residuals for high sulfur-producing events like the equatorial Tambora eruption (A.D. 1815) and the Icelandic Laki eruption (A.D. 1783) are 94 ppb and 134 ppb, respectively. Note that SO_4^{2-} residuals for three events between 5000 and 7000 B.C. exceed 650 ppb.
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Seven Million Years of Glaciation in Greenland

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Glacial till, glaciomarine diamictites, and ice-rafted detritus found in marine cores collected off the shore of southeast Greenland record multiple Late Cenozoic glaciations beginning in the Late Miocene. Distinct rock assemblages and seismic stratigraphic control correlate the diamictites with glaciation of the southeast Greenland margin. Glaciers advanced to the sea during several intervals in the Pliocene and Pleistocene. North Atlantic glaciation may have nucleated in southern Greenland rather than further north because of the high mountains and the high levels of precipitation in this region.

The Greenland Ice Sheet (GIS) is the only continental ice sheet in the Northern Hemisphere in the present interglacial period, but little is known about when it formed or its long-term history. Ice cores from the GIS show that an ice sheet was present during the last 200,000 years (*1*). Glacial sediments at two localities on Greenland are thought to have been deposited during latest Pliocene time, 1.8 to 2.0 million years ago (Ma) (*2, 3*). The earliest firm evidence of glaciation in the North Atlantic area has been from Iceland. There, glacial sediments date from 3.1 Ma (*4*), but glaciers there may not have grown large enough to reach the sea until 2.0 Ma (*5*). The earliest occurrence of abundant ice-rafted detritus (IRD) found widely in North Atlantic marine cores dates to about 2.4 Ma (*6–8*), but it is not known if ice sheets on Greenland were a source for this debris or if glaciers existed on Greenland at even earlier times. Low concentrations of fine-grain IRD have been reported from marine cores off mid-Norway and suggest that some North Atlantic glaciation could date back as early as 5.45 Ma (*8*). However, it has also been suggested that before 2.4 Ma, any glaciers in the North Atlantic area were too small to reach the sea (*5*). Hence, there is considerable uncertainty with regard to the location and timing of early glaciation within the North Atlantic.

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During Ocean Drilling Program (ODP) Leg 152, a transect of six sites (ODP sites 914 to 919) was drilled, extending from 40 to 185 km east of the southeast coast of Greenland (Fig. 1). Four sites (sites 914 to 917) were located on the continental shelf in a 500-m-deep trough, and two deep-water sites (sites 918 and 919) were located below the shelf break, 40 and 115 km seaward of the mouth of the trough, respectively. All sites are within the present-day limit of icebergs from the highly productive southeast Greenland coast (9). These marine cores contain an unusually complete record of glaciations of southeast Greenland (Fig. 2). The data show that substantial glaciation in Greenland began as early as 7 Ma in the Late Miocene following a relatively mild climate during the Middle Miocene.

The most complete record of Miocene and Pliocene glaciations was obtained at ODP site 918, drilled in 1800 m of water 110 km from the coast of Greenland (Figs. 1 and 2). The upper 550 m of sediment at the 1310-m-deep site 918 contains abundant silts and muds, within which numerous, typically granule- to pebble-size gravel clasts, but also occasionally cobble- to even boulder-size clasts, are suspended. In addition, a number of more massive, 0.3- to 10.0-m-thick beds of poorly sorted, ungraded silt, sand, and angular gravel are present (Fig. 2). The two types of sediments are interpreted as follows: (i) hemipelagic sediment and turbidites with discrete occurrences both of more fine grain IRD and larger dropstones and (ii) more massive glaciomarine diamictons. Both sediment types, therefore, reflect glacial, although variable, conditions within the source area. Indeed, intervals up to 40 m thick without macroscopic IRD exist in cores from site 918. The diamictons show relatively high magnetic susceptibility and high bulk density relative to the intercalated marine sediments. Some of these layers may be correlative with the extensive Heinrich layers of glaciomarine sediment described elsewhere in the North Atlantic, but most of the diamictite horizons are older than any previously recognized Heinrich layers (*10*).

The IRD and dropstones were present in situ, in places actually cored through, in undisturbed sediment cores for which the possibility of down-hole contamination with clasts can be excluded. However, the possibility exists that dropstones were transported within mass flows from unstable accumulations of glacial sediments of the

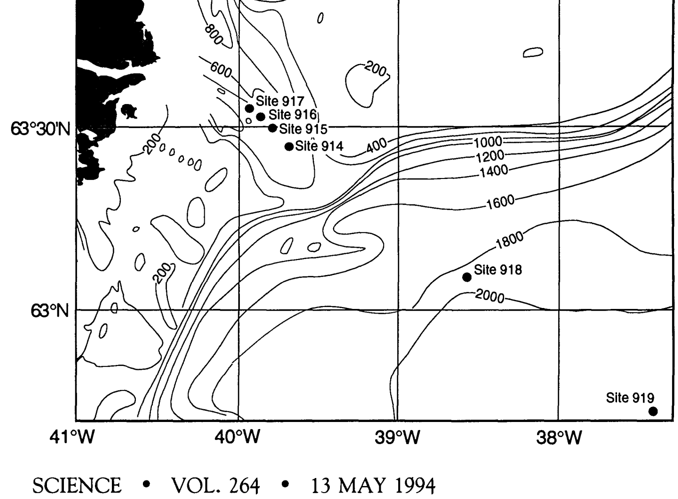

Fig. 1. Location of ODP sites 914, 915, 916, and 917 on the east Greenland shelf, and sites 918 and 919 within the deep Irminger basin. ODP site 919 lies about 75 km east of site 918. Depth values are given in meters.

shelf/slope region and into their present-day, deep-basin plain setting, although this is much more likely to occur in a direct-slope setting (*11*). The fine-grain nature of the matrix—the lack of thick or graded beds (or both) and the lack of distorted sediment structures or strong erosive bases—is not in support of mass flows generally capable of transporting the large clasts observed. This condition would also be inconsistent with the often close association of dropstones and finely structured patches of sandy to granule-size IRD.

The composition of the ice-rafted material reflects a provenance from rocks exposed along the coast of southeast and central east Greenland and allows the deep-sea record of alternating glaciomarine and marine sedimentation to be correlated with the growth and wastage of glaciers on the nearby coast. At least 50% of the gravel clasts in each diamictite consist of gneiss and granite from the Precambrian basement terrain of southeastern Greenland (*12, 13*). Basalt clasts are also abundant and were likely derived from thick Tertiary basalts exposed on the inner shelf and along the coast to the north (*14, 15*). Other less frequently encountered lithologies include schist, limestone, and sandstone, which were probably transported from the fjord zone of northeastern Greenland (*16*). The matrix of the diamictites consists of highly permeable, clay- to fine sand–size, quartz-rich rock flour and evidently was derived from glacial comminution of felsic high-grade basement rocks. Modern IRD from east Greenland has similar characteristics (*17*). Polar sea ice seasonally drifts southward through the study region but cannot be a source for the dominating clast assemblages. Because only limited amounts of sea ice form in the defined source region, we interpret the IRD and dropstones as mainly iceberg-transported.

The easternmost site, ODP site 919, was drilled 75 km seaward of site 918 in 2000 m of water (Fig. 1). This hole was only 145 m deep and recovered silts and muds with a lower abundance of IRD and dropstones than at the more proximal site 918 (Fig. 2). The ODP sites 914, 915, 916, and 917 were drilled on the continental shelf, only 40 to 75 km from the Greenland coast (Fig. 1). Cores from these sites recovered glaciomarine sediments intercalated with a strongly compacted glacial till, characterized by high shear strength measured in the shipboard physical properties laboratory to 150 kPa with the use of a motorized shear vane device. The till was evidently deposited and deformed below grounded shelf ice during a past advance of the GIS that extended at least 75 km onto the continental shelf including areas where present-day water depth exceeds 500 m. The till contains a clast assemblage with a lower proportion of basaltic material than at site 918, indicating a smaller contribution of IRD from basalt outcrops to the north. Seismic stratigraphic unconformities within the glacial shelf section were not observed in the cores because of low recovery and poor stratigraphic control within the glacial shelf sediments.

The seismic data correlate the distal diamictites at ODP site 918 with the proximal glacial deposits on the shelf (Fig. 3). The data show that the outer continental shelf for the main part is constructed of a stack of shingled, seaward-dipping beds (Unit II in Fig. 3). Landward and upward, this package can be traced into a subhorizontally bedded package (Unit I) that is coeval to younger sediment, comprising glaciomarine sediments and till (Figs. 2 and 3). During past advances of the GIS onto the shelf, debris from the continent, together with material reworked from below the glacier, was transported seaward and deposited as part of a large-scale progradational glacial fan (Unit II) at the shelf edge (*18*). Likewise, during ice recession, primarily vertical aggradation took place (Unit I).

The lowest occurrence of a diamictite and dropstones at site 918 is at 543.5 m below the sea floor (mbsf), where a 30-cm-thick zone of IRD contains gravel-size clasts of Greenlandic gneiss and basalt in a sandy matrix (Fig. 4). Below this diamicton is a transitional, 60-m-thick zone in which the percentage of $CaCO_3$ drops up-section from 40% to less than 10%. In the North Atlantic, this value is largely controlled by the influx of ice-rafted, non-carbonate debris (*6–8, 19, 20*). The underlying carbonate-rich sediments contain evidence of a fairly warm-water environment, as determined from the planktonic microfauna. Microscope smear slides show an increasing abundance of quartz and other silicate minerals upward through the transition zone and a decreasing abundance of nannofossils and foraminifers. Furthermore, a large increase

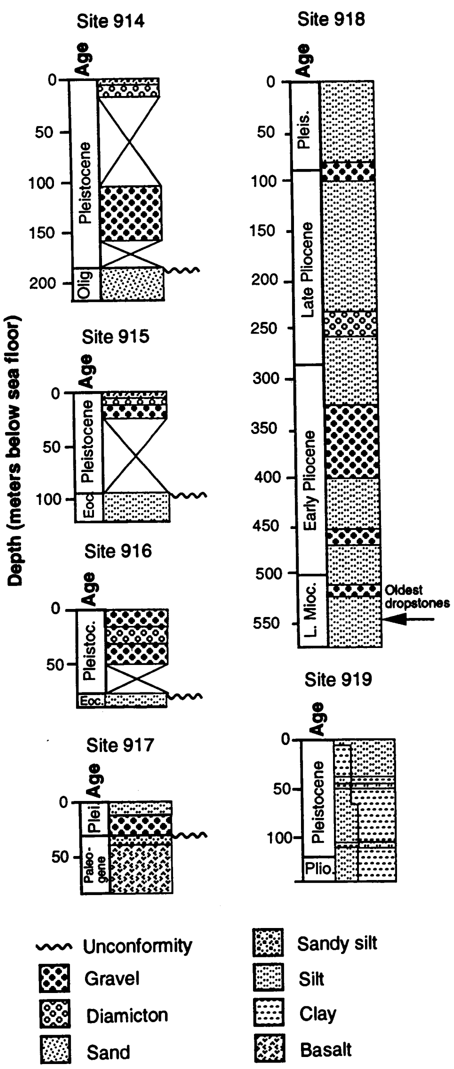

Fig. 2. Simplified logs showing the Late Miocene to recent sediments deposited at each ODP drill site. Note the erosive base to the sections at sites 914 to 917 and the expanded section at site 918. The short section at site 919 reflects a lack of deep drilling at that site.

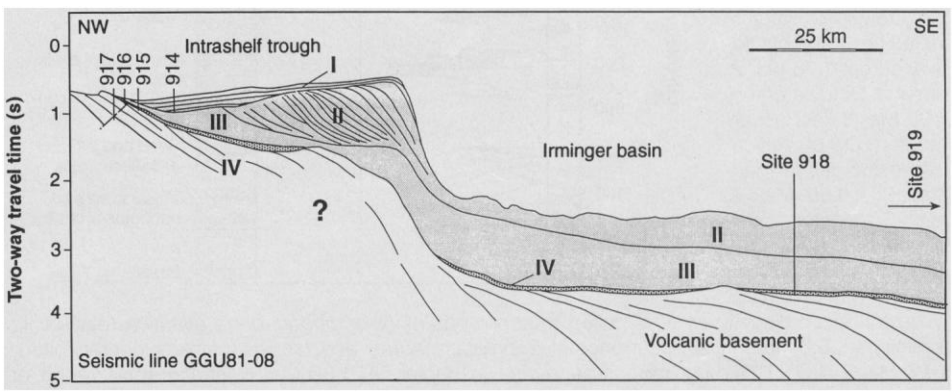

Fig. 3. Interpretation of seismic profile through glacial sediments on the east Greenland shelf and in the deep sea (*16*). Seismic Unit I: Pleistocene; Unit II: Late Miocene to Pleistocene; Unit III: Oligocene to early Late Miocene; Unit IV: Eocene.

in the average sedimentation rate takes place within the upper 500 m of sediments at site 918 (Fig. 4), suggesting considerable glacial erosion of the source area.

The 60-m transition zone below the diamicton at 543.5 m is interpreted as reflecting climatic cooling leading to increased erosion and shedding of clastic detritus from southern Greenland into the adjacent deep sea. The lowering of the carbonate content in the sediment may also reflect increased carbonate dissolution by lower water temperatures, although strongly reduced biogenic productivity because of extensive sea-ice cover is unlikely.

The diamicton at 543.5 m is interpreted as reflecting full glaciation of at least the southeast Greenland region, with glaciers extending to coastline or beyond and with the production of icebergs at a similar (or higher) level than at present. Mountain glaciers may have formed well before this diamicton, but possible IRD below 543.5 m was not evident from the shipboard analysis of the core. Core recovery was not continuous at site 918, but the Brunhes and Matuyama chrons and the Olduvai and Reunion events were recognized in the upper part of the drill hole (Fig. 4). Although the transition between the Matuyama and Gauss chrons was not recovered, normally magnetized sediments found below 385 mbsf were likely deposited during the Gauss chron (>2.6 Ma).

Microfossils provide a more accurate date on the lowest glaciomarine sediment at 543.5 mbsf (Fig. 4), with ages derived from bio- and magnetostratigraphic studies of high- to middle-latitude sites (*21, 22*). Above 543 mbsf, sediments contain the nannofossil *Discoaster quinqueramus* at 513 mbsf, a species that became extinct before 5.5 Ma (*21*), as well as the transition from dominantly dextral to dominantly sinistral coiling in the planktonic foraminifer *Neogloboquadrina atlantica*, an event dated to 6.6 Ma (*22*). Below the glaciomarine sediments, the lowest occurrence of *Neogloboquadrina acostaensis*, at 628 mbsf, indicates an age of 10.7 Ma. If a linear sedimentation rate is assumed between these biochronologic control points (Fig. 4), the age of the earliest glaciomarine sediment at 543 mbsf is 7.0 Ma, and the marked drop in $CaCO_3$ at 600 mbsf is dated at 9.6 Ma. The sequence cored between 543 and 490 mbsf contains dropstones and diamictites throughout. This record indicates that Greenland glaciers continued to extend to the sea and discharge icebergs for perhaps a million years after the deposition of the lowest diamictite layer.

The greatest concentration of diamictite layers is in a 70-m-thick package, including one deposit 10 m thick, from 100 to 170 m below the Reunion event of the Matuyama chron (approximately 2.21 Ma) and 70 to 140 m above sediments assigned to the Gauss chron (>2.6 Ma) (Fig. 4). One or more of the diamictite layers within this interval may correlate with the horizon of IRD found widely across the North Atlantic and dated at 2.4 to 2.5 Ma (*6–8*).

Thus, Greenland could have been the source of much of the IRD distributed across the North Atlantic at this time. However, the volume of dropstones and IRD with coarse or larger sand size found at the easternmost site 919 (Fig. 2) is less than 10% of that at site 918. The eastward decrease in glacial sedimentation recorded in the distal, offshore sites suggests that, as at present, a strong east-west climatic gradient existed and ice was mainly transported south. Although severe down-hole contamination problems exist in the cores of ODP site 646 south of Greenland, these cores are consistent with a Late Miocene glaciation of southern Greenland (*23*).

The glacially influenced deposits off east Greenland are separated by marine sediments completely free of dropstones or diamictites (Fig. 4), which apparently correspond to times when glaciers onshore Greenland retreated from coastal areas or perhaps disappeared entirely. These variations in the Pliocene climate may correspond to interglacial periods observed in the benthic foraminiferal $\partial^{18}O$ record, and whose maxima are dated to 3.1, 2.7, 2.6, and 2.4 Ma (*24*). Likewise, one or more of the apparent ice-free intervals in the Late Pliocene may correlate with an interval when warm conditions and Boreal forests prevailed in Greenland (*25, 26*).

Several lines of evidence suggest that globally significant climate perturbations generated glaciers in other parts of the Earth at about the same time glaciation began in the North Atlantic area on Greenland. Isotope data from marine benthic foraminifers record an increase of about 0.13 per mil in the $\partial^{18}O$ record of the oceans at 6 to 7 Ma. This increase has been thought to indicate the growth of ice caps and small ice sheets (*27, 28*). Global sea-level reconstructions show a regression occurring at the same time (*29, 30*). Given that the ocean $\partial^{18}O$ value changes by 0.11 per mil per 10 m of sea-level change (*31*), as much as a 12-m drop in sea level may have occurred at this time. In comparison, the GIS now contains about a 2.5×10^6 km^3 water equivalent, corresponding to a 5- to 7-m change in sea level. Significant glaciation occurred from the Late Miocene in southeast Alaska, where more than 5 km of glaciomarine sediments have been deposited since about 6.5 Ma (*32*). Ocean water also cooled at about 6.3 Ma in the northwest Pacific (*33*). In the Southern Hemisphere, ice rafting of debris from Antarctica peaked from 6.6 to 6.1 Ma, apparently as a result of advances of Antarctic glaciers and

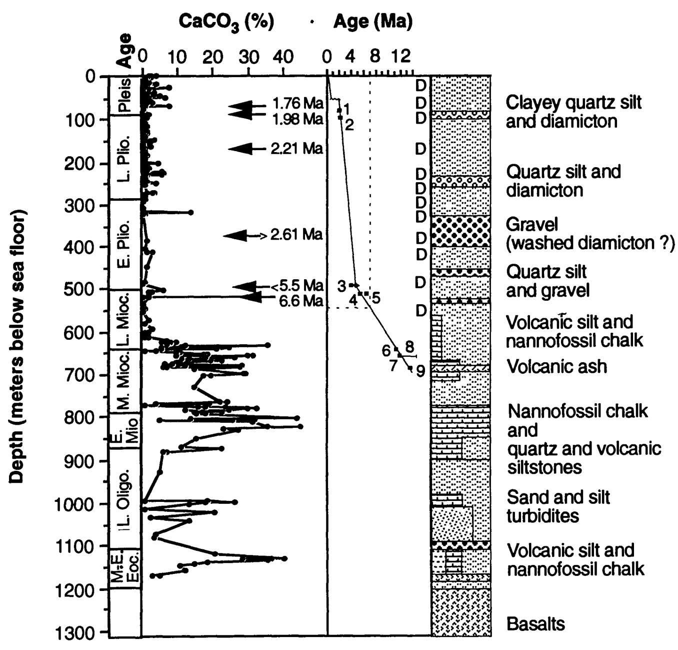

Fig. 4. Schematic sedimentary log of the section cored at site 918 showing diamictite layers (marked as "D"). The percentage of $CaCO_3$ in sediments shows a marked drop at 600 mbsf, corresponding to the first influence of glacial sedimentation. Sedimentation rate estimates are based on magnetic and biochronologic datums, including: 1, top of Olduvai chron, 1.76 Ma; 2, base of Olduvai chron, 1.98 Ma; 3, last occurrence (LO) of *Reticulofenestra gelida* (nannofossil), 3.65 Ma; 4, LO *Discoaster quinqueramus* (nannofossil), 5.5 Ma; 5, coiling change from dominantly dextral to dominantly sinistral coiled morphotypes of *Neogloboquadrina atlantica* (planktonic foraminifer), 6.6 Ma; 6, first occurrence of *Neogloboquadrina acostaensis* (planktonic foraminifer), 10.7 Ma; 7, LO of *Cyclicargolithus floridanus* (nannofossil), 11.9 Ma; 8, stratigraphic range of *Globorotalia praemenardii* (planktonic foraminifer), 12.0 to 14.5 Ma; 9, LO of *Sphenolithus heteromorphus* (nannofossil), 13.6 Ma. With assumed linear sedimentation rates, the lowest glaciomarine diamictite dates to 7 Ma, while the $CaCO_3$ drop in the sediments occurred at about 9.6 Ma.

ice shelves (*34*), and glaciation in Patagonia is reported to have taken place around 6 to 7 Ma (*35*).

Taken together, there is considerable evidence that significant global climate variability during the Late Miocene led to a growth of glaciers. Glaciers would readily form in southeast Greenland because of the combination of high precipitation and high topography in the area, and North Atlantic glaciation likely nucleated in this region rather than further north.

Our new data add considerable constraints to the long-term modeling of North Atlantic glaciation. Consistent with data from Iceland (*36*), they prove that the Middle Miocene was fairly mild, that cooling most likely started shortly after 10 Ma within the early Late Miocene, and that full glacial conditions in southeast Greenland were established around 7 Ma in the middle Late Miocene, contemporaneous with Southern Hemisphere glacial expansion. The Late Miocene and Pliocene climate was variable, with perhaps completely ice-free periods. North Atlantic glaciation may have nucleated in—and for the first million years, been largely restricted to—Greenland. The east-west gradient in the abundance of glacial material off southeast Greenland makes it unlikely that this part of Greenland has provided significant contributions to the northern North Atlantic IRD found elsewhere. Therefore, IRD from off mid-Norway and Svalbard dated to between 5.7 and 4.5 Ma (*8*, *23*) suggests that other North Atlantic ice sheets started to form no later than that time and that they were fully established at about 2.5 Ma.

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Isotopic Evidence for Neogene Hominid Paleoenvironments in the Kenya Rift Valley

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Bipedality, the definitive characteristic of the earliest hominids, has been regarded as an adaptive response to a transition from forested to more-open habitats in East Africa sometime between 12 million and 5 million years ago. Analyses of the stable carbon isotopic composition ($\delta^{13}C$) of paleosol carbonate and organic matter from the Tugen Hills succession in Kenya indicate that a heterogeneous environment with a mix of C3 and C4 plants has persisted for the last 15.5 million years. Open grasslands at no time dominated this portion of the rift valley. The observed $\delta^{13}C$ values offer no evidence for a shift from more-closed C3 environments to C4 grassland habitats. If hominids evolved in East Africa during the Late Miocene, they did so in an ecologically diverse setting.

Explanations for the origin of the Hominidae have invoked many different selective pressures, including bioenergetic (*1*), migratory (*2*), morphological (*3*), and thermoregulatory (*4*) considerations associated with foraging and feeding behavior, as well as aspects of life history patterns (*5*) and social systems (*6*). Implicit in most of these explanations is that as Middle to Late Miocene [15 million to 5 million years ago (Ma)] rain forests in Africa became restricted in distribution, drier and more seasonal woodland and grassland communities became widespread, and overall habitat diversity increased. It has been assumed that the divergence of hominids from the other African apes was associated with terrestrial adaptations to exploit resources in open habitats or in bridging forested patches. Origin of the genus *Homo* has also been

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