Chapter 13

QUATERNARY GEOLOGY OF THE ICE-FREE AREAS AND ADJACENT SHELVES OF GREENLAND

Co-ordinator
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SUMMARY

Greenland, the largest island in the world, has a general bowl shape with peripheral mountainous areas surrounding a central basin that extends below sea level. The Greenland Ice Sheet occupies the central bowl, covers much of the fringing mountains, and in places pushes to the coast where it calves into the sea. Ice-free regions at the fringes of the ice sheet are in most areas mountainous, cut by fiords and contain scattered thin deposits of till and local thick deposits of Quaternary nonglacial sediments of a variety of different ages.

Evidence from shelf areas indicates that an early glaciation of Greenland, which was more extensive than any succeeding one, occurred near the end of the Pliocene (about 2.4 Ma). A younger phase of glaciation (about 1.8 Ma) is recorded near the base of the Kap København Formation and in the Lodin Elv Formation. Sediments above deposits related to this glaciation were deposited under cool temperate conditions. Tree remnants included in these sediments suggest a climate incompatible with existence of an inland ice sheet.

Several areas contain a record of a glaciation that occurred prior to the last interglaciation. This has been referred to as Fiskebanke, Scoresby Sund, and Bliss Bugt glaciations in West, East, and North Greenland, respectively. On the basis of intensity of weathering it is suggested that these three are correlative. The glaciation is tentatively referred to Illinoian. This glaciation was more extensive than subsequent glaciations, and distribution of erratics indicates that ice in coastal areas was thick enough to move independent of the underlying topography.

The last interglaciation is recorded in the Kaffehavn and Langelandselv deposits that contain subarctic marine fossils which are near to or farther north than similar Holocene faunas. No terrestrial interglacial deposits have been found but data from cores of the Inland Ice have been used to suggest that the Greenland Ice Sheet did not exist at the peak of this interglaciation. The marine sediments that overlie the Langelandselv deposits contain an Arctic fauna and are found as much as 100 m above present sea level. These, the Jameson Land marine beds do not contain direct evidence of glaciation but the Arctic fauna indicates cooler conditions than during the preceding interglaciation and isostatic depression caused by a buildup of ice is required to explain their position well above sea level.

The ice-free areas of Greenland record only one main ice advance of Wisconsinan age. This ice advance occurred after 40 ka and is referred to as the Sisimiut, Flakkerhuk, and Independence Fjord glaciations in West, East, and North Greenland, respectively. Off West Greenland, this ice was grounded as far as 30-50 km offshore and locally off East Greenland it extended as far as 200 km. The culmination of this glaciation apparently occurred about 14 ka and large scale oscillations apparently were in phase in all parts of the ice sheet.

Ice retreat possibly began soon after 14 ka and by 10-11 ka the ice margin was located near the present coast. A readvance, possibly caused by increased precipitation, occurred between 10.3 and 9.5 ka in East Greenland. This oscillation, referred to as the Milne Land stade deposited moraines and outwash plains in many fiords. The Taserqat stade of West Greenland is of similar age. By about 7 ka the ice sheet had retreated to its present limits, and between then and 3 ka it lay as much as 10 km inside this position. Readvance after 3 ka brought the ice sheet to a maximum position in the late 19th Century and this was followed by minor retreat to the present limits.

Relative sea level has fallen in all areas since Wisconsinan glaciation largely due to emergence of the land. Maximum uplift (generally up to 100 m but locally as much as 140 m) is recorded near the outer coast with the level decreasing towards the present ice margin. Submergence, possibly caused by the late Holocene expansion of the Greenland Ice Sheet, has been occurring over the past few centuries.

During the early Holocene fell field vegetation was replaced by dwarf shrub heath and subarctic-boreal bivalves began to appear in coastal waters. These suggest that by 7-8 ka temperatures were slightly warmer than at present. The comparatively warmer water fauna and temperate vegetation began disappearing at different times in different areas. Late Holocene cooling apparently commenced in coastal East Greenland about 5 ka, in West Greenland about 4 ka, and in North Greenland about 3.5 ka.

Funder, S. (co-ordinator)
1989: Quaternary geology of the ice-free areas and adjacent shelves of Greenland; Chapter 13 in Quaternary Geology of Canada and Greenland, R.J. Fulton (ed); Geological Survey of Canada, Geology of Canada, no. 1 (also Geological Society of America, The Geology of North America, v. K-1).

INTRODUCTION

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The Quaternary geology of the ice-free land is closely associated with the former glacial regime of the Inland Ice, which in turn is a result of the interaction between bedrock geology, physiography, and climate. Consequently this chapter begins with a brief description of these environmental features.

At present the Inland Ice regimes range from cold-polar and dry in the north to subpolar and humid in the south. This pattern has existed for a long time and has played a major role in the creation of different types of landscapes and glacial deposits. These differences make it natural to discuss the Quaternary geology of Greenland in terms of three regions: West Greenland with its characteristic landscapes of heavily abraded bedrock and sparse Quaternary cover; East Greenland with its spectacular fiord landscapes, created by selective glacial erosion, and at least locally thick Quaternary deposits; and North Greenland exhibiting a variety of landscape types, including the thickest accumulations of Quaternary sediments found in Greenland.

The Quaternary has in general terms been an era of erosion for Greenland, and much of the eroded material can now be found on the coastal shelves. The record of the shelves hence forms an important adjunct to the terrestrial Quaternary record. Geological information from these areas is presently emerging as a by-product to oil exploration. A detailed account of the geology of the East Greenland shelf is given elsewhere in this series (Larsen, in press). A summary of the currently emerging Quaternary history of the shelves adjacent to Greenland is also presented in this chapter.

Other sections of this chapter discuss sea level history and the Quaternary development of marine and terrestrial ecosystems, with main emphasis on the Holocene. The final segment is a summary history that considers the development of climate, glaciers, and oceanographic circulation during the Quaternary.

Bedrock geology and physiography

Bedrock geology

The largest part of the country, probably including areas under the Inland Ice, is made up of Precambrian crystalline rocks — gneisses and migmatites with interbedded supracrustal and various plutonic rock types (e.g., Kalsbeek, 1982). Several mobile belts are recognized in this Precambrian Shield which was established as a craton by middle Proterozoic time (Fig. 13.1).

Along the northern and eastern margins of this stable block, sedimentary basins began to develop in mid-late Proterozoic time, and thick piles of sediment accumulated on the subsiding continental crust. In East Greenland, sandstone, pelites, and carbonates accumulated in the basin in Late Proterozoic and Early Paleozoic times and during the Caledonian Orogeny (Early Silurian); these sediments were folded, thrusted, metamorphosed, migmatized, and locally intruded by granite (Henriksen, 1985; Hurst et al., 1985). In North Greenland the sedimentary basin was occupied by a shallow shelf sea to the south, with mainly carbonate sedimentation (Peel, 1985), and a deep water trough to the north, with a sequence of mainly turbiditic sandstone and shale (e.g., Dawes and Peel, 1981; Surlyk and Hurst, 1984; Higgins et al., 1985). During the Innuitian Orogeny (Late Paleozoic) the deep water basin was deformed and the sediments folded and progressively metamorphosed up to amphibolite facies in the north, while the carbonate platform to the south escaped major deformation and metamorphism.

Following the Caledonian Orogeny, Greenland was part of a single North Atlantic landmass, comprising the North American and North Eurasian plates. In East Greenland thick deposits of Devonian and Carboniferous terrestrial sandstones were deposited in intramontane basins and testify to crustal instability and rapid downwasting of the newly formed mountain range (e.g., Birkelund and Perch-Nielsen, 1976). Later, especially in Mesozoic time, a new complex sedimentary basin arose by block faulting along lines parallel to the present coast (Surlyk et al., 1981). This basin was filled with continental and marine-epicontinental sandstone and shale. At right angles to the main direction of faulting, crossfaults with a northwest-southeast strike formed. Much later these determined the location of the spectacular fiords of East Greenland.

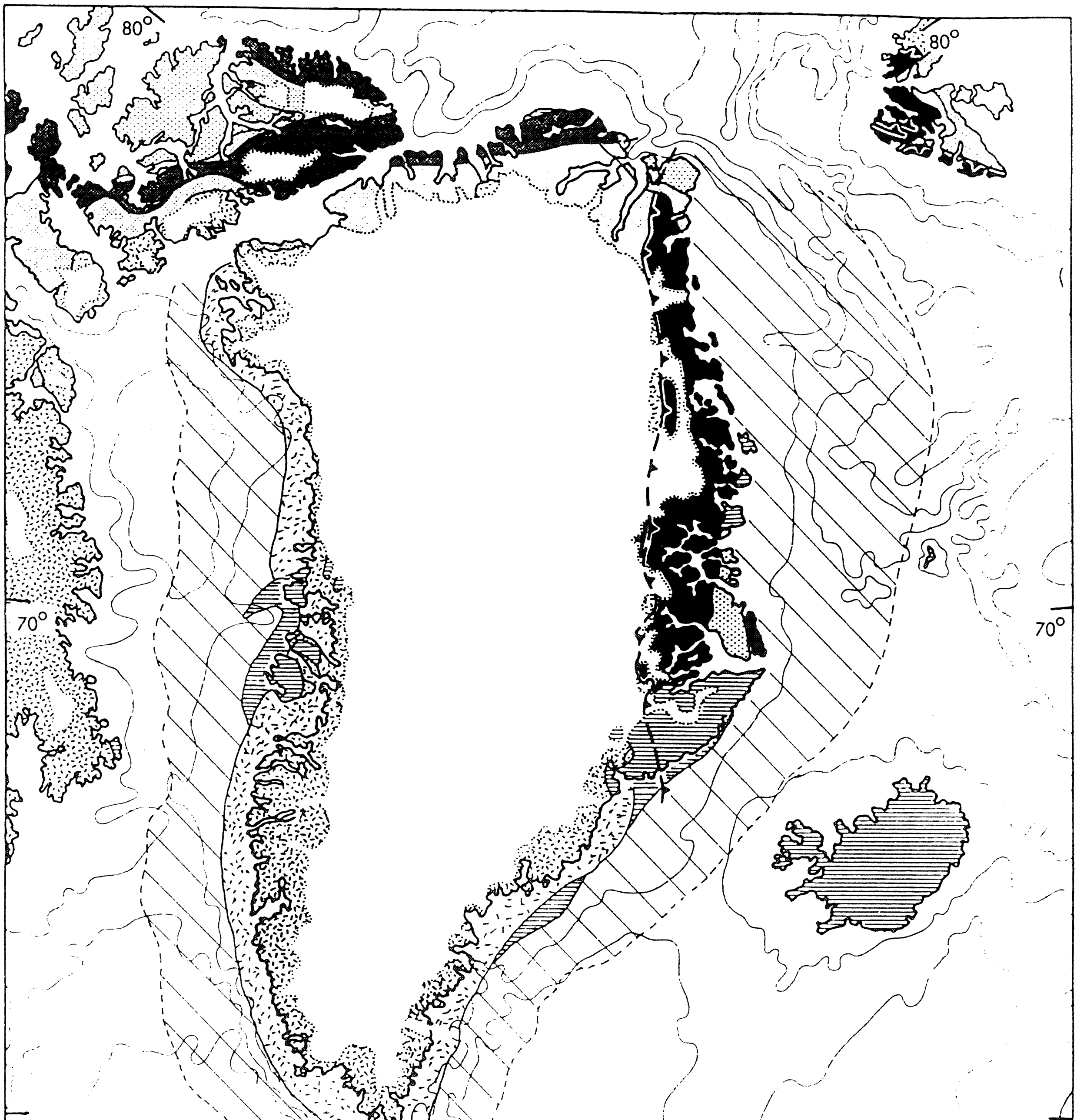
The Precambrian Shield in West Greenland also began to fragment in Mesozoic time, and a new sedimentary basin — the West Greenland Basin — was formed in the Late Cretaceous by rifting and faulting parallel to the present coastline. The sediments are exposed on land in the Nugssuaq Embayment as a thick pile of clastic marine and fluvial sandstone and shale but are mainly confined to the shelf (Henderson et al., 1981).

Thus, by Late Mesozoic time the stage was set for a decisive chapter in the history of Greenland — the history of how the country attained its present shape and physiography. This process was closely related to the formation, by active ocean floor spreading, of the Baffin Bay-Labrador Sea in the west and of the Greenland and Norwegian seas in the east. In the early Tertiary, ocean floor spreading was preceded by a period of effusive volcanism, which produced sheets of plateau basalts in the Nugssuaq Embayment of West Greenland (Clarke and Pedersen, 1976) and locally in East Greenland (Larsen, 1980; Brooks and Nielsen, 1982; Larsen and Watt, 1985).

During the ensuing period of ocean floor spreading vast amounts of terrigenous detritus were deposited in the West Greenland shelf area and in a newly formed sedimentary basin extending along the entire East Greenland coast.

Funder, S.
1989: Introduction (Quaternary geology of the ice-free areas and adjacent shelves of Greenland); in Chapter 13 of Quaternary Geology of Canada and Greenland, R.J. Fulton (ed); Geological Survey of Canada, Geology of Canada, no. 1 (also Geological Society of America, The Geology of North America, v. K-1).

Figure 13.1. Geology of Greenland's ice-free land and shelf in relation to neighbouring land areas (modified from Escher and Watt, 1976; shelf geology from Henderson et al., 1981; Larsen, 1983; and H.C. Larsen, unpublished).



Main areas of permanent ice cover

West and East Greenland sedimentary basins on shelf (Cretaceous to Quaternary)

Tertiary volcanic rocks, In Iceland includes Quaternary

Mesozoic and younger platform deposits

Paleozoic and older platform deposits

Innuitian orogenic system

Caledonian orogenic system

Mainly Proterozoic mobile belts

Archean mobile belts

Thrust of regional importance

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Seismic and aeromagnetic investigations have shown that these sediments, which were deposited mainly in the Tertiary and Quaternary, attain thicknesses of 7 km (Larsen, 1980; Henderson et al., 1981), and the record preserved in them provides an indirect record of the development of the physiography of the adjacent land.

Development of preglacial physiography

As noted above, the shaping of Greenland and its preglacial topography is a consequence of ocean floor spreading in adjacent oceans during the Tertiary. While the oceans formed, tectonic adjustments took place along the margins of the continental block, resulting in subsidence of the seaward border and uplift of the land.

Using geomorphological criteria, remnants of ancient uplifted terrain surfaces have been recognized in many parts of Greenland (see summary by Weidick, 1975a). The most extensive of these features is the "initial topography" described from East Greenland by Ahlmann (1941). The "topography" lies between 72° and 76°N, and extends from under the Inland Ice to the coast. It formerly was an undulating plain, but now is preserved as deeply dissected mountain plateaus and summit areas at approximately 2000 m elevation. The plain is thought to have developed during a prolonged period of denudation and fluvial erosion and to have been uplifted in the late Tertiary.

From the structures of early Tertiary plateau basalt and fission track dating of later intrusions in southeast Greenland, Brooks (1979) and Gleadow and Brooks (1979) were able to show that large-scale fluvial erosion was followed by epeirogenic uplift of up to 2.5 km, in Oligocene and Miocene times. Great thicknesses of Upper Oligocene to Upper Miocene terrigenous sediments on the adjacent shelf may be a consequence of this uplift (Larsen, 1984).

West Greenland also has experienced considerable uplift in coastal areas so that deep-crustal rock types on land, border on a thick sequence of mainly Cenozoic fluvial and marine sediments on the adjacent shelf. Precise timing of this uplift is still lacking; however, analyses from boreholes on the shelf indicate initial Paleocene-early Eocene sediment was derived from an extensive drainage system in a deeply weathered land area with mature relief. Late Eocene and Oligocene clastic sediments reflect rejuvenation of the relief by uplift of the land (Henderson et al., 1981).

Hence it appears that the mountains of Greenland — like those elsewhere around the North Atlantic — initially were formed by late Tertiary epeirogenic uplift. The uplift apparently was most intense in the east, causing the asymmetry of drainage. Presently the main drainage divide runs north-south near the eastern ice margin, leaving large parts of the Inland Ice to flow towards the west, while only smaller sectors drain eastwards (see Chapter 14 on the Inland Ice), the development of the eastern drainage pattern in Paleocene to Pliocene times has been described by Larsen (in press).

A major drainage outlet from the Inland Ice is located on the west coast in the Disko Bugt area (Fig. 13.2). In this area early seismic investigations showed the presence of deep subglacial channels extending more than 200 km inland from the ice margin (Holtzscherer and Bauer, 1954). It was suggested by Weidick (1975a, Fig. 1) that these channels were part of an extensive preglacial drainage system. Their presence was later confirmed by airborne radio echo sounding (Gudmandsen, 1978) and by analysis of Landsat satellite imagery of the Inland Ice surface (Thomsen, 1983).

Although the channels in their present form may well be glacially eroded, bathymetric investigations on the shelf give some support to the idea that the largest preglacial drainage outlet of Greenland was located outside the present Disko Bugt. On the shelf off the mouth of this bay a large half circular structure with a diameter of more than 200 km protrudes from the outer shelf margin, and was interpreted as a preglacial fluvial delta cone by Henderson (1975, Fig. 25). Similar, but smaller structures also occur outside other major fiord systems and developed as prograding deltas in the late Tertiary possibly in the Pliocene — at a time when base level was ca. 300 m lower than at present (Sommerhoff, 1979).

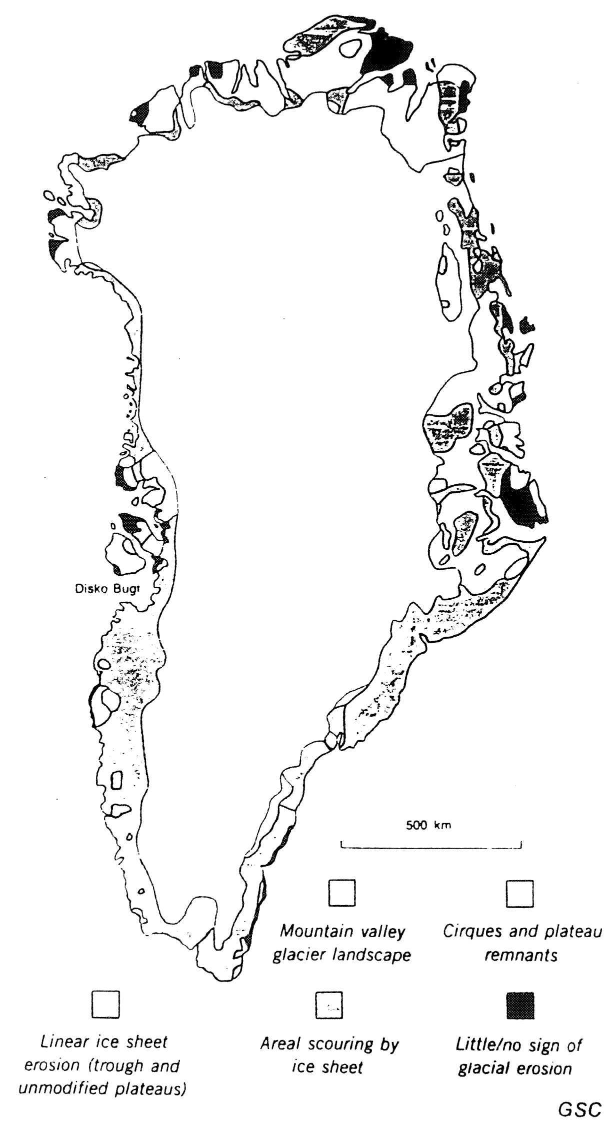

Figure 13.2. Landscapes of glacial erosion in Greenland (from Sugden, 1974).

It therefore seems probable that the main features of the present Inland Ice drainage were inherited from a pre-existing fluvial drainage system with a main outlet in the Disko Bugt area.

Present physiography — an overview

The main agent responsible for forming the Greenland landscape is ice — in the form of ice sheets and glaciers. An excellent survey of landscape types has been provided by

CHRONOSTRATIGRAPHY		ISOTOPIC STAGES	AGE, (ka)	WEST GREENLAND	EAST GREENLAND	NORTH GREENLAND
Holocene		1				
Wisconsinan	Late		10	Taserqat stade	Milne Land stade	
Wisconsinan	Late	2		Sisimiut glaciation	Flakkerhuk glaciation	Independence Fjord glaciation
Wisconsinan	Middle	3	25			
Wisconsinan	Early	4 to 5d	65	Svartenhuk marine episode	Jameson Land marine episode	
Sangamonian		5e	115	Kaffehavn interglaciation	Langelandselv interglaciation	
Illinoian		6	130	Fiskebanke glaciation	Scoresby Sund glaciation	? Bliss Bugt glaciation
				? Pâtorfik marine episode ? ↓		
Early Quaternary					Lodin Elv Formation: Zone II	Kap København Formation: member B
Pliocene			1800		Lodin Elv Formation: Zone I	Kap København Formation: member A

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Figure 13.3. Stratigraphy of pre-Holocene glacial and marine events in Greenland.

Sugden (1974; Fig. 13.2). The landscape types are classified from type and intensity of glacial erosion, ranging from areal scouring by an ice sheet to landscapes of selective linear erosion occurring in areas where movement is concentrated in ice streams. Figure 13.2 shows a general trend of decreasing erosion intensity from the south and west towards the north and east. This can be related to changes in bedrock elevation and lithology, and to climate.

Areas with little or no sign of glacial erosion occur especially in East and North Greenland. This type of landscape was thought to reflect polar type glaciation with no basal slip at the ice-bedrock contact (Sugden, 1974). As discussed below, however, stratigraphic evidence seems to show that some of these areas have escaped glaciation for a long time so the "little or no sign of glaciation" may be a factor of time since glaciation rather than style of glaciation. A possible implication from this interpretation is that the general distribution of landscape types is caused not just by conditions during the last glaciation, but by a repetition of this pattern during several glaciations — possibly throughout the Quaternary.

Quaternary stratigraphy and terminology

Modern stratigraphic work in Greenland has aimed at establishing local successions of marine and glacial events. The main units with their predominantly informal names are shown in Figure 13.3, and discussed in the regional sections below. Most of these units have been established within the last decade, as a result of the application of modern dating techniques, and some — the Independence Fjord and Bliss Bugt glaciations — are introduced here for the first time.

For chronostratigraphic correlations the North American, the northwest European, and even the central European terminologies have been used by field workers in Greenland. In the present report correlation is made with the North American chronostratigraphy which is considered to match that of northwest Europe, thus Illinoian is considered equivalent to Saalian, Sangamonian to Eemian, and Wisconsinan to Weichselian. This implies that the Sangamonian in this report is considered equivalent to substage 5e in the isotopic record, and hence has a short duration from ca. 130 to 115 ka (e.g., Shackleton and Opdyke, 1973; Mangerud et al., 1979). Consequently the Wisconsinan has a long duration from ca. 115 to 10 ka.

Table 13.1. Mean temperatures for warmest (w) and coldest (c) months and annual precipitation at five stations in the period 1969-1979 (from Publikationer fra det Meteorologiske Institut).

	Latitude	°C w	°C c	Precip. mm
Station Nord*	81°36'N	3	-34	256
Scoresbysund	70°25'N	3	-20	549
Godhavn*	69°14'N	7	-16	479
Narssarssuaq	61°11'N	10	-11	649
Prins Christian Sund	60°02'N	7	-6	2505

*Observations incomplete

Climate, permafrost, oceanography, and biogeography

This section presents a brief survey of the physical environment in the ice-free land, to serve as a background to the treatment of Quaternary ecosystems and paleoclimates. Details of the Inland Ice climate are given in Chapter 14 dealing with the Inland Ice. A comprehensive treatment of the climate of Greenland has been supplied by Putnins (1970).

The distribution of temperatures and precipitation is here illustrated in a general way by observations from five stations showing climatic gradients from north to south (Station Nord - Prins Christian Sund), from west to east (Godhavn - Scoresbysund), and from the outer coast to an interior fiord area at almost the same latitude (Prins Christian Sund — Narssarssuaq) (Table 13.1 and Fig. 13.4).

Owing to the stabilizing influence of the Inland Ice and the meridional pattern of air circulation, summer temperatures are remarkably uniform from north to south. However, the number of months with mean temperatures above 0°C, a measure of the length of growing season, increases from one in the north to seven in the south. The latitudinal effect is

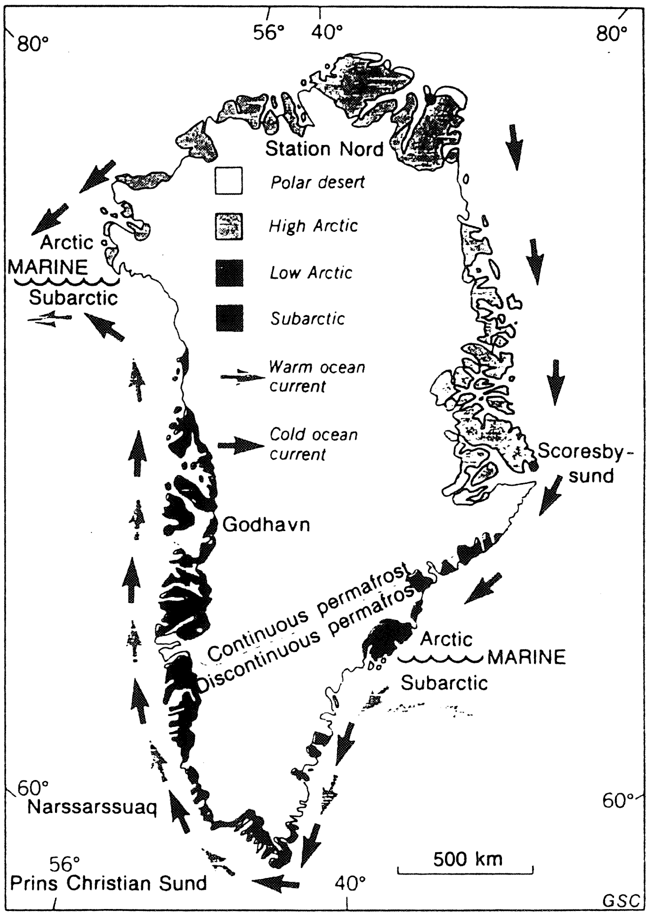

Figure 13.4. Terrestrial and marine biogeographic divisions and permafrost distribution in Greenland (modified from Funder, 1978c; permafrost boundary from Weidick, 1975a).

clearly visible in the biologically less important winter temperatures. Besides the gradient determined by latitude, all areas show a gradient from oceanic climate at the outer coasts to continental climate in the regions bordering on the Inland Ice margin. Precipitation is mainly supplied by maritime air following cyclone tracks along the southeast and west coasts, and is most abundant in the south.

As pointed out by Weidick (1975a), the southern limit for continuous permafrost seems to follow the mean annual temperature isotherm of −5°C and extends farthest south in continental areas close to the Inland Ice margin (Fig. 13.4). To the south of this limit, discontinuous and sporadic permafrost are encountered.

Especially in coastal regions, the climate is strongly influenced by the oceanographic circulation pattern. The main feature is the East Greenland Polar Current carrying cold polar water from the Arctic Ocean south along the east coast. Off southeast Greenland the polar water mixes with warm Atlantic water from the Irminger Current, and the mixture, forming the West Greenland Current, flows around the southern tip and northwards along the West Greenland coast, as far north as 78°N (Fig. 13.4).

Owing to the influence of the East Greenland Polar Current, East Greenland is colder than West Greenland at the same latitude. This asymmetry is apparent in the distribution of biogeographical zones (Fig. 13.4). The warmest summers occur in the interior south, where subarctic vegetation with birch and rowan woods occur in sheltered valleys. The major part of West Greenland is characterized by Low Arctic vegetation with willow and alder copses, while northeast and North Greenland falls within the High Arctic, with vegetation dominated by dwarf shrub heaths composed of dwarf-birch and a number of ericaceous dwarf-bushes. To this scheme may be added a zone of polar desert in coastal regions north of 80°N, where woody plants are absent or extremely rare.

In the shallow marine environment, the boundary between subarctic and arctic water masses is defined by the northernmost occurrence of such subarctic molluscs as *Mytilus edulis, Chlamys islandica,* and *Littorina saxatile.* In northwest Greenland this boundary has fluctuated over several degrees of latitude in this century (see section on *Paleofaunas and floras*).

QUATERNARY GEOLOGY OF WEST GREENLAND

S. Funder

Topography, drainage, and glaciation

West Greenland comprises the rim of ice-free land from Kap Alexander (78°N) to Kap Farvel (60°N) (Fig. 13.5). The rim attains maximum width, approximately 200 km, in the Søndre Strømfjord region, whereas at Melville Bugt to the north it is absent except for a few nunataks.

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The dominant landscape type is hilly upland composed of rounded knolls of crystalline bedrock at elevations between 300 and 1500 m. In some areas the hilly uplands abut on areas of distinctly alpine topography with elevations of 2000 m or more. Such areas occur in the south where the mountains extend below the ice cover, and locally between 65° and 67°N. In the latter area, the high mountains near the coast border on a 10 to 30 km-wide coastal strandflat, composed of heavily abraded gneiss at elevations below 300 m.

To the north of Disko Bugt the thick sequence of plateau basalt gives rise to a different type of topography characterized by gently undulating high mountain plateaus dissected by cirques and steep sided valleys which form a complex drainage pattern.

South of 65°N the land areas are dissected by numerous fiord troughs with depths down to 600 m below sea level, the fiords are usually headed by calving glaciers. To the north, up to 68°N, there are fewer fiords and they are headed not by glaciers but by broad valleys carrying meltwater from the Inland Ice margin.

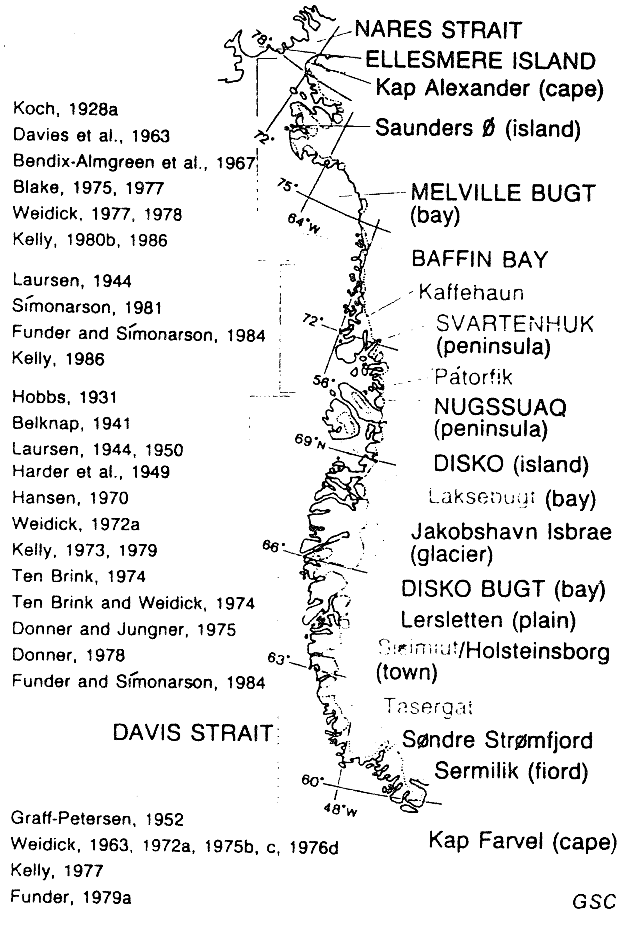

Figure 13.5. Regional Quaternary studies in West Greenland and locality names mentioned in text. Names shown in red have been utilized in stratigraphic terminology.

Disko Bugt is the largest inlet in the West Greenland coastline, and separates Disko Island from the "mainland". This inlet provides easy access into Baffin Bay for icebergs from several productive calving glaciers. The largest of these is Jakobshavn Isbrae which has an annual calving production of 25 km^3 water equivalent of ice, and is the single largest outlet from the Inland Ice (Reeh, 1989).

For a distance of some 300 km in Melville Bugt the Inland Ice margin is located close to the present shoreline. In this sector, the products of ablation by calving and melting are discharged directly into Baffin Bay.

As noted above, each general type of topography in this region appears to foster different mechanisms for ablation from the Inland Ice margin. Hence each sector may respond differently to climatic change and these differences are reflected in the history of Holocene deglaciation.

Quaternary studies

West Greenland south of 73°N supports the majority of Greenland's population and is the location of the centres of administration; as a consequence the area has a richer and longer record of scientific research than other parts of Greenland. Systematical geological studies began after 1850 and included work on the Quaternary; this work has mainly been associated with the mapping projects of the Geological Survey of Greenland.

Earlier reviews of the Quaternary geology in this region comprise works by Weidick (1968) and Kelly (1985), emphasizing the Holocene and Late Quaternary stratigraphy. A number of regional studies are listed in Figure 13.5, the results have been compiled by A. Weidick in two Quaternary maps, covering the area from 63° to 71°N (Geological Survey of Greenland, 1974, 1978).

Nature and distribution of Quaternary sediments and landforms

All of West Greenland — excluding only some high mountains near the coast — was covered by the Inland Ice during the Sisimiut glaciation of Late Wisconsinan age. This recent glaciation is clearly recorded by erosion rather than sediment accumulation in most areas. Thick Quaternary deposits are of restricted occurrence and are generally confined to major valleys and lowlands along the coasts.

Till. The most widespread glacial deposits are patches of loose gravelly and sandy diamicton and scattered erratic boulders considered to be melt-out till. These materials form a continuous cover in the interior near the present Inland Ice margin, whereas at the outer coasts glacial deposits are reduced to scattered erratics lying on the abraded bedrock surface. This thin sediment, modified by later slope wash, originated as sparse debris in the last ice body which covered the area, and was lowered down onto the terrain surface during a brief stage of stagnation and melting (e.g., Funder, 1979a). Thicker deposits of melt-out till occur in lateral and terminal moraines and are especially common between 64° and 67°N, where they form north-south trending zones reflecting periods of stillstand or even readvance of the Inland Ice margin in middle Holocene time (Weidick, 1972a; Ten Brink and Weidick, 1974; Ten Brink, 1975).

Whereas melt-out till is widespread, typical lodgment till is rare, occurring as patches on the stoss side of glacially abraded bedrock knolls (Sugden, 1972). The apparent rarity of this sediment may possibly be explained by the absence of fine grained source material for glacial erosion.

Since till deposits in all parts of the region were laid down during the deglacial stages following the Sisimiut glaciation, there is generally no discernible difference in surface freshness. An exception to this occurs in coastal mountains above 1000 m elevation where weathered erratics are associated with autochthonous felsenmeer and tors, showing that these areas were nunataks during the Sisimiut glaciation (Kelly, 1985).

Till clasts and transportation routes. Assessing source areas and transportation routes for the till components is made difficult by the monotony of the bedrock geology, which provides few indicator boulders. In an area of varied bedrock lithology in South Greenland, however, it has been shown that more than 50% of the stones, pebbles, and boulders could be accounted for by known bedrock exposures within 10 km of the site (Funder, 1979a). The tills probably also contain a long distance transport component, although this is rarely recognizable. This has been documented in the area north of Disko Bugt where Steenstrup (1883) found abundant gneiss erratics at the outer coast and on high mountain plateaus, 150 km from their nearest source areas to the east.

Considering that ice movement, possibly throughout the Quaternary, has been from the presently ice covered interior towards the coast, it is noteworthy that only in one area, to the south of Melville Bugt, have exotic erratics been found that cannot be referred to rock types exposed in the narrow rim of land which is now ice free (M. Kelly, University of Lancaster, Lancaster, England, personal communication, 1985).

A peculiar type of till clast, which has been observed especially in the most recent till deposits close to the ice margins, is a calcareous concretion which commonly contains a nucleus of organic matter. An interglacial age has been suggested for some concretions (Bryan, 1954), but it is more likely that the concretions were derived from middle Holocene marine deposits which, in late Holocene time have been overridden and eroded by glaciers (Kelly, 1975, 1980a).

Moraines. Moraines dating from Holocene deglaciation stages occur in all parts of the area, and in their general distribution follow that outlined for till deposits. They are especially abundant in the inland parts of the region which is the classic area for the study of the deglaciation history in Greenland (Weidick, 1968, 1972a; Sugden, 1972; Ten Brink and Weidick, 1974; Ten Brink, 1975).

Moraines generally have developed only along active sectors of the ice margin — lobes and outlet glaciers — while the regionally more extensive passive sectors have created few moraines. This is especially clear in fiord regions where moraines along the fiords testify to the former existence of fiord glaciers, while there are few or no traces of the corresponding ice margins on the interfluves between fiords. The location of moraines along the fiords — at fiord junctions and bends, and at places where the sides change from steep to gentle slopes — indicates that the moraines commonly were formed as an interaction between the glacier and the topography of its bed, rather than in response to climatic change.

From the location and dating of the moraines it appears that the sensitivity of the Inland Ice margin to climatic change in the Holocene was strongly controlled by the ablation mechanism. Consequently, in the Disko Bugt area and the fiords to the south, where ablation took place by calving, the marginal recession was faster by several millennia than it was in the intervening inland areas where melting was the main mechanism of ablation (Weidick, 1984).

Glaciofluvial and fluvial deposits. These sediments cover the floors of all major valleys, occurring as outwash plains and fluvial terraces deposited from braided rivers. The most extensive plains occur in the valleys which now connect the Inland Ice margin with the heads of fiords. Usually the valleys contain several generations of river terraces formed largely by changes in base level caused by glacial isostatic movements. In our century some of these plains have been utilized as air fields, and they are the main transportation routes in the country.

Glaciofluvial sand and gravel also occur as kame terraces along valley sides and — though of more restricted occurrence — as kame and kettle topography on some valley floors. These features, as well as the abundant meltwater channels which may be incised into bedrock, were formed mainly in a proglacial environment. There is sparse evidence for subglacial meltwater: eskers have been observed only in the interior continental areas, and potholes in bedrock are not common.

Marine deposits. Marine sediments ranging from coarse littoral gravel to massive or laminated silt are widespread in the coastal areas, occurring up to 140 m above present sea level — the maximum elevation of Holocene marine limit. Marine sediments commonly occur in a prodeltaic facies adjacent to major raised deltas at the mouths of large valleys. The most extensive marine deposits occur at Lersletten to the south of Disko Bugt. In this area marine silt and sand form a plain between knolls of gneiss and were deposited in early and middle Holocene time in a skaergaard (skerryguard) which was later isostatically raised. These sediments have yielded rich mollusc faunas which were the basis for the first attempts to establish a Quaternary chronology in Greenland (Jensen and Harder, 1910).

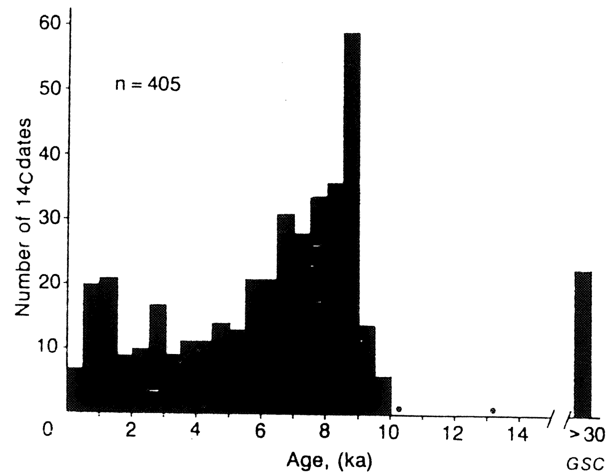

Figure 13.6. Age distribution of published ^{14}C dates from West Greenland, including dates obtained for archeological purposes. Dots denote single dates. Compiled from dating lists in reports of the Geological Survey of Greenland, Radiocarbon, and elsewhere.

Marine sand and silt older than the Sisimiut glaciation occur as scattered erosion remnants, especially in areas north of Disko Bugt. These deposits are especially important for the understanding of the Quaternary chronology, and their ages have been subject to much discussion, as mentioned below.

Periglacial and eolian features. The distribution of frozen ground features closely follows that of continuous permafrost (Fig. 13.4). Thus pingos, ice wedges, and rock glaciers are rare south of 67° N.

The large majority of pingos have been observed in valleys in the area of Mesozoic sediments north of Disko Bugt (Weidick, 1975a). Analyses of gas and water from the pingos have shown a very high content of methane which probably aided the formation of these pingos which are believed to be of the open system type (Henderson, 1969). In addition, rock glaciers seem to be especially common on Disko and Nugssuaq, on steep valley sides (Humlum, 1981).

Palsas and other types of frost mounds are most common in the border area between continuous and discontinuous permafrost. To the south of this area they may have formed in response to neoglacial permafrost expansion

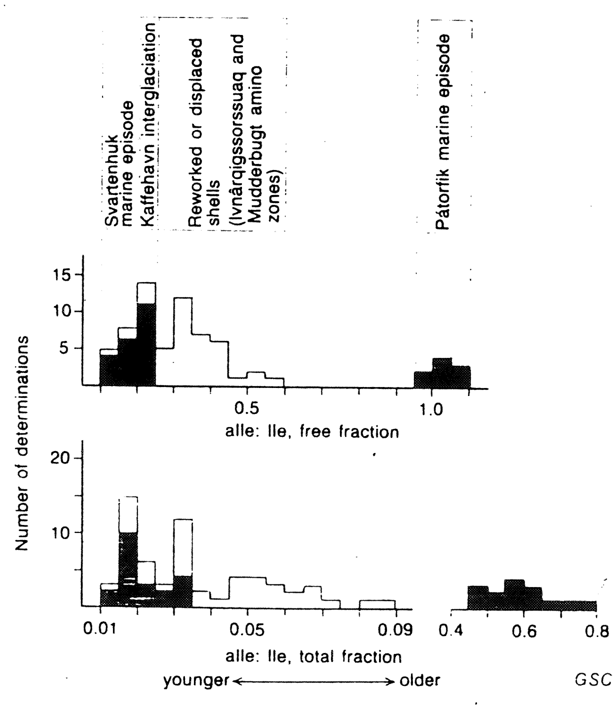

Figure 13.7. Frequency distribution of amino acid ratios on mollusc shells (*Mya truncata* and *Hiatella arctica*) and event stratigraphy in West Greenland. Shaded columns, shells found in situ; open columns, reworked shells or shells from reworked deposits. The ratios belong to 25 samples with 3-6 determinations in each. Total ratios obtained before 1982 have been corrected for laboratory fractionation (Kelly, 1986). Correlation is here based on ratios in the free fraction because ratios in the total fraction show more spread and less consistency, possibly as a result of leaching. Sources: Funder and Simonarson, 1984; Kelly, 1986; stratigraphy adapted from Kelly, 1985.

(Kelly, 1981), while in the north palsa-like peat mounds seem to date from the Holocene warm period (Brassard and Blake, 1978).

In the interior parts strong winds from the Inland Ice may raise dust storms over the large fluvial plains. Coarser sediments are deposited as small sand dunes in the valleys, while dust settles in vegetated areas nearby to form a thin layer of loess (Böcher, 1949; Hansen, 1970).

Succession of events

The Quaternary stratigraphy of the West Greenland region has been treated, with emphasis on the Holocene, by Weidick (1968). An excellent review of this and more recent work has been prepared by Kelly (1985), who carefully discussed the validity of the data and offered alternative interpretations. The presentation given here relies heavily on Kelly's work — both for concepts and stratigraphic terminology. However, I have chosen simple explanations where there is no compelling reasons for complex ones, and the stratigraphy presented here (Fig. 13.3) is a slightly modified version of Kelly's.

Approximately 400 ^{14}C dates, made mainly on bivalve shells, peat, and gyttja, have been obtained from the region in order to date Holocene and Wisconsinan events (Fig. 13.6). As elsewhere in Greenland, ages in the interval from ca. 10 to 20 ka are rare and may be due to contamination of the dated material. There seems to be no good reason, however, to suspect the age of 13 380 ± 175 BP obtained on marine shells in southern West Greenland (I-7624, Weidick, 1975c).

In recent years amino acid analysis of mollusc shells has become an important tool in the differentiation of older deposits (Fig. 13.7). Shells from 25 samples have been analyzed, and the results have been discussed by Funder and Símonarson (1984) and Kelly (1985, 1986).

As in other historical records the Quaternary stratigraphy in this area shows increasing detail with decreasing age. Owing to the ravages of the ice sheet during the Sisimiut glaciation, however, the record has an abrupt break; there is little evidence for the record before this event, while the time after is known in reasonable detail.

Sea level history, subfossil marine faunas, and vegetation development are treated in a later section which covers all Greenland.

Pátorfik marine beds. The Pátorfik marine beds at the coast of Nugssuaq peninsula (71°N, Fig. 13.8) comprise a 40 m-thick sequence of deltaic and prodeltaic sand, silt, and mud, exposed along 2.5 km of the coast. These sediments contain a rich mollusc fauna which attracted the attention of geologists as early as 1848. The deposits, as well as their long history of widely different dating estimates, have recently been described in detail by Símonarson (1981). The rather peculiar mollusc fauna combined with high amino acid ratios has resulted in an early Quaternary age being assigned to these deposits (Fig. 13.7 and see *Paleofaunas and floras*; Funder and Símonarson, 1984). The sediments probably owe their preservation to a covering bed of lithified talus breccia.

Fiskebanke glaciation and Kaffehavn interglaciation. Subarctic marine molluscs with infinite ^{14}C ages have been

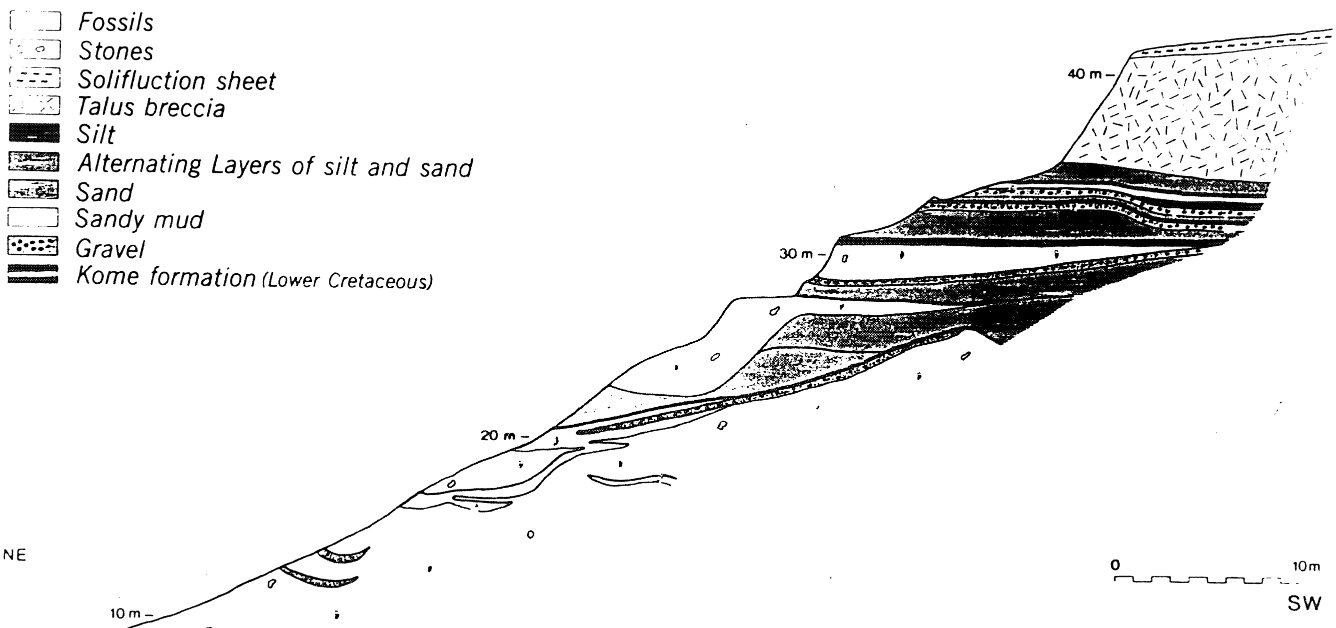

Figure 13.8. Section of the Pátorfik marine beds (from Simonarson, 1981) showing transition from prodeltaic (5-20 m a.s.l.) to deltaic (20-35 m a.s.l.) facies. The marine beds are covered by a younger talus breccia. Mollusc fauna is of boreal-subarctic type throughout the sequence.

found in marine deposits at sites in northern West Greenland and reflect a hydrographic pattern similar to the present (Funder and Símonarson, 1984; Kelly, 1985, 1986). Amino acid analyses and faunal composition support correlation of the deposits with subarctic molluscs in littoral gravel below till in a 7 m section at Kaffehavn. Known from four localities in northern West Greenland, these deposits are referred to the Kaffehavn interglaciation, provisionally correlated with the Sangamonian (Fig. 13.3).

The southernmost of these localities, Laksebugt, shows marine conditions colder than the present, and these deposits have tentatively been correlated with an early deglacial stage of the Kaffehavn interglaciation (Funder and Símonarson, 1984).

On Saunders Ø the subarctic marine fauna is underlain by till (Davies et al., 1963; Blake, 1975), which consequently should predate the Sangamonian and tentatively is referred to the Illinoian.

It is noteworthy that although the deposits at all these sites may well contain significant hiata, none contains positive evidence for more than two periods of extensive glaciation, and only one in the Wisconsinan. In more southerly parts of West Greenland the oldest glaciation phase is denoted by deeply weathered till on high coastal mountains representing the Fiskebanke glaciation, which is also — tentatively — correlated with the Illinoian. It should be pointed out, however, that age control is poor and is based mainly on the Saunders Ø section[1] (Kelly, 1985).

Svartenhuk marine episode. The Early and Middle Wisconsinan record is known from scattered localities in the northern part of the region where ice sheet erosion has been least severe (Fig. 13.9). These occurrences comprise marine fossiliferous sand and silt with sparse arctic molluscs, overlain by till. Some deposits are in situ while others appear to be megaclasts in younger till.

The marine deposits, here referred to as the Svartenhuk marine beds, give ages beyond ^{14}C dating limit or old-finite ^{14}C ages (more than 20 ka), and amino acid data indicate that they belong to the same depositional episode, following the Kaffehavn interglaciation. Sedimentation lasted well into the Wisconsinan (Fig. 13.7), and the episode possibly terminated about 40 ka (Kelly, 1986).

Shells from a number of "reworked" deposits have yielded amino acid ratios that would imply a somewhat older depositional period (Fig. 13.7). Since these deposits are glacially reworked or transported as megaclasts, however, the shells do not necessarily satisfy one of the basic requirements for providing correlatable amino acid ratios — they have not necessarily shared the same thermal history. Therefore, until the ratios can be duplicated from in situ deposits, they should not be included in correlation charts for this area.

Sisimiut glaciation. During the Late Wisconsinan Sisimiut glaciation the Inland Ice expanded and transgressed the present coastline in all parts of the region. The ice masses moved onto the present shelf where their margin may have been located ca. 50 km offshore on the inner shelf (Kelly, 1985). The glacial geomorphology of the shelf shows, as discussed in a later section, that the ice sheet at this time was mainly land based in a period of eustatically lowered sea level (see *Quaternary geology of the shelves adjacent to Greenland*).

A model of the ice flow, developed by Reeh (1984), shows a pattern similar to the present with westward directed flow from a central ice divide located near the present one. Only in the Nares Strait region of northwest Greenland did a more complex flow pattern develop as a result of the

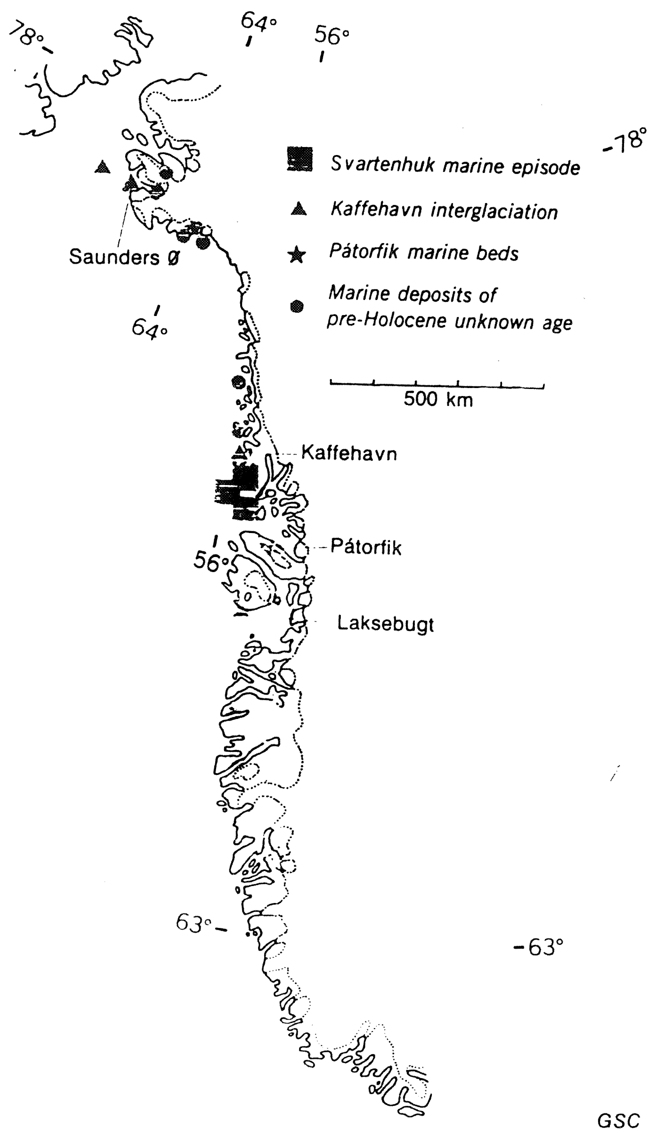

Figure 13.9. Occurrence of pre-Holocene marine deposits in West Greenland (modified from Kelly, 1985).

[1] This important locality, and others in the area, was investigated in detail by members of the NORDQUA expedition to the area in 1986, and extensive thermoluminescent dating, amino acid analyses, as well as faunal and lithological work have been carried out. Although the time frame remains, much new information has been gained, some of which alters concepts reported here. Preliminary results from this collective work have been reported by Feyling-Hanssen, Funder, Houmark-Nielsen, Kronborg, Mörner, Reeh and Thomsen, Sejrup and Sorby in Danmarks geologiske Undersøgelse(1988).

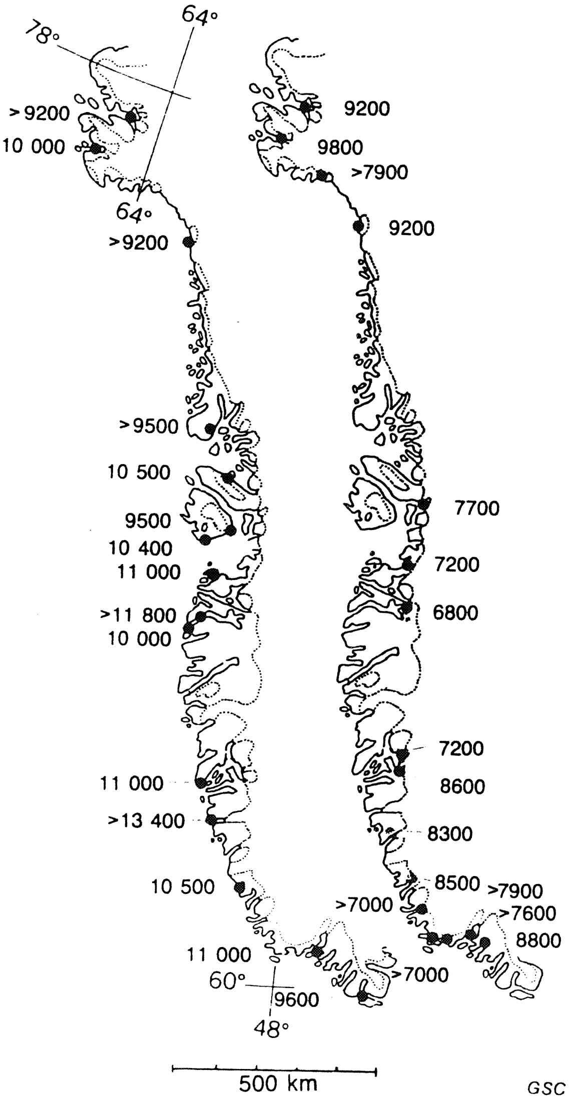

Figure 13.10. Ages for deglaciation at the outer coasts (left), and dates for the attainment of the present state of glaciation (right) (from Kelly, 1985). Deglaciation ages are based on ^{14}C dates of marine molluscs and uncertainties are ± 500 years. Ages for the attainment of present glaciation are from ^{14}C dates of marine shells in front of ice margins, and on organic material reworked in younger moraines (red).

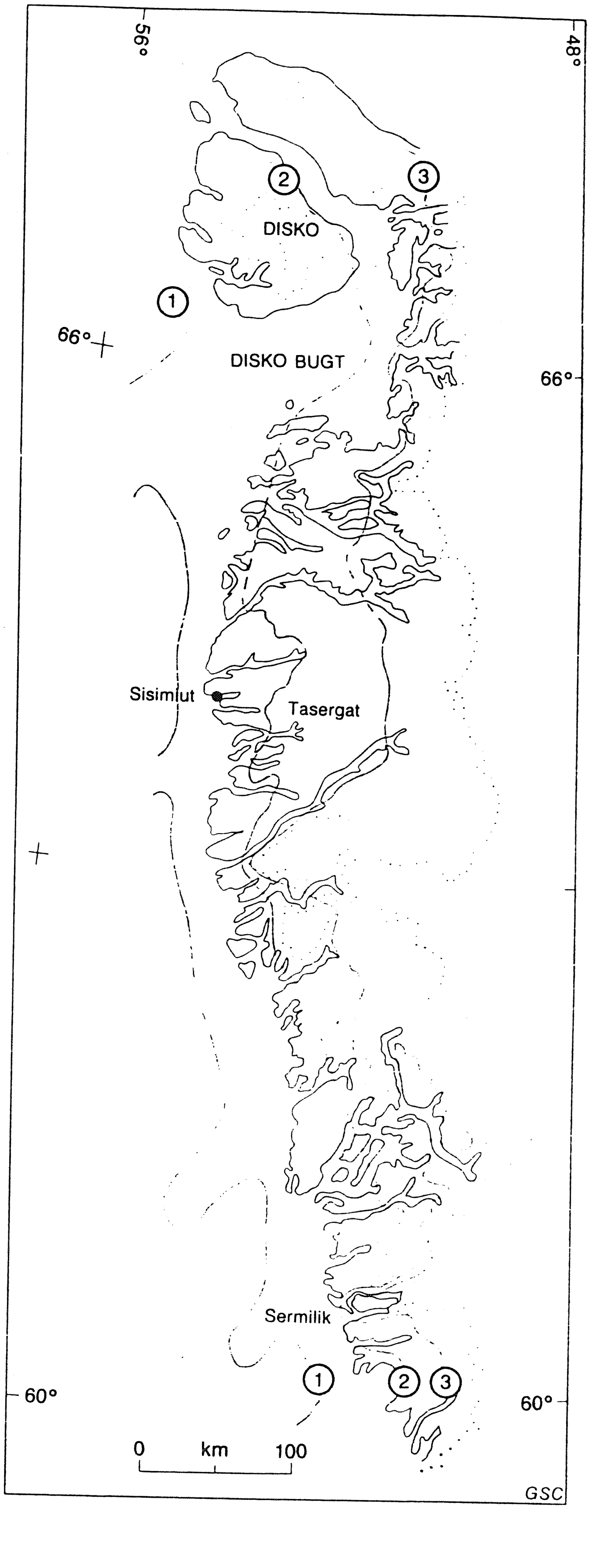

Figure 13.11. West Greenland Inland Ice margins during (1) Sisimiut glaciation (ca. 14 ka), (2) Taserqat stade (ca. 10 ka), (3) and Fjord stade (8 ka). Dotted line shows present ice margin. Sources: Weidick, 1975c, 1984; S. Funder, unpublished; shelf moraines from Figure 13.26.

Table 13.2. Ages and correlation of Holocene moraine systems in West Greenland (adapted from Kelly, 1985).

Age ka BP	Disko Bugt (Weidick, 1968; S. Funder, unpub.)	N. Isortoq N. Stromfjord (M. Kelly, unpub.)	Holsteinsborg S. Stromfjord (Ten Brink and Weidick, 1974)	Godthaabsjford (Weidick, 1975c)	Julianehaab Frederikshaab Narssaurssuaq (M. Kelly unpub.; Weidick, 1963)	
-		Isortoq			Sarfa	
10						
						Niaqornakasik
					Eqaluit	
		Y Isortoq	Taserqat			
	Disko					
-	stade	Itivdlerssuaq	Avatdleq			
	"Marrait"	Maligia	Old Fjord		Aussivik	
				Kapisigdlit		Tunugdliarfik
8	(Fjord 2)		Aukua 1 & 2	Young Fjord		
			Umivit			
-		Ugssuit				
	"Tasiussaq"		Mt. Keglen			
	(Fjord 1)					
6						
						Narssarssuaq
-						
2						
-						
			Orkendalen			
0	Historic	Historic	Historic	Historic	Historic	Historic

coalescence of the Inland Ice with an ice sheet over Ellesmere Island. This region is discussed in the section on North Greenland.

There is no dating control for the growth phase of the ice sheet. It is only known that maximum advance occurred after the Svartenhuk marine episode mentioned above. Retreat from the Wisconsinan limit began at or before 13.5 ka, as deduced from ^{14}C dates in the coastal areas (Kelly, 1985). The disintegration occurred in two distinct phases: disintegration of marine parts and melting of land-based parts.

The early phases of deglaciation are poorly known because they took place in areas that are now covered by the sea. It is noteworthy, however, that the radiocarbon dates indicate that the ice margin in all parts of the region was located near the present coastline at 10-11 ka (Fig. 13.10, 13.11). This synchroneity can best be explained by the assumption that the breakup of the ice sheet was triggered by a eustatic sea level rise rendering the shelf-based portions unstable along the entire margin. The ice sheet adjusted to the change in sea level by retreating until the margin was again land based, near the present coastline.

The shelf areas were not the only areas cleared of ice during this phase. Major inlets such as the fiords of South Greenland, Disko Bugt, and the fiords in the northwest, were also deglaciated as shown by ^{14}C dates. Thus by 10-11 ka the ice margin roughly coincided with the present coastline, and it was after this time that the present land was uncovered (Fig. 13.10, 13.11). At Sermilik Fjord, 63°N, a ^{14}C age of 13 380 ± 175 BP has been obtained for marine shells, indicating that in this particular area the ice margin had retreated from the shelf before this time, and remained stationary at the present coast line for the following five millennia (I-7624, Weidick, 1975c).

Holocene. The second stage in the retreat of the Sisimiut glaciation ice sheet involved melting of land-based ice. From the dating of moraines it can be seen that the melting proceeded at different rates in different areas with local climate and topography the main controlling factors.