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The status of the Neoglacial in western Greenland

by

Michael Kelly

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Abstract

The evidence relating to the Neoglacial history of the western sector of the Greenland Ice Sheet is critically examined. It is concluded that glacierisation began to increase about 3000–3500 B.P. from a significantly smaller extent than at present, but that in general this does not appear to have reached its maximum until the recent post-1000 B. P. advances. What little reliable evidence there is of greater early Neoglacial events can be considered to represent local, anomalous developments. It is emphasised that this model should be regarded as a working hypothesis which will be modified by future work.

CONTENTS

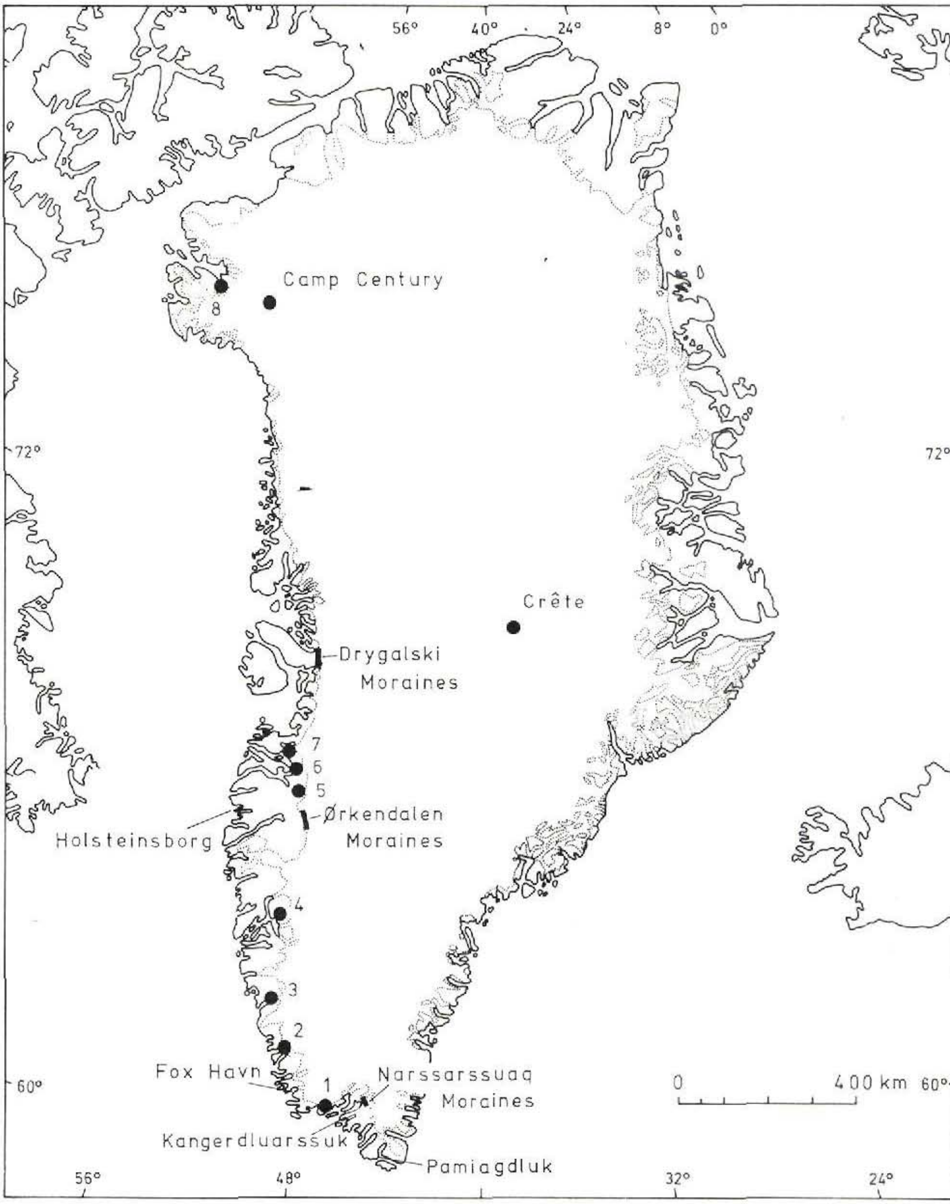

Fig. 1. Localities mentioned in the text and Table 1 – Ice Sheet Historical moraines associated with Holocene marine features (numbers).

INTRODUCTION

The existence of a deterioration in climate after the mid-Holocene climatic optimum has been recognised widely in the northern hemisphere; and because of the consequent increase in glacierisation this period has become known as the Neoglacial. This paper reviews the current state of knowledge about the Neoglacial behaviour of a major part of the largest ice mass then, and now, existing in the northern hemisphere – the Greenland Ice Sheet and its peripheral local glaciers; and as such it is a development of an earlier review by Weidick (1972a). The usage of the term Neoglacial follows the definition given above, and no constraint on duration is set except by the relationship to the mid-Holocene climatic optimum.

The area covered includes the western half of Greenland, from 59°–78°N. For convenience the recent period for which there is unequivocal evidence of glacier advance is designated the late Neoglacial, with the division from the early Neoglacial, with its advances of more uncertain status, placed around the turn of the last millenium (~1000 B.P.). This date also falls within, or at the termination of a major mild interval in the Neoglacial according to the palynological and cultural evidence cited by Fredskild (1973) and the ^{18}O data of Dansgaard *et al.*, (1975).

Most of the ^{14}C dates quoted are not corrected for fractionation or sea water age. Where a δ ^{13}C value is given the date has been normalised and also corrected for an apparent sea water age of 400 years. Although this figure appears to be appropriate for most of West Greenland (Krog & Tauber, 1974) its validity has not been established yet for the northern part. These corrected dates are comparable to the uncorrected ones since the fractionation error approximately cancels out this sea water age error.

LATE NEOGLACIAL

The latest phase of the Neoglacial is represented throughout Greenland by the Historical Moraine (Weidick, 1972a), which is a ubiquitous zone of fresh glacial deposits at the margins of the Ice Sheet and local glaciers, produced by recent glacial advances. The chronology of these advances was reviewed by Weidick (1968, 1972a), mostly on the basis of his own investigations using historical literary and photographic evidence, and those of Beschel (1958, 1961) using lichenometrical techniques. Weidick concluded that the period of glacial advances lasted from about 350 or 450 B.P. to the present, but that within this interval the date of maximum advance varied widely geographically. Whilst there is a tendency for increasingly early dates for the maximum towards the south – early 20th century in North Greenland, mid to late 19th century over most of the western sector and mid 18th century in the south; there is superimposed on this trend a local variation which can result in a more than 200 year difference in the timing of the maximum at adjacent sectors of the ice margin.

Very little information has been published subsequently about this part of the late Neoglacial. However at a section of the Ice Sheet margin (fig. 1) an earlier late Neoglacial advance has been distinguished from the Historical one by Ten Brink (1975). There the Ørkendalen Moraine System is dated to >350–700 B. P.from a ^{14}C date on organic lake sediments which provides a minimum age for the youngest moraine, and also calibrates a lichen growth rate used to date the oldest. Whilst some uncertainty may be associated with these dates there is possible support for the moraine being the product of a distinct glacial advance in the oxygen isotope date from the Greenland Ice Sheet cores; with Dansgaard *et al.* (1975) recognising a cold interval from ~575–950 B. P. in the Crête core.

EARLY NEOGLACIAL: GREENLAND ICE SHEET

Although a worsening of climate was probably experienced by Greenland at least 3000 years ago, as discussed below, the extent to which the ice increased in the early Neoglacial is extremely uncertain; in particular whether or not there were glacial advances greater than the later Historical advance.

Age of moraines near ice margin

Although well developed moraines, which were initially grouped together as the Inner Zone of deposits (Weidick, 1968), lie adjacent to the Historical moraine along many sectors of the margin these have been shown to include moraines of very different ages: from early Holocene to Neoglacial (Weidick, 1972a). Further assessment of these suggests that only Inner Zone moraines in two areas definitely show the critical contemporaneity with zero sea level, i.e. at its present level, which has been considered to be a criterion for a Neoglacial age (Weidick, 1972c). Although, as argued later, this is itself not certain evidence of age because of the probable existence of a Neoglacial transgression. The two sets of moraines are (fig. 1):

(1) The Drygalski Moraines of a 120 km sector of central West Greenland, which at two localities (Torssukátak and Store Gletscher) are seen to be younger than a zero sea level (Weidick, 1968).

(2) The Narssarssuaq Moraines of two adjacent outlet glaciers (Kiagtût sermia and Qôrqup sermia) in South Greenland, which again continue to present sea level (Weidick, 1963). Here the additional evidence of Norse buildings on the moraine (Weidick, 1963) and preliminary palynological data from deposits post dating the moraine (Funder, personal communication) puts them between 1000 and 2500 B. P.

Although no other locality has been shown critically to have moraines related to zero sea level there is one where a relationship has been claimed with a higher, possibly earliest Neoglacial sea level. This is near Usugdlûp sermia (fig. 1, loc. 6) where Jahn in 1938 (quoted in Weidick, 1972a) described a moraine related to a 12 m level, which from present knowledge of isostatic recovery (Kelly, 1975a) would date from ~4500 B. P. Since there is also contrary evidence from this area, dealt with later, this claim needs re-examining.

In the central sector of the western ice margin in general there are series of minor moraines, not directly dated, but lying in a 15–30 km zone between the late Neoglacial moraine and the youngest dated mid-Holocene moraine; for which there could be the chance of an early Neoglacial age. For example, at Søndre Strømfjord this possibility has been raised for the moraine sequence inside the Mt. Keglen Moraine (6500–7200 B. P.) (Weidick & Ten Brink, 1974). However in the adjacent Nordre Strømfjord area to the north the possible age of the moraines inside the similarly dated Ugssuit Moraine (6900–7000 B. P.) (Kelly, 1975a) is limited by the evidence that the Historical Moraine at two outlet glaciers there (Usugdlûp sermia and Inugpait qûat) (fig. 1, loc. 5 and 6) rests on marine sediments or shorelines from about 6000–6500 B. P. This accords with estimates of the date of the retreat of the margin to its present position calculated by extrapolation of earlier retreat rates.

In contrast to the central one the southern sector of the Ice Sheet margin, south of ~64°N, is characterised by both a poorer development of moraines and an increase in the age of the nearest dated moraine to the Historical margin, which appear to be of early Holocene, or earlier age, e.g.:

(1) Bjørnesund, ~8300 B. P. (indirectly dated only) (Weidick, 1975b) (fig. 1, loc. 3).

(2) Nigerdlikasik, Kvanefjord, >8500 B. P. (palynological date) or >9600 B. P. (^{14}C date) (Kelly & Funder, 1974) (fig. 1, loc. 2).

(3) Fox Havn, Arsuk Fjord, >8500 B. P. (indirectly dated only) (Kelly, 1977) (fig. 1).

Less is known about the situation in the area north of 73°N, although there is some suggestion that it may resemble that of the southern sector. However, for much of the sector the moraines have not been closely dated yet.

Dated marine features at ice margin

As the situation of the moraines mentioned above implies, the magnitude of any early Neoglacial advance is severely curtailed by the existence at many localities of early Holocene dated sediments lying close to the Historical Moraine (Table 1, fig. 1). Furthermore the possibility of such advances exceeding the Historical one of course disappears where the Historical Moraine actually cuts dated sediments or shorelines (Table 1).

In the case of the latter relationship involving an old marine limit, then the Historical advance is clearly the biggest advance since initial Holocene deglaciation. With sediments, which to varying degrees will be younger than the marine limit, the relationship gives only a minimum estimate of the duration of the period with less extensive ice cover.

At all but one of the sites listed the date has to be estimated from the elevation of the feature by extrapolation from an emergence curve. Although this is an imprecise method the dates are all clearly older than mid-Holocene.

Reworked biogenic material at ice margin

At a large number of localities along the whole of the western Ice Sheet margin reworked biogenic materials which are apparently mostly of Holocene age occur in the Historical

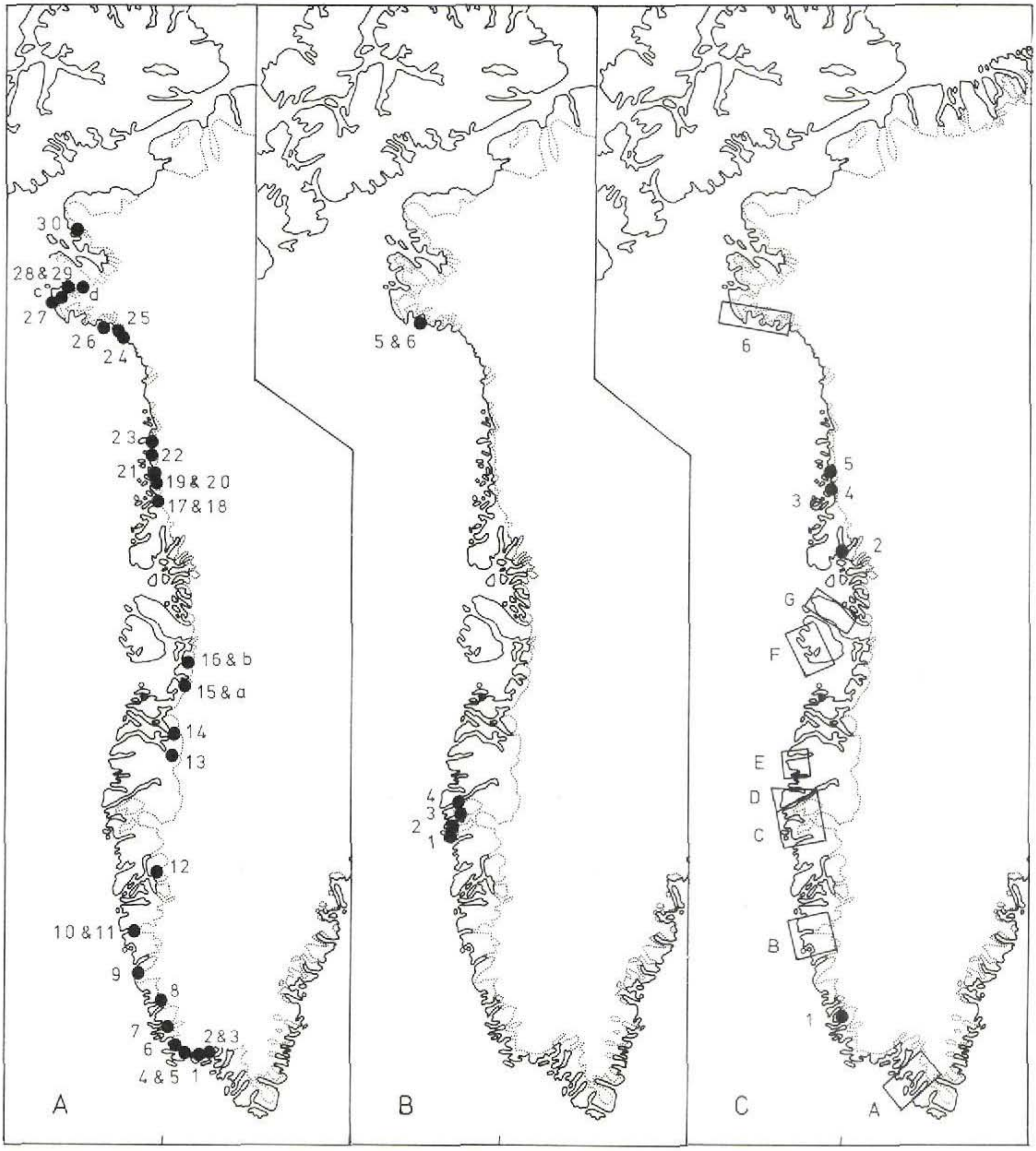

Fig. 2. A. Localities with reworked biogenic material at the Ice Sheet margin (Table 2). B. Localities with reworked or overlain marine material at local glacier margins (Table 3). C. Localities of local glaciers with (letters) or without (numbers) pre-Historical moraines (Table 4).

Table 1. Early/mid-Holocene marine features cut by or close to Historical Moraine

Locality	Evidence	Height m a.s.l.	Date B.P.	$\delta^{13}C$	Ref.
1 Qaleragdlit sermia	seds.	3	7570±150★	-0.27	1
Qaleragdlit sermia	m.l.	63	>9000		1
2 Nigerdlikasik	m.l.	52	>9000		2
3 Bjørnesund	m.l.†	60-65	~8300		3
4 Kangilínguata sermia	seds.	30	~6000		4
5 Inugpait qûat	seds.	30	~6000		5,6
6 Usugdlûp sermia	m.l.	42	~6500		5,6
7 Nordenskiölds Gletscher	seds.	8-12	~5000		5
8 Marie Gletscher	seds.†	10	5000-6000		4,7

Locality nos. refer to fig. 1. ★ ^{14}C date (BIRM-455) other dates from emergence curves, † close to Historical Moraine, seds. sediment, m.l. marine limit.
Refs: 1 Kelly (1975b); 2 Kelly (unpublished); 3 Weidick (1975b); 4 Weidick (1975c); 5 Weidick (1972a); 6 Kelly (1975a); 7 Weidick (1978c).

Moraine or the ice margin itself (Table 2; fig. 2A). Their presence clearly indicates that the Ice Sheet has been smaller at some point in the Holocene, although the interpretation of the actual date of this is not straightforward. Some inferences can be made about early Neoglacial history from these records, but again only with the acceptance of certain assumptions.

The majority of recorded material is of marine origin – whole or fragmented shells and shell bearing concretions, derived by the reworking of marine sediments by the Ice Sheet. Many of these have been ^{14}C dated but the interpretation of the results is complicated because the shells can be admixtures of different ages, and because there are several possible models for their incorporation in the moraine:

(1) erosion of Holocene marine sediments which represent a single episode of marine deposition,

(2) erosion of sediments from two or more marine intervals interrupted by one or more Neoglacial advances,

(3) erosion of early Neoglacial glacial sediments which themselves contain reworked marine sediments,

(4) erosion and mixing of Holocene and pre-Holocene sediments.

In all cases a ^{14}C date for the derived shells represents the maximum date for the end of the marine episode (s), but only in the first, whatever the degree of mixing, does the date unequivocally record a time when marine conditions existed. In the examples where whole shells of one species of similar growth form were dated the date may be the actual age of the shells. It is assumed that mixing of Holocene and pre-Holocene faunas has not occurred unless this possiblility is suggested by the presence of known pre-Holocene faunas close to the ice margin (Harald Moltke Bræ and Døcker Smith Gletscher (Kelly, 1975a)), or by the unusual age of the date (Frederikshåbs Isblink) (Table 2, loc. 9).

In the absence of direct evidence of early Neoglacial moraines the first model is the preferred one at most sites. According to this the older dates have the significance of showing that the Historical advance brought the ice margin back into areas last glaciated in the early Holocene, before the date in question. The younger dates, which predominate north of 72°N, with the same set of assumptions indicate that marine conditions have existed behind the present margin from original deglaciation to the date recorded. Thus any Neoglacial advance is later; though in fact most of the dates do not provide much constraint on the ages of subsequent advances.

The single date for concretions is yet more difficult to interpret since it represents the interplay of diagenetic factors with those already mentioned (Kelly, 1975b).

Whilst most of these derived faunas have been collected near to present sea level, several are known to occur at considerable heights and distances away from the shore, e.g. 10 km behind the Historical margin at Qaleragdlit (Weidick, 1963; Kelly, 1975b) and 7 km at Cornell Gletscher (Tarr, 1897). This provides some indication of the magnitude of the Neoglacial advance.

The reworked terrestrial organic material recorded from a few sites (Table 2; fig. 2A), can suffer from the same interpretative uncertainties as the marine, requiring similar assumptions for a simple interpretation. The most important occurrence is that at Nunatarssuaq (Table 2, loc. d) where the date puts the ice margin behind the present in the mid-Holocene and may imply the absence of an advance between then and the Historical.

EARLY NEOGLACIAL: LOCAL GLACIERS

Cirque and valley glaciers and plateau ice caps occur sporadically around the whole periphery of Greenland. Various reports, compiled by Weidick (1972a) allude to the existence of pre-Historical moraines at some of these, and many are claimed to be of early Neoglacial age.

However it is equally clear that pre-Historical moraines are entirely absent at other local glaciers, with the Historical Moraine therefore representing the glaciers maximum extent since the deglaciation of the area by the main ice sheet at some early, pre-Neoglacial date. One group of glaciers in this category are the outlet lobes of ice caps at Sukkertoppen and Melville Bugt whose Historical Moraines rest on, or have overridden Holocene marine sediments and hence contain reworked shells (Table 3; fig. 2B). Whilst the interpretation of dated, derived material requires the assumptions made earlier for the Ice Sheet, the evidence when superimposition occurs is conclusive, e.g. at Evighedsfjord, Sukkertoppen Ice Cap where undisturbed marine sediments dated to 6510 B. P. lie beneath the Historical Moraine at 20 m above sea level (Sugden, 1972). The height of the regional marine limit there is not known and this date will be a minimum for the time since when the area has been deglaciated.

The second group are those glaciers whose Historical Moraines are fronted by lateral moraines belonging to the recessional stages of the main ice sheet in the early Holocene or earlier (Table 4a; fig 2C).

On the island of Disko the Neoglacial advances of a large number of local glaciers are represented by rock glaciers, some of which extend to present sea level (Donner, 1978). Most of these belong to a main period of advance which is as yet undated, but may be late Holocene.

However whilst many more local glaciers do have pre-Historical moraines (Table 4b; fig. 2C), the essential decision to be made is whether these were formed before or after the climatic optimum.

Table 2. Reworked biogenic material at the Ice Sheet margin

	Locality	Evidence	^{14}C date B.P.	$\delta^{13}C$	Lab.No.	Ref.
	Marine					
1	Qaleragdlit sermia	concretions	4540±130	-15.64	BIRM-454	1(2)
2	Manitsup tunua	concretions				(2)
3	Kangerdluarssuk	concretions				(2)
4	Sermilik Bræ	shells + sed.	7045±120		I-9958	3(4)
5	Nordre Qipisarqo Bræ	shells	7880±125		I-9956	3
6	Søndre Qornoq Bræ	shells + conc.				(3,4)
7	Sioralik Bræ	shells	7005±120		I-9957	3
8	Nigerdlikasik	concretions★				(3)
9	Frederikshåbs Isblink	shells	21710±400		I-7622	5
		concretions				(4)
10	Sermilik	concretions				(5)
11	Alangordlia	concretions				(4)
12	Kangilînguata sermia	concretions				(4)
13	Inugpait qûat	concretions				(4)
14	Usugdlûp sermia	concretions				(4)
15	Alangordliup sermia	shells				(4)
16	Påkitsup ilordlia	shells + conc.				(4,6)
17	Upernavik Isstrøm	shells	600±80	+1.63	HAR-2944	3
18	Akudlikavsak	shells				(3)
19	Alángorssûp sermia	shells				(3)
20	Nunatakavsaup sermia	shells	3400±80	+1.65	HAR-2943	3
21	Qåneq	shells + sed.	2880±80	+2.24	HAR-2952	3
22	Ussing Bræ	shells	2980±80	+2.26	HAR-2942	3
23	Cornell Gletscher	shells + sed.	1770±70†	+1.11	HAR-2945	3(4)
24	Rink Gletscher	shells	1790±90	-0.3	HAR-3572	3
25	Døcker Smith Gletscher	shells	7910±90	+0.91	HAR-2950	3
26	Mohn Gletscher	shells	2510±80	+1.65	HAR-2947	3
27	Pitugfik Gletscher	shells				(7)
28	Harald Moltke Bræ	shells	7050±80	+1.68	HAR-2955	3(7)
29	Chamberlain Gletscher	shells	2650±105		I-9800	8
		shells	280±80		I-9801	8
30	Morris Jesup Gletscher	shells	650±80		I-9802	8
	Terrestrial					
a	Alangordliup sermia	wood				(4)
b	Påkitsup ilordlia	wood	285±100		I-5418	6(4)
c	Camp Tuto	plant debris				(4)
d	Nunatarssuaq	peat	4760±200		W408	9
			<200		W532	9

Locality nos. and letters refer to fig. 2A. ★ uncertain marine, † whole shells.
Refs: (undated occurrences in brackets) 1 Kelly (1975b); 2 Weidick (1963); 3 Kelly (unpublished); 4 Weidick (1972a, contains references to older citations); 5 Weidick (1975b); 6 Weidick (1972b); 7 Krinsley *in* Davies *et al.* (1963); 8 Dawes *in* Weidick (1978a); 9 Goldthwait (1960).

Table 3. Overlain or reworked marine material at local glacier margins

	Locality	Evidence	^{14}C date B.P.	Lab. No.	Ref.
1	Tasiussaq	shells + sed.	8510±100	UW-237	2(1)
2	Sermilinguaq	shells			(1)
3	Qingua avangnardleq	shells + sed.★	6510±140	K-1577	3(1)
4	Lyngbræ Gletscher	shells + sed.	8430±140	K-1578	3
5	Sermipaluk	shells + sed.	1130±70	HAR-2946	4
6	Kumait North	shells + sed.			(4)

Locality nos. refer to fig. 2B. ★ *in situ.*
Refs: 1 Weidick (1972a); 2 Weidick (1973); 3 Sugden (1972); 4 Kelly (unpublished).

Table 4. Absence or presence of pre-Historical moraines at local glaciers

Area/Locality	No. of glaciers	Sea level relations m	Date B.P.	Ref.
a) *absent*				
1 Neria	4			1
2 Karrat Isfjord	1			1
3 Upernavik - Sandersons Hope	2			1
4 Upernavik - Qaersorssuaq	4			1
5 Upernavik - Kangerdlugssuak	1			1
6 Melville Bugt	4			1
b) *present*				
A Nanortalik	21			2
Nanortalik - Kûkasik	1	>30 <52.3	8500-10000†	2
Nanortalik - Niaqornakasik D	1	>24 = 38.8	8000-9500†	2
B Bjørnesund				7
C Sukkertoppen - Søndre Isortoq	2			3
Sukkertoppen - Tasiussaq	1	>65	>7500-8000†	3
Sukkertoppen - Tasiussaq	1	<30	<5500-7000†	4
Sukkertoppen - Ikamiut	1	>30	>5500-7000†	3
Sukkertoppen - Ikâtûssaq	1	>80-90	>8500†	3
Sukkertoppen - Taseq qutdleq	1			3
D Søndre Strømfjord North	~26			5
Søndre Strømfjord North - Tunugdliarfik	3			4
E Nordre Isortoq	6			1
Nordre Isortoq - Natârnivingûp	1		>6630±110★	1
F Disko - South	2			3
Disko - Nordfjord	2			6
G Nûgssuaq	4			3

Locality nos. and letters refer to fig. 2C. ★ ^{14}C date (I-10433), † dates based on emergence data of Funder (1979); Ten Brink (1975); Kelly (1979).
Refs: 1 Kelly (unpublished); 2 Weidick (1963); 3 Weidick (1968); 4 Beschel (1961); 5 Weidick (1978b); 6 Donner (1978); 7 Weidick (1975b).

The classic examples are the glaciers lying to the north and south of the mouth of Søndre Strømfjord in central West Greenland, which have been the subject of a lichenometrical study by Beschel. Unfortunately a detailed report of the work was never published before his untimely death and only brief reviews are available (Beschel, 1958, 1961; Beschel & Weidick, 1973). In the first two it is quite clearly stated that lichenometry could only be applied to the Historical Moraine since the lichen diameters on older moraines were indistinguishable from those in the exterior surroundings because the species had reached its maximum size, i.e. the moraines were undateable.

> "Lichenometry can give only a minimum age of the moraines which lie closest to the [Historical] forelands. ... The age of both [pre-Historical] phases exceeds the maximum age of lichens in the coastal regions" (Beschel, 1961, p. 1060).
>
> "[Pre-Historical] moraines bear a lichen cover in balanced conditions and do not differ in this respect from the region outside the moraines. The lichen thalli have reached maximum diameters ..." (Beschel, 1958).

Unfortunately, although mentioning the possibility of an early Holocene age, on a diagram he tentatively assigned precise Neoglacial ages to the two sets of moraines – 2500 and 4000 B. P., apparently on the basis only of analogy with an Alpine chronology, as well as referring to them elsewhere in the text as Neoglacial (Hypothermal) moraines. These dates have been repeated in subsequent literature, and their origin has become lost sight of. It is worth emphasising that the local moraine systems around Søndre Strømfjord have not yet been successfully dated lichenometrically.

More significant evidence as to their age is given by the geological relations between the moraines and raised shorelines, and other marine evidence (Table 4b) (Weidick, 1968; Beschel, 1961). Although the ages of the shorelines are not known directly, estimates can be made from emergence curves reconstructed for nearby areas – outer Søndre Strømfjord (Ten Brink, 1975) and Holsteinsborg (Kelly, 1979). However because of the limitations of these curves there remains considerable uncertainty about the dates. Despite this the data show, reasonably reliably, that moraines at three of the sites are early Holocene. Where, as in this area, the moraines are cut by a sea level below the regional marine limit (~100 m, Weidick, 1976, fig. 375) the implication is that the moraines were formed just prior to the shoreline. Much more critical is the moraine at Tasiussaq referred to by Beschel (1961), which cuts and therefore post-dates a shoreline at 30 m, dated by the two emergence curves to 5500 or 7000 B.P. There is therefore some possibility that the moraine could be earliest Neoglacial and a re-examination of the site would be advantageous.

Well developed pre-Historical moraines at local glaciers occur also in the Nordre Isortoq area, 100 km to the north of Søndre Strømfjord (Kelly, 1975a). Again the moraines prove undateable by lichenometry, having lichen diameters (*Rhizocarpon geographicum* agg.) which are identical to those in areas beyond the moraines. Palaeo – sea level relations could not be established for any of the seven moraine systems but from one a ^{14}C date of 6630±110 B. P. (I-10433) has been obtained from a basal peat in a hollow dammed by the moraine; indicating a probable early Holocene age for the advance.

The only other local glacier moraines for which there is some evidence of their age are two of the numerous pre-Historical moraine systems in southernmost Greenland (Weidick, 1963). Again, although there has not been a detailed study of uplift in the area, data from adjacent areas suggest that the sea levels associated with the moraines are early Holocene, at the latest. In particular, the following minimum dates on marine regression horizons in lake sediments are critical for the dating of the low sea levels (fig. 1):

Kangerdluarssuk, 8 m above sea level, 8260±125 B. P. (Funder, 1979).
Pamiagdluk, 5.5 m above sea level, 9210±140 B. P. (Fredskild, 1973).

Thus, with the possible exception of one site at Sukkertoppen (Tasiussaq), no early Neoglacial moraines have yet been identified at local glaciers in Greenland. Although lichenometry is the easiest dating tool to be used in the further search for moraines from this period it may well prove to be largely beyond the range of the method. Although lichen growth rates are difficult to establish in Greenland because of the lack of suitable control data, there is a certain number of values available for *Rhizocarpon geographicum* agg., although all but one are based on a single data point (Table 5; fig. 3A). This list does not include the much quoted values shown in Beschel (1961, fig. 1) giving rates between 0.02–0.43 mm y^{-1}, since they appear to have been based on the subjective correlation of Historical Moraines at various sites.

Most variation in growth rates lies within a factor of four, but with a more limited range of 0.15–0.18 mm y^{-1} including sites with very contrasting climates. With the largest *R. geo-*

Table 5. Determinations of Rhizocarpon geographicum *agg. growth rates*

	Locality	Basis	Date B.P.	Growth rate mm y^{-1}	Ref.
1	Frederikshåb	graves	1884-1936	0.22(0.15★)	1
2	Sukkertoppen	grave	?	?	2
3	Ørkendalen	^{14}C dated moraine	1620±35	0.07★	3
4	Strømfjordshavn	photograph	1958-1970	0.17-0.18	3
5	Blæsedalen	cairn	1896	0.08★	4
6	Lyngmarksfjeld	moraine	>1898	0.15★	4
7	Qutdligssat	moraine	>1898	0.15★	4
8	Påkitsoq ilordlia	moraine	1880-1890	0.09★	4
9	Påkitsoq, Niaqornaq	grave	?	?	4
10	Sarqaq	grave	?	0.13★	4
11	Qeqertaq, Qôrorssuaq	?		0.16★	4
12	Torssukatak	?		0.09★	4
13	Qarajaqs Isfjord	?		0.06★	4
14	Sermikavsak	moraine	1934	0.16★	5
15	Kingitorssuaq	cairn	1250-1300	0.11★	6
16	North Star Bugt	grave	1849	0.22★	6

Locality nos. refer to fig. 3A. ★ rate includes initial colonisation lag.
Refs: 1 Pitman (1973); 2 Beschel (1961); 3 Ten Brink (1973); 4 Beschel & Weidick (1973); 5 Gribbon (1970); 6 Kelly (unpublished).

graphicum diameter of 229 mm on the Nordre Isortoq moraines, the maximum lichen age there is given by the above figures as (500–) 1500 (–4000) years. A maximum value of 262 mm for Upernavik district gives similar results, and this apparently accords with Beschel's experience at Søndre Strømfjord since he mentions maximum ages of 1500 to 4500 years.

PALAEONTOLOGICAL EVIDENCE

Palaeontological data is especially useful in its potential to provide an indication of conditions in the early part of the Neoglacial whose glacial geological expression will have been destroyed by the continuing advances, e.g. the date of the onset of climatic deterioration,

Table 6. Early Neoglacial faunal and floral changes due to climatic deterioration

	Locality	Date B.P.	Evidence	Interpretation	Ref.
2	Igaliko Fjord	3800★	benthic forams	cooler	1
7	Peary Land	3300★	pollen productivity	cooler	2
4	Frederikshåb	3200	*Juniperus* decline	cooler	3
6	Sermermiut	2350	bog growth	moister	2
1	Kap Farvel	2200	*Juniperus* decline	moister	2
7	Peary Land	2100★	pollen productivity	cooler	2
3	Qagssiarssuk	1900	*Juniperus* decline	deterioration	2
5	Godthåbsfjord	1900★	*Alnus* decline	deterioration	2
6	Sermermiut	1550	bog growth	moister	2

Locality nos. refer to fig. 3B. ★ dates subject to ^{14}C error or extrapolation uncertainty.
Refs: 1 Herman *et al.* (1972); 2 Fredskild (1973); 3 Kelly & Funder (1974).

and the relative status of early cold phases. Its problem of course lies in making the interpretative links between the responses of biota and glaciers to the climatic variables.

Various palynological studies in western Greenland identify inclement climatic phases in the upper Holocene following the interval of optimum climate (Fredskild, 1973; Kelly & Funder, 1974). The definition of the latter from the floristic evidence is itself difficult because of the strong control exercised on the presence of species by immigration delay effects, and also because of uncertainty about the influence of exotic pollen on the interpretation of the presence of a key species (*Alnus crispa*). However it is certain that conditions had improved to a level equivalent to the present late Neoglacial by 8000 B. P. The summary in Table 6 shows the range of dates suggested for subsequent decreases in temperature and /or increases in humidity for western Greenland and Peary Land, North Greenland. The dates are mostly fairly closely controlled by several ^{14}C dates in a sediment sequence.

The most important conclusion is that there is evidence of an early Neoglacial climatic

Table 7. Occurrence of extinct thermophilous molluscs in western Greenland

Species/Locality	Height m a.s.l.	Age B.P.	^{14}C Lab.No.	Ref.
Anomia squammula L.				
7 Igíniârfik				1
4 Ikerasarssuk	7	>3500-5000†		2
1 Nipisat	4.5	>3000-4500†		2
Cyprina islandica L.				
2 Itivdlinguaq }	35	>6000-7000†		1
3 Itivdleq }				2
5 Eqalunguit	4	6500±110[a]	I-10267	3
Panopaea norvegica (Spgl.)				
3 Itivdleq	35	>6000-7000†		2
Zirphaea crispata (L.)				
9 'Zirphaea halvøen'* }	6.8	4870±110	K-1816	1,4
'Zirphaea halvøen' }	6.8	5190±100	K-2021	1,5
10 'Zirphaea pynt' }	13	5040±140[a]	Hel-330	6
11 Orpigsûp tasia	40	>6700†		1
12 Magnetsandbukten }	6	>3500†		1
Magnetsandbukten }	6	7220±120[x]	I-10279	3
Emarginula fissura (L.)				
6 Gieseckes Sø	24-26	>5000-6000†		1
Acmaea virginea (Müll.)				
8 Egedesminde	6	>3500†		1
6 Gieseckes Sø	22.5	5660±100[x]	K-2024	1
Alvania jeffreysi (Waller)				
6 Gieseckes Sø				1
Littorina obtusata[b] L.				
9 'Zirphaea halvøen'	6.8	4870-5190	K-1816, 2021	1,4,5
6 Gieseckes Sø				1
4 Ikerasârssuk	7	>3500-5000†		2

Locality nos. refer to fig. 3C. * several occurrences, † dates based on emergence curves of Kelly (1979) and Donner & Jungner (1975), [a] species itself dated (otherwise other species in fauna were dated), [x] relationship to species uncertain, [b] limited modern occurrence.
Refs: 1 Laursen (1950); 2 Jensen (1942); 3 Kelly (1979); 4 Weidick (1972b); 5 Weidick (1974); 6 Donner & Jungner (1975). $\delta^{13}C = +0.6$ °/oo.

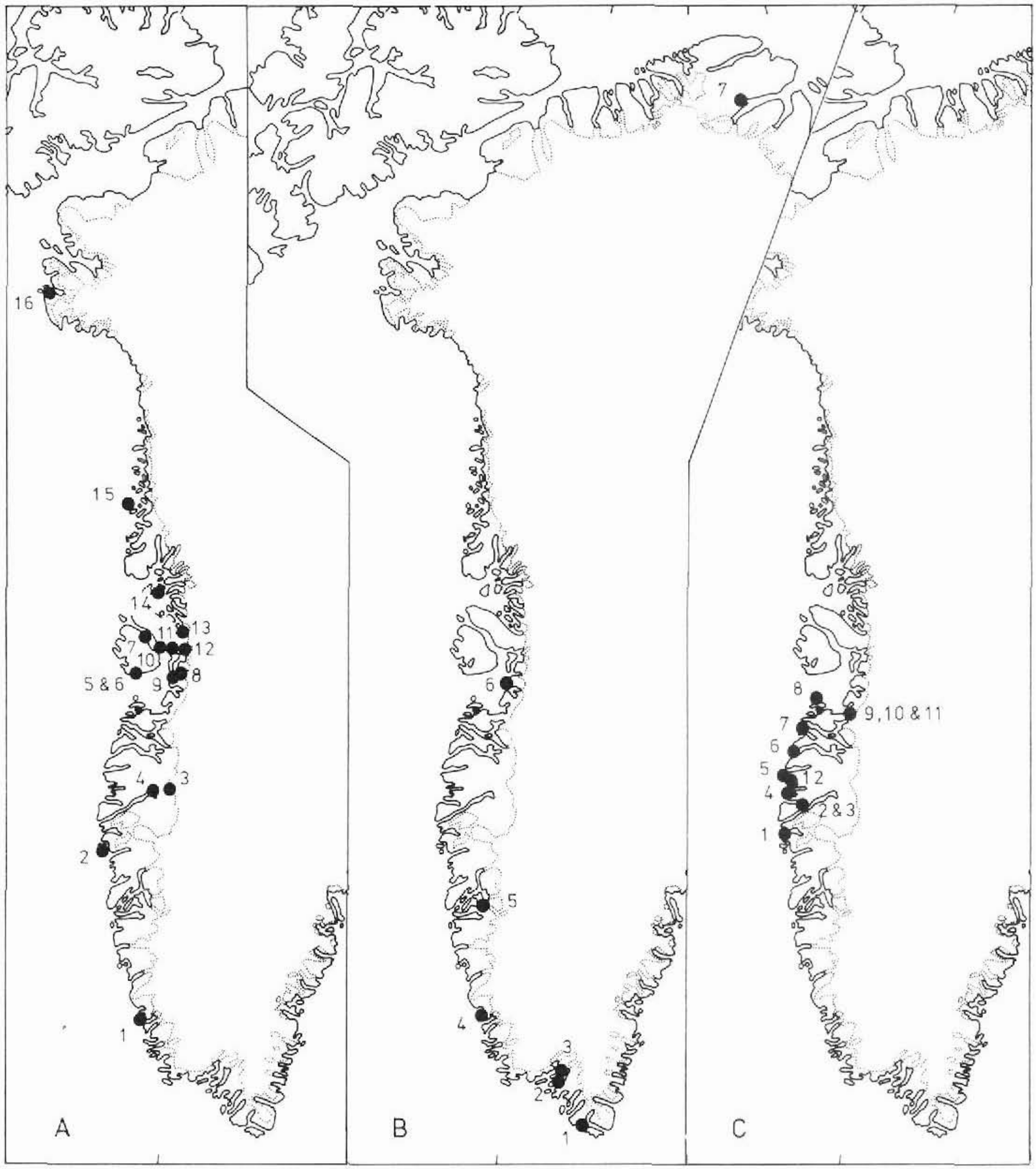

Fig. 3. A. Localities for *Rhizocarpon geographicum* growth rate determinations (Table 5). B. Localities with faunal or floral changes related to climatic deterioration (Table 6). C. Localities with extinct thermophilous molluscs (Table 7).

deterioration throughout western Greenland, giving conditions presumably appropriate for glacier expansion. The first, somewhat ambiguous, signs occur around 3200 B. P. , with a clearer indication of more severe conditions around 2000 B. P. Synchroneity of dates from different places however must not be expected since different floristic elements responding to different climatic factors will be involved, due to geographical and local variation.

Fredskild (1973) has identified the presence of a milder phase in the mid-Neoglacial at several localities, which is then followed by the late Neoglacial deterioration commencing at 500–700 B. P. There is no evidence in the data however of the relative intensities of the cold phases before and after 1000 B. P.

The marine faunal evidence includes an estimated date for the initial deterioration of 3800 B. P. This is deduced from a temperature related change in benthic foraminifera in a core from southern Greenland, dated by extrapolation from a single ^{14}C determination (Herman, O'Neil & Drake, 1972).

In addition there is the evidence of the extinction (or virtual extinction) of thermophilous marine mollusc species, whose presence marked the optimum in the marine climate. Table 7 (fig. 3C) lists the records of the occurrence of these species, many of which can only be dated indirectly from uplift data. From this it appears that the drop in temperature presumably responsible for their disappearance from western Greenland took place some time after 5000 B. P. It is probable that this date does not closely define the drop because faunas of younger date are going to occur very close to modern sea level, with less likelihood of preservation, or collection.

GLACIO-ISOSTASY

Some evidence of the Neoglacial glacier development is recorded in the glacio-isostatic history of Greenland.

For the major part of the Holocene all of western Greenland appears to have experienced isostatic emergence, although with a geographical variation in contemporaneous uplift rates. However a recent interval of submergence has been recorded by early tidal observations, and also by the inundation of Norse and Medieval and older Eskimo ruins (fig. 4A).

The tidal data is mainly approximate because of the nature of the sea level datum used, *Balanus* limit at six sites (Saxov, 1958), observed mean sea level at one (Gabel-Jørgensen & Egedal, 1940). However the trend seems clearly to indicate a period of subsidence from the late 19th century until 1940–1950, followed subsequently by uplift, with the maximum subsidence recorded being 0.475 m at Godhavn (1897–1946), equivalent to 10 mm y^{-1} (Table 8).

Mathiassen (*in* Gabel-Jørgensen & Egedal, 1940) states that at 72 sites from Upernavik to Kap Farvel there are Eskimo houses from recent cultural phases which are partly washed away due to submergence. Although it is possible that these include houses destroyed by lateral coast erosion only, in all areas there are some sites where the houses are now below high water mark (Mathiassen, 1930, 1931, 1934, 1936). The houses affected date from approximately A. D. 1600–1860. Although there are no records of submerged early Medieval Eskimo houses there are several Norse ruins below high water mark (Roussell, 1941) including Sandnes church in the West Settlement (Godthåbsfjord) abandoned around

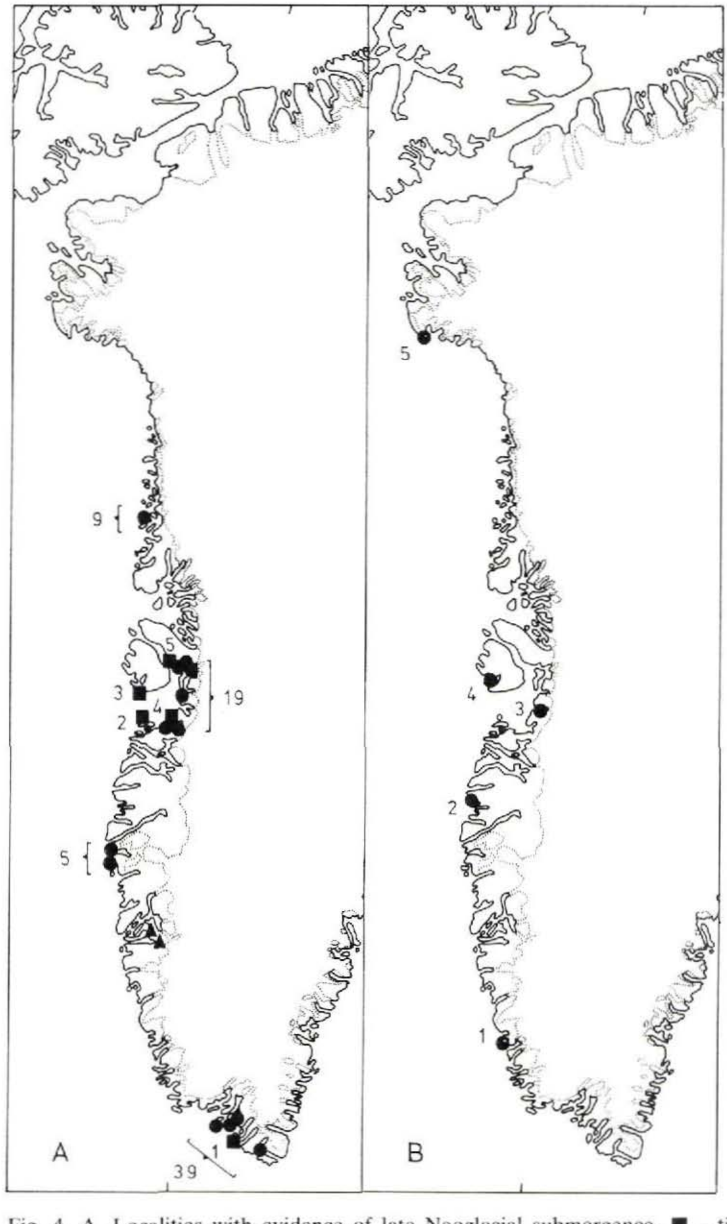

Fig. 4. A. Localities with evidence of late Neoglacial submergence, ■ – tidal data (Table 8), ▲ – submerged Norse ruins, ● – submerged Eskimo ruins. Total numbers of sites with washed away ruins in an area, according to Mathiassen (in Gabel-Jørgensen & Egedal, 1940), is shown with a bracket. B. Localities with dates relating to attainment of present sea level (Table 9).

Table 8. Recent sea level changes from tidal data

Locality	Period A.D.	Change in sea level m	Ref.
1 Nanortalik	1883-1933	-0.19	1
2 Egedesminde	1923-1946	-0.212	2
Egedesminde	1946-1957	+0.143	2
3 Godhavn	1897-1946	-0.475	2
Godhavn	1946-1957	+0.3	2
4 Christianshåb	1950-1957	+0.104	2
5 Sarqaq	1950-1957	+0.101	2

Locality nos. refer to fig. 4A.
Refs: 1 Gabel-Jørgensen & Egedal (1940); 2 Saxov (1958).

A. D. 1350. On the evidence of the latter site Roussell puts the subsequent submergence at at least 5 m.

Weidick (1975a) has pointed out the coincidence of the subsidence with the Historical glacial advance, presumably inferring that it was the direct isostatic response to the advance. The older idea (Gabel-Jørgensen & Egedal, 1940) that the subsidence was complementary to glacio-isostatic uplift beyond a hinge line does not seem tenable because of the distribution of the subsidence, which occurs both near the outer coast and the ice margin.

Palaeo-Eskimo sites dating back to 3500 B. P. are also found submerged and these together with other evidence presented in Table 9 show that submergence has caused the sea to transgress to levels on the land which originally emerged 3000–4000 B. P. or perhaps earlier in south Greenland.

It is not considered that emergence, or uplift, since the eustatic contribution was then negligible, had ceased at these dates. Rather it is suggested that this is an artifact of a Neoglacial transgression which would have occurred not only in the late Neoglacial as recorded, but also in the early Neoglacial, accompanying the initial increases in glacierisation. The magnitude of the submergence would be expected to vary regionally. For the late Neoglacial alone Weidick (1976) gives a general figure of a few metres whilst Roussell's (1941) estimate is 5 m. There are also geotechnical records of features below sea level identified as subaerially weathered surface layers of marine clays now below sea level, e.g. at

Table 9. Dates relating to the first attainment of present sea level

Location	Evidence	Height above HWMS	Min. (>) or Max. (<) date B.P. for present sea level	^{14}C Lab. No.	Ref.
1 Frederikshåb	basal lake sed.	~1 ★	<4780±120	K-1152	1
2 Kángârssuk	peat	1.2	>(<)1955±90	I-10281	2
Kángârssuk	peat	0.6	>(<)1300±130	I-10282	2
3 Qajâ	archaeol.	<0	>2700-3500		3,4,5
4 Ikineq	peat	<0	>970±110	Hel-945	6
5 Kap York	peat	<1 ★	>(<)2810±70	HAR-2885	5

Locality nos. refer to fig. 4B. ★ based on approx. spring tide height.
Refs: 1 Kelly *in* Weidick (1972c); 2 Kelly (1979); 3 Fredskild (1967); 4 Larsen & Meldgaard (1958); 5 Kelly (unpublished); 6 Donner (1978).

– 5 m at Holsteinsborg and – 8 m at Narssaq (Foged, 1979, and personal communication). The nature and extent of such a transgression would seem to be adequately explained by an extension of the marginal depressed zone around the ice sheet, according to the model of Walcott (1969), following the Neoglacial advance of the margin. With this model a subsidence of ~10 m could be produced at the outer coast at its farthest distance from the Ice Sheet margin by an overall advance of 15 km.

Theoretically the shape of emergence curves should express to some degree the detailed behaviour of the Ice Sheet in the Neoglacial, but in practice none of the uplift data available is sufficiently precise to be used in this way. Only the general conclusion can be drawn that the glacio-isostatic data for the early Neoglacial is compatible with an initial advance of the Ice Sheet before or around 3000 B. P., and that any transgression produced has culminated in the late Neoglacial at the time of the Historical advance.

DISCUSSION

The information given in Table 1, and other dates, demonstrate that the Ice Sheet had reached its present size in the west in the first half of the Holocene. This state appears to have been achieved earlier in the south, 8000–10000 B.P. than in the central sector, ~6500 B. P. The situation in the north is less clear but may parallel that in the south. Since the first indications of conditions suitable for glacier growth are not until 3000–3500 B. P. there is a long interval of 3000–6000 years with a climate probably milder than today which could have had a substantial effect on the size of the Ice Sheet. Only if temperature related ablation increases were partly offset by accummulation increases would this effect be minimised.

That the Ice Sheet has been smaller is clearly shown by the reworked non-glacial material in the Neoglacial moraines which in a few places indicate a retreat of at least 10 km. It is notable that at one of these localities (Qaleragdlit) this represents about 20 per cent of the total apparent Holocene retreat. Extrapolation of the retreat rates typical of the central sector from 6000–8000 B. P. (~0.02 km y^{-1} (Kelly, 1975a; Ten Brink, 1975)) into this mid-Holocene interval gives very large retreats behind the present margin of 60–120 km. Such values, implying in particular a major change in size of the south Greenland Ice Sheet, are probably not credible. Weidick (1975d) in his model of past Ice Sheet mass balances has emphasised the role of increased accummulation in producing a stable Ice Sheet in the late Holocene compared to its Wisconsin-Wurm condition. Similar but smaller magnitude changes could also play a role in minimising the probable mid-Holocene temperature related ablation increases. Despite this it does appear at the moment that an overall retreat of the margin of several tens of kilometres is allowed by the data at least.

Much of the evidence available points to the subsequent growth of the Ice Sheet in the Neoglacial having reached its maximum in most areas at the time of the late Neoglacial Historical advances. Only a few sections of the margin are known, so far, to have responded more to an earlier cold phase. This is not yet dated but may prove to correlate with the intensification of the climatic deterioration around 2000 B. P. suggested by the palaeo-botanical evidence. The growth of local glaciers also appears to have culminated in the late Neoglacial and no early Neoglacial advances of them have yet been positively identified.

Some local glaciers appear to have never had a greater extent than in the Historical whilst others have definitely been larger in the early Holocene.

This model of the behaviour of the Greenland ice bodies in the Neoglacial is of course not conclusively proven and further evidence may support one of the alternatives. Theoretically, between the extremes of a later or early Neoglacial maximum for glacierisation lies the intermediate alternative of ice margins responding more or less equally to a succession of comparable cold phases with local or regional factors determining which advance has the slight advantage. Added to these alternatives is the choice of a magnitude for the mid-Holocene retreat. The current wide range of climates in western Greenland: sub-arctic, low arctic and high arctic with maritime to continental gradations emphasises the probability of a geographical variation in behaviour in the Neoglacial; although the nature of the recorded response throughout Greenland to the later Neoglacial climatic changes puts this likely variation in perspective. What evidence there is suggests that in the Holocene in general three regions with somewhat different behaviours can be distinguished: north, central and south, approximately divided at 72°N and 64°N.

An assessment of the Neoglacial behaviour of the North and East Greenland sectors of the Ice Sheet, and their local glaciers, is premature as new work is in progress there. Weidick (1972a) summarised the older information available. This seems to point to a largely similar history to that proposed for western areas, with a late Neoglacial maximum and no definitely proven early Holocene advances. One departure from the western history recently described is an earlier date for the beginning of the climatic deterioration in East Greenland: 5000 B. P. at Scoresby Sund (Funder, 1978), with the earlier onset being related to the development of the northern hemisphere atmospheric circulation pattern.

The ultimate version of the history of the Ice Sheet itself should be that available from the isotope studies of the Ice Sheet cores (Dansgaard *et al*, 1973, 1975). Accepting that there remains some uncertainty about the relationship of the $\delta^{18}0$ values to temperatures and about the dating of the core, it still clearly records the main climatic development of the Holocene in considerably more detail than the generalised geological record can give. The main features of the Camp Century core from North-West Greenland are, the prolonged duration of a climatic optimum warmer than the present day datum (3500–8000 B. P. (^{14}C years)), two early Neoglacial cold intervals (2400–2800 and 3000–3500 B. P.), and a complex one in the late Neoglacial. The latter is covered in more detail in the Crête core from the centre of the Ice Sheet, referred to earlier, which shows a sequence of cold episodes for the whole late Neoglacial from about 900 B. P. Thus there is good agreement with the geological data about the beginning of climatic deterioration. However there is no evidence in the cores of a difference in severity of early and late Neoglacial cold intervals. Despite this if the ice margin had retreated considerably in the mid-Holocene the effects of the cold intervals might need to be cumulative to bring it to its present position, and hence the later Neoglacial advances would over-ride the earlier, as interpreted. For smaller ice masses, and special sectors of the ice margin, there might remain the possibility of a series of equal advances.

CONCLUSIONS

The current status of understanding about the behaviour of the Ice Sheet and local glaciers in western Greenland in the Neoglacial is one of uncertainty. No model of behaviour has been conclusively proven to be valid. However at the moment the most probable one is as follows. After a significant and perhaps large decrease in size in the mid-Holocene the Ice Sheet and local glaciers, responding to a climatic deterioration, began to grow about 3000–3500 B. P. Although there is evidence of severer climate around 2000 B. P. glacierisation did not reach its maximum until another cold phase after 1000 B. P. The intervening mild interval ~1500–1000 B. P. is used to separate the early and late Neoglacial periods. In the late Neoglacial the maximum was mostly reached in the final Historical advances 50–450 B. P., although at one section of the Ice Sheet an earlier late Neoglacial advance was larger. At two other sections of the Ice Sheet margin probable early Neoglacial moraines are known which are thought to represent an anomalous development. No early Neoglacial moraines have been identified conclusively yet at local glaciers.

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