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Greenland Ice Sheet History Since the Last Glaciation[1]

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The position of the Inland Ice margin during the late Wisconsin–Würm glaciation (ca. 15,000 yr BP) is probably marked by offshore banks (submarine moraines?) in the Davis Strait. The history of the Inland Ice since the late Wisconsin–Würm can be divided into four principal phases: (1) Relatively slow retreat from the offshore banks occurred at an average rate of approximately 1 km/100 yr until ca. 10,000 yr BP (Younger Dryas?) when the Taserqat moraine system was formed by a readvance. (2) At ca. 9500 yr BP, the rate of retreat increased markedly to about 3 km/100 yr, and although nearly 100 km of retreat occurred by ca. 6500 yr BP, it was punctuated by frequent regional reexpansions of the Inland Ice that formed extensive moraine systems at ca. 8800–8700 yr BP (Avatdleq–Sarfartôq moraines), 8400–8100 yr BP (Angujârtorfik-Fjord moraines), 7300 yr BP (Umîvît moraines), and 7200–6500 yr BP (Keglen–Mt. Keglen moraines). (3) Between 6500 and 700 yr BP, discontinuous ice-margin deposits and ice-disintegration features were formed during retreat, which may have continued until the ice margin was near or behind its present position by ca. 6000 yr BP. Most of the discontinuous ice-margin deposits occur within 5–10 km of the present ice margin, and may have been formed by two main phases of readvance at ca. 4800–4000 yr BP and 2500–2000 yr BP. (4) Since a readvance at ca. 700 yr BP, the Inland Ice margin has undergone several minor retreats and readvances resulting in deposition of numerous closely spaced moraines within about 3 km of the present ice margin. The young moraines are difficult to correlate regionally, but several individual moraines have the following approximate ages: A.D. 1650, 1750, and 1880–1920.

Inland Ice fluctuations in West Greenland were very closely paralleled by Holocene glacial events in East Greenland and the eastern Canadian Arctic. Such similarity of glacier behavior over a large area strongly suggests that widespread climatic change was the direct cause of Holocene glacial fluctuations. Moreover, historical advances of the Inland Ice margin followed slight temperature decreases by no more than a few decades, and ^{18}O data from Greenland ice cores show that slight temperature decreases occurred frequently throughout the Holocene. Therefore, we conclude that construction of the major Holocene moraine systems in West Greenland was caused by slight temperature decreases, which decreased rates of ablation and thereby produced practically immediate advances of the ice sheet margin, but did not necessarily affect the long-term equilibrium of the ice sheet.

INTRODUCTION

A nearly complete history of marginal fluctuations of the West Greenland Inland Ice since the Wisconsin–Würm glaciation is found in radiocarbon-dated moraine sys-

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FIG. 1. Index map of Greenland. Shaded area is the Søndre Strømfjord region (see Fig. 2).

tems in the Søndre Strømfjord area between 66°30′ and 67°00′ N. lat (Fig. 1). These moraine systems (Fig. 2) are a record of the past dynamic behavior of the Inland Ice throughout the areas of West Greenland covered by our individual investigations (Ten Brink, 1971a, 1971b, 1974; Weidick, 1968, 1972a, 1972b, 1972c; Weidick and Ten Brink, 1970). By combining our results we are able to present a comprehensive but simplified description of West Greenland glacial events. These results provide the first documentation of Inland Ice history for a West Greenland area which extends from the coast to the present Inland Ice margin. Therefore, the sequence of documented glacial events probably represents the history of the ice sheet for a very large region, and it has major implications for the archaeological, biological, and climatic history of much of the northern hemisphere as well as Greenland. The climatic significance of the dated moraine systems is specifically considered in our interpretation of the cause for their formation.

The model area (Fig. 2) for establishing a standard glacial chronology for West Greenland was selected because (1) it is one of the largest deglaciated coastal land areas, and (2) previous reconnaissance (Weidick, 1968; Goldthwait, 1964), shows it to contain an abundant variety of interrelated ice-margin and emerged marine deposits which can be dated by radiocarbon analysis of marine shells. Therefore, the Søndre Strømfjord area provides one of the most complete records of Greenland glacial history currently available.

BACKGROUND AND INVESTIGATIVE METHODS

The Inland Ice margin has progressively retreated about 175 km in central West Greenland since the last major glaciation, but frequently halts or readvances have interrupted the trend and formed extensive moraine systems such as those shown in Fig. 2. Removal of ice during deglaciation resulted in postglacial isostatic rebound of the Earth's crust and emergence of former marine shorelines to heights as great as 140 m above sea level (a.s.l.) (Weidick, 1972a; Sugden, 1972; Ten Brink, 1974). Ages of the emerged marine shorelines (strandlines) were determined by collecting and radiocarbon dating *in situ* marine shells that grew at the time of shoreline formation (Figs. 3 and 4, Table 1).

The radiocarbon dating of strandlines enabled us to date most major moraine systems by time-stratigraphic and/or morphologic interrelations between strandlines and moraines. The interrelations between glacial and emerged marine sediments were

FIG. 2. Map of major moraine systems in the Søndre Strømfjord region of West Greenland. Approximate and highly generalized distributions of six distinct moraine systems are indicated by the six different shaded patterns. Moraine system names assigned by Weidick (1972a, 1972c) in the northern part of the map area are given along the upper margin; names assigned by Ten Brink (1971b) in the southern map area are given along the lower margin. See Table 2 for moraine ages. Point elevations are given in meters above sea level.

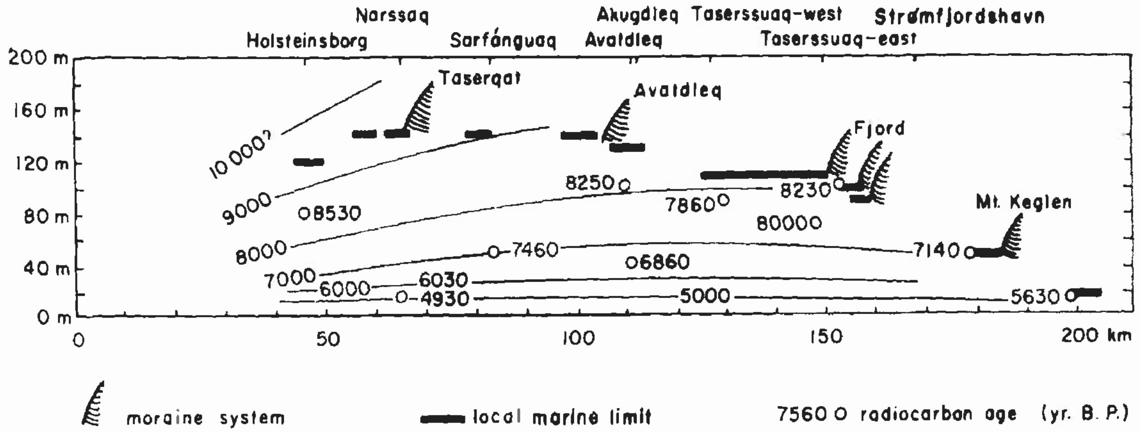

FIG. 3. Diagram of emerged shorelines for the area west of Søndre Strømfjord (cf. Fig. 2). The smooth curves, representing isochronous shorelines of ages given in ^{14}C yr BP, are based on the altitudes and radiocarbon ages of marine shell samples represented by open circles (cf. Table 1). The relation of the shorelines to moraine systems and local marine limits is shown schematically.

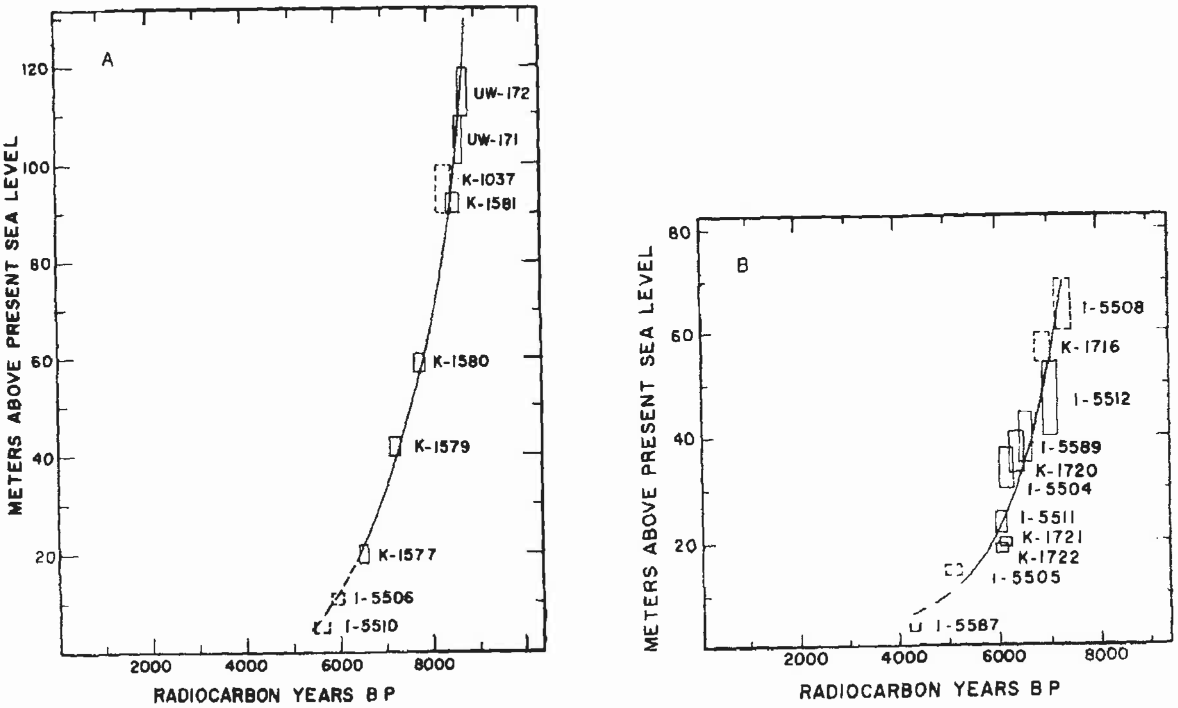

FIG. 4A. Emergence curve used to date the 125 ± 5 m marine limit related to the Sarfartôq moraines and the 115 ± 10 m marine limit related to the Angujârtorfik moraines. Each rectangle represents one dated shell sample, with width equal to the standard error of the date and height equal to the estimated uncertainty in assigning the shells to a relative sea level (cf. Table 1). Only those samples represented by solid rectangles were used to construct the curve. Dashed rectangles represent samples from outside the immediate source area of the curve. Open-topped rectangles represent samples that provide only a minimum limiting altitude because the shells could not be firmly related to a specific sea level on either stratigraphic or ecologic grounds. Laboratory identification symbol is given to the right of each rectangle (UW = University of Washington, K = Copenhagen Radiocarbon Dating Laboratory, I = Isotopes Inc.). Fig. 4B. Emergence curve used to date the 65 ± 5 m marine limit related to the Umîvît moraines and the 40 ± 5 m marine limit related to the Keglen moraines. Conventions and symbols as in Fig. 4A.

TABLE 1

RADIOCARBON-DATED MARINE SHELLS FROM WEST GREENLAND USED IN FIGS. 3, 4A AND 4B

	Radiocarbon laboratory number[a]	Altitude (m) of relative sea level dated by shell's age[b]	Radiocarbon age (yr BP)
Fig. 3	K-1033	40	6860 ± 150
	K-1037	100	8250 ± 130
	K-1382	76–80	8530 ± 120
	K-1386	50	7460 ± 130
	K-1562	≥10–15	6030 ± 120
	K-1563	≥10–15	4930 ± 130
	K-1662	70	8000 ± 110
	K-1663	100	8230 ± 140
	K-1664	≥45–50	7140 ± 130
	K-1665	90	7860 ± 140
	K-1715	10–15	5630 ± 110
Fig. 4A	I-5506	11 ± 1	5845 ± 115
	I-5510	5 ± 1	5615 ± 115
	K-1037	95 ± 5	8250 ± 130
	K-1577	20 ± 1	6510 ± 140
	K-1579	42 ± 1	7220 ± 130
	K-1580	59 ± 1	7730 ± 130
	K-1581	92 ± 1	8460 ± 140
	UW-171	105 ± 5	8610 ± 70
	UW-172	115 ± 5	8670 ± 100
Fig. 4B	I-5504	34 ± 4	6150 ± 115
	I-5505	15 ± 1	5070 ± 105
	I-5508	65 ± 5	7260 ± 120
	I-5511	24 ± 2	6045 ± 115
	I-5512	47 ± 7	7025 ± 120
	I-5587	4 ± 1	4335 ± 110
	I-5589	40 ± 5	6505 ± 120
	K-1716	60 ± 3	6880 ± 120
	K-1720	37 ± 4	6330 ± 120
	K-1721	20 ± 1	6140 ± 120
	K-1722	19 ± 1	6060 ± 120

[a] I = Teledyne Isotopes Westwood Laboratories (J. Buckley); K = Copenhagen National Museum Carbon-14 Laboratory (H. Tauber); UW = University of Washington Carbon-14 Laboratory (A. Fairhall).

[b] The location, stratigraphy, relation to a relative sea level, and species content of each shell sample have been described in detail in earlier papers (Weidick, 1972a: 26–29; 1972b: 58–65; Ten Brink, 1971b: 156–169).

produced because deglaciation synchronously initiated both marine invasion and postglacial uplift. Thus, the age of the highest marine strandline in each area (local marine limit) not only indicates the time at which the sea invaded the area, but also indicates the time at which the Inland Ice retreated from the last moraine system constructed in that area. Therefore, the age of the local marine limit within the area of each moraine system provides a minimum age for that moraine system.

For some of the moraine systems, minimum ages based on the date of local marine limit can be checked against dates based on marine shells from deltaic deposits which were deposited synchronously with moraine construction. Where such duplicate dating of moraines is possible, no significant difference between the two dates occurs. Therefore, even though most of the dates assigned to moraine systems in the following descriptions are minimum ages, the respective moraines are probably no more than a few centuries older at most.

The moraine systems shown in Fig. 2 represent a simplified classification of ice-margin deposits which were originally mapped in detail on air photos of approximately 1:50,000 scale. Local ground truth for the air-photo mapping was obtained both by helicopter reconnaissance flights and by field investigations conducted from remote camps established in key areas. The area northwest of Søndre Strømfjord (Fig. 2) was mapped by Weidick between 1965 and 1969; the area southeast of the fjord was mapped by Ten Brink during 1969 and 1970. All of our investigations were conducted for the Geological Survey of Greenland as part of a Quaternary geology mapping project (Weidick, 1971a, 1971b, 1973).

When the initial maps of ice-margin deposits were completed, the regional moraine systems shown in Fig. 2 were delineated on the basis of the following criteria:

(1) A *moraine system* was defined as a morphostratigraphic unit consisting of a group of closely associated ice-margin deposits, mostly end moraines, that had great linear extent and in places could not be differentiated (cf. "morainic system"

as used by William and Frye (1970: 44) and "end-moraine system" as defined by Flint (1971: 200)).

(2) Ice-margin deposits were considered to represent moraine systems only when they were traceable from a helicopter and/or air photos for several kilometers with few discontinuities.

(3) Each moraine system had to be represented by end moraines that occurred not only in valleys but also continued across uplands, thereby excluding local moraines formed only in favorable topographic locations.

(4) Ice-margin deposits had to be in similar topographic positions on both sides of local discontinuities to be included in a given moraine system.

(5) Finally, end moraines in geographically separate areas, but of the same radiometric age and relation to relative sea level as determined by independent data, were considered to be parts of the same regional moraine system.

INLAND ICE HISTORY
>10,000 BP

The precise position of the Inland Ice margin before ca. 10,000 yr BP is not yet known, but it must have lain to the west of the Taserqat moraines, because all the glacial and emerged marine deposits east of the Taserqat moraines are younger than ca. 10,000 yr BP (Fig. 2, Tables 1 and 2). This limiting age and the occurrence of multiple-ridged offshore banks, which morphologically resemble moraines, suggest that the ice margin was approximately in the position shown in Fig. 2 during late Wisconsin–Würm glaciation (ca. 15,000 ± yr BP). Although this is a reasonable suggestion in the light of available evidence, we regard it as highly speculative until tested against additional oceanographic and geophysical data from the offshore banks. Nevertheless, from our limited knowledge of the offshore banks it already seems that subdivision of these "Wisconsin–Würm moraines" may eventually be possible and that even older limits of the Inland Ice are probably represented by submarine ridges farther west.

In addition to the submarine ridges mentioned above, a system of terrestrial nunatak moraines occurs between 1000 and 1200 m a.s.l. and above the Taserqat moraines around the mountain massif of Qáqatoqaq (Fig. 2). These uppermost morianes may be late Wisconsin–Würm(?) in age—at least they are of the proper height and position to have been deposited at the Inland Ice surface when its margin was located at the offshore banks. Similarly, a lower set of nunatak moraines around the Qáqatoqaq massif occurs at a height and position indicating that the moraines were deposited contemporaneously with the Taserqat moraine system (Fig. 2).

The age of the Taserqat moraine system is somewhat questionable, but it undoubtedly was formed contemporaneously with or just before the local marine limit of 130–140 m that is developed below the moraines (Weidick, 1968, 1972a, 1972c). Therefore, the Taserqat moraines must be older than 9500 yr BP (Fig. 3), and they are tentatively assigned an age equivalent to Younger Dryas time, or ca. 10,200–11,000 yr BP (Weidick, 1972a: 15, 22).

If the ages suggested above for the offshore banks and the Taserqat moraines are approximately correct, then the net retreat of the Inland Ice between about 15,000 and 10,000 yr BP averaged only about 1 km/100 yr. (The distance between the offshore banks and Taserqat moraines is about 50 km.) This rate of retreat is markedly slower than the approximately 3 km/100 yr retreat rate during the following 3500-yr period discussed below.

INLAND ICE HISTORY
10,000–6500 BP

The Inland Ice margin retreated a net distance of about 100 km at the relatively rapid average rate of 3 km/100 yr from 10,000 to 6500 yr BP; the trend was inter-

TABLE 2

Moraine Systems Formed by the Inland Ice Between 10,000 and 6500 yr BP in West Greenland (cf. Fig. 2)

Moraine system name(s)	Contemporaneous local marine limit (m)	Radiocarbon age (yr BP)
Taserqat	130–140	≥9500
Avatdleq–Sarfartôq	125–130	8800–8700
Anqujârtorfik-Older Fjord	110–115	8400–8300
Intermediate Fjord	100	8300
Younger Fjord	90	8100
Umîvît	65	≥7300
Mt. Keglen–Keglen	40–50	<7200 ≥ 6500

rupted at least seven times by slight readvances or halts, during which most of the major moraine systems in West Greenland were formed (Fig. 2 and Table 2). The moraine system nomenclature used in Fig. 2 and Table 2 is from both Ten Brink (1971b) and Weidick (1972a). Therefore, two names connected by a hyphen are listed in Table 2 for three regional moraine systems that were mapped and named in separate areas and dated on the basis of independent sets of uplift data (Figs. 3 and 4). A brief description of the glacial history represented by the seven regional moraine systems listed in Table 2 is given below.

Between abandonment of the Taserqat moraines, ca. 9500 yr BP, and construction of the Avatdleq–Sarfartôq moraines, 8800–8700 yr BP, the Inland Ice margin retreated at an average rate of 2.5–3.5 km/100 yr. After the formation of the Avatdleq–Sarfartôq moraines, ice margin retreat attained its most rapid rate (5–10 km/100 yr). This phase of rapid retreat continued for 300–500 yr lasting until a halt or readvance formed the Angujârtorfik–older Fjord moraine system about 8400–8300 yr BP.

The next 1000 yr was again a period of relatively slow retreat (3–4 km/100 yr), but this trend was interrupted at least twice (ca. 8300 and ca. 8100 yr BP) during formation of the younger Fjord moraines north of Søndre Strømfjord (Fig. 2). Several small sets of discontinuous ice-margin deposits were also formed south of the fjord, but the deposits do not meet the criteria listed earlier for true moraine systems. This 1000-yr period of progressive retreat ended with the ca. 7300 yr BP formation of the Umîvît moraine system.

The Umîvît moraine system is one of the most massive and well developed in the area south of the fjord, and it may represent a very marked change in glacier regimen; however, the moraine system is difficult to trace north of the fjord. The Umîvît moraine system also may represent more than one glacial event as in some areas it consists of at least two distinct systems of ice-margin deposits separated by a few hundred meters.

After formation of the Umîvît moraines the Inland Ice margin withdrew entirely from the Søndre Strømfjord and allowed the sea to invade slightly beyond the present fjord head. This final marine invasion occurred about 7100 yr BP according to the oldest marine shells collected from emerged marine deposits at the fjord head and dated at 7140 ± 130 yr BP (K-1664) and 7025 ± 120 yr BP (I-5512). A date of ca. 7100 yr BP for deglaciation and marine invasion of the fjord head is also indicated by the age derived from Fig. 4b for the ca. 55-m local marine limit of the area (see Ten Brink, 1971b: 161, sample I-5512 for detailed description). According to the above dates, the ice margin retreated from the Umîvît moraines to the fjord head at a rate of 2.5–5 km/100 yr during the two centuries immediately following Umîvît moraine construction.

The history of ice margin retreat after deglaciation of the Søndre Strømfjord is difficult to reconstruct precisely, because the ice front was no longer in contact with the sea, and therefore marine shells and strandlines are not available for directly dating the rate of retreat. Nevertheless, the age of the next moraine system to be formed, the Keglen (Ten Brink, 1971b) or

Mt. Keglen (Weidick, 1972a) system, is indicated by both (1) the age of the relative sea level to which a valley train was graded from the Keglen moraines, and (2) the age of marine shells from a delta formed at the downstream end of the Keglen valley train.

Weidick's (1972a) determination that the Mt. Keglen valley train was graded to a 48–50 m relative sea level suggests an age of ca. 7200 yr BY for the Mt. Keglen moraine system. This age is based largely on a radiocarbon date of 7140 ± 130 yr BP (K-1664) for marine shells from foreset beds of the Keglen delta (Fig. 3, Table 1). However, according to an independent survey by Ten Brink (1971b), the altitude of the delta surface and the relative sea level to which the Keglen valley train was graded is only 40 m, which indicates an age of ca. 6500 yr BP according to the uplift curve of Fig. 4b. Additional evidence of a ca. 6500 yr BP age is a radiocarbon date of 6505 ± 120 yr BP (I-5589) for shells collected from the same deltaic deposits as sample K-1664 but about 10 m higher (Fig. 4b, Table 1).

The difference between our measurements for the Keglen delta altitude is due mostly to the use of different control points and base maps for the two surveys. Another reason for the discrepancy is slightly different delineation of the Keglen moraine system, which is in fact a several-kilometer-wide zone of moraines and drainage channels graded to the same delta surface; i.e., approximately the same relative sea level. The moraine system thus probably represents slow oscillatory recession during the construction of the Keglen delta and valley train.

Despite these relatively small-scale uncertainties, our combined data indicate that the Keglen delta was constructed between 7200 and 6500 yr BP and that the Keglen moraines were deposited during a relative stabilization of the ice margin that began after marine invasion of the head of Søndre Strømfjord. If the oscillatory recession that resulted in formation of the Keglen moraine system occurred between 7200 and 6500 yr BP, then the rate of recession during that period was only about 0.7 km/100 yr.

INLAND ICE HISTORY 6500–700 BP

From 6500 to 700 yr BP many discontinuous ice-margin deposits were formed in parts of the present map area between the Keglen and Ørkendalen moraine systems (Fig. 2). Numerous sets of small moraines in the area were deposited during sporadic retreat, but from large zones of ice-disintegration features in the area we infer that retreat was generally rapid. From the absence of ice-margin deposits that continue over long enough distances to be classified as moraine systems we also infer that widespread regional stabilizations of the ice margin did not occur between ca. 6500 and 700 yr BP. Further investigations are needed to determine if local sets of moraines formed during this interval date principally from two periods, 4800–4000 yr BP and 2500–2000 yr BP, as suggested for other West Greenland areas (Weidick, 1968: 141).

Although additional data from the Søndre Strømfjord area are needed, Weidick (1972c: 181) has gathered considerable evidence from areas farther north for extensive ice margin retreat immediately prior to ca. 5500 yr BP: in three areas, marine terraces estimated to be 5500–6500 yr old extend beneath the present Inland Ice margin. In order to allow deposition of these marine sediments, the Inland Ice must have retreated to a position behind its present margin between 5500 and 6500 yr BP. The retreat was followed by a readvance that buried marine sediments in areas north of Søndre Strømfjord. Although highly speculative, a similar sequence of events may have occurred in the Søndre Strømfjord area.

INLAND ICE HISTORY 700 BP–PRESENT

Beginning with an initial readvance lichenometrically dated to ca. 700 yr BP

(Ten Brink, 1971b: 70–71; 1973), the entire period from 700 yr BP to present was characterized by oscillatory advance and retreat of the Inland Ice margin within about a 3-km-wide zone. The best known record of these events in the present map area is found at the head of Ørkendalen (Fig. 2). Where a system of six distinct, but very closely spaced, moraine ridges was developed between ca. 700 and 300 yr BP. The younger age limit is based on a radiocarbon date of 330 ± 75 yr BP (UW-180) for organic detritus deposited in the basal strata of lacustrine sand in a moraine-dammed lake (Ten Brink, 1971b: 71).

Following the ca. 300 yr BP advance that culminated in construction of the youngest Ørkendalen moraine, the ice margin retreated slightly and then readvanced to form the "historical" moraines that fringe the present ice sheet. The most recent glacial readvance culminated between A.D. 1880 and 1920 in the northern part of the area according to historical records (Weidick, 1968: 42–45). In some areas of West Greenland, moraines were also formed at ca. A.D. 1750(?) and 1850(?) (Weidick, 1968), but if moraines of this age were built in the Søndre Strømfjord area, they were probably overridden or incorporated by the A.D. 1880–1920 readvance because it was the maximum historical advance.

After construction of the "historical" moraines, the Inland Ice rapidly thinned near its margin, especially behind the terminal moraines of long outlet glaciers. The recent thinning is shown by disintegrating ice-cored moraines, which often stand several meters above the stagnant margin of the Inland Ice, and by trimlines of lichen-bare rock up to 100 m above the present ice surface. Throughout West Greenland the rate of thinning was greatest between A.D. 1920 and 1940, after which the rate of thinning decreased (Weidick, 1968: 42).

The most recent event in the history of the Inland Ice is an incipient readvance indicated by active local overthrusting of the ice margin onto stagnant ice or onto the "historical" moraines. Evidence of a similar readvance that began in the late 1950s or early 1960s and was coincident with stable or decreasing temperatures since the 1940s, has also been reported from West Greenland areas farther north (Weidick, 1968: 42, 56; Gribbon, 1970).

DISCUSSION

We think there is convincing evidence that most of the major moraine systems constructed in West Greenland during the last 10,000 yr were deposited, not during stillstands, but at the culmination of slight readvances of the Inland Ice margin. Moreover, we postulate that the readvances were caused climatically by slight but regional decreases in mean ablation-season temperatures maintained over periods of several decades to a few centuries in duration. Arguments in support of these conclusions are given below.

There is a considerable body of stratigraphic evidence from West Greenland proving that many Holocene moraines are the result of at least minor readvances. This evidence consists of cross-cutting moraine relationships and glacially overridden Holocene marine sediments (Weidick, 1968: 35–45, 107–111; Weidick, 1972c: 181; Ten Brink, 1971b: 73–78). The possibility that most terminal moraines in West Greenland should be considered primarily as push moraines (Weidick, 1968: 75) is also consistent with the argument that the major moraine systems were formed by readvances of the ice margin.

There are also two morphologic characteristics of West Greenland moraine systems that are particularly important to any interpretation of their significance: (1) The continuation of moraine systems over several tens of kilometers indicates that they represent regional and synchronous positions of the ice margin. (2) The continuation of moraine systems across uplands, rather than being restricted to local valleys, indicates they were formed neither during continual retreat and downwasting nor simply in response to local topographic influences. Therefore, the major moraine systems must have been formed either at the culmination of regional readvances or during widespread stillstands of the Inland Ice margin.

The argument that the major moraine systems were formed by readvances caused by changes in climatic conditions is pragmatically far more tenable than the alternative that the moraines were deposited during delicately balanced stillstands caused by long periods of intricately balanced stability (cf. Flint, 1971: 205; Lasca, 1969: 42). This reasoning is supported for Greenland in particular by isotopic evidence from ice cores indicating that frequent temperature fluctuations have occurred throughout the Holocene (Dansgaard *et al.*, 1971); i.e., long periods of climatic stability were rare or nonexistent.

The collective evidence from West Greenland as well as from the eastern Canadian Arctic (Andrews *et al.*, 1970; Andrews and Ives, 1972; Carrara and Andrews, 1972; Miller, 1972, 1973) and several places in the Northern Hemisphere (Denton and Karlén, 1973; Porter and Denton, 1967) therefore corroborates the general view expressed by Flint (1971: 205): "Radiocarbon dates of end moraines built during the past 10,000 years or so suggest that many, possibly most, end moraines result, not from pauses during general shrinkage of a glacier, but from culminations of reexpansions during general shrinkage."

Our hypothesis that climatic changes caused deposition of the moraine systems shown in Fig. 2 is supported by several lines of independent evidence. Most of this evidence has been presented in detail but in separate parts (Weidick, 1968: 35–45; Ten Brink, 1971b: 94–132). The major points are summarized below.

One of the strongest indications of climatic control is that Holocene moraine systems were constructed synchronously, or nearly so, and regional deglaciation was contemporaneous with the ca. 9000 yr BP beginning of the warm Hypsithermal interval (Deevey and Flint, 1957) throughout large sectors of West Greenland, East Greenland, (Funder, 1970, 1971, 1972; Lasca, 1969; Weidick, 1972a, 1972c), and the eastern Canadian Arctic (Andrews, 1965, 1970; Andrews and Falconer, 1969; Andrews and Ives, 1972; Andrews *et al.*, 1970; Carrara and Andrews, 1972; Craig, 1969; Falconer, 1966; Ives, 1962; Miller, 1972, 1973). The cause of such similar glacier behavior seems necessarily to have been widespread synchronous climatic change, because it is probably the only mechanism that could synchronously and repeatedly affect glaciers over such a large area.

Temperature decreases, rather than precipitation increases, were almost certainly the primary cause of West Greenland glacier reexpansions in historic time, because slight decreases in mean summer temperature are known to have been either synchronous with widespread minor readvances or to have preceded the advances by no more than two decades (Weidick, 1968: 45). For the temperature and precipitation trends recorded historically in West Greenland, only temperature fluctuations were uniform over the whole area. Therefore, widespread temperature change must be considered as the principal cause of at least the most recent glacier activity and probably was also a major control of earlier Holocene glacial events. A similar conclusion was reached by Denton and Karlén (1973) on the basis of "worldwide" (Greenland data omitted) patterns of Holocene glacier fluctuations.

Control of Holocene glacial events by temperature is also consistent with the Holocene temperature fluctuations suggested by the ^{18}O data from the Camp Century, Greenland, ice core (Dansgaard *et al.*, 1971). For example, there is little doubt that the general warming indicated near the beginning of the Holocene by the ^{18}O data caused the progressive retreat of the ice margin that ended between 6500 and 4800 yr BP; however, more precise interpretation of Holocene temperature—glacier relations in Greenland is presently unwarranted due to uncertainty about the time scale and magnitude of temperature fluctuations recorded in the ice core.

Despite uncertainty about the timing and magnitude of Holocene temperature changes, there is no doubt that slightly lower regional temperatures during the ablation season would produce an "immediate" expansion of the ice sheet margin (W. F. Budd, personal communication). Such short-term marginal effects of temperature change would, however, have no appreciable effect on the overall ice-sheet profile unless sustained for thousands of years. Therefore, slightly lower mean temperatures during the ablation season, maintained regionally over periods of several decades or a few centuries, are postulated as the cause of marginal growth of the Inland Ice resulting in construction of the major moraine systems in West Greenland.

SUMMARY

The Inland Ice has progressively retreated about 175 km in West Greenland since the close of the last glaciation, but the general trend was interrupted frequently by reexpansions that formed extensive moraine systems subparallel to the present ice margin. Because the retreating ice margin was in contact with the sea in the major fjord troughs, deglaciation was synchronous with marine invasion of lowland areas. The combination of synchronous deglaciation and marine invasion resulted in postglacial isostatic uplift and the emergence above sea level of marine strandlines that now occur up to 140 m a.s.l.

Ages of several emerged marine strandlines were determined from radiocarbon dates of mollusk shells which were related ecologically or stratigraphically to a specific strandline altitude. The dated strandlines provide a basis for dating most of the moraine systems because the combination of glacial and isostatic processes resulted in deposition of time-stratigraphically equivalent glacial and marine deposits.

According to dates based largely on relations between moraine systems and relative sea levels, the history of the Inland Ice since the last glaciation can be divided into four principal phases: (1) Relatively slow retreat of the Inland Ice margin from the offshore banks apparently occurred at an average rate of approximately 1 km/100 yr until ca. 10,000 yr BP when the Taserqat moraines were formed, probably by a readvance. (2) At ca. 9500 yr BP the rate of retreat increased markedly to about 3 km/100 yr, and although nearly 100 km of retreat occurred by ca. 6500 yr BP, it was punctuated by frequent regional reexpansions of the Inland Ice which formed extensive moraine systems at ca. 8800–8700 yr BP (Avatdleq–Sarfartôq moraines), 8400–8100 yr BP (Angujârtorfik-Fjord moraines), 7300 yr BP (Umîvît moraines), and 7200–6500 yr BP (Keglen–Mt. Keglen moraines). (3) Between 6500 and 700 yr BP, discontinuous ice-margin deposits and ice-disintegration features were formed during retreat which probably was very rapid initially and may have continued until the ice margin was near or behind its present position by ca. 6000 yr BP. Most of the discontinuous ice-margin deposits occur within 5–10 km of the present ice margin and may have been formed by readvances presumed to have had two main phases at ca. 4800–4000 yr BP and 2500–2000 yr BP. (4) From ca. 700 yr BP to the present, the ice margin has undergone minor retreats and readvances resulting in the construction of several closely spaced moraines within about 3 km of the present ice margin.

From the above four-phase sequence, the pattern of Inland Ice History since the last glaciation can be further generalized: slow retreat occurred from ca. 15,000 to 10,000 yr BP, and was followed by oscillatory but generally more rapid retreat until the ice margin became semistable near its present position sometime between 6500 and 4800 yr BP. This long-term retreat was undoubtedly caused by well-documented, hemisphere-wide climatic warming.

The above sequence of events was very closely paralleled by glacial events in other Greenland areas and the eastern Canadian Arctic. Such similarity of glacier behavior over a large area suggests that widespread climatic change was the cause of periodic reexpansions of the Inland Ice margin during which moraines were formed. Moreover, historic evidence gathered by Weidick (1968) shows that minor advances of the Inland Ice margin followed slight temperature decreases by no more than a few decades. From the above factors, we infer that construction of the major Holocene moraine systems in West Greenland was caused by slight temperature decreases, which decreased rates of ablation and thereby produced practically immediate advances of the ice sheet margin, but did not necessarily affect the long-term equilibrium of the ice sheet.

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REFERENCES

Andrews, J. T. (1965). "Glacial Geomorphological Studies on Northcentral Baffin Island, Northwest Territories, Canada. unpublished Ph.D. dissertation, Univ. of Nottingham, 476 p.

Andrews, J. T. (1970). Differential crustal recovery and glacial chronology (6700 to 0 BP), West Baffin Island, N.W.T., Canada. *Arctic and Alpine Research* **2,** 115–134.

Andrews, J. T., Buckley, J. T., and England, J. H. (1970). Late glacial chronology and glacio-isostatic recovery, Home Bay, east Baffin Island, Canada. *Geological Society of America Bulletin* **81,** 1123–1148.

Andrews, J. T., and Falconer, G. (1969). Late-glacial and postglacial history and emergence of the Ottawa Islands, Hudson Bay, N.W.T.: evidence on the deglaciation of Hudson Bay. *Canadian Journal of Earth Sciences* **6,** 1263–1276

Andrews, J. T., and Ives, J. D. (1972). Late- and postglacial events (<10,000 B.P.) in the eastern Canadian Arctic with particular reference to the Cockburn moraines and break-up of the Laurentide ice sheet. *In* "Climatic Changes in Arctic Areas During the Last Ten-Thousand Years." (Y. Vasari, H. Hyvärinen, and S. Hicks, Eds.), pp. 149–171. Acta Universitatis Ouluensis, Series A, no. 3, Geologica no. 1. University of Oula, Finland.

Carrara, P., and Andrews, J. T. (1972). The Quaternary history of northern Cumberland Peninsula, Baffin Island, N.W.T., Part I: the late- and neoglacial deposits of the Akudlermuit and Boas glaciers. *Canadian Journal of Earth Sciences* **9,** 403–414.

Craig, B. G. (1969). Late-glacial and postglacial history of Hudson Bay. *Geological Survey of Canada Paper* **68-53,** 63–77.

Dansgaard, W., Johnsen, S., Clausen, H., and Langway, C. (1971). Climatic record revealed by the Camp Century ice core. *In* "The Late Cenozoic Glacial Ages." (K. K. Turekian, Ed.), pp. 37–56. Yale University Press, New Haven.

Deevey, E. S., and Flint, R. F. (1957). Postglacial hypsithermal interval. *Science* **125,** 182–184.

Denton, G. H., and Karlén, W. (1973). Holocene climatic variaitons—their pattern and possible cause. *Quaternary Research* **3,** 155–205.

Falconer, G. (1966). Preservation of vegetation and patterned ground under a thin ice body in northern Baffin Island, N.W.T., Canada. *Geographical Bulletin* **8,** 194–200.

Flint, R. F. (1971). "Quaternary and Pleistocene Geology." John Wiley & Sons, New York. 533 p.

Funder, S. (1970). Notes on the glacial geology of eastern Milne Land, Scoresby Sund, East Greenland. *The Geological Survey of Greenland Report* **30,** 37–42.

Funder, S. (1971). Observations on the Quaternary geology of the Rødefjord region, Scoresby Sund, East Greenland. *The Geological Survey of Greenland Report* **37,** 51–55.

Funder, S. (1972). Deglaciation of the Scoresby Sund fjord region, north-east Greenland. *In* "Polar Geomorphology." (R. J. Price and D. E. Sugden, Eds.). Institute of British Geographers Special Publication no. 4, pp. 33–42. Alden and Mowbray Ltd., Alden Press, Oxford.

GOLDTHWAIT, R. P. (1964). Tasersiaq area–Sukkertoppen Ice Cap Studies. *Ohio State University Research Foundation Report* **1701-*Final,*** 68 p.

GRIBBON, P. W. F. (1970). Frontal recession of Sermikavsak, West Greenland. *Journal of Glaciology* **9,** 279–282.

IVES, J. D. (1962). Indications of recent extensive glacierization in north-central Baffin Island, N.W.T. *Journal of Glaciology* **4,** 197–206.

LASCA, N. P. (1969). The surficial geology of Skeldal, Mesters Vig, Northeast Greenland. *Meddelelser om Grønland* **176,** no. 3, 56 p.

MILLER, G. H. (1972). Quaternary history of Northern Cumberland Peninsula, East Baffin Island, N.W.T., Canada, Part IX: Neoglacial chronology of the eastern margin of the Penny Ice Cap and nearby glaciers. *Geological Society of America, Rocky Mountain Section, 25th Annual Meeting (Abstracts with Programs)* **4,** 396.

MILLER, G. H. (1973). Late Quaternary glacial and climatic history of Northern Cumberland Peninsula, Baffin Island, N.W.T., Canada. *Quaternary Research* **3,** 561–583.

PORTER, S. C., AND DENTON, G. H. (1967). Chronology of Neoglaciation in the North American Cordillera. *American Journal of Science* **265,** 177–210.

SUGDEN, D. E. (1972). Deglaciation and isostasy in the Sukkertoppen Ice Cap area, West Greenland. *Arctic and Alpine Research* **4,** 97–117.

TEN BRINK, N. W. (1971a). Continued investigations of Quaternary deposits between Søndre Strømfjord, the Inland Ice, and the Sukkertoppen Ice Cap. *Geological Survey of Greenland Report* **35,** 13–17.

TEN BRINK, N. W. (1971b). "Holocene Deleveling and Glacial History Between Søndre Strømfjord and the Greenland Ice Sheet, West Greenland." Ph.D. Dissertation, University of Washington, Seattle, 191 p.

TEN BRINK, N. W. (1973). Lichen growth rates in West Greenland. *Arctic and Alpine Research* **5,** 323–331.

TEN BRINK, N. W. (1974). Glacio-isostasy: new data from West Greenland and geophysical implications. *Geological Society of America Bulletin* **85,** 219–228.

WEIDICK, A. (1968). Observations on some Holocene glacier fluctuations in West Greenland. *Meddelser om Grønland* **165,** no. 6, 202 p.

WEIDICK, A. (1971a). Quaternary Map of Greenland, 1:2,500,000. The Geological Survey of Greenland, Copenhagen.

WEIDICK, A. (1971b). Short explanation to the Quaternary Map of Greenland. *Geological Survey of Greenland Report* **36,** 15 p.

WEIDICK, A. (1972a). Holocene shore-lines and glacial stages in Greenland—an attempt at correlation. *Geological Survey of Greenland Report* **41,** 39 p.

WEIDICK, A. (1972b). C^{14} dating of survey material performed in 1971. *Geological Survey of Greenland Report* **45,** 58–67.

WEIDICK, A. (1972c). Notes on Holocene glacial events in Greenland. *In* "Climatic Changes in Arctic Areas During the Last Ten-Thousand Years, A Symposium Held at Oulanka and Kevo, Finland, 4–10 October 1971." (Y. Vasari, H. Hyvärinen, and S. Hicks, Eds.), pp. 177–204. Acta Universitatis Ouluensis, Series A, no. 3, Geologica no. 1. University of Oula, Finland.

WEIDICK, A. (1973). Quaternary Map of the Søndre Strømfjord-Nûgssuaq region. The Geological Survey of Greenland, Copenhagen.

WEIDICK, A., AND TEN BRINK, N. W. (1970). Quaternary deposits between the Sukkertoppen Ice Cap and Nordre Strømfjord. *Geological Survey of Greenland Report* **28,** 23–25.

WILLMAN, H. B., AND FRYE, J. C. (1970). Pleistocene stratigraphy of Illinois. *Illinois Geological Survey Bulletin* **94,** 204 p.