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INSIDE

Farthest North: Ocean Drilling in the Arctic Gateway Region

Leg 151 Shipboard Scientific Party

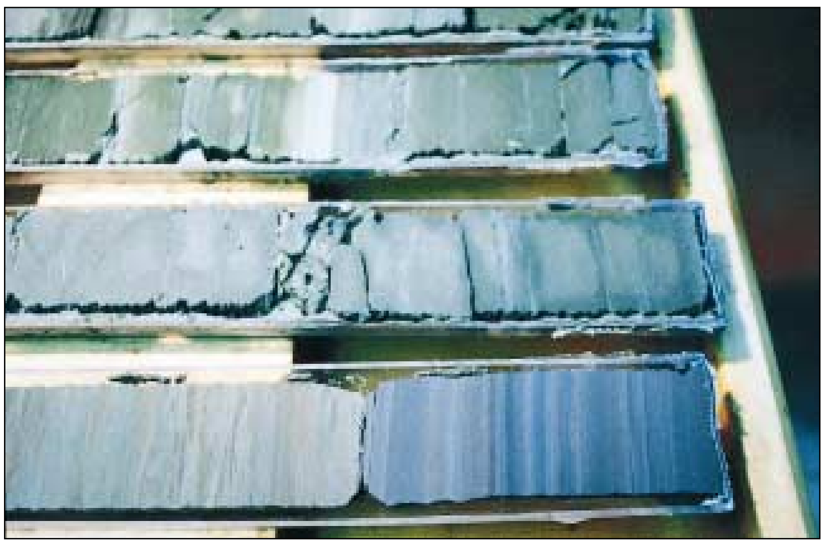

Figure 1. Left: Finnish icebreaker *Fennica* patrolling sea ice on the Yermak Plateau in the Arctic Ocean at lat ~80°N. Photo by Suzanne O'Connell, Wesleyan University. Above: Laminated biosiliceous oozes from the late Eocene on the East Greenland margin (site 913), showing rich green and blue surficial coloration attributed to the presence of vivianite. Photo by ODP Operations Superintendent Gene Pollard.

ABSTRACT

The Ocean Drilling Program (ODP) recently recovered the first deep-drilled sediment sequences from the Arctic Ocean, on Leg 151 in July–September 1993. The ODP drillship Resolution took advantage of late summer low-ice conditions in the region northwest of Svalbard to drill three sequences on the Yermak Plateau at lat ~80°N and long 5°–8°E. Despite being chased away several times by advancing sea ice, ODP Leg 151 successfully obtained the northernmost long sediment cores (>500 m) ever drilled. The sediment sequences obtained provide the first opportunity for high-resolution records of arctic climates and paleoceanography from the mid-Pliocene to present. Surprisingly high sedimentation rates involving high fluxes of glacially derived dropstones and terrigenous detritus attest to dynamic circumarctic continental ice sheets at least episodically since the mid-Pliocene. "Overconsolidated" Quaternary sediments at site 910 suggest that a massive ice sheet may have been grounded on the Yermak Plateau during at least some glacial intervals, perhaps derived from the Barents Sea shelf and buttressed by Svalbard. The oldest dropstones in the Arctic gateway region, recovered at Fram Strait site 909, were late Pliocene in age. At site 907 on the Iceland Plateau, however, an earlier appearance of dropstones during the late Miocene suggests individual ice sheets had different histories. Other ODP Leg 151 cores from Fram Strait, the East Greenland margin, and the Iceland Plateau provide important information on the Cenozoic paleoceanographic history of the Norwegian-Greenland Sea and its relation to global climates. In particular, late Miocene laminated biosiliceous sediments on the Iceland Plateau suggest that active deep convection did not occur in this area until ca. 7 Ma.

INTRODUCTION

Leg 151 of the Ocean Drilling Program (ODP) has ushered in a new era of scientific exploration of the arctic region by recovering the first deep-drilled sediment cores (>500 m) from the Arctic Ocean. The sediment sequences recovered, featuring high sedimentation rates with abundant ice-rafted dropstones, indicate a dynamic history for the arctic cryosphere since at least the mid-Pliocene. An integral part of a long-term effort for renewed study of the arctic region, ODP Leg 151 sailed exactly 100 yr after Fridjof Nansen's famous expedition across the Arctic Ocean. Nansen and his crew allowed their ship the *Fram* to be frozen into the arctic sea ice in the Laptev Sea north of Siberia in order to transit the Arctic Ocean, relying on the transpolar drift of the sea ice. As chronicled in Nansen's (1899) account of the journey and subsequent scientific papers, the *Fram* drifted toward Fram Strait in the northernmost North Atlantic over the course of 3 yr, providing the first scientific information from the Arctic Ocean. A century after the *Fram* expedition, the ODP drillship *Resolution* (SEDCO/BP 471), administered by the Joint Oceanographic Institutions for Deep Earth Sampling, drilled the first sites in the Arctic Ocean proper and its main gateway at Fram Strait.

One of the long-standing questions about Arctic Ocean climates is the history of the arctic cryosphere, including the circum-arctic continental ice sheets and the Arctic sea ice. The *Fram* expedition documented that the present-day sea-ice cover is a pervasive feature of the Arctic Ocean, which Nansen felt had existed "since the earliest dawn of time." Today, considerable uncertainty exists about the onset of an extensive Arctic sea-ice cover (e.g., Thiede et al., 1990). Estimates of its age range from middle to late Miocene (Clark, 1982) to late Quaternary (Herman, 1985). Based on the appearance of planktonic foraminiferal assemblages similar to modern communities, sea ice may have become a permanent feature as recently as ca. 0.9 Ma (Herman, 1970, 1974, 1985). Ice-rafted detritus in Arctic Ocean sediments suggests that the circumarctic ice sheets have existed since at least the early Pliocene (Herman, 1970; Margolis and Herman, 1980). These paleoclimatic interpretations are based exclusively on short piston cores (<10 m in length) in areas with low sedimentation rate, which provide greatly condensed records. A major advantage of deep-sea drilling in areas of high sedimentation rate is that long sediment sequences (>500 m) may be obtained for greater stratigraphic coverage and high-resolution sediment records. Specifically, such records should document the formation of the circumarctic continental ice sheets and the arctic sea ice, and their subsequent evolution in Quaternary glacial-interglacial cycles.

Reconstructing pre-glacial arctic environments will provide insights into possible future arctic environments that may develop in response to greenhouse warming. Very warm Arctic Ocean climates have been suggested for the mid-Pliocene, on the basis of fossil faunal distributions including planktonic foraminifera (Herman, 1970, 1974), sea otters and mollusks (Carter et al., 1986), as well as elevated sea-level terraces (Brigham-Grette and Carter, 1992). Documenting the pre-glacial arctic paleoenvironment and its subsequent evolution will illuminate its sensitivity to future anthropogenic climate change.

REGIONAL OCEANOGRAPHY

The ability of the *Resolution* to conduct operations in the Yermak Plateau region is directly tied to surface-water oceanography in this area. Relatively warm surface waters derived from the warm Norwegian Current flow north through the Norwegian Sea and enter the Arctic Ocean as the West Spitsbergen Current through the Fram Strait west of Svalbard. This current melts extensive sea ice and icebergs in this area in the summer, including the area over the Yermak Plateau. Correspondingly, cold surface waters of the East Greenland Current flow south along the east coast of Greenland and enter the North Atlantic Ocean through Denmark Strait west of Iceland. Thus, much of the western Greenland Sea receives arctic sea ice transported by the cold East Greenland Current, making this area inaccessible for deep-sea drilling by ships without icebreaker capabilities. These surface current systems create a strong east-west asymmetry in surface-water temperatures and strongly influence the climate of the surrounding lands, accounting for mild climates in Scandinavia at latitudes where glacial conditions prevail on Greenland.

In the present day, the North Atlantic–Arctic gateway region is also a center for deep-water exchange between the Arctic and North Atlantic Ocean, and the Norwegian-Greenland Sea is an important locus for deep-water formation. The only deep connection between the Norwegian-Greenland Sea and the Arctic Ocean is through the narrow Fram Strait, with a sill depth of ~2600 m. In the cyclonic gyre of the Norwegian-Greenland Sea, surface waters derived in part from the warm, salty Norwegian Current are sufficiently cooled to become dense, to sink, and to form cold deep waters. These waters fill the series of basins that comprise the Norwegian-Greenland Sea, enter the Arctic Ocean through Fram Strait, and spill over sills in the Denmark Strait (~600 m) and Iceland-Faeroe Channel (~1100 m) to contribute to the formation of North Atlantic deep water. Deep-water exchange thus occurs through both the northern gateway through Fram Strait and the southern gateway to the North Atlantic across the Greenland-Iceland-Faeroe ridge.

The present-day system in the Norwegian-Greenland Sea of surface-water inflow and deep-water outflow represents a lagoonal-style circulation

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that results in nutrient-depleted surface waters and oxygen-rich deep waters. This circulation system plays a significant role in heat transport to the high northern latitudes and contributes directly to North Atlantic deep-water formation, thereby representing an important driving force of the deep-ocean "conveyor belt" that transits the world ocean.

DRILLING RESULTS: ODP LEG 151

ODP Leg 151 is part of the North Atlantic–Arctic gateway (NAAG) project, a coordinated effort to study the paleoceanographic evolution of the Arctic Ocean, Norwegian-Greenland Sea, and northern North Atlantic during the Cenozoic. This research effort consists of two ODP drilling legs to this area, Leg 151 in the summer of 1993 and Leg 162 in the summer of 1995. These ODP drilling efforts are also linked to the Nansen Arctic Drilling Program, dedicated to studying the long-term climatic evolution of the Arctic Ocean. Obtaining long sediment sequences from the Arctic Ocean and the northern North Atlantic is central to documenting the Cenozoic evolution of climate and ocean circulation in the northern and southern gateway regions. The major objectives of this project are (1) to study the Cenozoic paleoceanography of the Nordic seas, including the history of surface- and deep-water exchange through the northern and southern gateways; (2) to investigate the role of the tectonic evolution of the North Atlantic–Arctic gateways in regional and global climatic change; (3) to examine the late Neogene evolution of arctic and subarctic sea ice and continental ice sheets; and (4) to document the latest Quaternary climatic history of the northern North Atlantic through high-resolution studies of Milankovitch- to millennial-scale variability.

NAAG I drillsites were planned to take advantage of late summer sea-ice–free conditions in the Norwegian-Greenland Sea and Arctic Ocean. Ice-free conditions are essential to the operation of the drillship JOIDES *Resolution.* In order to drill hundreds of meters below the sea floor in water depths of several hundreds to thousands of meters, the ship must be able to remain stationary for several days to a week or more. Consequently, the Finnish icebreaker *Fennica* was contracted to protect the drillship from any advancing sea ice or icebergs (Fig. 1). Although extensive sea-ice cover prevented drilling at two important sites (proposed sites Yerm-1 and Yerm-5), ODP Leg 151 recovered the first deep-drilled sedimentary sequences from the Arctic Ocean in August and September 1993. The JOIDES *Resolution* drilled three sites in a depth transect on the Yermak Plateau northwest of Svalbard at lat ~80°N and long 5°–8°E. Leg 151 also recovered material from two sites in Fram Strait between Svalbard and Greenland, and from one site each on the East Greenland Margin and the Iceland Plateau (Fig. 2). Nearly 3500 m of section were drilled, ranging in age from middle Eocene (~45 Ma) to present (Fig. 3).

The sites successfully drilled on the Yermak Plateau were the first drillsites in the Arctic Ocean proper, and are of particular interest to the scientific community. These sites were selected to study the Neogene evolution of arctic glacial conditions and to examine vertical differences in sediment properties, accumulation rates, and surface- to deep-water circulation. Sites 910, 911, and 912 were drilled in water depths of ~556, 902, and 1037 m, respectively. The drilling program included triple hydraulic piston coring, rotary coring, and well logging. The sediments recovered are silty clays and clayey silts with a large component of terrigenous material including glacial dropstones, and are Pliocene–Quaternary in age. Biogenic material occurs sporadically throughout the sequences but is abundant only in the upper Quaternary. Carbonate contents are very low, ranging from 1.5%–6%, and organic carbon values are high for such an open shelf setting, ranging from 0.7%–1.4%. The upper Quaternary is also marked by enhanced preservation of color banding; thin, very dark gray layers alternate with olive-gray sediments. The Yermak Plateau sequences are interpreted as nearly uniform hemipelagic sediments with a significant component of ice-rafted terrigenous material, including terrestrial organic carbon. High organic carbon contents are attributed to a combination of terrigenous flux and marine organic carbon supply associated with sea-ice edge productivity.

High Sedimentation Rates on the Yermak Plateau

Obtaining long sediment sequences from the Yermak Plateau to document the onset of arctic glacial conditions proved to be a difficult task, not only because of sea-ice conditions, but mainly because of an unexpectedly thick Pliocene–Quaternary sedimentary section. When drilling terminated at ~500 m below sea floor (m bsf) at both sites 910 and 911, the sediments were still Pliocene in age (Fig. 3). Sedimentation rates based on magnetostratigraphy at Site 911 range from ~17 cm/ka during the late Pliocene to ~10 cm/ka during the past 1 m.y. These rates are distinctly higher than those based on piston cores from the area; sedimentation rates for the last glacial-interglacial cycle on the Yermak Plateau range from 1.6 to 5 cm/ka (Gard, 1986, 1990, Baumann, 1990), and rates in the central Fram Strait average ~3 cm/ka (Eisenhauer et al., 1990; Köhler and Spielhagen, 1990).

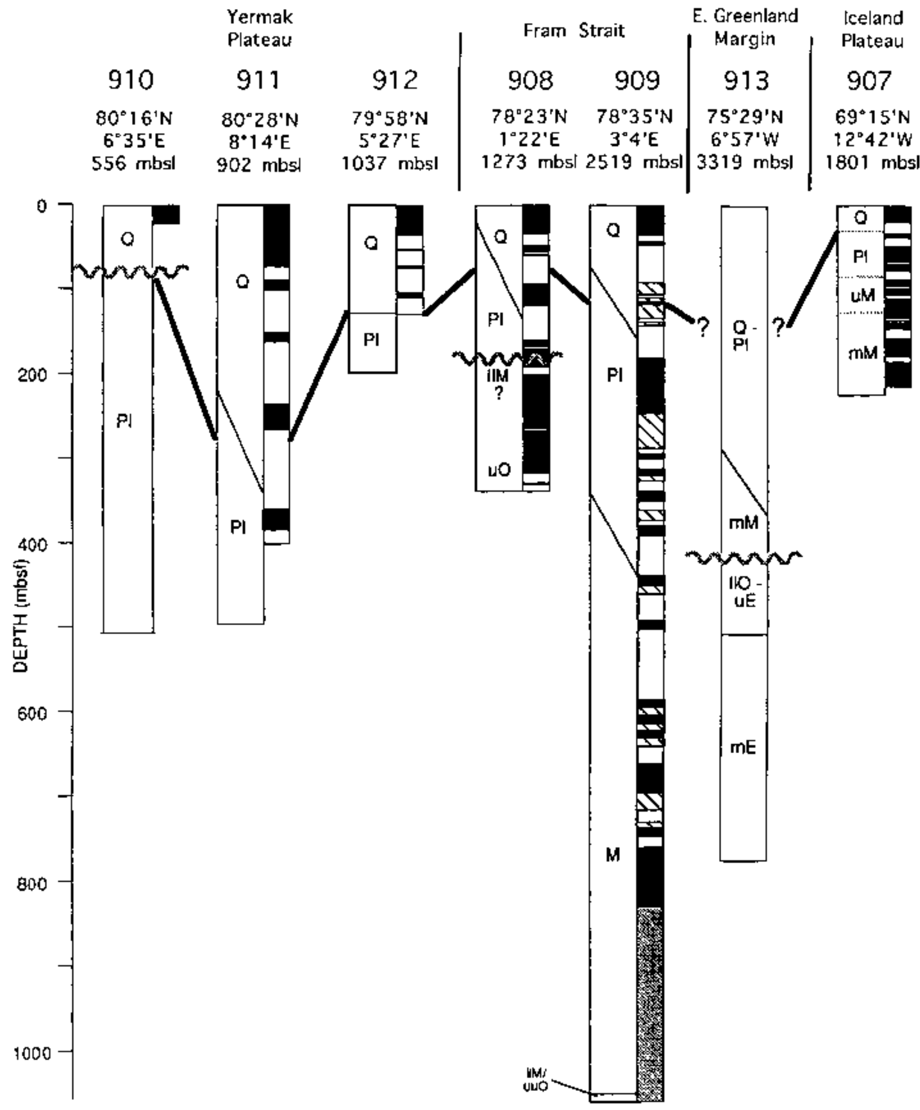

Figure 3. ODP Leg 151 drilled sequences vs. depth, grouped north to south as sites from the Yermak Plateau, Fram Strait, East Greenland margin, and Iceland Plateau. Location, water depth in meters below sea level (m bsl), age, major unconformities, and magnetic polarity records are shown for each site; llM = lower lower Miocene, llO = lower lower Oligocene and uuO = upper upper Oligocene.

The remarkable thickness of the Yermak Plateau sequences relative to upper Quaternary sediments from piston cores, and their large terrigenous component, need explanation. High sedimentation rates suggest that the Yermak Plateau was a locus of deposition for hemipelagic and terrigenous sediments, including ice-rafted material, during most of the Quaternary. When and how did conditions change such that hemipelagic sedimentation and supply of ice-rafted material to the Yermak Plateau decreased during the late Quaternary? One possible explanation is that decreased transport and melting of sediment-laden sea ice and icebergs derived from circumarctic land masses was due to changing surface current systems. In the present day, the transpolar drift funnels sea ice from the circumarctic across the Yermak Plateau through the narrow Fram Strait, where the warm West Spitsbergen Current accelerates sea-ice and iceberg melting and sediment deposition. Decreased strength of either the transpolar drift or the West Spitsbergen Current could account for such a decrease in detrital sedimentation rates. Alternatively, decreased supply of ice-rafted material could reflect the establishment of a semipermanent sea-ice cover and/or increased stability of circumarctic ice sheets. Refining the timing of this change in sedimentation rates and establishing the environmental changes that caused it may be key to reconstructing the glacial evolution of the Arctic gateway region during the Quaternary.

"Overconsolidated" Sediments at Site 910

The puzzle of relatively high Pliocene–Quaternary sedimentation rates is compounded by apparent "overconsolidation" of the sedimentary section within the Quaternary at site 910, which constitutes an important change in physical properties observed in the Yermak Plateau sites. Coring at site 910 met with "overconsolidated" silty clays and clayey silts, at ~19 m bsf, which were very difficult to penetrate with the hydraulic piston corer. Shipboard measurements of physical properties of these sediments (from ~9 to 20 m bsf) revealed a sharp increase in sediment strength with depth from <100 to >300 kPa, an increase in wet bulk density from 1.7 to 2.2 g/cm^3, and an abrupt decrease in porosity from 50% to 35%. One possible explanation for such overconsolidation prior to the latest Quaternary is that an expanded Barents ice shelf buttressed by Svalbard may have repeatedly become grounded in certain Quaternary glacial intervals and overcompacted shallow sediments on the Yermak Plateau. This possibility has implications for models of Barents Sea shelf glaciation in particular (e.g., Elverhøi et al., 1990) and ideas about the possibility of a large arctic ice sheet during the Pleistocene (e.g., Hughes et al., 1977). A fourth hydraulic piston core hole was drilled for more detailed shore-based geotechnical and stratigraphic studies, which are underway

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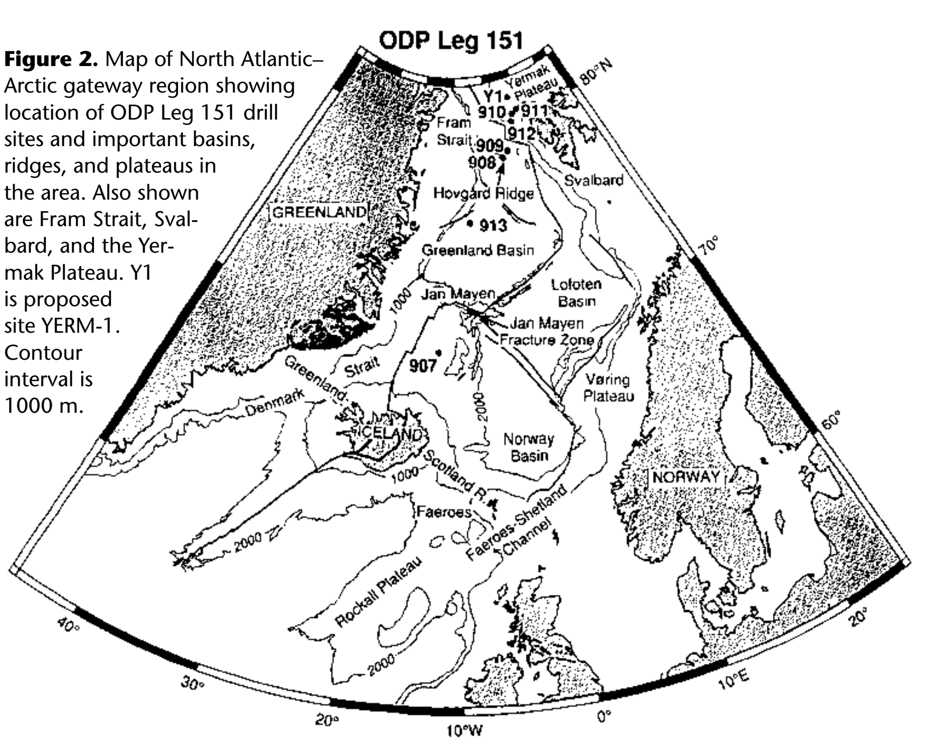

Figure 2. Map of North Atlantic–Arctic gateway region showing location of ODP Leg 151 drill sites and important basins, ridges, and plateaus in the area. Also shown are Fram Strait, Svalbard, and the Yermak Plateau. Y1 is proposed site YERM-1. Contour interval is 1000 m.

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to determine the mode and timing of sediment compaction.

Late Neogene Dropstone Input

Dropstones are found throughout the sequences recovered from the Yermak Plateau, which extend to the mid-Pliocene (site 910). Increases in dropstone input and siliciclastic abundances in these sequences suggest that glacial conditions in the Arctic gateway region became especially intense at ca. 1 Ma. The onset of arctic glacial conditions in this region is inferred from the first consistent occurrence of dropstones at Fram Strait sites 908 and 909 during the early Pliocene. Increased glacial conditions are indicated at ca. 2.5 and ca. 1 Ma. The oldest ice-rafted dropstones in the Leg 151 sites were seen in the late Miocene ca. 6.4 Ma at site 907 on the Iceland Plateau, significantly earlier than in the Fram Strait region. This finding is consistent with the age of the oldest dropstones known from the Vøring Plateau in the Norwegian Sea at ca. 10 Ma (Jansen et al., 1988, 1991; Krissek, 1989) and in the Greenland Sea in the late Miocene at ca. 7 Ma (ODP Leg 152). The glacial record in the Greenland-Iceland-Norwegian Seas clearly extends farther back in time than in the North Atlantic, where the onset of ice-rafted terrigenous material occurred in the late Pliocene ca. 2.5 Ma (Shackleton et al., 1984). Differential glacial histories of the source areas involved may account for these discrepancies in timing. Post-cruise research will attempt to address the individual histories of the circumarctic ice sheets.

Cenozoic Deep-Water Circulation in the Norwegian-Greenland Sea

The oldest sediments drilled during Leg 151 were middle Eocene in age from site 913 on the East Greenland margin. The sediments are finely laminated, highly organic and carbon rich (reaching peaks of >2%), and contain many sediment-gravity deposits. Biosilica content was very high in the late Eocene at this site, at a similar age to that observed elsewhere in the Atlantic Ocean (e.g., Berggren and Van Couvering, 1974). Laminated upper Eocene biosiliceous sediments are locally very colorful greenish blues and purplish blues, attributed to the presence of vivianite (Fig. 1B). These laminated sediments with high amounts of terrigenous organic matter and biosilica indicate a restricted basin with high surface productivity in close proximity to a continental source during the initial phase of rifting in the Greenland basin. Site 913 also recovered upper Eocene–lower Oligocene sediments with abundant biosiliceous material that will allow examination of the response of biosiliceous plankton in the Norwegian-Greenland Sea to high-latitude cooling at this time.

Laminated sediments with significant biosilica contents recovered in several upper Oligocene and lower Miocene sections suggest poor ventilation of deep waters continued into the Neogene. An unconformity encompassing much of the early Miocene–early Pliocene is present at site 908, below which are found biosilica- and biocarbonate-bearing upper Oligocene–lower Miocene sediments from ~190 to 330 m. These sediments are commonly laminated and color banded and have relatively high organic carbon values (~0.7%–2.2%), confirming that the early rifting phase in Fram Strait featured only limited deep-water exchange between the Arctic Ocean and Norwegian-Greenland Sea. The sequence at site 909 (~1060 m in length) provides a continuous lower Miocene–Quaternary record in Fram Strait. The presence of laminated and color-banded sediments through the middle Miocene, with organic carbon values ranging from ~0.7% to 1.5%, suggests low oxygen and high carbon dioxide levels in deep waters, indicative of sluggish deep-water circulation during this interval in Fram Strait.

Biosilica-rich deposition continued at site 907 on the Iceland Plateau (~1800 m water depth) well into the late Miocene until ca. 7 Ma. Accumulation of biosiliceous material until ca. 7 Ma at this site suggests that nutrients were concentrated in deep waters and upwelled to foster surface-water productivity. This pattern of circulation marked by deep-water inflow and surface-water outflow suggests an estuarine-style system, in contrast to the modern anti-estuarine circulation in the Norwegian-Greenland Sea, which is marked by deep convection. This inferred circulation history in the Norwegian-Greenland Sea suggests that deep convection could not have been a major contributor to North Atlantic deep-water formation until after ca. 7 Ma. This result needs to be reconciled with previous findings that northern component water formation has been significantly enhanced since ca. 12.5 Ma (Woodruff and Savin, 1989, 1991; Wright et al., 1992). One possible resolution is that during the interval from ca. 12.5 to 7 Ma, northern component water could have been derived mainly from other source areas such as the Labrador Sea, or from shallower depths in the Norwegian-Greenland Sea.

ODP Leg 151 also recovered material from distinctly warm intervals of the Cenozoic, including the mid-Pliocene at sites 907, 909, and 910, the late Oligocene–early Miocene at site 908, and the middle–late Eocene at site 913. Records from these sequences will help refine climate models by allowing comparison of northern polar and subpolar paleoenvironments to global climates.

FUTURE DRILLING

Sequences drilled by ODP Leg 162 in the summer of 1995 as part of NAAG II will improve the stratigraphic and geographic coverage of sediment records from this region. Two sites on the Yermak Plateau (proposed sites Yerm-1 and Yerm-5) not drilled on Leg 151 because of ice cover are high-priority targets for NAAG II. The major aim at these sites is to reach preglacial arctic sequences. A site proposed from the southern Svalbard margin is situated to better document the history of the Svalbard and Barents Sea shelf ice sheets. Sites on the Iceland Plateau are planned to study the dynamic history of surface- and deep-water circulation in the Norwegian-Greenland Sea during the Neogene. Additionally, several high-sedimentation-rate drift deposits near the southern gateway, including the Feni and Gardar drifts, are targeted to document the late Quaternary history of surface- and deep-water exchange across the Denmark Strait and the Iceland-Faeroe Ridge. The NAAG II drilling program will continue the effort to address the paleoceanographic and climatic history of the northern and southern gateway regions during the Cenozoic, including the late Neogene evolution of the arctic cryosphere. Further drilling within the Arctic Ocean proper by the Nansen Arctic Drilling Program awaits intensive efforts to develop a platform suited to the arctic pack ice.

SUMMARY

Despite logistical problems including dynamic sea-ice cover, ODP Leg 151 recovered the first deep-drilled sequences (>500 m) from the Arctic Ocean on the Yermak Plateau, as well as from Fram Strait, the East Greenland margin, and the Iceland Plateau. Material from these sites, ranging in age from middle Eocene (ca. 45 Ma) to present, allow investigation of the paleoceanographic and tectonic history in several important areas and intervals in the North Atlantic–Arctic gateway region.

Shipboard results from piston cores indicate much higher sedimentation rates on the Yermak Plateau and Fram Strait in the Pliocene–Quaternary than in the late Quaternary. A decrease in glacially derived sediments in the late Quaternary may have resulted from some combination of decreased supply from the circumarctic continental ice sheets, changes in surface circulation patterns, and possibly the establishment of a semipermanent sea-ice cover. Overconsolidated Quaternary sediments at site 910 on the Yermak Plateau suggest that a massive ice sheet may have become grounded in certain Quaternary glacial intervals, perhaps derived from the Barents Sea shelf and buttressed by Svalbard.

The oldest dropstones recovered from Leg 151 sites were of late Miocene age at site 907 on the Iceland Plateau, consistent with previous results from the Norwegian-Greenland Sea. However, the first appearance of dropstones in Fram Strait was during the early Pliocene, which may reflect differential histories of the circumarctic ice sheets. Important increases in dropstone input were observed throughout the region at ca. 2.5 and ca. 1 Ma.

Laminated sediments with significant biosilica and terrestrial organic matter recovered in several middle Eocene–middle Miocene sections suggest poor ventilation of deep waters during the early rifting phase in the Norwegian-Greenland Sea. Termination of laminated, biosiliceous sedimentation in the Norwegian-Greenland Sea in the late Miocene also suggests that active deep-water convection did not occur until perhaps ca. 7 Ma.

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Majority or Minority, Geology Still Matters

Jill S. Schneiderman, 1994–1995 GSA Congressional Science Fellow

After the Republicans overwhelmingly won the November 8 elections, the media used geological vocabulary to describe the election results—tsunami, landslide, tectonic shift—lending irony to a Republican success based on a promise, among many in the Republican "Contract with America," to abolish the U.S. Geological Survey. The personal impact of the election results was to leave me working for the would-be minority, rather than majority, leader, Senator Tom Daschle (D—S.D.).

While other fellows contemplated shifting their assignments, I delved into work in an office still in campaign mode. Senator Daschle's leadership campaign office was readjusting for his race for *minority* leader against Senator Christopher Dodd (D—Ct.) who had stepped into the race since Jim Sasser (D—Tn.) was not reelected. Sasser, and then Dodd, were the favored candidates for leader among the senior Democratic Senators who figured my boss too young for the job. Daily until December 2, the day set for the leadership race, four or five Senators came to our office to meet with Senator Daschle to discuss direction for the Democrats and the nature of the leadership needed to steer the party. Quickly, I became familiar with the faces of regulars such as Senators Barbara Mikulski (D—Md.), Jay Rockefeller (D—W.Va.), John Breaux (D—La.), Byron Dorgan (D—N.D.), and John Kerry (D—Ma.)

Leadership races are notoriously personal elections; since voting is by secret ballot, promises for support may not be firm. Thus, when Senator Daschle left our office the morning of December 2, we wished him good luck and waited anxiously for word on the vote. When the Senators met to hear the leadership nomination speeches in the Old Senate Chamber (restored to its 1859 appearance and open to the public), where Dolley Madison listened to Daniel Webster, Henry Clay, and John Calhoun debate the issues of their day, a proxy vote made Senator Daschle the new Democratic leader with a 24 to 23 count. Posted outside the Chamber, our staff person called the office to report the news. We cheered, not knowing the tumult into which it would send our office.

While Senator Daschle and his policy advisers met with colleagues to craft an agenda that meets the challenges sent by voters, I worked on the issue of flooding along the Missouri River in South Dakota. Constituents in the Pierre–Fort Pierre region had recently brought the matter to Senator Daschle's attention. The issue interests me, as a geologist and educator, for it occupies the intersection of appreciation for the cycles of Earth's rock sphere and hydrosphere and the necessity of living delicately on an ever-changing, heavily-populated Earth. Depending on one's approach, that intersection will be characterized by frustration in encountering obstacles or satisfaction in crafting durable solutions.

One of five major river basins in South Dakota, the Bad River originates in the South Dakota Badlands and flows 130 miles east into the Missouri River. It empties into the Lake Sharpe Reservoir at Pierre six miles downstream from the Oahe Dam. The Bad River drainage encompasses approximately 3120 square miles in western South Dakota which consist of easily eroded claystone and siltstone. The watershed, almost entirely privately owned land, is approximately 65% rangeland and 35% cropland.

The Bad River carries an average of 3.25 million tons of sediment into Lake Sharpe annually. Erosion and sediment accumulation from the drainage has caused water-quality concerns in the region over the past 30 years. Currently, aggradation of the Missouri River channel in the Pierre and Fort Pierre area from heavy sediment influx has restricted the main channel and causes flooding. The Corps of Engineers, though studying the problem, has not offered a remedy. Thus, potential flooding in winter months in Pierre and Fort Pierre prompted constituents to contact Senator Daschle. Though aggradation results in increased river stages throughout the year, during the winter, ice accumulation exacerbates the problem by further restricting the flow of water discharged from behind the Oahe Dam. In order to control the flooding during ice-affected conditions, Oahe Dam power plant releases are reduced. This practice interrupts power generation and is not a permanent solution; it imposes severe constraints on the ability of the Western Area Power Administration to meet power demands in the region during severe cold. The problem represents a difficult conflict between two important purposes of the dam—flood control and hydropower.

By speaking with professionals from the Corps of Engineers, the Natural Resources Conservation Service, the South Dakota Department of Environment and Natural Resources, and South Dakota constituents, I was able to absorb different viewpoints on the problem and to understand Senator Daschle's ability to facilitate a solution. Residents and city officials consider the situation untenable because storm sewers back up, streets flood, water inundates house foundations, leaking into basements, and water-supply well houses have been flooded, a threat to municipal water supplies.

In a 1992 reconnaissance report requested by Rep. Tim Johnson (D—S.D.), the Corps of Engineers investigated alternative solutions to alleviate the power constraints at the dam and control flooding. The corps suggested levee construction as an economically feasible means to provide flood protection. Water-resource management professionals at the South Dakota Department of Environment and Natural Resources view levee construction as a temporary measure that delays the inevitable additional flooding or construction of higher levees. Townspeople object to levees because of their aesthetic and economic impact. Additionally, they recognize that levees would adversely affect high-quality aquatic and terrestrial habitats of two riverine islands used by wintering wildlife populations. Power plant releases would produce higher stages and flood large areas of hardwood habitat and wetlands in LaFramboise and Farm Islands to several feet (U.S. Army Corps of Engineers, Omaha District, May 1992 report). In my opinion, after having

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