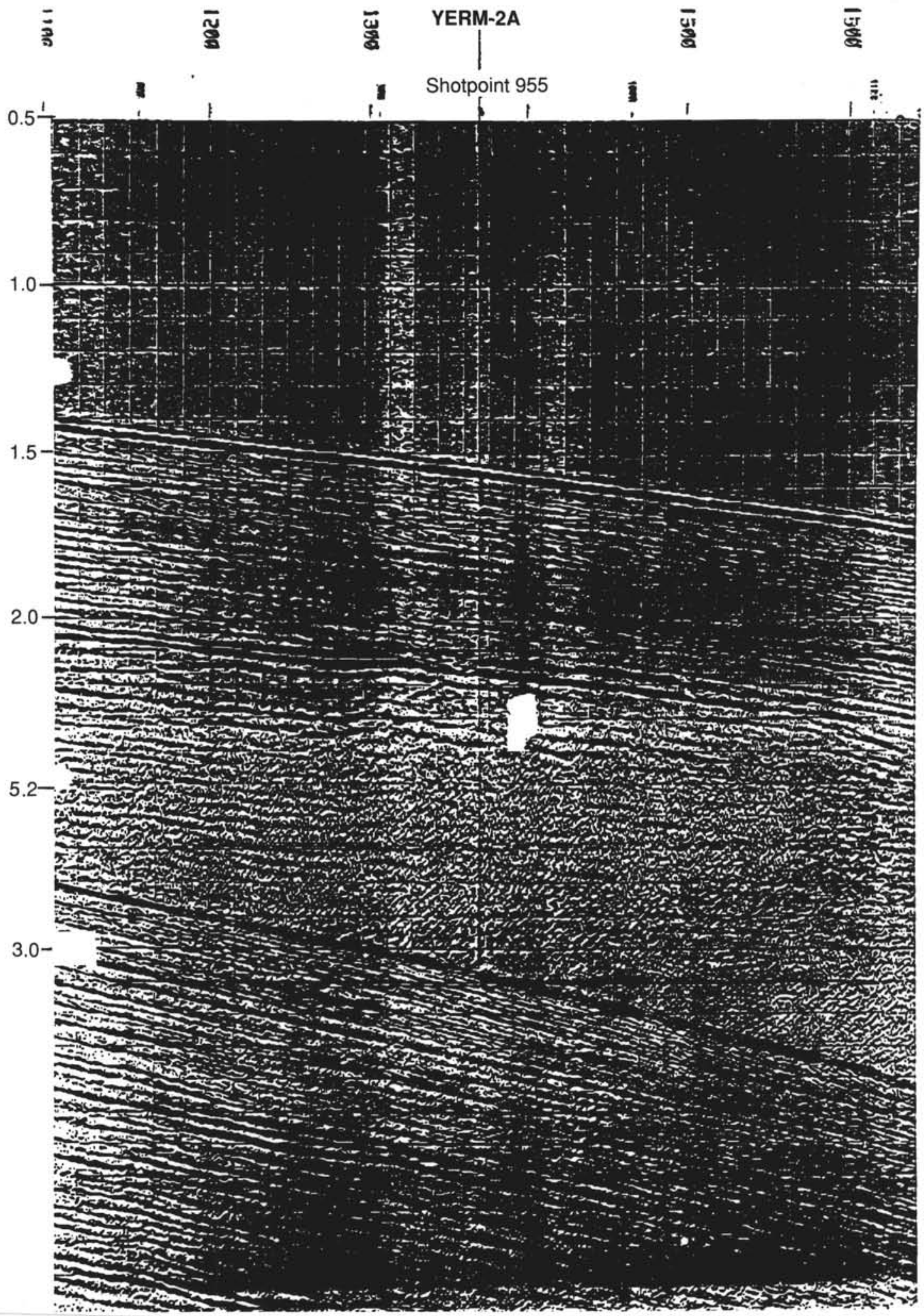
Site: YERM 2A
Priority: 2
Position: 79°54'N, 5°50'E
Water Depth: 1185 m
Sediment Thickness: >1400 m
Seismic Coverage: POLARSTERN Profile AWI-91131 SP 955

Objectives: To study the history of surface and deep water communication between the Arctic Ocean and the Norwegian-Greenland Sea. To investigate the Neogene glacial history of the Arctic. To study the history of North Atlantic water influx into the Arctic. To form an intermediate member of a bathymetric transect of sites. To study the subsidence history of the Yermak Plateau and its control on water-mass exchange through the Arctic gateway and identify the nature and age of basement if this site is chosen as an alternate site to YERM 1.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine muds, mudstones, sands, and basalts.



POLARSTERN Profile AWI-91131 showing the location of proposed site YERM 2A.

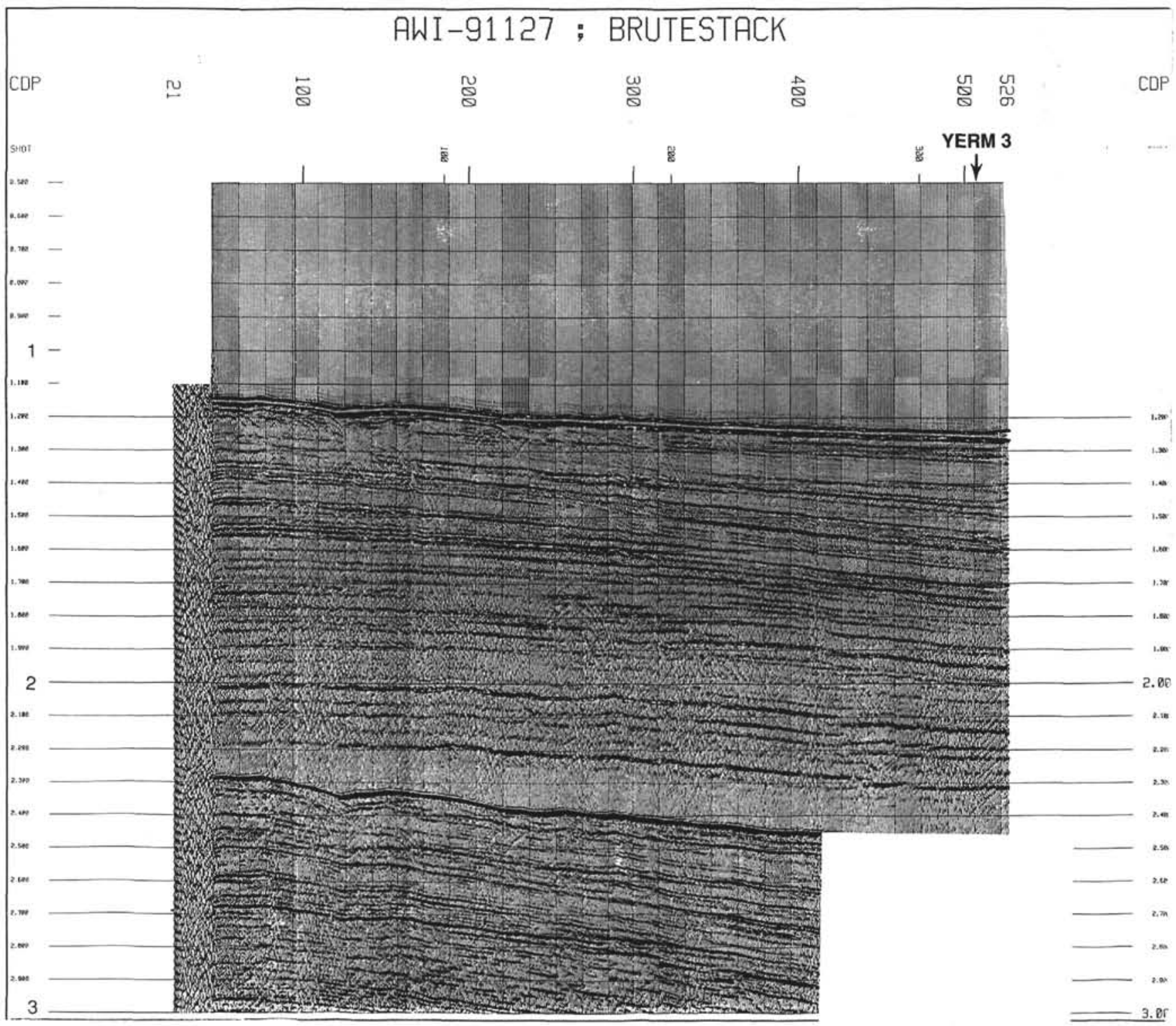
Site: YERM 3
Priority: 1
Position: 80°25.5'N, 8°13'E
Water Depth: 975 m
Sediment Thickness: 1700 m
Seismic Coverage: POLARSTERN Profile AWI-91127 SP 324

Objectives: To investigate the glacial history of the Arctic Ocean for the Neogene. To study the history of influx of North Atlantic surface water into the Arctic Ocean. To form the shallow water member of a bathymetric transect to study depth gradients in sediment accumulation.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments, hemipelagic muds.



POLARSTERN Profile AWI-91127 showing the location of proposed site YERM 3.

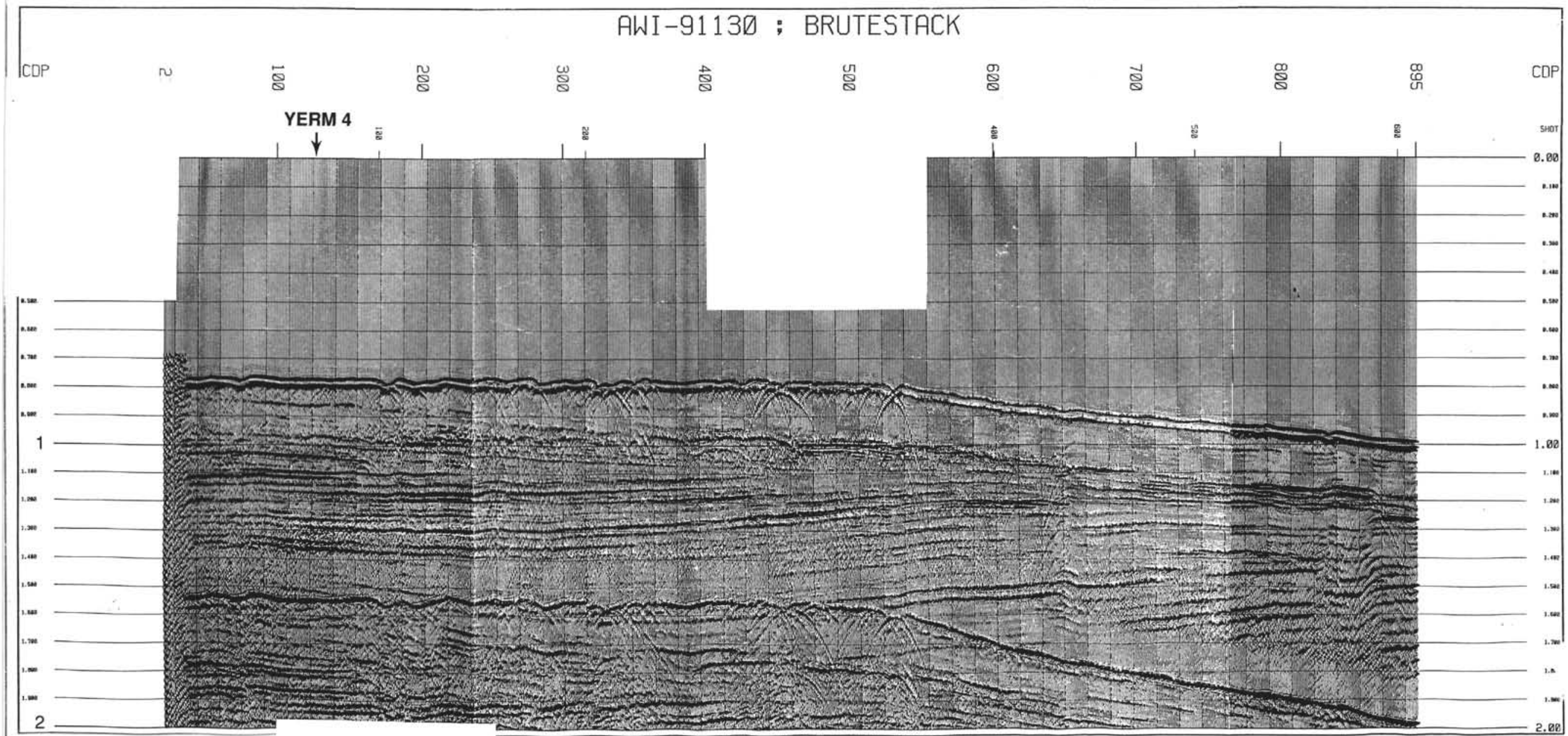
Site: YERM 4
Priority: 2
Position: 80°16'N, 6°38'E
Water Depth: 600 m
Sediment Thickness: >2000 m
Seismic Coverage: POLARSTERN Profile AWI-91130 SP 70

Objectives: To study the glacial history of the Arctic Ocean for the Neogene. To investigate the history of the influx of North Atlantic water into the Arctic Ocean. To form the shallow member of a bathymetric transect to study depth gradients in sediment accumulation.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments.



POLARSTERN Profile AWI-91130 showing the location of proposed site YERM 4.

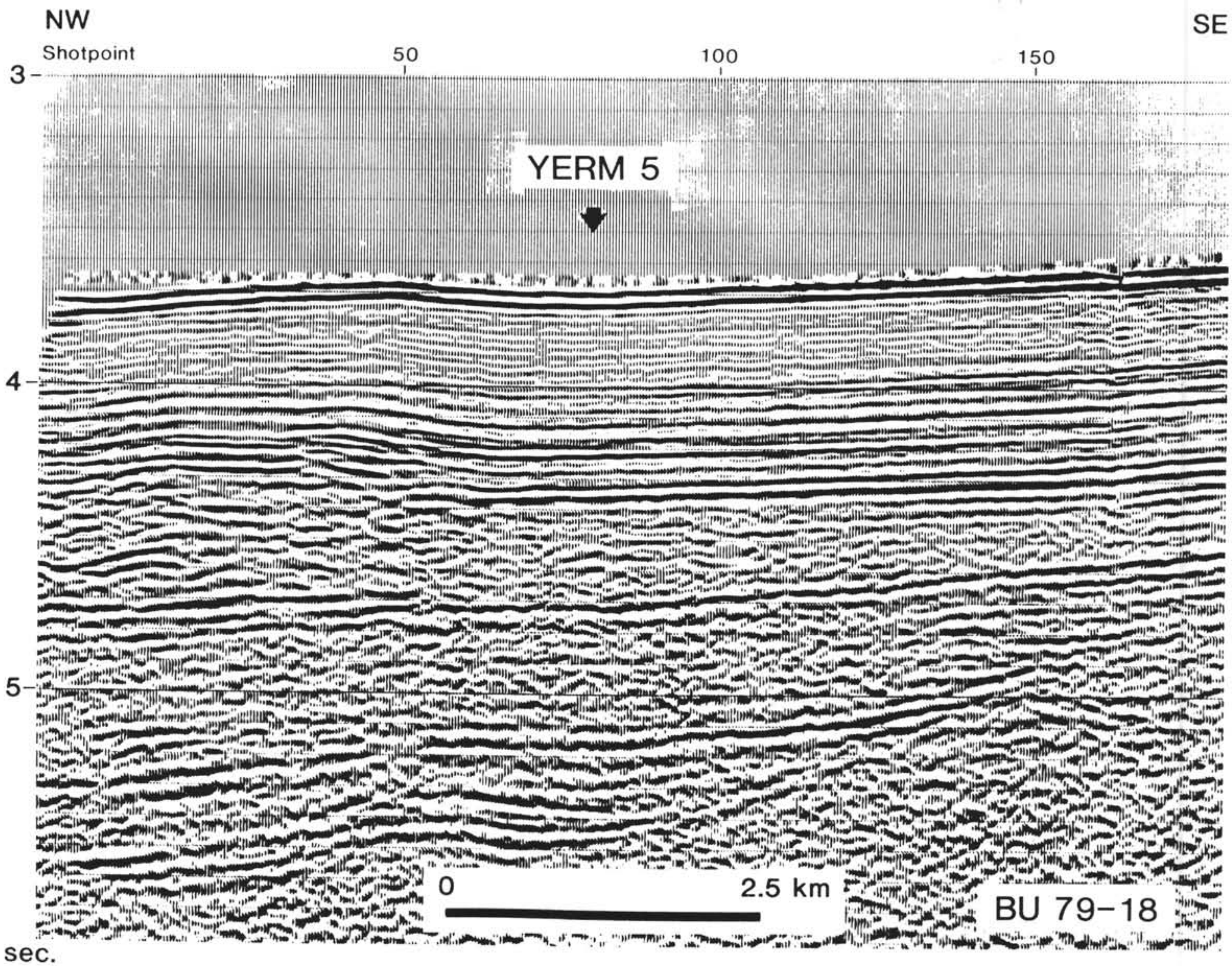
Site: YERM 5
Priority: 1
Position: 79°58.5'N, 1°42'E
Water Depth: 2850 m
Sediment Thickness: >2000 m
Seismic Coverage: BU 79-18 SP 80

Objectives: To study the glacial history of the Arctic Ocean for the Neogene. To investigate the history of the influx of North Atlantic water into the Arctic Ocean. To form the deep end-member of a bathymetric transect to study depth gradients in sediment accumulation.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments.



Seismic line BU 79-18 showing the location of proposed site YERM 5.

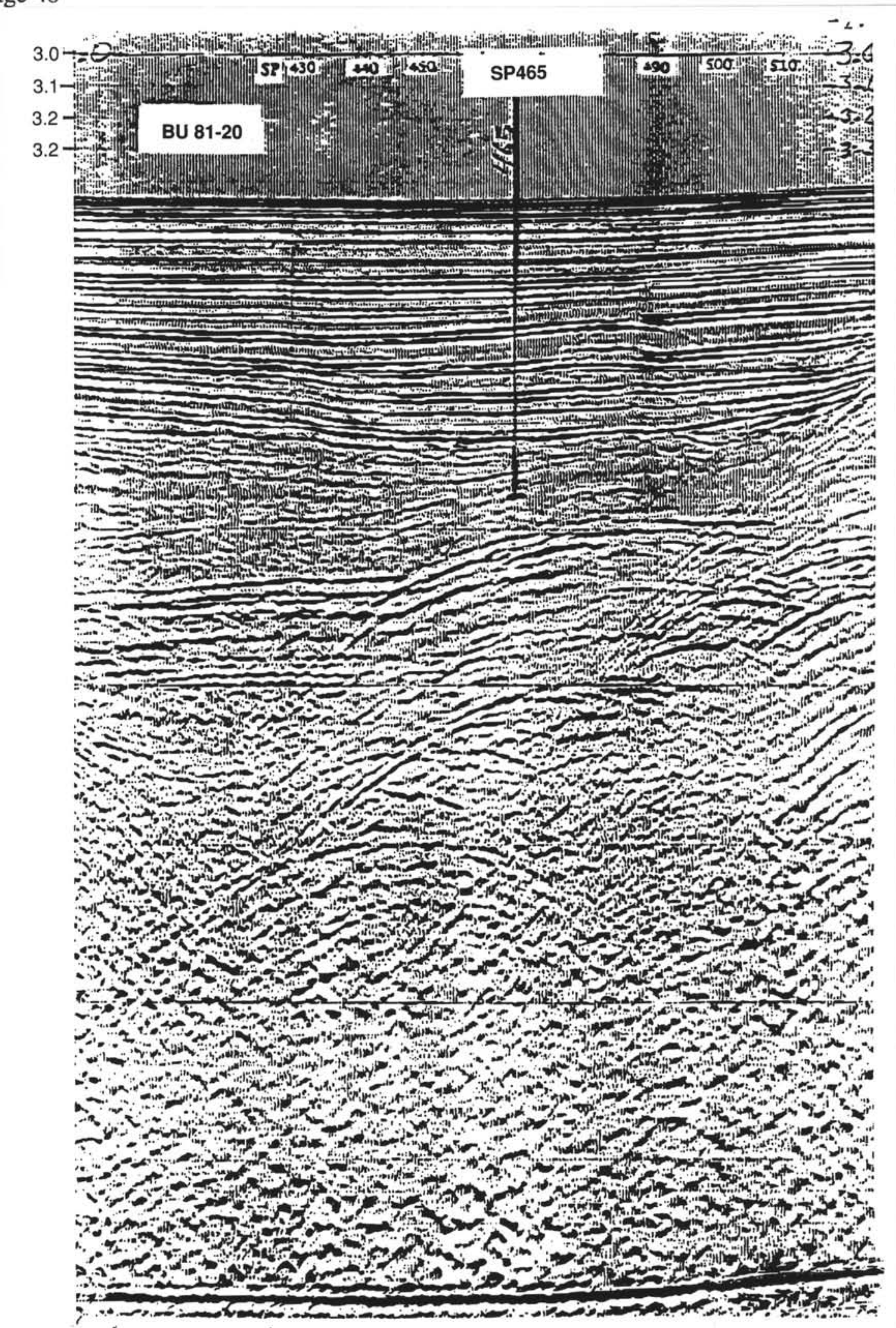
Site: FRAM 1A
Priority: 1
Position: 78°36'N, 3°E
Water Depth: 2590 m
Sediment Thickness: >945 m
Seismic Coverage: BU 81-20 SP 465 (MCS); BU 81-25 (x-ing); BU 81-26 (x-ing)

Objectives: Timing of the opening of the Fram Strait and the history of deep and shallow water-mass exchange between the Arctic and world oceans. To study the glacial history and climatic evolution of the Arctic Ocean.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine hemipelagic muds/ooze (calcareous/siliceous).



MCS line BU 81-20 showing the locations of proposed site FRAM 1A.

Site: FRAM 1B
Priority: 1
Position: 78°33'N, 5°E
Water Depth: 2500 m
Sediment Thickness: 1000 m
Seismic Coverage: BU 81-34 SP 1380 (MCS); BU 81-20 (x-ing)

Objectives: Timing of the opening of the Fram Strait and the history of deep and shallow water-mass exchange between the Arctic and world oceans. To study the glacial history and climatic evolution of the Arctic Ocean

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine and hemipelagic muds and biogenic oozes.

Site: FRAM 2

Priority: 2

Position: 78°22'N, 1°25'E

Water Depth: 1290 m

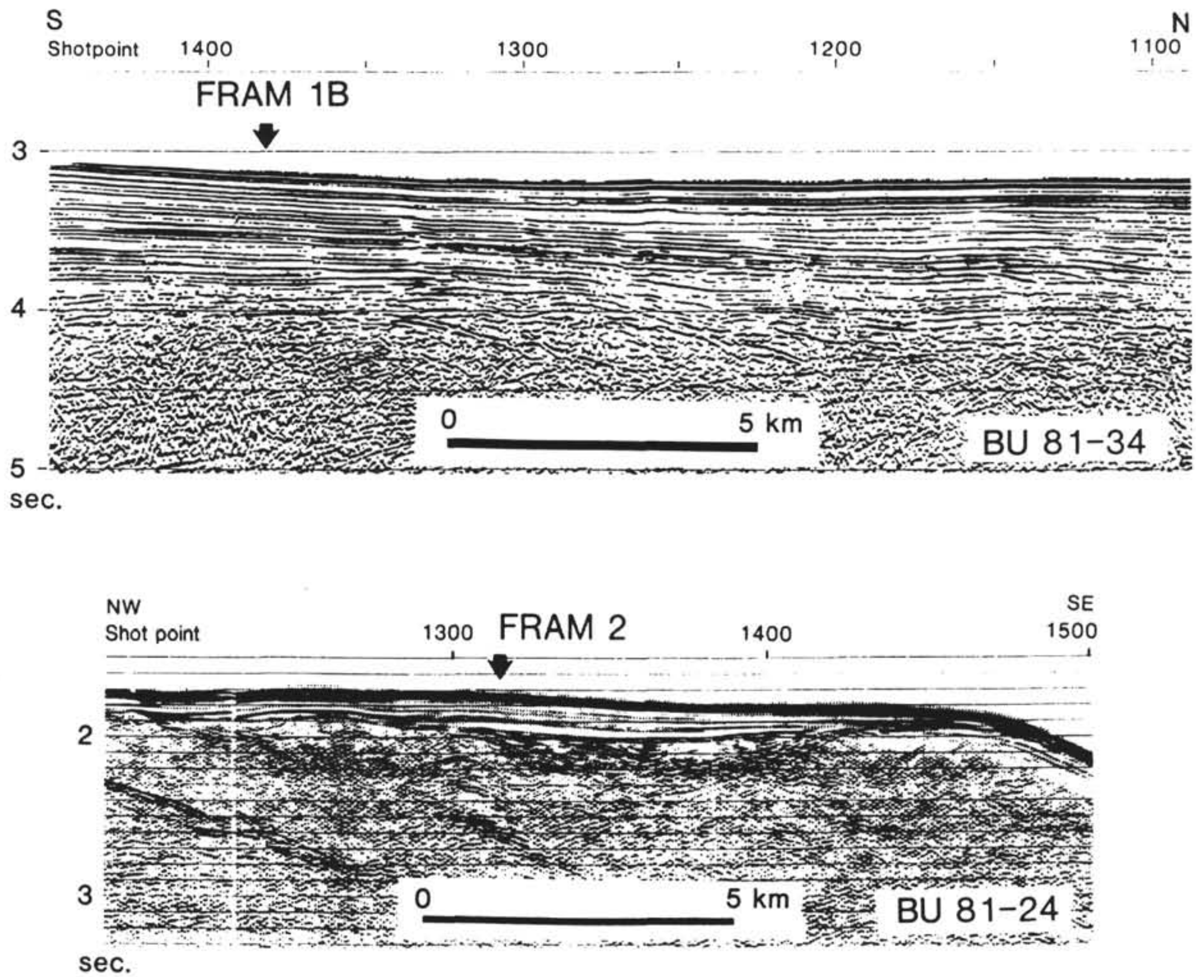
Sediment Thickness: 360 m

Seismic Coverage: BU 81-24 SP 1315 (MCS); BGR 31 (x-ing); BU 81-26 (x-ing)

Objectives: To determine the lithology and depositional history of the sedimentary units in the basins of the Hovgaard Ridge crest. To investigate the timing and variations of water-mass exchange in and out of the Arctic Ocean.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Glacial marine and hemipelagic muds and biogenic oozes.



MCS lines BU 81-34 and BU 81-24 showing the locations of proposed sites FRAM 1B and FRAM 2, respectively.

Site: EGM 1

Priority: 2

Position: 74°52'N, 10°06.5'W

Water Depth: 3250 m

Sediment Thickness: 850-900 m

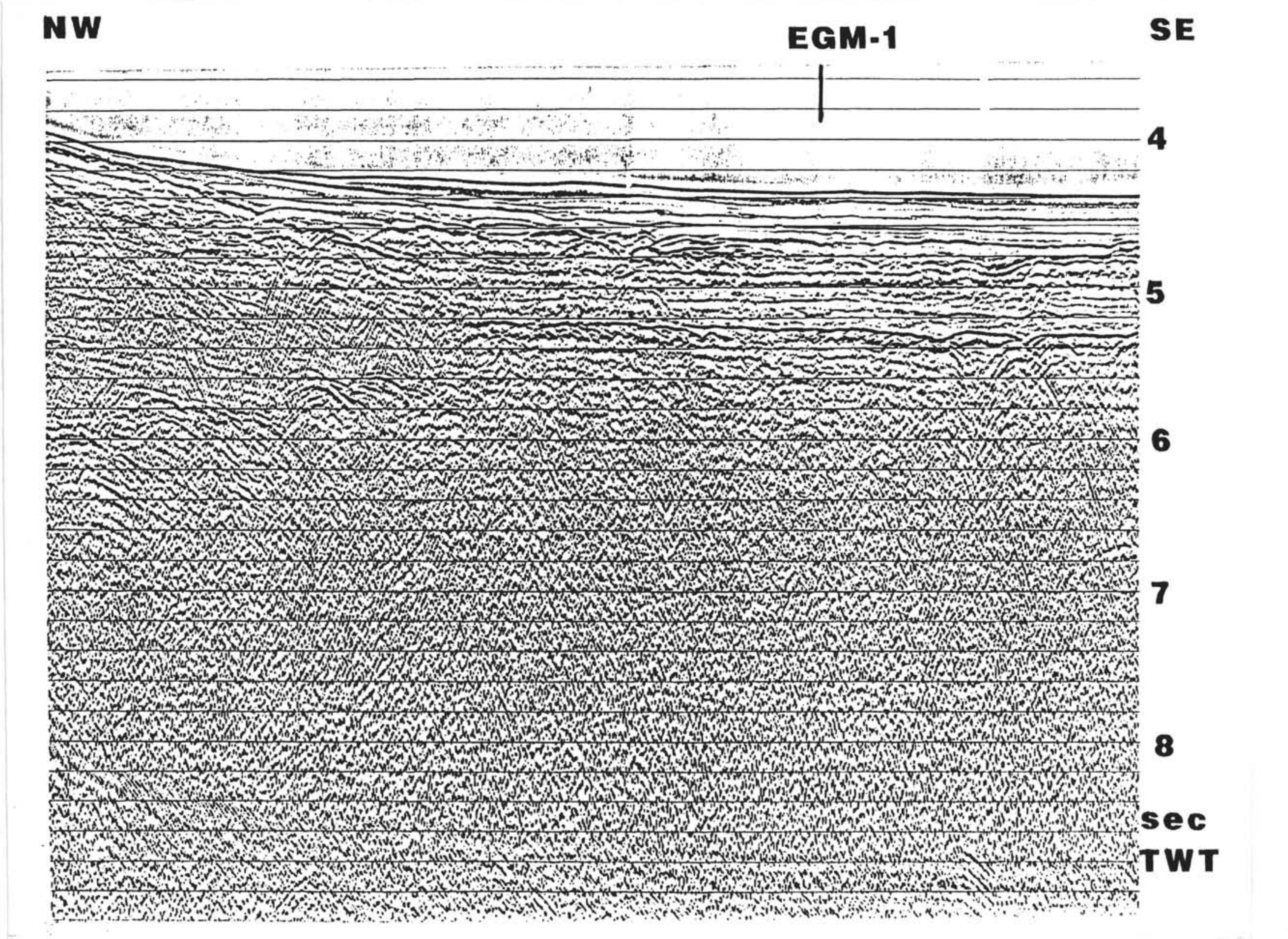
Seismic Coverage: MCS NGT 42 SP 136

Objectives: To date the onset of the East Greenland Current, monitor the development of deep-water formation in the Greenland Sea, and document the history of IRD inputs.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Seismic stratigraphy tools and geochemistry.

Nature of Rock Anticipated: Glacial marine and biogenic sediments, terrigenous mud.



MCS line NGT 42 showing the location of proposed site EGM 1.

Site: EGM 2

Priority: 1

Position: 75°25'N, 7°20'W

Water Depth: 3400 m

Sediment Thickness: ~750 m

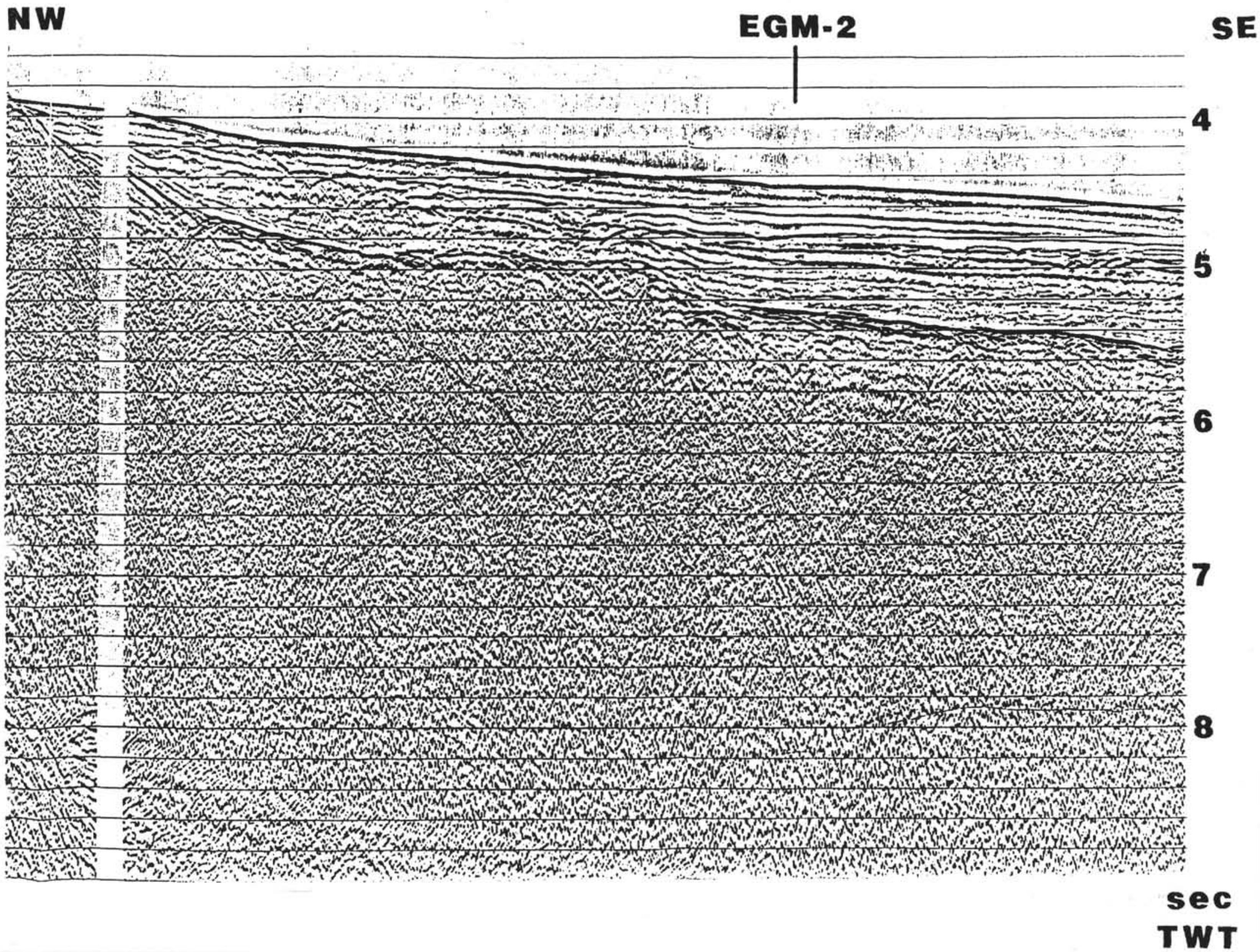
Seismic Coverage: NGT 39/2 SP 1315

Objectives: To date the onset of the East Greenland Current, monitor the development of deep-water formation in the Greenland Sea, and document the history of IRD inputs.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Seismic stratigraphy and geochemistry.

Nature of Rock Anticipated: Glacial marine and biogenic sediments, terrigenous mud.



MCS line NGT 39/2 showing the location of proposed site EGM 2.

Site: EGM 3

Priority: 2

Position: 73°28.5'N, 13°9'W

Water Depth: 2650 m

Sediment Thickness: ~1000 m

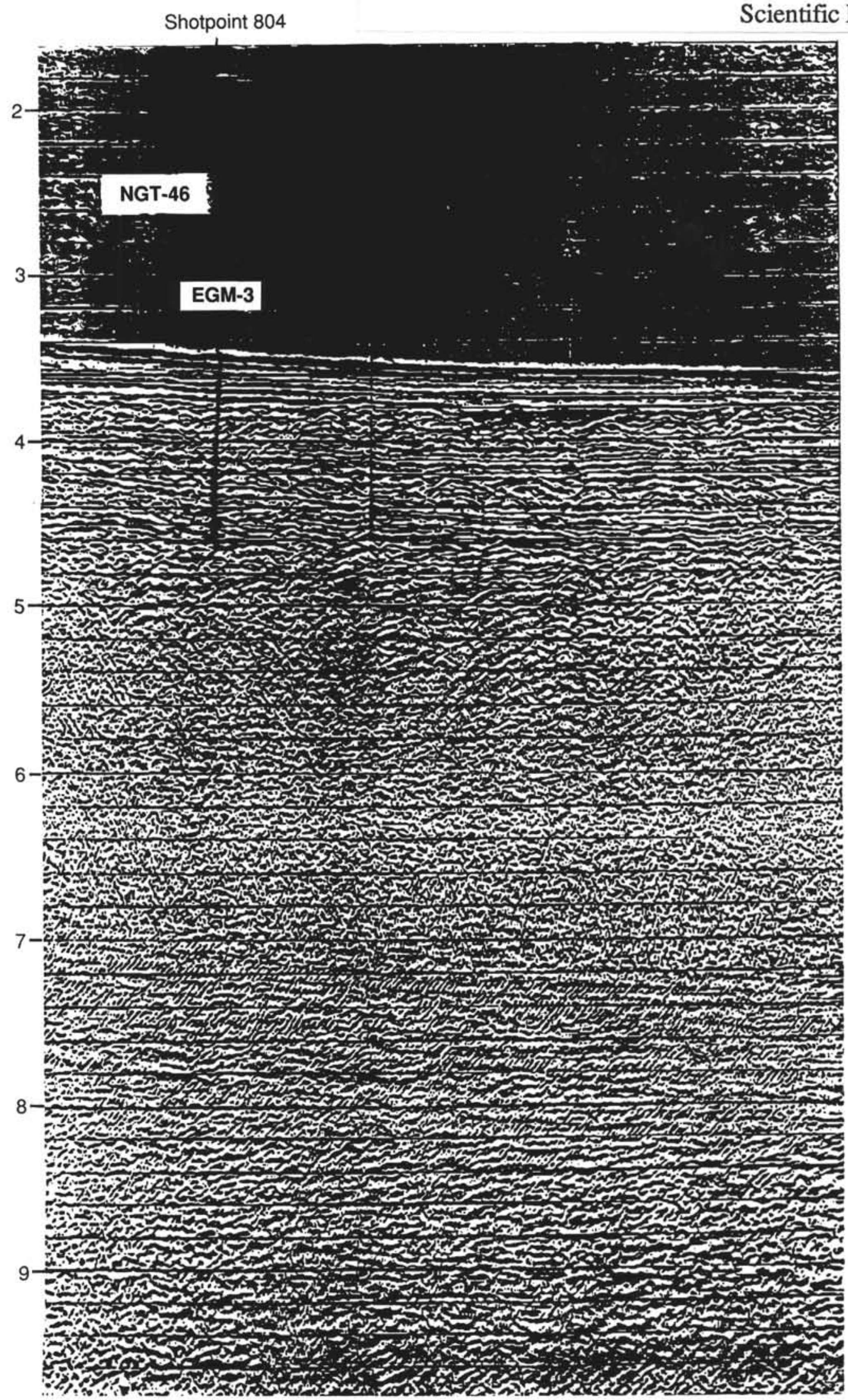
Seismic Coverage: NGT 46 SP 804

Objectives: To date the onset of the East Greenland Current, monitor the development of deep-water formation in the Greenland Sea, and document the history of IRD inputs.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Seismic stratigraphy and geochemistry.

Nature of Rock Anticipated: Glacial marine and biogenic sediments, terrigenous mud.



MCS line NGT 46 showing the location of proposed site EGM 3.

Site: EGM 4

Priority: 1

Position: 70°30'N, 18°20'W

Water Depth: 1670 m

Sediment Thickness: 1000 m

Seismic Coverage: GGU 82-12 SP 2270

Objectives: To monitor the history of the Greenland ice sheet and study the latitudinal development of the EGC.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Seismic stratigraphy and geochemistry.

Nature of Rock Anticipated: Glacial marine sediments.

Site: ICEP 1

Priority: 1

Position: 69°15'N, 12°42'W

Water Depth: 1950 m

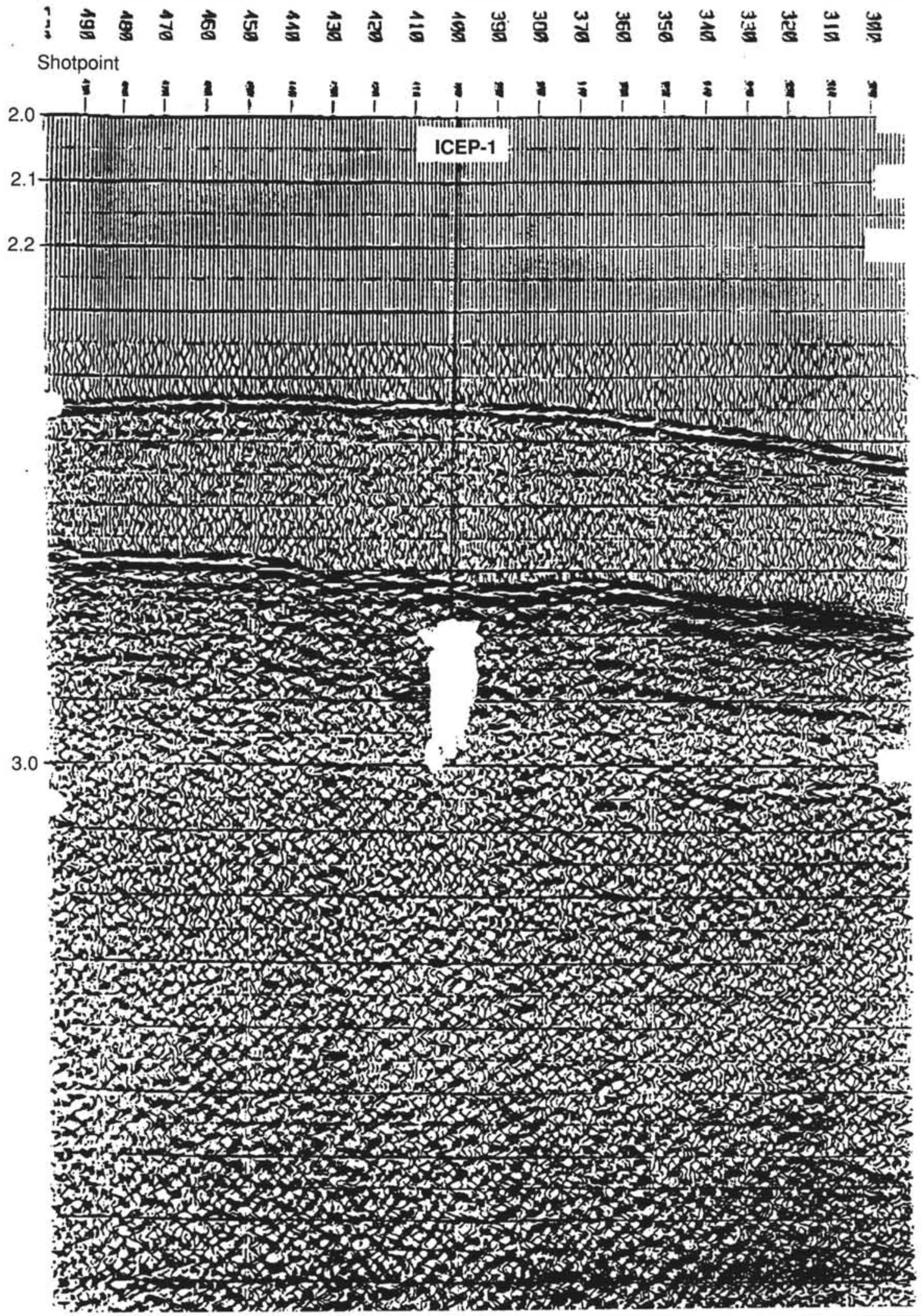
Sediment Thickness: 300 m

Seismic Coverage: UB-ICEP-1 Segment A SP 400; Segment H (x-ing)

Objectives: To monitor the formation and variations of oceanic and climatic fronts (proposed site is midpoint in E-W transect). To obtain an open-ocean record of IRD. To study the history of formation and chemistry of northern-source deep waters.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Siliceous and calcareous muds and oozes.



Seismic line UB-ICEP-1 Segment A showing the location of proposed site ICEP 1.

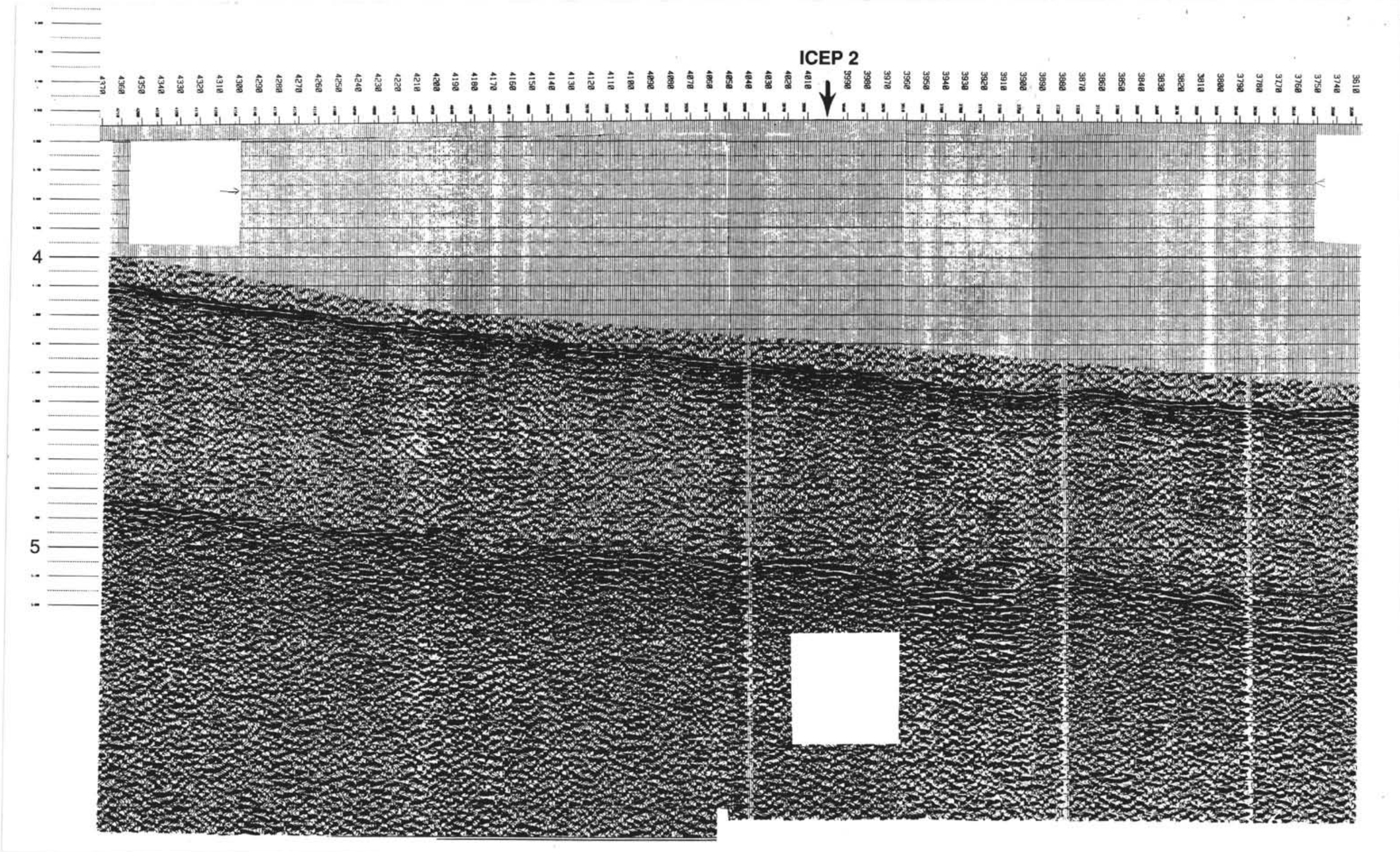
Site: ICEP 2
Priority: 3
Position: 66°54'N, 5°56'W
Water Depth: 3250 m
Sediment Thickness: 650 m
Seismic Coverage: UB-ICEP-2 Segment D SP 4000; Segment C (x-ing)

Objectives: To document the oceanic response to different stages of the opening of the Greenland-Scotland gateway. To form the deep end-member of a bathymetric transect of sites for monitoring the history of CCD, carbonate preservation, and biogenic silica sedimentation as a response to changing climatic and oceanographic conditions. To study the Neogene climate history of the Nordic seas. To form the east end-member of an E-W transect to study inception and changes in oceanic and climatic fronts.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments, calcareous and siliceous muds and oozes.



Seismic line UB-ICEP-2 Segment D showing the location of proposed site ICEP 2.

Site: ICEP 3

Priority: 1

Position: 66°56'N, 6°27'W

Water Depth: 2807 m

Sediment Thickness: 800 m

Seismic Coverage: UB-ICEP-2 Segment D SP 4700; Segment B (x-ing)

Objectives: To document the oceanic response to different stages of the opening of the Greenland-Scotland gateway. To form an intermediate member of a bathymetric transect of sites for monitoring the history of CCD, carbonate preservation, and biogenic silica sedimentation/accumulation as a response to changing climatic and oceanographic conditions.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Glacial marine sediments, calcareous and siliceous muds and oozes.

Site: ICEP 4

Priority: 3

Position: 67°2'N, 7°56'W

Water Depth: 1800 m

Sediment Thickness: 800 m

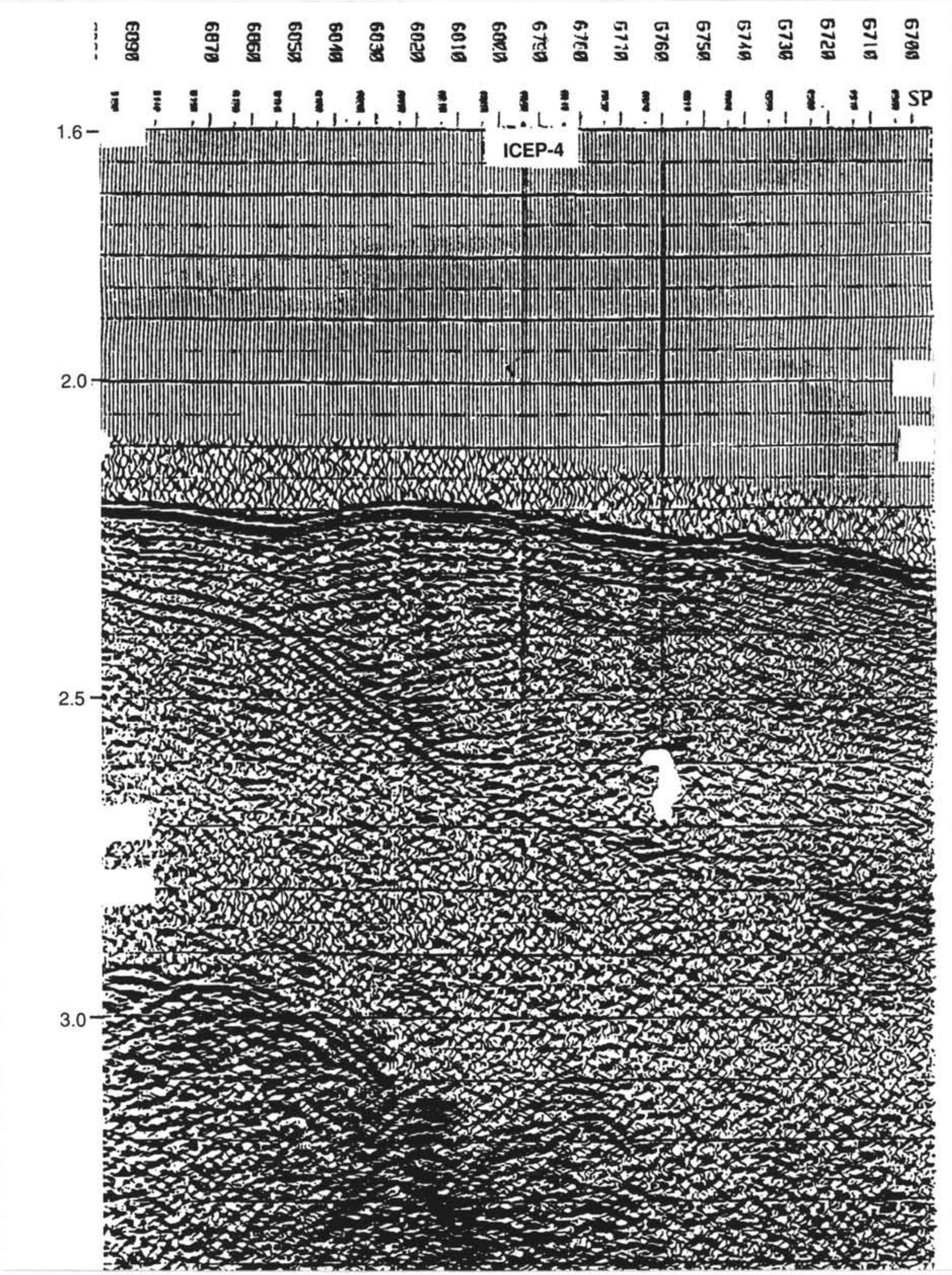
Seismic Coverage: UB-ICEP-2 Segment D SP 6615; Segment A (x-ing)

Objectives: To document the oceanic response to different stages of the opening of the Greenland-Scotland gateway. To form a shallow end-member of a bathymetric transect of sites for monitoring the history of CCD, carbonate preservation, and biogenic opal sedimentation/accumulation as a response to changing climatic and oceanographic conditions. To study the Neogene climatic evolution in high northern latitudes.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments, carbonaceous and siliceous muds and oozes.



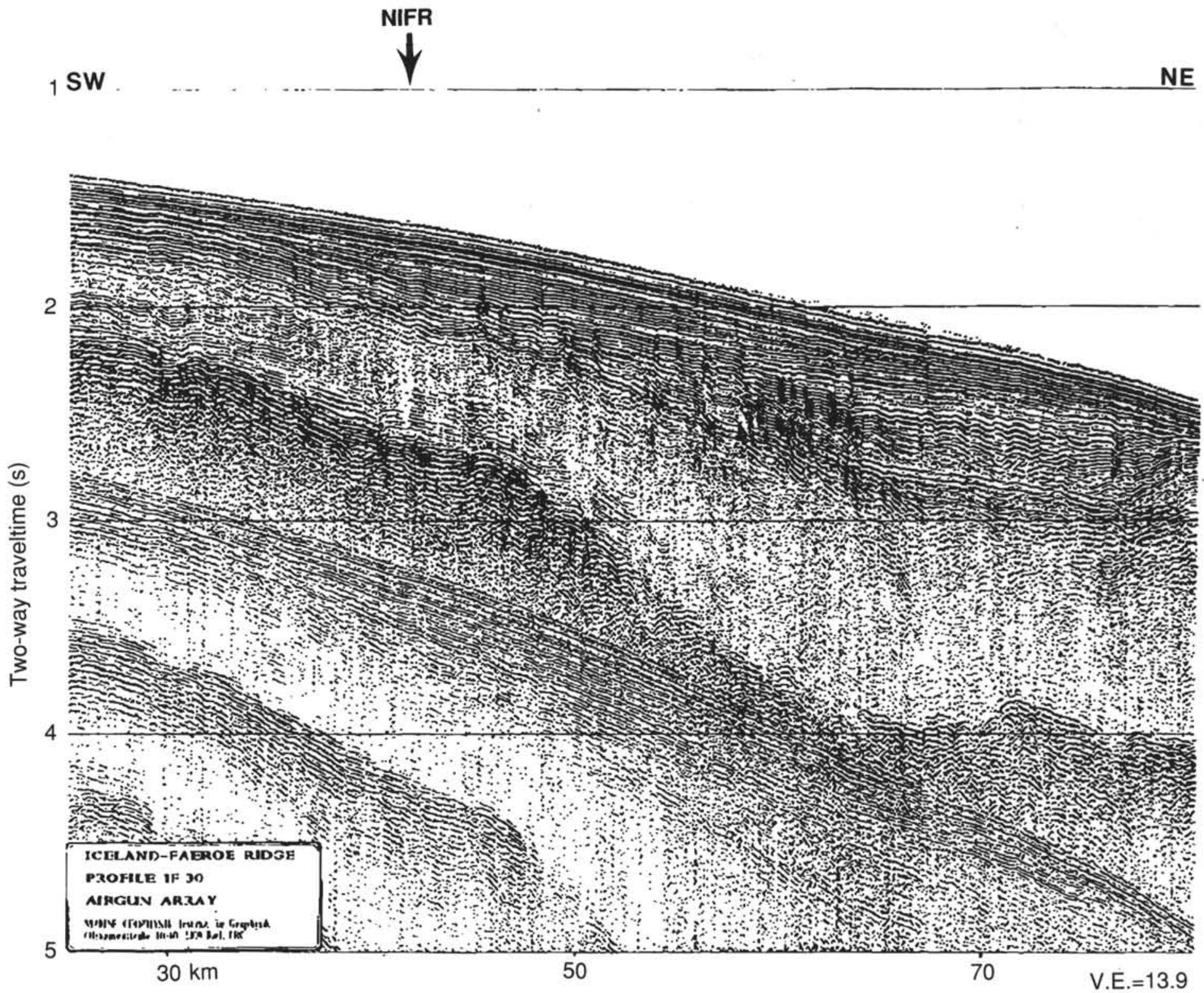
Seismic line UB-ICEP-2 Segment D showing the location of proposed site ICEP 4.

Site: NIFR 1
Priority: 3
Position: 63°26.55'N, 7°14.51'W
Water Depth: 1240 m
Sediment Thickness: >1200 m
Seismic Coverage: IF30; IF52 (x-ing)

Objectives: To determine age and nature of Iceland-Faeroe Ridge, document Paleogene environmental situations in the southern Norwegian Sea, and monitor the early phases of warm water inflow into the Norwegian Sea.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Hemipelagic biogenic muds.



Seismic profile IF 30 showing the location of proposed site NIFR 1.

Site: SIFR 1

Priority: 3

Position: 60°33.30'N, 11°29.0'W

Water Depth: 1215 m

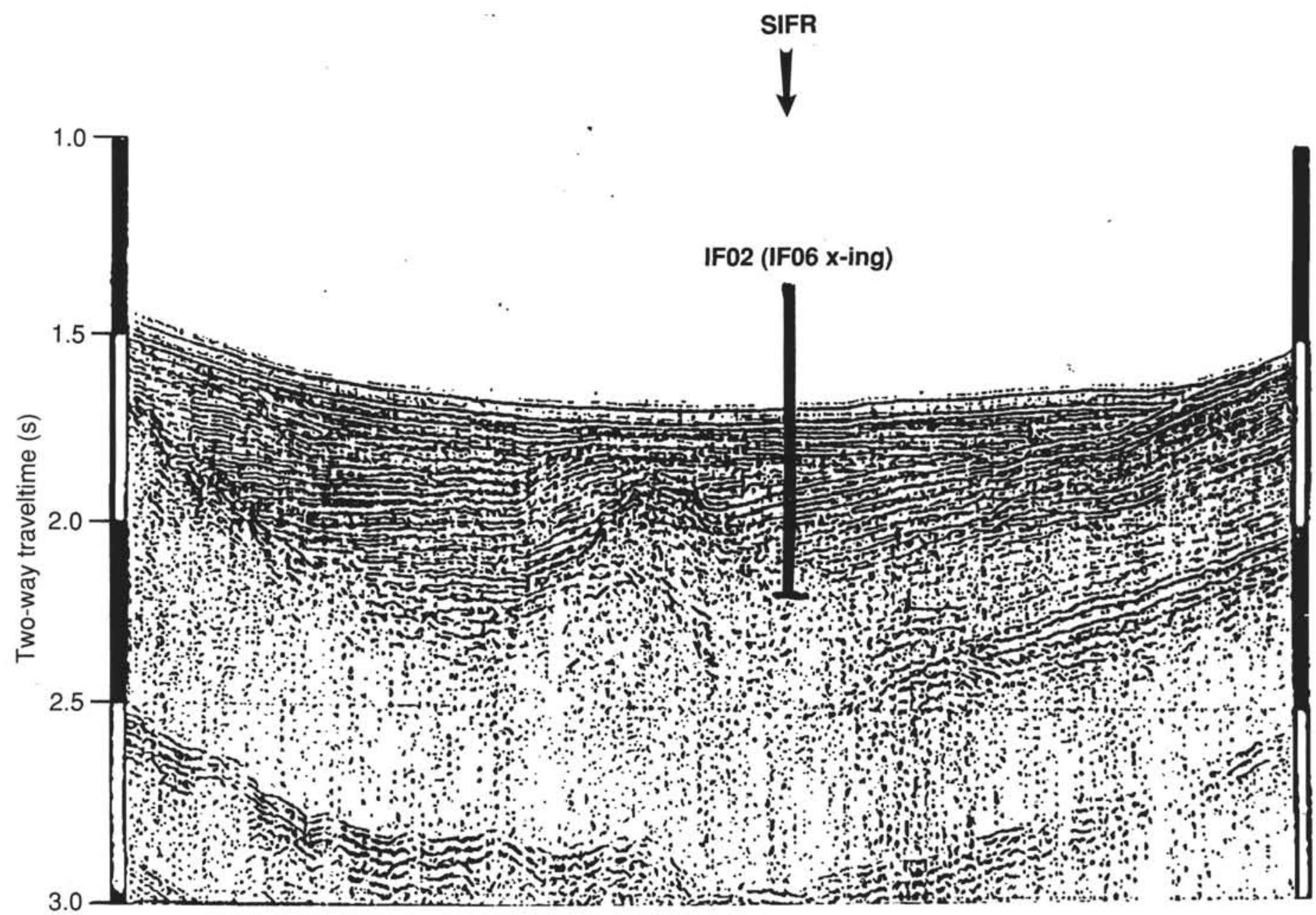
Sediment Thickness: >1200 m

Seismic Coverage: IF02; IF06 (x-ing)

Objectives: To reconstruct the early subsidence of the Iceland-Faeroe Ridge, document onset of Neogene surface-water exchange over the Iceland-Faeroe Ridge, and make a comparison of faunal assemblages north and south of the Iceland-Faeroe Ridge.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Hemipelagic/pelagic biogenic muds.



Seismic profile IF 02 showing the location of proposed site SIFR 1.

SCIENTIFIC PARTICIPANTS

OCEAN DRILLING PROGRAM LEG 151

Co-Chief Scientist:

Jörn Thiede
GEOMAR
Wischhofstrasse 1-3, Geb. 4
D-2300 Kiel 14
Federal Republic of Germany

Co-Chief Scientist:

Annik Myhre
Institutt for Geologi
Universitetet i Oslo
PostBoks 1047
N-0316, Oslo 3
Norway

Staff Scientist:

John Firth
Texas A&M University Research Park
Ocean Drilling Program
1000 Discovery Drive
College Station, TX 77845-9547

Sedimentologist:

Naokazu Ahagon
Ocean Research Institute
University of Tokyo
1-15-1 Minamidai
Nakano-ku
Tokyo 164
Japan

Sedimentologist:

Nancy Chow
Dept. of Geological Sciences
University of Manitoba
240 Wallace Bldg.
Winnipeg, Manitoba
R3T 2N2, Canada

Sedimentologist:

Michel Cremer
Chargede Recherche au CNRS
URA CNRS 197
Université de Bordeaux I
Avenue des Facultés
33405 Talence cedex
France

Sedimentologist:	Benjamin Flower Dept. of Geological Sciences University of California Santa Barbara, CA 93106
Sedimentologist:	Suzanne O'Connell Dept. of Earth & Environmental Sciences Wesleyan University Middletown, CT 06459
Sedimentologist:	Torben Fronval Geologisk Institutt University of Bergen, Avd. B, Allegaten 41 Bergen, N-5007 Norway
Sedimentologist:	Thomas Wolf GEOMAR Wischhofstr. 1-3, Geb. 4 D-2300 Kiel 14 Federal Republic of Germany
Physical Properties Specialist:	Kevin S. Black School of Ocean Sciences University of Wales (Bangor) Menai Bridge Anglesey Gwynedd LL59 5HN United Kingdom
Benthic Foraminifer Paleontologist:	Lisa Ellen Ostermann George Washington University Dept. of Geology Washington, D.C. 20052
Planktonic Foraminifer Paleontologist:	Dorothee G. Spiegler GEOMAR Wischhofstr. 1-3, Geb. 4 D-2300 Kiel 14 Federal Republic of Germany
Diatom Paleontologist:	Reed P. Scherer Byrd Polar Research Center Ohio State University 108 Scott Hall 1090 Carmack Road Columbus, OH 43210-1002

Diatom Paleontologist:	Nalan Koc Karpuz Geologisk Institutt University of Bergen, Avd. B, Allegaten 41 Bergen, N-5007 Norway
Radiolarian Paleontologist:	Donna Hull Programs in Geosciences University of Texas at Dallas P.O. Box 830688 Richardson, TX 75083-0688
Paleomagnetist:	David Williamson Laboratoire de Géologie du Quaternaire CNRS Case 907 Faculté des Sciences de Luminy 13 288 Marseille Cedex 09 France
Organic Chemist:	Ruediger Stein Alfred Wegener Institute for Polar and Marine Research Columbusstrasse D-2850 Bremerhaven Federal republic of Germany
Inorganic Chemist:	Garrett W. Brass RSMAS-MGG University of Miami 4600 Rickenbacker Causeway Miami, FL 33149
Physical Properties Specialist:	Birger Larsen Geological Survey of Denmark Thoravej 8 Copenhagen NV DK 2400 Denmark
JOIDES Logging Scientist:	Mitchell Lyle Dept. of Geoscience Boise State University Boise, ID 83725

Operations Superintendent:	Gene Pollard Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Development Engineer:	Leon Holloway Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Lab Officer:	Bill Mills Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Assistant Laboratory Officer:	"Kuro" Kuroki Ocean Drilling Program Texas A&M University 1000 Discovery Drive College Station, TX 77845-9547
Curatorial Representative:	Erinn McCarty Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Computer Specialist/System Manager:	Matt Mefferd Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Computer Specialist/System Manager:	Juan Flores Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Yeoperson:	Jo Claesgens Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547

Marine Laboratory Specialist/Chemistry:	Dennis Graham Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Laboratory Specialist/Chemistry:	Anne Pimmel Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Electronics Specialist:	Mark Watson Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Electronics Specialist:	Bill Stevens Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Laboratory Specialist/Photography:	Brad Cook Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Laboratory Specialist/Physical Properties:	Jon Lloyd Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Laboratory Specialist/Storekeeper:	Tim Bronk Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Laboratory Specialist/Magnetics:	Margaret Hastedt Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547

Marine Laboratory Specialist/X-ray:	Don Sims Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Laboratory Specialist/UWG/Fantail:	Dwight Mossman Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547
Marine Laboratory Specialist:	Jacque Ledbetter Ocean Drilling Program Texas A&M University Research Park 1000 Discovery Drive College Station, TX 77845-9547