GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 113

HOLOCENE HISTORY OF THE GREENLAND ICE SHEET BASED ON RADIOCARBON-DATED MORAINES IN WEST GREENLAND

BY

NORMAN W. TEN BRINK

WITH 10 FIGURES AND 5 TABLES IN THE TEXT,
AND 3 PLATES

KØBENHAVN
1975

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Abstract

The Greenland ice sheet margin retreated at least 125 km in West Greenland during the Holocene, but frequent halts or readvances interrupted the general trend and formed extensive moraine systems. Local deglaciation was synchronous with marine invasion of the fjords, resulting in deposition of interrelated glacial and marine sediments. The marine deposits have been uplifted by postglacial isostatic rebound and now occur as emerged-marine sediments and strandlines up to 125 ± 5 m a.s.l. The age and altitude values of 21 radiocarbon-dated samples of mollusc shells collected from the emerged-marine sediments define two postglacial emergence curves, which have been used to date moraine systems by means of their relations to former relative sea levels.

Major moraine systems were constructed by the inland ice about 8800 B.P., 8300 B.P., 7300 B.P., 6500 B.P. to perhaps 6000(?) B.P., and presumably *c.* 4800–4000 B.P. and 2500–2000 B.P. An advance of the inland ice about 3 km beyond its present margin *c.* 700 lichenometric years B.P. was followed by oscillatory retreat and advance, culminated by an advance 330 ± 75 C-14 years B.P. Moraines adjacent to the present ice margin were formed by a series of small advances culminated by local maxima between A.D. 1880 and 1920.

The episodes of moraine construction were probably caused by slight decreases in mean temperature over periods of several decades to a few centuries, resulting in decreased ablation and immediate growth of the ice sheet margin. Long-term dynamic responses of the entire ice sheet, requiring thousands of years, were not necessary to form the moraines. The suggested short-term climatic cause of Holocene moraine construction is supported by palynologic and regional glacial geological evidence as well as historic temperature-glacier relations in West Greenland. Net retreat of the ice sheet margin during the Holocene was almost undoubtedly caused by hemisphere-wide climatic warming recorded in the O^{18}/O^{16} data for the Camp Century, Greenland, ice core as well as palynologic data from several sites in the Northern Hemisphere.

CONTENTS

Page

Introduction 5
- Objectives, location and background 5
- Geological-geomorphological setting 6
- General methods of study 8

Major moraine systems and glacial chronology 9
- Nature of the evidence 9
- Major moraine systems 10
  - General 10
  - Methods of delineation 11
  - Methods of dating 13
  - Type areas and ages 17
- Glacial chronology 21
- Comparison with other areas 28
  - West Greenland 28
  - East Greenland 29
  - Eastern Canadian Arctic 34
  - Discussion and glacial-climatic implications 36
- Summary 38
- Acknowledgements 39

References 41

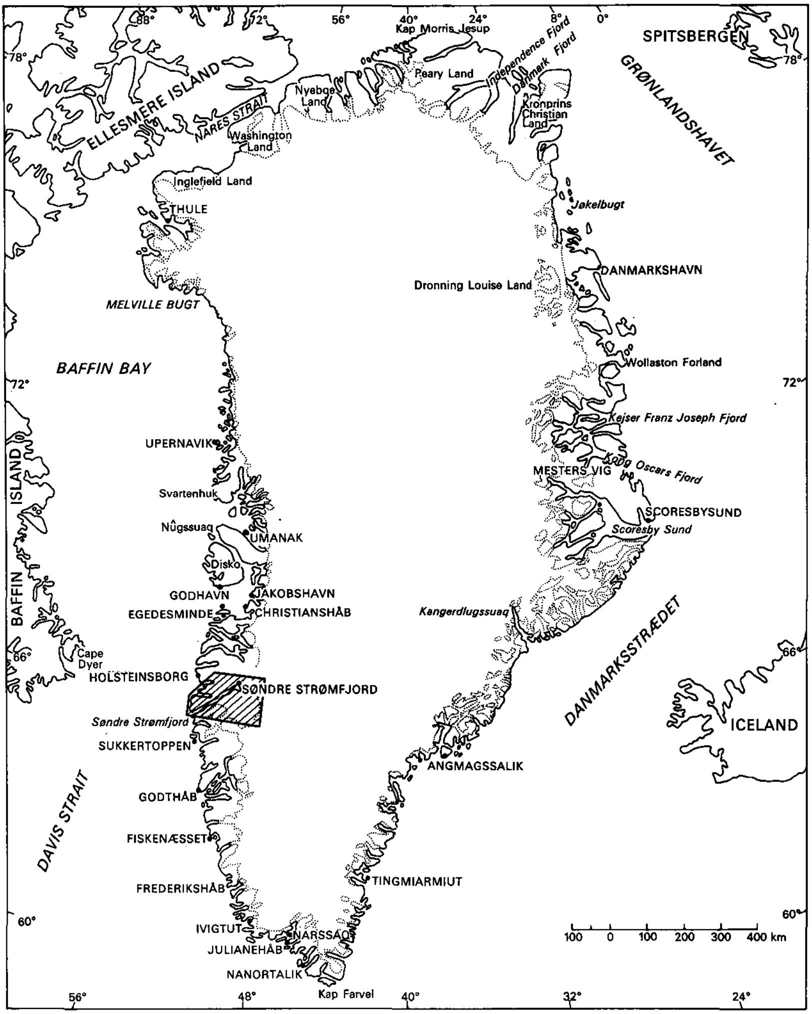

Fig. 1. Map of Greenland showing the location of the study area.

INTRODUCTION

Objectives, location and background

This paper presents the major results from glacial geological investigations of the *c.* 7000 km^2 area bounded by Søndre Strømfjord on the north-west, the inland ice on the east, and small local ice caps on the south-west (fig. 1). These results are part of a larger research project with the general objective of establishing a chronology of deglaciation and postglacial uplift for the entire area that is transected by Søndre Strømfjord and extends westward from the inland ice to the west coast of Greenland (fig. 1, plate 3).

The Søndre Strømfjord area was chosen as a potentially critical area for establishing the chronology of deglaciation and postglacial uplift of a larger sector of West Greenland on the basis of previous investigations by WEIDICK (1958, 1959, 1963a, 1965, 1968). The area was known to be one of the largest deglaciated areas in Greenland and to contain an abundant variety of interrelated glacial and isostatically uplifted marine deposits which could be dated by radiocarbon analysis of marine shells (cf. WEIDICK, 1968, plate 3, pp. 86–88, 104, 137).

During 1969 and earlier years, ANKER WEIDICK of the Geological Survey of Greenland (GGU) investigated the area lying north and west of Søndre Strømfjord (WEIDICK & TEN BRINK, 1970). During 1969 and 1970, the author was employed by GGU to investigate the area south-east of the fjord (TEN BRINK, 1971a). WEIDICK's results for the area north-west of the fjord have been published separately (WEIDICK, 1972a). Reports on the postglacial uplift of the Søndre Strømfjord area are also being published separately (TEN BRINK, 1972b; 1974), and a complete report of the writer's work is available on microfilm and through interlibrary loan (TEN BRINK, 1971b). The results of both investigators' glacial geological studies will be synthesized in Quaternary maps at 1:500000 scale (Geological Survey of Greenland, in preparation).

Geological-geomorphological setting

The bedrock of the area south-east of Søndre Strømfjord consists of Precambrian granitic gneisses with amphibolites and doleritic dykes (ESCHER *et al.*, 1970). Three principal lithologic units occur; granites, granulite facies gneisses and amphibolite facies gneisses.

The lack of lithostratigraphy in the gneisses precludes lithologic differentiation of the glacial deposits. Because ice movement was generally westward, drift and erratics throughout the entire study area consistently include rocks derived mostly from the immediate substrate along with rocks from each lithology that crop out farther east.

Morphologically, West Greenland is a classic fjord landscape with many similarities to western Norway (HOLMES, 1965, pp. 224–226; HOLTEDAHL, 1960, pp. 518–521; 1970). The fjords of the region are incised into a mountainous terrain with a maximum relief of about 2000 m and they terminate inland 0–25 km from the inland ice margin in large U-shaped valleys. At fjord heads, the U-shaped valley mouths either contain calving outlet glaciers or are partly filled with terraced glaciofluvial and marine sediments.

Søndre Strømfjord is one of the longest fjords in West Greenland, reaching inland for approximately 165 km and heading about 20 km from the inland ice. The Søndre Strømfjord trough is incised most deeply into the bedrock surface where it passes through the highlands at the north-west edge of the Sukkertoppen ice cap. In this area, the fjord walls rise almost vertically about 1500 m a. s. l. (plate 3).

The basic pattern of large-scale topographic features in the Søndre Strømfjord region is structurally controlled, and its origin (except for relief) is independent of glaciation. The area displays a predominant system of morphologic lineaments consisting of two sets: one trends north-east to south-west and is exemplified by the fjord itself, the other trends north-west to south-east and is exemplified by the major river valleys and elongate interfluves in the area north of the Sukkertoppen ice cap (plate 3). A system of bedrock joints and some faults are coincident with this system of lineaments, and the bedrock jointing is clearly discernible on both microscopic and megascopic scales (HOBBS, 1927; BELKNAP, 1941, pp. 238–255). Bedrock control of the lineaments is clearly shown by their parallelism with the strike of foliation in the bedrock units.

The intermediate and small-scale morphology of the area is typical of that developed by subglacial erosion of crystalline bedrock in many parts of the world, and almost every type of landform attributable to glacial erosion occurs at least locally (cf. FLINT, 1971, pp. 86–100, 127–146). Dome-like summits, rounded ridges, and smoothed cols are abundant up to 1300–1400 m, but well-preserved cirques and crests sharpened by frost action are extremely rare except on the currently glacierized Sukkertoppen highlands. Thus, the morphology corresponds to the classical description of an area once buried by an ice sheet with only a few possible nunataks above *c.* 1400 m (cf. FLINT, 1971, pp. 141–143, especially fig. 6–4, p. 142). In summary, the area is an undulating bedrock landscape in which westward-flowing ice has developed U-shaped valleys and streamlined stoss-and-lee forms parallel to the structural grain.

Landforms consisting of glacial sediments are very minor in comparison to erosional bedrock forms, almost all being less than 50 m in local relief and therefore not detectable on existing maps with 50 m contour intervals. In general, glacial deposits compose either a thin mantle of drift with little independent topographic expression or 3 to 50 m high ridges, which occur mostly as lateral moraines, terminal moraines, kame moraines and kame terraces in the major valleys. The only glacially derived deposits that are identifiable on topographic maps are terraces composed of glaciofluvial and emerged glacial-marine sediments. Some terraces have a relief of more than 100 m with terrace treads up to 1 km wide and several kilometres long.

In relation to glacial history, the most important topographic feature in the present map area is the broad highland with 1200 to 1800 m summits that extends north-westward across Søndre Strømfjord from beneath the Sukkertoppen ice cap (plate 3). This topographic high, referred to here as the Sukkertoppen highlands, forms an important glacial and climatic barrier between the coast and the inner Søndre Strømfjord area. As shown by plate 3, summit altitudes gradually decrease north-eastward from 1200–1500 m at the north-east edge of the Sukkertoppen highlands to 400–600 m near Sandflugtdalen. From Sandflugtdalen, a lowland with maximum altitudes rarely above 600 m extends northward for at least 100 km and westward to the north-north-west trending continuation of the Sukkertoppen highlands. These large-scale topographic features probably had the following three major influences on the inland ice during the Holocene.

(1) During extensive glaciation, westward drainage from a large sector of the inland ice was probably channelled through lowland areas, and hence was diverted around the north-eastern margins of the highlands in the area of this study. Therefore, the very deep and narrow Søndre Strømfjord trough may have been a relatively minor outlet channel through the Sukkertoppen highlands compared to the wider valleys that drain the lower inland areas north of Søndre Strømfjord (plate 3).

(2) The margin of the inland ice was maintained at relatively high altitudes, or 'dammed up' behind the highlands, just as is presently

indicated by the long arc-like re-entrant in the ice margin east of the highlands (plate 3). This effect of the highlands on the ice margin probably resulted in lower temperatures and slower ablation rates than in lowland coastal areas, and such a temperature–ablation effect would have mitigated against rapid retreat of the ice margin even when rapid retreat occurred in lower areas.

(3) The 'damming up' of the inland ice behind the highlands may have promoted unusually clear and concentrated development of ice-margin deposits during glacier advances because the ice had to advance up-slope. This is probably a principal reason for an extremely high frequency of well-developed moraines in the present map area (plate 3) and in the inner Holsteinsborg district immediately north of Søndre Strømfjord (WEIDICK, 1972a), compared to other deglaciated areas shown on the *Quaternary Map of Greenland* (WEIDICK, 1971a).

General methods of study

Significant areas of glacial and emerged-marine deposits were located by interpretation of aerial photographs and helicopter reconnaissance flights. Detailed investigations were then conducted from short-term camps established in the selected areas. Camps were established in inland areas by helicopter during 1969 and near the fjord by boat during 1970.

The amount, age and rate of postglacial emergence were determined by measuring the altitudes and ages of individual strandlines. The ages of strandlines were obtained by C-14 dating marine shells that were stratigraphically or ecologically related to a specific strandline.

The glacial history of the area was reconstructed by mapping the glacial deposits and determining the chronologic relations between major end-moraine systems and radiocarbon-dated marine deposits. This method of investigation was permitted by the fact that marine invasion of the Søndre Strømfjord trough occurred synchronously with deglaciation and the beginning of postglacial uplift; a combination of events that resulted in deposition of time-stratigraphically equivalent glacial and marine sediments that were subsequently exposed by isostatic uplift. The time-stratigraphic equivalence of glacial and marine sediments thus allowed moraine systems to be dated by the C-14 age of shells collected from emerged-marine sediments.

Detailed description of the important stratigraphic and morphologic relations between moraines and dated marine sediments is given in a later section of this paper (p. 13). The radiocarbon dating of emerged-marine sediments, including description of the methods used to construct emergence curves and evaluation of potential errors, is discussed in detail in other papers (TEN BRINK, 1971b, pp. 39–50; 1974).

MAJOR MORAINE SYSTEMS AND GLACIAL CHRONOLOGY

In this section the major characteristics and regional patterns of glacial deposits are described first, and then a regional glacial chronology is established by describing the relations between major end-moraine systems and radiocarbon-dated strandlines. Most detailed aspects of the glacial deposits are omitted from discussion unless they are regionally significant.

Nature of the evidence

Glacial drift is almost ubiquitous throughout the region (cf. WEIDICK, 1968, pp. 13, 66–79; 1971 a), which attests to complete glaciation. Numerous types of drift occur in different areas, but for the purpose of determining regional glacial history the sediments were broadly grouped into the following three principal categories:

(1) *Ice-margin deposits* that consist mainly of till in the form of end moraines but include a variety of sediments and landforms that have a diagnostic morphology determined by former margins of the inland ice. This category excludes, in so far as possible, those deposits that comprise landforms formed by local or stagnating ice that was not an integral part of the inland ice. (For further discussion and general usage of the term ice-margin deposits in Greenland, see WEIDICK (1968, 1971 b) and TEN BRINK (1971 b, pp. 6–7)).

(2) *Proglacial stratified drift* that consists of glaciofluvial sediments in the form of terraced valley trains which grade down-valley from ice-margin deposits into glacial-marine sediments.

(3) *Ice-contact stratified drift* that covers areas of at least a few square kilometres in extent and is characterized by kame and kettle topography. These deposits display a variety of ice-disintegration features such as small eskers, crevasse fillings, and hummocky ablation drift that do not record well-defined margins of the inland ice (cf. FLINT, 1957, p. 151; 1971, pp. 207–220).

This simple threefold classification of glacial drift corresponds to the following three major aspects of the sedimentary glacial record:

(1) The ice-margin deposits record semi-stable ice-margin positions and sequential changes in geometry of the inland ice.

(2) The proglacial sediments record the ages of ice-margin positions through the stratigraphic relations of ice-margin deposits to proglacial marine sediments that contain radiocarbon-dated shells.

(3) The areas of ice-contact stratified drift characterized by kame and kettle topography record ice stagnation and disintegration between semi-stable ice-margin positions.

A map of the Søndre Strømfjord area delineating the above units at 1:100000 scale was compiled from 1:40000 scale aerial photographs on which the units were originally mapped. The 1:100000 scale map was then used as the principal basis for reconstructing a semi-detailed glacial history of the Søndre Strømfjord area (TEN BRINK, 1971b, pp. 72–82); however, because of its size, the detailed map is not presented here. (A copy of the 1:100000 scale map is on file at the offices of the Geological Survey of Greenland in Copenhagen, and a limited number of copies reduced to 1:250000 may be obtained from the author). A simplified map at 1:500000 scale showing most of the major units will also be published by the Geological Survey of Greenland (in preparation). The major moraine systems delineated on the 1:100000 map are shown approximately in plate 3 and are described below.

Major moraine systems

General

The most important characteristic of glacial drift in the area is that it forms as systems of ice-margin deposits which are not restricted to local valleys but continue across upland areas between valleys (fig. 2). These systems, especially their continuation across uplands, are most significant because (1) they give direct evidence of regionally contemporaneous ice-margin positions, and (2) they permit correlation of principal terminal moraines between separate valleys that often contain numerous local moraines.

The term *moraine system* will be used throughout the remainder of this paper for a system of ice-margin deposits defined as a morphostratigraphic unit consisting of a group of closely associated ice-margin deposits, mostly end moraines, which have great linear extent and in places cannot be differentiated. Therefore, a moraine system is essentially equivalent to a 'zone' of ice-margin deposits as defined by WEIDICK (1968, p. 136), a 'morainic system' as defined by WILLMAN & FRYE (1970, p. 44, after LEVERETT, 1897), and an 'end-moraine system' as

Fig. 2. Aerial view of part of the Umîvît moraine system illustrating the continuation of the end moraines (dashed lines) across upland areas. View is northward approximately midway along an imaginary line joining site No. 16 (plate 3) and Sondrestrom Air Base (arrow). (Photograph NWTB 06.28.1969).

defined by Flint (1971, p. 200). Such moraine systems are ideal basic units for the mapping that is currently necessary to reconstruct Greenland glacial history because they are probably the only type of glacial units that can be consistently delineated for any significant distance.

Methods of delineation

Major moraine systems were delineated by means of the following criteria. (1) Only those ice-margin deposits which could be clearly traced for several kilometres with few discontinuities from a helicopter and/or aerial photographs were considered to represent moraine systems. (2) Each moraine system had to be represented by end moraines on uplands as well as in local valleys. (3) Ice-margin deposits had to be in similar topographic positions on both sides of local discontinuities to be included in a given moraine system.

Fulfillment of this last criterion was checked by computing 'equilibrium profiles' for radii of the inland ice that corresponded to the location of a given moraine system (Nye, 1959, p. 498, equation 9). Such an equilibrium profile, calculated for the time when the ice margin was at a dated set of moraines, allowed approximate determination of the altitudes

Fig. 3. Relations between glacial, glaciofluvial and marine sediments in the Angujârtorfik area. The local marine limit (below dashed line) 115 ± 10 m a.s.l. on the north wall of the bay Angujârtorfik represents the relative sea level to which the valley train (T) of the Angujârtorfik moraine system (M) was graded. View is north-westward from the terminal portion of the Angujârtorfik type-area moraines. (Photographs NWTB 02.30.1970 and 02.31.1970).

at which the ice margin intersected the land surface in other parts of the map area. (For discussion of the bases and limitations of mathematical equilibrium profiles, see WEERTMAN, 1961; COLLINS, 1968; PHILBERTH & FEDERER, 1970). A similar but more refined method has been used for correlating moraine segments in West Greenland by means of their 'surface characteristic' (WEIDICK, 1968, pp. 60–64).

That the moraine systems delineated by the above methods (plate 3) do in fact represent sediments deposited during regionally contemporaneous positions of the inland ice margin is indicated by two independent lines of evidence. First, where a given moraine system is dated by its relation to marine deposits in more than one locality, the system is of the same approximate age in each locality (cf. TEN BRINK, 1971b, fig. 6, plates 3-A, 3-B). Secondly, the moraine systems delineated south of Søndre Strømfjord continue north of the fjord as 'zones' of ice-margin deposits that are essentially the same age according to independent data (WEIDICK, 1972a).

Methods of dating

All but one of the moraine systems shown in plate 3 are dated by means of their stratigraphic or morphologic interrelation with radiocarbon-dated, emerged-marine deposits. This general method of dating moraines has been employed extensively in Arctic areas that have experienced postglacial uplift; e.g., ANDREWS (1969a, 1969b, 1970a, 1970b), ANDREWS & FALCONER (1969), ANDREWS *et al.*, (1970), FUNDER (1970, 1971, 1972), and WEIDICK (1968, 1972a). The two specific types of marine-glacial interrelations used to date moraine systems in the Søndre Strømfjord area are described below.

The first type of marine-glacial interrelation consists of terraced proglacial sediments that grade down-valley from ice-margin deposits into emerged-marine deltas located in valley mouths near the fjord (fig. 3). These terraced proglacial sediments were deposited as one continuous and contemporaneous valley train, which was graded from an ice margin to a relative sea level. That sea level is now recorded by the altitude of the delta surface at the terminus of the valley train. Therefore, the age of the relative sea level represented by the delta surface dates not only the delta and the valley train with which it is morphologically and stratigraphically continuous, but also dates the ice-margin deposits at the head of the valley train. The age of the relative sea level is given by its age–altitude value on the appropriate emergence curve for the area (fig. 4 or 7).

The age of the relative sea level represented by a delta may also be given in some cases by a specific sample of shells collected from the con-

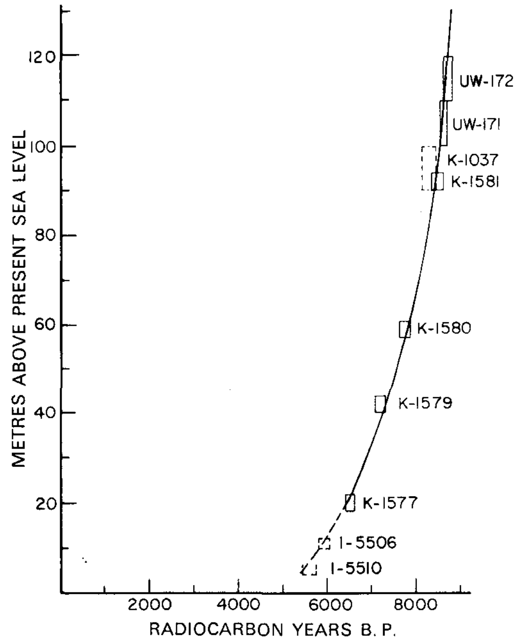

Fig. 4. Emergence curve for the Sarfartôq and Itivdleq areas. One radiocarbon-dated shell sample is represented by each rectangle, its width being equal to the standard error of the date and height being equal to both the estimated uncertainty of field altitude measurement and relation to relative sea level (cf. table 1). Only those samples represented by solid rectangles were used to construct the curve. Dashed rectangles represent samples from outside the source area of the basic data. The open-topped rectangle represents a sample that provides only a minimum limiting altitude for relative sea level because it could not be firmly related to a specific strandline on either ecologic or stratigraphic grounds.

tact zone between fore-set and top-set beds of the delta (e.g. sample I-5589, table 1). For such cases in the Søndre Strømfjord area, the age based on the emergence curve agrees with the age from the single shell sample. However, an age derived from an emergence curve is statistically more reliable than a single shell date because it is based on an established mathematical model that pools several dates.

The second type of marine-glacial interrelation consists of marine-limit strandlines that were developed below and inside a moraine system when the ice margin retreated and allowed the sea to invade valleys that had been occupied by calving outlet glaciers during construction of the moraine system (figs 5 & 6). The age of the marine-limit altitude in such cases is given by the appropriate emergence curve (fig. 4 or 7), and it dates the time at which the ice margin withdrew from the moraines and allowed the sea to enter.

Table 1. *Radiocarbon-dated marine shells from the Søndre Strømfjord area, West Greenland*

Radio-carbon lab. No.*	GGU No.	Site No. (pl. 3) of shell sample locality†	Field altitude (m) of *in situ* shells	Altitude (m) of relative sea level dated by shells' age†	C^{14} age (yr B.P.)
I-5504........	119550	1	34 ± 4	34 ± 4**	6150 ± 115
I-5505........	119552	2	15 ± 1	15 ± 1	5070 ± 105
I-5506........	119556	3	10 ± 1	11 ± 1	5845 ± 115
I-5508........	119560	4	14 ± 1	65 ± 5?	7260 ± 120
I-5510........	119566	5	3 – 4	5 ± 1	5615 ± 115
I-5511........	119574	6	24 ± 2	24 ± 2**	6045 ± 115
I-5512........	119575	6	10 ± 1	47 ± 7**	7025 ± 120
I-5587........	119579	7	1 – 1.5	4 ± 1**	4335 ± 110
I-5589........	119582	8	31 ± 1	40 ± 5**	6505 ± 120
I-5590§........	119583	9	00	00	$-\delta$ (C^{14}) = −119 ± 13
K-1037††......	79549	10	95 ± 5	95 ± 5	8250 ± 130
K-1577§§......		11	20 ± 1	20 ± 1	6510 ± 140
K-1579§§......		12	37 ± 1	42 ± 1**	7220 ± 130
K-1580§§......		13	55 ± 1	59 ± 1**	7730 ± 130
K-1581§§......		14	47 ± 1	92 ± 1**	8460 ± 140
K-1716††......	122266	15	57 ± 1	60 ± 3	6880 ± 120
K-1720........	119501	16	37 ± 1	37 ± 4**	6330 ± 120
K-1721........	119506	16	20 ± 1	20 ± 1**	6140 ± 120
K-1722........	119524	17	19 ± 1	19 ± 1**	6060 ± 120
UW-171.......	119523	18	105 ± 5	105 ± 5**	8610 ± 70
UW-172.......	119522	19	115 ± 5	115 ± 5**	8670 ± 100

* I = Teledyne Isotopes Westwood Laboratories (J. Buckley); K = Copenhagen Natural Museum Carbon-14 Dating Laboratory (H. Tauber); UW = University of Washington C-14 Dating Laboratory (A. Fairhall).

† The location, stratigraphic-ecologic relation to a relative sea level, and species content of the shell samples are given in comprehensive detail in Ten Brink (1971a, pp. 16–17; 1971b, pp. 156–169) and Weidick (1972b, pp. 61–65).

§ Shells of living *Mytilus edulis* collected from tidal flats and used as a check on C^{14} content of modern sea water; result indicates enrichment in C^{14} from nuclear devices.

** Altitudes used as the basis of the uplift curves because shells were stratigraphically and/or ecologically most directly related to these relative sea levels.

†† Collected by Weidick (1968, p. 191; 1972a, pp. 26, 28).

§§ Collected by Sugden (1972, pp. 110–111).

Fig. 5. Relations between glacial and marine features in the Umîvît area. Local marine-limit strandline (dashed line) 65 ± 5 m a.s.l. that was developed below and inside moraines (dotted line) of the Umîvît moraine system when the ice margin retreated from the moraines and allowed the sea to enter *c.* 7300 years B.P. View is westward along the north shore of Umîvît. (Photograph NWTB 02.27.1970).

Fig. 6. Relations between glacial and marine features in the Umîvît area. Local marine-limit strandline (dashed line) 65 ± 5 m a.s.l. that was developed below kame moraines (dotted lines) of the Umîvît moraine system similar to the strandline shown in fig. 5. View is north-eastward along the south shore of Umîvît. (Photograph NWTB 07.34.1969).

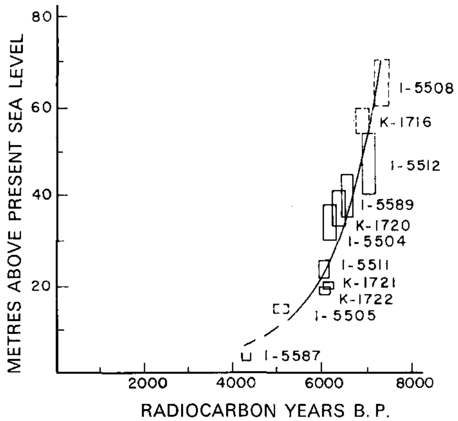

Fig. 7. Emergence curve for the Umîvît and Sondrestrom Air Base areas. Symbols and conventions are the same as fig. 4.

The age of a marine-limit strandline in cases such as that just described gives a date of local deglaciation rather than a direct date of moraine construction. Therefore, dates of moraine systems based on this second type of marine-glacial relation will be referred to as *deglacial* dates. This is distinct from the first type of marine-glacial interrelation, which yields dates based on deltaic materials deposited synchronously with moraine construction, and therefore referred to as *synglacial* dates.

Type areas and ages

Five moraine systems can be defined in the Søndre Strømfjord area, and their locations, names and ages are shown in plate 3. Each moraine system is formally defined below.

The *Sarfartôq moraine system* is named after its type area, which is the area within a 15 km radius north and east of the mouth of the Sarfartôq valley, and is defined as the moraine system that was deposited contemporaneously with the 125 ± 5 m relative sea level(s) recorded by local marine-limit strandlines within the type area (cf. SUGDEN, 1972, p. 108 and fig. 3). The Sarfartôq moraine system is assigned an age of *c.* 8800 years B.P. based on the age of the 125 ± 5 m local marine limit according to the outer Søndre Strømfjord emergence curve (fig. 4; cf. SUGDEN, 1972, p. 108, figs 3, 10). Because this is a 'deglacial' date as defined earlier, the oldest Sarfartôq moraines may be a few centuries older than *c.* 8800 years B.P.

The *Angujârtorfik moraine system* is named after its type area, which includes the lowest 10 km of the valley Angujârtorfiup kûa and the valley walls bounding the north and south sides of the bay Angujârtorfik (plate

1). It is defined as the moraine system deposited contemporaneously with 115 ± 10 m local marine-limit strandlines within the type area (fig. 3), and is therefore indirectly dated at *c.* 8300 years B.P. This is the estimated age of the 115 ± 10 m marine limit based on the assumption that the uplift of the Angujârtorfik area would be represented by a curve that lies midway between the inner and outer Søndre Strømfjord uplift curves (figs 4, 5). Although this date is approximate, it almost surely is within ± 300 years of the correct radiocarbon age because (a) the two known curves are separated by only 700–800 years, (b) the dates obtained from the intermediate Angujârtorfik area are spread between the inner-fjord and outer-fjord curves (sites 2–5, plate 3 and table 1), and (c) there is no physical reason for the Angujârtorfik uplift curve to fall outside the limiting curves.

It should be noted that the Angujârtorfik moraine system is the least continuous and therefore the most poorly defined of the moraine systems in the present map area. However, the Angujârtorfik moraines are locally some of the most massive moraines in the area and their regional significance is indicated by their continuation for several kilometres north-west of Angujârtorfik (WEIDICK, 1972a).

The *Umîvît moraine system* is named after its type area, which is the area within a 10 km radius north, east and south of the centre of Umîvît, and is defined as the moraine system that was deposited contemporaneously with the 65 ± 5 m relative sea level(s) recorded by local marine-limit strandlines within the type area (fig. 2, figs 5, 8, 6). The Umîvît moraine system is assigned a radiocarbon age of *c.* 7300 years B.P. based on the age of the 65 ± 5 m local marine limit according to the inner Søndre Strømfjord emergence curve (fig. 7). As shown by the relations illustrated in figs 5 & 6, 7300 B.P. is a 'deglacial' date marking the time of marine invasion and the *end* of Umîvît moraine construction. Therefore, construction of the Umîvît moraine system, which has two major parts in several areas, may have begun a few centuries prior to 7300 B.P.

The *Keglen moraine system* is named after its type area, which is the area within a *c.* 10 km radius of the mountain Keglen, and is defined as the moraine system that was deposited contemporaneously with the 40 ± 5 m relative sea level(s) recorded by local marine-limit strandlines within the type area (plate 2). The relative sea level related to the type Keglen moraines is represented by a 40 ± 5 m delta surface formed at the down-stream end of the Keglen valley train, which is now represented by paired terraces extending approximately from the confluence of Sandflugtdalen and Ørkendalen down-valley to the head of Søndre Strømfjord (plate 2). The Keglen moraine system is assigned a radiocarbon age of *c.* 6500 years B.P., based on both (a) the age of the 40 ± 5 m relative sea level indicated by the uplift data shown in fig. 7, and (b) the

Fig. 8. Series of moraines (between the two arrows) in the type area of the Ørkendalen moraine system along the north side of the head of Ørkendalen. View is east-south-east from a helicopter. Pre-Ørkendalen ice-margin drainage channels cut in drift are shown in the foreground. The 'modern' (A.D. 1880–1920) moraines can be seen adjacent to the ice margin. (Photograph NWTB 08.10.1969).

6505 ± 120 B.P. age of shells from below the fore-set/top-set bed contact in the delta at the termination of the Keglen valley train (sample I-5589, table 1). The 6500 year B.P. date for the Keglen system is 'synglacial' because the Keglen delta was constructed during Keglen moraine and valley-train formation, but the more inland moraines included in the Keglen system must have been formed somewhat after 6500 B.P.

The *Ørkendalen moraine system* is named after the Ørkendalen area in which the type moraines are located (plate 3). The system consists of six distinct lateral moraines and several smaller moraine segments on the north side of Ørkendalen within a *c.* 3 km distance of the present ice margin (fig. 8). The Ørkendalen moraine system is defined as the system deposited contemporaneously with the designated type moraines, which are tentatively assigned an age range of 700(?)–300 years B.P.

The younger limit of the Ørkendalen age range is based on a radiocarbon age of 330 ± 75 B.P. (U.W. 180) for organic detritus deposited in the basal strata of lacustrine sand in a moraine-dammed lake. The lake was formed when an ice marginal drainage channel was dammed by construction of the youngest Ørkendalen moraine against the north side of the valley (fig. 8).

The older age limit of 700(?) years B.P. is a lichenometric date based on the 5.0 cm maximum diameter of *Rhizocarpon tinei* thalli growing on boulders of the oldest Ørkendalen moraine, compared to the 2.2 cm maximum diameter of the same species growing on boulders of the 330 ± 75 B.P. youngest Ørkendalen moraine. The 2.2 cm lichens growing on the radiocarbon-dated moraine yield a lichen growth rate or 'lichen factor' (BESCHEL, 1957, p. 180) of approximately 7 ± 1.6 mm/100 years based on the single radiocarbon date and its standard error. This is appreciably greater than the extremely slow growth rate of 2.0–4.0 mm/100 years estimated for *Rhizocarpon tinei* in the area near the Sukkertoppen ice cap (BESCHEL, 1961, p. 1048, fig. 1, 'Kugssuaq A and B'). However, the 7 ± 1.6 mm/100 years calculated rate is consistent with the 2–12 mm/100 years total range of lichen factors determined for West Greenland areas that are similar to the Ørkendalen area in being at least 40 km from the open sea (BESCHEL, 1961, p. 1048, fig. 1). Furthermore, there is extreme local and regional climatic contrast in West Greenland, which repeatedly has been emphasized as the cause for variations of more than an order of magnitude in local lichen growth rates (BESCHEL, 1961, pp. 1055–1057). In conclusion, the approximate lichen factor of 7 ± 1.6 mm seems reasonable and is probably reliable up to 200 m a.s.l. for the local area in which it was determined. (A more detailed discussion of lichen growth rates in the Søndre Strømfjord area is given in TEN BRINK, 1973).

Since the *c.* 300 B.P. construction of the youngest Ørkendalen moraines, a system of unvegetated 'modern' moraines has been deposited adjacent to the present ice margin (fig. 8). Formation of these 'modern' moraines culminated between A.D. 1880 and 1920 in the northern part of the area according to historical records (WEIDICK, 1968, pp. 35–45). In the southern part of the area near the Sukkertoppen ice cap, the culmination of modern moraine building occurred about A.D. 1890 according to lichenometric dating by BESCHEL (1961, p. 1058, fig. 2).

On the scale of the present study, these moraines would probably be included in the youngest part of the Ørkendalen moraine system were it not for their diagnostic lack of vegetation and their contact with the present inland ice (fig. 8). Thus, relative to the older moraine systems, the 'modern' moraines represent only the most recent phase of the Ørkendalen moraine system.

In addition to the five major moraine systems defined above, there are many smaller moraine systems that cannot be consistently delineated throughout the map area. They can be followed from one valley to the next for several kilometres but then either diffuse into thick ground moraine or terminate as lateral moraines high on valley walls. Discontinuous moraine systems of this type are particularly abundant in the south-eastern part of the map area between the Keglen and Ørkendalen moraines. These smaller moraine systems have not been dated directly, but on the basis of their relative positions, most of them were formed between *c.* 6500 and 700 years B.P.

This age bracket is compatible with the results of regional mapping and dating by WEIDICK (1968, figs 2, 33, pp. 15, 85, 136, 140–141). He mapped some of the discontinuous moraines in the south-east part of the present map area and included them in the 'inner zone' of ice-margin deposits. The 'inner zone' was considered to represent several 'stages' of moraine construction, with the two major 'stages' presumably occurring 4800–4000 B.P. and 2500–2000 B.P. However, there is no definitive evidence from the Søndre Strømfjord area as to the age of these deposits, and the above estimates rest on one minimum local date of *c.* 3500 years B.P. and correlations suggested very tentatively by WEIDICK. Definitive C-14 dating of these deposits in the Søndre Strømfjord area, which could be accomplished by dating organic matter trapped in formerly ice-dammed and moraine-dammed lakes, should be an important goal of future research in the area.

Glacial chronology

There are two morphologic characteristics of West Greenland moraine systems that are particularly important to a reconstruction of glacial history. First, the continuation of moraine systems over several tens of kilometres indicates that they represent regional and synchronous positions of the ice margin. Secondly, 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 conditions is far more tenable than the alternative that the moraines represent delicately balanced stillstands caused by long periods of intricately balanced stability (cf. LASCA, 1969, p. 42; FLINT, 1971, p. 205). This reasoning is supported for Greenland in particular by isotopic evidence indicating that frequent temperature fluctuations occurred in Greenland throughout the Holocene (DANSGAARD *et al.*, 1969, 1970, 1971); i.e., long periods of climatic stability were rare or non-existent.

In addition to the improbability of delicately balanced stillstands, 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, pp. 35–45, 107–11; TEN BRINK, 1971b, pp. 73–78). The possibility that most terminal moraines in West Greenland should be considered primarily as push moraines (WEIDICK, 1968, p. 75) is also consistent with the argument that the major moraine systems were formed by readvances of the ice margin. Therefore, the collective evidence from West Greenland as well as from Arctic Canada (e.g., ANDREWS *et al.*, 1970) and several places in the Northern Hemisphere (PORTER & DENTON, 1967), corroborates the general view expressed by FLINT (1971, p. 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."

The evidence summarized above for a readvance origin of many Holocene moraines, together with the improbability of delicately balanced stillstands, convinces the writer that at least minor readvances were probably responsible for construction of the moraine systems delineated in the Søndre Strømfjord area (plate 3). However, such an origin has not yet been directly demonstrated for most of the major moraine systems in the Søndre Strømfjord area. Therefore, the glacial history outlined below is based entirely on the following principles. (1) Each major moraine system represents a regionally synchronous configuration of an inland ice margin that was either (a) in a steady-state equilibrium between rates of advance and ablation or (b) at the culmination of a re-expansion. (2) Zones of thick drift with or without discontinuous ice-margin deposits, but without extensive areas of stagnant-ice topography, represent relatively slow glacier advance and/or retreat during an absence of steady-state glacier conditions. (3) Extensive areas of ice-contact stratified drift characterized by kame and kettle topography represent stagnation and disintegration of the ice margin between periods of major moraine construction.

On the basis of these principles, the following sequence of glacial events occurred in the Søndre Strømfjord region.

(1) The inland ice margin was either semi-stable or readvancing when the Sarfartôq moraine system was formed at or a few centuries before *c.* 8800 B.P.

(2) Rapid ice-margin retreat from the Sarfartôq moraines began *c.* 8800 B.P., and was punctuated by numerous halts and/or readvances resulting in formation of the Angujârtorfik moraines and other discontinuous ice-margin deposits in local valleys. This long period of retreat

continued at an average rate of approximately 35 ± 5 km/1000 years until a little before 7300 B.P.

(3) The inland ice re-expanded or its margin became semi-stable for at least a few centuries during deposition of the Umîvît moraine system, which was formed by *c.* 7300 B.P.

(4) The ice margin then haltingly retreated from the Umîvît moraines until *c.* 6500 B.P. at an average rate of about 20 ± 5 km/1000 years. This retreat was considerably slower than post-Sarfartôq retreat, and was accompanied by formation of a series of kame terraces and small moraine segments typified by deposits near the head of Søndre Strømfjord and around lake Taserssuatsiaq (plate 2).

(5) The rate of inland ice retreat then decreased and the ice margin became semi-stable or readvanced during deposition of the Keglen moraine system, which was formed, at least in part, by 6505 ± 120 B.P. (cf. sample I-5589, table 1).

The duration of Keglen moraine deposition cannot be precisely evaluated, as is also the case for the earlier moraine systems, because the dates from related marine levels are all either 'deglacial' or 'synglacial' dates. However, the Keglen moraine system consists of numerous moraines and kame terraces distributed throughout a zone at least 10 km wide in several valleys (plate 3), and this wide expanse suggests that the Keglen moraines may have been deposited over a longer period than the other moraine systems. If the evidence for a *c.* 6500 B.P. age of the outermost Keglen moraines is accepted on the basis of the direct relation between the Keglen delta and valley train (plate 2), then deposition of the entire sequence of Keglen ice-margin deposits probably continued until *c.* 6000 B.P. This estimate is based on an average rate of oscillatory retreat approximating 20 km/1000 years during formation of the *c.* 10 km zone of ice-margin deposits up-valley from the outermost Keglen moraines in the Sandflugtdalen, Ørkendalen and Umîvît areas (plate 3). It does not seem likely that the average rate of retreat was any faster than this mean value and may have been somewhat slower. In any case, the estimated 20 km/1000 year retreat rate is probably not in error by more than 50 percent, and implies that the Keglen event lasted until about 6000 ± 300 B.P.

(6) After construction of the youngest Keglen moraines, the inland ice began to retreat, and may have continued to shrink in an oscillatory manner until the readvance that formed the oldest Ørkendalen moraines *c.* 700 B.P. Frequent readvances and/or halts, as well as slow retreat during parts of this *c.* 6000–700 B.P. period, are indicated by abundant discontinuous end moraines and thick drift in the south-eastern part of the map area. These deposits are part of the 'inner zone' (Weidick, 1968, fig. 33, pp. 85–88, 105, 136, 141), which represents two main 'stages' that presumably occurred 4800–4000 B.P. and 2500–2000 B.P.

Fig. 9. Aerial view of outlet glacier along the north-east margin of the Sukkertoppen ice cap. Lichen trimlines and ice-cored moraines are a result of glacier retreat since about A.D. 1900. (Photograph NWTB 06.36.1969).

Fig. 10. Minor pushing and over-thrusting of the 'modern' moraines by the inland ice near the head of Sandflugtdalen in 1970. Rucksac circled for scale. (Photograph NWTB 04.21.1970).

(7) The next semi-stable configuration of the inland ice margin that can be clearly defined resulted in formation of the Ørkendalen moraine system. The Ørkendalen event began with a probably minor readvance resulting in local overriding of older moraines *c.* 700(?) lichenometric years ago. The six or more contiguous Ørkendalen moraines subsequently constructed in most areas are interpreted as representing an oscillatory retreat and advance that culminated in construction of the youngest Ørkendalen moraine *c.* 300 B.P.

(8) Finally, the inland ice readvanced to its last semi-stable position, resulting in deposition of the 'modern' unvegetated moraines adjacent to the present ice margin. This modern event interrupted general glacier shrinkage during the past century (WEIDICK, 1968, pp. 35–45).

(9) Since construction of the 'modern' moraines about A.D. 1880–1920, the inland ice has rapidly thinned near its margin, especially behind the terminal moraines of long outlet glaciers. Evidence of such thinning is strikingly shown by disintegrating ice-cored moraines, which often stand several metres above the stagnant margin of the inland ice, and by trimlines of lichen-bare rock up to 100 m above the present ice surface (fig. 9). This period of rapid thinning reached a maximum throughout West Greenland between 1920 and 1940, after which the rate of thinning decreased (WEIDICK, 1968, p. 42).

(10) The most recent event in the history of the inland ice is an incipient readvance indicated by active local thrusting of the ice margin onto stagnant ice or onto the 'modern' moraines (fig. 10). Evidence of a

Table 2. *General summary of Holocene glacial events in the Søndre Strømfjord region*

Event	Age	Relative sea level
Incipient readvance of the ice margin	A.D. 1960s	
Rapid thinning of the inland ice margin and formation of stagnant-ice topography		
Maximum of several minor advances that formed the 'historic' moraines (WEIDICK, 1968) or 'modern' moraines (this report)	A.D. 1880–1920	
Readvance followed by oscillatory advance and retreat forming the Ørkendalen moraine system within *c.* 3 km of present inland ice margin	*c.* 700(?)–300 B.P.	
Probable minor retreat of unknown nature		
Probable readvance(s) (two main phases) forming the 'inner zone' moraines *c.* 5–10 km from the present ice margin (cf. WEIDICK, 1968)	presumably *c.* 4800–4000 & 2500–2000 B.P.	nearly present sea level
Ice-margin retreat (probably continuing until the ice margin was near or behind its present position) and formation of ice-disintegration features in many areas		
Formation of the Keglen moraine system during slow and oscillatory but progressive retreat	*c.* 6500 to 6000(?) B.P.	40 ± 5 m
Oscillatory retreat averaging 20 ± 5 km/1000 years that produced several kame terraces and areas of ice-disintegration features behind Umîvît moraines		
Prolonged halt or readvance (perhaps two major phases) resulting in formation of the often compound Umîvît moraine system	completed *c.* 7300 B.P.	65 ± 5 m
Oscillatory retreat averaging 35 km/1000 years that produced numerous discontinuous ice-margin deposits and some ice-disintegration features		
Halt or readvance resulting in formation of the Angujârtorfik moraine system	limited to *c.* 8300 ± 300 B.P.	115 ± 10 m
Oscillatory retreat averaging 35 km/1000 years that produced discontinuous ice-margin deposits		
Prolonged halt or readvance that formed the Sarfartôq moraine system	completed *c.* 8800 B.P.	125 ± 5 m

Read sequence from bottom to top of table.

Table 3. *Comparison of major glacial deposits in the Søndre Strømfjord area with those delineated elsewhere in West Greenland by* WEIDICK *(1968; 1972a)*

Major moraine systems south-east of Søndre Strømfjord (this report and WEIDICK, 1968)			'Stages' represented by 'zones' of ice-margin deposits regionally in West Greenland (WEIDICK, 1968) and north-west of Søndre Strømfjord (WEIDICK, 1972a)		
Name	Age	Relative sea level (m a.s.l.)	Name	Age	Relative sea level (m a.s.l.)
'modern'	1880–1920 A.D.		Historical stage: several phases (WEIDICK, 1968)	1920 A.D. 1890 1850(?) 1750(?) 1650(?)	
Ørkendalen	700(?)–300 B.P.				
'Inner zone' (WEIDICK, 1968, p. 85–88, 105, 136, 141)	presumably *c.* 4800–4000 & 2500–2000 B.P.	nearly present sea level	Inner zone: several stages; two main stages (WEIDICK, 1968)	presumably 4800 to 4000 & 2500 to 2000 B.P.	nearly present sea level
Keglen	*c.* 6500 B.P.	40 ± 5	Mt. Keglen stage (WEIDICK, 1972a)	*c.* 7200 B.P.	40–50
Umîvît	completed *c.* 7300 B.P.	65 ± 5	Three separate Fjord stages (WEIDICK, 1972a)	8400–8100 B.P.	90–110
Angujârtorfik	8300 ± 300 B.P.	115 ± 10		8400–8100 B.P.	
Sarfartôq	completed *c.* 8800 B.P.	125 ± 5	Avatdleq stage (WEIDICK, 1972a)	8700 B.P.	130
			Taserqat stage (WEIDICK, 1972a)	Younger Dryas? (*c.* 11,000–10,200 B.P.)	130–140

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, pp. 42, 56; GRIBBON, 1970).

The major aspects of Søndre Strømfjord Holocene glacial history (summarized in table 2) show a general trend of progressive but oscillatory deglaciation. Throughout approximately the past 9000 years, deglaciation of a *c.* 100 km wide area occurred with gradually decreasing average rates of ice-margin retreat. By 6000–4000 years B.P., the ice margin had retreated to within about 10 km of its present position. Since that time the ice margin has undergone oscillatory retreat and advance, with a maximum net displacement of approximately 10 km or less, while maintaining nearly its present configuration.

Comparison with other areas

West Greenland

In table 3 the glacial chronology for the area south-east of Søndre Strømfjord is compared to the glacial history of other areas in West Greenland as reported by WEIDICK (1958, 1959, 1963a, b, 1965, 1968, 1969, 1971a, b, 1972a). The most important result shown in table 3 is that essentially the same glacial history has been determined in different areas, and in some cases in overlapping areas, on the basis of completely independent data.

The independent nature of the uplift data on which the dates are based is especially noteworthy for two reasons. First, the validity of the methods used to date moraines is confirmed by the close agreement between dates that are based on separate uplift data for the Avatdleq–Sarfartôq and oldest Fjord–Angujârtorfik moraine systems (table 3). There is little doubt that each pair of these moraines comprises one and the same regional moraine system because of similarity in their positions on opposite sides of Søndre Strømfjord (plate 3) and similarity in their relations to relative sea level (table 3). Therefore, if the dating methods are valid, they should yield the same age for moraines separately mapped, named and dated on opposite sides of Søndre Strømfjord, and indeed this is the case (table 3).

The second reason that the independent nature of the uplift data is important lies in the reason for the two small-scale discrepancies between WEIDICK's and the writer's proposed glacial dates (youngest Fjord–Umîvît and Mt. Keglen–Keglen moraines (table 3). These dates should agree, if the dating methods are valid, because the overlapping map areas of the two workers leave very little doubt that the same regional moraine systems have been independently delineated. (The youngest two of WEIDICK's three Fjord stages are probably equivalent to the Umîvît moraine system, which as noted previously has two major sets of moraines in several areas). Therefore, the dating discrepancies are probably a function of the use and interpretation of different uplift data rather than real differences in moraine ages.

The ages assigned to the Fjord and Mt. Keglen moraines by WEIDICK are derived from extrapolated shorelines (isochrones) based on radiocarbon-dated shells (WEIDICK, 1972a, fig. 5d). However, the marine-limit and moraine ages for the Umîvît and Keglen moraines given in this report are based on the emergence curve for the inner Søndre Strømfjord area (fig. 7), and are 700–800 years younger than the dates proposed by WEIDICK. The emergence curve should provide the best available dates for moraines in the inner Søndre Strømfjord area because it is based on 11 shell dates, all from the immediate area of the moraines (plate 3). Therefore, the dates determined from figure 7 must be close to the 'true' moraine ages, unless most of the dated samples from inner Søndre Strømfjord are several hundred years too young or several metres too high. Such consisting dating error in several samples is statistically improbable, and, because shells provide a *lower* limit for relative sea level, it is even more improbable that the curve indicates erroneously high relative sea levels.

The slightly different ages currently proposed for different parts of the same moraine systems must also be viewed in the light of the two following facts: (1) the confidence limits of the inner Søndre Strømfjord emergence curve (fig. 7) imply a possible error range of *c.* ±500 years for marine-limit ages derived from the curve, and (2) the *c.* 7300 B.P. date for the Umîvît moraine system (youngest Fjord stage) is a 'deglacial' date marking the *end* of Umîvît moraine construction. Therefore, additional data are needed to firmly resolve the existing chronologic inconsistencies.

In conclusion, the most significant point is still that the same number and relative sequence of moraine systems have been delineated by both investigators. Thus, current results indicate essentially the same history of the inland ice for a very large area of West Greenland.

East Greenland

The Holocene glacial history of East Greenland, as it is known from recent work in Skeldal (LASCA, 1969) and current work around Scoresby Sund (FUNDER, 1970, 1971, 1972), is summarized in table 4. Only these sources are cited because they include earlier work and provide the most recent and well-documented results currently available for East Green-

Table 4. *Comparison of major moraine systems in the Søndre Strømfjord area, West Greenland, with glacial deposits and events in East Greenland*

(Dashed lines do not imply established correlation between areas)

Major moraine systems in the Søndre Strømfjord area, West Greenland (this report; WEIDICK, 1972a)			Phases of glacier withdrawal in Skeldal, Mestersvig, East Greenland (LASCA, 1969, p. 40) (Dates corrected by −550 years; LASCA, 1969, p. 48)			Glacial stages in the Scoresby Sund area, East Greenland (FUNDER, 1970, 1971, 1972)		
Name	Age	Relative sea level (m a.s.l.)	Name	Description	Age and relative sea level	Name	Age	Relative sea level (m a.s.l.)
'modern'	1880–1920 A.D.		Phase V	readvance of all glaciers producing the recent moraines	probably younger than *c.* 1500 B.P.	terminal moraines not yet named	probably less than a few hundred years old	
Ørkendalen	700(?)–300 B.P.							
Keglen	*c.* 6500 B.P.	40 ± 5				youngest Rødefjord stage	> 6650 ± 125 B.P. (6700 B.P. estimated)	> 35
Umîvît	*c.* 7300 B.P.	65 ± 5	Phase IV	downwasting and rapid recession of Skeldal ice	began by *c.* 8600 B.P.	intermediate Rødefjord stage	7140 ± 140 B.P. (FUNDER 1971, p. 52)	50
Angujârtorfik	8300 ± 300 B.P.	115 ± 10				oldest Rødefjord stage	*c.* 7500 B.P. (estimated)	60
Sarfartôq	completed *c.* 8800 B.P.	125 ± 5	Phase III	readvance of Skeldal ice to Kong Oscars Fjord & construction of 300 m moraine	> 8590 ± 300 B.P.; 110–120 m	younger Milne Land stage	> 8640 ± 140 B.P. (9500–9000 B.P. estimated)	90–95
Taserqat stage (WEIDICK, 1972a)	Younger Dryas? (11,000–10,200)	130–140	Phase I	ice covered the entire Skeldal & deposited the 500 m moraine	> 8590 ± 300 B.P.	older Milne Land stage	11,000–9500 B.P. (estimated)	110–130

land. Moreover, a summary of dated glacial events in East Greenland as well as in North and West Greenland has just been published (Weidick, 1972a), which should help to resolve uncertainties about radiocarbon dates from North Greenland (Davies, 1961, 1972; Krinsley, 1961; Davies & Krinsley, 1962; Fredskild, 1969).

A marked similarity between the relative sequence of glacial events in West and East Greenland is shown in table 4. In addition to this general similarity, the most consistent, and therefore most significant, aspects of Greenland glacial history are the following.

(1) The oldest dated postglacial marine deposits from all three areas have nearly the same radiocarbon ages, indicating that regional deglaciation of both coasts began contemporaneously by *c.* 8900 B.P. (see below).

(2) Deglaciation was preceded by formation of two major moraine systems in all three areas.

(3) Each of these two moraine systems was formed contemporaneously with a relative sea level which appears to be nearly the same age in all three areas according to independent uplift data. There is some chronologic uncertainty for East Greenland because (a) the highest strandlines in the Scoresby Sund region are dated indirectly by extrapolation of shell dates from lower altitudes (Funder, 1972), and (b) neither the age nor the altitude of the marine limit is precisely known in Skeldal, although it must be at least 8950 ± 300 radiocarbon years old (M-1615) and is probably about 120 m a.s.l. (Lasca, 1969, pp. 18, 20–21, 42–43, plate v). Despite a need for additional data to precisely date some of the East Greenland moraines, the consistent patterns enumerated above are well-documented facts. Their significance is discussed below.

The contemporaneous beginning of regional deglaciation is shown by the remarkably small age range of the following list of the oldest postglacial marine shell dates reported from the fjord areas of both coasts: 8780 ± 250 and 8780 ± 210 B.P. in Mesters Vig just a few kilometres down Kong Oscar Fjord from Skeldal (Washburn & Stuiver, 1962, pp. 68–69, Y-590 and Y-716), 8850 ± 120 B.P. at the head of Nathorst Fjord in Scoresby Land, East Greenland (Funder, 1970, pp. 43–44, K-1462), 8840 ± 170 and 9070 ± 160 B.P. at the coastal town of Holsteinsborg due west of the head of Søndre Strømfjord (Weidick, 1968, p. 191, K-1034; 1972a, p. 27, K-1377), and 8940 ± 70 B.P. from Nûgssuaq peninsula, West Greenland (Weidick, 1968, p. 191, K-994). (See fig. 1 for locations of regions). These six dates, with a range of 9070–8780 B.P., are not statistically different and have a mean of 8880 B.P. Therefore, despite very real uncertainties about absolute dating accuracy, especially for the East Greenland shells from areas with carbonaceous sediments, this coincidence strongly suggests that widespread deglaciation of Greenland fjord areas began contemporaneously by *c.* 8900 B.P. This leaves little doubt that deglaciation of most Greenland fjord areas began coincidentally with the Hypsithermal interval, and occurred in response to widespread climatic warming recorded in Europe (DEEVEY & FLINT, 1957), North America (HEUSSER, 1960) and Greenland (DANSGAARD *et al.*, 1969, 1970, 1971).

Such evidence for climatically controlled and nearly synchronous deglaciation, together with the generally similar pattern of glacial events in Greenland (table 4), strongly suggests that the two moraine systems formed along both coasts before the *c.* 8900 B.P. deglaciation are correlative interregionally. This correlation is further supported for the oldest of the two moraine systems by the facts that, in both East and West Greenland, (1) it is the oldest terrestrial moraine system that can be consistently delineated for any significant distance, and (2) rocks outside these oldest moraines are deeply weathered, indicating a long or intense period of weathering (WEIDICK, 1968, p. 128; LASCA, 1969, pp. 51–53; FUNDER, 1970, p. 41). Evidence for two glacier advances prior to deglaciation has also been reported from Kjoveland in East Greenland (SUGDEN & JOHN, 1965), and on the basis of uplift data, FUNDER (1970, p. 40) has already suggested that these two advances are equivalent to the two Milne Land stages. Therefore, the available evidence suggests that the Greenland ice sheet was responding synchronously between *c.* 11,000 and 9000 B.P.

One of the most interesting implications of this conclusion is that, if the Younger Dryas ages assigned to the Taserqat and oldest Milne Land stages can be firmly established, then the last glacial maximum in Greenland was coincident, not with the Wisconsin or Würm maximum, but with the cold Younger Dryas pulse. The evidence for this postulate is not compelling, but it is consistent with all the available evidence, including the apparent record of the Younger Dryas in the 0^{18} data from Camp Century (DANSGAARD *et al.*, 1969, 1970, 1971).

If the last maximum of the inland ice did occur during the Younger Dryas, then the cause may have been an increase in precipitation. Wastage of the North American and Scandinavian ice sheets, combined with decrease in sea ice cover and changing atmospheric circulation patterns, may well have increased precipitation in Greenland during the close of the last major glaciation (cf. LAMB & WOODROFFE, 1970). Such an increase in precipitation, which reached a maximum in terms of accumulation by the cold Younger Dryas Period, would have been a viable combination for producing a glacial maximum in Greenland while the major North American ice sheets were rapidly wasting.

Table 5. *Comparison between glacial events in the Søndre Strømfjord area of West Greenland and the eastern Canadian Arctic**

Søndre Strømfjord	Eastern Canadian Arctic
1750(?) a. d., 1850(?) a. d., A.D. 1890 and A.D. 1920 = 'historical moraine' formation during several minor readvances (WEIDICK, 1968, pp. 135–136)	*c.* 1740, 1790, 1890, 1905 and 1920 a. d. = Barnes Ice Cap recessional moraine construction (ANDREWS, 1965) *c.* 1875 a. d. = major cirque glacier advance in east Baffin Island (MILLER, 1972)
c. 300(?) b. p. = oldest 'historical moraine' construction (WEIDICK, 1968, pp. 135–136) 330 ± 75 B.P. = youngest Ørkendalen moraine construction	*c.* 300 b. p. = Barnes Ice Cap readvance (ANDREWS, 1965) 330 ± 90 B.P. = Boas Glacier readvance in east Baffin Island (CARRARA & ANDREWS, 1972, p. 409) 330 ± 75 B.P. = snowbank growth in north Baffin Island (IVES, 1962; FALCONER, 1966) *c.* 350 b. p. = cirque glacier advance in east Baffin Island (MILLER, 1972)
c. 700 b. p. = oldest Ørkendalen moraine construction	*c.* 700 b. p. = Barnes Ice Cap readvance (ANDREWS, 1970b, p. 130) *c.* 700 b. p. = cirque glacier advance in east Baffin Island (MILLER, 1972) *c.* 850 b. p. = Akudlermuit Glacier moraine no. 4 construction, Cumberland Peninsula (CARRARA & ANDREWS, 1972, p. 411)
c. 2500–2000 B.P. = late phase of 'inner zone' moraine construction (WEIDICK, 1968, pp. 83, 136, 141–142)	< 2400 – > 1700 b. p. = King Phase readvance of the Barnes Ice Cap (ANDREWS, 1965; 1970b, pp. 129–131) *c.* 2900 b. p. = cirque glacier advance in east Baffin Island (MILLER, 1972)
c. 4800–4000 B.P. = early phase of 'inner zone' moraine construction (WEIDICK, 1968, pp. 83, 136, 141–142)	*c.* 5000 B.P. = Flint Phase readvance of the Barnes Ice Cap (ANDREWS, 1965; 1970b, pp. 129–131)
c. 6500–6000 B.P. = construction of several small moraines and kame terraces of the Keglen moraine system during progressive but slow and oscillatory retreat	*c.* 6300–5700 B.P. = construction of tightly spaced, post-Isortoq moraines during recessional halts and/or readvances in both east and west Baffin Island (ANDREWS, 1970b, pp. 127–131; ANDREWS *et al.*, 1970, pp. 1141–1142)
6505 ± 120 B.P. = readvance or halt producing the oldest part of the Keglen moraine system	*c.* 6700–6500 B.P. = Isortoq Phase readvance or halt represented in east and west Baffin Island, north-west Labrador-Ungava and Frobisher Bay by moraines radiocarbon dated between 6700 ± 140 B.P. and 6560 ± 125 B.P. (ANDREWS, 1970b, pp. 127–131; ANDREWS *et al.*, 1970, pp. 1141–1142)

(continued)

Table 5 (continued)

Søndre Strømfjord	Eastern Canadian Arctic
c. 7300 B.P = end of readvance(s) or halt(s) that formed the Umîvît moraine system	7100 ± 140 B.P. and/or *c.* 7000 b. p. = moraine construction in east Baffin Island (CARRARA & ANDREWS, 1972, pp. 403, 412) *c.* 7200 b. p. = major readvance of glaciers in east Baffin Island (MILLER, 1972)
c. 8300 B.P. = readvance or halt producing the Angujârtorfik moraine system	*c.* 8000 ± 300 B.P. = Cockburn Phase readvance represented by various end moraines in the Baffin Island region (total range of dates cited is *c.* 8500–7500 B.P.) (ANDREWS & FALCONER, 1969, p. 1272; ANDREWS *et al.*, 1970, pp. 1137–1140)
c. 8800 B.P. = end or prolonged halt or readvance which resulted in formation of the Sarfartôq moraine system	> 8275 B.P., possibly > 8530 ± 220 B.P. = Cochrane readvance of the Laurentide Ice Sheet (HUGHES, 1965; ANDREWS & FALCONER, 1969, p. 1272; CRAIG, 1969, pp. 71–72) *c.* 9500–9000 B.P. = moraine construction in east Baffin Island (ANDREWS *et al.*, 1970, p. 1137)

* Some dates given in table 5 are based on lichenometric methods and therefore indicate the time of moraine stabilization subsequent to glacier retreat (cf. MILLER, 1972). These lichenometric dates are followed by lower case letters, either b. p. or a. d., to distinguish them from the dates associated with upper case letters that are based on relationships between moraines and radiocarbon-dated marine shells.

Eastern Canadian Arctic

Holocene glacial events reported from the eastern Canadian Arctic are summarized and compared with the glacial history of the Søndre Strømfjord area in table 5. Although detailed references are given in the table in order to avoid lengthy discussion of the basis and nature of each Canadian glacial event, the following points must be mentioned before drawing conclusions from the comparison.

(1) Some of the dates given in the table are based on lichenometric methods and therefore refer to the time of moraine stabilization subsequent to glacier retreat (cf. MILLER, 1972). These lichenometric dates are followed by small case letters, either b.p. or a.d., which distinguish them from the dates with capital letters that are based on relationships between moraines and radiocarbon-dated marine shells.

(2) Each Canadian glacial event is described in table 5 as an advance, readvance, recessional halt, or simply as a period of moraine construction, in accordance with the interpretation given by the original author. How-

ever, it must be remembered that the basis for such interpretation varies widely.

(3) The minimum age of 8275 B.P. for the end of the Cochrane readvance (HUGHES, 1965) is generally accepted. However, a radiocarbon date of 8530 ± 220 B.P. for post-Cochrane marine shells indicates a slightly greater age for readvance, unless, as believed by CRAIG (1969, pp. 71–72), the date is 'contaminated' by 'old' shells. Despite CRAIG's suggestion, there is no unequivocal evidence for 'contamination' of the 8530 ± 220 B.P. date, and it is only one of several shell dates from the Hudson Bay region that must be explained as 'anomalously old'. This leaves open a very real possibility that the Cochrane moraine is older than *c.* 8500 B.P. Therefore, the Cochrane readvance may have been a separate event, significantly older than the *c.* 8000 B.P. Cockburn Phase, not its correlative as suggested by ANDREWS *et al.* (1970, pp. 1139–1140). This possibility is noted in table 5 because it is particularly significant in view of the closely spaced, but distinctly twofold, periods of moraine construction in West Greenland at *c.* 8800 and 8300 B.P.

(4) Three minor episodes of moraine construction, noted in restricted parts of east Baffin Island, have been omitted from table 5 (*c.* 1825, 1650 and 1375 lichenometric years B.P.: CARRARA & ANDREWS, 1972, p. 411; MILLER, 1972). These events are omitted because their regional significance is poorly known for Canada and because comparable moraines of unknown significance in West Greenland have not yet been precisely dated. However, several small and discontinuous moraines in the Søndre Strømfjord area occur outside the Ørkendalen moraines (TEN BRINK, 1971b, fig. 6) and within the 'inner zone' of moraines (WEIDICK, 1968, fig. 33), which suggests that the moraines are between *c.* 2000 and 700 years old. Moreover, during this period several intervals of wetter and possibly cooler conditions in the Søndre Strømfjord area resulted in raised lake levels, which are now recorded by series of strandlines radiocarbon dated between 2330 ± 120 B.P. and 1080 ± 120 B.P. in one locality (BÖCHER, 1959, p. 60; HANSEN, 1970, pp. 45–60), and at 1860 ± 80 B.P. in another locality (TEN BRINK, 1971b, p. 127). Therefore, wetter and possibly cooler conditions conducive to glacier growth may have existed in West Greenland at several times between *c.* 2000 and 1000 B.P.; in fact, minor glacier advances during this period have been reported from many parts of the Northern Hemisphere (PORTER & DENTON, 1967, pp. 182, 187–191, 200; BENEDICT, 1968, pp. 82–84; MAYR, 1968, pp. 175–176; CURRY, 1969, p. 22; MAHANEY, 1971, p. 143). Nevertheless, the regional significance of these glacial events remains in question, and until the moraines representing WEIDICK's 'inner zone' can be precisely dated, interregional correlations with Greenland are unwarranted. Thus, these events are not included in table 5.

With the preceding qualifications in mind, table 5 clearly shows that there is a large body of evidence for a very similar sequence and contemporaneity of Holocene glacial events in West Greenland and the eastern Canadian Arctic. Moreover, the major glacial events appear to have been essentially synchronous in both regions, despite the variable precision of dating methods. Thus, even though a truly complete glacial chronology probably has not been established in either region, the current evidence strongly suggests that the major Holocene moraine systems in West Greenland and Arctic Canada are correlative.

Discussion and glacial-climatic implications

The preceding interregional comparisons indicate that a similar sequence of Holocene glacial events occurred throughout large areas of West Greenland, East Greenland and the Canadian Arctic (tables 3 to 5). There are most certainly some differences between the glacial records reported from these areas, but in view of the incomplete and, in some cases, imprecise dating of moraines, it is the similarity of events which is most striking. Especially pertinent are the facts that (1) at least the major glacial events were synchronous, or nearly so, and (2) regional deglaciation of fjords in all three regions was contemporaneous with the *c.* 9000 B.P. beginning of the Hypsithermal interval. The cause of such similar glacier behaviour 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. This conclusion is further supported by the several lines of evidence summarized below for contemporaneous Holocene climatic changes and glacier advances in Greenland.

About 94 percent of historic inland ice expansions in West Greenland were shown to have been in phase, and to have occurred between a few years and two decades after slight decreases in mean summer temperature (WEIDICK, 1968, pp. 43, 45). As pointed out by WEIDICK, the major trends of glacier fluctuation therefore cannot have been the result of local factors but must have been climatically caused.

Extremely detailed pollen profiles from West Greenland are consistent with climatic control of glacier advances since about 2500 B.P., indicating that wetter periods began about 700–500 B.P., A.D. 400, and A.D. 1300 (FREDSKILD, 1967b, p. 126). As pointed out by FREDSKILD, these dates correspond to principal recurrence horizons (RY III, RY II, and RY I), recognized in raised bogs of Iceland and north-western Europe and interpreted as marking the beginning of climatic deteriorations. The oldest and youngest dated pollen horizons also correspond to times of moraine construction in West Greenland and Baffin Island (table 5).

Another factor that probably reflects climatic trends in the Arctic is the amount of sea ice off the coasts of Iceland and southern Greenland (Koch, 1945; Schell, 1961; Vibe, 1967). The amount of ice was low from A.D. 800 to 1200, was greater from A.D. 1200 to 1400, decreased slightly from A.D. 1400 to 1600, and increased greatly from A.D. 1600 to 1900. Thus, the two periods of maximum sea ice corresponded with the construction of moraines at *c.* 700 B.P. and at several times between A.D. 1600 and 1920 in both West Greenland and Baffin Island.

It appears, therefore, that all the available evidence directly from the Greenland–Baffin sector of the Arctic indicates very close relations of widespread glacier expansions to either decreases in temperature or increases in moisture. For the temperature and precipitation trends recorded historically in West Greenland, only temperature fluctuations were uniform over the whole area (Weidick, 1968, p. 45). 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.

The strongest direct support for concluding that Holocene glacial events in West Greenland were caused by slight temperature decreases is the historic evidence that slight decreases in mean summer temperature were either synchronous with widespread minor advances of the inland ice or preceded the advances by no more than two decades (Weidick, 1968, p. 45). A temperature control of glacial events is also consistent with the Holocene temperature fluctuations suggested by the O^{18} data from the Camp Century, Greenland, ice core (Ten Brink, 1971b, pp. 94–100). However, interpretation of precise temperature-glacier relations is presently unwarranted due to uncertainty about the time scale and magnitude of temperature fluctuations recorded in the ice core (Dansgaard *et al.*, 1969, 1970, 1971). Nevertheless, slightly decreased ablation-season temperatures, on a regional scale, should theoretically produce an immediate effect upon the ice sheet margin by reducing ablation, even though they would not have an appreciable effect on the overall ice sheet profile unless sustained for thousands of years (W. F. Budd and T. J. Hughes, personal communication). Therefore, slightly lower mean temperatures during the ablation season, maintained regionally over periods of several decades or a few centuries, are postulated to have caused marginal growth of the Greenland ice sheet, and thereby, to have resulted in construction of the major moraine systems in the Søndre Strømfjord area (plate 5).

SUMMARY

The Greenland ice sheet progressively retreated about 125 km during the Holocene in the Søndre Strømfjord region of West Greenland, but the general trend was interrupted frequently by halts or readvances (stabilizations) 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. This combination of deglaciation–marine invasion resulted in postglacial isostatic uplift and the recording of postglacial emergence above sea level by the formation of marine strandlines.

The ages of several emerged-marine strandlines have been determined by radiocarbon dating mollusc shells which have been related ecologically or stratigraphically to a specific strandline altitude. The age and altitude values of 21 such dated shell samples define two postglacial emergence curves for separate parts of the Søndre Strømfjord area. One curve represents the area of maximum regional uplift, *c.* 125 km west of the present ice margin, where 125 ± 5 m of emergence has occurred since *c.* 8800 years B.P. The other curve represents an area *c.* 50 km west of the ice margin where 65 ± 5 m of emergence has occurred since *c.* 7300 years B.P.

These emergence curves provide a basis for dating the moraine systems in the Søndre Strømfjord area because the combination of glacial and isostatic processes that occurred during the Holocene resulted in deposition of time-stratigraphically equivalent glacial and marine deposits. That is, during stabilizations of the inland ice margin, moraine systems were constructed that, in some areas near the fjord, terminated in the sea at the ice front. In other areas, where the ice margin was located farther inland and did not reach the sea, valley trains were constructed from the stabilized ice margin to the relative sea level of that time. Thus, both of these marine-glacial interrelations permit moraine systems to be dated by determining from the emergence curves the age of the strandline representing the relative sea level that existed when the moraines were formed.

According to dates based largely on relations between moraine systems and relative sea levels, the following sequence of events occurred in the Søndre Strømfjord area. (1) A prolonged halt in retreat or a readvance occurred *c.* 8800 B.P. contemporaneously with a 125 ± 5 m relative sea level and formed the Sarfartôq moraine system. (2) Oscillatory retreat averaged *c.* 35 ± 5 km/1000 years. (3) A halt or readvance *c.* 8300 ± 300 B.P. produced the Angujârtorfik moraine system contemporaneously with a 115 ± 10 m relative sea level. (4) Oscillatory retreat averaged

c. 35 ± 5 km/1000 years. (5) A prolonged halt or readvance formed the Umîvît moraine system, which was completed *c.* 7300 B.P. contemporaneously with a 65 ±5 m relative sea level. (6) Oscillatory retreat averaged 20 ± 5 km/1000 years. (7) The Keglen moraine system was formed contemporaneously with a 40 ± 5 m relative sea level from 6500 ± 200 B.P. to perhaps 6000(?) B.P. during oscillatory but slowly progressing retreat. (8) Ice-margin retreat, probably continuing until the ice margin was located near or behind its present position, formed ice-disintegration features in many areas. (9) A probable readvance with two main phases at presumably *c.* 4800–4000 B.P. and 2500–2000 B.P. formed the 'inner zone' moraines *c.* 5–10 km beyond the present ice margin (WEIDICK, 1968). (10) A minor retreat of unknown nature probably occurred. (11) The Ørkendalen moraine system was formed within 3 km of the present ice margin by an initial readvance *c.* 700(?) lichenometric years B.P., followed by oscillatory retreat and advance, and culminated by a readvance *c.* 300 C-14 years B.P. (12) Several minor advances formed the present inland ice moraines, the maximum and last advance probably occurring between A.D. 1880 and 1920. (13) Rapid thinning of the inland ice margin was followed by an incipient readvance in the 1960s.

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 behaviour over a large area suggests that widespread climatic change was the cause of the periodic stabilizations of the inland ice margin during which the moraines were formed. Moreover, historic evidence gathered by WEIDICK shows that minor advances of the inland ice margin followed slight temperature decreases by no more than a few decades. These factors, taken together, imply that construction of the major Holocene moraine systems in West Greenland may have been 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 effect the long-term equilibrium of the ice sheet.

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Færdig fra trykkeriet den 21. juli 1975.

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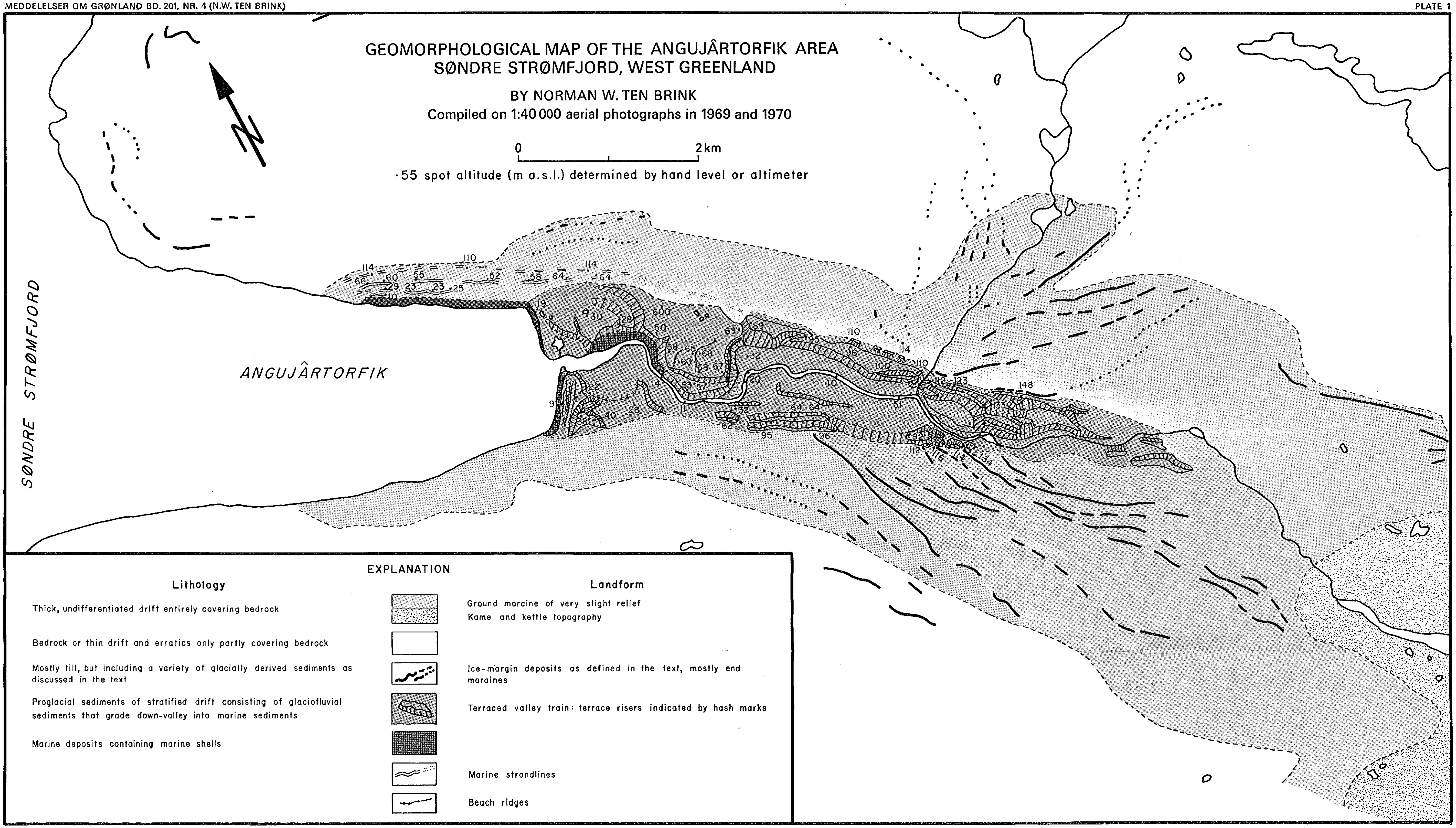
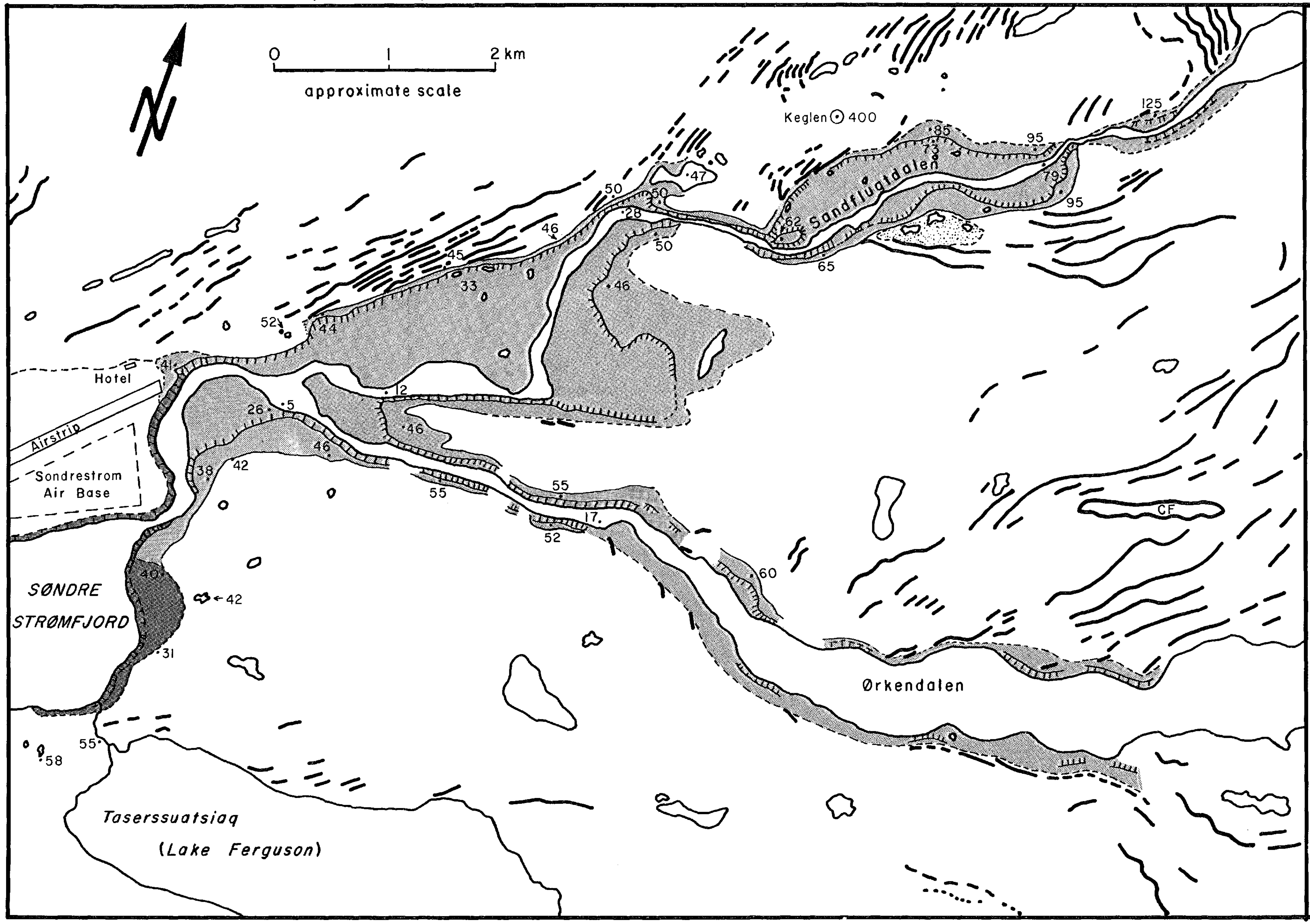


GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

MEDDELELSER OM GRØNLAND BD. 201, NR. 4 (N.W. TEN BRINK)



GEOMORPHOLOGICAL MAP OF THE REGION NEAR THE HEAD OF SØNDRE STRØMFJORD, WEST GREENLAND

BY NORMAN W. TEN BRINK

Compiled on 1:40 000 aerial photographs in 1969 and 1970

EXPLANATION

Lithology	Landform
Mostly till, but including a variety of sediments as discussed in the text	Ice-margin deposits as defined in text, mostly end moraines
Ice-contact stratified drift that does not record a well-defined margin of the inland ice	Kame and kettle topography Crevasse filling (CF)
Proglacial sediments of stratified drift consisting of glaciofluvial sediments that grade down-valley into marine sediments	Terraced valley train: terrace risers indicated by hash marks
Marine sediments containing marine shells	

•46 spot altitude (m a. s. l.) determined by hand level or altimeter

GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

MEDDELELSER OM GRØNLAND BD. 201, NR. 4 (N.W. TEN BRINK)

PLATE 3